Higher Secondary Course

ELECTRONICS

Class - XI

Government of Kerala

DEPARTMENT OF EDUCATION

State Council of Educational Research and Training (SCERT) Kerala

2016

THE NATIONAL ANTHEM

Jana-gana-mana adhinayaka, jaya he
Bharatha-bhagya-vidhata.
Punjab-Sindh-Gujarat-Maratha
Dravida-Utkala-Banga
Vindhya-Himachala-Yamuna-Ganga
Uchchala-Jaladhi-taranga
Tava subha name jage,
Tava subha asisa mage,
Gahe tava jaya gatha.
Jana-gana-mangala-dayaka jaya he
Bharatha-bhagya-vidhata.
Jaya he, jaya he, jaya he,
Jaya jaya jaya, jaya he!

PLEDGE

India is my country. All Indians are my brothers and sisters.

I love my country, and I am proud of its rich and varied heritage. I shall always strive to be worthy of it.

I shall give my parents, teachers and all elders respect, and treat everyone with courtesy.

To my country and my people, I pledge my devotion. In their well-being and prosperity alone lies my happiness.

State Council of Educational Research and Training (SCERT)
Poojappura, Thiruvananthapuram 695012, Kerala

Website : www.scertkerala.gov.in *e-mail* : scertkerala@gmail.com
Phone : 0471 - 2341883, Fax : 0471 - 2341869
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Foreword

Dear Students,

It is with immense pleasure and pride that State Council of Educational Research and Training (SCERT) Kerala brings forth its first textbook in Electronics for higher secondary students of XIth standard. Our endeavor to revise the syllabus and prepare a textbook of Electronics has fulfilled a long cherished dream of teachers and students of the subject at higher secondary level.

Electronics is a very highly demanded discipline in the modern era. It is a growing science which aims to make a difference in the world by dealing with technology advanced in all places and at all times. The rapid development of Electronics extremely influences the lifestyle of every human being and causes to improve the facilities in all fields of life. The tremendous career and research opportunities in the field of Electronics engineering and technology worldwide encourage many of the science students to go for their higher studies in this field. Moreover it is worthwhile if the study of science and technology in school level supports students in skill acquisition and develops aptitude towards entrepreneurship. These are some of the facts which led to the introduction of Electronics as an optional subject for higher secondary level. The students can utilize the knowledge acquired from the classroom to design and develop innovative devices to be used in various situations in their day to day life. I am sure that the study of Electronics at higher secondary level will be a stepping stone for students to enter the vast and amazing world of technology.

This textbook is the result of a combined effort of a team of practicing teachers and experts in Electronics in the state of Kerala. I hope that the students of this subject would make full use of the inputs offered in the book.

Wish you all success.

Dr P. A. Fathima
Director
SCERT; Kerala

TEXTBOOK DEVELOPMENT TEAM

Binukumar M.R.
HSST (Electronics)
Karimpuzha HSS, Thottara
Palakkad

Aneeshkumar T.V.
HSST (Electronics)
Govt. HSS, Aralam, Kannur

Baiju A.J.
HSST (Electonics),
St.Augastins HSS. Karimkunnam,
Idukki

Siji George
HSST (Electronics), St. George's HSS,
Muthalakodam, Idukki

Ferish George
HSST (Electronics),
St.Aloysius HSS, Elthuruth,
Thrissur

Amal John
HSST (Electronics)
St.Sebastian's HSS
Vazhithala, Thodupuzha

Kuryachan T.D.
(Design and Drawing)
Foreman (Hr. Grade)
College of Engineering
Karunagappally

Viphy Markose
HSST (Electronics)
Govt. HSS, Marayamuttam
Neyyattinkara

Nithya Prasannakumar
HSST (Electronics), Govt. V&HSS
Kulathoor, Neyyattinkara

EXPERTS

Dr. Vrinda V. Nair
Prof. & HOD, Dept. of ECE , College of Engineering, Trivandrum

Dr. Deepa P. Gopinath
Asst. Prof, Dept. of ECE, College of Engineering, Trivandrum

Ajayan K. R.
Associate Prof, Dept. of ECE, College of Engineering, Trivandrum

Leena T. L.
Asst. Prof.,(English), Govt. College, Kanjiramkulam, Trivandrum

ACADEMIC CO-ORDINATORS

Dr. Ancey Varughese
Research Officer, SCERT, Kerala

Reeja M.
Research Officer, SCERT, Kerala

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INTRODUCTION TO ELECTRONICS

INTRODUCTION

Have you ever thought about the importance of electronics in our daily life? The electronic devices and their usages have influenced our daily life in such a way that it is impossible to spend even a few hours without them. Right from the beginning of the day till the time we go to bed, we use a large number of electronic gadgets to simplify our work and to solve our problems. From small alarm watches to the complex computers, from mobile to the camcorders, from kitchen to toilet, from bedroom to office, everywhere electronic items can be seen. It seems that they are omnipresent.

Why have we become so dependent on electronics? The answer is very simple. They simplify our daily activities and lifestyle. Let us take the example of mobile phone. It has changed the definition of communication. In the beginning of the history of telephone system, no one would have imagined a combination of 'talking and walking.' The invention of mobile phones has made talking while walking possible.

CD drives, DVD players, record players, stereos and tape recorders are the result of the advancement in electronic technology in the last few decades. With the use of headphones, music can be heard without disturbing the people nearby.

The introduction of electronic technology in cameras has completely changed the history of photography. A digital camera is now available at an affordable price. The cell phones now include a fairly sophisticated digital camera that can capture still pictures and even video pictures. The videos and pictures can be easily transferred to a computer, where they can be saved, shared on internet or printed out in hard form. Such pictures taken from a camera can be edited, cropped, enhanced or enlarged easily with the help of electronics.

Even our kitchens are equipped with electronic equipment, from water coolers to microwave ovens. Doctors and scientists have found new uses of electronic systems in the diagnosis and treatment of various diseases. Equipment such as MRI, CT and the X-rays rely on electronics in order to do their work quickly and accurately.

Activity 1

Prepare a list of electronic equipment that are used in your day to day life.The figure 1.1 will help you to do this activity.

Fig 1.1 Some applications of electronics in daily life

- *Have you realized that electronics plays a very important role in your daily life?*
- *Do you wonder about the rapid development of electronic equipment in every field of life?*

1.1 WHAT IS ELECTRONICS?

The electronic equipment mentioned in the previous section have several electronic components in it like resistors, inductors, capacitors, diodes, transistors, ICs, etc. The components like diodes, transistors and ICs are made up of semiconductor materials. The working of these components is based on the amount and direction of current flowing through them.

The word electronics means -'pertaining to electrons'. Electronics can be defined as the branch of science and engineering which deals with the controlled flow of electrons through vacuum, gas or semiconductors.

Compared to the more established branches of engineering - civil, mechanical and electrical, electronics is a newcomer. Until around 1960, it was considered as an integral part of electrical engineering. But due to the tremendous advancement over the last few decades, electronics has now gained its own place. The advancement has been so fast that many sub-branches of electronics - such as Computer Science Engineering, Communication Engineering, Control and Instrumentation Engineering and Information Technology - are now full-fledged courses in many universities.

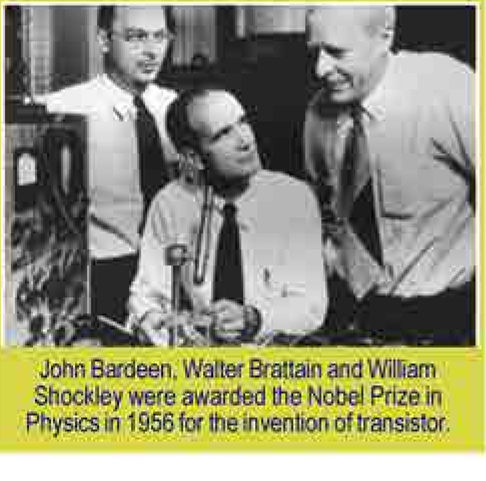
1.2 HISTORY OF ELECTRONICS

Invention of Vacuum Tubes

Electronics took birth in 1897 when J.A. Fleming developed a vacuum diode. Useful electronics came in 1906 when vacuum triode was invented by Lee De Forest. This device could amplify electrical signals. Later, around 1925, tetrode and pentode vacuum tubes were developed. These tubes dominated the field of electronics till the end of World War II.

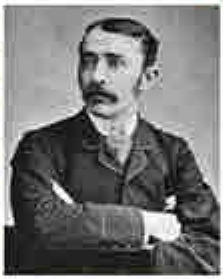
Invention of Transistor

The era of semiconductor electronics began with the invention of the junction transistor in 1948 at Bell Laboratories. Soon, the transistors replaced the bulky vacuum tubes in different electronic circuits. The tubes had major limitations: power was consumed even when they were not in use and filaments burnt out, requiring frequent tube replacements. By now, vacuum tubes have become obsolete.



John Bardeen, Walter Brattain and William Shockley were awarded the Nobel Prize in Physics in 1956 for the invention of transistor.

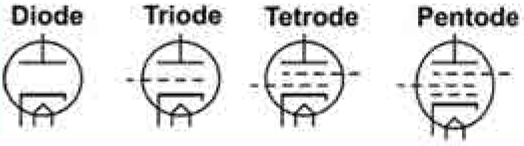
VACUUM TUBES



Sir John Ambrose Fleming

A vacuum tube, electron tube or thermionic valve is a device controlling electric current through a vacuum in a sealed container. The container is often made with thin transparent glass in a roughly cylindrical shape. The simplest vacuum tube, the diode, is similar to an incandescent light bulb with an added electrode inside. When the bulb's filament is heated red-hot, electrons leave its surface into the vacuum inside the bulb. If the electrode-called a "plate" or "anode"-is made more positive than the hot filament, a direct current flows through the vacuum to the electrode.

As the current flows only in one direction, it is possible to convert an alternating current applied to the filament to direct current. As electrodes are added, these devices can be used for various other applications. Tubes with three electrodes are known as triodes, that with four as tetrodes and five as pentodes.

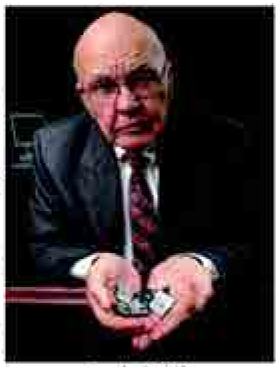


Earlier, the transistors were made of germanium, as it was easier to purify. In 1954, silicon transistors were developed. These afforded operations up to 200°C, whereas germanium device could work well only up to about 75°C. Today, almost all semiconductor devices are fabricated using silicon.

Invention of the Integrated Circuits (IC)

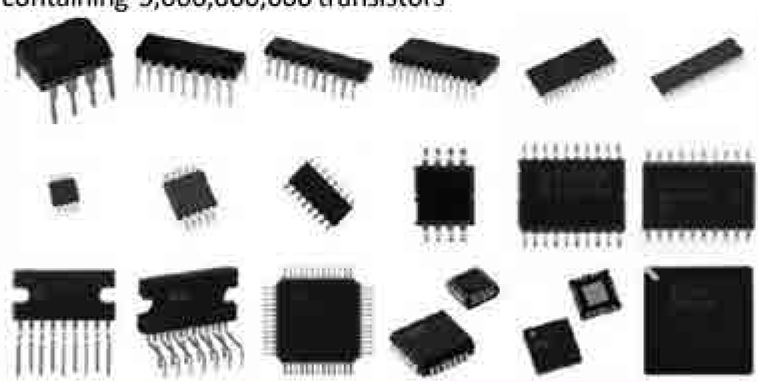
In 1958, Jack Kilby conceived the concept of building an entire electronic circuit on a single semiconductor chip. Later, all active and passive components and their interconnections could be integrated on a single chip. This drastically reduced the size and weight, as well as the cost of electronic equipment.

The following approximate data give some indication of the increasing component count per chip of area 3×5 mm^2 and thickness comparable with human hair.



Jack Kilby

- 1951 - Discrete transistors
- 1960 - Small-Scale Integration (SSI), fewer than 100 transistors.
- 1966 - Medium-Scale Integration (MSI), 100 to 1000 transistors.
- 1969 - Large-Scale Integration (LSI), 1000 to 10000 transistors.
- 1975 - Very-Large-Scale Integration (VLSI), more than 10000 transistors.
- 1994 - Ultra-large-scale integration (ULSI) more than 1 million transistors.
- 2012 - INTEL introduced a computer processor chip (62-Core Xeon Phi) containing 5,000,000,000 transistors



1.3 APPLICATIONS OF ELECTRONICS

Electronics plays an important role in almost every sphere of our life. Electronics has penetrated in every field from an ordinary wrist watch to super computers; from telephone repeaters buried deep under sea to the satellites far out in space; from the control of modern household appliances to the control of super tankers carrying cargo across the sea.

Communication and Entertainment

The progress of a nation depends upon the availability of cheaper and faster means of communication. The main application of electronics in the beginning was in the field of telephony and telegraphy. These utilize a pair of wires as communication channel. Later it was possible to transmit any message from one place to another without wires (wireless communication). Satellite communication has reduced the distance between people and places.

Sir Jagadish Chandra Bose (30 November 1858 - 23 November 1937) was a Bengali physicist, biologist, botanist, archaeologist, as well as an early writer of science fiction. He pioneered the investigation of radio and microwave optics, made very significant contributions to plant science and laid the foundations of experimental science in the Indian subcontinent.

Achievements of Sir J. C. Bose in the field of communication

- He invented the Mercury Coherer (together with the telephone receiver) used by Guglielmo Marconi to receive the radio signal in his first transatlantic radio communication over a distance of 2000 miles from Poldhu, UK to Newfoundland, St. Johns in December 1901.
- In 1895, he gave his first public demonstration of electromagnetic waves, using them to ring a bell remotely and to explode some gunpowder. He sent an electromagnetic wave across 75 feet passing through walls of the room and body of the Chairman, Lieutenant Governor of Bengal.
- He holds the first patent worldwide to detect EM waves using solid-state diode detector.
- He was a pioneer in the field of microwave devices.

Radio and TV broadcasting provide a means of both communication as well as entertainment. Electronic gadgets like tape recorders, music and video players, stereo systems, public address systems, etc. are widely used for entertainment.

Applications in Defence sector

In a war, success or defeat of a nation depends on the reliability of its communication system. In modern warfare, communication is almost entirely electronic. Guided missiles are completely controlled by electronic circuits.

One of the most important developments during World War II was the RADAR (Radio Amplification Detection And Ranging). By using RADAR it is possible not only to detect, but also to find the exact location of the enemy aircraft. The anti-aircraft guns can then be accurately directed to shoot down the aircraft. In fact the RADAR and anti-aircraft guns can be linked by an automatic control system to make a complete unit.

Applications of electronics in defence: Missiles, RADARS, warplane and communication setup

Instrumentation

Instrumentation plays a very important role in any industry and research organisation, for precise measurement of various quantities. Very accurate and user-friendly instruments like digital voltmeter (DVM), cathode ray oscilloscope (CRO), frequency counter, signal generator, strain gauge, pH-meter, spectrum analysers, etc. are some of the electronic equipment without which no research laboratory is complete.

Medical Electronics

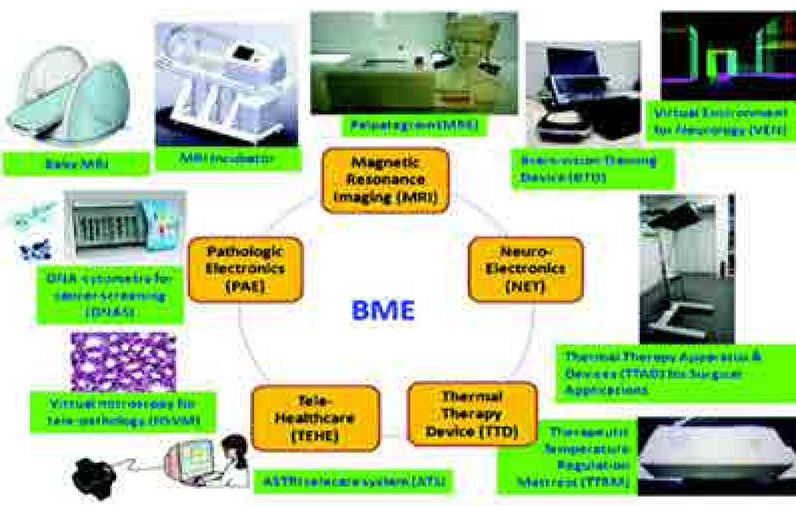


Fig 1.2
Some applications of electronics in Medical field

Electronic equipment are being used extensively in medical field. They not only assist in diagnosis but also help in the researches that provide treatment and cure for illnesses and even genetic anomalies. Examples are Electron microscope, ECG, EEG, X -rays, defibrillator, oscilloscopes, MRI, CT scanner, glucometer, etc. Some of the instruments are shown in the fig. 1.2.

Activity 2

Prepare a list of electronic devices that are used in medical field. Mention their applications also.

- *Do you know which instruments are used to determine the condition of heart of a patient?*
- *Which instrument is used to take pictures of the internal bone structure of a patient?*

Applications in Industries

Use of automatic control systems in different industries is increasing day by day. The thickness, quality and weight of a material can be easily controlled by electronic circuits. Electronic circuits are used to control the operations of automatic door openers, lighting systems, power systems, safety devices, etc.

Use of computer has made the ticket reservations in railways and airways simple and convenient. Even the power stations, which generate thousands of megawatts of electricity, are controlled by electronic circuits.

Applications in Automobiles

Several electronic equipment are used in cars for charging battery, enabling power assisting functions, measuring gauges and monitoring and controlling the engine performance. The most important application is electronic ignition, which provides better timing of the ignition spark, especially at high speeds.

Automobile industry is one of the fastest growing sectors in the world. The end users are demanding greater fuel efficiency, security and safety. This is possible because of the rapid development in the technology. Other areas of application in automobile are parking sensors, auto wipers, auto lights, safety (eg. Air bags), security, anti-theft systems, etc.

Consumer Electronics

We use fans in our home, class rooms, library, etc. You are familiar with the electronic regulators used with them. Have you ever thought of the mechanism behind that? Here we use an electronic component known as TRIAC to control the speed of the fan. The speed of the fan is directly proportional to the electric power reaching the motor. The regulator controls the speed by controlling the electric power. The regulator controls electric power according to the position of the knob. Special electronic components like Silicon Controlled Rectifiers (SCRs) are used in the speed-control of motors, power rectifiers and inverters.

ELECTRONICS INSIDE A CAR

Engine : The engine is the heart of a car. The circuit that automates the amount of fuel that should enter the engine is governed by the Electronic Control Unit (ECU). It decides the amount of fuel to be injected inside the engine with the help of the pressure sensor, throttle position sensor, oxygen sensor, fuel injector, etc. The main aim of using the ECU is to increase the fuel efficiency of a car.

Transmission : Typically, there are two types of transmission used in cars - manual and automatic, also known as manual gearing or automatic gearing. Electronics plays a more significant role in automatic-transmission. Herein, the automatic transmission of a car is controlled by the Transmission Control Unit (TCU). The TCU collects information from the sensors attached to the vehicle. It further uses the data to do gear shifting at the right time, which helps to increase the car's performance.

Brakes : Anti-lock Brake Systems (ABS) are becoming increasingly popular in cars. This system helps to stop the car faster without losing the balance. The ABS has four major parts- speed sensors, controllers, valves and pump. The first two utilizes electronic circuits.

Dashboard : The dashboard basically contains panels that show the readings of the different sensors. It gives indication of the fuel level, the speed at which the car is running, the information regarding the oil level, the neutral state of car, etc. The dashboard of a car can also have the GPS, audio systems, air-conditioner controls, etc.

Home appliances are used 24 hours a day, 7 days a week. It includes personal computers, telephones, audio equipment, televisions, calculators, washing machines, DVD players, etc. Some home appliances are shown in the fig. 1.3.

(a) (b) (c) (d)

Fig 1.3 (a) Washing machine (b) TV (c) Radio (d) Mobile Phone

> **Activity 3**
>
> *Prepare a list of electronic equipment that you know like those given below and classify them according to their fields of applications*
>
> *eg. Radio, Television, Home theatre, Radar, X ray, ECG, Electric Piano, Traffic control.*

1.4 ELECTRONIC COMPONENTS - ACTIVE AND PASSIVE

Electronic components can be broadly classified into active and passive components. Active Components are electronic components which are capable of amplifying or processing an electrical signal, e.g.: Diodes, Transistors, etc. Passive Components are electronic components which are not capable of amplifying or processing an electrical signal, e.g.: resistors, capacitors and inductors.

1.5 RESISTORS

A resistor is a two terminal component which provides resistance to the flow of current in a circuit. The symbols are shown in fig. 1.4.

All resistors have power ratings. It is the maximum power that can be dissipated without damaging the component. Thus, a 1 watt resistor with a resistance of 100 Ω can pass a maximum current of 100 mA.

The size of a resistor is usually bigger if its wattage rating is higher, so as to withstand higher power dissipation. Resistors can be broadly classified into two groups-fixed and variable.

Fig 1.4 Symbols of Resistor

Fixed Resistors

A fixed resistor is one for which the value of its resistance is specified and cannot be varied in general. These resistors may be carbon-composition resistors, carbon film resistors or wire wound resistors.

Carbon composition resistor

The resistive material in carbon composition resistor is of carbon-clay composition. The two materials are mixed in the proportions needed for the desired value of the resistor. The value of the resistor is directly proportional to the amount of the mixture. The resistor element is enclosed in a plastic case as shown in figure, for insulation and mechanical strength.

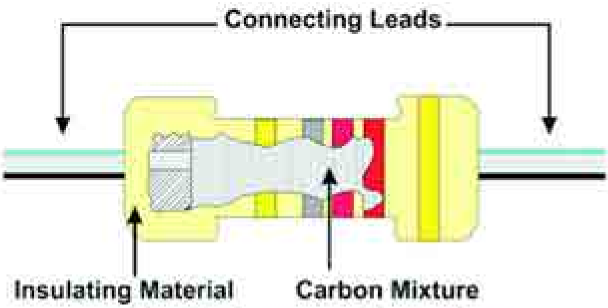


Fig 1.5 Carbon composition Resistor

The leads are made of tinned copper. Resistors of this type are readily available in values ranging from a few ohms to about 22 MΩ, with tolerance range of 5 to 20 %, and wattage ratings of ¼ W, ½ W, 1 W and 2W.

Carbon film resistors

Carbon film resistors are made by depositing a homogeneous film of pure carbon over a glass, ceramic or other insulating core. Its basic structure is shown in fig. 1.6.

Desired values are obtained by either trimming the layer thickness or by cutting helical grooves of suitable pitch along its length. During this process the value of resistance is monitored constantly. The cutting of grooves is stopped as soon as the desired value of resistance is obtained. Contact caps are fixed on both ends. This type of film resistor is sometimes called precision type as it can be obtained with tolerance of ±1 %.

Wire wound resistor

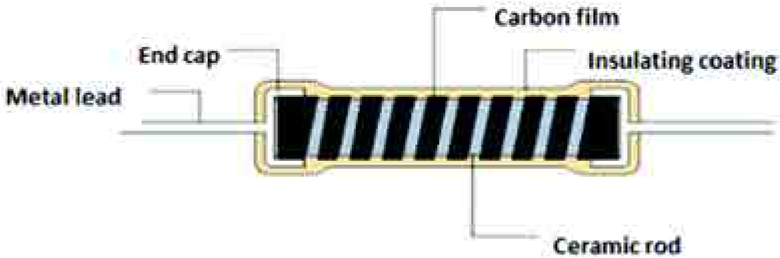


Fig 1.6 Carbon Film Resistor

When ratings of more than 1 watt are required, we generally use wire wound resistors. It uses a resistance wire such as nichrome. A thin nichrome wire is wound on a ceramic or porcelain core. The ends of the wire are attached to metal pieces inserted in the core. Tinned copper wire leads are attached to these metal pieces. This assembly is coated with enamel containing powdered glass. These resistors are available in the range of 1 Ω to 100 kΩ, and power ratings up to about 200 W.

Fig 1.7 Wire wound Resistor

Colour coding of Resistors

Carbon-composition and carbon film resistors are small in size. It becomes almost impossible to print the ratings on their body. Therefore, a standard colour coding is used to indicate the ratings.

The resistance is given in the form of four (or five) coloured signs (or bands) painted on the body. The coloured bands are always read from left to right from the end that has the bands closer to it, as shown in Fig. 1.8.

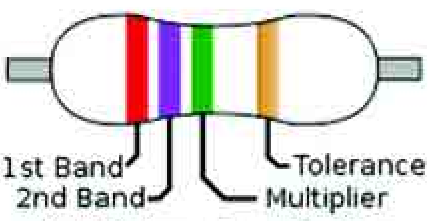


Fig 1.8 Colour coding of Resistors

The first and second colour bands represent the first and second numbers (significant digits) of the resistance value. The third band indicates the multiplication factor. The fourth band represents tolerance. It is a measure of the precision with which the resistor was manufactured. In case the fourth band is not present, the tolerance is assumed ±20 %. Resistance value calculation from colour coding is shown in Fig 1.9.

Colour	Significant figures	Multiplier	Tolerance
Black	0	$x10^{0}$	–
Brown	1	$x10^{1}$	±1%
Red	2	$x10^{2}$	±2%
Orange	3	$x10^{3}$	-
Yellow	4	$x10^{4}$	(±5%)
Green	5	$x10^{5}$	±0.5%
Blue	6	$x10^{6}$	±0.25%
Violet	7	$x10^{7}$	±0.1%
Gray	8	$x10^{8}$	±0.05%
White	9	$x10^{9}$	-
Gold	-	$x10^{1}$	±5%
Silver	-	$x10^{2}$	±10%
None	-	--	±20%

Fig 1.9 Colour Coding Table

For example a resistor has a colour band sequence: yellow, violet, orange and gold. With the help of the colour coding table in Fig. 1.9, we can calculate the value of this resistor as shown in the table below.

1st band	2nd band	3rd band	4th band	Value
Yellow	Violet	Orange	Gold	
4	7	10^3	± 5 %	47k Ω ± 5 %

Now 5% of 47k Ω is 2.35k Ω. Therefore, the resistance should be within the range 47 k Ω ± 2.35 k Ω, or between 44.65 k Ω and 49.35 k Ω.

In most electronic circuits, it is not necessary to use resistors of exact values. The circuit works satisfactorily even if the resistances differ from the designed values by as much as ±20 %. Therefore, we don't have to manufacture resistors of all values.

In the case of five band coding, the first three colour bands represent the significant digits, fourth band for the multiplication factor and fifth band for tolerance.

Standard values of commercially available resistors (with 10% tolerance)

Ohms (Ω)			Kilohms (kΩ)			Megohms (MΩ)	
1.0	10	100	1.0	10	100	1.0	10
1.2	12	120	1.2	12	120	1.2	12
1.5	15	150	1.5	15	150	1.5	15
1.8	18	180	1.8	18	180	1.8	18
2.2	22	220	2.2	22	220	2.2	22
2.7	27	270	2.7	27	270	2.7	
3.3	33	330	3.3	33	330	3.3	
3.9	39	390	3.9	39	390	3.9	
4.7	47	470	4.7	47	470	4.7	
5.6	56	560	5.6	56	560	5.6	
6.8	68	680	6.8	68	680	6.8	
8.2	82	820	8.2	82	820	8.2	

Check your progress

1. *We need a resistor of 4.7Ω with ±5 % tolerance. Find the sequence of the colour band on the resistor.*
2. *A resistor has a colour band sequence: red, red, green, yellow and silver. Find the range in which its value lies as per manufacturer's tolerance.*

Variable Resistors

In electronic circuits, sometimes it becomes necessary to adjust the values of currents and voltages while the equipment is in use. For example, it is often desired to change the volume of sound, the brightness of a television picture, etc. Variable resistors can be used to do such adjustments.

Big size variable resistors are usually called rheostats. In electronic circuits, we use small size variable resistors, and they are called potentiometers (usually abbreviated to 'pots'). The symbol for potentiometer is given in Fig. 1.10 (a). The arrow indicates the movable contact. The moving contact is used to vary the value of resistance in the circuit. Some have wire wound resistance as their primary elements, while others have a carbon film element. Figure 1.10(b) shows the basic construction of a wire wound pot. A resistance wire is wound over a dough-shaped core of Bakelite or Ceramic. There is a rotating shaft at the centre of the core. The shaft moves an arm and a contact point from end to end of the resistance element. The outer two terminals are the end points of the resistance element and the middle leads to the rotating contact.

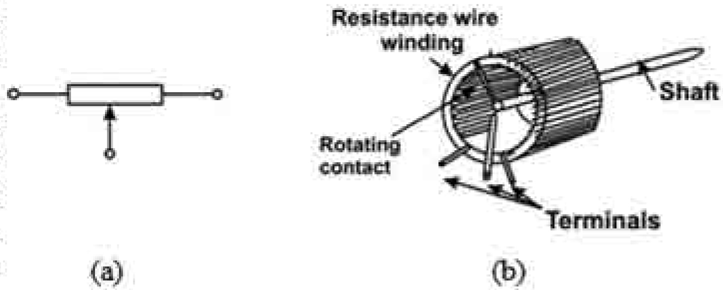


Fig 1.10 Potentiometer
(a) Symbol (b) Basic construction of a wire wound potentiometer

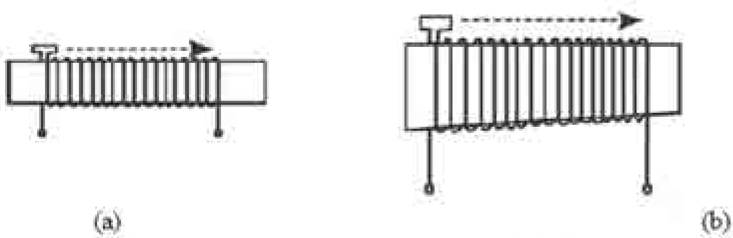


Fig 1.11 Wire wound potentiometer (a) Linear (b) Non linear

The variation of resistance in a potentiometer can be either linear or nonlinear. As shown in Figure 1.11(a), the linear type has the core (or former) of uniform height and that is why the resistance varies linearly with the rotation of contact. In a nonlinear potentiometer fig 1.11(b), the height of the former is not uniform. The core of the non-linear type is made from a tapered strip. The pots used as volume control in radio, tape recorders, etc. are generally of nonlinear type (with logarithmic variation).

1.6 CAPACITORS

A capacitor can store electrical energy in its electric field, and release it whenever desired. A capacitor opposes any change in the potential difference applied across its terminals. The capacitance of a capacitor is measured in farads (F). Capacitors vary in shape and size, but the basic configuration is two conductors separated by an insulating medium.

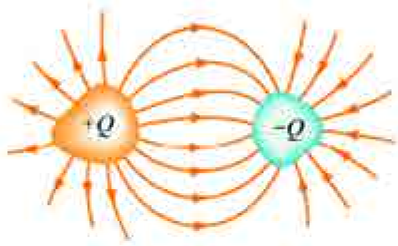


Fig 1.12 Basic configuration of a capacitor.

In the uncharged state, the charge on both of the conductors in a capacitor is zero. A capacitor can be charged by connecting a battery across it. During the charging process, a charge Q is moved from one conductor to the other, giving one conductor a charge +Q , and the other one a charge -Q. A potential difference is created, with the positively charged conductor at a higher potential than the negatively charged conductor. Note that whether charged or uncharged, the net charge on the capacitor as a whole is zero.

The simplest example of a capacitor consists of two conducting plates of area A, which are parallel to each other, and separated by a distance d, as shown in Figure 1.13.

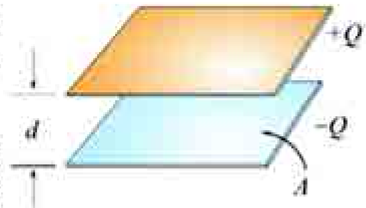


Fig 1.13 Parallel-plate capacitor

In a capacitor the plates are separated by an insulating material known as a dielectric. The factors affecting capacitance of a capacitor are dielectric material, area of the plate, thickness of the dielectric and the distance between the plates.

All other factors being equal, larger plate area gives higher capacitance. This is because larger plate area results in more charge to be collected on the plates for a given voltage across the plates. Closer plate spacing gives higher capacitance and larger plate spacing gives less capacitance. The higher permittivity of the dielectric gives larger capacitance and less permittivity gives less capacitance.

The capacitance of any parallel-plate capacitor can be calculated by the formula;

$$C = \frac{\varepsilon A}{d} \quad \text{.............1.1}$$

Where **C** is capacitance in farads and ε is permittivity of the dielectric.

Experiments show that the amount of charge Q stored in a capacitor is directly proportional to the electric potential difference (V) between the plates.

$$\mathbf{Q = C\ V} \quad \text{.................1.2}$$

Figure 1.14(a) shows the symbol which is used to represent capacitors in circuits. For a polarized capacitor (usually called electrolytic capacitor) which has a definite polarity, figure 1.14(b) is sometimes used. Figure 1.14 (c) is used to represent a variable capacitor.

Similar to resistor, a capacitor offers resistance to a signal passing through it. This is known as capacitive reactance. Capacitive reactance is given as:

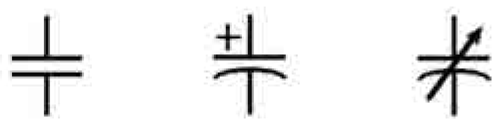


Fig 1.14 Capacitor symbols

$$\mathbf{Xc} = \frac{1}{\omega C} = \frac{1}{2\pi f C} \quad \text{..................1.3}$$

Where Xc is the capacitive reactance, ω is the angular frequency, f is the frequency in Hertz, and C is the capacitance. The unit of capacitive reactance is Ω. It is clear from the above equation that the reactance of a capacitor increases with decreasing frequency.

At zero frequency (DC)[1] the capacitor has an infinite resistance and hence behaves as an open circuit. So a low frequency signal will not pass through it. At high frequency, the capacitive reactance becomes very low and the capacitor acts almost as a short circuit. That is a high frequency signal will pass through the capacitor. From this it is clear that a capacitor blocks DC while passes AC[2] signal. So, capacitors are used to couple AC voltage from one circuit to another and block DC voltage from reaching the next circuit.

Like resistors, capacitors can either be fixed or variable. Some of the most commonly used fixed capacitors are mica, ceramic, paper, and electrolytic. Variable capacitors are mostly air-gang capacitors.

Fixed Capacitors

Mica capacitors

Mica capacitors are made from plates of aluminium foil separated by sheets of mica, as shown in Fig. 1.15. The plates are connected to two electrodes. The mica capacitors have excellent characteristics even under temperature variations and high voltage applications. Available capacitors range from 5 to 10^3 pF. Mica capacitors can be used upto 500 V.

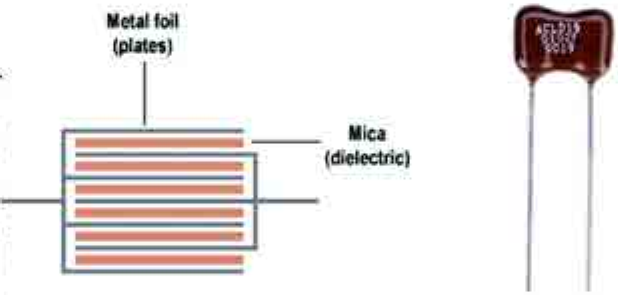


Fig 1.15 Construction of mica capacitor

Ceramic capacitors

A ceramic capacitor consists of a metal such as copper or silver coated on two sides of a ceramic disc. These coatings act as two plates. After attaching tinned-wire leads, the entire unit is coated with plastic and marked with its capacitance value either using numerals or colour code. The colour coding is similar to that used for resistances. Ceramic capacitors are very versatile. Their working voltage ranges from 3 V (for use in transistors) up to 6000 V. The capacitance value ranges from 3 pF to about 3 μF.

Fig 1.16 Ceramic disk capacitors

Paper capacitors

This capacitor consists of two metal foils separated by strips of paper. This paper is impregnated with a dielectric material such as wax, plastic or oil. Since paper can be rolled between two metal foils, it is possible to concentrate a large plate area in a small volume.

Paper capacitors have capacitances ranging from 0.0005 μF to several μF, and are rated from about 100 V to several thousand volts. They can be used for both DC and AC circuits.

---

1. *DC is the abbreviation of direct current. When a DC voltage is applied across a circuit the current always flows in the same direction. Frequency is number of cycles per second. So DC voltage has zero frequency.*
2. *AC is alternating current which when applied across a circuit, the current changes its direction periodically*

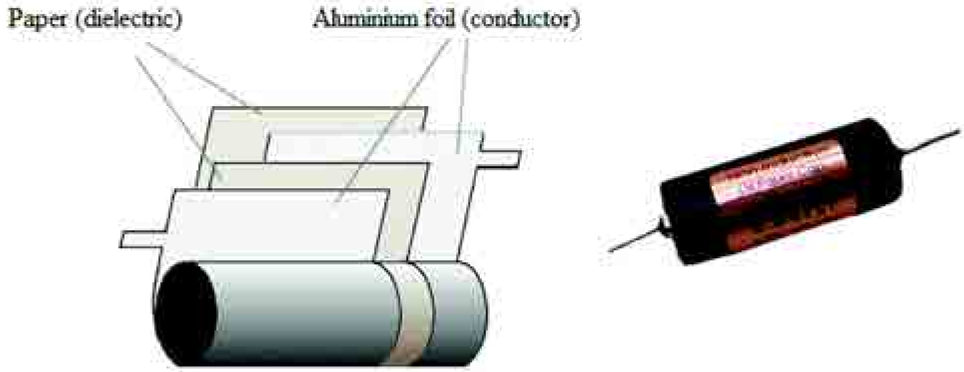


Fig 1.17 Paper Capacitors

Electrolytic capacitors

Fig 1.18 Electrolytic capacitor

An electrolytic capacitor consists of an aluminium-foil electrode which has an aluminium-oxide film covering on one side. The aluminium plate serves as the positive plate and the oxide as the dielectric. The oxide is in contact with a paper or gauze saturated with an electrolyte. The electrolyte forms the negative plate of the capacitor. Another layer of aluminium without the oxide coating is also provided for making electrical contact between one of the terminals and the electrolyte. In most cases, the negative plate is directly connected to the metallic container of the capacitor. The container then serves as the negative terminal for external connections.

The aluminium oxide layer is very thin. Therefore, the capacitor has a large capacitance in a small volume. It has high capacitance-to-size ratio. The terminals are marked +ve and -ve. The capacitance value may range from 1 μF to several thousand micro farads. The voltage ratings may range from 1 V to 500 V.

Variable capacitors

Fig 1.19 Air-gang capacitor (variable)

In some circuits, it is necessary to change the value of capacitance (e.g. tuning circuit used in radios to select different channels). This is done by means of a variable capacitor. The most common variable capacitor is the air-gang capacitor, shown in Fig. 1.19. The dielectric for this capacitor is air. By rotating the shaft at one end, we can change the common area between the movable and fixed set of plates. The greater the common area, the larger the capacitance.

In some applications, the user need not vary the capacitance value frequently. One setting is sufficient for all normal operations. In such situations, we use a variable capacitor called a trimmer (sometimes called padder). Both mica and ceramic are used as the dielectric for trimmer capacitors (Fig. 1.20).

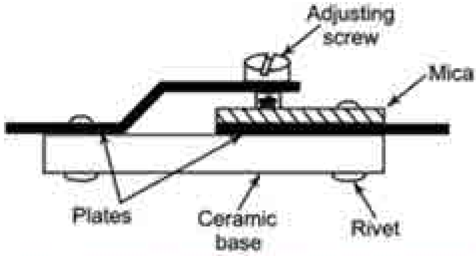


Fig 1.20 Basic construction of a mica trimmer

1.7 INDUCTORS

An inductor is a device that stores electrical energy in the magnetic field surrounding it. Inductance is the property of a coil (the inductor) to oppose a change in current. In its simplest form, an inductor consists of a wire loop or coil. The inductance of an inductor is directly proportional to the number of turns in the coil. Inductance also depends on the radius of the coil and on the type of material (core) around which the coil is wound. The schematic symbols for inductors are shown in figure 1.21. The unit of Inductance is henry (H).

An inductor offers opposition to the passage of any change in current through it. This opposition is called inductive reactance. Inductive reactance is defined as:

$$X_L = \omega L = 2\pi f L \quad (1.4)$$

where X_L is the inductive reactance, ω is the angular frequency, f is the frequency in Hertz, and L is the inductance. The unit of inductive reactance is Ohm. The reactance of an inductor increases with increase in frequency.

At zero frequency, the inductive reactance becomes zero and the inductor acts almost as a short circuit. So low frequency signal will pass through it. At high frequency, the inductor has high resistance and hence behaves as an open circuit. It means that a high frequency signal will not pass through an inductor. From this it is clear that an inductor blocks AC where as it passes DC signal. This is exactly opposite to the function of a capacitor.

All inductors can be classified into two categories: fixed and variable. According to the constructional features, inductors can be further classified in to three: air core inductor, iron core inductor and ferrite core inductor. Air core inductor is made of thin copper wire wound without any core. It has low value inductance of the range milli and micro henry.

Iron core inductor is made of copper wire wound over a laminated iron core. Iron core inductors are very suitable for audio frequency applications.

Ferrite core inductor is made of copper wire wound on a solid core made of ferromagnetic material called ferrite. In variable type ferrite core inductors, the ferrite core is made movable in and out of the coil. When the core is completely inside the inductor, the inductance value is maximum. It is used for high frequency applications.

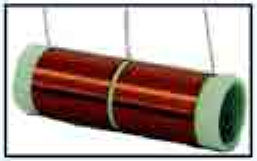
(a) Air core (b) Iron core (c) Ferrite core

Fig 1.21 Symbols of Inductors

Inductors are used in different frequency ranges

Chokes which are used in smoothing the pulsating voltage produced by rectifying AC(50 Hz) in to DC are called filter chokes. The range of inductance is normally from 5 to 20 H. A filter choke has many turns of wire wound on iron core. They are usually fixed value inductors.

Audio frequency chokes (AFCs) are used for audio frequency application (20 Hz to 20kHz). Compared to filter chokes, they are smaller in size and have lower resistance.



Radio frequency chokes (RFCs) are variable type inductors used in high frequency applications (more than 20 kHz). It has a shaft attached to its core so that the inductance can be varied by tuning it, as shown in Fig, 1.19. RFCs are having a low inductance value of the order of micro Henry.

1.8 TRANSFORMER

A transformer is similar in appearance to an inductor. It consists of two inductors having same core (Fig. 1.22). One of these inductors, or windings, is called primary. The other is called secondary. When an alternating current is applied at the primary, an induced voltage appears in the secondary. In a step up transformer, the number of turns in the secondary is more than that in the primary, so the secondary voltage is more than the primary. If the number of turns in the secondary is less than that in the primary, the voltage will be stepped down. Such transformers are called step down transformers

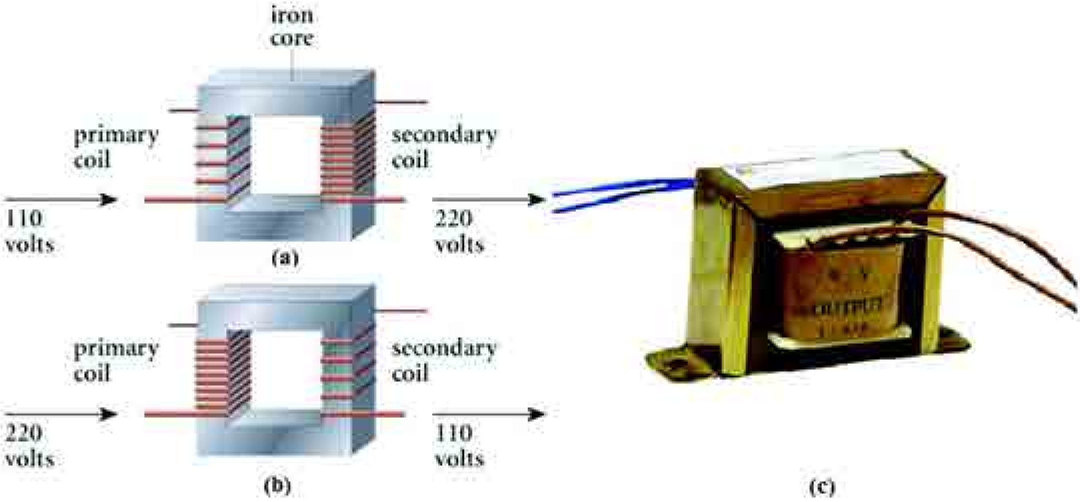


Fig 1.22 a) Step up transformer b) Step down transformer c) picture of a low power transformer

Let us sum up

Electronics is an integral part of every field of life. The invention of transistors is a major turning point in the development of electronics. Integrated circuits and their development through SSI, LSI, VLSI technologies led to the fast growth of electronics in all fields. Communication and entertainment, defence, control and instrumentation, medical, industrial applications, automobiles, home appliances, etc. are some of the fields of applications of electronics. Electronic components are classified into passive and active components. There are various types of resistors, capacitors and inductors which are used for various applications. The value of resistors can be found using colour coding. A capacitor passes AC and blocks DC but an inductor passes DC and blocks AC.

Learning outcomes

The learner is able to

- Explain the origin and history of development of electronics.
- Point out the significance of electronics in day to day life.
- Classify the applications of electronics into various fields.
- Identify the basic components in electronics.
- Classify the important components in electronics as active and passive.
- Recognize resistors, capacitors and inductors of various types from their physical appearance.
- Identify the value of resistors using their colour coding.
- Draw the symbols of different active and passive components.
- Explain the specifications of various types of resistors, capacitors and inductors.

What's the best strategy for learning circuits/electrical engineering as a hobby?

1) Invest in a soldering iron and practice soldering until it becomes second nature.
2) Get some more hardware like breadboards, wire clippers, etc.
3) Subscribe magazines or purchase books, that not only provide you with schematics for simple circuitry, but also take you on a component walk-through, explaining the purpose for each part. You can likely find the books advertised in the magazines.

Read more: http://www.physicsforums.com

http://www.epanorama.net/

Evaluation items

Multiple choice questions

1. A ___________ is a circuit element which takes energy from driving source and does not return it.

   (a) capacitor (b) resistor (c) inductor (d) diode

2. Example of an active device is

   (a) electric bulb (b) diode (c) transformer (d) loud speaker

3. A ___________ is a circuit element that stores energy in a magnetic field and returns it.

   (a) capacitor (b) resistor (c) zener diode (d) inductor

4. A 100 μF capacitor is required in an electronic circuit. Such a large value of capacitance is possible if the capacitor is a/an

   (a) ceramic capacitor (b) mica capacitor (c) electrolytic capacitor (d) paper capacitor

5. A resistor has a colour band sequence: brown, black, green and gold. Its value is

   (a) 1 kΩ $\pm$ 10% (b) 1MΩ $\pm$ 5% (c) 10 kΩ $\pm$ 5% (d) 1 MΩ $\pm$ 10%

6. A ___________ is the circuit element that stores energy in an electric field and returns it.

   (a) resistor (b) inductor (c) capacitor (d) none of these

7. With the help of a RADAR we can

   (a) perform mathematical calculations very fast

   (b) listen to more melodious music

   (c) detect the presence of an aircraft as well as locate its position

   (d) cure the damaged tissues in the human body.

8. The colour bands on a fixed carbon resistor are brown, red, black(given sequentially). Its value is

   (a) 12 Ω (b) 21 Ω (c) 120 Ω (d) 210 Ω

9. The term IC used in electronics denotes

   (a) Indian culture (b) integrated circuits (c) internal combustion (d) industrial control

10. Which one of the following is used as a passive component in electronic circuits.

    (a) Vacuum triode (b) transistor (c) resistor (d) field effect transistor (FET)

Answer key

1) b 2) b 3) d 4) c 5) b 6) c 7) c 8) a 9) b 10) c

Descriptive type questions

1. Our daily life is influenced by electronics. Justify.
2. Differentiate between active devices and passive devices.
3. What is meant by RADAR?
4. Write at least three applications of electronics in the field of

   (a) communication and entertainment

   (b) defence

   (c) medical sciences.
5. What is meant by tolerance in resistors?
6. Explain constructional features of a carbon composition resistor. What is the wattage rating for carbon composition resistors?
7. Describe different types of potentiometers.
8. Write short notes on

   (a) capacitor

   (b) inductor.
9. Explain the applications of capacitors.
10. What forms the dielectric of an electrolytic capacitor? Why is the electrolytic capacitor polarized?
11. What are the specifications of a capacitor? State the factors affecting the capacitance of a capacitor.
12. When you adjust the volume control knob of your radio receiver, which component is varied inside the set?
13. Explain briefly the difference between air- gang (variable) and trimmer capacitors.
14. What is an inductor? What is the unit of inductance?
15. Classify the inductors and explain briefly.
16. Name a few active components used in electronic circuits.

2

ELECTRICAL FUNDAMENTALS

INTRODUCTION

We know that electronics has become an integral part of our life, through its vast range of applications. In the forthcoming chapters we will go through the basic concepts of semiconductors, electronic devices like diodes, transistors and other special devices, basic circuits of rectifiers, amplifiers and oscillators, fundamentals of digital electronics and measuring devices. Before that, let us go through the basic concepts of electricity, which is the source of energy that makes all electronic devices work. To begin with we shall look into what electric current, voltage and power are, how electric current is maintained through a conductor and how the electric current varies according to the change in potential difference. We shall also discuss the resistors and capacitors and the effect of series and parallel combinations of them. Further on, we will see how to find the voltage across and the current through different components in electrical circuits with the help of Ohm's law and Kirchoff's law.

2.1. ELECTRIC CURRENT

Can you say, what actually happens when you press the switch of a torch light? The basic arrangement inside a torch is as shown in fig. 2.1. When the switch 'S' is closed (switch pressed), electric current

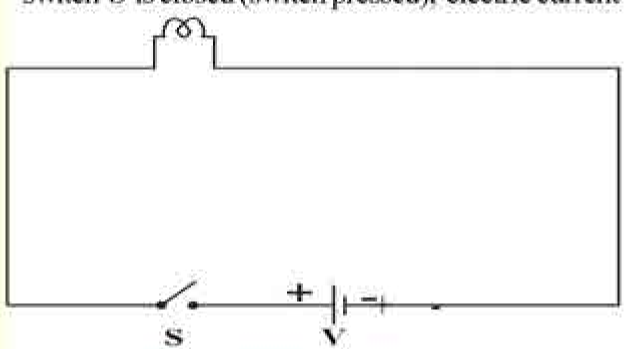


Fig 2.1 Simple electric circuit

flows through the circuit. The flow of electric current makes the bulb glow. The direction of electric current is from positive terminal of the battery to the negative terminal of the battery.

Electric current flows from a higher potential point to a lower potential point. In case of battery, positive terminal is considered as at a higher potential compared to negative terminal.

The electric current or electric current intensity is defined as the rate of flow of electric charges. If q is the amount of charge that crosses any section of a conductor, in a time interval t, then the current 'I' is given by

$$\mathbf{I} = \frac{\Delta q}{\Delta t}$$

The unit of electric current is Ampere (A). A current of one ampere equals a flow of 1 coulomb of charge per second. Ammeter is the instrument used for measuring electric current.

2.2. THE VOLTAGE

The voltage between two points is the work done (energy required) to move a unit positive charge from one point to the other. It is also called as potential difference or electromotive force (emf).

$$V = \frac{W}{Q}$$

where

V - potential difference or voltage in volts

W - energy spent in joules

Q - charge in coulombs

One volt is defined as the potential difference between two points in an electric circuit such that one joule of work must be done to move a charge of one coulomb between the points. Thus if an electric power line has a voltage of 220V, it follows that 220 J of work has to be done to transfer each coulomb of electric charge through any apparatus connected between the two wires.

1 Volt = 1 Joule/coulomb or 1V = 1 J/C. Voltmeter is the instrument used for measuring voltage.

2.3. ELECTRIC POWER

Electric power is the time rate of doing work for moving charges from one point to another. It is represented by the symbol 'P' and the unit of power is 'watt'. 'Watt' is practically defined as the rate at which work is being done in a circuit in which a current of 1 ampere is flowing when the voltage applied is 1 volt.

The electric power consumed by a resistor is determined by the voltage across it multiplied by the current flowing through it.

Power = Voltage × Current

$P = V \times I$ or $P = VI$

2.4. OHM'S LAW

We have seen that when potential difference is more, the current increases. It can be said that at constant temperature, the potential difference across a conductor is directly proportional to the electric current through it.

Ohm's law can be written as $V \propto I$ at constant temperature

V/I = Constant.

This constant of proportionality is termed as the resistance of the conductor. Its SI unit is ohm (Ω).

Those conductors which obey Ohm's law are called ohmic conductors. Examples for non-ohmic conductors are semiconductors.

2.5. SERIES AND PARALLEL COMBINATION OF RESISTORS

Suppose for a certain circuit we require a 200Ω resistor, and for some other circuit we need a 50Ω resistor. But we have only 100Ω resistors with us. How can we solve this problem?

It is possible to get these values by combining the available resistors.

Activity 1

Assemble two circuits as shown in fig 2.2 and fig 2.3.

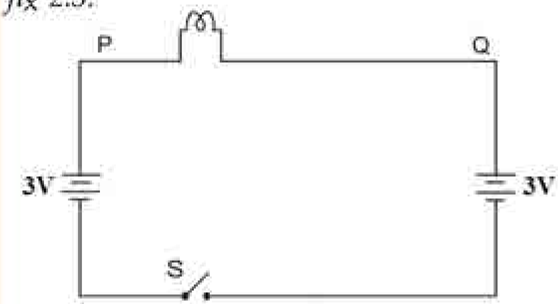


Fig 2.2 Same potentials applied at both the ends

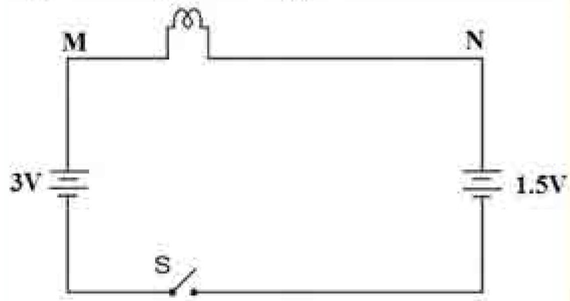


Fig 2.3 Unequal potentials applied at the ends

- *What do you observe ?*
- *When the switches are closed, which bulb glow and which does not?*
- *Think why these circuits behave differently.*
- *Justify your observation*

The bulb in the fig 2.2 does not glow since there is no potential difference between the points P and Q. In the fig 2.3 potential applied at the terminals of bulb (points M and N) are different. So the current flows through the bulb and it glows. Thus we can conclude that electric current can be established through a conductor only if there is a potential difference across its ends. Now if the potential at 'M' is increased, the bulb glows more and more brightly due to higher current flow. Try to do that.

The two ways of combining resistors are

1. Series Combination
2. Parallel Combination

Series Combination

Two or more resistors are said to be connected in series when they are connected in such a way that the same current flows through all those resistors. Consider three resistors R_1, R_2 and R_3 connected in series and a voltage of 'V' volts is applied across it as in fig.2.4

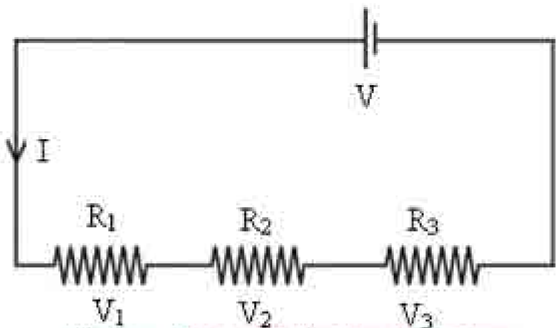


Fig 2.4 Series combination of resistors

In this circuit the current through each resistor will be the same but the potential difference across each is different. It can be obtained using Ohm's law.

Potential difference across R_1, $V_1 = IR_1$

Potential difference across R_2, $V_2 = IR_2$

Potential difference across R_3, $V_3 = IR_3$

If 'V' is the effective potential drop and 'R' the effective resistance, then the effective potential difference across the combination is

$$V = IR$$

Total voltage across the combination is equal to the sum of the voltages across each resistor.

$$V = V_1 + V_2 + V_3$$

Substituting the values of voltage

$$IR = IR_1 + IR_2 + IR_3$$

Eliminating I from all the terms, we get

$$R = R_1 + R_2 + R_3$$

Thus the effective resistance of the series combination of a number of resistors is equal to the sum of the resistances of individual resistors.

Parallel Combination

A number of resistors are said to be connected in parallel when they are connected in such a way that the same voltage appears across each of those resistors. Consider three resistors R_1, R_2 and R_3 are connected in parallel across a potential difference of V as in fig 2.5.

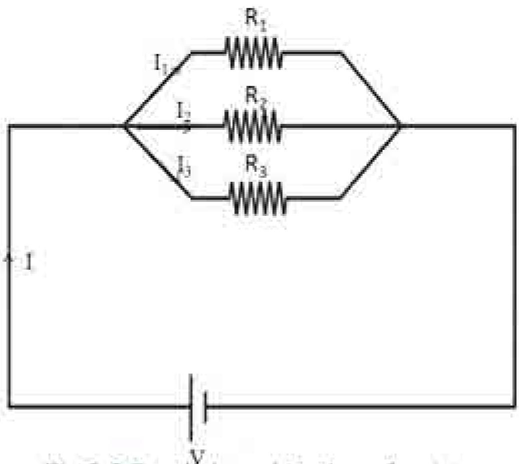


Fig 2.5 Parallel combination of resistors

Here, since all the resistors are connected across the same terminals, the potential differences across all of the resistors are equal. But the current will be different in each resistor and is given by Ohm's law.

Current through R_1, $I_1 = \frac{V}{R_1}$

Current through R_2, $I_2 = \frac{V}{R_2}$

Current through R_3, $I_3 = \frac{V}{R_3}$

The total current through the combination is $I = \frac{V}{R}$, where 'R' is the effective resistance of this circuit.

The total current through the combination = the sum of the currents through each of the resistors

$$I = I_1 + I_2 + I_3$$

Substituting the values of currents, we get

$$\frac{V}{R} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

Eliminating V from all the terms we get

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

Thus in parallel combination the reciprocal of the effective resistance is equal to the sum of the reciprocals of individual resistances. The effective resistance in a parallel combination will be smaller than the value of the smallest resistance.

When only two resistors of values R_1 and R_2 are connected in parallel, the effective resistance of the combination is $R = \frac{R_1 R_2}{R_1 + R_2}$

Check your progress

Find the total current flowing through the circuit in fig 2.6 and the current through each of the resistors.

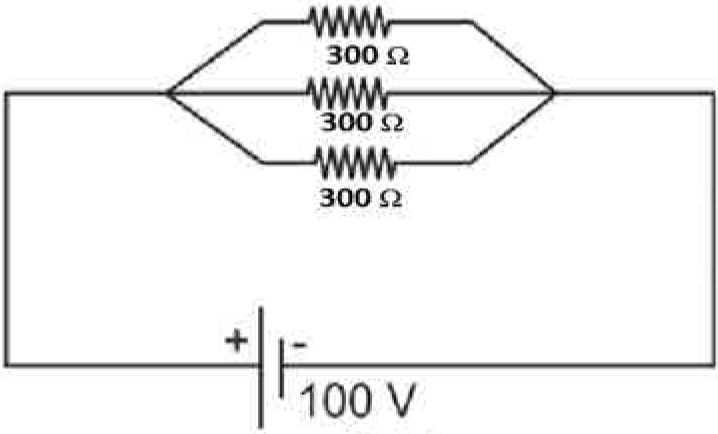


Fig 2.6

Solution

The resistors each of value 300 ohms are in parallel.

Effective resistance can be obtained as follows.

$$\frac{1}{R} = \frac{1}{300} + \frac{1}{300} + \frac{1}{300}$$

$$R = \frac{300}{3}$$

$= 100$ ohms

Total current in the circuit.

$$= \frac{V}{R} = \frac{100}{100} = 1 \text{ ampere}$$

Since $R_1 = R_2 = R_3$,

The current through each of the resistors = Total current/ No. of resistors

$$= \frac{1}{3} \text{ ampere}$$

From the above problem it can be noted that if 'n' resistors each of value R ohms are connected in parallel the effective resistance of the combination, R_{eff} is

$$R_{eff} = \frac{R}{n}$$

Activity 2

Now try to solve the problem stated in the beginning of the section 2.5 (To get effective resistances of 200Ω and 50Ω using 100Ω resistors).

- *Draw the circuits required.*
- *What happens to the effective resistance of the circuit when more resistors are added*

  a) in series and b) in parallel

When two 100 ohm resistors are connected in series we get a circuit resistance of 200 ohms because in series combination, $R_{effective} = R_1 + R_2$. For getting a 50 ohm effective resistance we have to combine two 100 ohm resistors in parallel since for parallel combination, $1/R_{effective} = 1/R_1 + 1/R_2$. Hence it is clear that when resistors are connected in series, the effective circuit resistance increases and when connected in parallel, the effective circuit resistance decreases.

2.6 COMBINATION OF CAPACITORS

Capacitors can also be connected in series and in parallel.

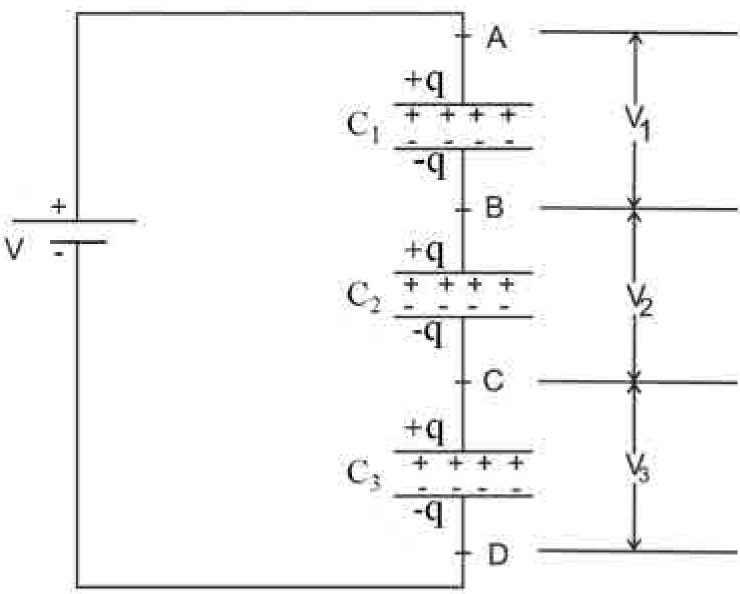


Fig 2.7 Series combination of capacitors

Capacitors in series :

Consider three capacitors of capacitances C_1, C_2 and C_3 connected in series across a potential difference of 'V' volts. Here the same charge is stored in all the three capacitors. But the voltage across each will be different. The total voltage across the circuit is equal to the sum of voltages across individual capacitors.

$$\text{So } V = V_1 + V_2 + V_3 \text{ \_\_\_\_\_\_\_\_\_\_ } (1)$$

If the effective capacitance of the circuit is 'C' and since

Voltage = Charge/Capacitance

equation (1) becomes

$$\frac{q}{C} = \frac{q}{C_1} + \frac{q}{C_2} + \frac{q}{C_3}$$

Eliminating 'q' from all the terms

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

If there are only two capacitors connected in series

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} \quad \text{or} \quad C = \frac{C_1 C_2}{C_1 + C_2}$$

Capacitors in parallel

If three capacitors C_1, C_2 and C_3 are connected in parallel across a battery of V volts, the potential difference across each capacitor will be the same. ie ,V volts. But the charge acquired by each capacitor will be different.

If q_1, q_2 and q_3 are the charges acquired by C_1, C_2 and C_3 respectively, the total charge drawn from the battery.

$$q = q_1 + q_2 + q_3$$

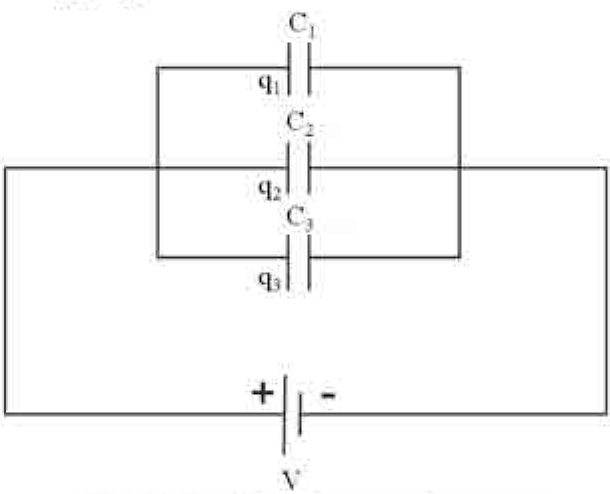


Fig 2.8 Parallel combination of capacitors

If 'C' is the effective capacitance of the combination .

$$CV = C_1 V + C_2 V + C_3 V$$

OR

$$C = C_1 + C_2 + C_3$$

So the effective capacitance of a number of capacitors connected in parallel is equal to the sum of individual capacitances.

In series combination the effective capacitance is smaller than the smallest in the combination while in parallel connection the effective capacitance is larger than the largest in the combination.

Check your progress

Three Capacitors each of value 9 pF are connected a) in series and b) in parallel. If the combinations are connected to a 30V DC supply, find out the effective capacitance in each case and the charge on each capacitor

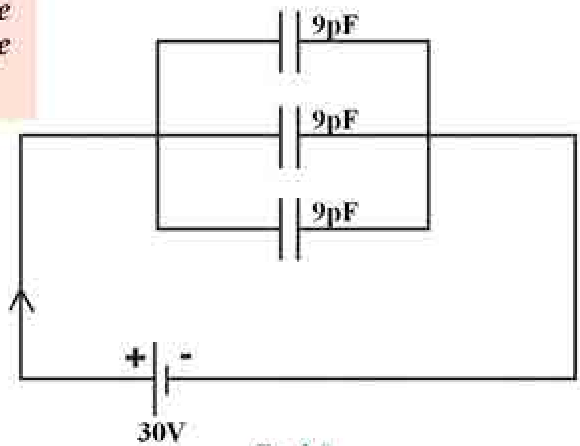


Fig 2.9

Solution

Effective capacitance in parallel

$C = C_1 + C_2 + C_3 = 9 + 9 + 9 = 27$ pF

Charge on a 9 pF Capacitor

$$CV = 9 \times 10^{-12} \times 30$$
$$= 27 \times 10^{-11} \text{ C}$$

Total charge $q = q_1 + q_2 + q_3$

$= C_1V + C_2V + C_3V$

$= 3 \times 27 \times 10^{-11}$ C

$= 71 \times 10^{-11}$ C

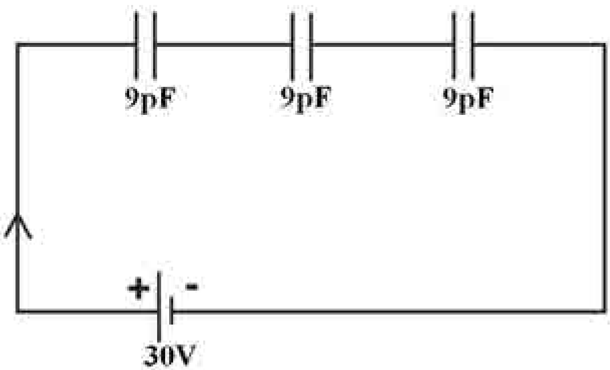


Fig 2.10

Effective capacitance in Series

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

$$\frac{1}{C} = \frac{1}{9} + \frac{1}{9} + \frac{1}{9}$$

or $C = \frac{9}{3} = 3$pF

In series combination, the charge on each capacitor will be the same

$$q = CV$$
$$= 3 \times 10^{-12} \times 30$$
$$= 9 \times 10^{-11} C$$

2.7 KIRCHHOFF'S LAWS

Analyze the circuit given in fig 2.11

The above circuit cannot be reduced to a simple parallel or series combination as the resistors are neither in series nor in parallel with each other. So such circuits cannot be solved simply using Ohm's law. Gustav Robert Kirchhoff proposed two general rules for solving such networks.

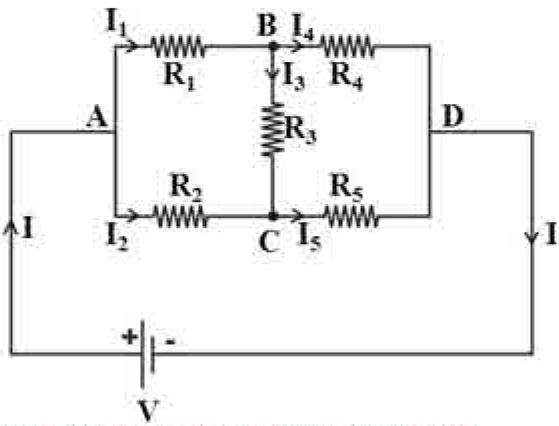


Fig 2.11 Demonstration of Kirchhoff's law

Kirchhoff's Current law (KCL)

In the words of Kirchhoff at any junction of several circuit elements, the sum of currents entering a junction must be equal to the sum of currents leaving the junction. Considering the circuit given in fig 2.11

For the junction A, $I = I_1 + I_2$

For the junction B, $I_1 = I_3 + I_4$

For the junction C, $I_3 + I_2 = I_5$

For the junction D, $I_4 + I_5 = I$

If the current entering a junction is taken as positive and current leaving the junction as negative then Kirchhoff's current law can be stated as "The algebraic sum of currents meeting a junction is zero".

Consider the diagram shown in figure 2.12 in which the current I_1 and I_2 are entering the junction 'O' and the currents I_3, I_4, and I_5 are leaving the junction.

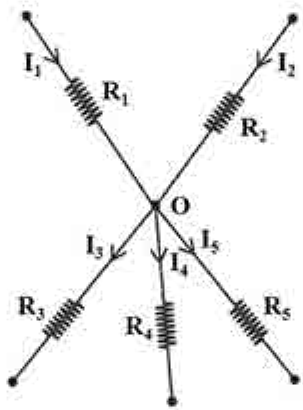


Fig 2.12 Demonstration of KCL

Using Kirchhoff's current law (KCL)

$$I_1 + I_2 - I_3 - I_4 - I_5 = 0$$

Kirchhoff's Voltage law (KVL)

Kirchhoff's voltage law can be stated as "The algebraic sum of change in potential around any closed loop must be zero".

Illustration

Consider the following circuit. Sign convention is very important while applying KVL. The following illustration will help you to understand it.

Let us take the loop ABCDA and assign anticlockwise direction for the tour starting from the point A.

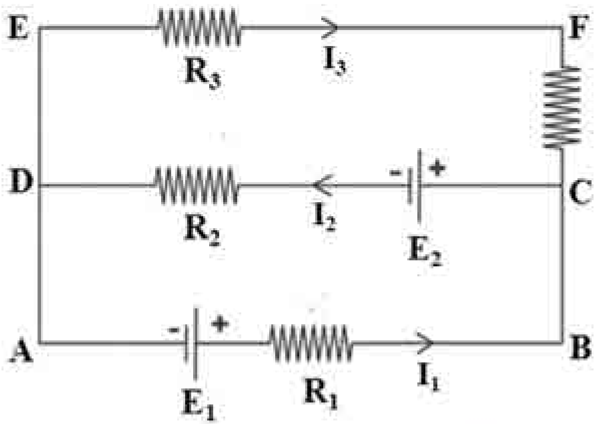


Fig 2.13 Sign convention for KVL

1. As we move through the cell of emf E_1, direction is from -ve to +ve, so E_1 is taken as positive.
2. The direction of tour and the direction of current are the same in the case of R_1 hence the potential difference across R_1 is taken as negative i.e., $-I_1R_1$.
3. As we go through the cell of emf E_2, direction is from positive to negative. So E_2 is taken as negative.
4. Similarly the potential difference across R_2 is found to be negative i.e. $-I_2R_2$.

Therefore as per KVL, for the loop ABCDA

$$E_1 - I_1R_1 - E_2 - I_2R_2 = 0$$

Solved problem : 2.1

Find the current through each resistor in the following circuit

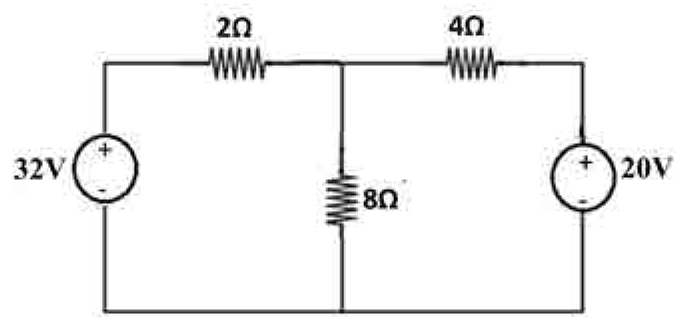


Fig 2.14

Solution

Let us solve this problem using KVL

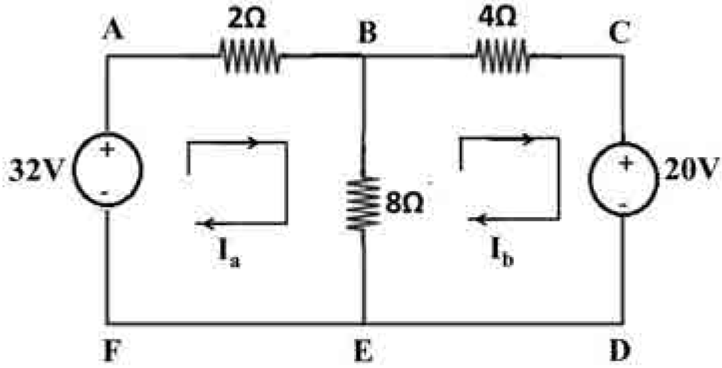


Fig 2.15

Applying KVL to loop ABEFA

$$-2I_a - 8(I_a - I_b) + 32 = 0$$

Applying KVL to loop BCDEB

$$-4I_b - 20 - 8(I_b - I_a) = 0$$

we can rewrite these equations as

$$10\,I_a - 8\,I_b = 32$$

$$-8\,I_a + 12\,I_b = -20$$

Which can be solved to get

$$I_a = 4A,\ I_b = 1A$$

Current through 2Ω = $I_a = 4A$

Current through 8Ω = $I_a - I_b = 3A$

Current through 4Ω = $I_b = 1A$

2.8 VOLTAGE SOURCES

Consider a perfect battery whose internal resistance is zero. If there is no internal voltage drop in the battery, full battery voltage will appear across the load connected across it. Such a battery is an example of ideal voltage source.

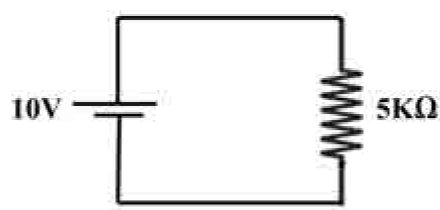


Fig 2.16

In the circuit in fig. 2.16 according to Ohm's law, 2 mA current will flow through the load. If we reduce the load resistance to 1K., the load voltage is still 10V, the load current however increases to 10 mA.

An ideal voltage source produces an output voltage that does not depend on the value of load resistance and other quantities. Suppose the load resistance in the above circuit is reduced to zero, then the load current approaches infinity. But no real voltage source can produce infinite current because of the presence of some internal resistance. Therefore it should be understood that a real voltage source has some internal resistance.

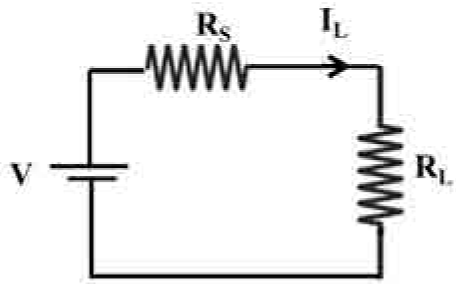


Fig 2.17

In a real voltage source the internal resistance (R_S) appears in series with the load resistance (R_L). Here suppose the load resistance is reduced to zero.

Then using Ohm's law, $I_L = \frac{V}{Rs}$.

This is the maximum load current that the real voltage source can deliver.

The load current under normal condition

(When R_L is considerable)

$$I_L = \frac{V}{R_S + R_L} \text{ and hence the load voltage } V_L = \frac{VR_L}{R_S + R_L}$$

Here as the load resistance (R_L) increases, the load voltage V_L also increases. When the load resistance approaches infinity $R_S << R_L$ and hence R_S can be neglected and the load voltage approaches the ideal source voltage. Symbol of voltage source is as shown in fig 2.18.

Note that in real voltage source internal resistance is shown in series with an ideal voltage source .

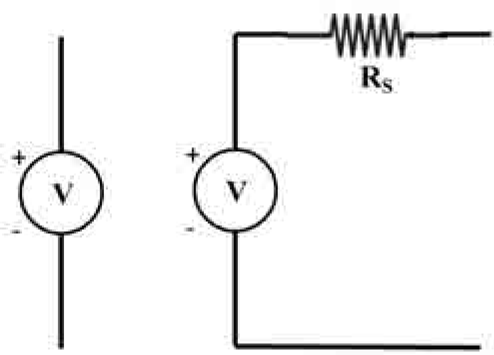


Fig 2.18 (a) Ideal voltage source (b) Real voltage source

2.9 CURRENT SOURCES

A voltage source has a very small internal resistance while a current source has a very large internal resistance. Ideally, the internal resistance is infinity and hence the output current produced by a current source does not depend on the value of load resistance.

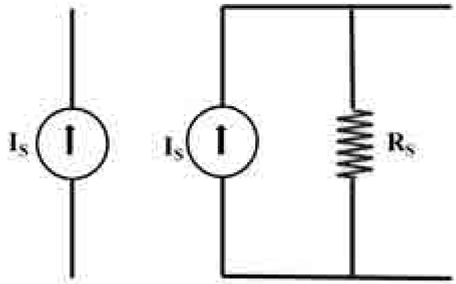


Fig 2.19 (a) Ideal current source
(b) Real current source

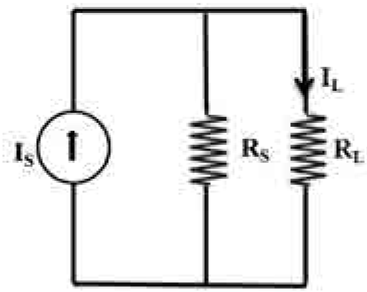


Fig 2.20 Current source with internal resistance connected to a load

The internal resistance of a real current source is always shown in parallel with an ideal current source.

From figure 2.20 it is clear that when the load terminals are shorted ($R_L = 0$) full circuit current flows through the shorted load. Let it be I_L. As the load resistance R_L is increased certain current flows through the internal resistance also and hence the load current is reduced. So to make load current fairly constant, internal resistance has to be very high.

2.10 DIRECT CURRENT (DC) AND ALTERNATING CURRENT (AC)

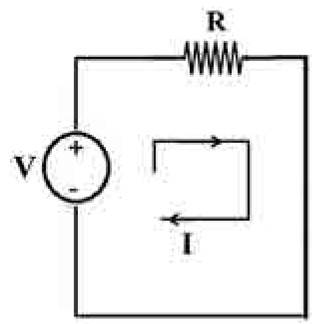


Fig 2.21 DC voltage source connected in a circuit

We know that the voltage supplied by a battery is DC voltage and that supplied by house hold distribution system is AC voltage. In this section we shall discuss the basic differences between direct current system and alternating current system.

Direct current flows only in one direction in a circuit. Therefore it is also called unidirectional current flow. Voltage has a fixed polarity and its magnitude remains constant. The direction of current flow is indicated by an arrow mark originating from the positive terminal towards the negative terminal of the battery. But the real direction of electron flow is from negative terminal towards the positive terminal of the battery. ie, opposite to the direction of conventional current flow.

Examples of sources of DC are battery, DC generator etc.

Alternating Current

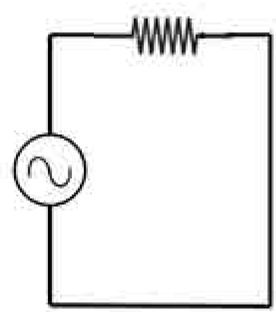


Fig 2.22 AC voltage source connected in a circuit

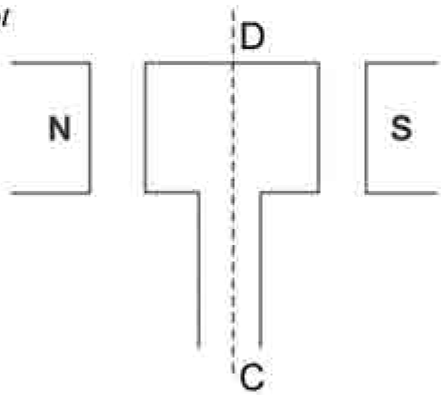
Alternating Current or Voltage varies in magnitude and its terminal polarity reverses periodically. It means that the alternating current will flow first in one direction and then in opposite direction. Alternating current source is as shown in fig 2.22.

In previous classes you have studied that according to Faraday's law of electromagnetic induction, whenever the magnetic flux linked with a coil changes, an emf is induced in the coil. As per Faraday's second law the emf induced is directly proportional to the rate of change of flux linkages. The direction of induced emf is in such a way as to oppose the cause producing the change in flux. Consider a rectangular loop of conducting wire of area 'A' and number of turns 'N' rotating at a steady angular velocity 'ω' about an axis 'CD' in a uniform magnetic field of strength 'B'. At any instant 't', let $\theta = \omega t$ be the angle that the normal to the plane of the coil makes with the direction of 'B'. Then the area of the coil that faces (perpendicular to) the field is $A\cos\theta$.

The total magnetic flux passing through the coil at that instant is,

$$\phi = NBA\cos\theta$$

$$= NBA\cos\omega t, \text{ since } \theta = \omega t$$



The emf induced in the coil,

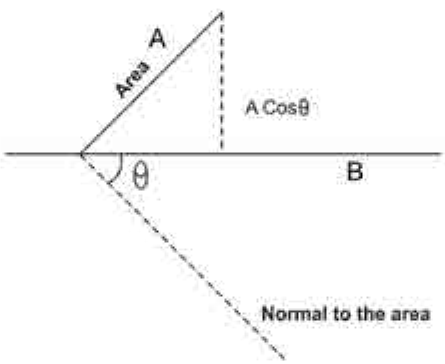
$$v = -\frac{d\phi}{dt}$$

$$= -\frac{d(NBA\cos\omega t)}{dt}$$

$$= -NBA\frac{d(\cos\omega t)}{dt}$$

$$= -NBA(-\omega\sin\omega t)$$

$$= NBA\omega\sin\omega t$$



This equation can be represented as $V = V_o\sin\omega t$, where $V_o = NBA\omega$ the peak (maximum) value of emf and ωt is the phase of the emf. This is a function of 'sine' and therefore AC wave form generated here is a sine wave form. On rotating the coil through 180^0 the induced emf or current increases from zero to maximum and then decreases to '0'. When the coil is rotated further through 180^0 the induced emf or current again increases in the opposite direction from 0 to negative maximum and then decreases to zero. One complete rotation (360^0) of the coil is known as a cycle.

2.11 FREQUENCY, TIME PERIOD AND PHASE ANGLE

One complete set of positive and negative half cycles can be termed as a cycle. The number of cycles completed by an alternating current in one second is known as the frequency (f) of AC. It is generally expressed in Hertz (Hz) or in cycles per second (cps). As we know the household AC supply has a frequency of 50 Hz. The time taken by an alternating current or voltage to complete one cycle is known as time period(T). It is the reciprocal of frequency, $T = \frac{1}{f}$.

An AC waveform can be approximated as a sum of sine waves. A sine wave can be represented by the expression $V = V_o \sin(2\pi ft+\varphi)$, where V_o is the peak or maximum amplitude, 'f' is the frequency of the wave and φ is the phase angle. If the waveform starts at zero amplitude the phase is zero. If it starts at any other value the corresponding angle will be the phase angle of the waveform.

Graphical representation of sine wave

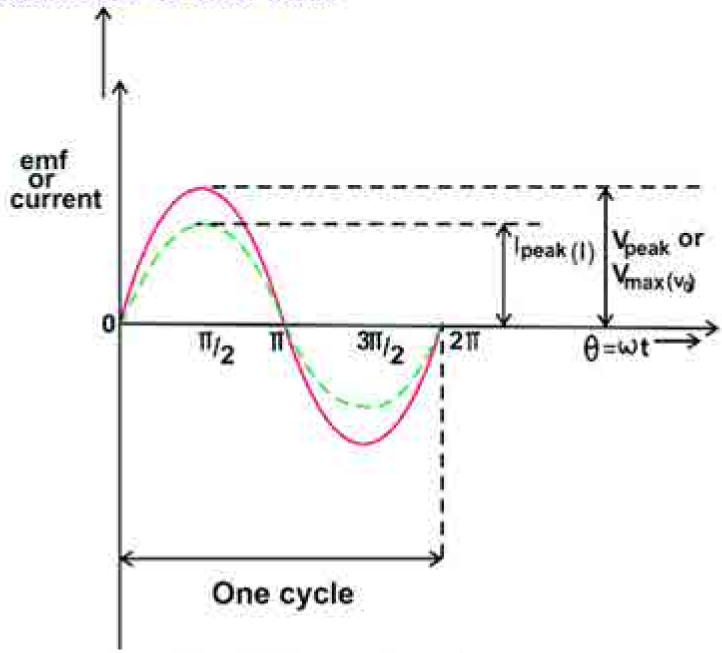


Fig. 2.23 Sinusoidal waveform

Observe the table below to analyze how a sinusoidal current and voltage vary with time

$\theta = \omega t$	$V = V_o \sin \omega t$	$I = I_o \sin \omega t$
0	0	0
$\frac{\pi}{2}$	V_o	I_o
π	0	0
$\frac{3\pi}{2}$	$-V_o$	$-I_o$
2π	0	0

2.12 AVERAGE AND RMS VALUES OF AC

AC voltage varies with time. The average value will give the DC equivalent voltage corresponding to the AC voltage. The average value of a sine wave over a cycle is zero. It can be found over a half cycle.

$$I_{average} = 1/(T/2) \int_0^{T/2} I_o \sin \omega t \, dt$$

On integration and then by substituting $\omega = \frac{2\pi}{T}$ it can be seen that $I_{average} = \frac{2Io}{\pi}$

But the average value or mean value of AC does not give accurate values when used to calculate energy changes associated with AC. So it is needed to go for a more suitable value. It will be more accurate if we define the effective value of AC in terms of heating effect because for both half cycles the amount of heat developed is equal for a full cycle and it does not average to zero.

The RMS or Root Mean Square values of AC is defined as the DC equivalent which produce the same amount of heat energy in the same time as that of an AC. The heat developed for a small interval of time dt is dH= p dt, where p is the power developed in time 'dt'

Total heat energy developed for a full cycle of AC is

$$H = \int_0^T p\,dt$$

$$= \int_0^T i^2 R \, dt$$

$$= \int_0^T Io^2 \sin^2 \omega t \, R \, dt$$

On integration, it can be seen that

$$H = \frac{Io^2 R}{2} T \quad (1)$$

If a DC current I_{rms} produces the same amount of heat

$$H = I^2_{rms} RT \quad (2)$$

Equating (1) & (2)

$$I_{rms} = \frac{Io}{\sqrt{2}}$$

Rms value of current or voltage of AC can also be defined as the square root of the mean of the squares of all instantaneous values over one complete cycle.

Illustration

To illustrate the above definition for rms value, see the following signal.

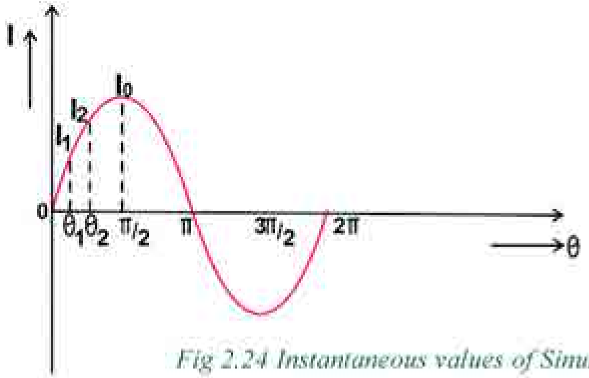


Fig 2.24 Instantaneous values of Sinusoidal Waveform

In fig 2.24 I_1, I_2, I_3 etc are the instantaneous value of the current at angles θ_1, θ_2, θ_3 etc. and I_0 is the maximum value. Then according to the definition of rms value of current

$$I_{rms} = \sqrt{\frac{I_1^2 + I_2^2 + \_\_\_\_\_}{2\pi}}$$

$$= \sqrt{\frac{\int_0^{2\pi} I^2 d\theta}{2\pi}}$$

Substituting $I = I_0 \sin\theta$ and using integral calculus this can also be solved to get the same result as we got earlier.

i.e., $I_{rms} = I_0/\sqrt{2}$ and

$V_{rms} = V_0/\sqrt{2}$

Activity 3

Try to get a 6V output from the 230V 50 Hz supply using a 230/6V transformer in your school electronics laboratory. Use a CRO to measure and analyze this 6V AC. Observe AC waveform obtained & measure the maximum value of voltage and its frequency. Calculate the rms value.

- *How do you calculate the exact value of maximum voltage, from the waveform obtained on the CRO?*
- *Is the maximum value greater than the transformer secondary voltage which is 6 V?*
- *Which among the following is the AC voltage 6 V obtained from the secondary terminals of the transformer.*

  (a) rms (b) average (c) maximum

Check your progress

What is the significance of rms value of AC ?

Solved problem 2.2

The instantaneous value of an AC voltage is represented by V = 141 sin (314t). Find its frequency and rms values.

Solution

$$V_o = 141\ V$$

$$2\pi f = 314$$

$$f = \frac{314}{2\pi} = 50\ Hz$$

$$V_{rms} = \frac{V_o}{\sqrt{2}} = 141/1.41 = 100\ V$$

2.13 CONCEPT OF IMPEDANCE

As you know AC is preferred for all commercial and domestic purposes because AC can be economically transmitted over long distances. Other than ohmic resistance (R) the presence of inductances (L) or capacitances (C) significantly affects the flow of alternating current. Similar to the ohmic resistance (R) the opposition to the current flow offered by the inductance (L) of an inductor is called the inductive reactance (X_L) and that offered by the capacitance of a capacitor is called the capacitive reactance (X_C). Resistance, inductive reactance and capacitive reactance are measured in ohms.

Impedance is a measure of overall opposition of a circuit to the current flow through it. It is like resistance but it also takes into account the effects of capacitance and inductance.

AC circuit with resistance only

Consider the circuit in fig 2.25 in which only ohmic resistance is present.

As you have already studied the instantaneous value of voltage

$$V = V_o \sin \omega t \quad \text{———} (1)$$

Since I=V/R , the instantaneous value of current through this circuit

$$I = V_0 \sin \omega t / R$$

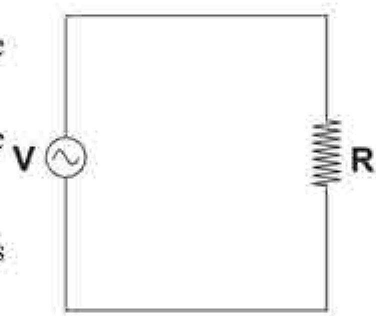


Fig 2.25 AC circuit with resistance only

Since Vo /R= Io, the maximum value of current.

the above equation can be written as

$$I = I_o \sin \omega t \text{———} (2)$$

From equation (1) and (2) it can be noted that the current and voltage are in the same phase.

Now let us analyze an AC circuit with an inductor of inductance L only

AC circuit with inductance only

In the circuit given in fig 2.26, a potential difference of $V = V_o \sin \omega t$ is applied across an inductor of inductance 'L' henry. You know that according to Faraday's law of electromagnetic induction, coil produces an induced emf $e = -d\Phi/dt$

$$e = -L\, dI/dt, \quad \text{since } \Phi = LI$$

For the above loop as per KVL

$$V_o \sin \omega t - L\, dI/dt = 0$$

$$dI/dt = (V_o/L) \sin \omega t$$

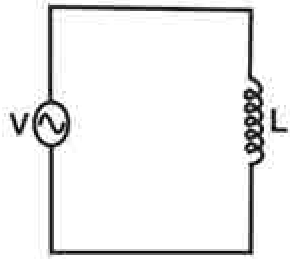


Fig 2-26 AC circuit with inductance only

Therefore $I = \int \left(\frac{V_o}{L}\right) \sin \omega t\, dt$

Using integral calculus we get $I = \frac{V_o}{\omega L}(-\cos \omega t)$

But using trigonometric identity

$$\sin(90 - \omega t) = \cos \omega t$$

$$\text{Or } \sin(\omega t - 90) = -\cos \omega t$$

If I_o is the maximum value of current through the inductor

$$I = I_o \sin(\omega t - 90) \quad \text{where } I_o = V_o / L\omega$$

The equations for current and voltage show that the current through the inductor lags behind the voltage by 90 degree or $\pi/2$ radians.

The ratio of the peak value of voltage across the inductor to the peak value of current through it is a constant and is called the inductive reactance (X_L) which is similar to the resistance.

$$X_L = V_o / I_o = L\omega = 2\pi f L \quad \text{where } \omega = 2\pi f$$

Therefore it is seen that the inductive reactance depends on the supply frequency. i.e., X_L is directly proportional to the frequency. The unit of inductive reactance X_L is ohm itself. It can be concluded that for a purely inductive circuit the current lags behind the voltage by 90 degrees or $\pi/2$ radians

AC circuit with capacitance only

In the circuit in fig 2.27 the supply voltage V=Vo sin ωt is applied across a capacitor of capacitance 'C'.

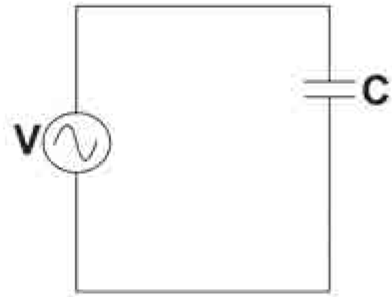


Fig 2.27 AC circuit with capacitance only

The charge on the capacitor at any instant

$$q = CV_o \sin \omega t$$

You have already studied that the current through a capacitor is equal to the rate of change of charge on it.

$$i = dq/dt = d(CV_o \sin \omega t)/dt$$

using differentiation it can be seen that

$$i = CV_o \omega \cos\omega t$$

using trigonometric relations

$$\cos\omega t = \sin(\omega t + \pi/2)$$

Therefore the above equation becomes

$$i = CV_o \omega \sin(\omega t + \pi/2)$$

From the above expression for voltage and current it is clear that the current through the capacitor leads the voltage by $\pi/2$ radians or 90 degrees.

Now for a given frequency the ratio of the maximum value of voltage to the maximum value of current for a capacitor is a constant and is called the capacitive reactance X_C.

Now let us discuss how the combination of L, C and R behaves in an AC circuit.

AC circuit with resistance, capacitance and inductance

Try to analyse the circuit in fig 2.28.

Here inductor, capacitor and resistor are connected in series across a supply of 'E' volts

The amplitude of voltage across 'R', $V_R = I_o R$ and as seen earlier it is in phase with the current.

The amplitude of voltage across 'C', $V_R = I_o X_L$ which leads the current by $\pi/2$ radians

Now let us indicate all these voltages using a phasor diagram (fig 2.29) in which the circuit current is taken as reference.

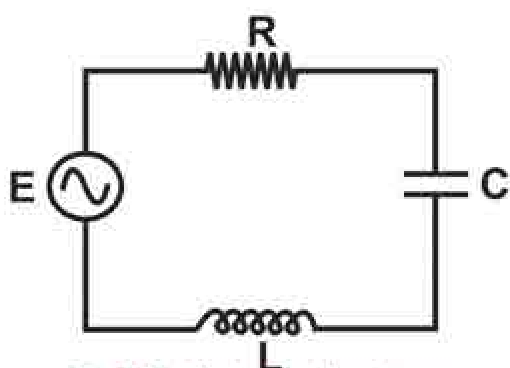


Fig. 2.28 AC circuit with resistance, capacitance and inductance

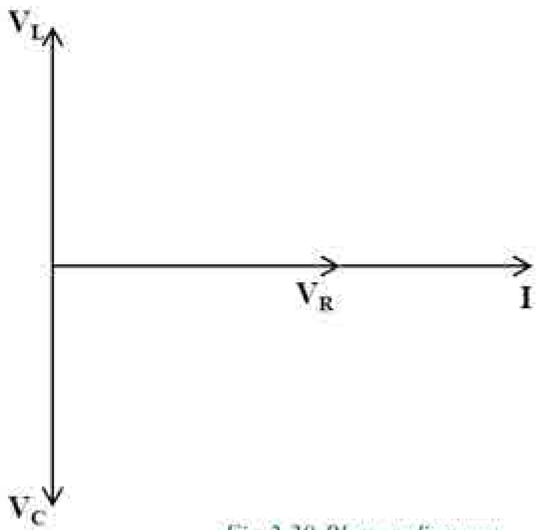


Fig 2.29 Phasor diagram

From this phasor diagram it is clear that the voltage across the resistor is in phase with the current, the voltage across the inductor is ahead by π/2 radians and the voltage across capacitor is behind the current by π/2 radians.

Using vector addition principles we can find out the effective value of voltage across the combination (refer fig 2.30).

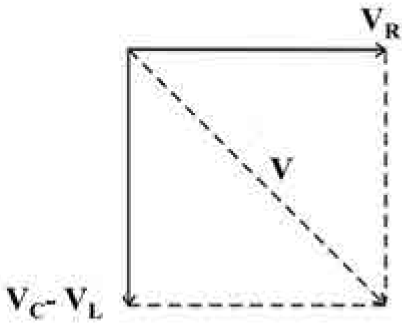


Fig 2.30 Calculation of effective value of potential difference

The effective potential difference

$$V = \sqrt{V_R^2 + (V_c - V_L)^2}$$

Therefore the peak value of this voltage

$$V_0 = \sqrt{(I_0R)^2 + (I_0X_c - I_0X_L)^2}$$

$$= I_0\sqrt{(R^2 + (X_c - X_L)^2)}$$

From this equation it can be noted that the ratio of peak value of voltage to the peak value of current is a constant for a given frequency. This constant is called the impedance of the circuit whose unit is ohm itself.

So impedance $Z = V_0/I_0 = \sqrt{R^2 + (X_c - X_L)^2}$

The phasor diagram in fig 2.31 is also called impedance triangle. Here Φ is the phase difference between the circuit current and the effective voltage.

$\tan \Phi = (X_c - X_L) / R$

In this equation if $X_C > X_L$ Tan Φ is positive, so Φ is positive which means the current is ahead of voltage or the current leads the voltage. The circuit is more capacitive.

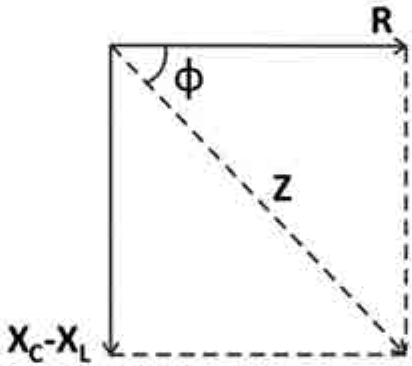


Fig 2.31 Impedance triangle

If $X_C < X_L$ tan Φ is negative, so Φ is negative and therefore the current lags the voltage. The circuit is more inductive.

If $X_C = X_L$ the circuit is purely resistive.

Impedance (Z) can also be indicated in the complex form with a real part R (resistor) in series with an imaginary part (+jX for inductor and – jX for capacitor)

$Z = R + j X_L$ if the circuit contains a resistor R and a coil which offers a reactance X_L

$Z = R - j X_c$ if the circuit contains a resistor R and a capacitance which offers a reactance X_L

Therefore generally for an RLC series circuit , the impedance can be obtained as

$Z = R + j (X_L - X_C)$

$= R + jX$ where $X = X_L - X_C$

In an RLC series circuit what should be the frequency of supply so that the inductive reactance is equal to the capacitive reactance? In such condition what will be the impedence of the circuit?

For Inductive reactance = Capacitive reactance

$X_L = X_C$

ie, $2\pi fL = 1/2\pi fC$

Or $f = 1/2\pi \sqrt{LC}$

At this frequency

$$Z = \sqrt{R^2 + (X_c - X_L)^2}$$

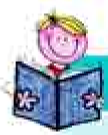
$$= \sqrt{R^2 + O}$$

$$= R$$

So the impedance of the circuit is minimum and is equal to the resistance of the circuit. In this case when the inductive reactance becomes equal to the capacitive reactance at a particular frequency, the RLC circuit is said to be in resonance.

Let us sum up

The rate of flow of electric charges is called electric current or electric current intensity. The work done per unit charge when a charge is moved from one point to another is called the potential difference between the two points. Electric power is the rate of doing this work. It is the product of voltage and current. According to Ohm's law $V \alpha I$ or $V = IR$. The unit of resistance is ohms. When resistors are combined in series, the effective resistance increases. $R_{eff} = R_1 + R_2 + R_3 + ...$ When these are combined in parallel the effective resistance becomes less than the least. $1/R_{eff} = 1/R_1 + 1/R_2 + 1/R_3 + ...$ If capacitors are combined in series $1/C_{eff} = 1/C_1 + 1/C_2 + 1/C_3 + ...$ and when they are combined in parallel $C_{eff} = C_1 + C_2 + C_3 + ...$ For solving complicated networks Kirchhoff's laws are used. In a real voltage source the internal resistance is shown in series with the source. The equation for AC supply voltage is represented by $V = V_o \sin\omega t$ and AC current is represented by $I = I_o \sin\omega t$. The rms value is given by $Vrms = Vmax/\sqrt{2}$ and the average value $V_{average} = 2V_{max}/\pi$. Impedence is a measure of overall opposition to the AC current flow through a circuit having resistance, capacitance and inductance. It is like resistance but includes resistance, inductive reactance and capacitive reactance. In a RLC series circuit when the capacitive reactance is greater than the inductive reactance ie, $X_C > X_L$, $\tan \Phi = (X_C - X_L)/R$. is positive and so the current leads the voltage. If $X_C < X_L$, $\tan \Phi$ is negative and so the current lags the voltage. If $X_L = X_C$ the circuit is purely resistive. The impedance $Z = \sqrt{R^2 + (X_C - X_L)^2}$ or in the vector form $Z = R + j(X_L - X_C)$.



Learning outcomes

The learner is able to

- Differentiate the basic parameters of electricity
- Utilize Ohm's law for solving electric circuits
- Solve electrical networks containing series & parallel combination of resistors and capacitors.
- Solve networks using Kirchhoff's laws
- Explain the characteristics of ideal voltage and current sources.
- Distinguish between DC and AC voltages.
- Explain the characteristics such as frequency and phase angle of AC voltage.
- Explain the significance of rms and average values of AC
- Explain the concept of impedance

Evaluation items

Multiple choice questions

1) 1 Joule / coulomb is equal to

a) 1 Watt b) 1 Ampere c) 1 ohm d) 1 Volt

2) Three resistors each of value 'R' are connected in parallel. The effective resistance will be

a) 3R b) R/3 c) 3/R d) None of these

3) If two Capacitors C_1 and C_2 are connected in series the effective Capacitance will be

a) $\frac{C_1C_2}{C_1+C_2}$ b) C_1C_2 c) C_1+C_2 d) None of these

4) For an ideal voltage source

a) The internal resistance is Zero

b) Output voltage depends on the value of load resistance

c) Internal voltage drop is Considerable

d) All of the above are true

5) For an ideal current source

a) The internal resistance is infinity.

b) The internal resistance is negligible

c) As load resistance increases, the load current also increases

d) All of the above are true

6) The average value of a sinusoidal wave with maximum voltage V_m over one complete cycle is equal to

a) $V_m/2$ b) $2V_m$ c) Zero d) V_m

7) An ac voltage is represented by v=100 sin (314t). The peak value of voltage and frequency are respectively

a) 100V and 100Hz

b) 50V and 50Hz

c) 100V and 50Hz

d) 50V and 100Hz

8) For a purely resistive circuit the current and voltage

a) Differ in phase by ∏/2

b) Differ in phase by ∏

c) Are in phase

d) Are vector quantities

9) The reactance of an inductor is

a) Directly proportional to the supply frequency

b) inversely proportional to the supply frequency

c) Independent of frequency

d) None of the above are true

10) When the supply frequency $f = \frac{1}{2\pi\sqrt{LC}}$

a) $X_L > X_C$

b) $X_L < X_C$

c) $Z > R$

d) $X_L = X_C$

11) The current lags behind the voltage for

a) capacitive load

b) inductive load

c) resistive load

d) no load

Key for multiple choice questions

1) d 2) b 3) a 4) a 5) a 6) c 7) c 8) c 9) a 10) d 11) b

Descriptive type questions

1) Define the potential difference between two points. What is its unit?

2) Give the SI unit and dimensional formula of resistance

3) If three resistors R_1 ,R_2 and R_3 are connected in series combination discuss their effective resistance in the circuit.

4) If the above resistors are connected in parallel, discuss how to find out their effective resistances.

5) Explain Kirchhoff's current law

6) Explain Kirchhoff's voltage law

7) Derive an expression to find the effective capacitance of three capacitors connected in series.

8) Derive an expression to find the effective capacitance of a parallel combination of three capacitors

9) If "n" resistors each of value 'R' ohms are connected a) in series b) in parallel. Discuss and compare the effective resistances in each case.

10) What is an ideal voltage source? Obtain an expression to find the load current through the source.

11) Explain an ideal current source.

12) Discuss the terms

A) Cycle B) Time period C) Frequency and D) phase of an AC signal

13) What is the significance of RMS and average values?

14) Distinguish between RMS and average values of AC voltage.

15) Three resistors each of value 2Ω are connected in series. What is the effective resistance of the combination? If a 12V battery is connected across this circuit, find out the potential drop across each resistor (neglect internal resistance)

16) Three resistors each of value 15Ω are connected in parallel. What is the effective resistance of the combination? If a battery of 20V is connected across the circuit find the current through each resistor and the total current drawn from the battery.

17) 'n' resistors each of value 'R'Ω are to be combined to get (i) maximum effective resistance (ii) minimum effective resistance.

a) How will you do these? b) What is the ratio of maximum to minimum resistance?

18) A 220v, 50Hz AC supply is applied to a circuit of resistance 100Ω. What is the RMS value of current in the circuit? What is its maximum value?

19) An AC supply voltage is represented by v = 100 Sin 100t. Find a) RMS value of voltage b) average value of voltage c) supply frequency d) time period.

20) Obtain the equation for impedance of a RLC series circuit.

21) You are given the tangent of the phase angle between the resistance R and the impedance Z of a RLC series circuit. Are you able to find out whether the circuit is purely resistive, more inductive or more capacitive? How?

22) A 100Ω resistor, a 50mH inductor and a 20 μF capacitor are connected in series across an AC supply of 230V 50Hz. Calculate the impedance of the circuit.

3

SOLID STATE FUNDAMENTALS

INTRODUCTION

Semiconductors are the basic materials used in solid state electronic devices like junction diodes, transistors and integrated circuits. Research on semiconductor materials started in the early nineteenth century. The most commonly used semiconductor materials are Silicon(Si) and Germanium (Ge). There are compound semiconductors like Gallium Arsenide (GaAs) and Gallium Phosphide (GaP) which are built with two different elements, Gallium and Arsenic. Such composite semiconductors have special electrical or optical properties.

In nineteen fifties, Germanium was the most commonly used material. However, it is not suitable for high temperature applications. Later Silicon became the more preferred material than Germanium because of its better temperature stability, lower cost, strong crystal structure and availability.

3.1 ENERGY LEVEL DIAGRAM

According to Bohr's atom model, each electron orbit has a fixed amount of energy associated with it. An electron moving in a particular orbit possesses the energy of that orbit (Fig 3.1). The larger the orbit, the greater is its energy. It is clear that the outer orbit electrons possess more energy than the inner orbit electrons. In an isolated atom, the energy levels of electrons in various orbits can be represented by horizontal lines. Such a diagram is called Energy Level Diagram. Fig 3.2 shows the Energy Level Diagram (ELD) of an isolated atom. E_1 represents the energy level of the first orbit , E_2 that of the second orbit and so on.

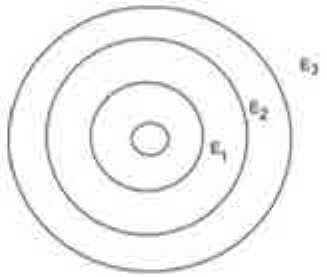


Fig. 3.1 Structure of an atom

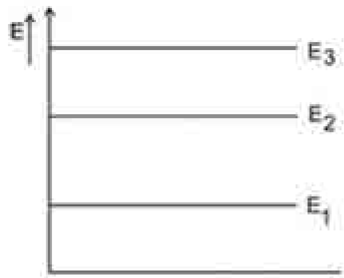


Fig. 3.2 Energy level diagram

In 1913, Niels Bohr, a Danish physicist gave the explanation of atomic structure. According to him an atom consists of a positively charged nucleus surrounded by negatively charged electrons revolving in different fixed orbits. The number of electrons in each orbit is fixed. Hence the number of electrons in an isolated atom that can possess a particular energy value is also fixed.

3.2 ENERGY BANDS IN SOLIDS

So far we have considered electron energy levels in a single isolated atom. Atoms of gases can be considered isolated because of their greater spacing under normal pressure and temperature. Hence the energy levels of such atoms are not affected by other distant atoms. But there are significant changes in the energy levels when atoms exist close together as in solids. When atoms come closer the outer orbit electrons come close together and even overlap. Because of this interaction the energy levels are split up. These energy levels are discrete but closely spaced forming almost a continuous range of energy called energy band. We also know that the number of electrons in the outermost orbit decides valency. These valence electrons are not free to move about from one point to another. If they get sufficient energy they can reach higher energy levels so that they become free to move about. This results in electrical conduction.

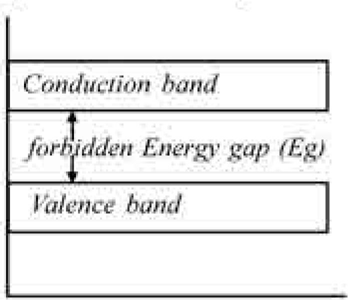


Fig. 3.3 Energy band diagram

Valence Band

The electrons in the outermost orbit of an atom are called valence electrons. The energy band occupied by the valence electrons is called valence band. The valence band may be either completely filled or partially filled, but can never be empty.

The range of energies possessed by valence electrons is known as valence band

Conduction band

The electrons which have left the valence band are called conduction electrons. The range of energy occupied by these electrons is called conduction band.This band lies next to the valence band. It may be either empty or partially filled with electrons. In conduction band, electrons move freely and conduct current through the solid.

The range of energies possessed by conducting electrons is known as conduction band

If a substance has empty conduction band, it means that the current conduction is not possible in that substance. Generally, in insulators conduction band is empty. On the other hand, in conductors it is partially filled.

Forbidden Energy Gap

Electrons cannot take energy level in between valence band and conduction band. The separation between conduction band and valence band on the energy band diagram is known as forbidden energy gap (band gap, E_g).

The width of the energy gap is a measure of the bondage of valence electrons to the atom. The greater the energy gap, the more tightly the valence electrons are bound to the nucleus. In order to push an electron from valence band to the conduction band, external energy equal to the forbidden energy gap must be supplied.

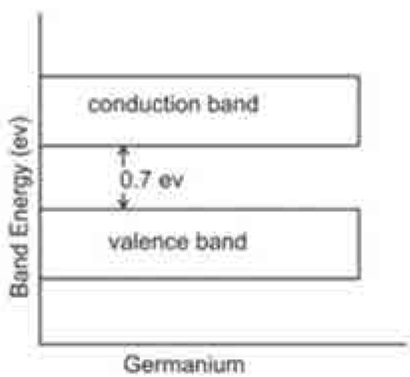


Fig. 3.4 Energy band diagram of Germanium

3.3 CLASSIFICATION OF SOLIDS

The electrical conduction properties of solids can be explained on the basis of forbidden energy gap. The solids can be classified into three types. Fig. 3.5 shows the energy band diagram of different solids.

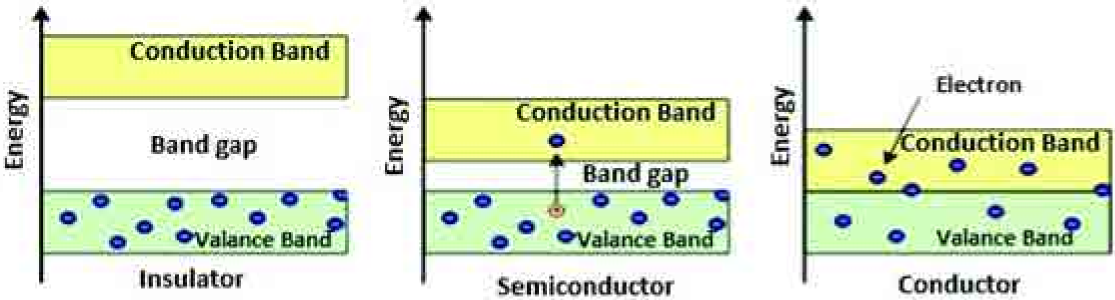


Fig. 3.5 Energy band diagram of solids

Insulators

As shown in Fig 3.5 the insulators (eg. Wood, Glass) have a large forbidden energy gap. The electrons are found only in valence band at room temperature.

To achieve conductivity, electrons from the valence band have to move into the conduction band. This is not possible in insulators because of large forbidden energy gap.

Conductors

Conductors (eg. Copper, Aluminium) have

a) overlapping valence and conduction bands

b) plenty of free electrons in the conduction band

In conductors there is no band gap between the valence band and conduction band. Due to this even, a slight potential difference across the conductor is enough to move the free electrons resulting in electric current.

Semiconductors

A semiconductor is one whose electrical properties lie in between insulators and conductors (Eg. Silicon and Germanium).

In terms of energy bands, semiconductors at room temperature have a very narrow forbidden energy gap. At 0^0K, there are no electrons in the conduction band of semiconductors, whereas their valence band is completely filled. Therefore at absolute zero temperature, semiconductor behaves as an insulator. However with increase in temperature, electrons get liberated from the valence band. These free electrons can move towards the conduction band, since the energy gap is small.

Activity 1

Create a table of matching words using the following terms

Rubber, Energy gap very small(< 3eV), Conductor, Energy gap very large(>3eV), Valence band & Conduction band overlap, Copper , Silicon, Insulator,Semiconductor, Continuous current flow, No current flow, Partial conductivity.

- *From the table note down your observations based on what you have learned in the above section.*
- *Which material rubber, copper or silicon needs the highest amount of energy to move an electron from the valence band to the conduction band? Why is it so?*

Now check whether your table matches with that given below.

Conductor	Insulator	Semiconductor
Copper	Rubber	Silicon
Valence band and conduction band overlap	Energy gap very large(>3eV)	Energy gap very small(<3eV)

Check your progress

Distinguish between conductors, insulators and semiconductors on the basis of energy band diagram.

3.4 BONDS IN SEMICONDUCTORS

The atoms of every element are held together in a molecule by the bonding action of valence electrons. This bonding action is due to the fact that there is a tendency of each atom to complete its outermost orbit by acquiring 8 electrons in it. However, in most of the elements, the outermost orbit is incomplete. In order to acquire 8 electrons in the outermost orbit, atoms share electrons with other atoms. To do so, the atom may donate, accept or share valence electrons with other atoms. In semiconductors, bonds are formed by sharing of valence electrons. Such bonds are called covalent bonds. In the formation of covalent bond, each atom contributes equal number of valence electrons and the contributed electrons are shared by the atoms engaged in the formation of the bond.

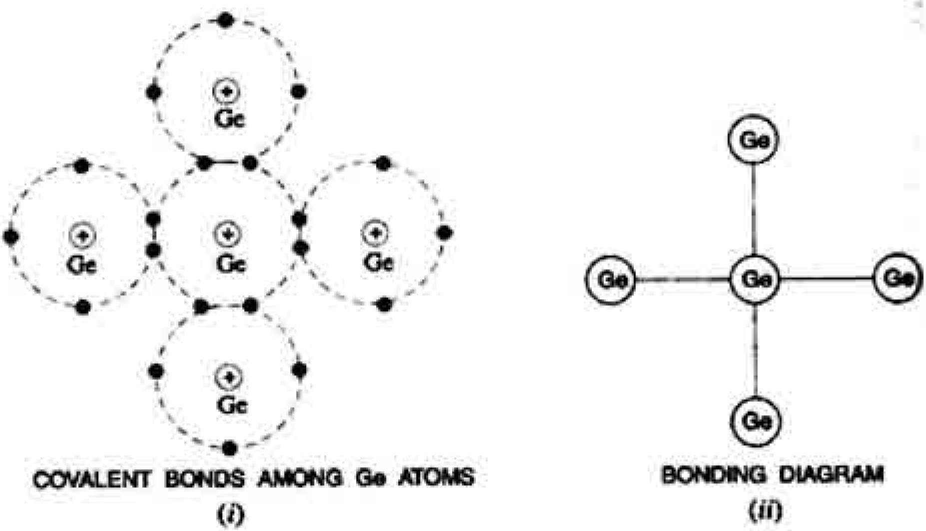


Fig. 3.6 Germanium bond structure

Fig 3.6 shows the covalent bonds among germanium atoms. A germanium atom has four valence electrons. There is a tendency in each germanium atom to have eight electrons in the last orbit. To do so each germanium atom positions itself between four other germanium atoms as shown in fig 3.6. Each neighbouring atom shares one valence electron with the central atom. In this way the atom completes its outermost orbit by having eight electrons revolving round the nucleus.

3.5 COMMONLY USED SEMICONDUCTORS

There are many semiconductors available, but very few of them have practical applications in electronics. The two commonly used materials are Germanium(Ge) and Silicon(Si). In Ge and Si, the energy required to break the covalent bond (energy required to release an electron) is very small. For Ge it is 0.7 eV and for Si it is 1.1 eV.

(i) Germanium: Germanium is an earth element and is recovered from the ash of certain coals. Generally recovered Germanium is in the form of germanium dioxide powder which is then purified by chemical reduction techniques.

The atomic number of Germanium is 32. Therefore, it has 32 protons and 32 electrons. Two electrons are in the first orbit, eight electrons in the second, eighteen electrons in the third and four electrons in the outer or valence orbit (See Fig. 3.7). It is clear that Germanium atom has four valence electrons making it a tetravalent element.

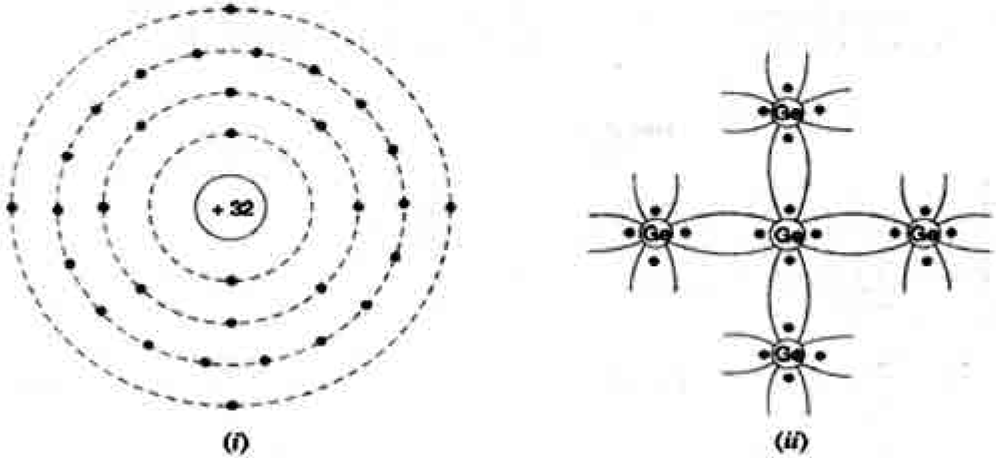


Fig 3.7 Atomic structure and bonding of Germanium

(ii) Silicon

Silicon compounds are commonly available in the form of sand (silicon dioxide). Silicon is obtained by purifying Silicon dioxide by chemical reduction techniques.

The atomic number of silicon is 14. Two electrons are in the first orbit, eight electrons in the second orbit and four electrons in the valence orbit. It is clear that silicon atom has four valence electrons, that is, it is tetravalent. Fig. 3.8 shows how various Silicon atoms form covalent bonds.

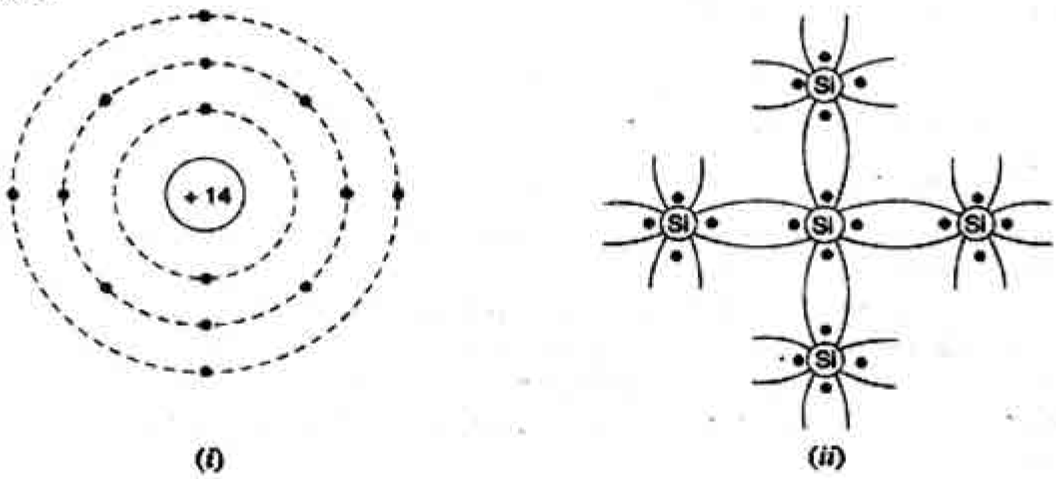


Fig. 3.8 Atomic structure and bonding of Si

3.6 TYPES OF SEMICONDUCTORS

Semiconductors may be classified as shown below.

Semiconductors

Intrinsic or Pure Semiconductors | Extrinsic or Impure Semiconductors

3.7 INTRINSIC SEMICONDUCTORS

Semiconductor in its extremely pure form is called intrinsic semiconductor. At 0^0K it behaves as an insulator because there are no free electrons. At room temperature a few electrons get sufficient energy to break the covalent bond. These electrons can move freely and act as charge carriers. A vacancy is created in the covalent bond when a free electron is formed and this vacancy is called a hole. Holes in the valence band, can be filled by other electrons in the valence band. This results in movement of holes in the valence band. These holes can be viewed as positive charge carriers.

In intrinsic semiconductor the number of holes in valence band is equal to the number of free electrons. The free electrons exist in conduction band and holes exist in valence band.

Movement of Holes in Semiconductors

If an electron in the valence band gets sufficient energy, it can jump across the forbidden energy gap and enter the conduction band. Suppose a covalent bond 'A' breaks due to the external energy received by the atom and an electron is released. A hole is left behind in the valence band. Under favorable condition the electron from another covalent bond 'B' jumps into the hole at 'A'. This fills the original hole but creates a new hole in 'B'. Next an electron from another bond 'C' jumps into the hole in 'B' and so on. In this way a succession of electron movement takes place. So we can say that the hole is moved from 'A' to 'C'. Even if the actual movement is by electrons, for convenience we will consider it as hole movement.

It should be noted that holes are filled by electrons which move from adjacent atoms without passing through the forbidden energy gap. It means that hole movement takes place in valence band only. No additional hole is created if an existing hole is filled by an adjacent electron.

Let us conclude the above facts as follows:

1. Holes exist in and flow in the valence band.
2. Conduction electrons are found in and flow in the conduction band.
3. Hole current is in valence band and electronic current is in conduction band.
4. Conduction electrons move twice as fast as the holes.

3.8 EXTRINSIC SEMICONDUCTORS

As you have seen earlier, a pure form of semiconductor is a bad conductor of electricity because of the absence of charge carriers which are free to move about. Therefore inorder to have conduction, more free charge carriers have to be created in the crystal structure. This can be achieved by adding suitable materials (impurity) to pure semiconductors. Impurity added semiconductors are called extrinsic semiconductors. The process of adding impurities to a semiconductor is known as doping. Now let us discuss how these free charge carriers are formed when impurity atoms are added.

The purpose of adding impurity is to increase either the number of free electrons or holes in the semiconductor. If a pentavalent impurity(having 5 valence electrons) is added to the semiconductor, free electrons are produced in the semiconductor. On the other hand, addition of trivalent impurity (having 3 valence electrons) creates holes in the crystal. Depending on the type of impurity added, extrinsic semiconductors are classified into:

(i) **N- type semiconductor**

(ii) **P- type semiconductor**

3.9 N-TYPE SEMICONDUCTORS

N – type semiconductors are obtained by adding pentavalent impurities (Bismuth, Antimony, Arsenic and Phosphorous) to a pure semiconductor. The four valence electrons of impurity atom form covalent bond with four neighboring semiconductor atoms and the fifth electron is free to move in the crystal. Thus the addition of pentavalent impurity atom provides free electrons to the semiconductor. The pentavalent impurities which produce N-type semiconductor are known as donor impurities because they donate or provide free electrons to the semiconductor crystal.

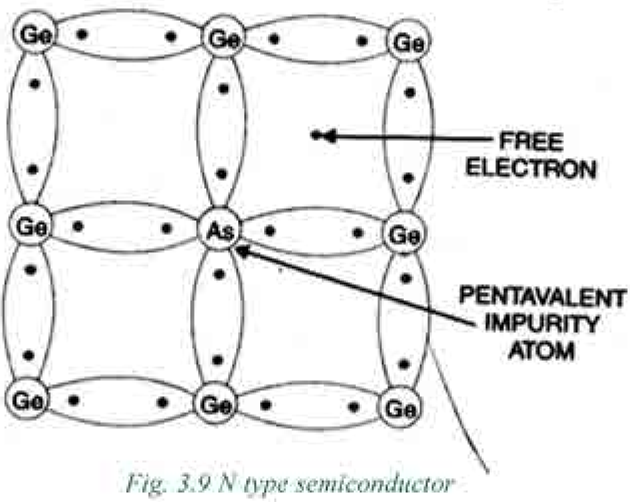


Fig. 3.9 N type semiconductor

In an N- type semiconductor a large number of free electrons are created by doping which improves its conductivity. But there will be a very small amount of free holes created because of thermal agitation. Free electrons are much more in number and so they can be termed as majority carriers and holes are comparatively much less and hence they can be termed as the minority carriers. Therefore in N-type semiconductor electrons are the majority charge carriers and holes are the minority charge carriers.

3.10 P-TYPE SEMICONDUCTOR

P-type semiconductors are obtained by adding trivalent impurities (Boron, Gallium, Indium, Aluminum) to a pure semiconductor. The three valence electrons of impurity atom form covalent bond with four neighbouring semiconductor atoms and the fourth covalent bond has a vacancy. This gives rise to a hole in the semiconductor. Thus the addition of trivalent impurity atom creates holes in the semiconductor. The trivalent impurities which produce P-type semiconductors are known as acceptor impurities, because the holes created can accept the electrons.

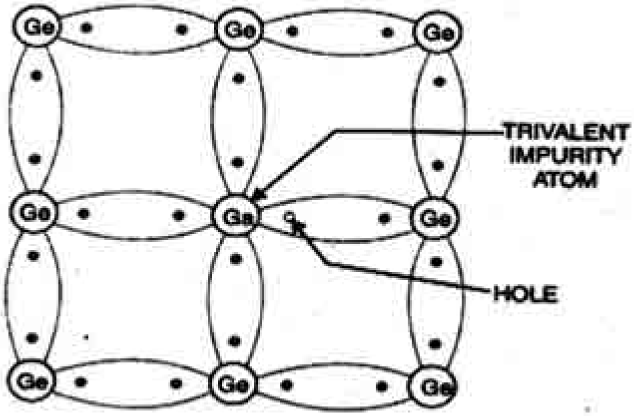


Fig. 3.10 P type semiconductor

In a P-type semiconductor a large number of free holes are created by doping which improves its conductivity. But however there will be a very small amount of free electrons created because of thermal agitation. Free holes are much more in number and so they can be termed as majority carriers and free electrons are comparatively less and hence they can be termed as the minority carriers. Therefore in P-type semiconductor, holes are the majority charge carries and electrons are the minority charge carriers.

As discussed earlier, the N-type semiconductor has excess of electrons and the p-type semiconductor has excess of holes. Do you think that the N-type semiconductor has net negative charge and P-type semiconductor has net positive charge? The term excess in the context means that the number of electrons is more than that required to fill the valence band. It does not mean that the total number of electrons is more than the number of protons. So P type and N type semiconductors are electrically neutral.

3.11 CHARGE CARRIER TRANSPORTATION IN SEMICONDUCTORS

The movement of charge carries in semiconductor material is classified as diffusion and drift.

Diffusion is a charge transportation mechanism taking place because of the concentration gradient. On the other hand the drift in a charge carrier movement is under the influence of an electric field. Majority carriers have both drift and diffusion transportation whereas minority carriers undergo only drift.

Activity 2

Complete the following table.

N type semiconductors	*P type semiconductors*
Pentavalent impurity atoms are added to intrinsic semiconductors	
	Excess holes improve conductivity
Holes are minority carriers	

- *Due to doping which type of carriers are created - majority or minority?*
- *Can you give examples for both the types of impurity atoms mentioned in the table?*

Now you can verify whether your solution matches with the following.

N type semiconductors	*P type semiconductors*
Pentavalent impurity atoms are added to intrinsic semiconductors	*Trivalent impurity atoms are added to intrinsic semiconductors.*
Excess electrons improve conductivity	*Excess holes improve conductivity*
Holes are the minority carriers	*Electrons are minority carriers*

By doping charge carriers are created which cause conduction. But the minority carriers are only a few which are formed due to some other reasons such as thermal agitation.

Boron, Gallium, Indium, Aluminium, etc. are trivalent and Arsenic, Antimony, Bismuth, etc. are pentavalent impurity atoms.

Let us sum up

Electrons in each orbit of an atom have a certain fixed amount of energy. The energy levels of electrons in a particular orbit is called energy band. Difference in energy between the valence band and the conduction band is called forbidden energy gap. Classification of materials such as conductors, insulators and semiconductors can be explained using energy band diagram.The conductivity of intrinsic or pure form of semiconductors can be improved by doping. If they are doped using pentavalent impurity N type semiconductors are formed. If doped with trivalent impurity we get P type semiconductors.

Learning outcomes

The learner is able to :

- Draw and explain the structure of an atom.
- Explain the energy bands in solids and classification of solids.
- Explain the properties of semiconductors and their significance.
- Explain the need for doping and how is it done.
- Classify semiconductors on the basis of doping.
- Explain the formation of majority and minority charge carriers.
- Explain how the charge carriers affect the current conduction through semiconductors

Evaluation items

Multiple choice questions

1) The P-type semiconductor

   a) has positive charge b) has negative charge c) is electrically neutral d) has either positive or negative charge.

2) Minority carriers in N- type semiconductors are

   a) electrons b) holes c) neutrons d) positive ions

3) For metals the forbidden energy gap is

   a) <3eV b) in between 3eV & 9 eV c) >3eV d) 9 eV

4) When Germanium crystal is doped with Phosphorous atoms, it becomes

   a) a P type semiconductor b) an n type semiconductor c) an intrinsic semiconductor d) a conductor

5) The deficiency of an electron in an atomic structure is a

   a) valence electron b) hole c) free electron d) negatively charged ion

6) Major part of the current in an N type semiconductor is due to

   a) conduction band electrons b) valence band electrons

   c) holes in the valence band d) thermally generated electrons

7) Addition of pentavalent impurity to a semiconductor creates many

   a) free electrons b) holes c) valence electrons d) intrinsic semiconductor

8) An N- type semiconductor is

a) positively charged b) negatively charged

c) electrically neutral d) none of these

9) When an atom looses an electron, the atom

a) becomes a positive ion b) becomes a negative ion

c) becomes electrically neutral d) is then free to move

10) The forbidden energy gap of Silicon is

a) 0.7eV b) 0eV c) 0.3eV d) 1.1eV

Key for Multiple choice questions

1) c 2) b 3) a 4) b 5) b 6) a 7) a 8) c 9) a 10) d

Descriptive type questions

1. Explain why the discrete energy levels of an isolated atom split into a band of energy when atoms combine together to form a solid.
2. Explain the difference between insulators, conductors and semiconductors using the energy band diagrams.
3. Define valence band, conduction band and forbidden energy gap.
4. Explain the reason why the conductivity of germanium is more than that of silicon at room temperature.
5. Define a hole. Explain how hole movement takes place in a semiconductor.
6. Explain the need of adding an impurity to an intrinsic semiconductor.
7. What are the majority carries in an N-type semiconductor?
8. What do you understand by intrinsic and extrinsic semiconductors?
9. Why does semiconductor behave as insulator at absolute zero temperature.
10. Name two commonly used semiconductors. Write the forbidden energy gap of those semiconductors.

4

SEMICONDUCTOR DIODE

INTRODUCTION

In the previous unit we studied about the N-type and the P-type semiconductors. Now let us see what happens when we join a P-type semiconductor to an N-type semiconductor. This can be done by special fabrication technique. When a P-type semiconductor is suitably joined to an N-type semiconductor, the contact surface is called P-N junction. Most semiconductor devices contain one or more P-N junctions. P-N junction is very important because, in effect, it controls the behavior of semiconductor devices.

4.1 PROPERTIES OF P-TYPE AND N-TYPE MATERIAL

Before going into the details of P-N junction formation, let us go through the properties of P-type and N-type semiconductors. In the Fig. 4.1, left side material is a P-type semiconductor having negative acceptor ions and positively charged holes. The right side material is N-type semiconductor having positive ions and free electrons. Comparison of P- type and N-type materials is given in table 4.1 below.

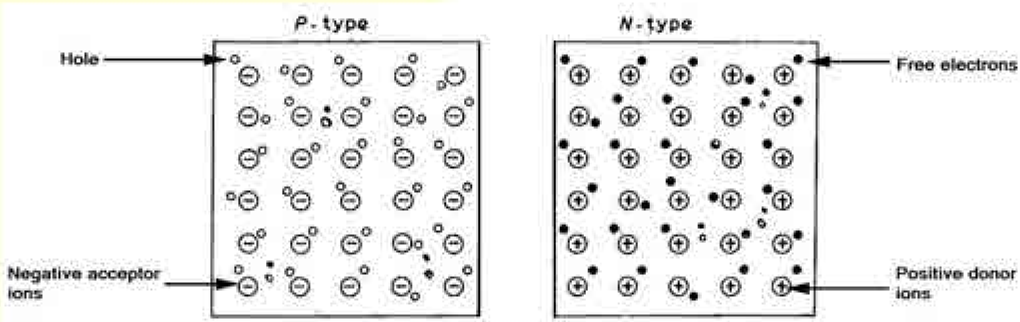


Fig. 4.1 P type and N type materials

P-type material	N-type material
• Semiconductor material is doped with acceptor impurity atoms. • Material has high hole concentration. • Concentration of free electrons in p type material is very low. • Contains negatively charged acceptor ions (immobile) and positively charged holes (free).	• Semiconductor material is doped with donor impurity atoms. • Material has high free electrons concentration • Concentration of holes in N-type material is very low. • Contains positively charged donor ions (immobile) and negatively charged electrons (free).

Table 4.1 Comparison of P-type and N-type semiconductors

4.2 FORMATION OF P-N JUNCTION

The Fig. 4.2 shows a P-N junction just formed with no external voltage applied.

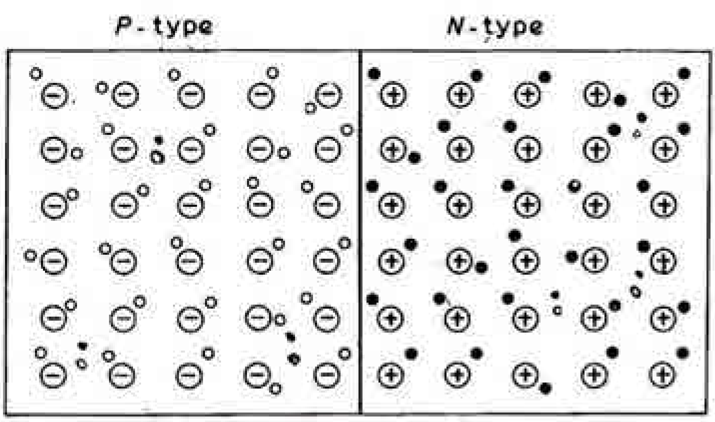


Fig. 4.2 PN junction

As soon as the P-N Junction is formed the following processes are initiated.

1. Holes from the P region diffuse into the N region. Then they combine with the free electrons in the N region.
2. Free electrons from the N region diffuse into the P region. These electrons combine with the holes in the P region.
3. When a hole is moved from the P-side towards the junction, there forms a net negative charge at the P-side due to the presence of immobile negative ions.

4. When an electron is moved from the N-side towards the junction, there forms a net positive charge at the N-side due to the presence of immobile positive ions.
5. Negative charge at the P- side stops electrons from further diffusion.
6. Positive charge at the N- side stops holes from further diffusion.
7. This process results in the formation of a barrier region which prevents the respective majority carriers crossing the junction.

It should be noted that outside the barrier on each side of the junction the material is still neutral. Only inside the barrier, there is a positive charge on the N side and a negative charge on the P side. This region is called **depletion layer** or **space charge region**. It is so called because the mobile charge carriers (free electrons and holes) have been depleted.

Fig. 4.3 shows the depletion layer when a P type and N type material are joined. The region contains immobile ions which are electrically charged. The physical distance from one side of the barrier to the other side is referred to as the width of the barrier. With no external batteries connected, the barrier is of the order of fractions of a volt. For a Silicon P-N junction, the barrier potential is about 0.7V, whereas for Germanium P-N junction it is approximately 0.3V.

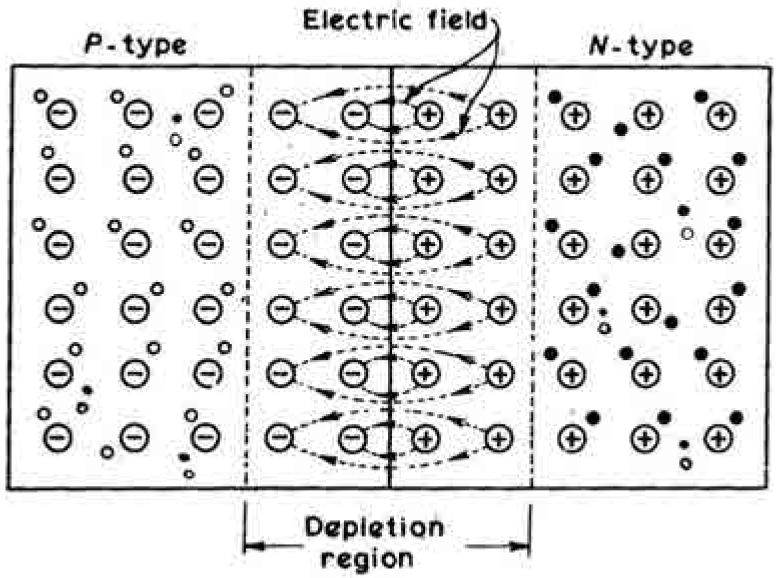


Fig. 4.3 Space charge region or depletion region is formed in the junction

Semiconductor Diode

A semiconductor diode is an electronic device which is basically a P N junction. The Fig. 4.4 shows the P N junction, the schematic symbol of a diode and a physical image of a typical diode. The diode has two terminals called the Anode and the Cathode.

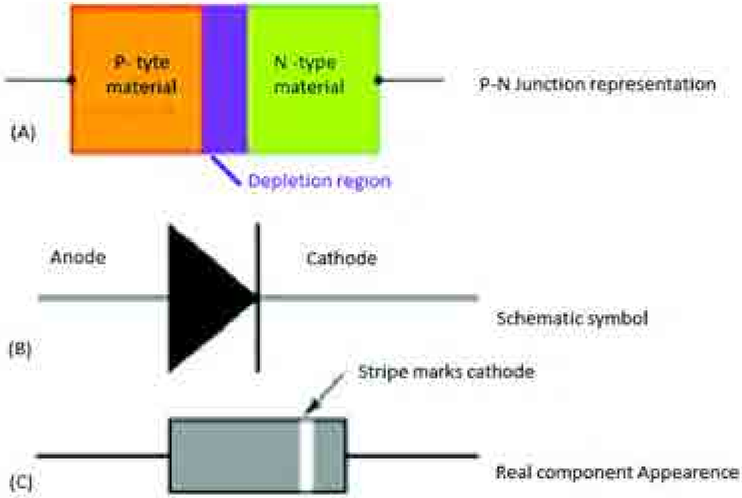


Fig 4.4 Diode

4.3 P-N JUNCTION BIASING

Activity 1

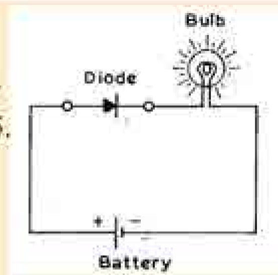


Fig. 4.5 Forward biased diode

Take a semiconductor diode and connect with a battery of 3V or above and DC bulb (torch bulb) in series as shown in the Fig. 4.5.

- *Does the bulb glow in the circuit?*
- *If yes, do you agree that the diode connected in this manner conducts current or it acts as a closed switch?*

When the diode is connected in this manner the lamp glows. This means the diode is conducting and the current is flowing in the circuit.

Activity 2

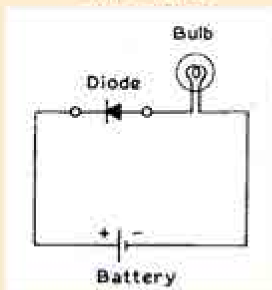


Fig. 4.6 Reverse biased diode

Now connect the diode in the circuit with its terminals reversed as shown below when the two terminals of the diode are reversed. It is shown in Fig. 4.6.

- *Does the bulb glow in this circuit?*
- *If not, what does it infer?*

When the diode is connected as in fig. 4.6 the lamp does not glow. It means no current is flowing in the circuit although the battery is present. The diode does not permit the current flow.

From the above activities we find that a diode conducts in one direction only. The unidirectional conduction property of a diode finds much application in electronics. The diode has different electrical properties depending on the polarity of voltage across its terminals. The voltage given to the diode to control its characteristics is called the bias voltage of the diode.

P-N junction with Forward Bias

Suppose we connect a battery to the P-N junction diode such that the positive terminal of the battery is connected to the P side and the negative terminal to the N side as shown in Fig. 4.7. In this condition the P-N junction is said to be forward biased.

When the P-N junction is forward biased, the holes repel due to the positive potential of the battery and are forced to move towards the junction. The electrons are repelled from the negative terminal of the battery and drift towards the junction. Because of their extra energy (due to the applied voltage) some of the holes and free electrons penetrate the depletion region, this will

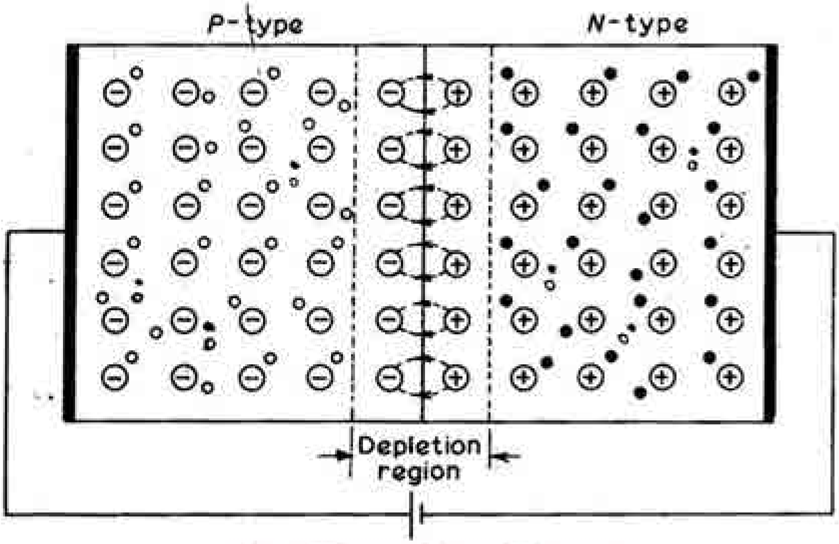


Fig. 4.7 Forward biased PN junction

reduce the potential barrier. Then more majority carriers drift across the junction. Once the potential barrier is eliminated (ie when the applied voltage becomes equal to the barrier potential) by the applied voltage, junction resistance becomes almost zero and a low resistance path is established. This results in a flow of current in the circuit. This is called the forward current.

P-N Junction with Reverse Bias

The positive terminal of a DC source is connected to the N side of the diode and the negative terminal to the P side. This type of connection is known as reverse bias. The Fig. 4.8 shows a reverse biased PN junction.

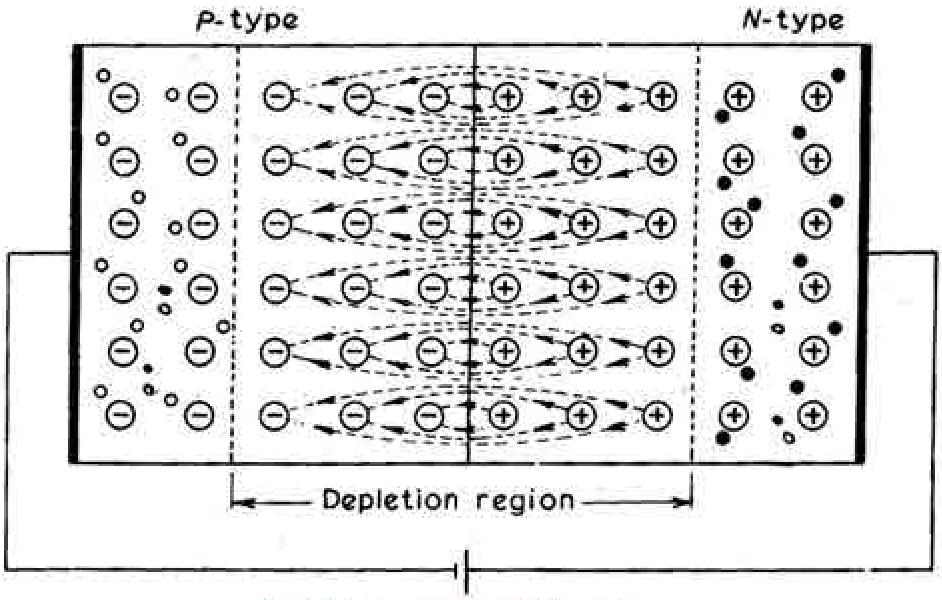


Fig. 4.8 Reverse biased PN junction

The holes in the P region are attracted towards the negative terminal of the battery. The electrons in the N region are attracted towards the positive terminal of the battery. Thus the majority carriers are drawn away from the junction. This action widens the depletion region and increases the barrier potential. i.e. the potential barrier widens. The increased barrier potential makes it more difficult for the majority carriers to diffuse across the junction.

In earlier chapters we have seen that a few minority carriers are also generated due to thermal agitation. As soon as a minority carrier is generated it is drifted across the junction because of the applied voltage. The rate of generation of minority carriers depends upon the temperature. If the temperature is fixed, the rate of generation of minority carriers remains constant. Therefore the current, due to the flow of minority carriers remains the same whether the battery voltage is low or high. For this reason this current is called **reverse saturation current**. This current is very small as the number of minority carriers is less and is of the order of nano amperes in silicon diode and micro amperes in germanium diode. This is one of the reasons for which silicon diodes are more preferred than germanium diodes.

4.4 V-I CHARACTERISTICS OF A P-N JUNCTION DIODE

Fig. 4.9 shows the V-I Characteristics of a P-N junction diode. It is the graphical representation of the relation between voltage across the junction and the current through the diode. Usually voltage is taken along x -axis and current along y-axis.

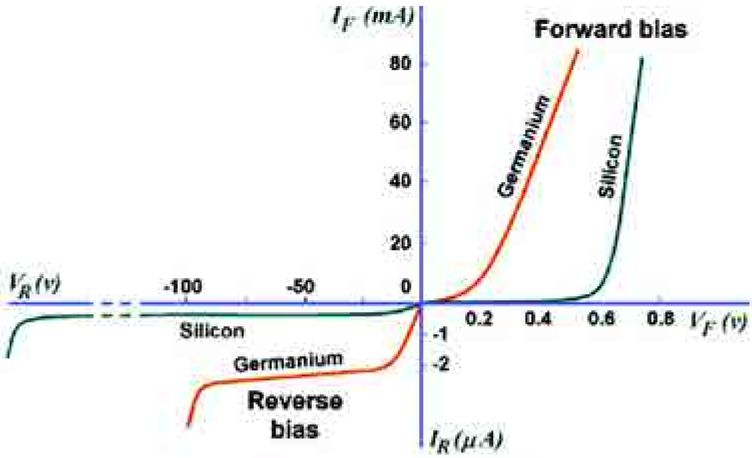


Fig 4.9 V-I characteristics of a P-N junction

Fig. 4.10 shows the circuit arrangement for determining the V-I characteristics of a P-N junction.

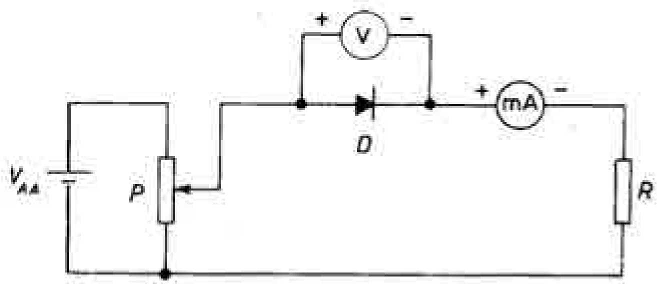


Fig. 4.10 Circuit arrangement for forward characteristics

Activity 3

Using your school laboratory select meters of appropriate ratings and assemble a circuit as shown in Fig. 4.10. Increase the input voltage from zero onwards and note down the corresponding meter readings and draw the forward characteristic curve of the Si diode.

- *What are the voltage and current ratings of voltmeter and ammeter selected respectively? Can you select a 0-250 V voltmeter and 0-10A ammeter? Why?*
- *Verify whether the curve obtained matches with that given in the following section.*

In the above circuit the maximum voltage across the diode to be measured is less than 1V. For this if we select a 0-250 V voltmeter it is difficult for us to note the reading. The Current through the diode expected is only of the order of milli ampere. So if we select 0-10A ammeter, the reading on the ammeter may not be properly readable. That is why we should select meters of appropriate range.

Forward Bias characteristics

From this circuit we find that the diode current is very small for the first few tenths of a volt. The diode does not conduct well until the external voltage overcomes the barrier potential. As we approach 0.3v for Ge and 0.7v for Si, larger number of free electrons and holes start crossing the junction. Above that voltage even a small increase in the voltage produces a sudden increase in the current. The voltage at which the current starts to increase rapidly is called **cut in voltage** or **knee voltage**. Here the P-N junction behaves as an ordinary conductor.

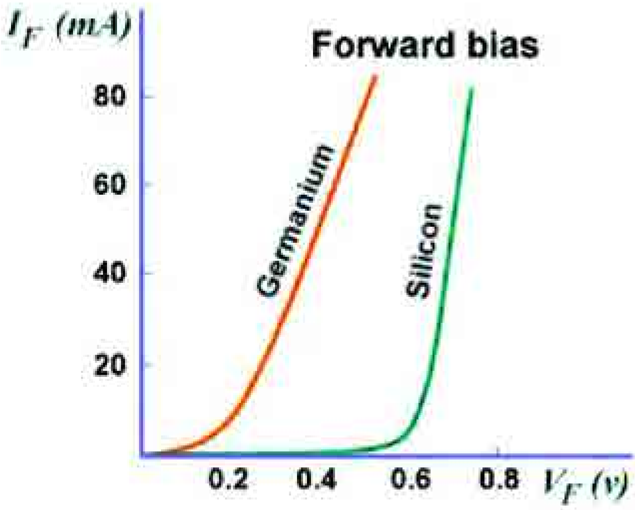


Fig 4.11 Cut in voltages of Si and Ge

From the graph (Fig. 4.11) it is noted that for a silicon diode the cut in voltage is approximately 0.7V whereas for a germanium diode it is about 0.3V.

Ideal diode

We have seen that a diode has a very important property that it permits only unidirectional conduction. It conducts well in the forward direction and poorly in the reverse direction. It would have been ideal if a diode acted as a perfect conductor when forward biased and as a perfect insulator when reverse based. The V-I characteristics of such an ideal diode would be as shown in Fig. 4.12. An ideal diode acts like a switch. The forward biased diode acts as a closed switch and offers zero resistance whereas the reverse biased diode acts as an open switch and offers infinite resistance.

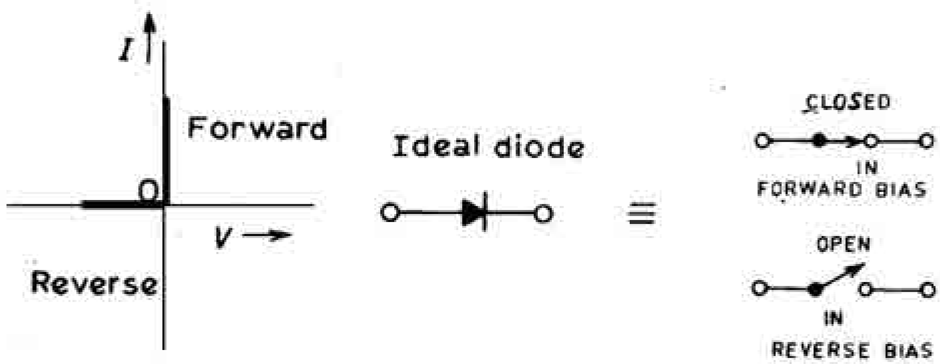


Fig. 4.12 Ideal diode characteristics

Static and Dynamic Resistance of a Diode

No diode can act as an ideal diode. A diode does not behave as a perfect conductor when forward biased .It offers small resistance when forward biased. Fig. 4.13 shows the forward characteristics of a typical silicon diode.

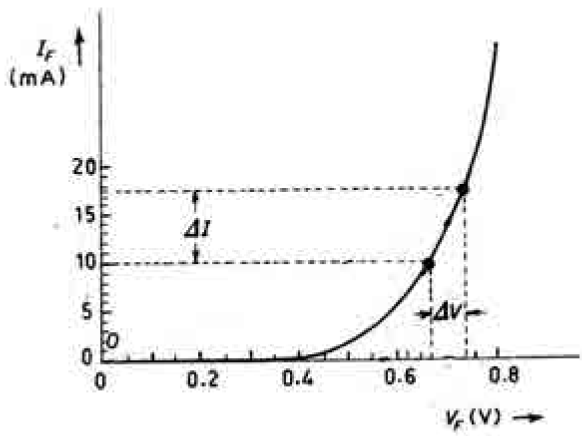


Fig. 4.13 forward characteristics of a silicon diode

DC Resistance or Static Resistance

When forward biased a diode offers a definite resistance in the circuit. This resistance is known as the forward resistance of the diode. The DC resistance or static resistance is simply the ratio of the DC voltage across the diode to the DC current flowing through it.

$$R_{dc} = \frac{V}{I}$$

It is clear from the Fig. 4.13 that the dc resistance of a diode varies as the current changes.

AC Resistance or Dynamic Resistance

The resistance offered by the diode to the AC signal is called dynamic resistance. It is the ratio of change in voltage to the change in current.

$$R_{ac} = \frac{\text{Change in Voltage}}{\text{Change in Current}} = \frac{\Delta V}{\Delta I} = \frac{V_2 - V_1}{I_2 - I_1}$$

Note:- *The Greek letter Δ (Delta) means:" a change of". So ΔI is the change in current. Generally it indicates a small scale.*

Reverse Bias Characteristics

To obtain the reverse bias characteristics we use the same circuit with few changes as shown in the Fig. 4.14. First we reverse the terminals of the diode. Second the milli ammeter is replaced by a micro ammeter.

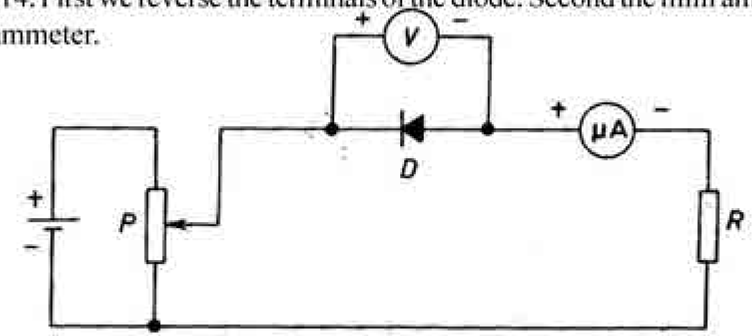


Fig. 4.14 Circuit arrangement for reverse characteristics

With reverse bias to the P-N junction ie P-type connected to the negative terminal and N-type connected to the positive terminal, potential barrier at the junction is increased. Therefore the junction resistance becomes very high and practically no current flows through the circuit. However in practice very small current flows in the circuit as shown in Fig. 4.15 and it is due to the minority carriers.

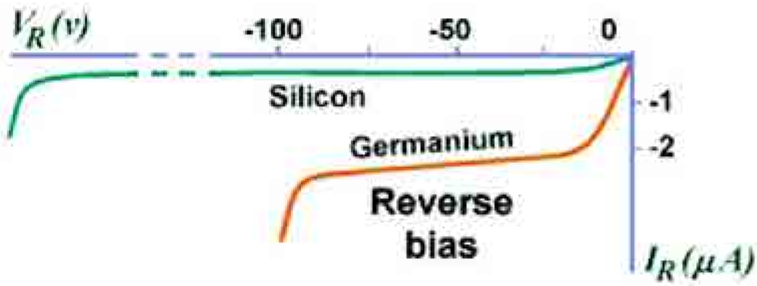


Fig. 4.15 Reverse characteristics of Si and Ge diodes

If the reverse voltage is increased continuously the kinetic energy of electrons may become high enough to knock out electrons from the semiconductor atoms. At this stage breakdown of the junction occurs, characterized by a sudden rise of reverse current and a sudden fall of the resistance of barrier region .This may destroy the junction permanently.

4.5 JUNCTION BREAK DOWN

If the reverse voltage applied to the P-N junction is increased, a point is reached when the junction breaks down and the reverse current rises sharply. This critical value of the voltage is known as break down voltage. The junction offers zero resistance at this point.

The break down voltage depends on the width of the depletion region which depends on the doping level.

There are two processes which can cause junction break down.

1. Avalanche breakdown
2. Zener breakdown

Avalanche breakdown

Avalanche breakdown occurs in the junction which is lightly doped and have wide depletion region. Due to the applied voltage, there forms an electric field in the depletion region. The minority carriers which are thermally generated acquire energy from this electric field and collide with the electrons in the covalent bond. Due to this collision with the valence electrons covalent bonds are broken and electron hole pairs are generated. These newly generated charge carriers also acquire energy from the same field and collide with the covalent bond and produce new charge carriers. This leads to an **avalanche** of charge carriers and the junction offers very low resistance. This cumulative phenomenon is called avalanche multiplication. This leads to the breakdown of the P-N junction and it is known as avalanche breakdown.

Zener breakdown

Zener breakdown occurs in the junction which is heavily doped and thereby has narrow depletion region. The breakdown voltage sets up a very strong electric field across this narrow region and this field is strong enough to break the covalent bonds thereby generating electron hole pairs. This can be a large current flow. This mechanism of breakdown is called Zener breakdown A comparison of the two types of junction breakdown processes are given in Table 4.2.

Avalanche breakdown	Zener breakdown
1. This occurs at junctions which are lightly doped and have wide depletion layers.	1. This occurs at junctions which are heavily doped and have narrow depletion layers.
2. Here electric field is not strong enough to produce Zener breakdown.	2. This breakdown voltage sets a very strong electric field across this narrow layer.
3. Here minority carriers collide with semi conductor atoms in the depletion region, which breaks the covalent bonds and electron-hole pairs are generated. Newly generated charge carriers are accelerated by the electric field which results in more collision and generates avalanche of charge carriers. This results in avalanche breakdown.	3. Here electric field is very strong to rupture (break) the covalent bonds thereby generating electron hole pairs. So even a small increase in reverse voltage is capable of producing large number of current carriers. Hence the junction now has a very low resistance. This leads to Zener breakdown.
4. This breakdown occurs above 6V.	4. Zener breakdown occurs below 6V.

Table 4.2 Comparison of Avalanche breakdown and Zener breakdown

4.6 ZENER DIODE

As seen earlier a P-N junction diode under reverse biased condition breaks down at a particular reverse voltage after which the diode becomes damaged. But if it becomes possible for a diode to be properly used even under breakdown condition it will help us to improve several electronic devices and circuits. Such a specially designed diode is called the Zener diode.

Zener diodes are special diodes designed to operate in the breakdown region without damage. Zener diodes have a heavily doped P-N junction which is operated in the break down region. Zener break down occurs due to the breaking of covalent bonds by the strong electric field set up in the depletion region. It produces extremely large number of holes and electrons which constitute the reverse saturation current called Zener Current I_z. The reverse voltage at which Zener break down takes place is called Zener voltage (V_z).

The satisfactory explanation of reverse breakdown in diode was first given by the Americal Scientist C. Zener. This break down is known by his name as zener breakdown.

A properly doped crystal diode which has a sharp break down voltage is known as a zener diode.

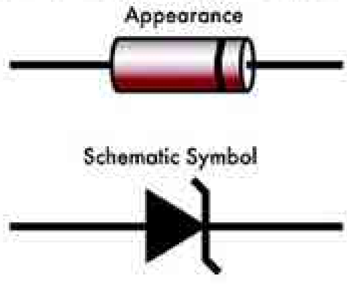


Fig 4.16 Symbol of Zener diode

The symbol of a zener diode is same as that of an ordinary diode except that the bar is turned into Z shape. The break down region is the knee of the reverse characteristics as shown in the Fig. 4.17. From the graph it can be understood that for a large variation of current the voltage across the diode is almost constant.

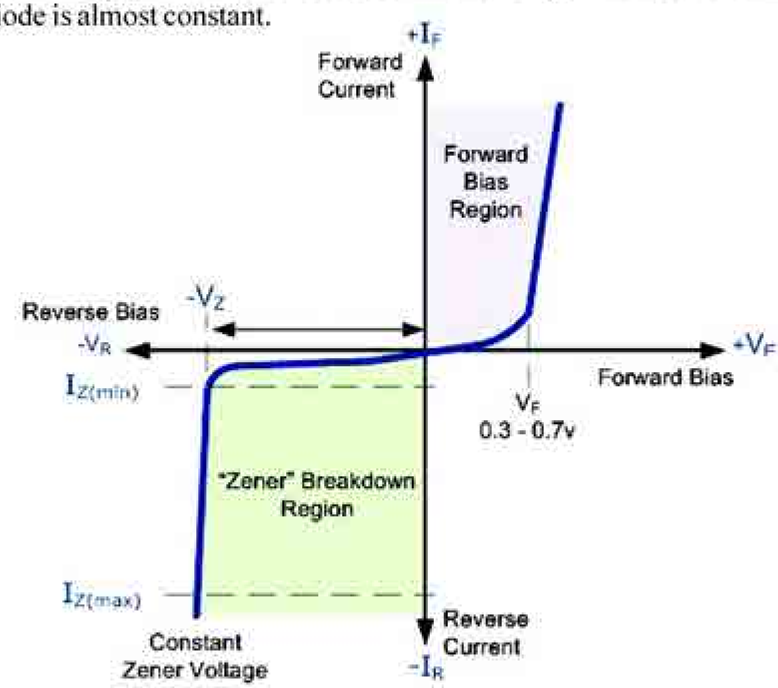


Fig 4.17 V-I characteristics of a zener diode

The following points may be noted about zener diode:-

1. A Zener diode is like an ordinary diode except that it is properly doped so as to have a sharp breakdown voltage.
2. A Zener diode is always reverse connected i.e. it is always reverse biased.
3. A Zener diode has sharp breakdown voltage called Zener voltage Vz.
4. When forward biased its characteristics is same as that of an ordinary diode.

5. The reverse breakdown voltage of a Zener diode is small compared to the ordinary diode and it can be operated in the break down region.

4.7 ZENER DIODE AS VOLTAGE REGULATOR

Zener diodes are widely used as voltage references and as shunt regulators to regulate the voltage across circuits. A Zener diode can be used as a voltage regulator to provide a constant voltage from a source whose voltage may vary over the specified range. The circuit arrangement is shown in Fig. 4.18. It consists of a resistor connected in series with the input voltage and a zener diode connected in parallel with the load.

The working of this circuit is explained below.

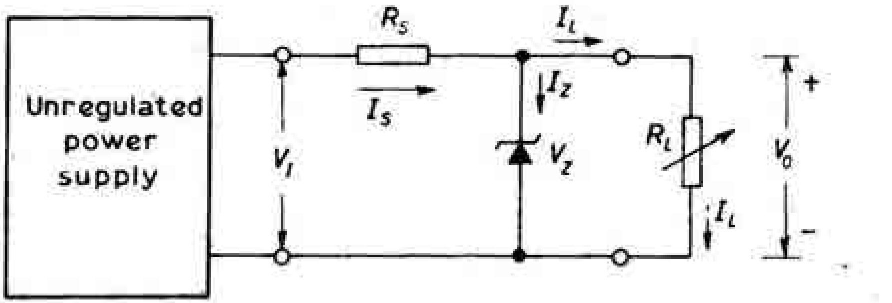


Fig. 4.18 Zener Voltage Regulator

The voltage regulator utilises the property of the Zener diode that when the breakdown is reached the voltage remains constant. At the same time the current through it varies as the applied voltage changes. When the input voltage varies above V_Z of the Zener diode, it will be in the reverse breakdown and the output voltage [which is same as V_Z] remains constant. The voltage V_I - V_Z drops across the series resistor R_S. When the input voltage increases, the output voltage remains constant at V_Z and the current I_S increases.

$$I_S = [V_I - V_Z] / R_S$$

But $I_S = I_Z + I_L$. As I_S increases, I_Z increases keeping I_L constant. Thus output voltage remains constant as $V_O = I_L \times R_L$. When input voltage decreases, the current I_S decreases and hence I_Z decreases keeping I_L constant. As I_L is kept constant, the output voltage remains constant. So the Zener diode keeps the output voltage constant by varying the current through it accordingly while keeping the voltage V_Z constant in the breakdown region. This voltage regulation is called line regulation.

In this circuit, an input voltage Vi, is regulated down to a stable output voltage Vo. The breakdown voltage of diode is stable over a wide current range and holds Vo relatively constant even though the input voltage may fluctuate over a fairly wide range.

Let us sum up

A PN junction is generally known as a diode. When a PN junction is formed, the charge carriers diffuse across the junction and due to the formation of the energy barrier or depletion layer nearby the junction, further movement of carriers is prevented. When external energy is supplied to the junction, it is called biasing. When forward biased, the diode conducts after knee voltage. When reverse biased, the diode acts almost as an open switch and only reverse saturation current flows. The reverse biased PN junction after break down conducts very large current and gets damaged. The Zener diode is a specially designed diode to be used under reverse biased condition after break down. This diode can be used as a voltage regulator because its output voltage is constant.

Learning outcomes

The learner is able to

- Draw and explain the structure of an atom.
- Explain the effect of movement of charge carriers in a P-N junction.
- Explain how barrier potential is set up in a P-N junction.
- Draw the circuits and thus explain the characteristics of a diode under forward biased and reverse biased conditions.
- Draw and explain the V-I characteristics of a diode.
- Distinguish between the characteristics of germanium and silicon diodes.
- Explain different types of breakdown in diodes.
- Draw the circuit diagram and hence explain the working of Zener diode and its characteristics.
- Demonstrate and thus explain the working of Zener diode voltage regulator.

Evaluation items

Multiple Choice Questions

1. The forward voltage drop across a silicon diode is about………………
   (a) 2.5V (b) 3V (c) 10V (d) 0.7V
2. An ideal diode is one which behaves as a perfect…………………when forward biased
   (a) conductor (b) insulator (c) resistance material (d) none of these
3. The leakage current in a diode is due to.......................
   (a) minority carriers (b) majority carriers (c) junction capacitance (d) none of these

4. If the temperature of a diode increases, leakage current will…………….
(a) remain the same (b) decrease (c) increase (d) become zero

5. If the doping level of a diode is increased the breakdown voltage………….
(a) remains the same (b)is increased (c) is decreased (d) none of these

6. The knee voltage for a crystal diode is approximately equal to the ……………..
(a) applied voltage (b) breakdown voltage (c) forward voltage (d) barrier potential

7. A Zener diode is always ……………biased.
(a) reverse (b) forward (c) either reverse or forward (d) none of these

8. In the breakdown region a Zener diode behaves like a…………….source
(a) constant voltage (b) constant current (c) constant resistance (d) none of these

9. A Zener diode has …………. breakdown voltage.
(a) undefined (b) constant (c) zero (d) none of these

10. Zener diode is ……………… doped than ordinary diode.
(a) lightly (b) heavily (c) moderately d) none of these

Answer Key:

1) d 2) a 3) a 4) c 5) c 6) d 7) a 8) a 9) b 10) b

Descriptive type questions

1. Explain the formation of a depletion region in an open circuited P-N junction.
2. What do you understand by an ideal diode? Draw its V-I Characteristics.
3. Describe the action of P-N junction under forward bias and reverse bias.
4. Explain how unidirectional current flow is possible through a diode.
5. Explain the V-I characteristics of diode.
6. Explain the mechanism of Avalanche breakdown and Zener breakdown
7. Explain any one application of a Zener diode.
8. The figure 4.18 shows the circuit of a simple constant voltage supply using a Zener diode. The constant voltage value across the Zener diode is 5V. Find the current through 1kW load.
9. With V-I characteristics show how Zener diode is used as voltage regulator.

5 TRANSISTORS

INTRODUCTION

The transistor is a fundamental building block of modern electronic circuits. It is a semiconductor device with three terminals. Following its development in the early 1950s, the transistors have caused the fast development of electronics. It has led to the invention of smaller and cheaper radios, calculators, computers and the vast arena of electronic equipment we see around us.

Have you ever seen a transistor? Different types of transistors are shown in fig.5.1. Do you know how many terminals a transistor has? In fig 5.1 different packages of transistors are shown[1]. We can observe that transistor is a three terminal device.

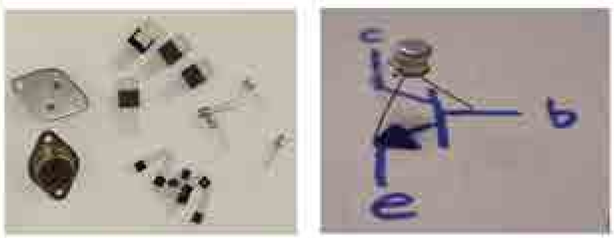


Fig.5.1 Different types of transistors

Although several companies produce over a billion individually packaged (known as discrete) transistors every year, a vast majority of transistors are now produced in integrated circuits (ICs), along with diodes, resistors, capacitors and other electronic devices. We know that diode is a two terminal device and has two semiconductor regions'. Can you say how many semiconductor regions transistors have?

Transistors are commonly used for amplification and switching. Amplifiers are used to increase the amplitude of a signal (e.g. in public address system amplifiers are used to increase the loudness of the sound signal or audio signal). Switches are used to make a device or system ON or OFF using electrical signal.

The word 'Transistor' was developed from the terms 'trans' which means transfer and 'istor' which means resistor. Therefore 'Transistor' means transfer of resistance from input terminals to the output terminals. The resistance across the input terminals (input resistance) and that between the output terminals (output resistance) can be controlled by changing the voltage given to the transistor terminals. This feature allows us to use transistors for various applications like amplification, switching etc.

5.1 BIPOLAR JUNCTION TRANSISTOR (BJT)

As we have already studied a P-type and an N-type semiconductor when joined together, a PN junction or diode is formed and its electrical properties are different in forward bias and reverse bias. In a bipolar junction transistor (BJT) there are two PN junctions. We know that in P-type semiconductors holes are the majority carriers and in N-type semiconductors electrons are the majority carriers. In BJTs both the charge carriers, electrons and holes take part in conduction, and hence the name bipolar[2].

Structure of BJT

Based on the types of semiconductor layers used, BJTs are classified into

1 NPN Transistor

2 PNP Transistor

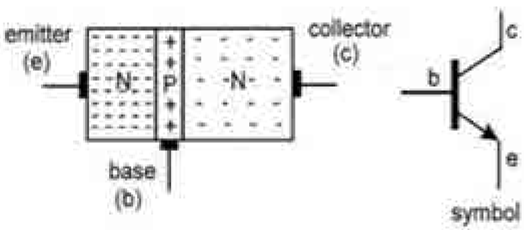


Fig.5.2.a. n-p-n Transistor

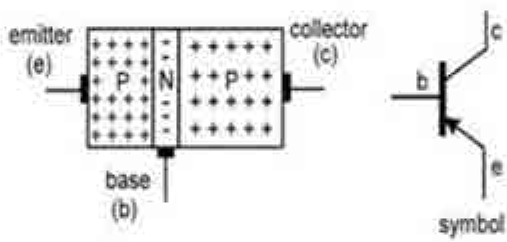


Fig.5.2.b. p-n-p Transistor

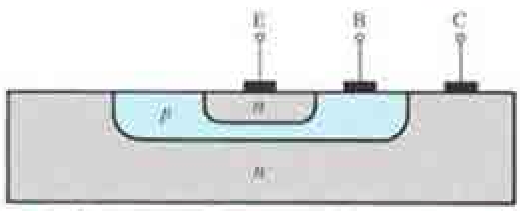


Fig.5.2.c. n-p-n Transistor (Cross - section)

[1] *The name diode is derived from the fact that it has two electrodes - 'di' meaning two and 'ode' for electrode. Transistor is the semiconductor version of triode (vacuum tube), which is derived from 'tri' and 'ode'.*

[2] *Transistors in which current conduction is caused by any one type of charge carriers are referred to as unipolar transistors. The field-effect transistors (FET) are examples which we will study in the forthcoming chapters*

When a P type semiconductor layer is sandwiched between two N-layers, the transistor is known as **n-p-n** transistor (fig.5.2.a). Similarly, when an n-layer is sandwiched between two p-layers, the transistor is known as **p-n-p** transistor (fig.5.2.b). fig.5.2.c shows the cross-section of npn transistor. Transistors are made either from Silicon (Si) or Germanium (Ge) crystal.

A Transistor (**n-p-n** or **p-n-p**) has the following regions

(i) **Emitter:** This region of the transistor emits charge carriers. It is more heavily doped in comparison to other regions. The physical size of this region is in between that of collector and base regions.

(ii) **Base:** Base is the middle region of the transistor which is lightly doped and physically very thin. This region accepts some of the charge carriers by recombination and passes most of the carriers to the collector region.

(iii) **Collector:** The collector region collects majority of the charge carriers from the emitter region through the base. This is moderately doped. The collector region is made physically larger than the emitter region. This is due to the fact that the collector has to dissipate more heat.

In the transistor symbol, arrow head is there at the **emitter,** which indicates the direction of the conventional current flow. *i.e.,* in the case of **n-p-n** transistor it is from base to emitter (base is positive with respect to emitter), while in the case of **p-n-p** it is from emitter to base (emitter is positive with respect to base).

The following are some important points about a transistor –

- Emitter layer is heavily doped. It has the largest number of charge carriers.
- Area of emitter layer is medium.
- Area of base layer is the smallest. It is a very thin layer.
- Base layer is lightly doped. It has a very few number of charge carriers.
- Area of collector layer is the largest.
- Collector layer is moderately doped. It has medium number of charge carriers.
- The junction between collector layer and base layer is called Collector-Base junction or C-B junction.
- The junction between base layer and emitter layer is called Emitter-Base junction or E-B junction.

Activity 1

Make a matching table of the structure of a BJT using the following words.

Emitter, lightly doped, moderately doped, collector, heavily doped, largest physical size, very thin, moderate size, supplies charge carriers, passes most of the carriers, accepts most of the carriers.

- *Do you agree that the recombination occurring in the base region is very less? If so why?*
- *Which region is with the largest area? Why?*

Verify whether your table matches with the following.

Emitter	*Base*	*Collector*
Heavily doped	*Lightly doped*	*Moderately doped*
Supplies charge carriers	*Passes most of the carriers*	*Accepts most of the carriers*
Largest physical size	*Very thin*	*Moderate size*

The base region is lightly doped and very thin. So it has a very less number of carriers for recombination and therefore it passes most of the carriers to the collector region. The collector region is made physically large as this region has to dissipate more heat energy.

5.2 TRANSISTOR BIASING

As we studied earlier a PN junction diode can be biased in two ways either forward or reverse. When the positive terminal of the battery is connected to the anode of the diode and the negative terminal of the battery is connected to the cathode of the diode, the diode is forward biased. When the positive and negative terminals of the battery are reversed it is reverse biased.

The different electrical properties in forward and reverse bias make the diode useful as a unidirectional device.

Similarly a transistor should also be biased for making it useful in various applications. In a transistor there are two PN junctions, emitter-base junction and collector-base junction. Both these junctions have to be biased. Based on how these junctions are biased, there are three different modes of operation for a transistor.

Emitter- Base (E-B) Junction	Collector- Base (C-B) Junction	Mode of Operation
Forward	Reverse	Active
Forward	Forward	Saturation
Reverse	Reverse	Cut-Off

First we shall see the active mode of operation, which is used when the transistor acts as an amplifier. Amplification is the most common use of a BJT. Transistor biasing for active mode of operation is as shown in Fig 5.3. The Emitter-Base (E-B) junction is forward biased and Collector-Base(C-B) junction is reverse biased. For this purpose a battery V_{EE} is connected between the emitter and the base and a battery V_{CC} is connected between the collector and the base[1].

In the case of p-n-p transistor, (Fig.5.3.a) the emitter base junction of p-n-p is forward biased by connecting the positive terminal of V_{EE} to the emitter and negative terminal to the base. The collector base junction is reverse biased by connecting the negative terminal of V_{CC} to the collector and the positive terminal to the base.

Similarly for n-p-n transistor, (Fig.5.3.b) the emitter base junction of n-p-n is forward biased by connecting the negative terminal of V_{EE} to emitter and positive terminal to base. The collector base junction is reverse biased by connecting the positive terminal of V_{CC} to the collector and negative terminal to the base. The forward biasing of emitter base junction makes the resistance in the emitter circuit low and reverse-biasing of collector-base junction makes the resistance in the collector circuit high.

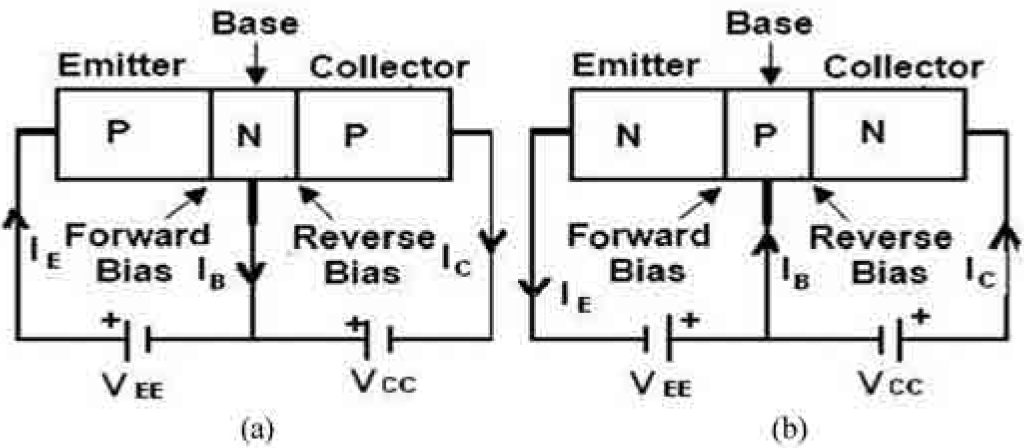


Fig.5.3 Transistor biasing

Fig.5.3 shows the conventional flow of currents in a transistor. The emitter terminal of the transistor emits charges which results in the emitter current (I_E). Some of these carriers are recombined in the base region which causes the base current (I_B) to flow. Most of the carriers are collected by the collector region which constitutes the collector current (I_C).

---

[1]Supply voltage is named according to which terminal it is connected to and is denoted by double subscripts. For example V_{EE} means it is a source voltage and it is connected in the emitter terminal. Similarly, V_{CC} means source voltage which is connected in the collector. The voltage across the junction is also denoted by double subscripts, and the more positive terminal is written first. In transistor the voltage across the emitter and the base junction is written as V_{BE} which denotes the base voltage with reference to the emitter. Similarly, the voltage across the collector and the base junction is written as V_{CB} which denotes the voltage at collector with reference to the base.

5.3 WORKING OF NPN TRANSISTOR

In the **N-P-N Transistor** the emitter is connected to the negative terminal of the battery V_{EE} for making it forward biased and the collector terminal is connected to the positive terminal of the battery V_{CC} for making it reverse biased (fig.5.4). I_E is the current flowing through Emitter terminal of the **transistor**, I_B is current flowing through the base and I_C is the current flowing through the collector.

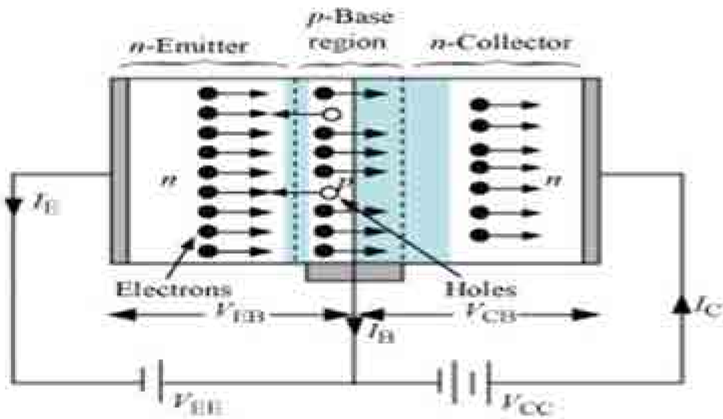


Fig.5.4 N-P-N Transistor

In the N-Type emitter the majority carriers are free electrons. So, the negative terminal of V_{EE} repels the electrons of the emitter region and the positive terminal of the battery (V_{CC}) attracts the electrons emitted by the emitter. Since the emitter junction is forward biased, the potential barrier at this junction is reduced and so the electrons supplied by the emitter start moving towards the base. This constitutes the emitter current I_E. As the base region is very thin and lightly doped, only some of the electrons emitted from the emitter recombine with the holes, which are the majority carriers in this region. This constitutes the base current I_B. The injected majority carriers from emitter to base become minority carriers in the base region. This minority carriers can drift through the reverse biased collector - base junction and reach the collector region and constitute the collector current I_c.

$$\mathbf{I_E = I_B + I_c}$$

5.4 WORKING OF P-N-P TRANSISTOR

In the P-N-P Transistor, the emitter is connected to the positive terminal of the battery V_{EE} for making it forward biased and the collector terminal is connected to the negative terminal of the battery V_{CC} for making it reverse biased as shown in fig.5.5. I_E is the current flowing through the emitter terminal, I_B is the current flowing through the base and I_C is the current flowing through the collector region.

In the P-type emitter the majority carriers are holes. So, the positive terminal of the supply V_{EE} repels the holes of the emitter and negative terminal of the battery V_{CC} attracts the holes emitted by the emitter. So, holes start moving from the emitter to the collector. This constitutes

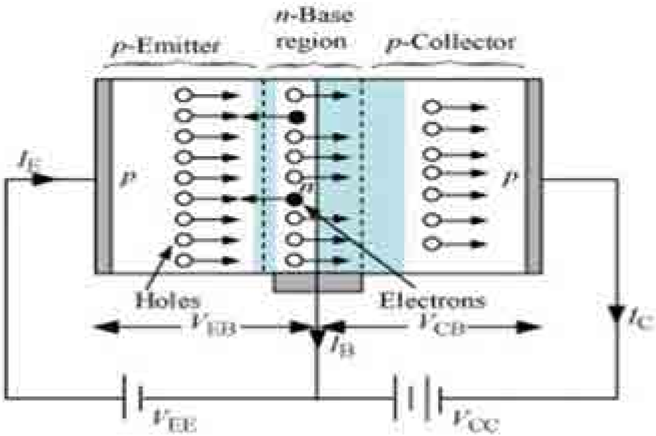


Fig.5.5 P-N-P Transistor

emitter current I_E. During the motion from emitter to collector, holes will pass through the base region where some of the holes may recombine with electron. Very small percentage of the holes emitted by the emitter recombines with the electrons in base region and this constitutes base current I_B. The rest of the holes are able to reach the collector which produces collector current I_C.

5.5 TRANSISTOR CONFIGURATIONS

When a device is used in a circuit we need two terminals each to connect the input signal and the output signal. As the **Transistor** is a three terminal device, one terminal has to be common with input and output. There are three possible ways to connect the transistor, within an electronic circuit with one terminal being common to both the input and output. In each method of connection, the circuit responds differently to the input signal, because the characteristics of each configuration is different. The three transistor configurations are

- Common Base Configuration (CB configuration)
- Common Emitter Configuration (CE configuration)
- Common Collector Configuration(CC configuration)

Common Base (CB) Configuration

In Common Base configuration the base is common to both the input and the output (fig.5.6). The input signal is applied between the emitter and the base terminals and the output is taken across the collector and the base terminals. The base terminal is grounded or connected to a fixed reference voltage.

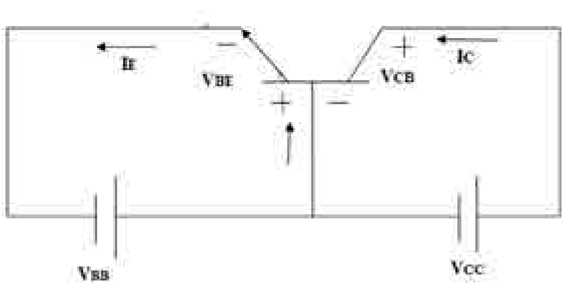


Fig.5.6 Common Base (CB) Configuration

Input voltage	= V_{BE}	Output voltage	= V_{CB}
Input Current	= I_E	Output Current	= I_C
Input resistance (R_i)	= V_{BE}/I_E	Output resistance (R_o)	= V_{CB}/I_C

In the expression for input resistance, numerator V_{BE} is the voltage across a forward biased junction which is very small, whereas denominator is the total current I_E and it is comparatively large. Therefore the input resistance is very low. The output resistance of CB configuration is very high because of its reverse biased junction.

Current amplification factor or Current gain α (Alpha)

Current amplification factor or current gain is the ratio of the output current to the input current. In common base configuration the emitter current (I_E) is the input current and the collector current (I_C) is the output current. Therefore in CB configuration current gain is the ratio of the collector current (I_C) to the emitter current (I_E). It is denoted as alpha (α).

$$\alpha = \frac{I_C}{I_E}$$

As we know, the emitter current is always greater than the collector current. So the value of alpha (α) is always less than unity. The practical values in the commercial transistors range from 0.9 to 0.99.

Expression for total collector current

From the above equation for α, collector current I_C is α times I_E. We know that when a transistor is in its active mode of operation, the collector base (CB) junction is reverse biased. So even when $I_E = 0$ some current will flow through the collector because of the presence of minority charge carriers and this current is called reverse saturation current I_{CBO}. I_{CBO} is the reverse saturation current in CB configuration and it is the current between the **C**ollector and the **B**ase when the emitter is **O**pen. Therefore total collector current,

$$\mathbf{I_C = \alpha I_E + I_{CBO}}$$

The current I_{CBO} is very small and for practical cases it may be neglected.

Solved Problem 5.1

A transistor in common base configuration has the following parameters. I_B is 20 µA and I_C is 2mA. Calculate the value of α.

Ans : I_C=2mA.

I_B = 20µA = 20×10^{-3}mA

α = I_C/I_E

We know that in a transistor $I_E = I_B + I_C$

I_E = $20\mu A + 2mA$

= $20 \times 10^{-3} mA + 2mA = 2.02mA$

Therefore

$\alpha = I_C/I_E = 2mA/2.02mA$

= 0.99

Solved Problem 5.2

In a transistor in CB configuration the emitter current is 5 mA and the collector current is 4.92 mA, calculate the value of α.

Ans: I_E = 5mA

I_C = 4.92mA

$\alpha = I_C/I_E$

$\alpha = I_C/I_E = 4.92\ mA/5\ mA$

= 0.984

Solved Problem 5.3

In a transistor in common base configuration, the emitter current is 1mA. When the emitter circuit is open, the collector current is 50µA. Find the total collector current. Given that α=0.92.

I_E = 1mA

I_{CBO} = $50\ \mu A = 0.05mA$

α = 0.92

Therefore the total collector current

$I_C = \alpha I_E + I_{CBO}$

$= 0.92 \times 1 + 0.05$

$= 0.92 + 0.05 = 0.97$ mA

Check Your Progress

In a transistor in CB configuration the emitter current is 1 mA and the collector current is 0.956 mA, calculate the value of α.

Voltage gain

The ratio of the output voltage to the input voltage is called voltage gain. In CB configuration, the output current is almost equal to the input current. At the same time, the output impedance is high and the input impedance is low. So the voltage developed across the output will be high. Therefore the voltage gain of CB configuration is also high.

Common Emitter (CE) Configuration

In Common Emitter configuration the emitter is common to both the input and the output . The input signal is applied between the base and the emitter terminals and the output is taken across the collector and the emitter terminals. As shown in fig.5.7 the emitter terminal is grounded or connected to a fixed voltage point.

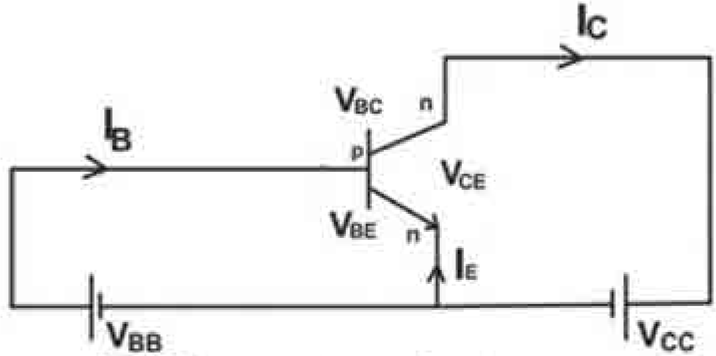


Fig.5.7 Common emitter configuration

Input voltage	=	V_{BE}	Output voltage	=	V_{CE}
Input Current	=	I_B	Output Current	=	I_C
Input impedance (R_i)	=	V_{BE}/I_B	Output impedance (R_o)	=	V_{CE}/I_C

The input current I_B in C.E configuration is very small compared to the input current I_E in CB configuration. Therefore the input impedance of the transistor is medium. But since the output voltage V_{CE} and output Current I_c are large - compared to those of C.B. configuration, the output impedence is also medium.

Current amplification factor or Current gain β (Beta)

Current amplification factor or current gain is the ratio of output current to input current. In common emitter configuration (CE configuration) the base current (I_B) is the input current and the collector current (I_C) is the output current. Therefore in CE configuration current gain is the ratio of the collector current (I_C) to the base current (I_B). It is denoted as beta (β).

$$\beta = \frac{I_C}{I_B}$$

Expression for total collector current

As per the equation for β, the collector current I_C is β times I_B. We know that when a transistor is in its active mode of operation, the collector junction is reverse biased. So even when $I_B = 0$ some current will flow through the collector because of the presence of minority charge carriers and this current is called reverse saturation current I_{CEO}. I_{CEO} is the reverse saturation current in CE configuration and it is the current between the **C**ollector and the **E**mitter when the base is **O**pen. Therefore the total collector current,

$$\mathbf{I_C = \beta I_B + I_{CEO}}$$

The current I_{CEO} is small and so may be neglected in practical cases.

Relationship between α and β

We know that $\alpha = \frac{I_C}{I_E}$

Since $I_E = I_B + I_C$ the above equation becomes $\alpha = \frac{I_C}{I_C + I_B}$

Dividing both numerator and denominator of RHS by I_C,

$$\text{we get } \alpha = \frac{1}{1 + \frac{1}{\beta}}$$

$$\text{ie, } \alpha = \frac{\beta}{\beta + 1}$$

Therefore,

$$\alpha\ (1 + \beta) = \beta$$

$$\alpha + \alpha\ \beta = \beta$$

$$\alpha = \beta - \alpha\beta$$

$$\alpha = \beta\ (1 - \alpha)$$

$$\text{Therefore } \beta = \frac{\alpha}{1 - \alpha}$$

Voltage gain

The ratio of the output voltage to the input voltage is called voltage gain. In CE configuration, the output impedance is high, and the input impedance is low and also output current I_C is very large compared to the input current I_B. So the voltage developed across the output will be high. Therefore the voltage gain of CE configuration is high. The CE configuration has high voltage gain and current gain. So power gain in CE configuration is high. Hence it is widely used as power amplifiers.

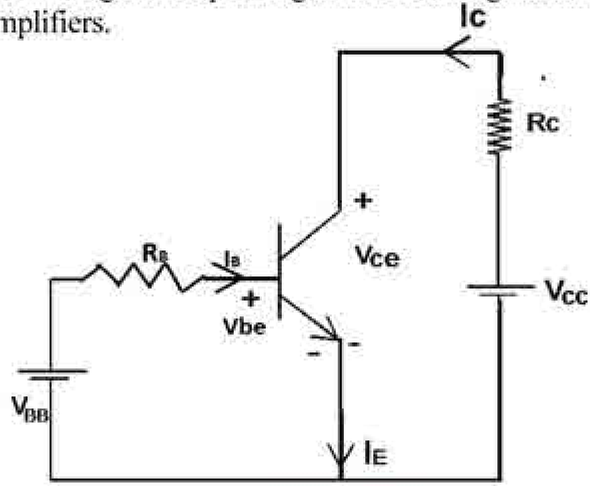


Fig.5.8 CE Amplifier

Fig. 5.8 shows a CE configuration which is used as an amplifier. The input is applied between the emitter and the base and the output is taken from the collector and the emitter. A small change in base current results in a large change in the collector current ($I_C = \beta I_B$). The output resistance of this configuration is high. The voltage is the product of current and resistance. So an amplified output is obtained across the collector.

Solved problem 5.4:

In a transistor CE configuration the emitter current is 2 mA and collector current is 1.95 mA, calculate the value of β.

I_E = 2mA

I_C = 1.95mA

β = I_C/I_B

I_B = $I_E - I_C$

= 2 - 1.95 = 0.05mA

β = I_C/I_B

= 1.95mA/0.05mA

= 39

Solved problem 5.5:

In a transistor CE configuration the base current is 50 μA, calculate the value I_E.(β is given as 50)

I_B = 50μA = 0.05mA

β = I_C/I_B

I_C = βI_B

$= 50 \times 0.05mA = 2.5mA$

$I_E = I_B + I_C$

$= 0.05 + 2.5 = 2.55mA$

Common Collector (CC) Configuration

In this Common Collector configuration collector is common to both the input and the output (fig. 5.9). The input signal is applied between the base and the collector terminals and the corresponding output is taken between the emitter and the collector terminals.

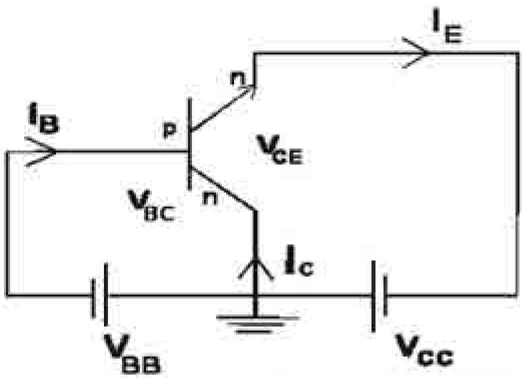


Fig. 5.9 Common Collector (CC) Configuration

Input voltage	$= V_{BC}$	Output voltage	$= V_{CE}$
Input Current	$= I_B$	Output Current	$= I_E$
Input impedance (R_i)	$= V_{BC}/I_B$	Output impedance (R_o)	$= V_{CE}/I_E$

Since the collector base junction is reverse biased the input impedance is very high and the output impedance is very low. This configuration is also called emitter follower.

In fig. 5.9 we can see that $V_{BC} = V_{CE} - V_{BE}$. Since V_{BE} is very small compared to V_{CE}, $V_{BC} \approx V_{CE}$. So the voltage gain of this circuit is unity. This implies that the emitter voltage (Output voltage) follows the input votage and hence this circuit is known as an emitter follower.

Current amplification factor or current gain γ (Gama)

$\gamma = \frac{I_E}{I_B}$. Therefore γ is high since $I_E >> I_B$.

Relationship between α, β and γ

From the above equation for γ, we have

$\gamma = \frac{I_B + I_C}{I_B}$. Dividing both the numerator and denominator by I_B, we get

$$\gamma = \frac{1+\frac{I_C}{I_B}}{1}$$

$$\gamma = 1 + \beta \qquad (\beta = I_C / I_B)$$

$$\text{Also } \gamma = 1 + \beta = 1 + \frac{\alpha}{1-\alpha} = \frac{1}{1-\alpha}$$

5.6 CHARACTERISTICS OF TRANSISTOR IN CE CONFIGURATION

The VI characteristics give the graphical representation of input voltage and input current as well as output voltage and output current variations. In order to measure these variations ammeters are connected in series with the base and the collector to measure the base current and the collector current respectively. Voltmeters are connected in parallel to measure the input voltage (V_{BE}) and the output voltage (V_{CE}).

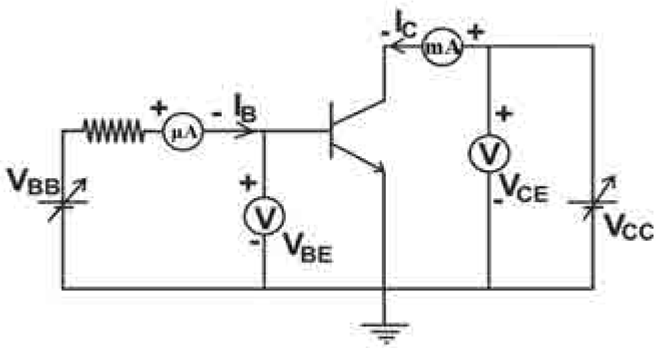


Fig.5.10 Circuit arrangements for CE characteristics

Input characteristics

To study the input characteristics, the output voltage, V_{CE} is made constant and the changes of the input current for the variations in the input voltage is measured and plotted in the graph. A family of curves may be drawn for different values of V_{CE}.

From the graph the following points can be noted.

1. The input characteristics resemble the forward characteristics of a PN junction diode.
2. For small changes of V_{BE} there will be a large change in base current I_B. i.e., input impedance is small.
3. Input impedance, $r_i = \Delta V_{BE} / \Delta I_B$ for V_{CE} = constant

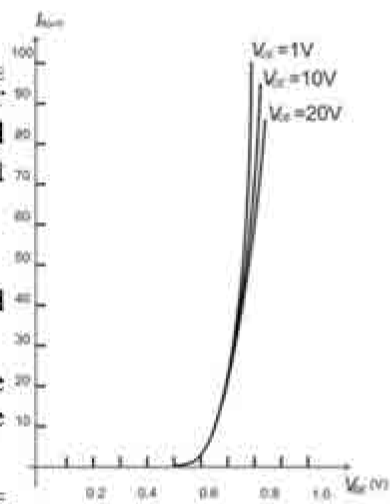


Fig.5.11 CE input characteristics

Activity 2

Draw the forward characteristics of an ordinary PN junction diode and observe the similarities and differences with the input characteristics of a CE configuration.

As already said the input characteristics of CE configuration resemble the forward characteristics of a PN junction diode. In both the cases the current is zero till the input voltage is increased above the cut in voltage of the PN junction. After that for a very small change in voltage the current increases rapidly.

Since there is a large change in the current flow for a small change in the input voltage, the input impedance which is equal to $\frac{\Delta V_{BE}}{\Delta I_B}$ *is very small for a CE transistor configuration.*

Output characteristics

It is the curve between the output current (I_C) and the output voltage (V_{CE}) at constant input current (I_B). To study the output characteristics, the input current, I_B is kept constant and the change in the output current with the variation of output voltage is measured and the same is plotted in the graph (V_{CE} Vs I_C). The curve is as shown in Fig. 5.12.

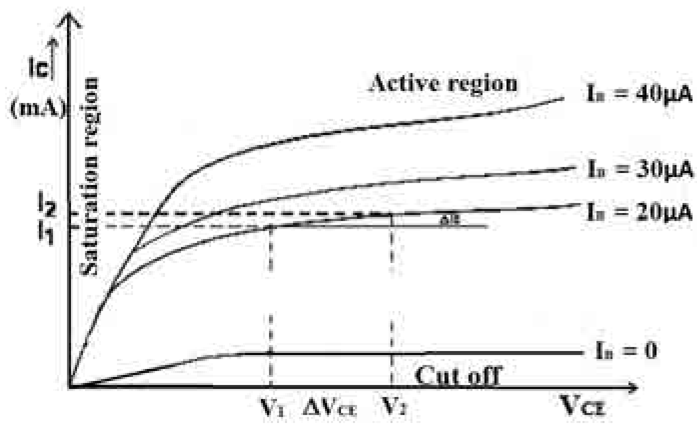


Fig.5.12 CE output characteristics

From the graph we can see that,

1. ***Cut off Region:*** Region below the curve (I_B= 0) is called cut-off region. In this region the emitter base and the collector base junction are reverse biased. Since I_B= 0 only reverse saturation current I_{CEO} flows through the transistor. This current is negligible. So the transistor is **off** in this region.

2. ***Saturation Region:*** In this region the emitter base (EB) and the collector base (CB) junctions are forward biased. In the saturated region, the base current I_B does not produce a corresponding change in the collector current I_C.

3. ***Active Region:*** In this region the emitter base (EB) junction is forward biased and the collector base (CB) junction is reverse biased.

4. Very large changes of V_{CE} produce a small change in I_C i.e. the output impedance is high.

5. Output impedance $r_o = \Delta V_{CE} / \Delta I_C$ at constant I_B

5.7 COMPARISON AMONG CB, CE AND CC CONFIGURATION

Characteristics	**CB**	**CE**	**CC**
1) Input impedance (r_i)	Very Low (about 25Ω)	Low (about 2.5KΩ)	Very high
2) Output impedance (r_o)	Very high (about 400 KΩ)	High (about 50 KΩ)	Low (about 50Ω)
3) Current amplification factor	$\alpha = \frac{\beta}{\beta+1}$	$\beta = \frac{\alpha}{1-\alpha}$	$\gamma = \frac{1}{1-\alpha}$
4) Current gain	Less than unity	High	High
5) Voltage gain	High	High	Less than unity

5.8 DC LOAD LINE

In the common emitter configuration with collector resistance R_c shown in fig. 5.8, the relation between the collector to the emitter voltage V_{CE} and the collector current I_C is $V_{CE} = V_{CC} - I_C R_C$ Suppose that we mark the different values of V_{CE} and I_C for a given R_C in a CE circuit. When we join these points together we get a straight line which corresponds to the equation $V_{CE} = V_{CC} - I_C R_C$. This line is called the DC load line. Two points on this line is enough to draw the line. This can be done by knowing the maximum values of the output voltage V_{CE} and the output current I_C. When $I_C = 0$ mA the collector-emitter voltage V_{CE} is maximum and when $V_{CE} = 0$ the collector current I_C becomes maximum.

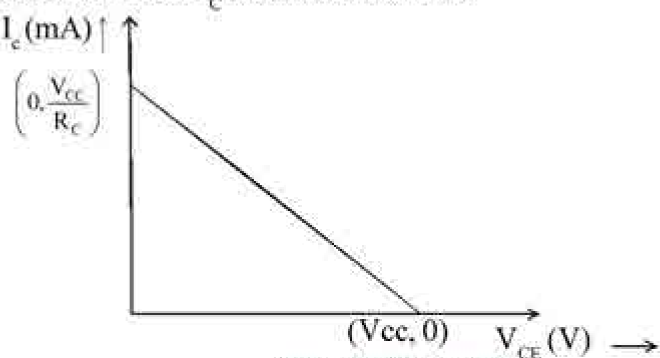


Fig.5.13 DC load line

The out put side of a transistor in CE configuration can be represented by the equation.

$$V_{CE} = V_{CC} - I_C R_C$$

When the collector current $I_C = 0$, then the collector-emitter voltage is maximum and equal to V_{CC},

i.e. $V_{CE} = V_{CC}$

This gives a point on x- axis. The co-ordinate of this point is (V_{CC},0). This point is known as cut-off point.

When $V_{CE} = 0$, we get a point on the y-axis

$$V_{CE} = V_{CC} - I_C R_C$$

$$0 = V_{CC} - I_C R_C$$

Therefore, $I_C = \frac{V_{CC}}{R_C}$. The co-ordinates on y-axis is ($0, V_{CC}/R_C$). This point is known as saturation point. The current is maximum at this point.

Fig. 5.14 shows the DC load line of a transistor connected in CE configuration.

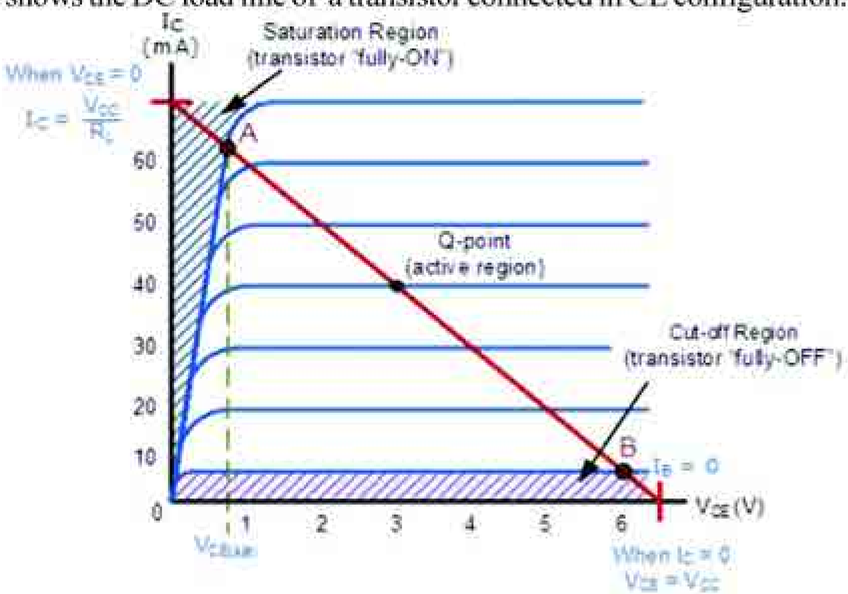


Fig.5.14 DC load line of transistor in CE configuration

The load line establishes the relation between the output voltage and the output current when the load is varied from zero to infinity.

Operating Point (Q)

The operating point is a point on the DC load line which represents the values of the output voltage V_{CE} and the output current I_C of the transistor for a given input current I_B when no signal is applied. When an AC signal is applied to the base of the transistor (for amplification) the collector current and the collector emitter voltage will both vary around these values. Therefore this operating point is much important in the design of transistors for particular applications. This is also known as Quiescent point or working point. This is the intersection of DC load line and input current I_B in the output characteristics curve in Fig. 5.14.

Activity 3

For the C.E amplifier circuit shown in Fig. 5.8 draw the DC load line if V_{CC} = 12V and R_C = 6kΩ

- *Do you know that the equation for output voltage $V_{CE} = V_{CC} - IcRc$ represents a straight line? (Similar to $y = mx + c$)*
- *Why is the load line called so?*
- *Does the load line intersect at some point on the output characteristics curve? What is the significance of that point?*

For any value of input base current the load line gives the value of output voltage and load Current. The load line will intersect at a particular point on the output characteristic curve and that point is called the operating point or Q point which has been explained in the above section.

For V_{CC} = 12V, Collector resistance, R_C = 6kΩ

The cut-off point on x-axis is (VCC,0)

Where $I_C = 0$, $V_{CE} = V_{CC}$ = 12V   Therefore the point on x-axis is (12,0)

The saturation point on y-axis is (o,V_{CC}/R_C)

When $V_{CE} = 0$, $I_C = V_{CC}/R_C$ = 12V/6kΩ

i.e., IC=2 mA.

The point on y axis is (0,2mA)

5.9 TRANSISTOR AS A SWITCH

When used as an amplifier, the transistor's base biasing voltage is applied in such a way that it always operates within its "active" region. However, bipolar transistors can be made to work as "ON/OFF" type solid state switches by biasing the transistor to operate in cut-off and saturation regions.

Solid state switches are one of the main applications for the use of transistors. **Transistor switches** can be used for controlling high power devices such as motors, lamps, and can also be used in digital electronics and logic gate circuits.

A transistor acts as a switch by driving it back and forth between its cut-off (OFF) and saturation (ON) regions. The operating region is shown in Fig 5.15.

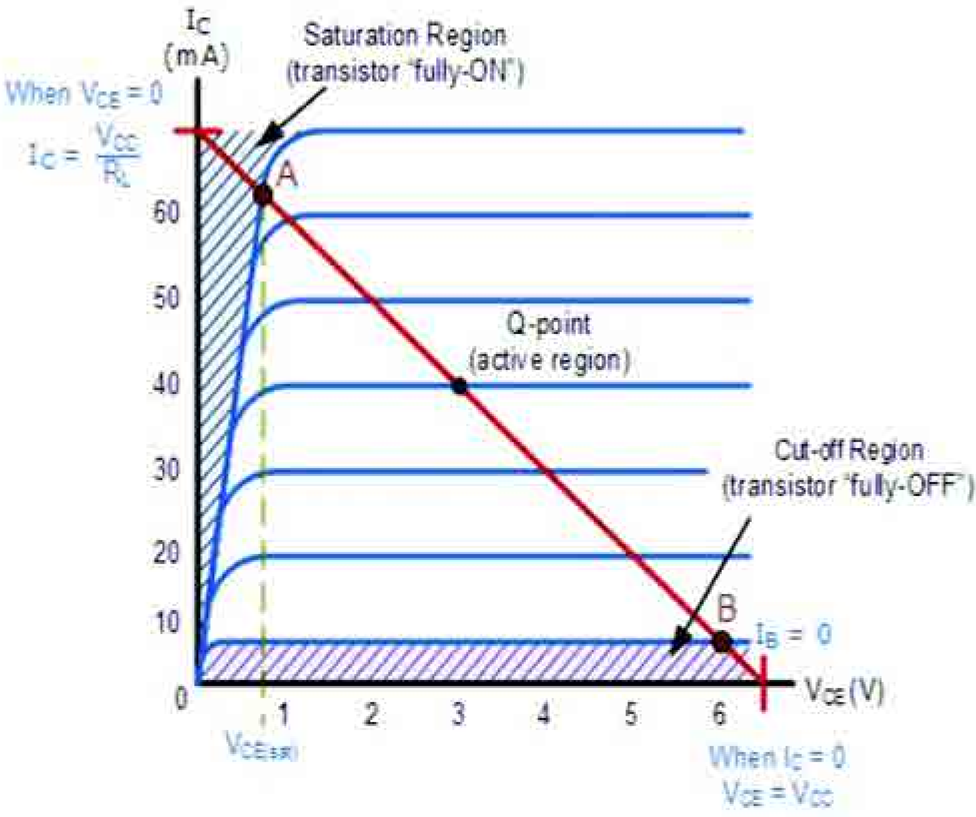


Fig.5.15 Operating Region

Cut-off Region

In this region the emitter base and collector base junctions are reverse biased. Therefore the transistor is switched OFF.

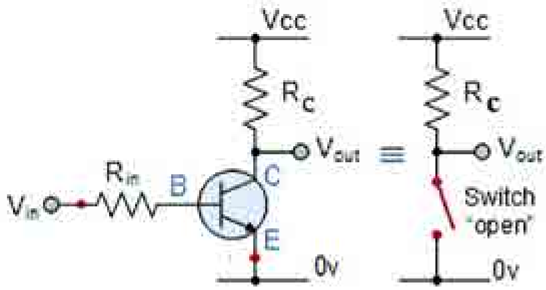


Fig.5.16 Transistor as an open switch

- Base-Emitter voltage $V_{BE} < 0.7v$
- Base-Emitter junction is reverse biased
- Collector base junction is reverse biased
- Transistor is in OFF state
- Zero collector current flows.
- $V_{CE}=V_{CC}$
- Transistor operates as an open switch

Saturation Region

In this region the emitter base (EB) and the collector base (CB) junctions are forward biased. So maximum amount of base current (I_B) is applied, resulting in maximum collector current (I_C) Therefore the transistor is switched "Fully-ON".

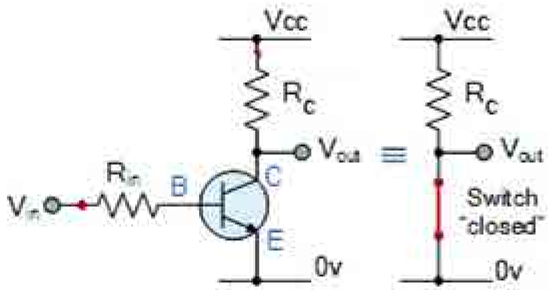


Fig. 5.17 Transistor as a closed switch

- Base-Emitter voltage $V_{BE} > 0.7v$
- Base-Emitter junction is forward biased
- Base-Collector junction is forward biased
- Transistor is "fully-ON" (saturation region)
- Max Collector current flows ($I_C = V_{cc}/R_C$)
- $V_{CE} = 0$ (ideal saturation)
- $V_{OUT} = V_{CE} =$ "0"
- Transistor operates as a "closed switch"

Let us sum up

In bipolar junction transistors, there are two PN junctions and both the charge carriers - holes and electrons are there for charge conduction. The three regions - emitter, base and collector differ in physical size and doping level. The two PN junctions are biased in three different ways which cause three different modes of operation; active, saturation and cut-off modes. Under active mode a transistor acts as an amplifier. The total current in transistor is the emitter current which is equal to the sum of base and collector currents. α, β and γ represent the current amplification factors for CB, CE and CC configurations respectively. The input characteristics of CE resemble the forward characteristics of a PN junction diode. In the output characteristic curve, active, saturation and cut off regions can be shown. The output voltage and current conditions can be represented by DC load line which is a straight line drawn on the output characteristics represented by $V_{CE} = V_{CC} - I_C R_C$. The operating point is the one which represents the zero signal values of I_C and V_{CE} for a given input current I_B. Transistor can be used as a switch by driving it back and forth between cut off and saturation regions.

Learning outcomes

The learner is able to

- Explain the significance of transistor in electronic devices and circuits.
- Draw the structure of a bipolar transistor and thus point out the importance of its terminals.
- Point out the importance of different modes of operations of a transistor.
- Draw the circuits and explain the applications of different transistor configurations.
- Explain the input output characteristics of the CE transistor configuration.
- Construct the DC load line and thus explain its significance.
- Explain the working of transistor as a switch.

Evaluation items

Multiple choice questions

1 When transistors are used as switch they usually operate in the

a. active region
b. breakdown region
c. saturation and cutoff regions
d. linear region

2 A transistor has a β of 250 and a base current I_B of 20 µA. The collector current, I_C, equals

a. 500 µA
b. 5 mA
c. 50 mA
d. 5 A

3 A current ratio of I_C/I_E is usually less than one and is called

a. Beta b. Theta
c. Alpha d. Omega

4. The ends of a load line lie in

a. saturation and cutoff
b. the operating point
c. the power curve
d. the amplification factor

5. The current gain for a transistor in C.E configuration is

a. I_C/I_B
b. I_C/I_E
c. I_B/I_E
d. I_E/I_B

6. The output characteristic curve of a transistor in CE configuration shows

a. emitter current (I_E) versus collector-emitter voltage (V_{CE}) with (I_B) base current held constant

b. collector current (I_C) versus collector-emitter voltage (V_{CE}) with (I_B) base current held constant

c. collector current (I_C) versus collector-emitter voltage (V_C) with (I_E) emittercurrent held constant

d. emitter current (I_E) versus collector-emitter voltage (V_{BE}) with (I_B) base current held constant

7. When a silicon transistor is forward biased, what is V_{BE} for a C-E configuration?

   a. collector voltage
   b. 0.4 V
   c. 0.7 V
   d. emitter voltage

8. What is the current gain for a common-base configuration where I_E = 4.2 mA and I_C = 4.0 mA?

   a. 16.80
   b. 1.05
   c. 0.20
   d. 0.95

9. In a transistor, the collector current is controlled by

   a. collector voltage
   b. base current
   c. collector resistance
   d. all of these

10. Total emitter current is

   a. I_E - I_C
   b. $I_C + I_E$
   c. $I_B + I_C$
   d. I_B - I_C

Answer key

1) c 2) b 3) c 4) a 5) a 6) b 7) c 8) d 9) b 10) c

Descriptive type questions

1. Sketch the input and output characteristics of a transistor in CE configuration and explain the shape of the characteristics qualitatively.
2. Define β and α parameters and state the relation between them.
3. What are the configurations of a BJT?
4. What are the applications of an emitter follower? Why is this circuit referred to as emitter follower?
5. Which transistor configuration has the highest power gain?

6

SPECIAL TYPE ELECTRONIC DEVICES

INTRODUCTION

In the last chapter we studied the working of a bipolar transistor. We know that the transistor is a semiconductor device that can be used for amplification, switching etc. Transistors may be roughly grouped into two major divisions: bipolar and field-effect. In this chapter, we can study the general concept of the field-effect transistor (FET). FETs are low power consuming devices than BJT and hence it makes them ideal for use in integrated circuits (IC's).

The electronic devices used in high power applications such as motor control are called power electronic devices. The symbols and applications of power electronic devices such as SCR, TRIAC, DIAC and UJT are also included in this chapter.

Another type of special electronic device is the photo sensor (photo detector) which is used to sense light energy and produce corresponding electrical energy. Photo diodes, photo transistors and solar cells are examples. Light dependent resistors (LDR) are also photo sensors, whose resistance vary when light falls on them.

We are familiar with different types of displays used in electronic devices, home appliances, electronic speedometers, etc. In this chapter we will discuss the operations of LED (light emitting diode) and LCD (liquid crystal display).

Thermistors are temperature sensing electronic components which will change its resistance in accordance with temperature applied to it. Varactor diode is a kind of diode which acts as variable capacitor when its biasing voltage is changed. In this chapter we will also discuss integrated circuits (IC's), their classification, typical examples and advantages.

6.1. FET (Field Effect Transistors)

Field Effect Transistor (FET) was developed in the early 1960's. FET is a voltage controlled device where as BJT is current controlled. FET's are broadly classified into two.

1. Junction Field Effect Transistor (JFET)
2. Metal Oxide Semiconductor FET (MOSFET)

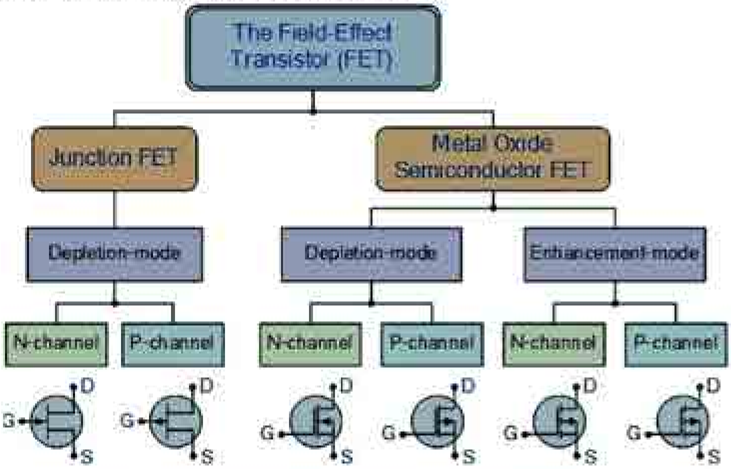


Fig 6.1 Classifications of FET and its symbols

Junction Field Effect Transistor (JFET)

Construction of JFET

A JFET consists of a P-type or N-type silicon bar containing a pn junction as shown in fig. 6.2. The bar forms the conducting channel for the charge carriers. If the bar is of N-type, it is called N-channel JFET, shown in fig 6.2.(a) and if the bar is of P-type, it s called a P-channel JFET, shown in fig 6.2.(b). The two PN- junctions forming diodes are connected internally and a common terminal called gate is taken out. Other terminals are source and drain that are taken out from the bar as shown.

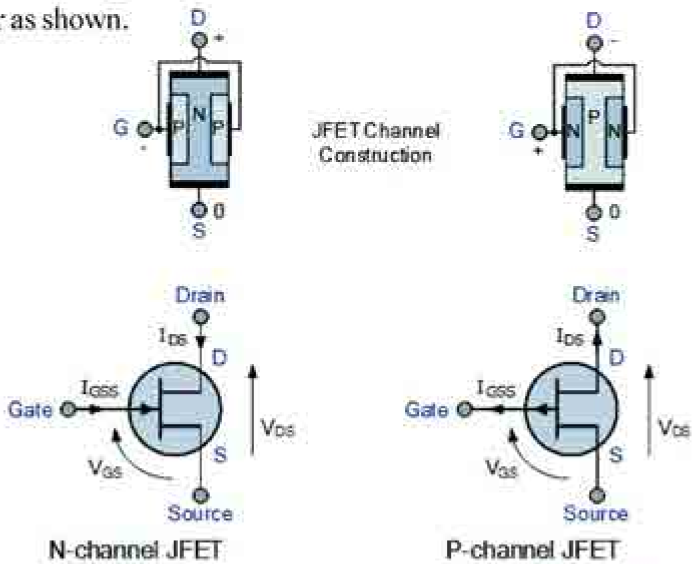


Fig 6.2 (a) *Fig 6.2 (b)*

Field effect transistor has three terminals which are called source, drain and gate. Drain and Source are similar in function to the collector and the emitter respectively of the bipolar transistor. The current path between these two terminals is called the "channel" which may be made of either a P-type or an N-type semiconductor material. The control of current flowing in this channel is achieved by varying the voltage applied to the Gate.

- Source (S):-The terminal through which majority carriers enter the channel.
- Drain (D):- The terminal through which majority carriers leave the channel.
- Gate (G):- The terminal formed by joining the two other semiconductor regions on either side of the channel internally. It controls the flow of majority carriers from Source to Drain.

Working Principle of JFET

Generally the semiconductor "channel" of the JFET is a resistive path through which a drain current I_D flows when a voltage is applied between the drain and the source (V_{DS}). The JFET can conduct current equally well in either direction. The magnitude of the current flowing through the channel between the Drain and the Source terminals is controlled by a voltage applied to the Gate terminal, which is reverse-biased. In an N-channel JFET this Gate voltage is negative while for a P-channel JFET the Gate voltage is positive.

In JFET, under normal working condition, the Gate junction is reverse-biased and hence the Gate current is practically zero. The reverse biased junction forms a depletion region around the Gate area. JFETs are therefore known as depletion mode devices. If a small negative voltage ($-V_{GS}$) is applied to the Gate the size of the depletion region begins to increase reducing the effective area of the channel and thus reducing the current flowing through it. When the applied reverse voltage is increased the width of the depletion region increases which in turn reduces the width of the channel and this causes the current to decrease.

Since the PN-junction is reverse biased, only a little current will flow through the gate terminal. As the Gate voltage ($-V_{GS}$) is made more negative, the width of the channel decreases until no more current flows between the Drain and the Source and the FET is said to be "pinched-off" (similar to the cut-off region for a BJT). The gate voltage at which the channel closes is called the "pinch-off voltage", (V_P).

Comparison between BJT and FET

1. In a JFET, there is only one type of carrier, holes in P-type channel and electrons in N-type channel. For this reason, it is called a unipolar transistor. However, in a BJT, both the holes and the electrons play part in conduction. Therefore, an ordinary transistor is called a bipolar junction transistor.
2. As the input circuit (i.e. Gate to source) of a JFET is reverse biased, the device has high input impedance (of the order of 100 MΩ). However the input circuit of an ordinary transistor is forward biased and hence has low input impedance.
3. The drain current (I_D) is determined by the gate voltage (V_G) in JFET, whereas the base current determines the collector current in bipolar junction transistors. That means, JFET

is a voltage-controlled device, and the bipolar junction transistor (BJT) is a current-controlled device.

4. As there is only one type of carrier (majority) takes part in conduction, FET is less temperature dependent. But in BJT both the majority and minority carriers take part in conduction. Therefore it is temperature dependent.

5. There are no junctions in the current path of FET, but in BJT there are two junctions in the current path (E-B junction and C-B junction). Therefore FET is less noisy compared to BJT.

Applications of JFET

The junction field effect transistor has many applications in the field of electronics and communication. Some of these applications are stated below.

1. Low noise and high input impedance amplifier
2. Switching applications
3. Voltage Variable Resistance (VVR)

MOSFET

The second type of FET is Metal - Oxide semiconductor FET (MOSFET). Like JFET, it also has a source, gate and drain. However, unlike JFET, the gate of a MOSFET is insulated from the channel. Because of this the MOSFET is sometimes known as IGFET which stands for insulated gate field effect transistor.

MOSFETs are further classified into two- Depletion type MOSFET and Enhancement type MOSFET. The primary difference between the two types of MOSFETs is in their constructions and modes of operation. Fig. 6.3 shows the symbol of N-channel and P-channel depletion mode MOSFET.

Fig.6.4 shows the symbol of N-channel and P-channel Enhancement mode MOSFET.

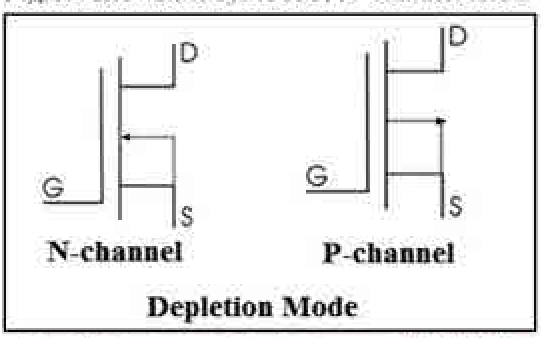


Fig.6.3. Symbols of depletion mode MOSFETs

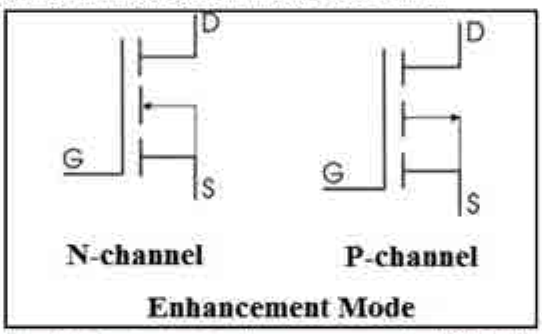


Fig.6.4. Symbols of enhancement mode MOSFETs

Application of MOSFET

1. Used in digital ICs, Microprocessors, memories etc.
2. High input impedance amplifiers
3. UPS and Inverters.

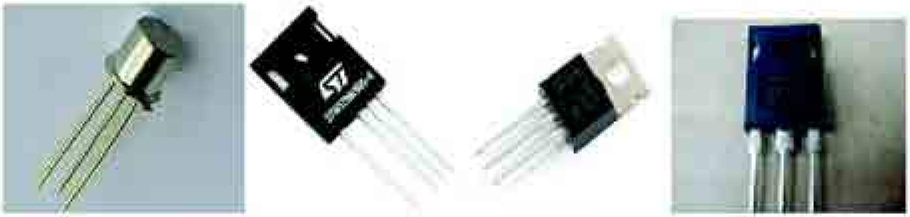


Fig.6.5. Typical JFET and MOSFET Packages

Complementary MOS (CMOS)

Have you heard about CMOS technology? CMOS means complementary metal-oxide-semiconductor and it is a technology used for constructing very low power digital ICs. CMOS uses a combination of P-channel and N-channel Enhancement-mode MOSFETs (PMOS and NMOS), wired in series.

The main advantage of CMOS design is its extremely low power consumption. The total power dissipation of the circuit is in nano watts. Hence CMOS ICs are normally used in calculators, digital watches, computers and satellites.

6.2. POWER ELECTRONIC DEVICES

Power electronic devices are those, which can handle currents up to several thousand amperes and voltages up to kilo volt range.

SCR (Silicon Controlled Rectifiers)

The SCR is a three terminal semiconductor switching device which is probably the most important circuit element other than diode and transistor. SCR can change AC to DC and at the same time it can control the amount of power to the load. Apart from a normal diode SCR has a third terminal called the gate for controlling the rectification. SCR consists of four semiconductor layers and three pn junctions. It can be considered as an ordinary rectifier (PN-junction) and a junction transistor (NPN) combined in one unit to form pnpn device as shown in fig. 6.6.

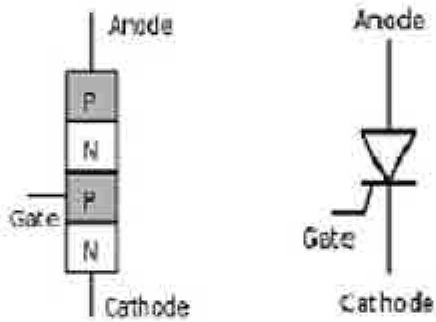


Fig.6.6. SCR - structure and symbol

Fig.6.6 shows the symbol of SCR. Three terminals are taken- one from the outer P-type material called Anode (A), second from the outer N-type material called Cathode (K) and the third from the base of transistor section called Gate (G). In normal operating conditions of SCR, anode is held at a high positive potential with respect to cathode and the gate at a small positive potential with respect to cathode.

Working of SCR

In a silicon controlled rectifier, load is connected in series with anode. The anode is always kept at positive potential with respect to cathode. The working of SCR is as follows.

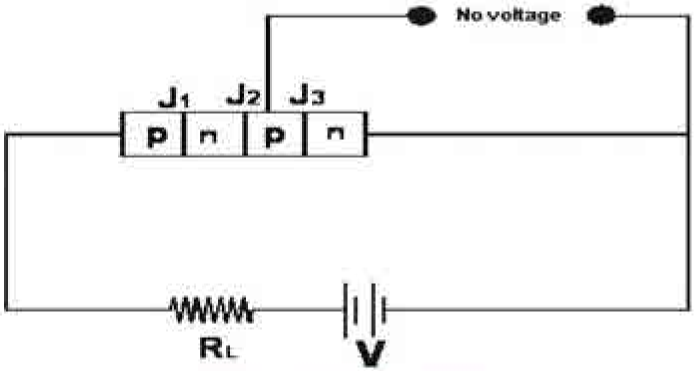


Fig.6.7 SCR with gate open

(1) When Gate is open: Fig.6.7 shows the SCR circuit with gate open i.e. no voltage is applied to the gate. Under this condition, junction J_2 is reverse biased while junction J_1 and J_3 are forward biased. Hence, the situation in the junctions J_1 and J_3 are just as in NPN transistor with base open. Consequently, no current flows through the load R_L and the SCR is Cut-off. However, if the applied voltage is gradually increased, a stage is reached when reverse biased junction J_2 breaks down. The SCR now conducts heavily and is said to be in the ON state. The applied voltage at which SCR conducts heavily without gate voltage is called breakover voltage. Commercially available SCRs have breakover voltages from about 50 V to 800 V.

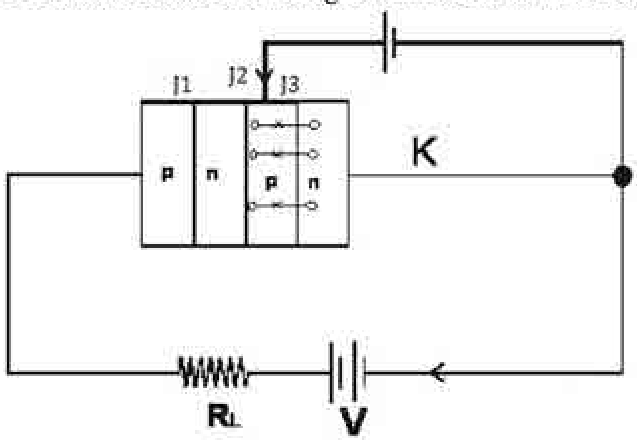


Fig.6.8 SCR with gate voltage applied

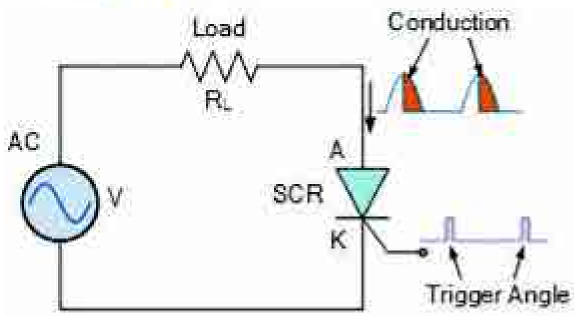
(2) When the gate is positive with respect to cathode: The SCR can be made to conduct heavily at smaller applied voltage by applying a small positive potential to the gate as shown in fig. 6.8. Now the junction J_3 is forward biased and junction J_2 is reverse biased .The electrons from N-type material start moving across junction J_3 towards left whereas holes from P-type towards right. Consequently, the electrons from the junction J_3 are attracted across junction J_2 and gate current starts flowing. As soon as the gate current flows, the anode current increases. The increased anode current in turn makes more electrons available at the junction J_2.This process continues and in an extremely small time, junction J_2 breaks down and SCR starts conducting

heavily. Once SCR starts conducting, the gate loses its control. Even if the gate voltage is removed, the anode current does not decrease at all. The only way to stop conduction (i.e. to bring SCR in the off state) is to reduce the applied voltage to zero.

SCR Phase control

Consider that an AC signal is applied to the circuit shown in fig. Then during the positive half cycle of an AC sinusoidal waveform, the SCR is forward biased (anode positive) and can be triggered "ON" using a gate signal or pulse. During the negative half cycle, the anode becomes negative while the cathode is positive. The SCR is reverse biased by this voltage and cannot conduct even if a gate signal is present.

So by applying a gate signal at appropriate time during the positive half of an AC waveform, the SCR can be triggered into conduction until the end of the half cycle. Thus phase control (as it is called) can be used to trigger the SCR at any point along the positive half of the AC waveform and this property of SCR is utilised in the power control of AC systems.



Applications of SCR

1. Heat control
2. Speed control of motor
3. Light-dimming circuit
4. Battery charger
5. UPS

Activity 1

Consider the circuit shown in fig. 6.9, when the switch S_1 is closed, what happens to the intensity of the lamp while adjusting the variable resistor R_1?

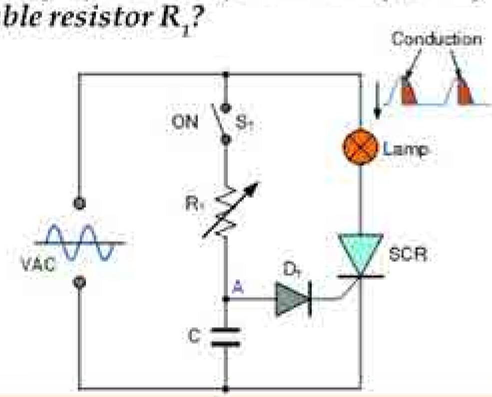


Fig. 6.9

TRIAC

The TRIAC is a three terminal device, which can conduct in either direction, when triggered by a positive or a negative pulse irrespective of the polarity of the voltage across its main terminals. The TRIAC behaves like two SCRs connected in parallel but in opposite direction, with a common gate terminal i.e. the anode of one SCR is connected to the cathode of the other and their gates are connected together. Thus anode and gate voltage applied in either direction will trigger the TRIAC. It is due to the fact that the applied voltage will trigger at least one of the SCRs connected in opposite direction.

The TRIAC's are available with very high current ratings and high voltage. When voltage in the positive half cycle of AC exceeds the positive break over voltage (break over voltage of the SCR in that direction), the TRIAC conducts in that direction. Similarly when the voltage in the negative half cycle of AC exceeds the negative break over voltage (break over voltage of the SCR in that direction), the TRIAC conducts in that direction. These conducting voltages in either direction can be varied by varying the gate current.

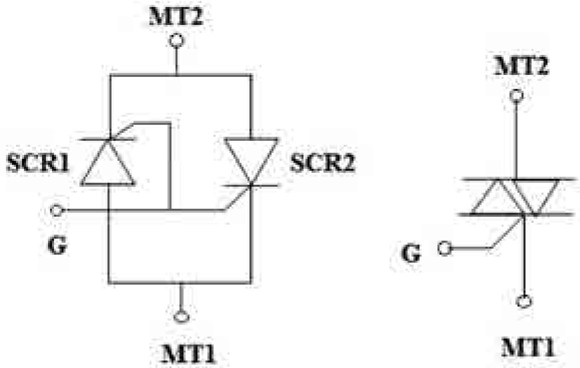


Fig 6.10 TRIAC - equivalent circuit and symbol

Application of TRIAC

The TRIAC has an important property that it can conduct current in either forward or reverse direction, depending upon the polarity of the voltage across its terminals. This property makes the triac very useful to control AC machines. Some applications of TRIAC are given below

1. Electronic Fan Regulators
2. Motor speed control
3. Battery charger & UPS

Fig.6.11 Typical SCR and TRIAC Package

DIAC

The DIAC (Diode for Alternating Current) is a two terminal device. The basic construction of DIAC is similar to a TRIAC, but without a gate terminal as shown in fig 6.12.

The working of the DIAC is similar to that of the TRIAC except that it has no gate terminal. Because of this, the conducting voltage (break over voltage) of the DIAC cannot be varied.

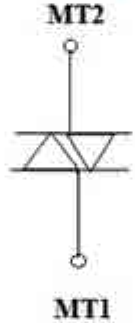


Fig 6.12 DIAC symbol

Applications of DIAC

DIAC is normally used with a TRIAC in control circuits such as light dimming, heat control, motor speed control etc.

Activity 2

Consider the circuit shown in fig. 6.13. The load may be a light or a fan. What happens to the load when the potentiometer is varied?

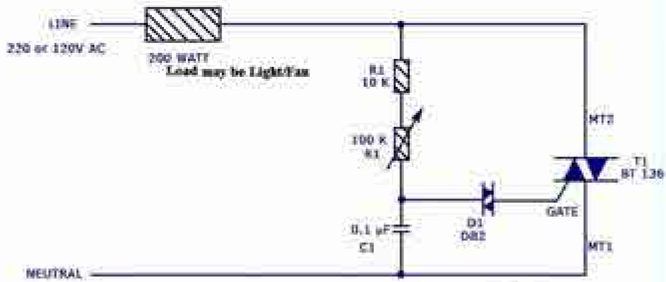


Fig 6.13

UNIJUNCTION TRANSISTOR (UJT)

UJT (Unijunction Transistor) is a three terminal semi conductor device with one junction. Since the device has only one (P-N) junction, it is called the Unijunction device.

UJT Symbol and Construction

Fig.6.14.a shows the basic structure of a unijunction transistor. It consists of a lightly-doped N-type silicon bar with a small piece of heavily doped P-type material alloyed to its one side to produce single P-N junction. The UJT has three terminals: an emitter (E) and two bases (B1 and B2). The two base leads are taken from the N-type silicon bar. The emitter is of P-type and it is heavily doped. The emitter (E) junction is usually located closer to base-2 (B2) than base-1 (B1). Fig. 6.14b shows the symbol of UJT.

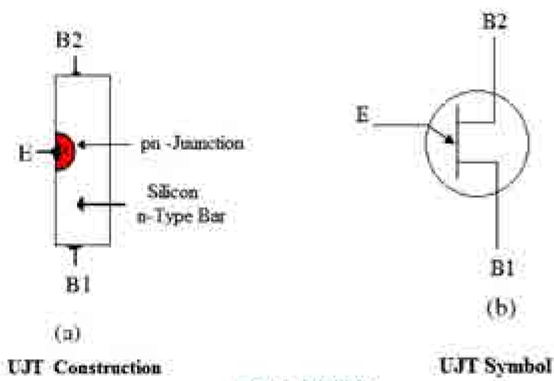


Fig 6.14 UJT

Applications

1. Sawtooth waveform generator
2. Phase and Timing control circuits

Fig.6.15 A typical UJT N2646

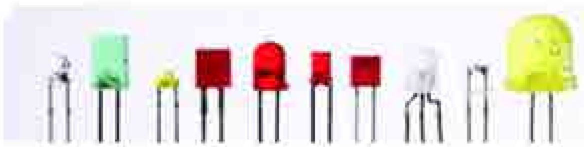
6.3. LIGHT-EMITTING DIODE (LED)

Have you heard about LED? Where is it used?

An LED (light emitting diode) is a diode that gives visible light when forward biased. It is mainly used as light source, displays and for making indicators.

In LED electrical energy is converted into optical energy. These are example of electro-luminescence, the process in which emission of photons takes place by the recombination of excess electrons and holes in a direct band gap semiconductor. The main advantages of using these are low energy consumption, longer lifetime (more than 20 years), faster switching, smaller size etc. Fig.6.16 shows the symbol and commonly used LED's.

Symbol of LED



Commonly used LED

Fig.6.16 LED

Working of LED

When a PN-junction is forward biased, recombination of holes and electrons will occur at the junction. During recombination, a large amount of energy is released in the form of heat or light.

How does a PN-junction generate light?

Consider a simple semiconductor, which is forward biased. When an electron from the bottom of the conduction band falls into a hole at the top of the valance band.

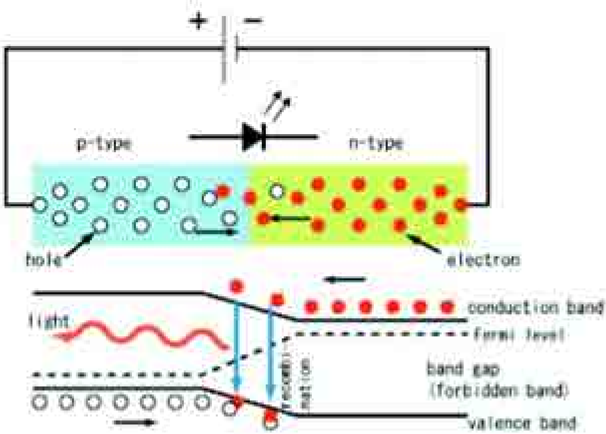


Fig.6.17 Working of LED

an energy equal to band gap energy (Eg) is released in the form of EM radiations whose frequency is given by $\nu = \frac{Eg}{h}$ Here h is $\gamma \frac{Eg}{h}$, the Plank's constant. In Silicon and Germanium, the band gap energy is small (0.7eV and 1.1eV) so that the frequency of the generated EM radiation is small and great percentage of this energy is given off in the form of heat (thermal energy) and as a result, no light is emitted.

In some semiconductor materials like gallium arsenide (GaAs) or Gallium Phosphide (GaP), the band gap energy is large so that the frequency of emitted radiation falls in the visible range. The colour emitted from the LED depends on the frequency of emission which in turn depends on the band gap energy of the material used. Thus we can say that the colour of the LED depends on the nature of materials used to make it. The wave length of output optical signals depends upon the band gap energy. The output wave length can be made to be within certain limits by using compound semiconductors, so that a particular color can be observed, provided the output is in visible range. The forward voltage rating of most LEDs is from 1V to 3 V and forward current rating ranges from 5 mA to 100mA.

BICOLOUR LED

A LED that emits one colour when forward biased and another colour when reverse biased is called bicolor LED. Fig.6.18 shows the working of a typical Red-Green bicolor LED.

A typical bicolour LED contains two pn junctions that are connected in reverse - parallel i.e.: they are in parallel, with anode of one being connected to the cathode of the other. If positive potential is applied to the top terminal as shown in fig.6.18 (i), the PN junction on the left will glow in red colour. If the polarity of the voltage source is reversed as shown in fig.6.18 (ii), the pn junction on the right will glow in green colour.

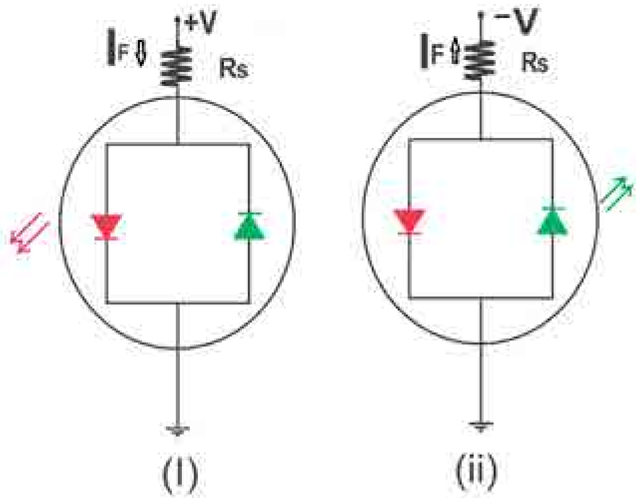


Fig.6.18 Working of Red - Green multi-colour LED

Bicolour LEDs are typically red when biased in one direction and green when biased in the other. If a bicolour LED is switched fast enough between two polarities, the LED will produce a third colour. A red /green LED will produce a yellow light when rapidly switched back and forth between biasing polarities.

Applications of LED

Light-emitting diodes are used in applications as power indicator, seven-segment display, automotive lighting, advertising LED boards, dot-matrix display, background light source in LED-

TV and traffic signals. Infrared LEDs are also used in the remote control units of many commercial products including televisions. LED lamps are used for household applications.

The table below shows different colours of LEDs and the name of materials used

Color	Wavelength λ (nm)	Materials
Infrared	$\lambda > 760$	Gallium arsenide (GaAs)
		Aluminum gallium arsenide (AlGaAs)
Red	$610 < \lambda < 760$	Aluminum gallium arsenide (AlGaAs)
		Gallium arsenide phosphide (GaAsP)
Orange	$590 < \lambda < 610$	Gallium arsenide phosphide (GaAsP)
		Aluminum gallium indium phosphide (AlGaInP)
Yellow	$570 < \lambda < 590$	Gallium arsenide phosphide (GaAsP)
		Aluminum gallium indium phosphide (AlGaInP)
Green	$500 < \lambda < 570$	Gallium phosphide (GaP)
Blue	$450 < \lambda < 500$	Zinc selenide (ZnSe)
		Indium gallium nitride (InGaN)
Violet	$400 < \lambda < 450$	Indium gallium nitride (InGaN)
Ultraviolet	$\lambda < 400$	Boron nitride
		Aluminum nitride (AlN)
		Aluminum gallium nitride (AlGaN)
		Aluminum gallium indium nitride (AlGaInN)

Table 6.1 LED colour and materials

6.4. LIQUID-CRYSTAL DISPLAY (LCD)

Activity 3

Prepare a list of equipment or appliances which are using LCDs.

Liquid Crystal Displays (LCDs) are commonly found like television, computers, digital watches mobile phone displays etc. They have become very common among display devices replacing Cathode Ray Tubes (CRT). CRT draws more power than LCD and is also bigger and heavier. Let us discuss the working of an LCD.

We get the definition of LCD from the name "Liquid Crystal" itself. It is actually a combination of two states of matter - the solid and the liquid. They have both the properties of solids and liquids and maintain their respective states with respect to another. Further studies have shown that the liquid crystal materials behave more as in liquid state than as in solid state. It must also be noted that liquid crystals are more heat sensitive than usual liquids. A little amount of heat can easily turn the liquid crystal into a liquid.

Basic structure of an LCD

A liquid crystal cell consists of a thin layer (about 10 mm) of a liquid crystal sandwiched between two glass sheets with transparent electrodes deposited on their inside faces. With both the glass sheets which are transparent, the cell is known as transmittive type cell. When one glass is transparent and the other is with a reflective coating, the cell is called reflective type. The LCD does not produce any illumination of its own. It, in fact, depends entirely on illumination falling on it from an external source for its visual effect.

Fig.6.19 Some examples of LCD displays

Advantages and Disadvantages of LCD

The liquid-crystal display has low power consumption, typically of the order of microwatts. It is of low cost and good contrast. LCDs do not emit electromagnetic fields.

The main drawbacks of LCDs are additional requirement of light source, poor visibility in low ambient lighting and low viewing angle.

Applications of LCD

LCDs are used in a wide range of applications including computer monitors, televisions, instrument panels and Vehicles' (Car) Dash board. They are common in consumer devices such as video players, gaming devices, clocks, watches, calculators, microwave ovens and mobile phone display.

6.5. PHOTODETECTORS (PHOTOSENSORS)

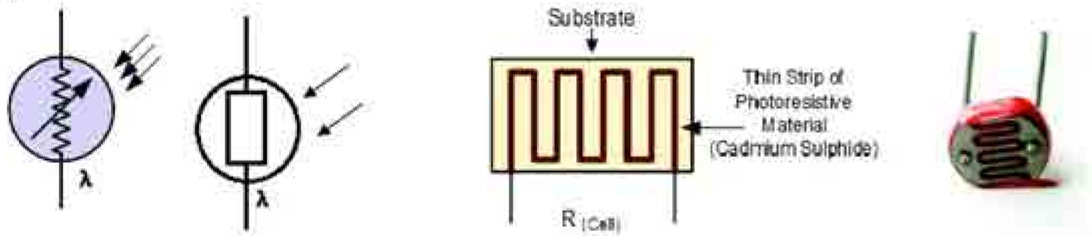
Photodetectors (Photosensors) are used for detecting light signals. The photo detector devices can be classified as follows

1. Photoresistors [Light Dependent Resistors (LDR)]
2. Photodiode
3. Phototransistor
4. Photovoltaic cells (solar cells)

PHOTORESISTORS OR LIGHT DEPENDENT RESISTORS (LDR)

A photoresistor or light dependent resistor (LDR) is a resistor whose resistance decreases with increasing incident light intensity. In other words, it exhibits photoconductivity. LDR is used in automatic light sensing circuits, safety systems, amusement etc.

Fig.6.20.(a) shows LDR symbol. Photoresistors are of various types. Fig 6.20.b shows constructional view of LDR. In this, a strip of photoresistve material is made by cadmium sulphide. This material is inexpensive, so it is used in many consumer items such as camera light meters, alarm devices, outdoor clocks, solar street lamps, bed lamps etc. Fig 6.20.c shows typical LDR.



(a) LDR Symbol **(b) LDR Constructional view** **(c) Typical LDR**

Fig.6.20 LDR

A photoresistor is made of a high resistance semiconductor. If light falls on the device, photons absorbed by the semiconductor give bound electrons enough energy to jump into the conduction band. The resulting free electron (and its hole partner) conduct electricity, thereby lowering resistance. Normally the resistance of an LDR is very high, sometimes as high as 1MΩ, but when they are illuminated with light the resistance drops dramatically. Photoresistors are basically photocells.

Activity 4

Set up this circuit and observe the status of LED when the torch is made ON and OFF.

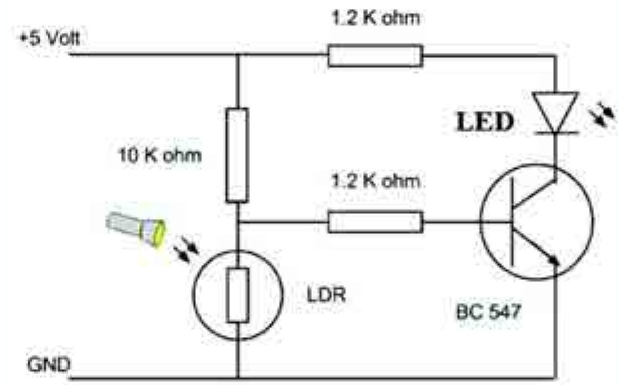


Fig 6.21 LED switching

PHOTODIODE

A photodiode is a reverse-biased silicon PN junction in which the reverse current increases when the junction is exposed to light. The reverse current in photo-diode is directly proportional to the intensity of light falling on its pn junction. This means that greater the intensity of light falling on the PN-junction of photo diode, the greater will be the reverse current.

Fig 6.22 shows the symbol of photodiode .The inward arrows represent the incoming light. Fig 6.22 also shows the typical structure of photo diode. It consists of a PN junction and a glass window is mounted on the top of the case to allow light to enter and strike the PN junction. The two leads extending from the case are labelled anode and cathode.

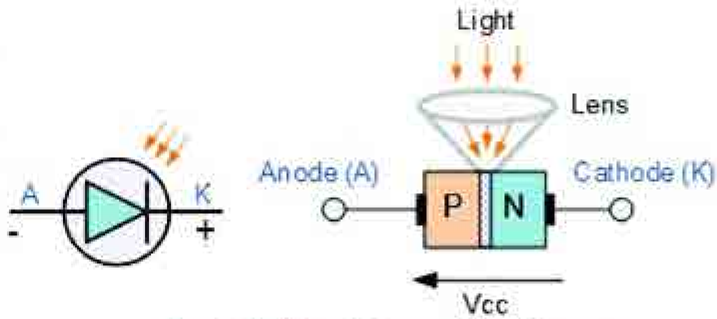


Fig 6.22 Photodiode symbol and structure

Applications of photodiode

1. Burglar alarm
2. Photodiodes are often used for measurement of light intensity. For e.g. camera light meters
3. They are also widely used in various medical applications, such as detectors for computer tomography.
4. It is often used for optical communications and in lighting regulation.

PHOTOTRANSISTOR

The phototransistor is a semiconductor light sensor formed from a basic transistor with a transparent cover which allows light to fall on the base of the transistor. The principle of working of phototransistor is same as that of a photodiode. A phototransistor, however, is much more sensitive to light and produces more output current for a given light intensity than a photodiode does. A phototransistor has a photosensitive collector base PN junction. The current induced by the photoelectric effects is the base current I_B of the transistor .The resulting amplified collector current is given as $Ic=\beta I_B$. The fig. 6.23 and fig.6.24 below shows the symbol and physical appearance of a phototransistor.

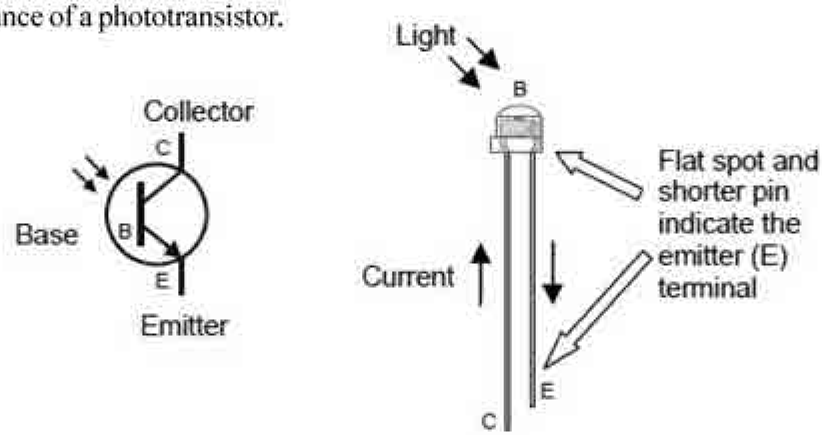


Fig.6.23 Phototransistor

Application

They are used in light controllers in highways, level indicators and counting system.

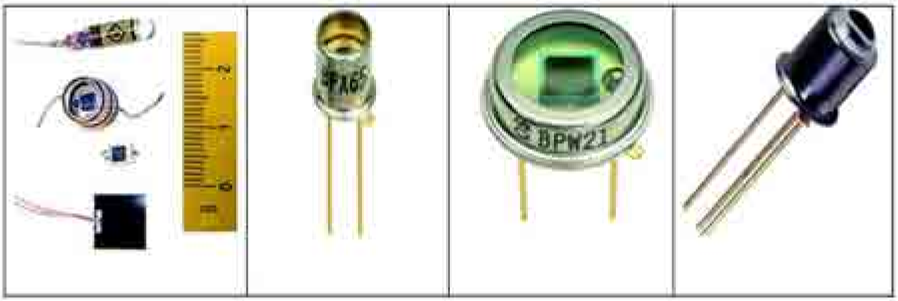


Fig.6.24 Typical Photo diode and photo transistor packages

SOLAR CELL (PHOTOVOLTAIC CELL)

Solar cell (a photovoltaic cell) is a device which converts light energy into electrical energy. It is a form of photoelectric cell (the electrical characteristics-e.g. current, voltage, or resistance-vary when light is incident upon it) which, when exposed to light, can generate and support an electric current without being attached to any external voltage source.

Photovoltaics is the field of technology and research related to the practical application of photovoltaic cells in producing electricity from light, though it is often used specifically to refer to the generation of electricity from sunlight. Cells can be described as photovoltaic even when the light source is not necessarily sunlight (lamplight, artificial light, etc.).

A PN junction of suitable material like silicon, germanium, selenium etc can be used as solar cell. Figure 6.25 (a) shows the basic construction of silicon PN junction solar cell. The top surface area must be perpendicular to sunlight to ensure maximum power. The metallic conductor connected to the P-type material and thickness of the P-type material is such that a maximum number of photons of light energy will reach the junction.

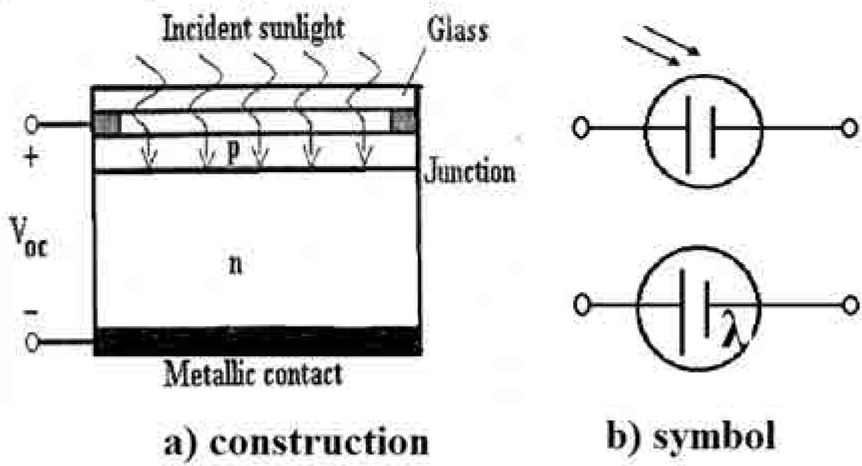


Fig.6.25 Photovoltaic cell

Light from the sun is allowed to fall on an unbiased PN junction as shown in fig 6.25 (a). Photons of light energy in this region collide with the valance electrons and generate a conduction band electrons and holes. This phenomenon will occur on either side of the junction.

In the P-region, newly generated electrons are minority carriers. As in an ordinary diode, these minority electrons will move freely across the junction to the N-region. Similarly, the minority holes from the N-region will move to the P-region. This results in reverse current due to minority carriers in the PN crystal. If an external resistor is connected between the contacts on P and N-regions, current will flow through it. The voltage across the diode terminal is photovoltaic emf and is of the order of 0.5V for silicon cell and 0.1V for germanium cell.

6.6. THERMISTORS

Have you ever thought how the temperature is sensed?

We can sense (detect) temperature using a thermistor. This is a type of resistor whose resistance varies significantly with temperature, more than that in standard resistors. 'Thermistor' is the combination of the words 'thermal' and 'resistor'. The typical package of a thermistor is as shown in fig.6.26.

Fig.6.26 Thermistor- Typical package

The thermistor is a temperature sensitive resistor; that is its terminal resistance is related to its body temperature. It is not a junction device and is made of Ge, Si or a mixture of oxides of cobalt, nickel, strontium or manganese. The compound employed will determine whether the device has positive or negative temperature coefficient. They have great resistance at low temperatures but when they warm up their resistance decreases rapidly. Current can then flow through them. This makes them ideal for a temperature sensor. Thermistors achieve a higher precision within a limited temperature range, typically -90 °C to 130 °C.

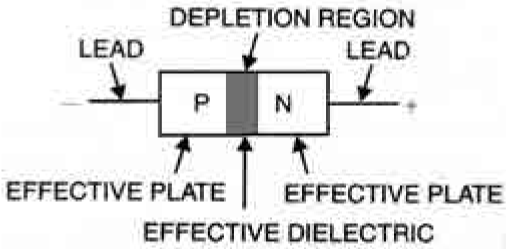
Applications of Thermistor

Thermistors are widely used as current limiters, temperature sensors, resistance thermometers, and self-regulating heating elements

- The first NTC (Negative Temperature Co-efficient) thermistor was discovered in 1833 by Michael Faraday, who reported the semiconducting behavior of silver sulphide. Faraday noticed that the resistance of silver sulphide decreases dramatically as temperature is increased. Since early thermistors were difficult to be produced and technology were limited, commercial production of thermistors began only after 1930s.
- The thermistor was invented by Samuel Ruben in 1930

6.7. VARACTOR DIODE (VARICAP)

We have studied about variable capacitors. But a Junction diode which acts as a variable capacitor under the influence of varying reverse bias voltage is known as Varactor diode. The Varactor diode is also called Varicap diode and Variable capacitance diode.



(a)

(b)

Fig.6.27 Varicap - construction and symbol

The capacitance is formed with P and N regions as conducting plates and the depletion region as dielectric. When the reverse voltage is varied, the width of the depletion region varies. So the capacitance varies as the separation between the conducting plates changes. Thus the varactor acts as a voltage controlled capacitance.

Application

Varactors are used as voltage-controlled capacitors. They are commonly used in voltage-controlled oscillators, and frequency multipliers. Voltage-controlled oscillators have many applications such as frequency modulation for FM transmitters

6.8. INTEGRATED CIRCIUT (IC)

The most advanced electronic circuits contain millions of diodes, transistors, resistors, and capacitors. These components are fabricated onto wafers, or chips, of semiconductor material, usually silicon. The chips are enclosed in little boxes or cans with pins for connection to external components.

IC - Classification

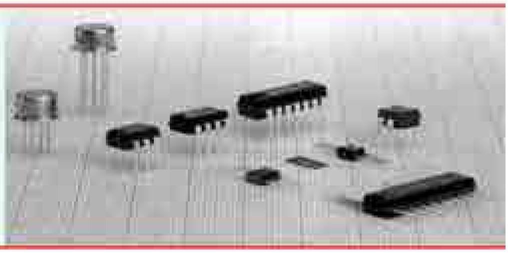
An integrated circuit consists of various electronic components and their inter connections in a single small semiconductor chip. There are four basic types of constructions employed in the manufacturing of integrated circuit, namely

1. Monolithic IC:-In this IC all electronic components (resistors, capacitors, diodes and transistors) are made on a single wafer (substrate) of semiconductor. This type of IC's are used widely.
2. Thin -film IC :- In this IC, the thickness of the substrate is kept 0.001 inch or 0.0025 cm only.
3. Thick -film IC :- Thickness of substrate material is kept more in this type of IC, in comparison to a thin film IC.
4. Hybrid:- These ICs are formed either by combining two or more monolithic IC's or by combining monolithic IC's with thick film or thin film components.

IC -Package type

There are four popular IC packages are available.

1. The metal can (TO) package
2. The Dual Inline Package(DIP)
3. The Single Inline Package (SIP)
4. The Flat package or flat pack



Advantages of IC technology

Integrated circuits have several advantages over individual, or discrete, components.

1. Compactness-extremely small size
2. High speed
3. Low power requirement
4. Reliability

Evolution of ICs

In early days of integrated circuits, only a few transistors could be placed on a chip. So the degree of integration was small, the design process was relatively simple. Now-a-days with good design and thorough planning millions and billions of transistors could be placed on one chip. The table below shows classification of IC technology based on the number of transistor's fabricated on the chip.

First Integrated circuit

In 1958 - Jack Kilby -Texas Instruments developed Integrated circuit

A device having multiple electrical components and their interconnections manufactured on a single substrate.

This is shown in photo

Fig.6.29 FIRST IC

Technology Name	Number of Transistors per chip
SSI-Small Scale Integration	<10
MSI-Medium Scale Integration	10- 100
LSI-Large Scale Integration	100-1000
VLSI-Very Large Scale Integration	1000- 10,000
ULSI-Ultra Large Scale Integration	10,000-1,00,0000 >
GSI- Giga Scale Integration	> 1,00,0000

Typial examples of- IC

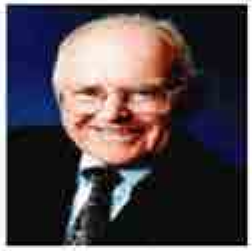
Integrated circuits can be divided into two further groups: analog (linear) and digital. The output voltage of linear circuits is continuous and follows changes in the input.

OP AMP- IC-741

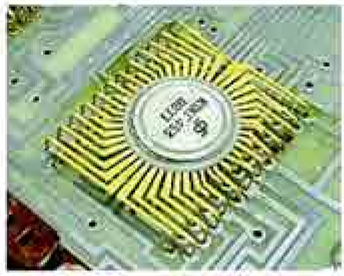
Typical representative of a linear IC is an Operational Amplifier (OPAMP-741). Fig 6.30 below shows symbol and DIP package of IC-741. Operational amplifier is also termed as Op-Amp. Basically it is a differential amplifier having two inputs and the output is the amplified form of the difference of the two signals applied to these two inputs. Out of these two inputs, one input is known as inverting input and the other input is called non inverting input. The main features of this IC are its very high gain and very large bandwidth.

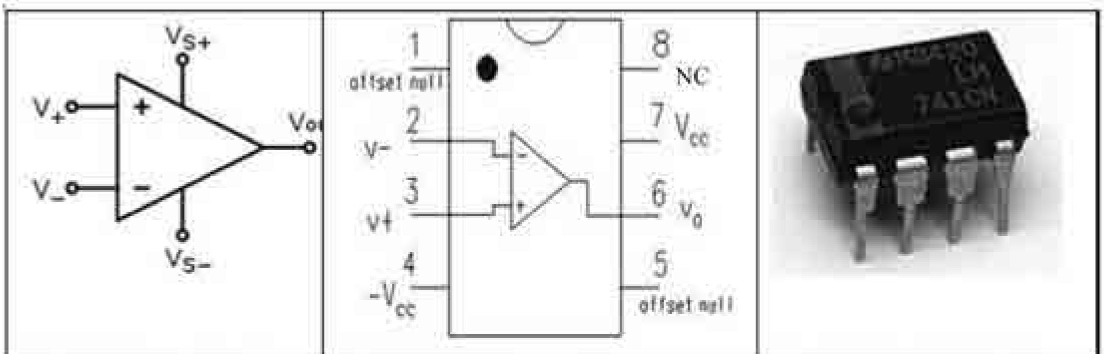
This IC is widely used for performing various mathematical operations such as addition, subtraction, multiplication, division, integration, differentiation, logarithm, antilogarithm etc. This is the reason why the IC is known as operational amplifier.

MOORE'S LAW



In 1965, Gordon Moore noted that the number of transistors on a chip doubled every 18 to 24 months.





(i) OPAMP Symbol | (ii) OPAMP-Pin-out diagram | (iii)OPAMP-DIP Package

Fig.6.30 Op-amp symbol, pin diagram and package

Digital ICs

About 80 percent of the IC's in market are digital ICs. Their output voltage is not continuous. It is either LOW or HIGH and it changes from one state to the other very quickly i.e.: switching functions. Digital IC's include circuits such as logic gates; memory chips, calculator's chips, microprocessors etc. Typical examples for digital IC's are given below.

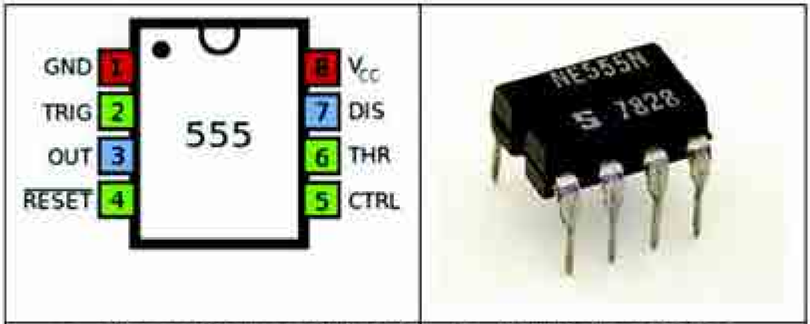
A. Timer IC-555

One of the most popular and widely used IC in electronic circuits is IC-555, which is called Timer. The IC is mainly used as monostable and astable multivibrators. It can produce accurate and highly stable timing pulses or time delays.

Important features of IC-555

1. It operates on +5V to +18V dc supply voltage.
2. Adjustable duty cycle.
3. The timing of the pulse can be varied from micro seconds to hours.

The pin-out diagram and NE-555 with DIP- package are shown in fig.6.31 (a) and (b)



a. Pin-out diagram of IC-555 b. DIP Package IC-555

Fig.6.31 555 IC - Pin diagram and package

Application of IC-555

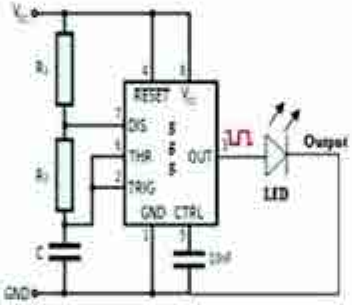
1. Rectangular/square wave generator A 555 astable multivibrator is used to generate a rectangular wave of any duty cycle. It can be modified to generate square waves. Also the circuit can be modified as a ramp generator. The 555 Timer IC is widely used in decorative displays and various security systems.
2. Timer circuit
3. Music generation

B. Inverter or NOT Gate 7404

The Logic NOT Function is simply a single input inverter that changes the input of a logic level "1" to an output of logic level "0" and vice versa. The logic NOT function is so called because its output state is NOT the same as its input state. Commonly available logic NOT gate is two types i.e. TTL Logic Types and CMOS Logic Types. The table below shows some examples of Inverter IC's.

Activity 6 Try these circuits

Circiut-1: Astable Multivibrator

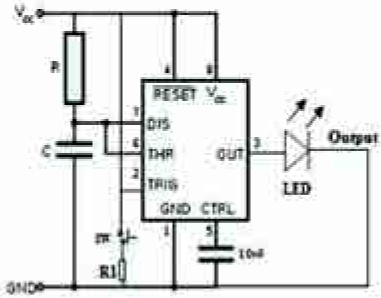


R1=100 KΩ

R2=10 KΩ

C=10 µF

Circuit 2- Monostable Multivibrator



R=1MΩ

R1=330 Ω

C=10µF

Fig.6.32 Multivibrator circuits

TTL Logic Types	CMOS Logic Types
74LS04 -Hex Inverting NOT Gate	
74LS04- Hex Inverting NOT Gate	
74LS100-4 Hex Inverting Drivers	CD4009 -Hex Inverting NOT Gate
CD4069- Hex Inverting NOT Gate	

Let us sum up

BJT is a current controlled device while FET is voltage controlled in which current conduction is caused by only one type of charge carriers i.e., either electrons or holes. Hence it is called unipolar. Flow of carriers from source to drain is controlled by the gate. The negative gate- source voltage applied increases the size of the depletion layer and hence reduces the current flow through the channel. The gate voltage at which the channel closes and no current flows through the channel is called pinch off voltage. JFET is used as a buffer amplifier. In MOSFET the gate is insulated from the channel. When gate voltage is negative the device operates in the depletion mode and when gate voltage is positive the device operates in the enhancement mode. Digital IC's, microprocessor memories, amplifiers, oscillators, communication systems etc. use MOSFET. CMOS circuits use a combination of PMOS and NMOS. CMOS technology is used for microprocessors, microcontrollers, RAM and other logic circuits. SCR, TRIAC, DIAC and UJT are power circuit devices which can handle currents upto several thousand amperes and voltages upto several kV. SCR can be considered as an ordinary rectifier and a junction transistor. It can change AC to DC and at the same time control the amount of power to the load. It is used for the speed control of motor, light dimming circuit, UPS etc. TRIAC is a three terminal device which can conduct in either direction. It is used for electronic fan regulators, motor speed control, UPS etc. DIAC which is a two terminal device is used as a triggering circuit for TRIAC. UJT is used as wave form generator, oscillator triggering circuit, phase control circuit etc. LED is a diode that emits visible light when forward biased. It is used as light source in displays and indicators. LCD's are used in computer monitors, TV's, video players etc. Photo resistors, photo diodes, photo transistors, solar cells etc. are photo sensors used for detecting light signals. Thermistor is a temperature sensitive resistor. A varactor diode acts as a variable capacitor under changing reverse bias. The most advanced electronic circuits containing millions of diodes, transistors, resistors and capacitors fabricated into chips of semiconductor materials are called IC's. IC technologies are developed in SSI, MSI, LSI, VLSI, ULSI and GLSI stages. Timer IC 555, Inverter IC 7404 etc. are examples of digital IC's.

Learning outcomes

The learner is able to

- Explain the working of electronics devices like FET, MOSFET and CMOS.
- Identify the power electronics devices such as SCR, TRIAC, DIAC and UJT and point out their applications.
- Explain the working and applications of photo sensor devices like LDR, photo diode, photo transistor and solar cell.
- Distinguish between the features of LED, LCD, seven segment and dot-matrix display.
- Draw the symbols and point out the applications of varactor diode and thermistor.
- Classify different types of Integrated Circuit technologies and explain their advantages.

Evaluation items

Multiple choice questions

1. FET operates on

   a) majority carrier only   b) minority carrier only

   c) positively charged ions only   d) negatively charged ions only

2. A JFET is also called ----------- transistor

a) unipolar b) bipolar
c) unijunction d) none of these

3. Which of the following statements is true in the case of FET?

a) It has high input impedance b) It is less noisy than BJT
c) It has large gain bandwidth d) all of these

4. The channel of JFET is between the -----------

a) gate and drain b) drain and source
c) gate and source d) input and output

5. A JFET has high input impedance because -----------

a) It is made of semiconductor material
b) Input is reverse biased
c) Of impurity atom
d) None of these

6. A JFET is a

a) Current controlled device with high input resistance
b) Voltage controlled device with high input resistance
c) Voltage controlled device with low input resistance
d) Current controlled device with low input resistance

7. A MOSFET is sometimes called ----------- JFET

a) Many gate b) Open gate
c) Insulated gate d) None of these

8. An SCR is semiconductor device which consists of

a) Four PN-junctions b) Three PN-junctions
c) Two PN-junctions d) One PN-junctions

9. The control element in SCR is -----------

a) Cathode b) Anode
c) emitter d) Gate

10. An SCR combines the features of -----------

a) A rectifier and resistance b) A rectifier and transistor
b) A rectifier and capacitor d) None of these

11. A TRIAC is a ----------- switch

a) Bidirectional b) Unidirectional
c) Mechanical d) None of these

12. The device that does not have the gate terminal

a) TRIAC b) FET
c) SCR d) DIAC

13. A DIAC is ------------ switch

a) an AC b) a DC
c) a mechanical d) none of these

14. A LED, emits visible light when its ------------

a) P-N junction is reverse biased b) depletion region widens
c) holes and electrons recombine d) PN- junction become hot

15. When the light increases, the reverse current in a photo diode

a) increases b) decreases
c) is unaffected d) none of these

Answer key

1.a 2.a 3.d 4.b 5.b 6.b 7.c 8.b 9.d 10.b 11.a 12.d 13.a 14.c 15.a

16. Match the following

Devices	Terminals
SCR	Emitter, base, collector
TRIAC	Source ,drain, gate
FET	Anode ,cathode ,gate
BJT	Emitter ,base-1, base-2
UJT	Gate,MT-1,MT-2

17. Match the following

Devices	Application
IC-555	Thermistor
UJT	Burglar alarm
Photo diode	voltage-controlled capacitors
Varactor diode	Timer circuit
Sawtooth generator	Thermometers

Descriptive type questions

1) Explain the construction and working of JFET.
2) What is the difference between a JFET and BJT?
3) Give some practical applications of JFET.
4) Explain the construction of MOSFET.
5) Explain the construction of an SCR.
6) Draw the equivalent circuit of an SCR.
7) Discuss some important applications of SCR and TRIAC.
8) Explain the construction of a TRIAC.
9) Explain the construction of a UJT.
10) Explain working of LED.
11) Give two applications of LED.
12) How LED differs from an ordinary diode?
13) How does photo diode work?
14) Give two applications of photo diode.
15) What is varactor diode and give its applications?

7

RECTIFIERS

INTRODUCTION

Do you know that electric energy available in homes and industries is in the form of alternating voltage? In India electric power supplied through AC mains, is 230 V at a frequency of 50 Hz. At the same time we know that for the operation of most of the electronic devices, DC voltage is needed. One way to obtain DC supply is to use battery. But batteries are expensive and can be used only for shorter periods. So we need devices for converting the alternating voltage obtained from the main supply into DC voltage. AC voltage can be converted into DC by means of rectifier circuits. It is a device which converts alternating voltage or current into unidirectional voltage or current. But this DC output is not a pure DC as obtained from a battery source. This rectified output is unidirectional, but fluctuates with time because it contains undesired AC components (ripples) also. If this output is directly fed to an electronic device, it will not function properly. For removing these undesired AC components, filter circuits are used. There are various types of rectifiers and filters.

Let us study rectifiers and filters in this chapter.

7.1 DIODE AS RECTIFIER

Can you suggest an electronic component that can be used to convert a bidirectional current or alternating current (AC) into a unidirectional current or DC? PN junction diode is such a device. We have already studied that a PN junction diode conducts only in one direction. It conducts when forward biased while it practically does not conduct when reverse biased. Hence it can be used to convert AC voltage to DC voltage. In other words diode can be used for rectification. Let us now see how diode acts as a rectifier. With the help of your teacher perform activity 2.

You might have observed that the presence of diode has resulted in suppression of negative half cycles. The output consists of positive half cycles only. The direction of current flow reverses during negative half cycle. Negative half cycles are suppressed i.e., diode allows the current to flow only in one direction. We can say that the diode is not allowing current to alternate its direction or it converts AC to DC.

The circuit supplies current to the load resistor only for half the time or in other words only half wave is obtained. Hence this is called half wave rectification. How can we get full wave rectification or current during the whole time period (both cycles), without alternating current direction? Is it possible if we use more than one diode?

Activity 1

Let us have a look at some of the household equipment around us. Can you find out the source of supply needed for their working? See whether AC is converted into DC in them. Discuss.

Equipment	*AC supply*	*DC supply*
Ceiling fan		
Refrigerator		
Pen torch		
Clock		
Mobile phone		
Television		
Computer		

- *Do you have any AC/DC adapter for charging laptop or any other device in your home?*
- *Have you ever thought of the function of a mobile charger or AC/DC adapter?*

7.2 HALF WAVE RECTIFIER

As we have seen, in half-wave rectification, when AC supply is applied at the input, only positive half cycle appears across the load, whereas, the negative half cycle is suppressed. Fig7.1shows the circuit of a half – wave rectifier. Generally AC supply is given through a transformer. The transformer is used for two purposes. It is to step down the AC input voltage and to isolate the rectifier circuit from power line for reducing the risk of electric shock. In most of the cases where rectifier is used, stepping down of voltage is required, because the voltage needed for most of the semiconductor devices and ICs for its working is in the range of 5V to 30V. The output of the transformer is applied in series with the diode and load resistance R_L.

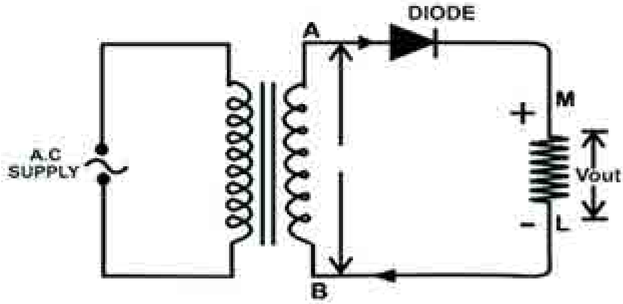


Fig7.1 Half Wave Rectifier

Activity 2

Use a CRO in your school laboratory to verify the output waveforms from the following circuits.

- *Connect the primary of a 230/6 V transformer to AC supply as shown in Fig 7.2 and observe the signal in the transformer secondary using a CRO. What is your observation?*

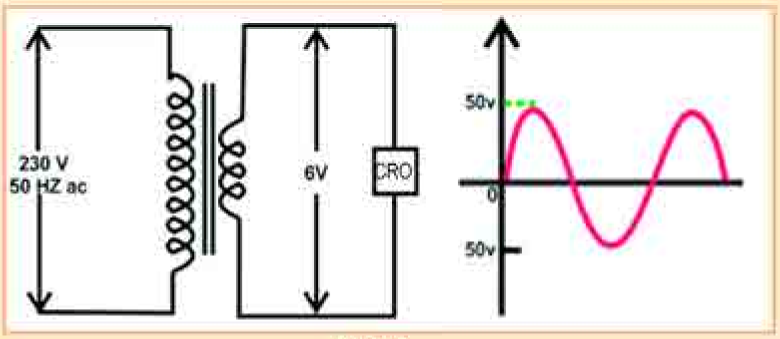


Fig7.2

- *Connect a diode and a resistor as shown in Fig7.3 in series with the above circuit and observe its output waveform. What difference do you observe? What does the diode do?*

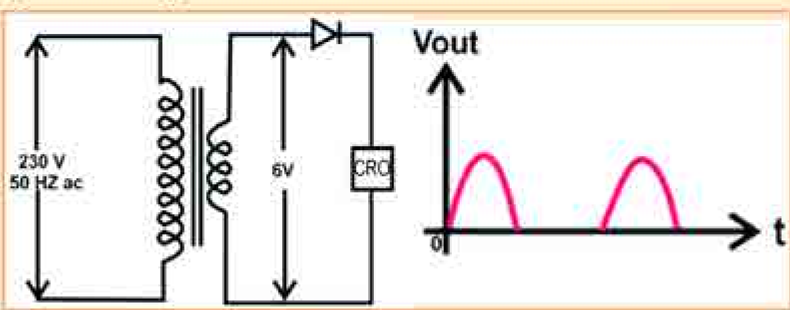


Fig7.3

The primary winding of the transformer is connected to the power mains. Voltage across the secondary winding of the transformer changes polarity after every half-cycle, since primary is connected to an AC voltage. Voltage V_m is the peak value of this alternating voltage.

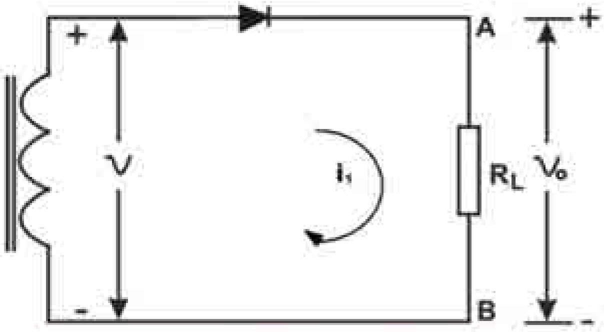


Fig7.4(a) Half Wave Rectifier (positive half cycle)

During the positive half cycle of input AC voltage, end A becomes positive with respect to end B as shown in Fig7.4(a). This makes the diode forward biased and hence it conducts current. The direction of current is from A to B. Since a forward biased diode offers a very low resistance, the voltage drop across it is also very small(about 0.3V for Ge diode and about 0.7V for Si diode). Therefore, the voltage appearing across the load resistance R_L is approximately the same as that of the input voltage.

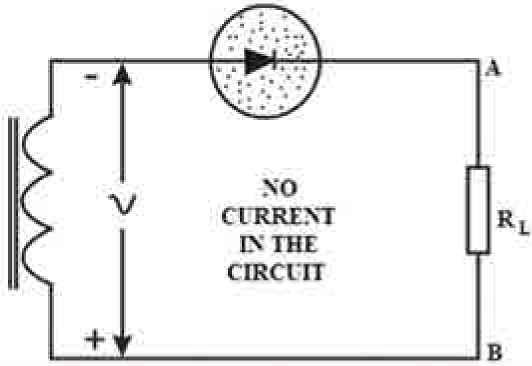


Fig7.4(b) Half Wave Rectifier (negative half cycle)

During the negative half cycle of the input, end A is negative with respect to end B as shown in Fig 7.4(b). Under this condition, the diode is reverse biased. It is shown shaded in the Figure to indicate that it is non-conducting. That is no current flows through the circuit. Therefore, almost no voltage is developed across the load resistance R_L. All the input voltage appears across the diode itself.

Therefore it can be concluded that during positive half cycle, the voltage at the output is almost the same as the input voltage. During the negative half cycle, no voltage is available across the load. Current flows through the load R_L only in one direction. Hence a DC output is obtained across R_L. Waveform of the voltage across the load is shown in Fig7.4(c). It may be noted that even though output voltage across the load is unidirectional, it is in the form of pulses (pulsating DC). If we compare this with the DC voltage obtained from a battery, we can say that the rectified signal is not a perfect DC (constant). It can be considered as the sum of a DC component (constant voltage) and an AC component (varying voltage). These undesired AC components are called **ripples.** The DC value is obtained by taking the average value of instantaneous voltages (voltage at each instant of time).

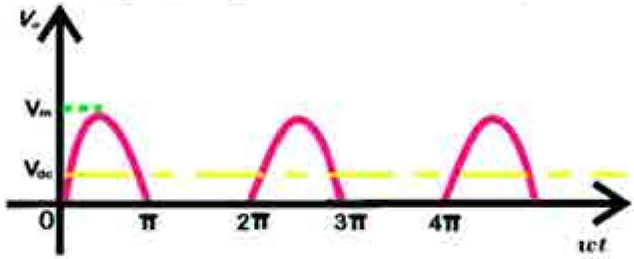


Fig7.4 (c) Waveform of the voltage across the load

Peak Inverse Voltage

Let us focus our attention again on the diode in Fig7.4(b) . During the negative half cycle of the input, the diode is reverse biased. All the input voltage appears across the diode (as there is no voltage across the load resistance). When the input reaches its peak value Vm, in the negative half-cycle, the voltage across the diode is also maximum. This maximum voltage is known as the peak inverse voltage(PIV). It represents the maximum voltage appearing across the diode, when the diode is reverse biased. Thus, for a half wave rectifier,

$$PIV = V_m$$

Activity 3

Assemble the following circuits. Apply a 6V AC using a 230/6V transformer and observe the corresponding output wave forms on a CRO.

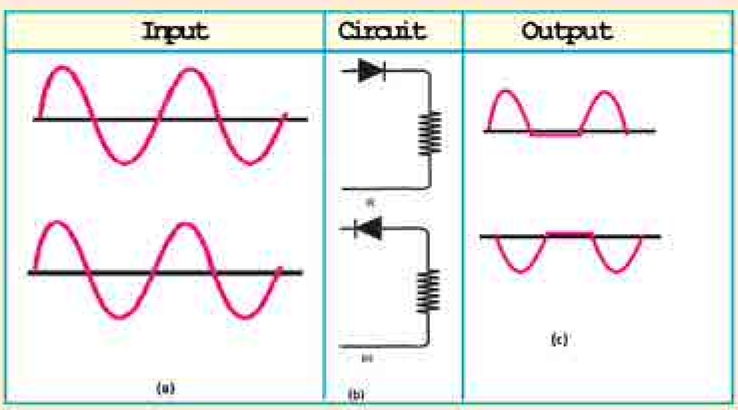


Fig7.5

- *In both the circuits you applied the same AC supply. But why did you get different output waveforms?*
- *In both the waveforms only one half of the signal is present and the other half is cut off. Why ?*
- *From the waveforms obtained, have you got an idea of how full wave rectification can be obtained?*

7.3 FULL WAVE RECTIFIER

In full wave the rectification, current should flow through the load in the same direction for the both half cycles of input AC voltage. The following two circuits are commonly used for full wave rectification:

(i) Centre- tap full wave rectifier

(ii) Bridge rectifier

Centre- tap full wave rectifier

The circuit of a centre tap rectifier is shown in Fig 7.6. It uses two diodes D_1 and D_2 and a center tapped transformer.

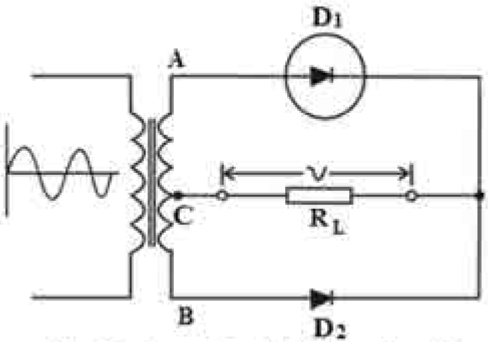


Fig 7.6 Centre-Tap Full Wave Rectifier

During the positive half cycle of input signal, the end A of the secondary winding becomes positive and the end B becomes negative with respect to the point C as shown in Fig. 7.7(a) This makes the diode D_1 forward biased and diode D_2 reverse biased. So, the diode D_1 conducts while D_2 does not. The current flows through the diode D_1, load resistor R_L and the upper half of the secondary winding .

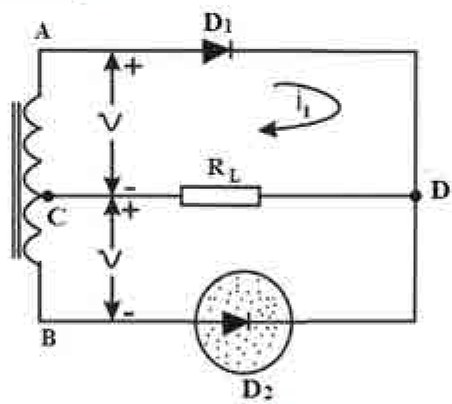


Fig7.7(a) Centre-Tap Full Wave Rectifier (positive half cycle)

During negative half cycle, the end A of the secondary becomes negative and the end B becomes positive with respect to the point C. This makes the diode D_2 forward biased and diode D_1 reverse biased. The diode D_2 alone conducts. The current flow is through diode D_2, load R_L and lower half of secondary winding as shown in Fig7.7(b).

It may be seen that the current in the load is in the same direction (D to C) for both half-cycles of the input AC voltage as shown in Fig7.7(c) . Therefore DC output is obtained across the load R_L.

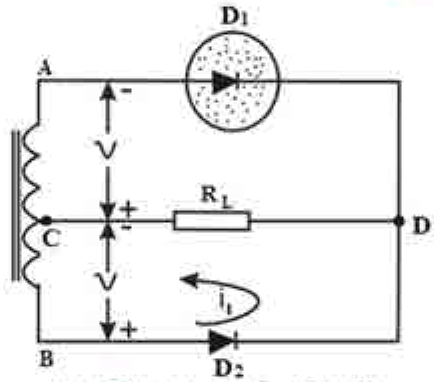


Fig 7.7(b) Centre-Tap Full Wave Rectifier(negative half cycle

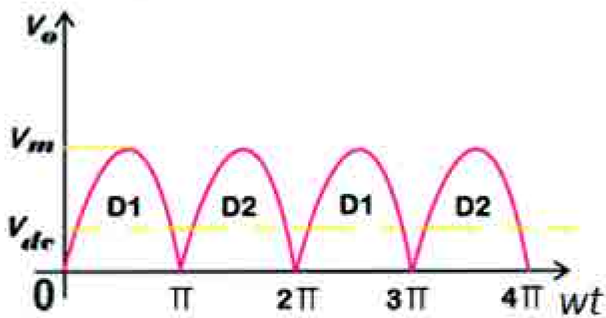


Fig7.7(c) Waveform of voltage across load

Peak Inverse Voltage

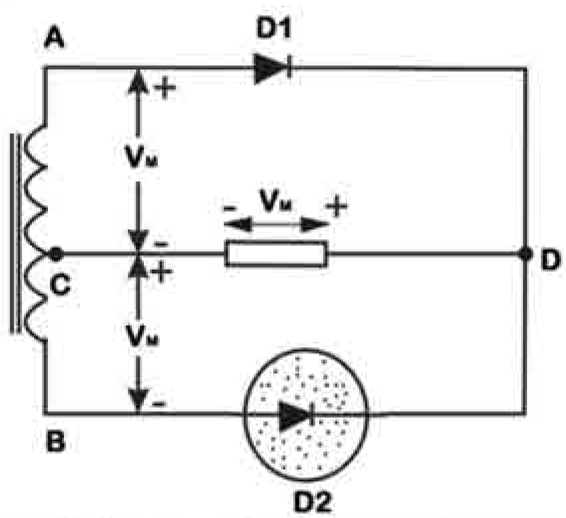


Fig7.8 Full wave Rectifier when input voltage is maximum.

To find the peak inverse voltage, let us consider the instant at which the input voltage attains maximum value $+V_m$. At this instant the diode D_1 is conducting and it offers almost zero resistance (Fig 7.8). The whole of the voltage V_m across the upper half winding appears across the load resistor R_L. Therefore, the reverse voltage that appears across the non conducting diode is the sum of the voltages across the lower half winding and the voltage across the load resistor R_L.

$$\text{i.e, PIV} = V_m + V_m = 2V_m$$

Full Wave Bridge Rectifier

A more widely used full wave rectifier circuit is the bridge rectifier .The need for a center – tapped transformer is eliminated in the bridge rectifier. It contains four diodes connected to form a bridge as shown in Fig 7.9 .The input AC is applied to the diagonally opposite ends of the bridge through the transformer. Between the other ends of the bridge, the load R_L is connected.

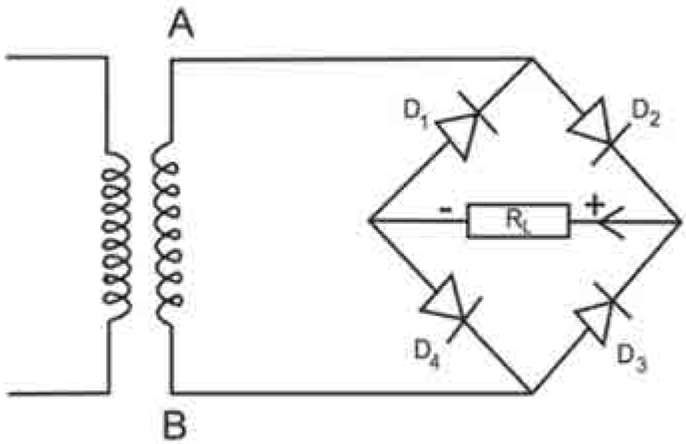


Fig 7.9 Full Wave Bridge Rectifier

Operation

During the positive half cycle of the secondary voltage, end A of the secondary winding becomes positive and the end B becomes negative. This makes the diodes D_2 and D_4 forward biased and the diodes D_1 and D_3 reverse biased. Therefore, only diodes D_2 and D_4 conduct. The current flow is through the diode D_2, load R_L, diode D_4 and the secondary winding, as shown in Fig 7.10(a).

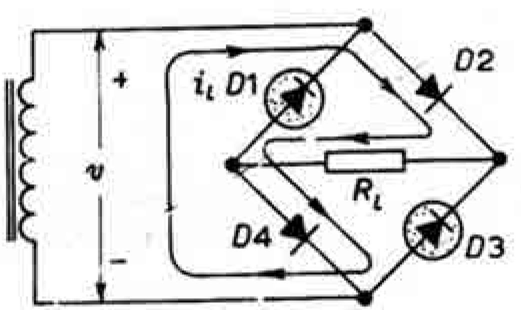


Fig 7.9 Full Wave Bridge Rectifier

During the negative half cycle of the secondary voltage, the end A becomes negative and end B positive. This makes diodes D_1 and D_3 forward biased while diodes D_2 and D_4 are reverse biased. Therefore, only diodes D_1 and D_3 conduct. The current flow is through diode D_1, load R_L, diode D_3 and the secondary winding as shown in Fig 7.10 (b).

It may be seen that the current in the load is in the same direction for both the half cycles of input AC voltage. Therefore, a unidirectional voltage is obtained across the load R_L. The load voltage waveform is shown in Fig 7.10(c).

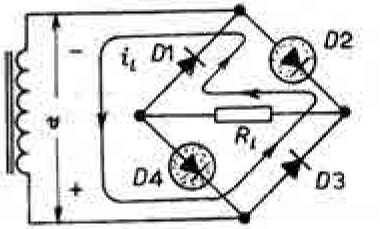


Fig7.10(b) Full Wave Bridge Rectifier(negative half cycle)

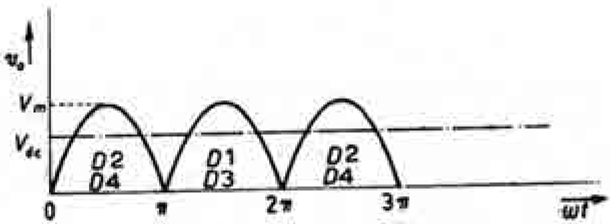


Fig7.10(c) Waveform of voltage across load

Peak Inverse Voltage

Consider the bridge rectifier circuit shown in Fig7.11 and assume the instant at which secondary voltage reaches its positive peak value, V_m. The diodes D_2 and D_4 are conducting, whereas diodes D_1 and D_3 are reverse biased and are nonconducting . The entire voltage V_m across the secondary winding appears across the load resistor R_L. Also we can see that the points A and B are almost at the same potential as similar to points C and D. The reverse voltage across the nonconducting diode D_1 (or D_3) is hence V_m. PIV of each diode is equal to the maximum secondary voltage.

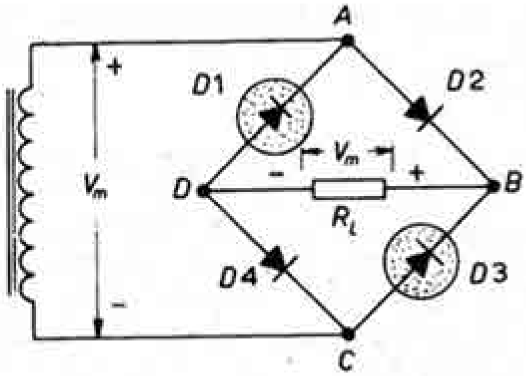


Fig7.11Bridge Rectifier when input voltage is maximum

$$PIV = V_m$$

7.4 RIPPLE FACTOR

The ripple current is undesirable and its value should be the smallest possible in order to make the rectifier effective. Ripple factor 'r' is a measure of the purity of the DC output of a rectifier and is defined as the ratio of rms value of the AC component in the output to the average or DC component present in the output. Smaller the value of this factor, lesser is the AC component in comparison to DC component.

$$r = \frac{\text{rms value of AC component in the rectified output}}{\text{DC component}}$$

The general expression for ripple factor is (derivation not needed)

$$r = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1}$$

For half wave rectifier, it can be derived that

$$I_{rms} = I_m/2$$

$$I_{dc} = I_m/\pi$$

Where I_{rms} = rms value of load current

I_m = maximum value of load current

I_{dc} = average value of load current

by substituting the above values in general expression, we get

$$r = 1.21$$

This expression shows that the percentage of AC in the output is 121% of the DC voltage. That is, the output of a half wave rectifier contains more ripples than the DC component. Hence half wave rectifiers are poor converters of AC to DC.

For full wave rectifier[centre tap and bridge]

$$I_{rms} = I_m/\sqrt{2}$$

$$I_{dc} = 2I_m/\pi$$

By substituting the above values in general expression, we get

$$r = 0.48$$

This indicates that the ripple contents in the output are 48% of the DC component which is less than that of the half wave circuit. In other words, the output of a full wave rectifier contains lesser percentage of ripples. Hence full wave rectifiers are better converters of AC to DC, compared to half wave rectifiers.

7.5 EFFICIENCY

The rectifier efficiency tells us what percentage of total input AC power is converted into useful DC output power. Thus, rectifier efficiency is defined as the ratio of DC output power P_{dc} to AC input power P_{ac}.

$$\text{Hence, } \eta = \frac{\text{Output DC power}}{\text{Input AC power}}$$

For half wave rectifier

Output DC power, $P_{dc} = I_{dc}^2 R_L$

$= (I_m / \pi)^2 . R_L$

where , R_L = load resistance

Input AC power , $P_{ac} = I_{rms}^2 R_L$

$= (I_m/2)^2 R_L$

$\eta = P_{dc}/P_{ac}$

$= (I_m / \pi)^2 . R_L \ /(I_m/2)^2 R_L$

$= 0.406 \ R_L / R_L$

$= 0.406$

$= 40.6\%$

Theoritically the maximum value of rectifier efficiency of a half wave rectifier is 40.6 percent. This shows that a half wave rectifier can convert a maximum of 40.6% of AC power in to DC power.

For full wave rectifier

$P_{dc} = I_{dc}^2 R_L$

$= (2I_m / \pi)^2 . R_L$

$P_{ac} = I_{rms}^2 R_L$

$= (I_m / \sqrt{2})^2 R_L$

Therefore, $\eta = P_{dc}/P_{ac}$

$= (2I_m / \pi)^2 . R_L /(I_m / \sqrt{2})^2 R_L$

$= 0.812 R_L / R_L$

$= 0.812$

$= 81.2\%$

Theoritically the maximum value of rectifier efficiency of a full wave rectifier is 81.2 %.

Solved Problem 7.1

Transformer secondary voltage of a half wave rectifier circuit is $v = 50\sin\omega t$ and the load resistance $R_L = 800\Omega$, find (i) I_m , I_{dc} & I_{rms} (ii) ac input power and DC output power (iii) DC output voltage and (iv) efficiency of rectification.

Solution

Maximum voltage, $V_m = 50V$

$I_m = V_{RL}$

$R_L = \frac{50}{800} = 62mA$

$I_{dc} = I_m/\pi$

$= 62/\pi$

$= 19.74mA$

$I_{rms} = I_m/2$

$= 62/2 = 31mA$

(ii) AC input power $P_{ac} = I^2_{r.m.s.} R_L$

$= (31\times10^{-3})^2x(800)$

$= 0.768W$

DC output power $P_{dc} = I_{dc}^2 \times R_L$

$= (19.74\times10^{-3})^2\times800$

$= 0.312W$

(iii) DC output voltage $= I_{dc}\times R_L$

$= 19.74mA\times800\Omega$

$= 15.79V$

Alternatively,

DC output voltage $= V_m/\pi$

$= 50/\pi$

$= 15.82V$

(iv) Efficiency $= (P_{dc}/ P_{ac})\times100$

$= (0.312/0.768)\times100$

$= 40.62\%$

Solved Problem 7.2

Transformer secondary voltage of a full wave rectifier circuit is $v = 10 \sin(\omega t)$ and the load is $2K\Omega$. Neglecting diode's forward resistance, calculate

(a) V_{dc} (b) I_{dc} (c) PIV (d) V_{rms} of output (e) ripple voltage

Solution

(a) $V = 10 \sin(\omega t)$

$V_m = 10V$

$$V_{dc} = \frac{2\times10}{\pi} = 6.369V$$

(b) $I_{dc} = V_{dc}/R_L$

$$= \frac{6.369}{2\times10^3} = 3.1845\times10^{-3}A$$

$= 3.1845mA$

(c) $PIV = 2V_m$

$= 20V$

(d) $$V_{rms} = \frac{V_m}{\sqrt{2}}$$

$$= \frac{10}{\sqrt{2}}$$

$= 7.071\ V$

(e) Ripple voltage $=$ ripple factor $\times V_{dc}$

$= 0.482 \times 6.369$

$= 3.069\ V$

Activity 4

Complete the table (Table 7.1). Analyze the table and state your inferences.

Sl. No.	*Parameter*	*Half wave Rectifier Full wave rectifier*	*Center tapped*	*Bridge Rectifier*
1.	I_{rms}			
2.	I_{dc}			
3.	V_{dc}			
4.	% efficiency			
5.	Ripple Factor			
6.	Peak Inverse Voltage			
7.	Number of Diodes			

- *Which rectifier, half wave or full wave is more efficient ? Why ?*
- *Peak Inverse Voltage of center tapped and bridge recifiers are different even though both of them are full wave rectifiers. Why?*

Activity 5

With the help of your teacher, setup the circuit of a half wave rectifier and a full wave rectifier in your lab and observe the input and output waveforms in CRO.

- *List the components you used for assembling the circuit ?*
- *Measure the voltage across the transformer secondary winding using an AC volt meter and the peak value of the output waveform using CRO. Compare the voltages obtained and state your comments.*

The AC voltmeter gives the rms value of the transformer secondary voltage. From CRO we measure the maximum value or peak value. Hence both are not equal.

7.6 FILTER CIRCUITS

The object of rectification is to provide a steady DC voltage, similar to the voltage from a battery. It is seen that the output of a rectifier circuit is not pure DC, but it contains unwanted AC components. If this pulsating DC is fed directly to the electronic devices they will not function properly. Hence it becomes essential to reduce the ripples in the pulsating DC voltage available from rectifier circuits. This is achieved by using a filter circuit which removes the AC components and allows only the DC components to reach the load. These circuits are connected

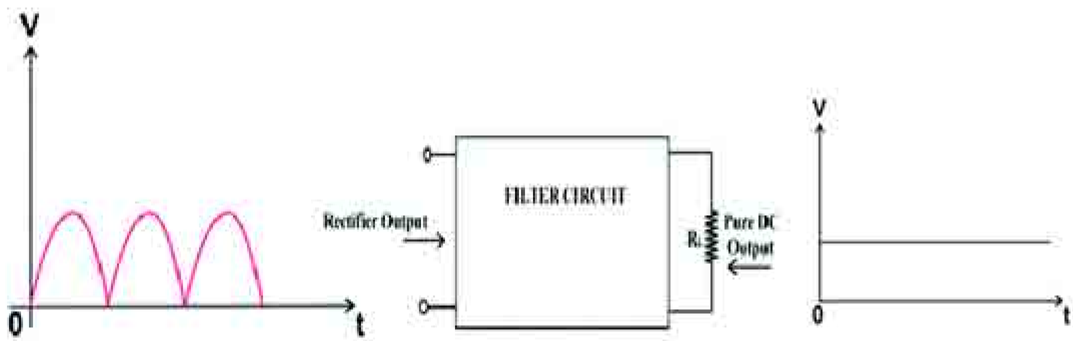


Fig 7.12 Schematic Diagram of Filter Circuit

between the rectifier and the load. Fig 7.12 shows the schematic diagram of filter circuit. The input to the filter circuit is the output of the rectifier. At the output of the filter, we get a signal with ripples suppressed.

Capacitor Filter

This is the simplest and cheapest filter. It consists of a capacitor C placed across the rectifier output in parallel with the load R_L. The pulsating DC voltage of the rectifier output is applied across the capacitor. It uses the capacitor to bypass the AC components (provides an easy path for AC) and there by AC is not allowed to flow through the load. This is possible, since the oppositions offered by the capacitance to AC and DC are different.

The opposition offered by a capacitor is called capacitive reactance and its value is determined by

$$X_c = 1/2\pi fC$$

for DC (f = 0), the value of capacitive reactance is infinity and hence it provides an open circuit for DC. However, it provides an easy path for AC (as f increases, X_c decreases). That means a capacitor offers a low reactance path to the AC components, where as to DC it acts as an open circuit.

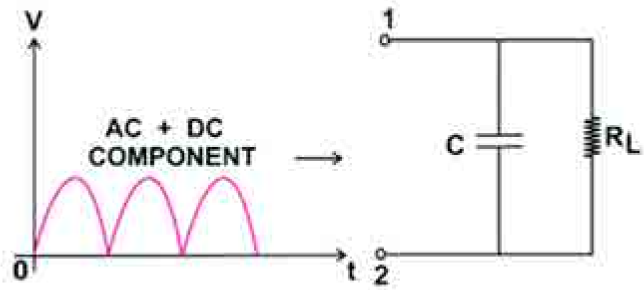


Fig 7.13: (a) Capacitor Filter

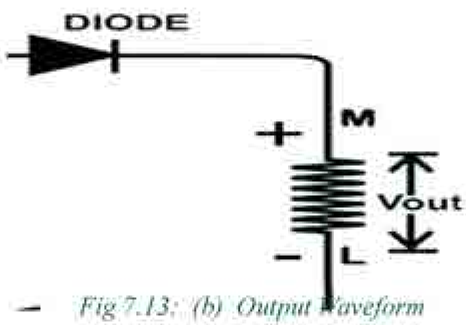
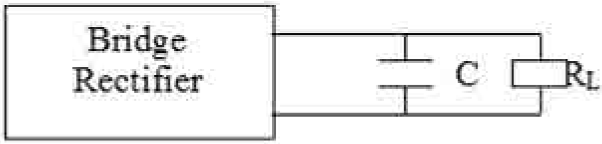


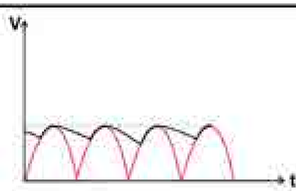
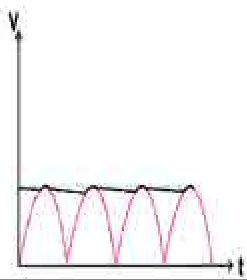
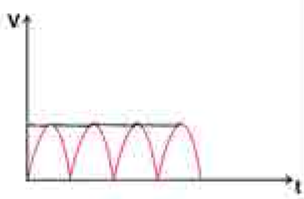
Fig 7.13: (b) Output Waveform

DC component will flow through the load. Only a small part of the AC components passes through the load, producing a small ripple voltage. The ripple voltage depends on the value of the capacitor. Do you know why?

Activity 6

Connect the following circuit (Fig. 7.14). Use capacitors of different values such as 1μ f, 10μ f and 100μ f, one after the other and observe the output waveforms on a CRO in each case. Compare the results and state your comments.



CASE	CAPACITANCE VALUE	OUTPUT WAVEFORM	OBSERVATION
CASE I	C=1 μF		
CASE II	C=10 μF		
CASE III	C=100 μF		

- *Does the value of capacitances affect the ripple content of output voltage ?*
- *If yes , why is it so?*

From the above activity we can see that the ripple gets reduced as we increase the value of the capacitor. This is because the capacitance increases as the capacitive reactance decreases and hence impedance offered to AC component decreases. So more AC will flow through the capacitor and less will flow through the load. Therefore by using a higher value of capacitance we get DC output with less ripple content. Capacitor filter is very popular because of its low cost, small size, light weight and good performance. It can be used with both the half wave and the full wave rectifier circuits.

Let us sum up

Alternating voltage or current can be converted to DC by means of rectifier circuits. P-N junction diode is used for rectification because of its unidirectional current conduction property. For half wave rectification only a single diode is used. Maximum reverse voltage across the diode is called the peak inverse voltage (PIV). It is V_m for a half wave rectifier. For fullwave rectification either two or four diodes are used. Two diodes along with a center tapped transformer are used for making center tapped fullwave rectifier. The PIV for a center tapped fullwave rectifier is $2V_m$. Four diodes are used for making bridge rectifier. The PIV for a fullwave bridge rectifier is V_m. The output from a rectifier is not pure but pulsating DC. Ripple factor is a measure of purity of the rectifier. For a half rectifier it is 1.21 and for full wave rectifier it is 0.48. The efficiency of a rectifier is the ratio of DC power output to the AC power input. The maximum efficiency of a half wave rectifier is 40.6% and for fullwave rectifier it is 81.2%.

Learning outcomes

The learner is able to

- Explain the need for rectifiers.
- Demonstrate and thus explain how a diode acts as a rectifier.
- Explain the working of a half wave rectifier.
- Derive and calculate the efficiency of rectifiers.
- Explain the concept of ripple factor.
- Explain the working of full wave rectifier.
- Distinguish between RMS and average values of rectified output.
- Explain the need for filter circuits in rectifiers.

Evaluation items

Multiple choice questions

1. The ripple factor of a bridge rectifier is

   a) 0.406 b) 0.812

   c) 0.48 d) 1.11

2. In a center tap full wave rectifier, if V_m is the peak voltage between the center tap and one end of the secondary the maximum voltage across the reverse biased diode is

   a) V_m b) $2V_m$

   c) 1/2 V_m d) none of the above

3. If V_m is the peak voltage across the secondary of the transformer in a half wave rectifier (without any filter circuit), then the maximum voltage on the reverse biased diode is

   a) V_m b) $2V_m$

   c) 1/2 V_m d) none of the above

4. In a half wave rectifier, the load current flows for

   a) the complete cycle of the input signal

   b) only for one half cycle of the input signal

   c) less than half cycle of the input signal

   d) more than half cycle but less than the complete cycle of the input signal

5. In a full wave rectifier, the current in each of the diode flows for

   a) the complete cycle of the input signal

   b) half cycle of the input signal

   c) less than half cycle of the input signal

   d) zero time

6. To filter the AC component from the output of a rectifier, we can use the following component

   a) Inductor b) Capacitor

   c) Inductor or capacitor d) Resistor

7. The filtering will be improved if we use a

   a) large value capacitor b) small value capacitor

   c) value doesn't matter d) inductor only

8. In a full wave bridge rectifier, if one diode is spoiled, we get

   a) full wave rectifier output b) half wave rectifier output

   c) no output d) sine wave

9. The maximum efficiency of a full wave rectifier is

a) 40.6% b) 81.2%

c) 50% d) 100%

10. The value of ripple factor is always

a) 0.48

b) 1.21

c) either 0.48 or 1.21 depending on the rectifier

d) any value below 1.21

Answer Key

1. c 2. b 3. a 4. b 5. b 6. c 7. a 8. b 9. b 10. c

Descriptive type questions

1. If the peak value of voltage across the secondary winding in a half wave rectifier is 9V, what is the value of DC component in the output voltage and what is the maximum efficiency of rectification?
2. Draw the output voltage waveform of a half wave rectifier and then show the effect, on this waveform, of connecting a capacitor across the load resistance.
3. In practical circuits, full wave bridge rectifier is preferred over other rectifiers. Explain.
4. Filter circuits are used to remove the ripples in the output of the rectifier. How is filtering improved when the value of the capacitor is increased?
5. Explain how the term ripple factor is used to compare the performance of rectifiers.
6. The efficiency of a half wave rectifier is just 40%. What happens to the remaining 60% power?
7. The frequency of the output of a half wave rectifier is 50Hz and that of a full wave rectifier is 100Hz. Give reason.
8. If any voltage variation occurs in the power supply, it will change the output DC voltage of a rectifier. Explain

8

AMPLIFIERS

INTRODUCTION

Suppose you want to make an announcement to a large gathering. The voice may not be heard to all without enhancing the sound. So we need a system to increase the strength of the voice signal. The enhancement of audio signal can be done with the help of a mega phone. But it is insufficient. If we can convert the voice signal or audio signal to an electrical signal, we can increase the amplitude or strength of the signal using electronic amplifiers. A device which converts one form of energy into another is called a transducer. So we need a transducer which can convert audio signal into the corresponding electrical signal. Microphone is such a device. The electrical signal obtained from the microphone is strengthened or amplified using an electronic circuit called amplifier. Now we need another transducer to convert the amplified electrical signal back to the sound form. A loud speaker can be used to serve this purpose. The system which contains microphone, loudspeaker and amplifier is called as a public address system (PA system) which can be used to deliver sound to a large gathering.

8.1 CONCEPT OF AMPLIFICATION

An amplifier is an electronic device which increases the amplitude of a given signal. See Fig. 8.1. A 2mV input signal is amplified to a signal of the same shape with an amplitude of 100mV. This implies that the amplitude is increased 50 times. The amount of increase is called 'gain' of the amplifier. It is the ratio of the output amplitude (amplitude of the output signal) to the input amplitude (amplitude of the input signal).

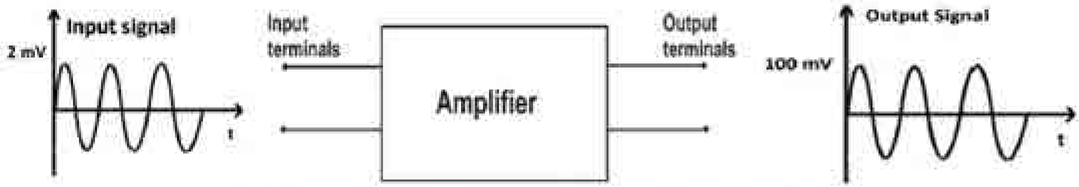


Fig. 8.1 Amplifier showing input and output waveforms

Amplifiers are mainly of three types – voltage amplifiers, current amplifiers and power amplifiers. In voltage amplifiers, the output voltage is greater than the input voltage which means that the voltage is amplified. Similarly in current amplifiers, the current is amplified and in power amplifiers, the power is amplified.

$$\text{Gain of the amplifier, A} = \frac{\text{Output amplitude}}{\text{Input amplitude}}$$

Amplifiers find wide applications in communication systems, control systems and instrumentation systems. For example our TV and radio receivers have amplifiers to increase the amplitude of the signal received. Do you know that when we rotate the knob of the volume control of a radio, we are actually changing the gain of an amplifier inside?

8.2 TRANSISTOR AS AN AMPLIFIER

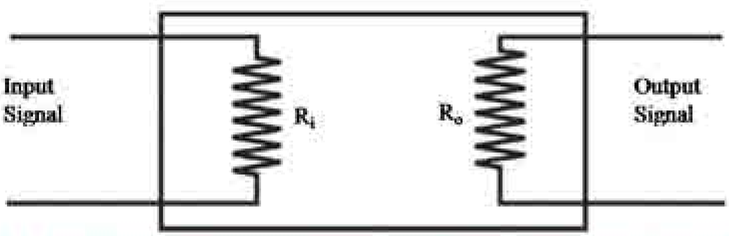


Fig. 8.2 Amplifier showing Input impedance Ri and output impedance Ro

If we apply a voltage V_i to a device across its input resistance R_i, it produces an input current $I_i = V_i/R_i$. If the output current is I_o, then the voltage developed across the output resistance is $I_o R_o$. If R_i is small and R_o is large and if $I_o \geq I_i$, then the output voltage will be very high compared to the input voltage. This results in voltage amplification. Any device that has such characteristics can be used for voltage amplification. Bipolar junction transistor is one such device.

As we have studied in chapter 5, when a transistor is operated in the active region, the input junction is forward biased and the output junction is reverse biased. Hence it has low input resistance and high output resistance. The transistor can function as an amplifier, because of the transfer of current from a low resistance junction to a high resistance junction[1]. In both common emitter and common base configurations, since the resistance values have the above

[1] The name transistor comes from this transfer of resistance – "transfer-resistance"

feature, these can be used for voltage amplification. At the same time in the common collector configuration, the input resistance is not low and the output resistance is not high. Hence the common collector configuration cannot be used for voltage amplification.

The transistor is a current controlled device. The base current I_B controls the collector current I_C. In CE configuration, the input current is I_B and output current is I_C. Since I_C is β times I_B, CE configuration can provide current amplification also (current gain equal to β). Similarly CC configuration can also provide current amplification (current gain equal to $\beta+1$). However, in CB configuration current gain is less than unity. Do you know why?

Among the three transistor configurations - CE, CB and CC, the CE configuration is commonly used for amplification due to its ability to provide high voltage gain and current gain. So CE configuration is the focus of our further discussion.

8.3 BIASING OF TRANSISTOR FOR AMPLIFICATION

Usually the input signal of an amplifier is AC[2]. The AC signals have both positive and negative values. To keep the transistor in the ON condition and to have the base current flowing, the base to emitter voltage of the transistor should be kept around 0.7 V. This happens for the positive values above 0.7 V of the input signal. But for the input voltages below 0.7 V (including the entire negative values), the transistor can be made conducting by applying a DC voltage at the base of the transistor and it is called **biasing.**

Consider the circuit shown in Fig 8.3(a). It can also be drawn conveniently as in Fig. 8.3(b). The emitter base junction is forward biased by V_{BB} and the collector base junction is reverse biased by V_{CC}, for operating the transistor in an active region. The V_{CC} should be greater than V_{BB} in order to reverse bias the collector-base junction.

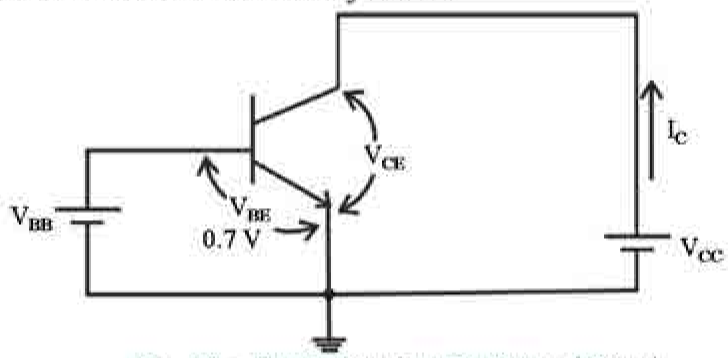


Fig. 8.3.a Emitter base junction forward biased and collector base junction reverse biased.

To keep the transistor in the active region, the value of V_{BE} should be between 0.6 V to 0.7 V. To get the desired base current the value of V_{BE} must be fixed precisely. A resistor of proper value can be used in series with the voltage source V_{BB}, to get the required base

[2] For DC amplification, we use special circuits, which will be discussed later.

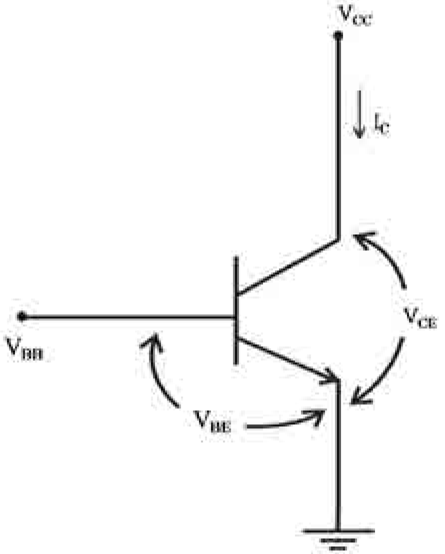


Fig. 8.3.b Circuit in Fig. 8.3.a - simplified.

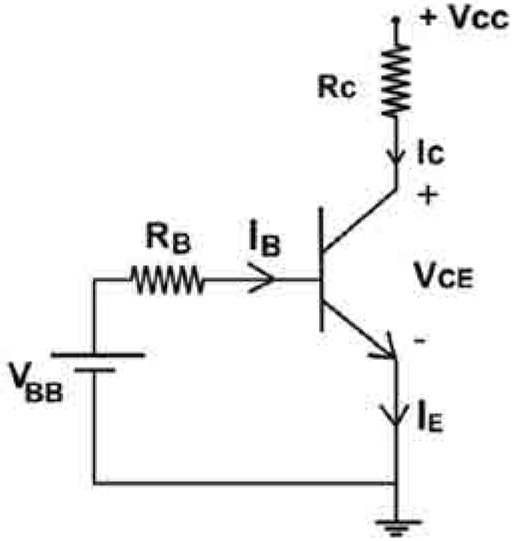


Fig. 8.3.c Circuit showing resistors R_B and R_C

current (Fig. 8.3.c). To fix the operating point (I_C and V_{CE}) at the required value, a resistor R_C is placed at the collector terminal.

The biasing circuit can be redrawn as in Fig. 8.3.d

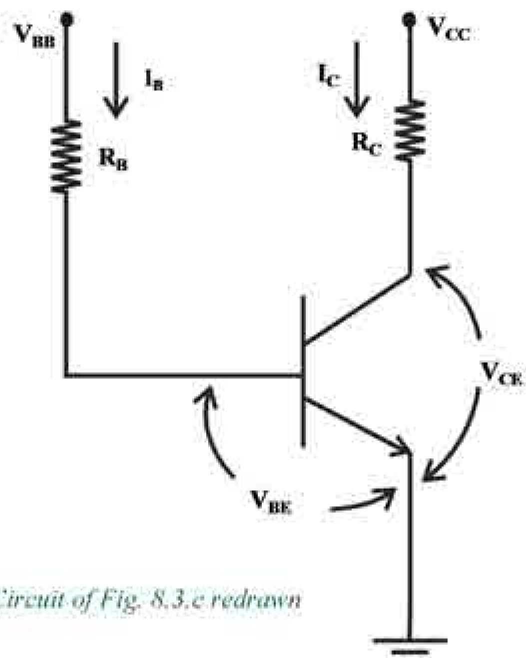


Fig. 8.3.d Circuit of Fig. 8.3.c redrawn

It is inconvenient and expensive to use two separate voltage sources in a circuit. Hence we can obtain two voltages from a single source as shown in Fig. 8.3.e .

Considering the input section and applying Ohm's law

$$V_{CC} = I_B R_B + V_{BE}$$

$$I_B = (V_{CC} - V_{BE}) / R_B$$

Since $V_{BE} << V_{CC}$, it can be neglected.

$$I_B = V_{CC} / R_B$$

Here as V_{CC} is constant, once R_B is selected I_B becomes fixed. So this circuit is called **fixed bias** circuit.

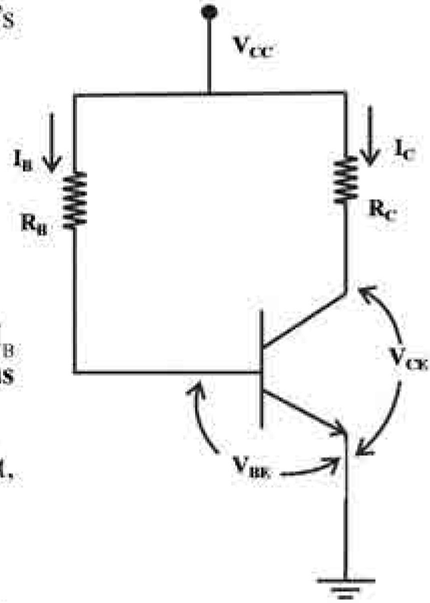


Fig. 8.3.e Circuit of Fig. 8.3.d redrawn with a single voltage source.

Considering the output side of the circuit, $V_{CC} = I_C R_C + V_{CE}$

$$\text{So } I_C = (V_{CC} - V_{CE}) / R_C$$

The supply voltage, V_{CC} and R_B fix the value of I_B and hence I_C ($I_C = \beta I_B$). Once I_C is fixed, V_{CE} is also fixed (see equation) . Now both I_C and V_{CE} are fixed and hence the operating point is also fixed. In this way, the transistor can be placed in the active region of operation by choosing appropriate values of V_{CC} and R_C.

But the fixed biasing has the following disadvantages

1) The operating point depends on beta of the transistor
2) It cannot stop thermal runaway.

These two cases are explained below.

Flow of collector current produces heat in the collector junction. This increases the temperature. Hence more minority carriers are generated in CB junction. This increases the reverse leakage current and hence the collector current. As the collector current increases, it will again result in an increase in collector current. This process goes on and finally, the temperature at the collector junction increases to such an extent causing the junction to breakdown. This process is called thermal runaway. The biasing configuration shown in Fig. 8.3.f avoids thermal runaway. Moreover in this configuration, dependence of I_C and V_{CE} on beta of the transistor is reduced considerably. This is desirable since if they are dependent on beta, as I_C and V_{CE} change, the operating point is also varied. Beta varies from transistor to

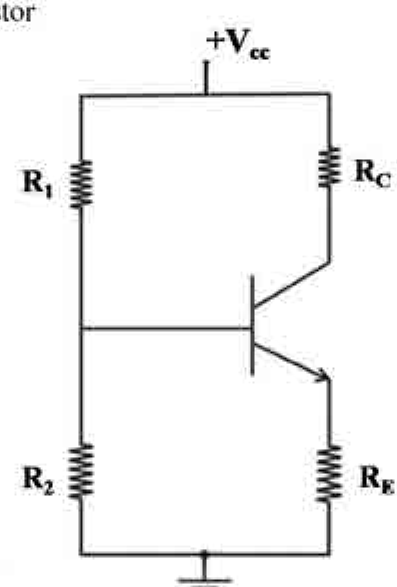


Fig. 8.3.f Voltage divider biasing circuit

transistor. It also varies with temperature and with the value of the collector current.

Fig. 8.3.f shows a voltage divider or potential divider network.

Voltage Divider biasing circuit

Voltage divider biasing circuit is the most widely used biasing circuit. Compared to the fixed biasing circuit, voltage divider biasing circuit contains an additional resistor R_2 between the base and the ground. R_1-R_2 forms the potential divider circuit. By suitably selecting the values of R_1 and R_2 the operating point of the transistor can be fixed.

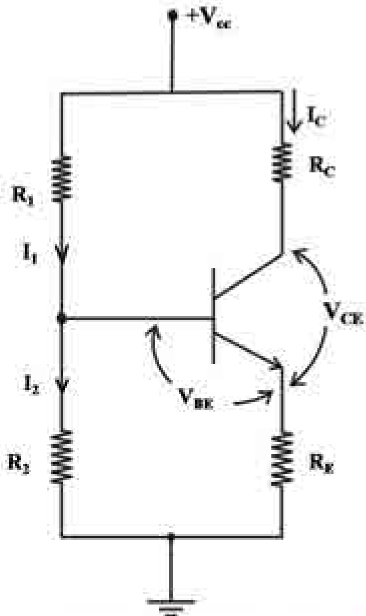


Fig. 8.4 Voltage divider biasing circuit with various currents and voltages shown

I_1 is the current through R_1 and I_2 is the current through R_2. The base current I_B is very small. Therefore $I_1 = I_2 + I_B$ and since I_B is very small and can be neglected $I_1 = I_2$

Considering the input side as in Fig. 8.4,

$$I_1 = I_2$$

Applying ohm's law to the input circuit, $V_{CC} = I_1(R_1+R_2)$

or

$$V_{CC} = I_2(R_1 + R_2)$$

Voltage drop across $R_2 = V_B = V_{CC} \times (R_2 \div (R_1 + R_2))$

$$\mathbf{V_B = V_{CC} \times (R_2 \div (R_1 + R_2))} \text{ .... } \mathbf{(1)}$$

$$\text{But } V_B = V_{BE} + V_{RE}$$

$$\mathbf{V_{RE}} = \mathbf{V_{CC}} \times \frac{R_2}{R_1 + R_2} - V_{BE}$$

$$I_E = V_{RE}/R_E$$

Since I_c is approximately equal to I_E

$$\mathbf{I_C = V_{RE}/R_E} \text{ .... } \mathbf{(2)}$$

Considering the output side,

$$V_{CC} = I_C R_C + V_{CE} + V_{RE}$$

$$V_{CC} = I_C R_C + V_{CE} + I_E R_E$$

$$V_{CC} = I_C R_C + V_{CE} + I_C R_E$$

$$V_{CC} = I_C(R_C + R_E) + V_{CE}$$

$$\mathbf{V_{CE} = V_{CC} - I_C(R_C + R_E) \ldots\ldots\ldots\ (3)}$$

From equations 2 and 3, it can be seen that I_C and V_{CE} are independent of beta. Thus the operating point remains where it is fixed. Also changing the transistor does not affect the operating point. Due to these reasons potential divider biasing circuit is also called the universal biasing circuit.

Now let us discuss the effect of the emitter resistor R_E. It avoids thermal runaway by reducing the collector current that occurs due to temperature rise. When I_C increases, I_E also increases, thereby increasing V_{RE}

$$V_B = V_{BE} + V_{RE}$$

Since V_B is a constant as seen in eqn (1), increase in V_{RE} results in a decrease in V_{BE}. This results in a decrease in I_B, which in turn reduces I_c. Thus I_C is not allowed to rise to a high value causing a rise in temperature in the collector junction. Thus thermal runaway is avoided.

Solved problem 8.1

For the circuit in Fig.8.4 find V_{CE} and V_E values neglecting the value of V_{BE}. Given R_1=10 kΩ, R_2=5 kΩ, R_E=10 kΩ, R_C=5 kΩ

$$V_E = V_B - V_{BE}$$

$$V_E = V_B \text{ (if } V_{BE} \text{ is neglected)}$$

Voltage at the emitter, $V_E = V_{CC} \times (R_2 \div (R_1 + R_2)$

$$= 15 \times \frac{5k}{15k}$$

$$= 5V$$

$$I_E = V_E/R_E$$

$$= 5/10K$$

$$= 0.5mA$$

$$I_C = I_E = 0.5mA$$

$$V_{CE} = V_{CC} - I_E(R_E + Rc)$$

$$= 15 - (0.5 \times 15) = 7.5V$$

Activity 1

Calculate the DC bias voltages and currents for the potential divider biasing circuit shown in fig.8.4 in which R_1=40 kΩ, R_2=5 kΩ, Rc=5 kΩ, RE=1 kΩ, V_{CC} =12 V, V_{BE}= 0.3 V, Ω= 100. Verify these values using a voltmeter and ammeter.

8.4 FIXING THE OPERATING POINT

In order to work as an amplifier, the operating point of the transistor should be in the active region. Now let us discuss how to fix the operating point so as to get the best performance. Consider three different points A,B,C in the load line of the output characteristics of a CE configuration shown in Fig. 8.5.a

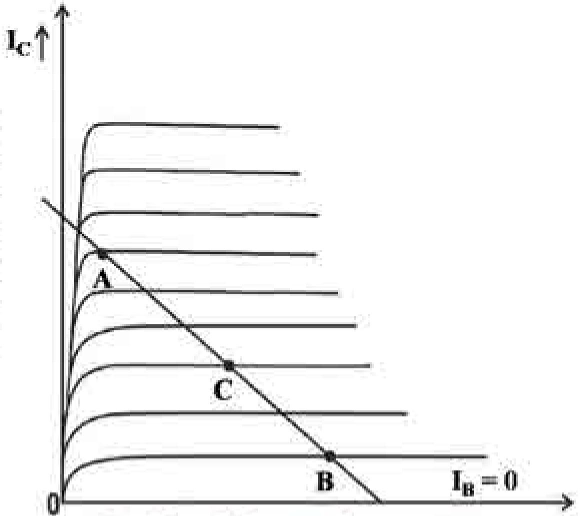


Fig. 8.5.a CE output characteristics showing the load line and operating points A, B and C

Case 1: Operating point in the middle of the active region (point C)

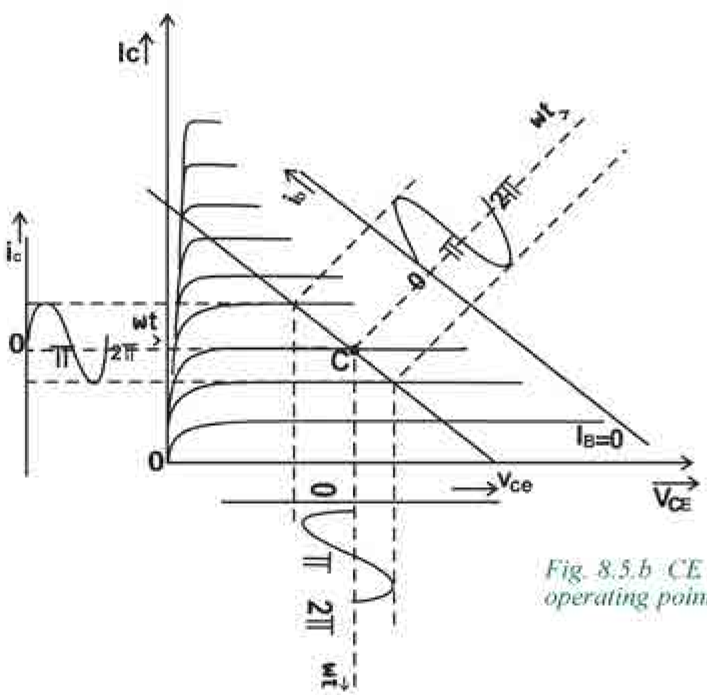


Fig. 8.5.b CE output characteristics showing operating point in the middle of the load line.

in Fig.8.5b it can be seen that the operating point 'C' is in the middle of the load line. The variation of I_B due to the input signal is shown in the graph of i_b in the figure.

The corresponding changes in I_C and V_{CE} can be observed. Since the output voltage is proportional to I_C, the output signal will vary in the same manner. That means the output signal will have the same shape as the input signal. Since the operating point is in the middle, I_B, I_C and V_{CE} can swing in both the directions to the maximum possible range. Now let us see what happens if it is not in the middle.

Case 2: Operating point near the saturation region (point A)

In Fig 8.5.c, it can be seen that the waveform of i_c is clipped. Hence the output waveform is also clipped. The wave shape of the output signal is not sinusoidal or in other words, it is distorted. For small input signals there may not be any distortion. But if we compare with Case 1, it is clear that the maximum swing is not possible.

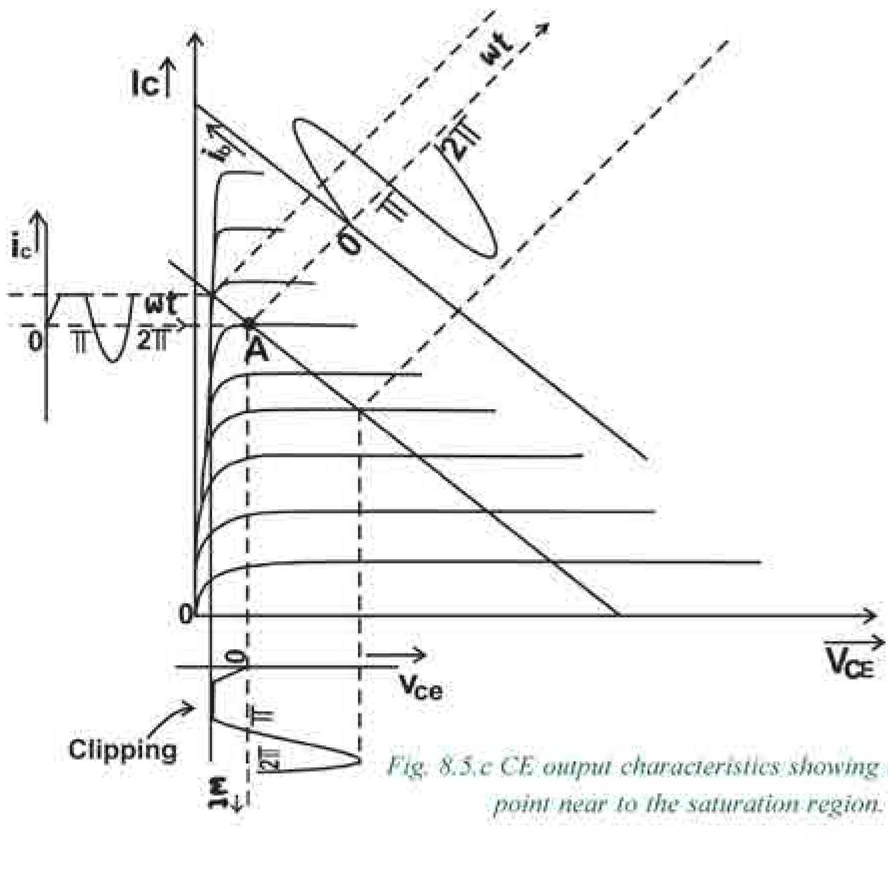


Fig. 8.5.c CE output characteristics showing operating point near to the saturation region.

Hence A is not a suitable operating point for amplification.

Case 3: Operating point near the cut off region (point B)

As in Case 2, it can be understood from Fig 8.5.d that the output signal will be clipped. Maximum swing is not possible in this case also. Hence B is also not a suitable operating point for amplification.

From the above discussions, it is clear that the most suitable position of the operating point is around the middle point of the load line. At this point V_{CE} is half V_{CC} as seen in Fig 8.5.b.

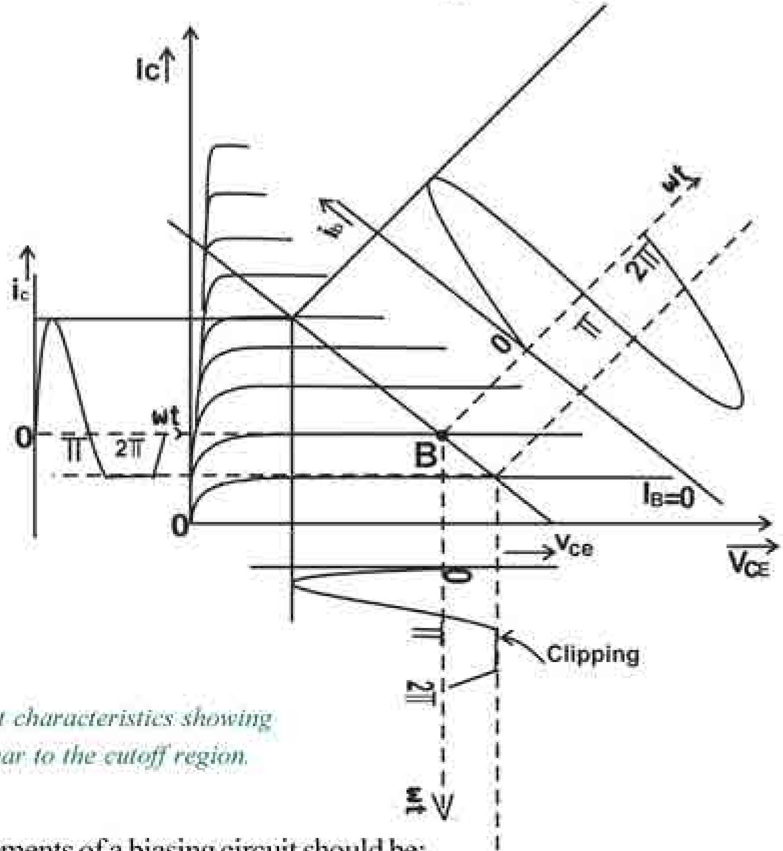


Fig. 8.5.d CE output characteristics showing operating point near to the cutoff region.

So the main requirements of a biasing circuit should be:

1. To establish the operating point at the center of the active region so that on applying the input signal, the instantaneous(varying) operating point does not shift towards saturation or cut off.
2. To stabilize the collector current against temperature variations.
3. To make the operating point independent of transistor parameters so that the operating point does not shift when the transistor is replaced by a new one.

8.5 SINGLE STAGE RC COUPLED AMPLIFIER

We have now understood how we can bias a transistor for working as an amplifier. Now let us discuss the circuit diagram of an amplifier. A typical amplifier circuit is shown in Fig. 8.6.

The input signal to be amplified is given between the base emitter junctions. The output voltage is taken from the collector terminal. C_b is used to couple the AC input signal to the base. At the same time it ensures that, biasing is correctly maintained. In the absence of C_b DC bias voltage at the base will reduce drastically, since it gets grounded through the source (source resistance is very low) . C_c acts as a coupling capacitor giving the AC voltage to the output (or next stage) blocking the DC components.

As we have seen already R_E is a stabilizing resistor that prevents thermal runaway by developing a voltage whose polarity is opposite to the forward bias applied to the base. In the absence of AC input signal, the variation in the collector current is due to temperature variations. Change

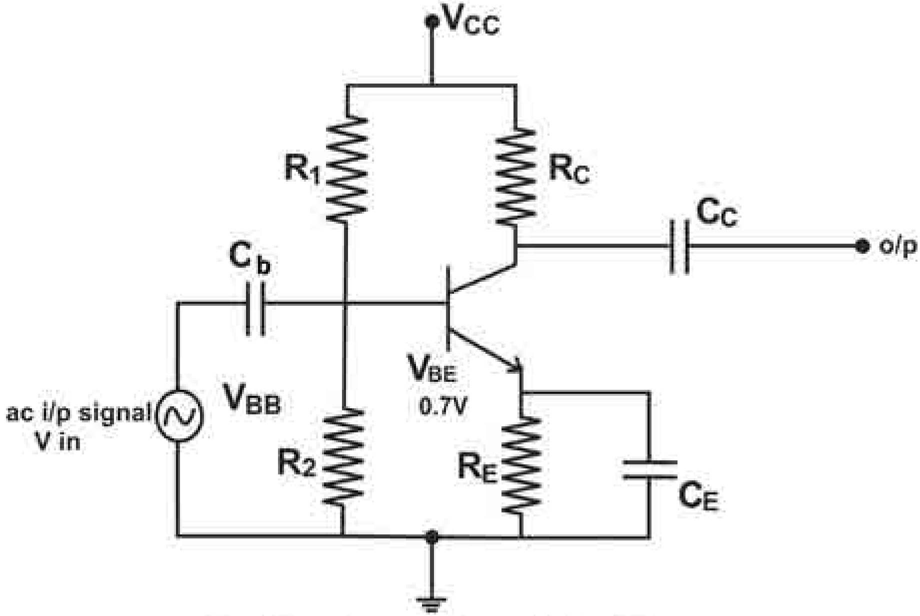


Fig. 8.6 Single stage RC coupled amplifier

in DC bias voltage due to this is prevented by the voltage V_E, developed across R_E. The input voltage to transistor base $V_{BE} = V_B - V_E$. When the value of V_E is increased, the input voltage to transistor base is reduced which reduces the collector current. Thus any unwanted variation in collector current is suppressed by the presence of R_E. At the same time the collector current variations due to an input signal which is necessary for amplification will also be reduced by the effect of R_E. This will reduce the output voltage and in turn the gain of the amplifier. To prevent this we place a capacitor C_E across R_E. As we know, a capacitor offers only a low impedance to AC. The effective emitter resistance is thus very low for AC. That means C_E will prevent AC voltage developing across R_E which would otherwise oppose the input signal voltage and reduce the gain of the amplifier. At the same time for DC it acts as an open circuit and will not affect the DC bias. C_E thus bypasses the AC components without being dropped across R_E. Hence it is called bypass capacitor. The output of the amplifier is coupled with to the load using the coupling capacitor C_C and the collector resistor R_C, hence the name RC coupled amplifier.

Gain

The expression for voltage gain of a CE amplifier is

$$\text{Voltage gain, A} = \frac{\text{Output voltage } (V_{out}) \text{ at the collector terminal}}{\text{Input voltage } (V_{in})}$$

$$= i_c.R_C / i_b.R_i$$

But $R_i = \beta\, r_e$ and $i_c = \beta\, i_b$

where R_C is the resistance connected in the collector terminal and r_e is the emitter diode resistance.

$$\text{Therefore A} = R_C / r_e$$

$$r_e = 26\text{mV}/I_C \text{ (approximately)}$$

Gain of an amplifier is usually expressed in decibel (dB).

$$\text{Gain in dB} = 20 \log_{10} (V_{out}/V_{in}) = 20 \log_{10} (A)$$

Solved problem 8.2

If the gain of an amplifier is 10, find the gain in dB

$$\text{Gain in dB} = 20 \log_{10} \frac{V_2}{V_1} = 20 \log_{10} 10$$

$$= 20 \times 1 = 20 \text{ dB}$$

Activity 2

Set up a single stage transistor amplifier circuit using the following components and analyze the results obtained.

R_1 = 33 kΩ

R_C = 1.5 kΩ

R_2 = 3.3 kΩ

R_E = 330 kΩ

C_{in} = 10 μF

Cc = 10 μF

C_E = 100 μF

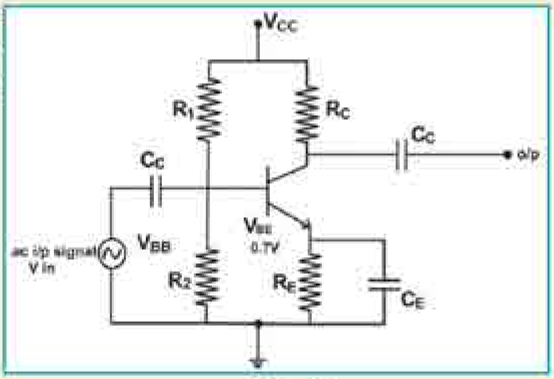


Fig. 8.7

1. *Measure the collector current and collector to emitter voltage using CRO.*
2. *Measure the maximum signal voltage that can be amplified by the amplifier without having clipped output.*
3. *Measure the voltage gain of the amplifier at 1kHz.*
4. *Measure the voltage gain of the amplifier for different values of load resistor R_L.*

DECIBEL SYSTEM

Logarithmic scale is used to compare two powers. This is because an individual's seeing or hearing power varies non linearly. The number of bels by which a power P_2 exceeds power P_1 is defined as

$$\text{Number of bels} = \log_{10} \frac{P_2}{P_1}$$

Decibel is a smaller unit than bel;, decibel is one – tenth of a bel

$$\text{Number of dB (decibel)} = 10 \times \text{Number of bels}$$

$$= 10 \log_{10}\left(\frac{P_2}{P_1}\right) \text{dB}$$

For an amplifier P_1 represents the input power and P_2 the output power. If V_1 and V_2 are the input and output voltage of the amplifier

$$P_1 = \frac{V_1^2}{R_1}$$

$$P_2 = \frac{V_2^2}{R_1}$$

R is the resistance across which the power is developed.

$$\therefore \text{Number of dB} = 10 \log_{10} \frac{V_2^2/R}{V_1^2/R}$$

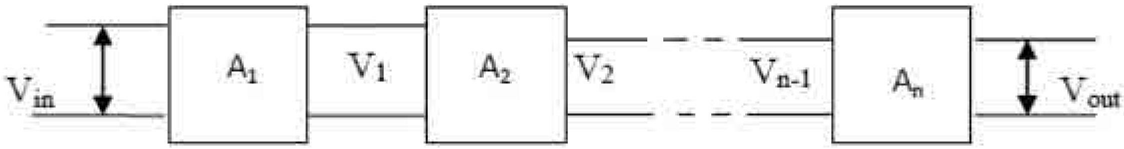
$$\therefore 10 \log_{10} \frac{V_2^2}{V_1^2} = 2 \times 10 \log_{10} \frac{V_2}{V_1}$$

$$= 20 \log_{10}\left(\frac{V_2}{V_1}\right) = 20 \log_{10}(\text{Voltage gain})$$

$$\text{or (Voltage gain) dB} = 20 \log_{10}(\text{Voltage gain})$$

8.6 MULTISTAGE AMPLIFIER

A single stage amplifier may not be sufficient to provide the desired gain in certain cases. To increase the gain more than one stage can be connected in series (cascaded). Such a cascade of amplifiers is known as a multistage amplifier or cascaded amplifier.



$V_1 = A_1V_{in}, V_2 = A_2V_1, \ldots\ldots\ldots, V_{out} = V_{n-1}A_n$

Fig. 8.8 Multistage Amplifier

Overall voltage gain $A = A_1.A_2\ldots\ldots\ldots A_n$ where $A_1, A_2, \ldots\ldots\ldots, A_n$ represent the individual amplifier gains

Gain of Multistage amplifier in dB

$$20 \log_{10} A = 20 \log_{10} A_1 + 20 \log_{10} A2 + \ldots\ldots\ldots + 20 \log_{10} An$$

$$\therefore A_{(dB)} = A_{1(dB)} + A_{2(dB)} + \ldots\ldots + A_{n(dB)}$$

Solved problem 8.3

A multistage amplifier consists of three stages with voltage gain 30,50 and 80 respectively. Calculate the overall voltage gain in dB.

Overall gain $A_{(dB)} = A_{1(dB)} + A_{2(dB)} + A_{3(dB)}$

$A_{1(dB)} = 20 \log_{10} 30 = 29.54$ dB.

$A_{2(dB)} = 20 \log_{10} 50 = 33.98$ dB

$A_{3(dB)} = 20 \log_{10} 80 = 38.06$ dB

$A_{(dB)} = 29.54 + 33.98 + 38.06$

$= 101.58$ dB

Alternatively,

$A = A_1 \times A_2 \times A_3$

$= 30 \times 50 \times 80$

$= 120000$

$\therefore$ Overall voltage gain in dB $= 20 \log_{10} 120000$

$= 101.58$ dB

8.7 FREQUENCY RESPONSE OF AN AMPLIFIER

Frequency response gives the response of the amplifier for different frequencies. It is indicated in a graph with frequency along x-axis and voltage gain along y-axis. Fig. 8.9.a shows the typical frequency response curve of a single stage RC coupled amplifier.

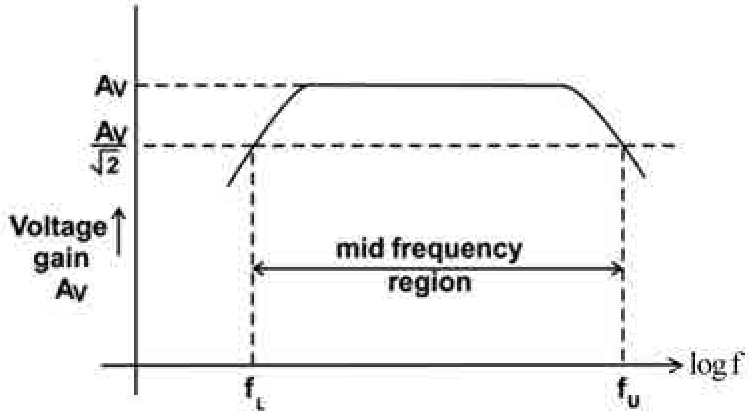


Fig. 8.9.a Frequency response of amplifier

From the frequency response curve it can be seen that the gain remains constant only at mid frequencies. Gain decreases at low and high frequencies. Mid frequency region is defined as the range of frequencies between lower cut off frequency (f_L) and upper cut off frequency (f_U).

The lower and upper cut off frequencies are defined as those frequencies where power gain of the amplifier decreases to half the mid frequency gain. These points are also called half power points. In decibels, the power decreases by 3dB. Correspondingly at half power points, the voltage gain falls to $\frac{1}{\sqrt{2}}$ (or 0.707) of the mid frequency gain.

Bandwidth

The mid frequency range of an amplifier is specified by the parameter bandwidth. It is the difference between the cut off frequencies f_U and f_L. The bandwidth specifies the range of frequencies over which the amplifier can provide constant gain.

Fall of gain at low frequencies

The coupling and bypass capacitors are provided to offer almost zero impedance to AC signals. In other words they should act as short circuit to AC. But capacitive reactance is inversely proportional to frequency.

$$X_C = \frac{1}{2\pi fC}$$

So as frequency decreases, the capacitive reactance increases. Hence they cannot be replaced by short circuits at low frequencies.

The input coupling capacitance offers a high reactance at low frequencies. Due to this a significant input voltage is dropped across the input coupling capacitance. Thus only a portion of the input signal to be amplified reaches the transistor base. This causes gain reduction at low frequency. Similarly the coupling capacitance connected at the output side also cannot couple the signal completely to the next stage. C_E which is used to bypass R_E also cannot do the bypassing action effectively due to its high reactance to AC. This causes a voltage drop across R_E resulting in gain reduction.

Fall of gain at high frequencies

We know that the depletion layer is formed in the base emitter and the base collector junctions. The depletion layer does not have any charge carriers, where as in either side of the region there are charge carriers. This results in a capacitive effect.

Capacitance C_{bc} between the base and the collector connects the output with the input Fig. 8.9.b. At low frequencies, since the reactance is high it is almost an open circuit and hence there is no effect. But at high frequencies since the capacitive reactance is small, it provides a conducting path between the input and the output. This will effectively reduce the input and there by the gain.

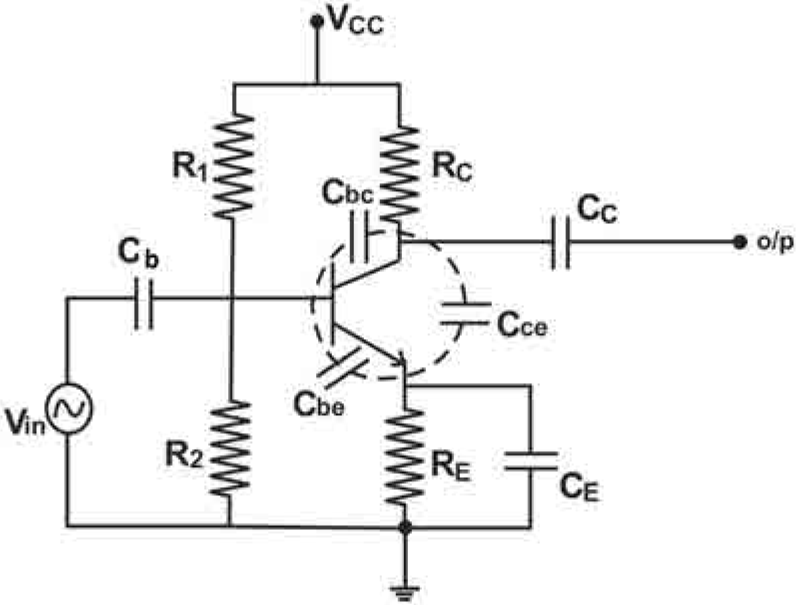


Fig. 8.9.b Diagram showing junction capacitances at high frequencies.

Activity 3

Set up a single stage RC coupled amplifier referring fig. 8.7 and

1. ***Measure the Q point values using CRO.***
2. ***Measure the voltage gain of the amplifier for different frequencies like 200 Hz, 600 Hz, 1 kHz, 1500 Hz, 2 kHz, 3 kHz, 1 MHz etc.***
3. ***Plot the frequency response curve.***
4. ***Measure the bandwidth.***

Based on the frequency of operation, amplifiers can be broadly classified as audio frequency amplifier, radio frequency amplifier and video amplifier. Audio frequency amplifier is for frequencies between 15 Hz and 20 kHz, radio frequency amplifier for frequencies between 10 kHz and 1000 GHz and video amplifier for frequencies between DC to 6 MHz.

Check your progress

- ***Specify the significance of frequency response curve in the design of amplifiers.***

8.8 AUDIO POWER AMPLIFIERS

As the name implies, audio amplifiers are used to amplify the audio signals. It is an essential component in public address systems, radio, tape recorder, TV etc. The RC coupled amplifier we have discussed, can be used as an audio amplifier. As we have seen, it is a voltage amplifier. In many systems, we need multistage amplifier to get the desired gain. The initial stages will be voltage amplifiers, whereas the final stage will be a power amplifier, so as to deliver the maximum power to the output device (eg. loud speaker).

Let us now look at a typical audio power amplifier that can be used at the final stage of a public address system (Fig. 8.10a). The output device connected to an audio amplifier is a loud speaker. The impedance of a typical loudspeaker is 8 ohms. So if it is connected directly the effective load resistance will be very low. This in turn makes the gain very low. This problem can be solved

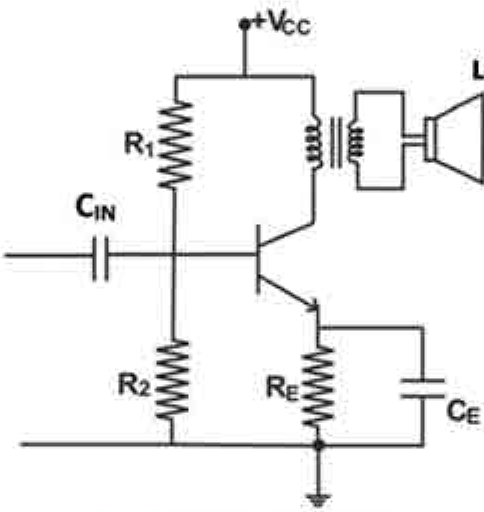


Fig. 8.10 (a) Power Amplifier

by using a transformer to couple the output to the loud speaker. This arrangement is hence called transformer coupled amplifier. The transformer functions as an impedance matching element, which converts the low impedance of the output device into an effective high impedance.

Figure shows the block diagram of a simple public address system (PA SYSTEM)

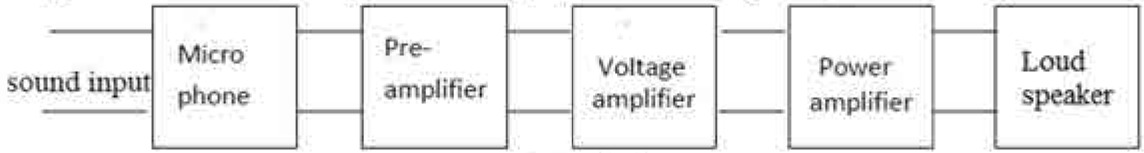


Fig. 8.10 (b)

8.9 OPERATIONAL AMPLIFIERS

Operational Amplifiers, or **Op-amps** as they are more commonly called, are one of the basic building blocks of analog electronic circuits. Operational amplifiers are devices used extensively for signal conditioning, filtering and for performing mathematical operations such as addition, subtraction, multiplication, division, integration and differentiation. It consists of several circuits, with many stages of amplification, built specifically to attain ideal characteristics required for an amplifier on a single silicon chip. The main characteristics of an op-amp are

- Very high gain (ideally infinite)
- Very high input impedance (ideally infinite) and very low output impedance (ideally zero)
- Very high bandwidth (ideally infinite)

An operational amplifier only responds to the difference between the voltages on its two input terminals, known commonly as the "*Differential Input Voltage*". Then if the same voltage is applied to both the terminals the resultant output will be zero. So a noise voltage which appears common to both inverting and non-inverting inputs can be eliminated.

An **Operational Amplifier** is a device which consists of two high impedance inputs, one called the **Inverting Input**, marked with a negative or "minus" sign, (-) and the other one called the **Non-inverting Input**, marked with a positive or "plus" sign (+) and one output.

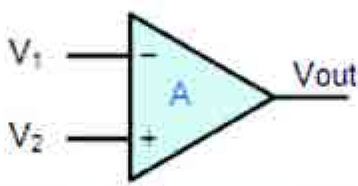
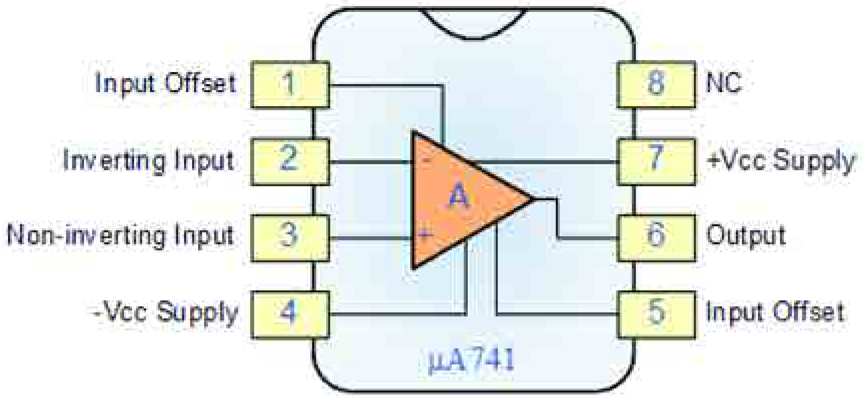


Fig. 8.11.a Symbolic representation of opamp

The input to the Op-amp can be given either to the inverting terminal or to the non- inverting terminal. If the input is given to the inverting terminal, the output will be inverted in comparison with the input, whereas when it is given to the non-inverting terminal, it will be in phase with the input.

741C is a popular operational amplifier which is an 8 pin IC.



Inverting Amplifier

When the Op-amp is used as inverting amplifier, the input signal is given to the inverting input. Now the output signal is 180° out of phase with the input signal.

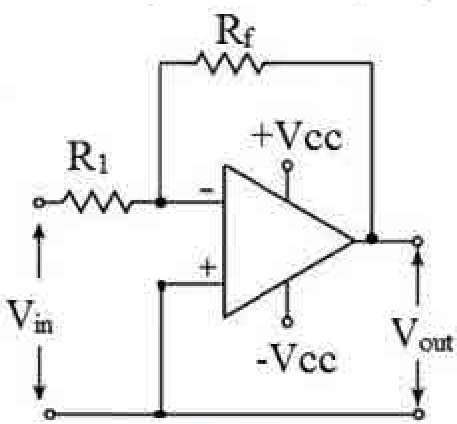


Fig. 8.11.b Inverting Amplifier Circuit

$$A = \frac{-R_f}{R_1}$$

Where A represents the gain of the inverting amplifier

Non Inverting Amplifier

When the Op-amp is used as non inverting amplifier, the input signal is given to the non inverting input. Now the output signal is in phase with the input signal.

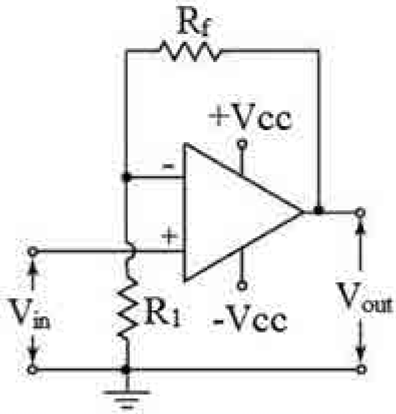


Fig. 8.11.c Non-Inverting Amplifier Circuit

The gain of the non-inverting amplifier is given by;

$$A = 1 + \frac{R_f}{R_1}$$

Activity 4

Set up an integrator Circuit and a differentiator circuits with R=1K and C= 0.02 μF. Set up a square wave of 1KHz frequency and 1V peak to peak value as input V_{in}.Observe the output waveform on the CRO.

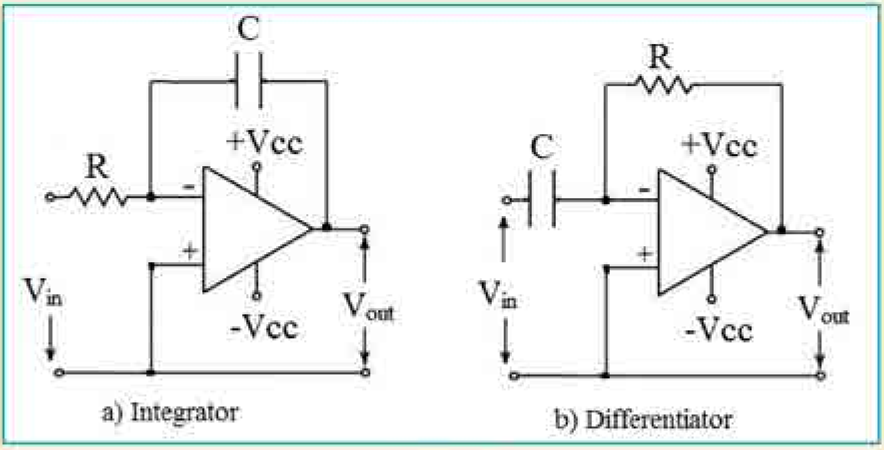


Fig 8.12

Check your progress

- ***Design an inverting amplifier for unit voltage gain***

Let us sum up

An amplifier is a device used to raise the strength of a weak signal. Amplifiers can be classified into voltage and power amplifiers. In voltage amplifiers the output resistance is much greater than the input resistance. CE configuration is commonly used due to its high voltage and current gain. When a transistor is used as an amplifier, the flow of I_C produces heat in the collector junction due to which more minority carriers are generated causing more reverse leakage current and hence more I_C. Thus the temperature of the collector junction increases and the junction breaks down. This process is called thermal runaway. The voltage divider bias with emitter resistor, avoids thermal runaway. In fixed bias circuit, once R_B is selected, I_B becomes fixed and $V_{CC} = V_{CE} + I_C R_C$. In voltage divider bias circuit, the equation for the output side is $V_{CC} = I_C R_C + V_{CE} + I_C R_E$. Here since dependence of I_C and V_{CE} on beta are reduced significantly, the operating point remains fixed and this circuit is also called universal biasing circuit. For the transistor to act as an amplifier, the operating point must be in the active region. The most suitable position of the operating point is at the middle of the load line where $V_{CE} = \frac{V_{CC}}{2}$. The gain of an amplifier in dB is $20 \log \frac{V_{out}}{V_{in}}$. If a number of amplifiers with gains $A_1, A_2, A_3 \ldots\ldots\ldots$ are cascaded, the gain of this multistage amplifier $A = A_1 \times A_2 \times A_3 \times \ldots\ldots$ and expressed in db is $A_{(dB)} = A_{1(dB)} + A_{2(dB)} + \ldots\ldots + A_{n(dB)}$. The response of an amplifier at different frequencies can be obtained using frequency response curve. From this curve, it can be seen that the gain remains constant only at mid-frequency region. i.e. the frequencies between the lower cut-off frequency (f_L) and the upper cut-off frequency (f_U). Thus the range of frequencies ($f_U - f_L$) over which the amplifier provides constant gain is called bandwidth. An Op-amp is a three terminal device consisting of two high impedance inputs i.e. inverting and non-inverting inputs. So it can be used as inverting and non-inverting amplifiers. Op-amp are extensively used for signal conditioning, filtering and for performing mathematical operations.

Learning outcomes

The learner is able to

- Explain the concept of amplification
- Point out the use of transistor as an amplifier
- Identify the need for biasing circuits in transistor amplifiers
- Draw the graph and thus explain the gain and frequency response of the amplifier

- Explain the reasons for gain reduction at low and high frequencies
- Point out the significance of operational amplifiers in linear circuits
- Draw the the Pin configuration of 741C
- Explain the importance of having operational amplifiers as amplifier circuits
- Draw the circuit diagrams and thus explain the inverting and non inverting configuration of 741C.

Evaluation items

Multiple choice questions

1) The transistor configuration which can't be used for voltage amplification is

a. CE configuration b. CB configuration
c. CC configuration d. All of these can be used

2) Which transistor configuration is most commonly used for amplification

a. CE configuration b. CB configuration
c. CC configuration d. None of these

3) The transistor biasing method which helps to avoid thermal runaway

a. Fixed bias b. Voltage divider bias
c. Collector to base bias d. Emitter to base bias

4) When voltage divider bias circuit is used

a. Operating point depends on current gain
b. Operating point shifts towards saturation region.
c. Operating point is independent of transistor parameters
d. Collector current varies as temperature raises

5) The gain of an amplifier is given by

a. $\log V_{out}/V_{in}$ b. $20 \ln V_{out}/V_{in}$
c. $20 \log V_{out}/V_{in}$ d. $\ln V_{out}/V_{in}$

6) The voltage gain of an ideal Op-amp is

a. Zero b. 100%
c. Infinite d. Cannot be predicted

7) The input impedance, output impedance and bandwidth of an ideal Op-amp are respectively

a. Infinite, zero, infinite
b. Zero, infinite, zero
c. Zero, zero, infinite
d. Infinite, infinite, zero

8) If A_1, A_2 and A_3 are the voltage gains of the three amplifiers which are cascaded then the overall voltage gain will be

a. $A_1 + A_2 + A_3$
b. $A_1 . A_2 . A_3$
c. $A_1 A_2 + A_1 A_3$
d. $A_1 A_2 A_3 / A_1 + A_2 + A_3$

9) When Op-amp is used as inverting amplifier the out signal is

a. In phase with the input
b. 90^o out of phase with input
c. 180^o out of phase with input
d. 270^o out of phase with input

10) Which of the following is also called universal bias circuit of an amplifier?

a. Fixed bias
b. Voltage divider bias
c. Emitter to base bias
d. Base bias

Answer Key

1) c 2) a 3) b 4) c 5) c 6) c 7) a 8) b 9) c 10) b

Descriptive type questions

1. Draw and explain the function of the fixed bias circuit used in amplifiers.
2. Compare fixed bias and voltage divider bias used in amplifiers. What are the advantages of voltage divider bias circuit?
3. What are the main requirements of a biasing circuit in an amplifier?
4. With a neat circuit diagram explain the working of a single stage RC coupled amplifier.
5. Draw the required curve and thus explain the frequency response of an amplifier.
6. Find an expression for the gain (in dB) of a multistage transistor amplifier.
7. Draw the circuit diagram and thus explain the inverting and non inverting configurations of an Op-amp.
8. Show that the most suitable position of the operating point of an amplifier is at the middle of the load line.
9. Classify amplifiers on the basis of their frequencies of operation.
10. What are the applications of Op-amp.

9 OSCILLATORS

INTRODUCTION

An electronic oscillator is a circuit that produces a repetitive, oscillating electric signal, often a sine wave or a square wave. Oscillators generate AC signals of different frequencies by drawing power from a DC power supply. Oscillators generate frequencies ranging from a few Hz to several MHz. They are mainly used in electronic communication circuits such as radio, television, RADAR etc. In various communication circuits, oscillators are used to generate high frequency signals to carry messages. Oscillators are often characterized by the frequency of their output signal.

- An audio frequency (AF) oscillator produces frequencies in the audio range (20Hz - 20kHz).
- A radio frequency (RF) oscillator produces frequencies in the radio frequency range. (100kHz -30MHz)

Square waves are generated with the help of multivibrators. The other wave forms such as triangular waves can be obtained by shaping the square waves.

9.1 ALTERNATING SIGNAL GENERATORS

We are familiar with the electric supply voltage provided in our houses which is of sine wave having a frequency of 50Hz. It is produced by an alternator (AC generator). An alternator is a mechanical device having rotating parts. It converts mechanical energy into electrical energy. But an alternator cannot produce very high frequencies, since the mechanical parts cannot be moved at a faster rate. An oscillator differs from an alternator in the following aspects.

1. An oscillator is not a mechanical device; so the operation is quite silent.
2. It can produce wide range of frequencies.
3. The frequency of the signal can be easily changed when required.

Activity 1

Find the frequencies of FM channels in your locality.

9.2 TYPES OF OSCILLATIONS

Sinusoidal oscillations can be damped or undamped. The electrical oscillations whose amplitude goes on decreasing with time are called damped oscillations see Fig 9.1 (a). This happens because the circuit in which oscillations are generated has ohmic losses and energy is being lost as oscillations are produced.

In undamped oscillations Fig 9.1 (b), the maximum amplitude of sine wave does not change with time. In this case, right amount of energy is being supplied to overcome the energy losses in the circuit. In electronic oscillators, an amplifier is used to supply energy to compensate the losses.

Have you ever thought about what the frequencies denoted by various FM and AM channels mean? They denote the frequency of the carrier signals used to carry the audio signals. The carrier is a high frequency signal used in a long distance communication where the message is added in the carrier (or modulated) for transmission. If the message is contained in the amplitude of the carrier it is Amplitude Modulation (AM) and if it is contained in the frequency, it is called Frequency Modulation (FM).

FM channels	Frequency
Ananthapuri FM	101.9 MHz
Kochi AIR FM	102.3 MHz
Kannur AIR FM	101.5 MHz

FM channels	Frequency
Thrissur AIR	630 KHz
Alappuzha AIR	550 KHz
Kozhikkode AIR	684 KHz

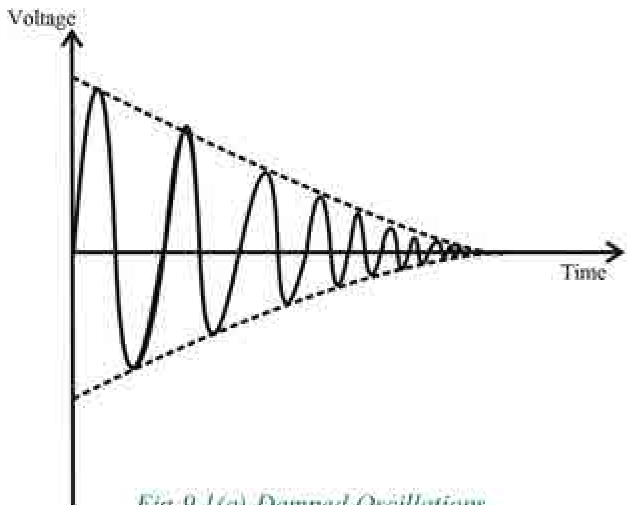


Fig 9.1(a) Damped Oscillations

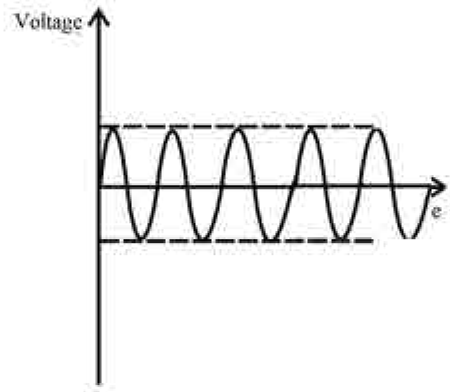


Fig 9.1(b) Undamped Oscillations

Activity 2

Take one long piece of rope and fix its one end. You hold its other end in your hand and move your hand up and down.

If you make only one move, then you can see oscillations in the rope and these oscillations die soon. It is an example of damped oscillation.

Instead of making one move, if you continuously move your hand up and down, you can see sustained oscillations in the rope. In this case you are giving energy continuously to keep the oscillations in the rope. These oscillations are undamped or sustained oscillations.

9.3 GENERATION OF SINE WAVES

In an electronic oscillator, the circuit which produces oscillations of any desired frequency is known as tank circuit. To understand the generation of oscillations, we shall have a look into the mechanical oscillations produced by a simple pendulum.

A pendulum consists of a mass (known as a *bob*) attached by a string to a pivot point. If we push the bob to one side the pendulum moves and it sweeps out a circular arc, moving back and forth in a periodic fashion (or it oscillates). During the oscillation, the bob goes to the extreme position at one side, stops there for a while and returns to the mean position. It does not stop at the mean position, but moves towards the other extreme position and returns from there to go to the previous extreme position. The oscillation continues in this way. The potential energy of the pendulum is maximum at the extreme positions but the kinetic energy is zero since the pendulum rests there for a while. When the bob returns from there, the potential energy decreases and kinetic energy increases and the kinetic energy is maximum at the mean position. The pendulum oscillates because of the energy transfer between potential and kinetic forms. The oscillations continue in this way for any long time and we get undamped oscillations if there is no loss of energy during this transfer. But due to air friction, the energy of the pendulum decreases and oscillation decreases or the amplitude of the oscillation decreases gradually and it dies out finally. If we give energy to compensate this loss, the oscillation becomes steady and we get sustained oscillations.

The oscillation produced in the tank circuit of an oscillator is analogous to the oscillation of the pendulum. In the LC tank circuit, the oscillations are produced when the energy changes between the magnetic and the electric forms. The magnetic energy is stored in the inductor and the electric energy is stored in the capacitor. The working of the tank circuit is discussed in the next section.

Tank circuit

An LC circuit, also called a resonant circuit, tank circuit, or tuned circuit, consists of an inductor L and a capacitor C (fig 9.2). When connected together, they can act as an electrical resonator. LC circuits are used either for generating signals at a particular frequency, or picking out a signal at a particular frequency from a more complex signal. They are the key components in the LC oscillators.

The LC circuit we have discussed is an idealized model since it is assumed that, there is no dissipation of energy due to resistance. But the practical implementation of an LC circuit always includes loss of energy resulting from a small but non-zero resistance within the components (L and C) and connecting wires. The purpose of an LC circuit is usually to oscillate with minimal damping, so the resistance is made as low as possible. The operation of a tank circuit is explained below.

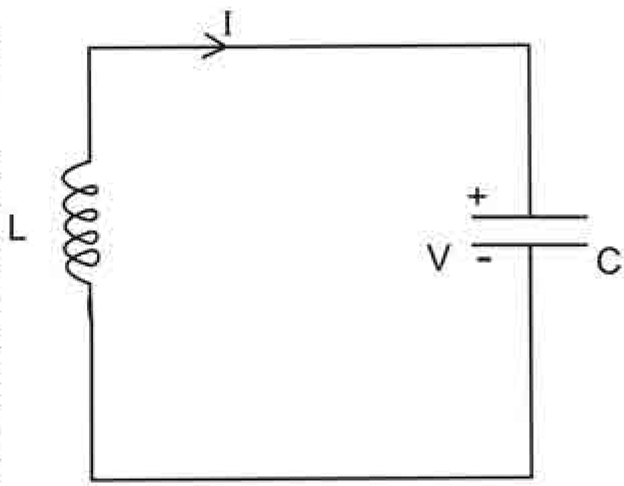


Fig. 9.2 Tank circuit

The capacitor stores energy in its electric field E and the inductor stores energy in its magnetic field B. If a charged capacitor is connected across an inductor, charge will start to flow through the inductor, building up a magnetic field around it. The voltage across the capacitor decreases due to the discharging of the capacitor. Eventually all the charge on the capacitor is lost and the voltage across it reaches zero. However, the current continues to flow, because the inductors resist changes in current. The energy to keep the current flowing is extracted from the magnetic field. So the magnetic field begins to decline. As current flows, the capacitor will start charging, developing a voltage of opposite polarity. When the magnetic field is completely dissipated, the capacitor will be fully charged. The capacitor now starts discharging and the current flows charging the magnetic field. Then the cycle will begin again, with the current flowing in the opposite direction.

The charge flows back and forth between the plates of the capacitor, through the inductor. The energy oscillates back and forth between the capacitor and the inductor. These oscillations gradually decrease, as the energy is lost in the internal resistances and the oscillations die out soon. This action is similar to a pendulum swinging back and forth. The frequency of oscillations generated in the tank circuit is the resonant frequency of the LC circuit. If we plot the variation of the current in the inductor or the variation of voltage across the capacitor with respect to time, we get a sinusoidal graph. This changing voltage or current is the output of the oscillator.

Similar to the air friction that causes loss of energy during the oscillation of the pendulum, the electrical resistances of the inductor and the capacitor cause loss of energy in electronic oscillator. In order to get sustained oscillation, we need to supply energy continuously to the system. We give this energy to a pendulum in the form of regular external push, whereas it is given to an oscillator with the help of an amplifier in the circuit.

Basically we have two types of oscillators. They are LC oscillators and RC oscillators. An oscillator has two parts - an amplifier and a feedback network. If the feedback circuit is an LC circuit, the oscillator is called LC oscillator and if the feedback circuit is an RC circuit, the oscillator is called an RC oscillator.

The generation of oscillations in RC oscillators will be discussed later in this unit after studying the Barkhausen criterion for oscillations.

Frequency Selectivity

You might have heard about tuning of the radio. We can select programs from different radio stations by tuning them. Such tuner circuits have frequency selectivity. The ability of a circuit to select a signal of a particular frequency from a group of large number of signals having different frequencies is known as frequency selectivity. An LC tank circuit is a tuner which can select a frequency which is equal to its resonant frequency.

How is a particular frequency selected by an LC circuit? It is explained below.

The total impedance of LC circuit is given by

$$Z = R + j\,(X_L - X_C)$$

where R is the total internal resistance of the inductor and the capacitor.

X_L is the reactance of the inductor.

X_C is the reactance of the capacitor.

Now the impedance of the circuit is minimum or the current in the circuit is maximum when X_L is equal to X_C. So Z = R. Thus at a particular frequency for which X_C becomes equal to X_L, the circuit produces maximum response or current. This frequency is known as resonant frequency. In this condition, the circuit is said to be in resonance. For other frequencies, the response of the circuit will be less. The tank circuit thus selects its resonant frequency from all other frequencies by providing maximum response to this frequency. At resonant frequency,

$$X_L = X_C$$

$$2\pi f_o L = 1/(2\pi f_o C)$$

$$\text{we get, } f_o = \frac{1}{2\pi\sqrt{LC}}$$

It is seen that different frequencies can be selected by varying the value of L or C. Usually C is varied with a variable capacitor and this process is called tuning.

An LC oscillator has an LC tank as its feedback circuit. When the DC power supply of the oscillator is switched ON, a very large number of different frequencies are produced in the circuit (refer the content given in the box). The LC tank circuit of the oscillator is a resonant circuit and it selects only one frequency which is equal to its resonant frequency from these different frequencies. This frequency will be amplified by the amplifier and sustained oscillation of that particular frequency is obtained. Thus frequency of oscillation is determined by the LC tank circuit.

A sudden change in voltage contains a large number of sine waves having different amplitudes and different frequencies. These frequencies occur as harmonics. The frequencies range from a few Hz to several MHz.

Consider that a voltage source of 10V is switched ON, the voltage changes suddenly from 0V to 10V as shown below in fig 9.3(i).

Fig. 9.3

Similarly, a sudden voltage change occurs when the power supply is switched OFF as shown in Figure 9.3 (ii).

Such sudden voltage transitions contain infinitely large number of sine waves of varied frequencies and amplitudes.

The LC oscillators are not used for generating low frequencies below 20KHz.Why?

The frequency of oscillation of an LC oscillator is given by

$$fo = 1/2\pi\sqrt{LC}$$

They are good for generating high frequencies. But for low frequencies, (say audio frequencies), the LC oscillators are impractical since high value of inductance and capacitance is required according to the above equation. The size of the inductor and the capacitor are very large, if the value is high. In this case RC oscillators are suitable, since large value resistance is not large in size. Also with the advancement of IC technology, RC oscillators are more feasible since it is very difficult to make large value inductance in ICs. Therefore RC oscillators are becoming increasingly popular.

9.4 CONCEPT OF FEEDBACK

Feedback is the process of providing a fraction of output back to the input of a system. It is used to control or improve the performance of the system. In electronic circuits, we use two types of feedback - positive feedback and negative feedback. In positive feedback, the feed back voltage is in the same phase as that of the input voltage and hence when it is added, the effective input increases. On the other hand, in the negative feedback, the feed back voltage has a phase difference of 180^0 with input voltage and hence when it is added, the effective input decreases.

Positive Feedback

In Figure 9.4, the amplifier has gain 'A' and the feedback factor is 'β'. Now a part of the

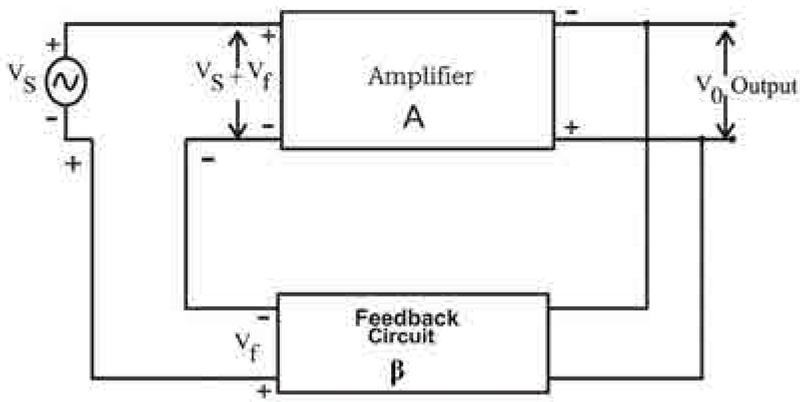


Figure 9.4 Positive Feedback

output voltage is taken back to the input side so that this feedback voltage V_f supports the actual input signal V_s. Note the polarity of the signals V_f and V_s. Now the input of the amplifier is

$V_s + V_f$. The type of feedback here is positive feedback.

Activity 3

Analyze Figure 9.4 and note the difference in gain without feedback and with positive feedback.

Without feedback

Input voltage = V_S

Output voltage , $V_O = A\ V_S$

With feedback

Input voltage = $V_S + V_f$

Output voltage, $V_O = A\ (V_S + V_f)$

It is clear that the output voltage is greater with feedback. In other words we can say that the positive feedback given has resulted in the increase in the gain of the amplifier system. Positive feedback is mainly used in oscillators for obtaining sustained oscillations.

Negative Feedback

Here the feedback voltage V_f opposes the input signal V_S. Note the polarities of the voltages V_S and V_f (V_f is 180^0 out of phase with V_s, hence negative polarity). Now the effective input to the amplifier is V_S - V_f. This type of feedback is known as negative feedback.

The input voltage without feedback is V_S and the corresponding output voltage is $V_O = AV_S$. With feedback, the effective input voltage is V_S - V_f. So the output voltage is $V_O = A\ (V_S - V_f)$.

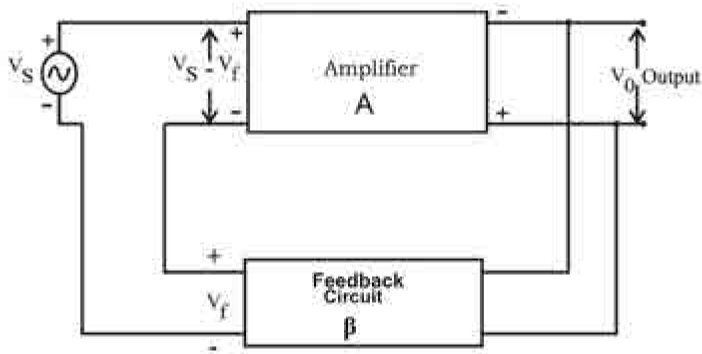


Fig. 9.5 Negative Feedback

Clearly the output voltage decreases when there is a negative feedback in the system. In other words the negative feedback reduces the gain of the system. Negative feedback is mainly used in amplifiers to reduce the noise effects and to increase the band width.

9.5 BARKHAUSEN CRITERION FOR OSCILLATION

Consider the block diagram of an oscillator containing amplifier and feedback circuit.

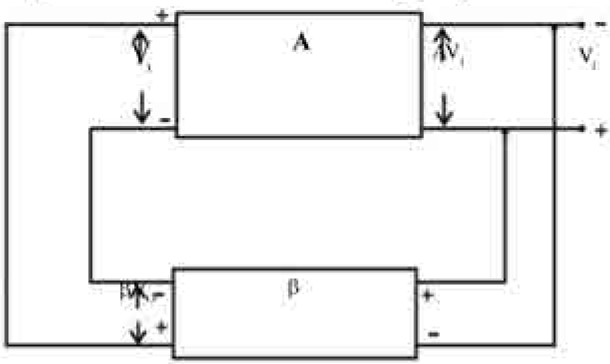


Fig. 9.6 Block diagram of an oscillator

The gain of the amplifier is A and the gain of the feedback network (or feedback factor) is β. We know that an oscillator generates an AC signal, taking energy from a DC source voltage. It does not require any AC input signal. Then from where does the oscillator get sine wave? As we have discussed in section 9.4, when the DC voltage source is switched ON, the voltage change or voltage spike is the source of sinusoidal oscillation.

From Figure 9.6, we can see that a fraction of the output voltage βV_O reaches the input of the amplifier as V_i.

Thus we have $V_O = AV_i$

$$V_i = \beta V_O$$

$$\text{or } V_O = AV_i = A\beta V_O$$

This is possible only if $A\beta = 1$.

If the output of the system has to remain constant at V_O with time (sustained oscillation), then $A\beta$ should be unity.

What happens if $A\beta$ is not unity?. We shall discuss it with an example. Consider that at a particular time, the output sine wave of the oscillator has an amplitude of 1V.

Case I, $A\beta < 1$

Take $A\beta = 0.8, A = 2, \beta = 0.4$ (see Figure 9.6)

If $V_O = 1$

Input $V_i = \beta V_O = 0.4 \times 1 = 0.4V.$

Now output voltage Vo $= Vi \times A = 0.4 \times 2 = 0.8$

ie output voltage is decreased from 1V to 0.8V

What happens next?

Now $V_O = 0.8$ volts.

$V_i = \beta V_O = 0.4 \times 0.8 = 0.32V$

So output $V_O = 2 \times 0.32 = 0.64.$

In this way, the amplitude of the output voltage continuously decreases and after some time the oscillations die out. Such an oscillation is called a damped oscillation. Refer Figure 9.7 (a).

Case II, $A\beta > 1$

Take $A = 2, \beta = 0.6$ or $A\beta = 1.2$ (see Figure 9.6)

we have output $V_O = 1$volt.

So the input $V_i = \beta V_O = 0.6 \times 1 = 0.6V$

Now output $V_O = AVi = 2 \times 0.6 = 1.2V$

Now output voltage is increased from 1V to 1.2V. What happens next?

Now $V_O = 1.2V$

Input $V_i = \beta V_O = 0.6 \times 1.2 = 0.72V$

So output $V_O = AVi = 2 \times 0.72 = 1.44V$

In this way the amplitude of the output voltage continuously grows and such oscillations are called growing oscillations. Refer Figure 9.7 (b)

Case III, $A\beta = 1$

Take A = 2, = β0.5

we have $V_O = 1v$

So the input $V_i = \beta V_O = 0.5 \times 1 = 0.5v$

With this input, output $V_O = AV_i = 2 \times 0.5 = 1v$

We see that the output voltage remains the same in this case and such oscillations are called sustained oscillations. Refer Figure 9.7 (c). We need sustained oscillation at the output of an oscillator.

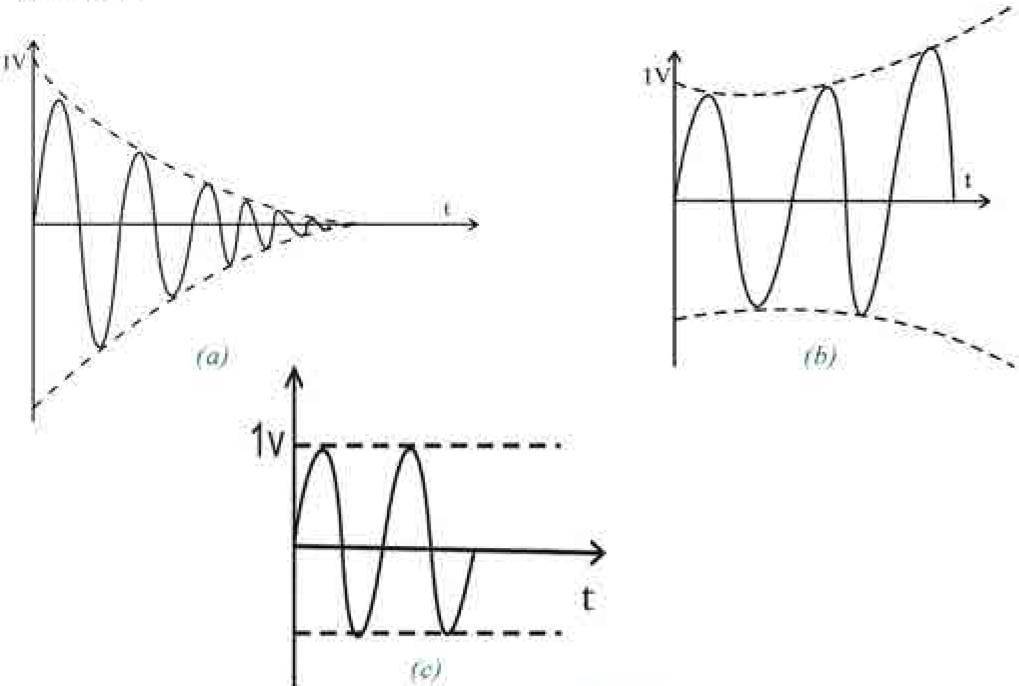


Fig 9.7

Now we have learned that the magnitude of **Aβ** should be unity ($|A\beta| = 1$) to get a sustained oscillation. The second condition is that the total phase shift introduced in the signal when it moves around the closed loop containing amplifier and feedback network must be 360° or 0° (Vi = βVo, so the polarity of Vi and βVo should be the same). In other words we can say that the phase angle of **Aβ** should be 360° or 0°. If the amplifier introduces a phase shift, the feedback network should produce an additional phase shift, so that the total phase shift becomes 360^0. For example if a CE amplifier is used, then it introduces 180° phase shift between its input and output. So the feedback network should introduce 180° phase shift or the phase of β should be 180°.

Thus we can conclude that the conditions for sustained oscillations are;

Magnitude of $A\beta = 1$ and

Phase of $A\beta = 0°$ or $360°$

These conditions are known as Barkhausen criterion for oscillation.

> The gain of an amplifier with positive feedback is given by $A_F = \frac{A}{1-A\beta}$. When the loop gain $A\beta = 1$, the gain of positive feedback system becomes infinity. So an oscillator has infinite gain. In other words, we can say that an oscillator produces an output signal without an input because it has infinite gain.

9.6 OSCILLATION IN RC OSCILLATORS

RC oscillators have feedback circuit containing RC network. The phase shift produced by an RC network depends on the frequency of the signal. The phase shift produced by an RC network is given by

$$\theta = \tan^{-1} [1/(2\pi fRC)]$$

Thus if the amplifier produces 180° phase shift, then the RC network must produce another 180° phase shift. So the sustained oscillation will be produced in the oscillator at that particular frequency for which the RC network makes 180° phase shift. Thereby an RC network selects the frequency of oscillation.

9.7 RC OSCILLATORS

The two most important RC oscillators are

(1) phase shift oscillator

(2) Wien bridge oscillator

Phase Shift Oscillators

Let us discuss an oscillator for which Op-amp acts as amplifier stage and three RC sections function as feedback circuit (Fig 9.8).

The Op-amp used is in inverting mode and hence there is 180^0 phase shift between its input and output. The three cascaded RC sections should provide the additional 180^0 phase shift for the oscillation to start. Since we have used three identified RC sections, each RC section must provide 60^0 phase shift.

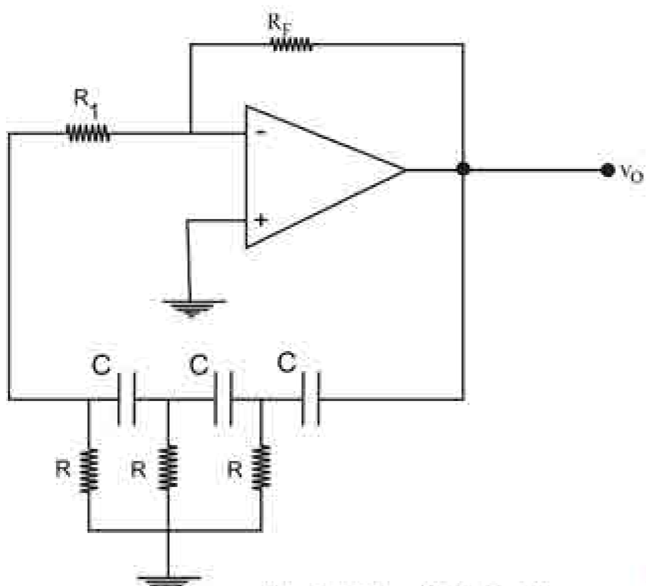


Fig. 9.8 Phase Shift Oscillator

As we have already seen, a large number of different frequency sine waves are generated when the DC supply is switched ON. At a specific frequency when the phase shift of one RC section is 60°, the phase shift of three RC sections becomes 180° and the circuit will oscillate at that frequency (Fig 9.9).

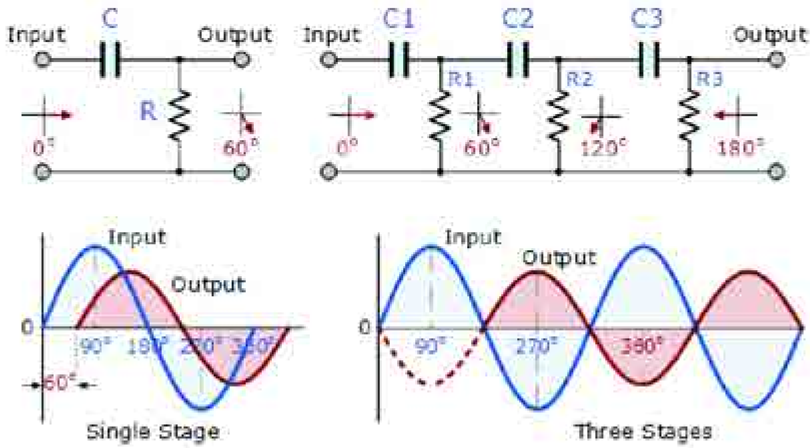


Fig. 9.9 RC stages and corresponding phase shifts

The frequency of oscillation is given by

$$f_o = 1/(2\pi RC\sqrt{6})$$

If we calculate the value of feedback factor β at this frequency, we get

$$\beta = 1/29$$

(Note: derivation is out of the scope of this textbook)

So as per Barkhausen criteria A = 29

For the inverting configuration, $A = -R_F/R_1$

$$|A| = R_F/R_1$$

$$\text{or } R_F = 29\,R_1$$

To obtain a desired frequency of oscillation, choose a particular value for the capacitor, C and then calculate the value of R from equation for 'f_o'.

Solved Problem 9.1

Design a phase shift oscillator for 400Hz.

Solution

Let C = 0.1 uF, then from equation

$f_o = 1/2\pi RC\sqrt{6}$ we have

$R = 1/2\pi foC\sqrt{6} = 1/(2\pi \times 400 \times 0.1 \times 10^{-6} \times \sqrt{6})$

$= 1.63\ K\Omega$

Take $R_F = 29R_1$

Check your progress:

Design a phase shift oscillator for i) 1kHz and ii) 600Hz

Wien Bridge Oscillator

The Figure 9.10 shows the circuit of a Wien bridge oscillator. Here a Wien bridge circuit is connected between the input and the output terminals of the Op-amp. The bridge has series RC circuit in one arm and parallel RC circuit in the adjoining arm. The resistors R_1 and R_F are connected in the remaining two arms of the bridge.

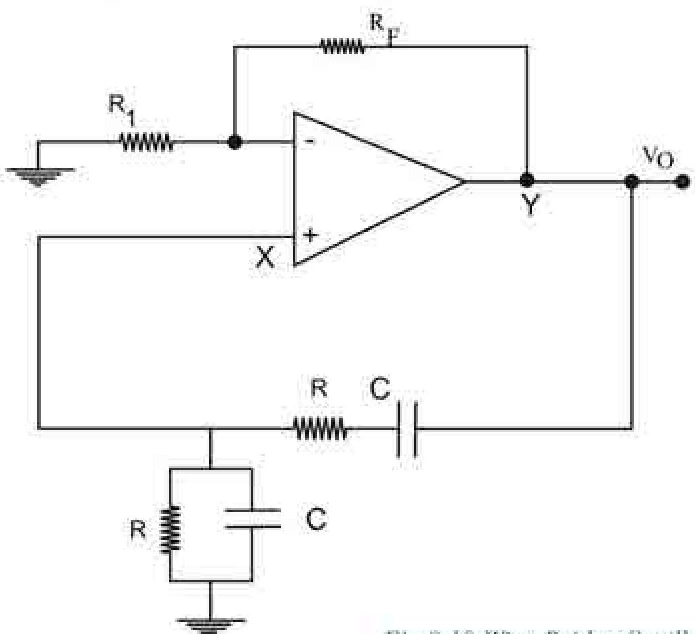


Fig 9.10 Wien Bridge Oscillator

For sustained oscillation, the total phase shift around the network must be 0° or 360°. In this circuit, the Op-amp is in non inverting mode and hence there is no phase shift between its input and output. So the feedback network should not introduce any phase shift in the signal. This condition occurs only when the bridge is balanced or when it is at resonance.

The frequency of oscillation is the same as the resonant frequency of the balanced Wien bridge and it is given by

$$fo = 1/2\pi RC$$

If we calculate the feedback factor, β at this frequency, we get

$$\beta = 1/3$$

To satisfy the Barkhausen criterion, the gain of the amplifier

$$A = 1/\beta = 3$$

So the gain of the non inverting amplifier, $A = 1+R_f/R_1 = 3$ or $R_f/R_1 = 2$.

$$\text{ie., } R_F = 2R_1$$

Wien bridge oscillator has a very good frequency stability and the frequency can be varied easily to a large range.

Check your progress:

Design a Wien bridge oscillator for i) 950 Hz and ii) 1.5KHz.

9.8 ASTABLE MULTIVIBRATOR

It is a square wave generator and its output waveform has only two voltage levels; either high state or low state. Here the Op-amp operates in saturated regions - positive saturation ($+V_{sat} = +V_{CC}$) and negative saturation ($-V_{sat} = -V_{CC}$). The output of the Op-amp swings between $+V_{sat}$ and $-V_{sat}$ continuously resulting in a square wave output. An astable multivibrator circuit using Op-amp is shown below:

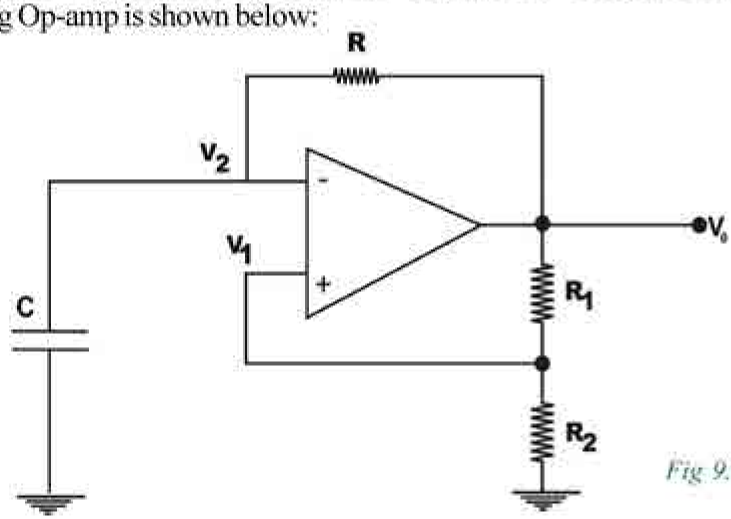


Fig 9.11 Astable Multivibrator

The operation of the circuit is explained below.

The differential input voltage of the Op-amp, $V_{id} = V_1 - V_2$

if V_{id} is positive, or $V_1 > V_2$, the output of the Op-amp goes to positive saturation, $+V_{CC}$.

If V_{id} is negative, or $V_1 < V_2$, then output of the Op-amp goes to negative saturation, $-V_{CC}$.

Assume that the capacitor, C is initially uncharged and voltage across it is zero. So $V_2 = 0$. Now, when DC supply is switched ON, there will be a small output offset voltage, '$V_{o(offset)}$'. If we assume that, this $V_{o(offset)}$ is positive, then this voltage is divided between resistors R_1 and R_2. Hence there will be a small positive voltage V_1. Now V_{id} is positive, and so the output of the Op-amp becomes $+V_{CC}$.

$$\text{So } V_o = +V_{CC} \quad \text{................ (9.10)}$$

At the same time, the capacitor, C starts charging through R with the voltage +V. The voltage across the capacitor gradually builds up and when this voltage slightly goes above V_1,

$$V_{id} = V_1 - V_2 \text{ becomes negative.}$$

The output now switches to $-V_{CC}$. So $V_o = -V_{CC}$

V_1 is now a negative voltage.

Now the capacitor discharges and charges negatively through 'R'. So the voltage across the capacitor increases negatively. When this voltage V_2 goes more negative than V_1, V_{id} becomes positive and the output of the Op-amp goes to $+V_{CC}$. This process repeats and the output of the Op-amp switches between $+V_{CC}$ and $-V_{CC}$ after fixed time intervals. Thus we get square wave output.

The time period of the output square wave,

$T = 2RC \ln [(2R_2 + R_1)/ R_1]$

To simplify this equation, take $R_1 = 1.16 R_2$

Then we get

$T = 2RC$

or frequency, $f_o = 1/T = 1/(2RC)$

Thus the frequency of the square wave can be easily varied by a variable resistor or a variable capacitor. The square wave form with variable ON and OFF time can be used for different timing applications.

Solved problem 9.2

Design a square wave generator for 1 kHz.

Solution

Take R_1 = 1.16 R_2 so that we can use simplified equation, fo = 1/(2RC)

Let R_2 = 10 KΩ, So R_1 = 1.16 ×10 = 11.6 KΩ

Let C = 0.01 uF

So R = $1/(2foC) = 1/(2\times1\times10^3\times0.01\times10^{-6})$

= 50 KΩ

Check your progress:

Design an astable multivibrator of frequency i) 15 kHz ii) 100Hz

9.9 CRYSTAL OSCILLATOR

The most important feature of an oscillator is its frequency stability. The frequency of the signal produced by an oscillator should remain constant irrespective of time and ambient conditions. The frequency stability of LC and RC oscillators is not superior. But a crystal oscillator has a very precise frequency. It uses a piezoelectric crystal which can produce mechanical vibrations when excited with an AC signal. The most common type of piezoelectric material used is the quartz crystal, so the oscillator circuits incorporating them came to be known as crystal oscillators. Quartz crystals are manufactured for frequencies from a few tens of kilohertz to tens of megahertz. They are used for consumer devices such as wrist watches, clocks, radios, computers, and cell phones.

Piezoelectricity

When a crystal of quartz is properly cut and mounted, it can be distorted in an electric field by applying a voltage to an electrode near to or on the crystal. When the field is removed, the quartz will generate an electric field as it returns to its previous shape, and this can generate a voltage. If an AC voltage is applied to the crystal, it will vibrate (contract and expand) at a frequency equal to that of the applied voltage. Otherwise, if the crystal is made to vibrate mechanically, it will generate an AC voltage at a frequency equal to that of the vibration. This property is known as piezoelectricity. The result is that a quartz crystal behaves like a circuit

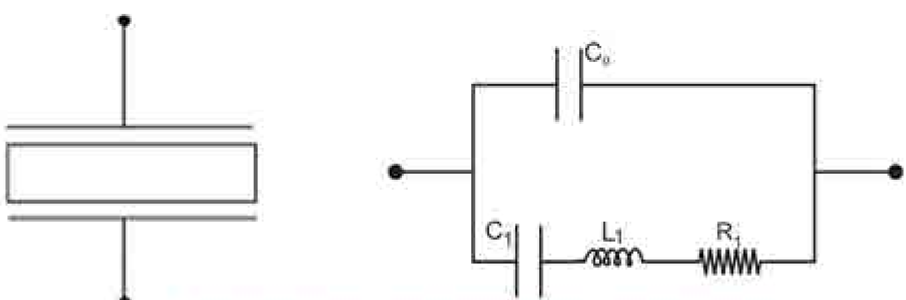


Fig. 9.12 quartz crystal symbol and equivalent circuit

composed of an inductor, a capacitor and a resistor, with a precise resonant frequency. The resonant frequency of a crystal is determined by the cut and size of the crystal. The symbol and equivalent circuit of the crystal is given in Fig. 9.12

A quartz crystal provides both series and parallel resonance. The series resonant frequency is a few kilohertz lower than the parallel resonant frequency. Crystals below 30 MHz are generally operated between series and parallel resonance. Crystals above 30 MHz (up to 200 MHz) are generally operated at series resonance where the impedance is at its minimum and equal to the series resistance. To obtain higher frequencies, a crystal can be made to vibrate at one of its overtone modes, which occur near multiples of the fundamental resonant frequency. Only odd numbered overtones are used. Such a crystal is referred to as a 3rd, 5th, or even 7th overtone crystal. To accomplish this, the oscillator circuit usually includes additional LC circuits to select the desired overtone produced by the crystal. Also the frequency produced by the crystal oscillator is almost independent of temperature.

Activity 4

Set up an astable multivibrator to switch an LED ON and OFF with a time period of one second.

Solution

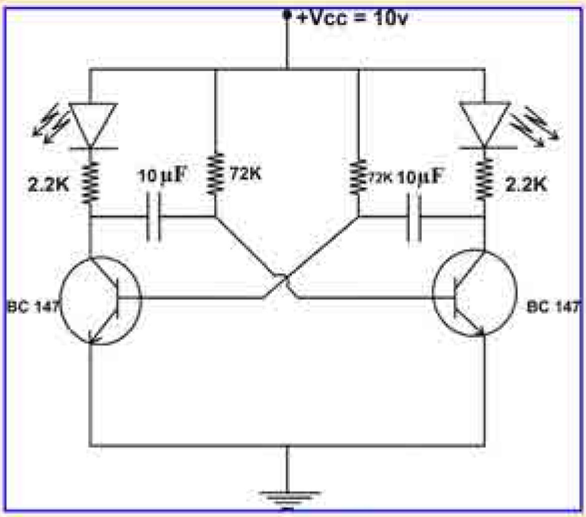


Fig. 9.13

Connect the LEDs in the collector of the multivibrator as shown in Figure.

The period of astable multivibrator is $T = 1.38R_BC$. We have to generate a square waveform with a time period of 1 second.

Let $C = 10\mu F$

Now $1 = 1.38R_B \times 10 \times 10^{-6}$ *or* $R_B = 72\ K\Omega$

The LEDs will be ON and OFF alternately; ie when one LED is ON, the other will be OFF and vice versa. The ON and OFF durations of LEDs are 0.5 second each.

Let us sum up

An electronic oscillator is an amplifier with positive feedback. Oscillators are essential for a variety of applications in electronics. One main application is in the field of communication. The function of amplifier in an oscillator is to supply necessary energy to the oscillating circuit so that sustained oscillations are set up. In LC oscillators, the LC tank circuit is used to produce oscillations and in RC oscillators, the RC network selects a particular frequency from the noise signal which is produced when the DC source is switched ON. Also the LC circuit has the property of resonance and frequency selectivity. The amplifiers use negative feedback to improve its response and at the same time positive feedback is used in oscillators. The Barkhausen criterion is a necessary condition for oscillation and it says that the magnitude of loop gain $A\beta$ should be unity and angle of $A\beta$ is 360^0.

The two common RC oscillators are phase shift oscillator and Wien bridge oscillator. The CE amplifier produces a phase shift of 180^0. In phase shift oscillator the remaining 180^0 phase shift is produced by the feedback network since each of the three RC sections produces a phase shift of 60^0 . The frequency of oscillation is determined by the values of R and C in the RC network. In Wien bridge oscillator, the amplifier as well as the feedback network produce zero phase shift. This oscillator has better frequency stability.

The astable multivibrator generates square waves. It uses two cross coupled transistor circuits and the transistors are alternately switched ON and OFF automatically by the circuit operation. Its frequency of operation is determined by the circuit components R and C.

The crystal oscillator uses piezoelectric materials such as quartz crystal to determine the frequency of oscillation. The frequency is dependent on the thickness of the crystal. The thinner the crystal, the higher is the frequency produced. A crystal oscillator has a very good frequency stability also.

Learning outcomes

The learner is able to

- Point out the need for oscillators.
- Explain the generation of oscillations.
- Explain the working of a tank circuit
- Point out the significance of feedback.
- Explain Barkhausen criterion for oscillation.
- Explain the generation of oscillations in RC oscillators.
- Explain the construction of RC oscillators
- Draw the circuit diagram and hence explain the working of square wave generator.

Evaluation items

Multiple choice questions

1. Which of the following is a feature of an oscillator?
   a) The operation is noisy.
   b) The frequency of operation cannot be varied easily.
   c) It can produce very high frequencies.
   d) It is a mechanical device.

2. An oscillator is an ....
   a) amplifier with negative feedback
   b) amplifier with infinite gain
   c) amplifier with unity gain
   d) none of these

3. An RC oscillator is suitable for generating ....
   a) RF frequency b) audio frequency
   c) microwave frequency d) all of these

4. An LC oscillator cannot be used to generate very low frequency because ....
   a) the size of L and C becomes very small
   b) the size of L and C becomes very large
   c) oscillations will not start at low frequencies
   d) the oscillator becomes unstable

5. For an oscillator circuit, the phase shift around the loop is ....
   a) 90^0 b) 180^0
   c) 360^0 d) 270^0

6. An RC phase shift oscillator has .... RC sections
   a) 2 b) 3
   c) 4 d) 5

7. The minimum gain of the amplifier in RC phase shift oscillator is.............
   a) 10 b) 50
   c) 100 d) 29

8. Generally negative feedback is used in ....
   a) amplifiers b) oscillators
   c) multivibrators d) all of these

9. The frequency of an oscillator is determined by.............

a) gain of the amplifier
b) the specifications of the Op-amp
c) the components in the tank circuit
d) the value of feedback factor

10. In Wien bridge oscillator, the phase shift introduced by the feedback network is.............

a) 0^0 b) 90^0
c) 180^0 d) 120^0

11. The signal generator generally used in the laboratories is.............

a) Wienbridge oscillator b) Hartley oscillator
c) Crystal Oscillator d) Phase shift oscillator

12. In an oscillator, the gain of the amplifier is 50. The attenuation of the feedback circuit must be.............

a) 1 b) 0.01
c) 10 d) 0.02

Answers

1. c	2. b	3. b	4. b	5. c	6. b	7. d
8. a	9. c	10. a	11. a	12. d		

Descriptive type questions

1. What do you understand by damped and undamped oscillations?
2. What are the two requirements for oscillation?
3. Why is amplifier circuit necessary in oscillators?
4. What are the drawbacks of LC oscillators?
5. Why do you use three RC sections in RC phase shift oscillators?
6. Write short notes on the following.
   a) RC oscillator b) phase shift oscillator c) Wien bridge oscillator
7. For a phase shift oscillator, $C = 0.1\mu F$, $R = 3.9k\Omega$. Determine the frequency of oscillation.
8. A Wien bridge oscillator uses $R = 3.9k$, $C = 0.01\mu F$. What is the oscillating frequency?
9. Design an astable multivibrator circuit to blink an LED with a time period of one second.

10

DIGITAL ELECTRONICS

INTRODUCTION

As you know analog signals are also called continuous signals or continuously varying signals. These signals have infinite number of values. Alternating current or voltage wave forms which are of sinusoidal shape are examples of analog signals.

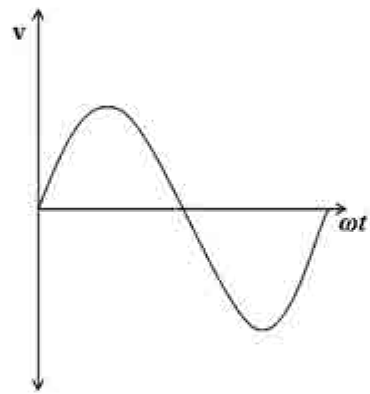


Fig 10.1 Analog Signal

But digital signals have only two states-the 'ON' state and the 'OFF' state. Each of the two states are designated as logic1 and logic 0 states. These can also be characterized as true or false. The signal can be represented as a square wave form as follows.

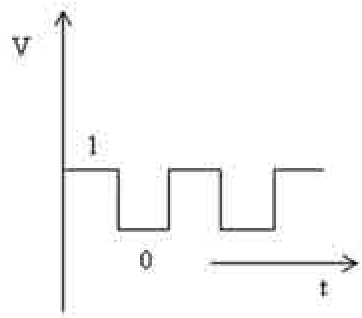


Fig 10.2 Digital Signal

In digital signals, a logic 1 can be represented by a +5v and logic '0' can be represented by a '0v'. In analog circuits or devices, the electrical variable such as current or voltage is continuous. That means an analog circuit processes continuously varying signals or analog signals. But in a digital circuit only discrete values of variables are recognized. A digital circuit or device processes digital signal.

10.1 NUMBER SYSTEM

Do you know the name of the number system which you use in your daily life? This number system which uses digits from 0 to 9 ie 0,1,2,3,4,5,6,7,8 and 9 is called decimal number system. 'Deci' means 10'. This number system is termed as decimal system because the base of this system is '10'. Similarly we have a wide variety of number systems. Each of these is based on a specific base or radix. The binary number system is based on the base '2', octal number system is based on the base '8' and hexadecimal number system has the base '16'.

Activity 1

Let us examine the formation of the number $(429)_{10}$ where 10 represents its base.

$$(429)_{10} = 4x10^2 + 2x10^1 + 9 \times 10^0$$

i.e 429=400+20+9

Here '4' is in the hundredth position '2' is in the tenth position and the digit '9' is in its unit's position. Similarly we can represent numbers in any other number system using its base.

10.2 BINARY NUMBER SYSTEM

Binary number system is the soul of digital electronics. The base of this number system is '2'. A number in this system is represented by '0's and '1's.

Consider a binary number 10110 similar to the previous activity showing the meaning of decimal number. Starting from the least significant bit '0' towards left in the above binary number 10110,'0' is in the unit's $(2^0)^{th}$ position, '1' is in the 2^{nd} (2^1) position, the next '1' is in the 4^{th} (2^2) position, next '0' is in th 8^{th} (2^3) position and the next 1 is in the 16^{th} (2^4) position. Digital signals are represented by binary number system.

In the system '0' is equivalent to '0' in the decimal system and 1is equivalent to '1' in the decimal system. The next number is '1 0' in the binary number system which is equivalent to '2' in the decimal system. Similarly the following number is '11' which is equivalent to '3' in the decimal system.

Conversion of a Binary number to a Decimal number

Try to analyse the following table.

Binary	Equivalent decimal
0	0
1	1
10	2
11	3
100	4

Table 10.1

The representation of a binary number and its meaning have been illustrated above. Keeping these in mind the binary number $(10110)_2$ can be converted into a decimal number as follows.

The representation of a binary number and its meaning have been illustrated in the previous section. Keeping these in mind the binary number $(10110)_2$ can be converted into decimal as follows.

$$\begin{array}{ccccc} \mathbf{1} & \mathbf{0} & \mathbf{1} & \mathbf{1} & \mathbf{0} \\ \downarrow & \downarrow & \downarrow & \downarrow & \downarrow \\ \mathbf{2^4} & \mathbf{2^3} & \mathbf{2^2} & \mathbf{2^1} & \mathbf{2^0} \end{array}$$

$$(10110)_2 = 1*2^4+0*2^3+1*2^2+1*2^1+0*2^0$$

$$= 1*16+0*8+1*4+1*2+0*1$$

$$= (22)_{10}$$

So $(10110)_2 = (22)_{10}$

Where 22 is the decimal equivalent value of binary number 1 0 1 1 0 .

Check your progress:

Convert the following numbers into decimal number system.

a) $(1111)_2$

b) $(10101)_2$

Conversion from Decimal to Binary

To convert a number in the decimal system into binary ,firstwe have to divide the number by '2'. If it is exactly divisible write '0' against the number on its right hand side. If not exactly divisible put '1' against the number. Again divide the result obtained by '2' and proceed until the result is '1'. Then read up the number starting from the last resultant digit through all digits on the right hand side. As an example, let us convert $(61)_{10}$ into binary.

The arrow shown represents how to read up the binary number .

2	61	1 ↑
2	30	0 ↑
2	15	1 ↑
2	7	1 ↑
2	3	1 ↑
2	1	1 ↑
	0	

ie, 1 1 1 1 0 1

So $(61)_{10} = (1\,1\,1\,1\,0\,1)_2$

Check your progress:

Convert the following numbers into binary number system.

a) $(131)_{10}$

b) $(346)_{10}$

Decimal and Binary Fractions

To understand the meaning of representation of decimal fractions let us consider such a number say $(36.2012)_{10}$

The Expansion for this number is

$(36)_{10} \quad = \quad 3\times10^1 + 6\times10^0$, and

$(0.2012)_{10} \quad = \quad 2\times10^{-1} + 0\times10^{-2} + 1\times10^{-3} + 2\times10^{-4}$

So the Positional values of the above number can be shown as below

3	6	2	0	1	2
↓	↓	↓	↓	↓	↓
10^1	10^0	10^{-1}	10^{-2}	10^{-3}	10^{-4}

Similarly the positional values of a binary fraction say 1 0 1 . 1 1 0 1 can be shown as

1	0	1	1	1	0	1
↓	↓	↓	↓	↓	↓	↓
2^2	2^1	2^0	2^{-1}	2^{-2}	2^{-3}	2^{-4}

Conversion of Binary Fraction to Decimal

Let us Consider the binary fraction $(1\,0\,1.1\,1\,0\,1)_2$. This may be written as follows

$$(1\times2^2 + 0\times2^1 + 1\times2^0) + (1\times2^{-1} + 1\times2^{-2} + 0\times2^{-3} + 1\times2^{-4})$$

So the decimal equivalent of this binary becomes

$$5 + (1/2 + 1/4 + 1/16) = (5.08125)_{10}$$

Conversion from Decimal Fraction to Binary

We have studied in the earlier sections that to convert decimal whole number to binary whole number,a division by '2' has to be performed. To convert decimal fractions to binary fractions we have to multiply by '2'. If the product of each number is greater than '1' put a '1' below that number otherwise put a'0.' To understand this, let us consider the following.

Conversion of decimal fraction $(0.8125)_{10}$ into binary:

Number	0.8125	0.625	0.25	0.5
Base	2	2	2	2
	1.6250	1.250	0.50	1.0
Remainder	1	1	0	1

Therefore $(0.8125)_{10} = (0.1101)_2$.

10.3 OCTAL NUMBER SYSTEM

The octal number system uses digits 0,1,2,3,4,5,6 &7 ie , eight digits. So the base of this number system is '8'.

$(127)_8$ which is in octal number system can be represented as

$(127)_8 = 1 \times 8^2 + 2 \times 8^1 + 7 \times 8^0$

$$\begin{matrix} 1 & 2 & 7 \\ \downarrow & \downarrow & \downarrow \\ 8^2 & 8^1 & 8^0 \end{matrix}$$

Conversion from Octal to Decimal

Keeping the above representation in mind, let us find the decimal equivalent of the octal number$(127)_8$-

$$\begin{aligned} (127)_8 &= 1*8^2 + 2*8^1 + 7*8^0 \\ &= 64+16+7 \\ &= (87)_{10} \end{aligned}$$

So the decimal equivalent of $(127)_8$ is $(87)_{10}$

Conversion from Decimal to Octal

We have already studied how to convert decimal number into binary. Similarly we can convert a decimal number to an octal number by dividing the given number by '8' repeatedly, until the result is less than '8'.

Let us convert $(87)_{10}$ to the octal number system.

So $(87)_{10} = (127)_8$

8	87	7
8	10	2
	1	

Check your progress:

Convert the following decimal numbers into octal numbers

a) 256

b) 728

Octal to Binary Conversion

To convert an octal number into binary we should first proceed to convert the octal number to decimal. Then the decimal number obtained is to be converted to binary. Consider the octal number $(127)_8$. Let us try to convert this number into a binary number.

For this, first, we have to convert $(127)_8$ to decimal

ie, $(127)_8 = 1\times8^2 + 2\times8^1 + 7\times8^0$

$= 1\times64 + 2\times8 + 7\times1$

$= (87)_{10}$

Now $(87)_{10}$ may be converted to binary.

$(87)_{10} = (1010111)_2$

2	87	1
2	43	1
2	21	1
2	10	0
2	5	1
2	2	0
	1	

Therefore $(127)_8 = (1010111)_2$

So the binary equivalent to the octal number 127 is 1 0 1 0 1 1 1

10.4 HEXA DECIMAL NUMBER SYSTEM

The number system with base 16 is called hexa decimal number system. The 16 characters including numbers and alphabets used in this system are 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E and F

The following table illustrates the above fact

Decimal	Hexa decimal
0	0
1	1
2	2
3	3
4	4
5	5
6	6
7	7
8	8
9	9
10	A
11	B
12	C
13	D
14	E
15	F

Table 10.2

According to this system the next hexadecimal number is 10 which is equivalent to 16 in the decimal system.

ie, $(10)_{16} = (16)_{10}$

Similarly $(11)_{16} = (17)_{10}$

$(12)_{16} = (18)_{10}$ and so on .

Similar to the methods adopted in the earlier sessions we can convert a decimal number to hexa decimal number and vice versa. Let us convert the decimal number $(269)_{10}$ to a hexa decimal number.

```
16 | 269   13
16 | 16    0
      1
```

13 is equivalent to D in hexa decimal

Therefore $(269)_{10} = (10D)_{16}$

Let us now convert the hexadecimal number F9 into decimal. We know that F is equivalent to 15 in the decimal system, so

$$(F9)_{16} = 15\times16^1 + 9\times16^0$$
$$= 240 + 9$$
$$= (249)_{10}$$

Therefore the decimal equivalent of the hexadecimal F9 is 249

Check your progress:

a) Convert the following decimal numbers to hexadecimal numbers

i) 148 ii) 84

b) Convert the following hexa decimal numbers to decimal numbers

i) $(19)_{16}$ ii) $(2C)_{16}$

10.5 BINARY ADDITION

Binary addition follows the same basic rules of addition. In binary system there are only two digits and the largest digit is "1", so any "SUM" greater than 1 will result in a "CARRY". This carry "1" is passed over to the next column for addition and so on. Consider the single bit addition below.

0	0	1	1
+ 0	+ 1	+ 0	+ 1
0	1	1	10

The single bits are added together and "0 + 0", "0 + 1", or "1 + 0" results in a sum of "0" or "1". When you do "1 + 1", the sum is equal to "2" in decimal system. In binary it is '1 0'. Here the bit '0' is the sum bit and bit '1' is the carry bit. The addition of two bit numbers is given below.

00	00	01	01
+ 00	+ 01	+ 00	+ 01
00	01	01	10

Let us now practice addition of binary numbers.

a) 100 +101 b) 1001 + 0111 c) 1101 +1010

a)		b)		c)	
	100 +		1001 +		1101 +
	101		0111		1010
	1001		10000		10111

Check your progress:

Add the given binary numbers

a) 1001 +1010 b) 10010 + 01110 c) 110101 +101011

10.6 LOGIC GATES

A logic gate is the primary building block of a digital circuit. It is a circuit with one or more inputs and one output. At any given moment, logic gate takes one of the two binary conditions 0 (low) or 1 (high) depending upon its function and input values. Low and High states are represented by different voltage levels. For example +5V may represent a logic 1 and 0V may represent a logic 0.

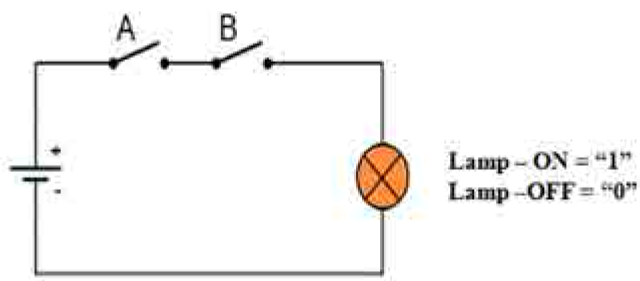
There are three primary logic gates namely, AND, OR and NOT. Also we have other logic gates like NAND, NOR, XOR and XNOR. Out of these NAND and NOR gates are called the universal gates, because either of these gates alone could be used to realize the primary logic gates.The circuit symbol and the truth table of these logic gates are explained below.

AND GATE

The AND gate is so named because the gate acts in the same way as the logical "AND" operator. The output will be 1 if both inputs are 1; otherwise the output is 0. In other words, if 0 is called 'LOW' and 1 is called 'HIGH', the output is 'HIGH' only when both inputs are 'HIGH', otherwise, the output is 'LOW'.

Activity 2

In the circuit shown in figure 10.3 can be used to explain the function of an AND gate. Here a bulb is connected to supply through two switches connected in series. Let us try to explain the operation.



Switch A – Open = "0" , Closed = "1"
Switch B – Open = "0" , Closed = "1"

Fig 10.3 Switch represenation of AND gate

Here the two switches, A and B are connected together to form a series circuit. These switches are considered as the inputs to the AND gate and bulb as output. Therefore, in the circuit above, both the switches A and switch B must be closed (Logic "1") in order to put the lamp ON (Logic "1"). If any or both of the switches are open (Logic "0"), the bulb will be OFF (Logic "0"). Thus the working of this circuit clearly reveals the function of an AND gate.

Here A and B are used to represent the two input boolean variables and the output is represented by the variable Y. In boolean algebra, a variable can take any of the values '0' or '1'. The logical symbol of the AND gate is shown in fig. 10.4.

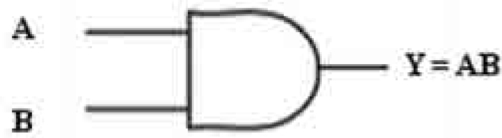


Fig 10.4 Symbol of AND gate

The action of AND gate is represented by writing the boolean expression as follows.

$$Y = A \text{ AND } B$$

In boolean algebra the multiplication sign stands for the AND operation. Therefore, the output of the AND gate is also represented as

$$Y = A . B$$

Or simply as $Y = AB$

Here we have considered a two input AND gate. Therefore there are four possible input combinations: 00, 01, 10 and 11. For example if the inputs are 0 & 1, then the output will be

$$Y = A . B$$

$$Y = 0 . 1$$

$$Y = 0$$

The input and the output information of any logic gate or circuit can be plotted into a table to give a visual representation of the switching function of the circuit and this is commonly called a **Truth Table**. The truth table of a logic gate shows each possible input combination to the gate with the resultant output depending upon the combination of these inputs.

The truth table for AND gate is shown below

Input		Output
A	**B**	**Y**
0	0	0
0	1	0
1	0	0
1	1	1

Table 10.3 Truth table for AND gate

Figure 10.5 shows the circuit implementation of AND gate using diodes and resistor. Can you explain, how this circuit acts as an AND gate?

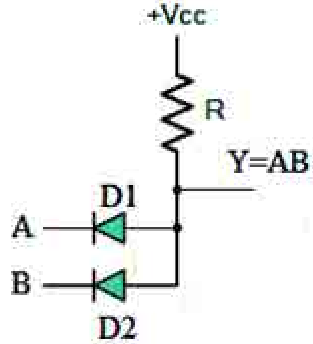


Fig 10.5 AND gate using diodes and resistor

The working of the above circuit can be explained as follows. Here logic 0 is represented by a voltage near to 0V and logic 1 is represented by the voltage near to +Vcc.

Case 1: A=0, B=0: In this case both the diodes D1 and D2 are forward biased by the supply Vcc. Hence at the output Y, there will be a voltage of 0.7V(which is the voltage drop of the forward biased diode). Since 0.7V is near to 0V, the output is treated as logic 0.

Case 2: A=0, B=1: Here the diode D1 is forward biased and D2 is reverse biased. As one of the diodes is forward biased, the voltage at Y is 0.7V. Again the output is treated as logic 0.

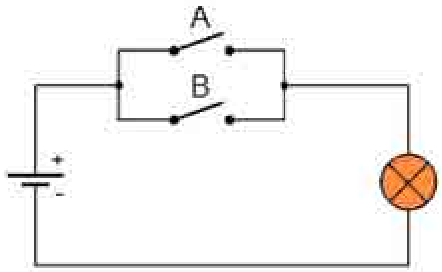
Case 3: A=1, B=0: Here the diode D1 is reverse biased and D2 is forward biased. As one of the diodes is forward biased, the voltage at Y is 0.7V. Again the output is treated as logic 0.

Case 4: A=1, B=1: Here both the diodes D1 and D2 are not in conducting state as voltages are equal at either sides of these diodes. Since both the diodes are not conducting, the voltage at point Y is +Vcc. Now the output Y is at logic 1.

OR GATE

The OR gate is so named because the gate acts in the same way as the logical "OR" operator. The output is 1 if one or both of the inputs are 1; otherwise the output is 0.

As in the case of AND gate, the function of an OR gate can be explained by using the circuit shown in fig. 10.6 . Here a bulb is connected to supply through two switches connected in parallel. Let us try to explain the operation.



Lamp – ON = "1"
Lamo – OFF = "0"

Switch A – Open = "0", Closed = "1"
Switch B – Open = "0", Closed = "1"

Fig 10.6 Switch representation of OR gate

Here the two switches A and B are connected in parallel. Either switch A, switch B or both can be closed (logic 1) in order to put the lamp ON. The lamp will be OFF only if both the switches are open (logic '0'). These switches are considered as the inputs to the OR gate and bulb as output.

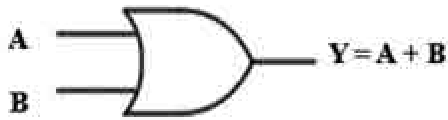


Fig 10.7 Symbol of OR gate

The logic symbol of the OR gate is shown in fig. 10.7.

The output of the OR gate can be expressed as

$$Y = A \text{ OR } B$$

The symbol used for OR operation is '+'. Therefore

$$Y = A + B$$

For example if the inputs are 1 & 0, then the output is

$$Y = 1 + 0$$

$$Y = 1$$

The truth table for OR gate is given in Table 10.3

Input		Output
A	**B**	**Y**
0	0	0
0	1	1
1	0	1
1	1	1

Table 10.4 Truth table for OR gate

Similar to AND gate, the function of an OR gate can also be implemented by using the following circuit. It consists of two diodes and one resistor. Let us try to explain its working.

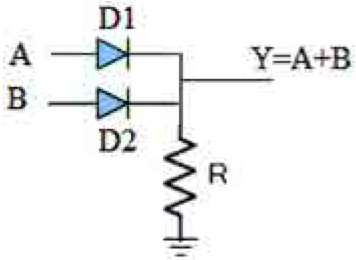


Fig 10.8 OR gate using diodes and resistor

The working of the circuit shown in fig. 10.8 can be briefly explained as follows

Case 1: A=0, B=0: Now both diodes are unbiased and hence no current flows through the resistor R. So the output voltage is zero and Y is at logic 0.

Case 2: A=0, B=1: Here the diode D1 is unbiased and D2 is forward biased. Now current flows through R, since D2 is conducting and a high voltage appears at the output. So the output is at logic 1.

Case 3: A=1, B=0: In this case D1 is forward biased and D2 is unbiased. The current flows through R as D1 is conducting and a high voltage appears at output. So the output is at logic 1.

Case 4: A=1, B=1: Here both the diodes are forward biased and both of them conduct and the current flows through R resulting in a high voltage at the output. So the output is at logic 1.

A 2-input logic OR gate can be constructed using resistor-transistor switches connected together as shown in figure 10.9 below, with the inputs connected directly to the transistor bases. Either transistor must be saturated or "ON" for a high output at Y. Can you explain the working of this circuit?

If any of the inputs (A or B) get a high (logic 1) voltage, the transistor becomes ON and current flows from supply voltage (V_{cc}) to ground through the resistor R2. This will produce a voltage drop across R2 and is available at the output Y. If both the inputs are low (logic 0), both the transistors will be in OFF state and no current flows through R2. Therefore no voltage will be available at the output Y.

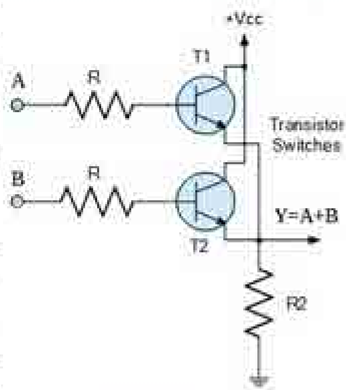


Fig 10.9 OR gate using transistor and resistor

NOT GATE

The NOT gate is also called as logical inverter. It has only one input. It reverses the logical state. In other words the output Y is always the complement of the input. ie. If the input is 0, output will be 1 and if the input is 1, the output will be 0. The logical symbol of the NOT gate is shown in fig.10.10.

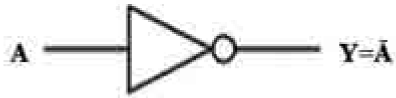


Fig 10.10 Symbol of NOT gate

The NOT operation is expressed as

$$Y = \text{NOT } A$$

In boolean algebra the NOT operation is represented by an over bar. Therefore

$Y = \bar{A}$

If $A = 0$, $Y = \bar{0} = 1$

If $A = 1$, $Y = \bar{1} = 0$

It can also be represented as Y=A'.

The truth table for NOT gate is given below.

Input	Output
A	**Y**
0	1
1	0

Table 10.5 Truth table for NOT gate

Activity 3

A very simple NOT gate can be made using just a single transistor switching circuit as shown in fig.10.11. Can you explain how this circuit acts as an inverter (NOT gate)?

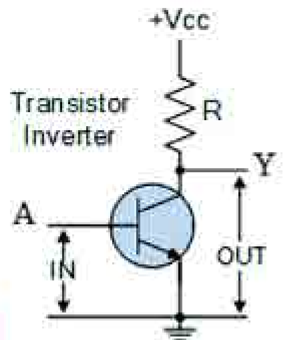


Fig 10.11 NOT gate using transistor

When the transistor's base input "A" is HIGH, the transistor goes to saturation and the collector voltage is nearly zero. Therefore the output "Y" is LOW.

Similarly, when the transistor's base input "A" is LOW (0V), the transistor goes to cut off and no collector current flows through the resistor. This results in an output voltage at "Y" at a value near to +Vcc (HIGH).

Thus, with an input voltage "A" HIGH, the output "Y" will be LOW and an input voltage "A" LOW the resulting output voltage "Y" will be HIGH producing the complement or inversion of the input signal.

NOR GATE

The NOR gate circuit is an OR gate followed by an inverter as shown in fig.10.12 Its output is 'HIGH' only if both of the inputs are 'LOW', otherwise the output is 'LOW'.

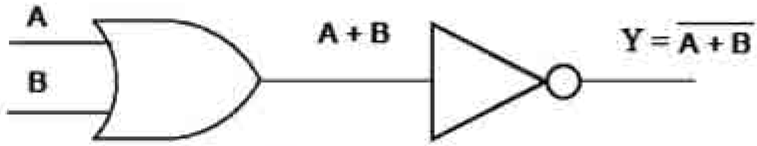


Fig 10.12 NOR gate using OR and NOT

The logic symbol for the NOR gate is given in 10.13.

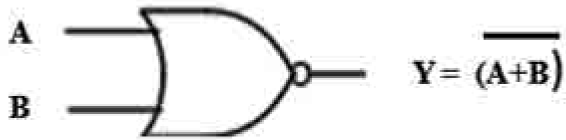


Fig 10.13 Symbol of NOR gate

Note: From the above figure, it is clear that the bubble in the symbol for NOR gate represents NOT gate. Thus in the digital logic circuits, this bubble represents NOT (inversion) operation.

The output of the NOR gate can be expressed as

$$Y = (\overline{A + B})$$

For example, if both of the inputs are 1 the output will be

$$Y = (\overline{1+1}) = \overline{1} = 0$$

The truth table for the NOR gate is given below.

Input			Output
A	B	A + B	$Y = (\overline{A + B})$
0	0	0	1
0	1	1	0
1	0	1	0
1	1	1	0

Table 10.6 Truth table for NOR gate

NAND GATE

The NAND gate circuit is formed by an AND gate followed by a NOTgate as shown in fig.10.14. It acts in the manner of the logical operation 'AND' followed by inversion. The output is 'LOW' only if both of the inputs are 'HIGH', otherwise, the output is 'LOW'. In other words the output of the NAND gate is 0 if and only if both of the inputs are 1, otherwise the output is 1.

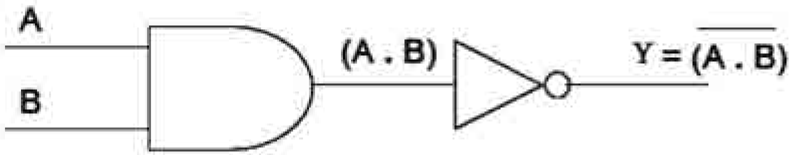


Fig 10.14NAND gate using AND and NOT

The logic symbol for NAND gate is shown in fig.10.15.

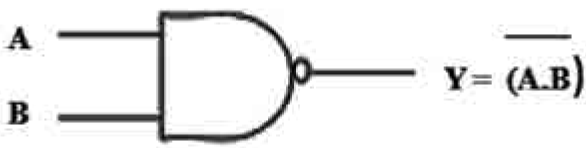


Fig 10.15 Symbol of NAND gate

The output for the NAND gate is expressed as

$$Y = \overline{A.B}$$

For example, if both of the inputs are '0', the output will be 1.

$$Y = (\overline{0.0}) = \overline{0} = 1$$

The truth table for the NAND gate is given in table 10.6.

Input			Output
A	B	A.B	$Y = \overline{A.B}$
0	0	0	1
0	1	1	1
1	0	1	1
1	1	1	0

Table 10.7 Truth table for NAND gate

EXCLUSIVE OR (XOR) GATE

The XOR(EX-OR) gate will give a logic 1 at the output if both of the inputs are different and a logic 0 if the inputs are same. The output is 'HIGH' if either, but not both, of the inputs are 'HIGH'. The output is 'LOW' if both of the inputs are 'LOW' or if both of the inputs are 'HIGH'. The logic symbol for XOR gate is shown in fig. 10.17.

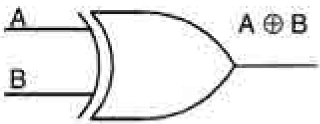


Fig 10.17 Symbol of XOR gate

The output of the XOR gate is

$$Y = \overline{A}B + A\overline{B}$$

In boolean algebra the XOR operation is represented by ⊕

$$Y = A \oplus B$$

The truth table of the XOR gate is shown below:

Input		Output
A	**B**	**Y**
0	0	0
0	1	1
1	0	1
1	1	0

Table 10.8 Truth table for XOR gate

NAND gate using resistors and transistors

A simple 2-input logic NAND gate can be constructed using Resistor-transistor switches connected together as shown in fig. 10.16 with the inputs connected to the transistor bases. Any one transistor must be cut-off for an output at Y. Try to find out the working of this circuit.

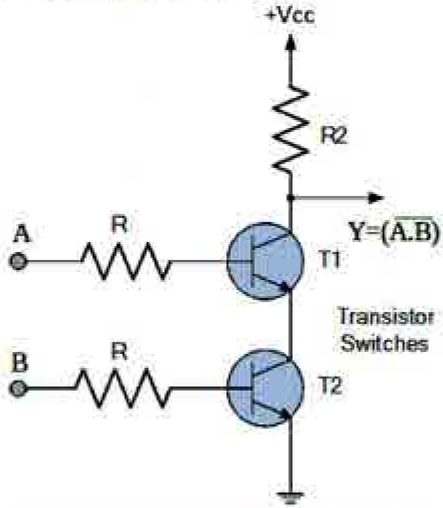


Fig 10.16 NAND Gate using transistors and resistors

If any or both of the input is low (logic 0), the corresponding transistor(s) will be OFF and the supply voltage will reach at the output Y (logic 1). If both the inputs are high (logic1), transistors will be in ON state and the current flows to ground through the resistor and transistors. Therefore the voltage at output Y will be low (logic 0).

XNOR GATE

The XNOR (exclusive-NOR) gate is formed by placing a NOT gate at the output of XOR gate as shown in fig.10.18. Its output is 'HIGH' if the inputs are the same and 'LOW' if the inputs are different. In simple words, the output is 1 if the input are the same, otherwise the output is 0.

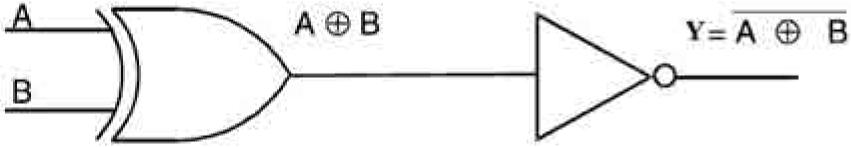


Fig 10.18 XNOR gate using XOR and NOT

The logic symbol of XNOR gate is given below.

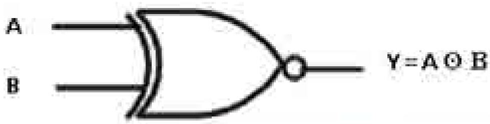


Fig 10.19 Symbol of XNOR gate

$$Y = \overline{A}\,\overline{B} + AB$$

The output of the XNOR gate is

$$Y = \overline{A \oplus B}$$

The XNOR operation is represented by

$$\mathbf{Y = A \odot B}$$

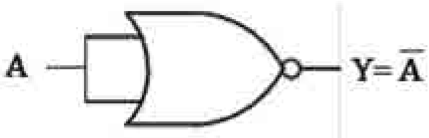
The truth table of the XNOR gate is shown below

Input		Output
A	**B**	**Y**
0	0	1
0	1	0
1	0	0
1	1	1

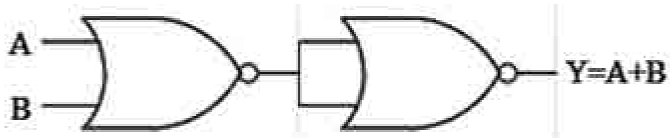
Table 10.9 Truth table for XNOR gate

10.7 UNIVERSAL GATES – NAND AND NOR

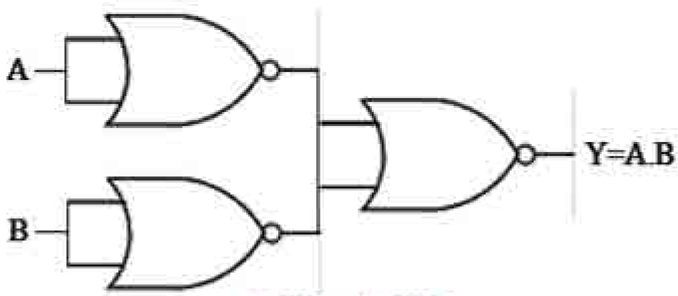
We have already seen that all the boolean functions can be expressed in terms of the fundamental gates namely AND, OR and NOT. In fact, these fundamental gates can be expressed in terms of either NAND gates or NOR gates only.That is only NAND or NOR gates can be used to perform all the Boolean and other logic gate functions. Therefore these gates are known as **universal gates.** Some of the gate functions implemented only using NOR gates are shown in fig.10.20.



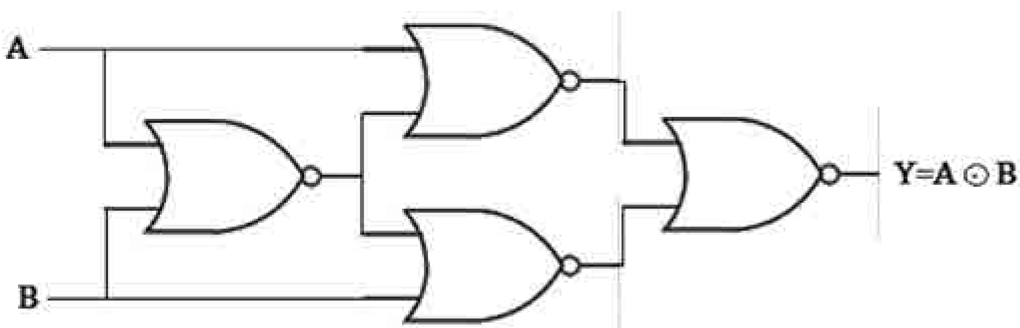
(a) NOT using NOR



(b) OR using NOR



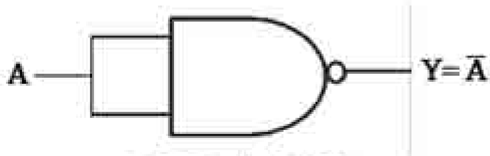
(c)AND using NOR



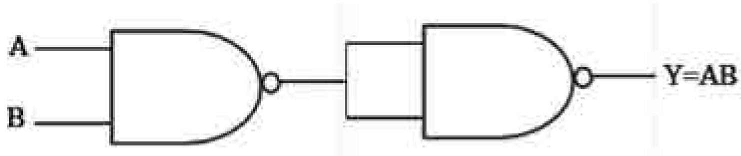
(d) EXNOR using NOR

Fig 10.20 Fundamental gates using NOR only

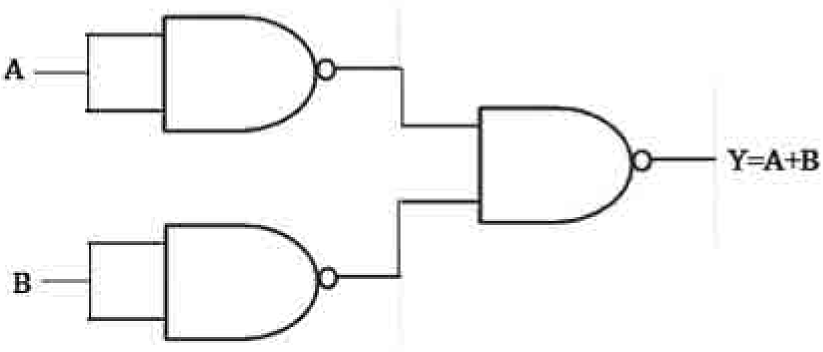
Like the NOR gate seen now, the NAND gate is also a "Universal" type gate.NAND gates can be used to produce any other type of logic gate function just like the NOR gate. Some of the gate functions implemented using only NAND gates are shown in figure 10.21.



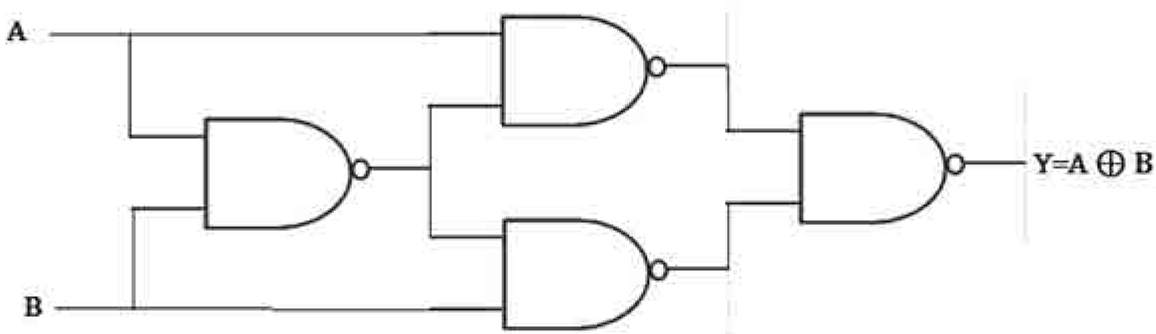
(a) NOT using NAND



(b) AND using NAND



(c) OR using NAND



(d) EXOR using NAND

Fig 10. 21 Fundamental gates using NAND only

> *Activity 4*
>
> ***Now you try to design a logic circuit to implement the function of EXOR gate using NOR only and that of EXNOR using NAND only.***

10.8 BOOLEAN ALGEBRA

Digital circuits perform the binary arithmetic operations with binary digits 1 and 0.These operations are called logic functions or logical operations. The algebra used to describe logic functions symbolically is called *Boolean algebra*. Boolean algebra is a set of rules and theorems by which logical operations can be expressed symbolically in equation form which can be manipulated mathematically.

The theorems of boolean algebra are known as the ***Laws of Boolean.*** We can use these "Laws of Boolean" to reduce the number of logic gates and analyze digital circuits. As with the ordinary algebras, the alphabet (e.g. A,B,C etc) can be used to represent the variables. Boolean algebra differs from the ordinary algebra in that boolean constant and variables can have only two values; 0 and 1.

Certain basic Laws of boolean algebra such as commutative law, associative law and distributive law are similar to those in ordinary algebra.

10.9 DESCRIPTION OF THE LAWS AND THEOREMS

1) Laws of Complementation

The term complement simply means to change 1s to 0 s and 0 s to 1s.

Theorem 1 : If $A = 0$, then $\overline{A} = 1$

Theorem 2 : If $A = 1$, then $\overline{A} = 0$

Theorem 3 : The complement to complement of A is A itself.

$$\overline{\overline{A}} = A$$

2) Basic properties of AND operator

Theorem 4 : $A.\ 1 = A$

If A equals 0 and the other input is 1, the output is 0.

If A equals 1 and the other input is 1, the output is 1.

Thus the output is always equal to the input A.

Theorem 5 : $A.0 = 0$

As one input is always 0, irrespective of A, the output is always 0.

Theorem 6 : $A.A = A$

The output is always equal to the input A.

Theorem 7 : $A.\overline{A} = 0$

Regardless of the value of A, the output is 0.

3) Basic properties of OR operator

Theorem 8 : $A + 1 = 1$

If A equals 0 and the other input is 1, the output is 1.

If A equals 1 and the other input is 1, the output is 1.

Thus the output is always equal to 1 regardless of what value A takes on.

Theorem 9 : $A + 0 = A$

The output assumes the value of A.

Theorem 10 : $A + A = A$

The output is always equal to the input A.

Theorem 11 : $A + \overline{A} = 1$

Regardless of the value of A, the output is 1.

4) Commutative Law

Theorem 12:

A mathematical operation is commutative if it can be applied to its operands in any order without affecting the result. Addition and multiplication operations are commutative.

Example: $A + B = B + A$

$$AB = BA$$

Subtraction is not commutative:

$$A - B \neq B - A$$

There is no subtraction operation in boolean algebra.

5) Associative Law

Theorem 13:

A mathematical operation is associative if its operands can be grouped in any order without affecting the result. In other words, the order in which one does the OR operation does not affect the result.

$$(A + B) + C = A + (B+C) = (A + C) + B$$

Similarly, the order in which one does the AND operation does not affect the result.

$$(AB)\,C = A\,(BC) = (AC)\,B$$

6) Distributive Law

Theorem 14:

The distributive property allows us to distribute an AND across several OR functions.

Example: $A(B+C) = AB + AC$

The following distributive law is worth mentioning because it differs from what we would find in ordinary algebra.

$$A + (B\,.C) = (A + B)\,.(A + C)$$

10.10 DE-MORGAN'S THEOREM

A mathematician named De Morgan developed a pair of important rules regarding group complementation in boolean algebra.

Theorem-1

The theorem states that the complement of a product is equal to the sum of the complements. That is, if the variables are A and B, then

$$\overline{A.B} = \overline{A} + \overline{B}$$

Proof:

A	B	$\overline{A}$	$\overline{B}$	$\overline{A.B}$	$\overline{A}+\overline{B}$
0	0	1	1	1	1
0	1	1	0	1	1
1	0	0	1	1	1
1	1	0	0	0	0

Table 10.10

A study of the above table makes clear that the last two columns are equal .Therefore De-Morgans 1st theorem is proved.

Theorem -2

The theorem states that, the complement of a sum is equal to the product of complements. It can be written as

$$\overline{A+B} = \overline{A}\,.\,\overline{B}$$

Activity 5

Complete the columns as per De-Morgan's theorem

A	B	$\overline{A}$	$\overline{B}$	$\overline{A}.\overline{B}$	$\overline{A+B}$
0	0	1		1	
0	1		0		0
1	0	0		0	
1	1		0		0

Table 10.11

These theorems are illustrated using logic gates in fig 10.22.

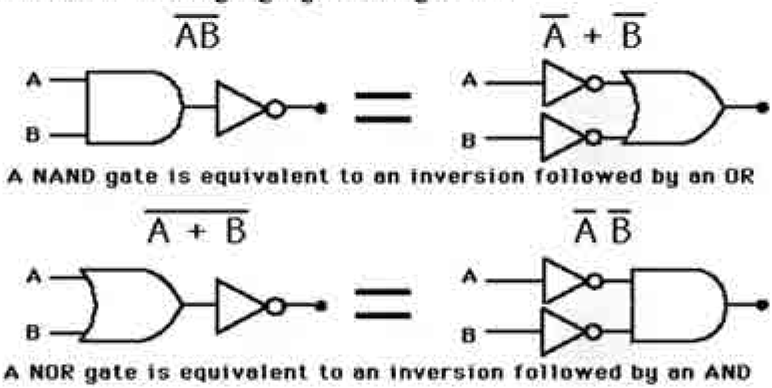


Fig 10.22 Gate equivalency of De-Morgan theorem

DeMorgan's Theorems

Fig 10.23 Illustration of De-Morgan's theorems

TABLES FOR THE LAWS OF BOOLEAN

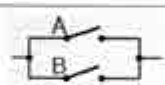
Boolean Expression	Description	Equivalent Switching Circuit
$A + 1 = 1$	A in parallel with closed = "CLOSED"	
$A + 0 = A$	A in parallel with open = "A"	
$A . 1 = A$	A in series with closed = "A"	
$A . 0 = 0$	A in series with open = "OPEN"	
$A + A = A$	A in parallel with A = "A"	
$A . A = A$	A in series with A = "A"	
$\overline{\overline{A}} = A$	NOT NOT A (double negative) = "A"	
$A + \overline{A} = 1$	A in parallel with not A = "CLOSED"	
$A.\overline{A} = 0$	A in series with not A = "OPEN"	
$A+B = B+A$	A in parallel with B = B in parallel with A	
$A.B = B.A$	A in series with B = B in series with A	
$\overline{A + B} = \overline{A} . \overline{B}$	invert and replace OR with AND	De-Morgan's theorem
$\overline{A.B} = \overline{A} + \overline{B}$	invert and replace AND with OR	De-Morgan's theorem

Table 10.12

Solved problem 10.1

Obtain the logic equation and truth table for the circuit in figure 10.24

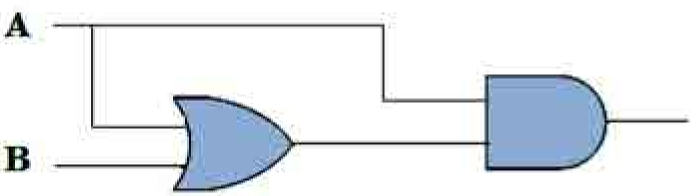


Fig 10.24 (a) Logic Circuit

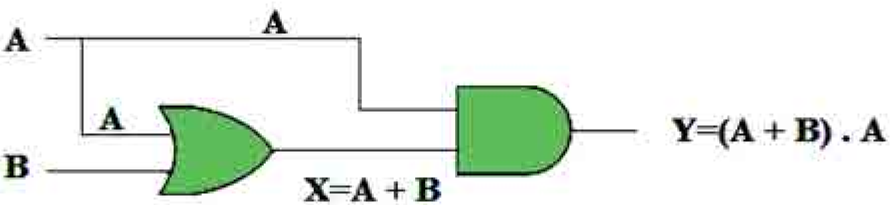


Fig 10.24(b) Logic Circuit With Output Expression Marked

The circuit consists of only 2 inputs. So there can only be four possible combinations of the input. The truth table of the logic circuit is given below:

It is seen that the columns 'Y' and 'A' are same or $(A+B).A=A$. So the above logic circuit can be simplified as a circuit without any gate.

Inputs		Output	
A	B	X	Y
0	0	0	0
0	1	1	0
1	0	1	1
1	1	1	1

Table 10.13

Solved problem 10.2

Draw the logic circuit corresponding to the equation $Y = AB + BC + \overline{B}C$ using basic logic gates. Simplify the equation and again implement the logic circuit corresponding to the simplified expression.

- *How many logic gates are required to implement the circuit for the given equation?*
- *How many logic gates are required to implement the circuit for the simplified equation?*

The logic gate circuit for the above equation is shown in fig. 10.25(a)

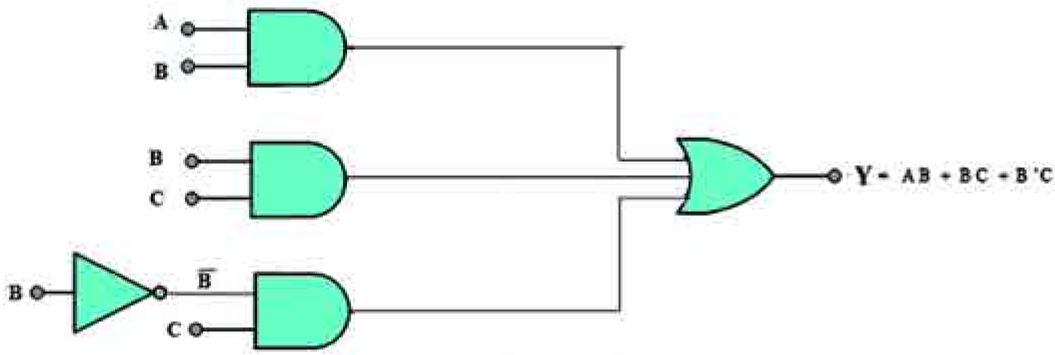


Fig 10.25(a) Logic Circuit

Using boolean law we can simplify it.

$$AB + BC + B'C = AB + C(B + B')$$
$$= AB + C.1$$
$$= AB + C$$

We can implement the simplified equation

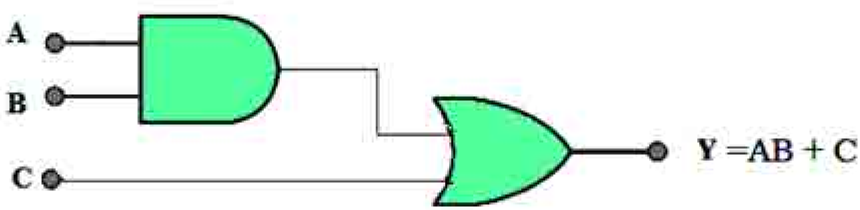


Fig 10.25(b) Simplified Circuit

From the above example we can see that by using boolean algebra the size of the circuit is reduced.

In the direct implementation, we have used three AND gates, one NOT and one OR gate, but in the second case we use only one AND and one OR gate since the logic expression is simplified.

Solved problem 10.3

Using the boolean law simplify the following expression: (A + B) (A + C)

Y = (A + B)(A + C)		
AA + AC + AB + BC	-	Distributive law
A + AC + AB + BC	-	Identity AND law (A.A = A)
A(1 + C) + AB + BC	-	Distributive law
A.1 + AB + BC	-	Identity OR law (1 + C = 1)
A(1 + B) + BC	-	Distributive law
A.1 + BC	-	Identity OR law (1 + B = 1)
Y = A + BC	-	Identity AND law (A.1 = A)

Then the expression: (A + B) (A + C) can be simplified to A + BC

Solved problem 10.4

Simplify the following Boolean Expression: A' B C' + A' B C

Let x = A' B and y = C'

The above Boolean expression becomes x y + x y'

= x (y + y')

= x = A' B

Solved problem 10.5

Prove that **A + A' B = A + B**

According to Distributive Law

A + A' B = (A + A') (A + B) = 1 · (A + B) = A + B

Solved problem 10.6

Simplify the given expression : A + A.B' + A'B

A + A.B' + A'B = A (1 + B') + A'B

= A .1 + A'B

= A+A'B

= A+B

Solved problem 10.7

Simplify the following boolean expression :A' B' C' + A' B C' + A' B C + A B' C'

= A' C' (B' + B) + A' B C + A B' C'

= A' C' + A' B C + A B' C'

$$= A'(C' + BC) + A B' C'$$
$$= A'(C' + B)(C' + C) + A B' C'$$
$$= A'(C' + B) + A B' C'$$
$$= A'C' + A'B' + A B'C'$$

Solved problem 10.8

Simplify the given expression : $ABC + AB'C + ABC'$

$$= AC (B + B') + ABC'$$
$$= AC .1 + ABC'$$
$$= AC + ABC'$$
$$= A (C + BC')$$
$$= A (C + B)$$

Solved problem 10.9

Construct a Truth Table for the logical functions at points C, D and Y in the circuit shown in figure 10.26 (a) and identify a single logic gate that can be used to replace the whole circuit.

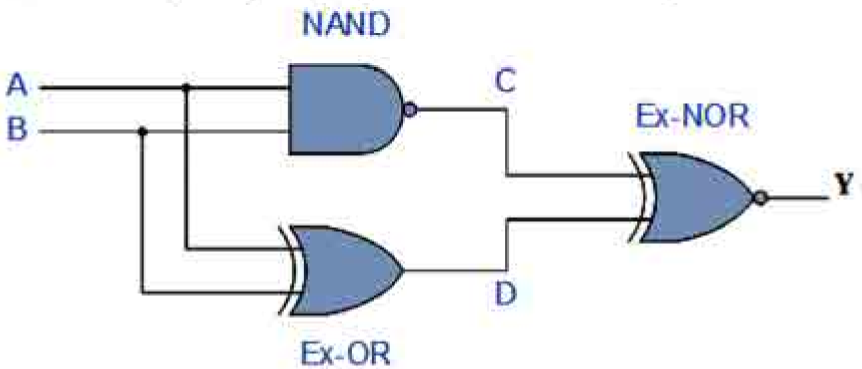


Fig 10.26(a) Logic Circuit

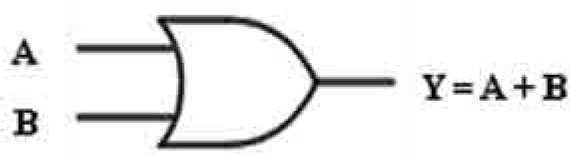


Fig 10.26(b) Simplified Logic Circuit

First observations tell us that the circuit consists of a 2-input NAND gate, a 2-input EX-OR gate and finally a 2-input EX-NOR gate at the output. As there are only 2 inputs to the circuit labelled A and B, there can only be 4 possible combinations of the inputs (2^2) and these are: (0, 0), (0,1), (1,0) and finally (1,1). Plotting the logical functions from each gate in a tabular form will give us the following truth table for the whole of the logic circuit.

Inputs		Output at		
A	B	C	D	Y
0	0	1	0	0
0	1	1	1	1
1	0	1	1	1
1	1	0	0	1

Table 10.14

From the truth table above, column C represents the output function generated by the NAND gate, while column D represents the output function from the Ex-OR gate. Both of these two output expressions then become the input condition for the Ex-NOR gate at the output.

It can be seen from the truth table that an output at Y is 1 when any of the two inputs A or B is at logic 1. The only truth table that satisfies this condition is that of an OR Gate. Therefore, the whole of the above circuit can be replaced by one **2-input** OR Gate.

Solved problem 10.10

Find the Boolean algebra expression for the circuit in figure 10.27 (a).

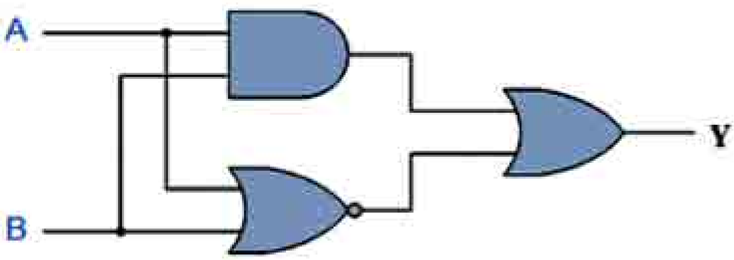


Fig 10.27(a) Logic Circuit

The system consists of an AND Gate, a NOR Gate and finally an OR Gate. The expression for the AND gate is A.B, and the expression for the NOR gate is A+B. Both these expressions are the inputs to the OR gate. Thus the final output expression is given as:

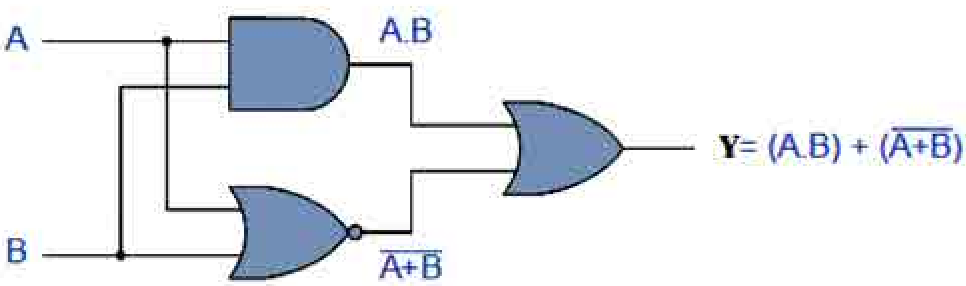


Fig 10.27(b) Redrawn With Output Expression

Inputs		Intermediates		Output
B	A	A.B	$\overline{A+B}$	Y
0	0	0	1	1
0	1	0	0	0
1	0	0	0	0
1	1	1	0	1

Table 10.15

This expression $Y=(A.B)+(\overline{A+B})$ can be simplified as follows.

According to De Morgan $\overline{A+B}=\overline{A}.\overline{B}$.

Therefore the above expression becomes $Y=A.B+\overline{A}.\overline{B}$.

This expression is the output of XNOR gate. Therefore the above circuit can be replaced by a single ExNOR gate.

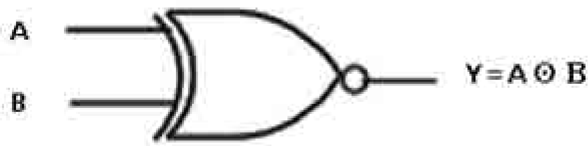


Fig 10.27 (c) Simplified Circuit

Activity 5

Find the boolean algebra expression for the following system.

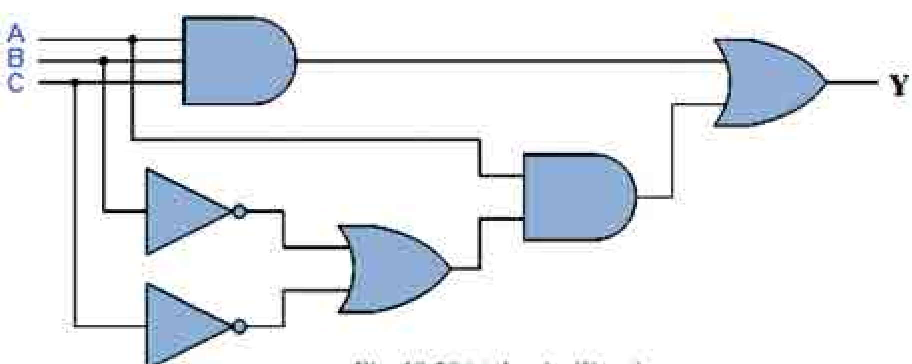


Fig 10.28(a) Logic Circuit

This circuit seems to be more complicated than the earlier one to analyze.But it consists of only AND, OR and NOT gates connected together. As with the previous boolean example, we can write the boolean notation for each logic function in turn to give us a final expression for the output Y.

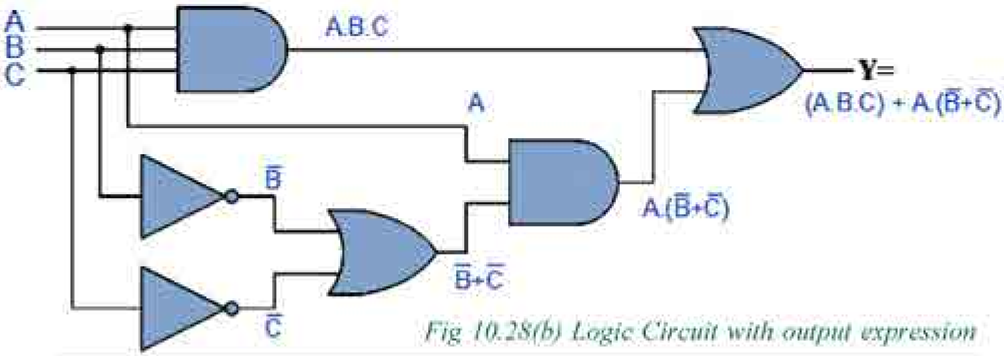


Fig 10.28(b) Logic Circuit with output expression

Inputs			Intermediates					Output
C	B	A	A.B.C	B	C	B+C	A.(B+C)	Y
0	0	0	0	1	1	1	0	0
0	0	1	0	1	1	1	1	1
0	1	0	0	0	1	1	0	0
0	1	1	0	0	1	1	1	1
1	0	0	0	1	0	1	0	0
1	0	1	0	1	0	1	1	1
1	1	0	0	0	0	0	0	0
1	1	1	1	0	0	0	0	1

Table 10.16

If we analyse this circuit the following facts can be noted.

1. Only if all of the inputs A, B, and C are ***high*** the product A.B.C will be high. At the same time $A.(\overline{B}+\overline{C})$ is zero and the output will be ***high.***

2. If A is ***high*** and either B or C is low then A.B.C will become low but $A.(\overline{B}+\overline{C})$ becomes high and so the output becomes ***high.***

3. If A is ***low*** and both of the inputs B and C are high A.B.C will be low. At the same time $A.(\overline{B}+\overline{C})$ is also low and so the output will be ***low.***

4. If A is ***low*** and either of the inputs B or C is low A.B.C will become low and $A.(\overline{B}+\overline{C})$ will also be low. Therefore the output will be ***low.***

In all these cases what ever is the input 'A' will appear as the output Y. So the gates shown need not get the required output and the entire circuit can be replaced by only one input labelled 'A'. So the boolean expression is Y = A.

10.11 DIGITAL SYSTEMS

The digital systems consist of two types- Combinational logic circuits and Sequential logic circuits

Augustus De-Morgan was an English scientist born in India, who wrote an article entitled "Theory of Probabilities" in the Encyclopaediametropolitana(1845). In this article, De Morgan presented (again) Laplace's TheorieAnalytique. De-Morgan was instrumental in the advancement of logic, reforming the restrictive approach of Aristotle, and is best remembered for his De Morgan's Laws, which are widely used in probability theory.

1. Combinational logic circuits

The outputs of **Combinational Logic Circuits** are determined only by the logical function and their current input state, logic "0" or logic "1", at any given instant of time as they have no feedback, and any changes applied to their input signals will immediately have an effect on the output. In other words, in a **Combinational Logic Circuit**, the output is dependant at all times only on the combination of its inputs .If the state of input is changed, the output will also be changed as the combinational circuits have "no memory", "timing" or "feedback loops". These logic gates are the building blocks of combinational logic circuits. The combinational logic circuits can be classified as shown in figure 10.29.

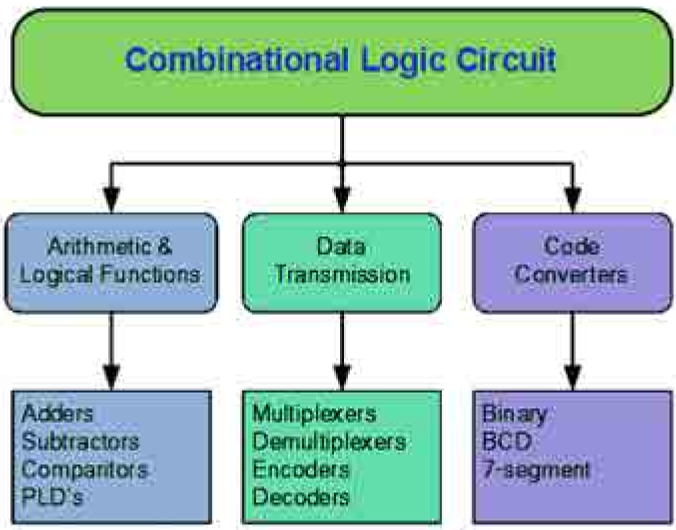


Fig.10.29 Classification Of Combinational Logic Circuit

1. Sequential logic circuits

Sequential Logic Circuits depend on their present inputs as well as their previous output states giving them some form of Memory.

10.12 HALF ADDER

The circuits that perform addition within the Arithmetic and Logic Unit (ALU) of the Central Processing Unit (CPU) of a computer and calculators are called adders. A unit that adds two binary digits is called a half adder and the one that adds together three binary digits is called a full adder. A half adder sums two binary digits to give a sum and a carry.

The Figure.10.30 shows the logic symbol of a half-adder, the two inputs are designated as A and B and the two outputs are designated as sum (S) and carry (C). The half-adder performs binary addition operation for the two binary inputs as shown in the table 10.17.

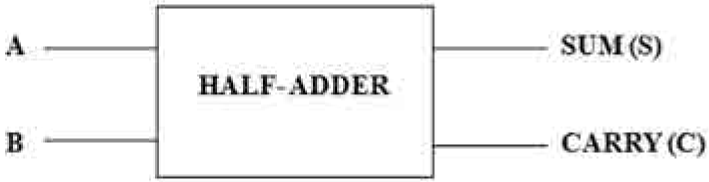


Fig10.30 Logic Symbol of Half Adder

The boolean realization of binary addition is shown in the truth table. Here A and B are the inputs to give a sum S and a carry C.

INPUT		OUTPUT	
A	B	SUM	CARRY
0	0	0	0
0	1	1	0
1	0	1	0
1	1	0	1

Table 10.17 Truth Table

The boolean functions corresponding to the sum and carry are

$$S = \mathbf{A} + B$$

$$C = A.B$$

This can be realized using the logic circuit as shown in fig. 10.31.

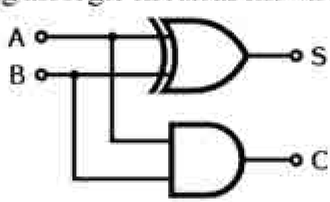


Fig 10.31 Logic Circuit of Half -Adder

In a half adder, an AND gate is added in parallel to the XOR gate to generate the carry and sum respectively. The 'sum' column of the truth table represents the output of the XOR gate and the 'carry' column represents the output of the AND gate.

10.13 FULL ADDER

A half adder logic circuit is a very important component of the computing systems. As this circuit cannot accept a carry bit from a previous addition, it is not enough to fully perform additions for binary number greater than 1. A full adder sums three input bits. It consists of three inputs and two outputs. Two of the inputs represent the two significant bits to be added and the third one represents the carry from the previous significant position. The Logic Symbol of Full Adder is shown in figure 10.32.

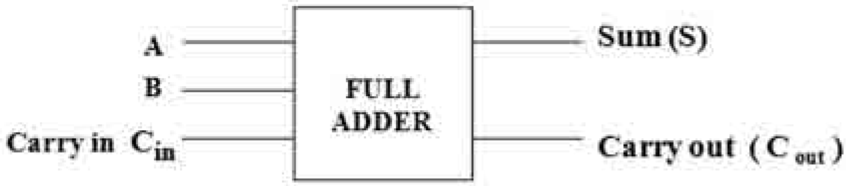


fig .10.32 Logic Symbol of Full-Adder

Here A and B are referred to as the inputs, C_{in} is the carry from the previous stage, C_{out} is the carry output and S is the sum. The truth table of Full Adder is shown in table 10.11.

INPUT			OUTPUT	
A	B	C_{in}	S	C_{out}
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

Table 10.18 Truth Table of a Full-Adder

The carry bit $\mathbf{C_{out}}$ is 1 if both *A* and *B* are 1, or if one of *A* and *B* is 1 and the input carry, C_{in} is 1. The sum bit *S* is 1 if there exist odd number of '1's in the three inputs. S is the XOR of the three inputs. Hence, Logic equations for the output of the full adder are;

$$S = A \oplus B \oplus C_{in}$$

$$\mathbf{C_{out}} = (A.B) + (C_{in}.(A \oplus B)$$

Logic circuit of the full adder is shown in fig.10.33.

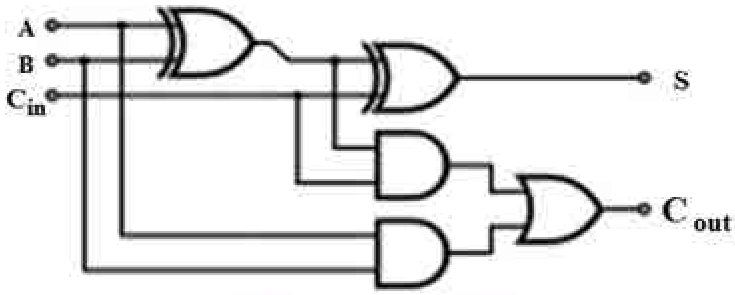


Fig 10.33 Logic circuit of Full -Adder

Parallel Binary Adder (Ripple-carry adder)

In most of the digital systems, addition of binary numbers with more than 1-bit is required. For example, computers and calculators use numbers with 8 to 64 bits. The addition of multi bit numbers can be accomplished using several full-adders. The 4-bit adder using full-adder circuits is capable of adding two 4-bit numbers. An example of a 4-bit adder is given below.

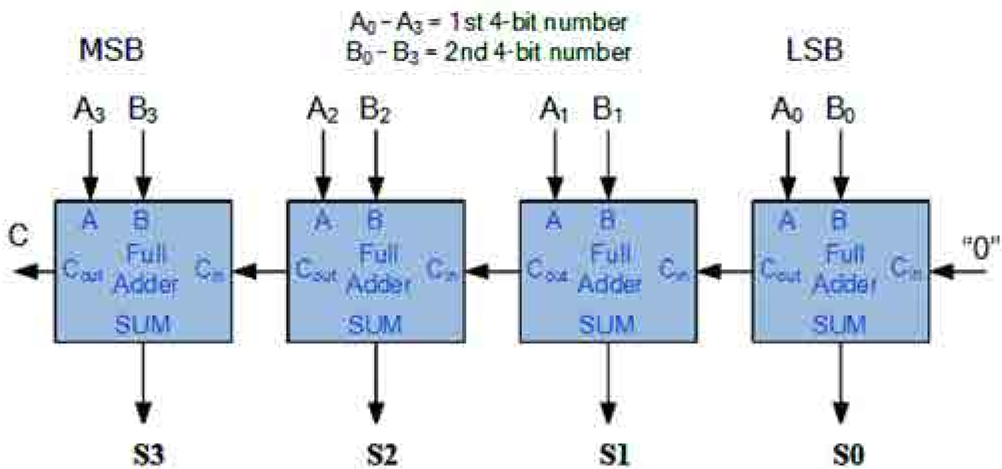


Fig.10.34 Four Bit Full Adder

Consider the addition of the following two 4-bit binary numbers:

0 1 1 1 + where A3 = 0, A2 = 1, A1 = 1 and A0 = 1

0 0 1 1 where B3 = 0, B2 = 0, B1 = 1 and B0 = 1

1 0 1 0 where S3 = 1, S2 = 0, S1 = 1, S0 =1 and Cout = 0

The operation of the adder may be checked as follows. Since A_0 and B_0 are the least significant BITs, they cannot receive a carry from a previous stage. So C_{in} of the LSB adder is usually grounded.

Step-1 In the problem above both A_0 and B_0 are 1. Their sum is therefore 0 and a carry is generated which is given to the C_{in} of the next full-adder for bits A_1 and B_1.

Step-2 Bits A_1 and B_1 are both 1 and the carry input is also 1. Therefore the sum output line S_1 gets a 1 and the carry line to the next stage is also 1.

Step-3 Since A_2 is a 1, B_2 is a 0 and the carry input is 1, the sum output line S_2 becomes 0, and the carry to the next stage becomes 1.

Step-4 Both inputs A_3 and B_3 are equal to 0, and the carry input line to this adder stage is equal to 1. Therefore, the sum output line S_3 will represent a 1 and the carry output line will have a 0 output. The sum should therefore be S_3=1, S_2=0, S_1=1 and S_0=0.

Let us sum up

Other than the commonly used decimal number system, there are other number systems such as binary with base 2,octal with base 8, hexadecimal system with base 16 etc. Any number in one number system can be converted into the corresponding number in any other number system. Hexadecimal number system consists of 16 characters including numbers from 0 to 9 and alphabets from A to F. A logic gate gives output according to some logic relationships with the inputs. Primary logic gates are AND, OR and NOT. Other gates like NAND, NOR, XOR, XNOR etc. are derived gates. NAND and NOR gates are called universal gates. If A and B are the inputs then the AND gate output is A.B. OR gate output is A+B and if A is the input, the NOT gate output is $\overline{A}$. A two input XOR gate gives high output when either of the inputs is high. Algebra using binary numbers as variables is called boolean algebra. DeMorgan's theorem gives that the complement of a product of two variables is equal to the sum of individual complements and the complement of the sum of two variables is equal to the product of individual complements. Combinational logic circuits and sequential logic circuits are the two types of digital systems. The outputs of combinational logic circuits are determined only by the logic function of their current input state. Sequential logic circuits on the other hand depend on their present inputs as well as their previous output state. A unit that adds two binary digits is called a half adder and a unit that adds three bits is called a full adder. The addition of multi bit numbers can be accomplished using several full adders. Combination of such several full adders is referred to as the parallel binary adder or ripple carry adder.

Learning outcomes

The learner is able to;

- Explain the details of different types of numbering systems.
- Convert a number from one number system to another.
- Perform binary addition.
- Draw the symbols and truth tables of logic gates.
- Identify the logic equations of various gates.
- Point out the universal property of NAND and NOR gate.
- Explain the basics of boolean algebra and its theorems.
- Apply De-Morgan's theorem to solve various logic equations.
- Point out the responses of different logic systems - Combinational and Sequential logic circuits.
- Draw and explain the working of half adder, full adder and parallel binary adder circuits.

Evaluation items

Multiple choice questions

1. In boolean algebra ,the plus sign (+) indicates ....

   a) AND operation b) OR operation c) NOT operation d) None of these

2. $\overline{A+B}$ = ...

   a) A + B b) A + B c) A.B d) A.B

3. A+ A.B = ...

   a) B b) A c) A + B d) none of these

4. (110110)2 = (   )10

   a) 24 b) 38 c) 54 d) 108

5. The base of a hexadecimal number is..........

   a) 2 b) 8 c) 15 d) 16

6. The decimal equalent for 1111 in binary is..........

   a) 15 b) 7 c) 8 d)16

7. In Boolean algebra ,the plus sign (+) indicates ....

   b) AND operation b) OR operation c) NOT operation d) None of the above

8. Output is low when both of the inputs are high for..........

   a) OR gate b) AND gate c) Ex OR gate d) None of these

9. Select the odd man from the following.

   a) AND b) NAND c) NOT d) OR

10. When both of the inputs are low output will be high for..........

    a) OR b) NAND c) Ex OR d) AND

11. $(A+B)$ = ...

    a) $A + B$ b) $A + B$ c) $4A.B$ d) $A .B$

12. $A + A.B$ = ...

    a) B b) A c) $A + B$ d) none of these

13. Sum and Carry for a half adder circuit are obtained respectively using the gates..........

    a) Ex OR and OR b) Ex OR and NOT c) OR and AND d) Ex OR and AND

14. There are three inputs and two outputs for..........

    a) NAND gate b) Half adder c) Full adder d) Ex NOR

Answer Key

1.b 2.d 3.c 4.c 5.d 6.a 7.b 8.c 9.b 10.b 11.d 12.c 13.d 14.c

Descriptive type questions

1. A unit that adds two binary digits is called a ___________
2. A full adder can be constructed from two ___________ and a ___________ gate.
3. Simplify $Y=AB'+(A'+B)C$.
4. Simplify $Y=(A'+B)(A+B)$.
5. Simplify the expression $A'B+A.B+A'B'$.
6. Draw the logic circuit for the equations.

i.	Q	=	$AB'+A'B$	ii.	Y	=	$A'B'+C$
iii.	Q	=	$AB+AC+BC$	iv.	Z	=	$(A+B).C$
v.	X	=	$(A'+C).(A+B')$	vi.	Z	=	$(A+B).(B+C).(A+C')$

7. State De Morgan's Theorem.
8. Determine the truth table for the following boolean functions $E=A'+(B.C)+D'$.
9. Draw the logic symbol and logic circuit of half adder.
10. What is the basic difference between half and full adder circuits?
11. Convert the logic circuit shown in fig.10.35 into a boolean equation.

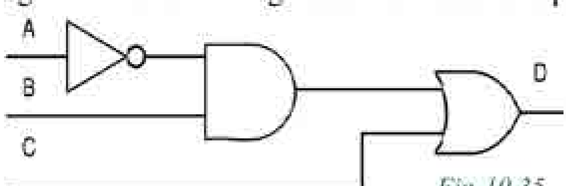


Fig 10.35

11 MEASURING INSTRUMENTS

INTRODUCTION

Suppose that an electronic device such as TV or Radio is not working properly. How can we find out the problem inside it? For this, we need to measure various electrical parameters like voltage, current, resistance etc.

Electrical and electronic measuring instruments are used to measure these electrical parameters. There are instruments which can be used to visualize and analyse signal waveforms to determine the properties of signals such as amplitude, frequency, phase etc. In this chapter let us discuss some of the important measuring instruments.

A Cathode Ray Oscilloscope (CRO) is used to see the waveforms at different points in a circuit. For example, now you are familiar with RC phase shift Oscillator. Using CRO, you can see the waveforms at different points of the phase shifting network. A CRO can also be used for other purposes like measuring voltage, time period, frequency and phase.

11.1 GALVANOMETER

Are you familiar with a galvanometer? It contains a pointer which moves over a particular scale. Have you ever wondered how the movement is caused?

The galvanometer consists of an iron coil mounted between the poles of a permanent magnet. The coil is wound on a bobbin and is free to move by 90^0. An aluminium pointer is attached to the coil. When the coil rotates, the pointer moves over a scale.

How does the pointer move? A current flowing through the coil creates a magnetic field. This magnetic field interacts with the magnetic field of the permanent magnet. This produces a force (called deflecting force) which moves the pointer. A galvanometer is specified in terms of its full scale deflection current and internal resistance. A galvanometer can be converted into an ammeter or a voltmeter.

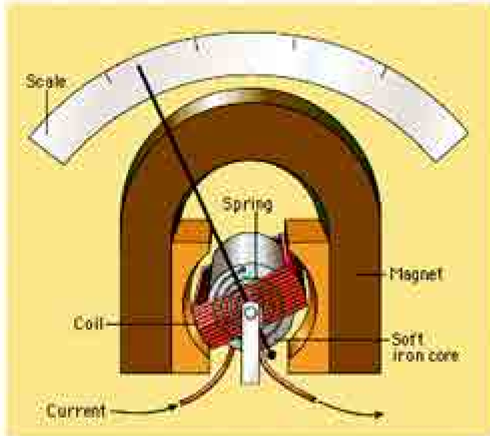


Fig. 11.1 Galvanometer - Internal diagram

11.2 VOLTMETER

Consider a galvanometer with internal resistance of 500Ω and a full scale deflection current of 0.1mA. So the maximum voltage that can be applied to the terminals is 0.1mA × 500Ω = 50 mV. So 0-50mV can be directly measured by this meter by placing a voltage scale below the pointer. The maximum reading on the scale is 50mV.

Then how can we measure a voltage higher than 50 mV? This can be done by connecting a high value resistance R_S in series with the meter as shown in the fig. 11.2 whereby the excess voltage can be dropped across it.

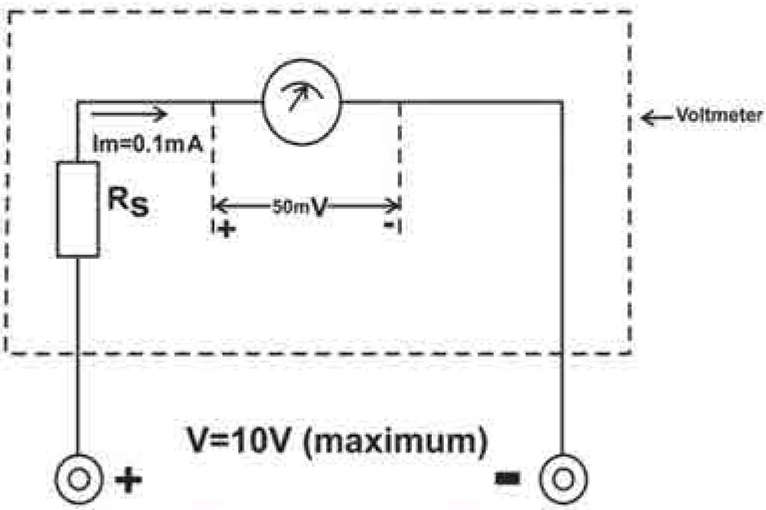


Fig. 11.2 Galvanometer as a voltmeter

Let us see how we can convert this meter to measure 0 – 10V.

From the figure,

$$(0.1 \times 10^{-3} \times R_S) + 500 \times 0.1 \times 10^{-3} = 10V$$

$$(R_S + 500)\, 0.1 \times 10^{-3} = 10V$$

$$R_S + 500 = 10/(0.1\times10^{-3})$$
$$= 10^5\Omega$$

Or $$R_S = 99.5\ k\Omega$$

So when 99.5kΩ is connected in series with the meter and 10V is applied, 0.1mA flows through the meter and it shows full deflection. If we place a voltage scale 0-10V in this meter, it will show 10V as reading. If the applied voltage is 5V, then the current in the circuit will be 0.05mA and it is half of the full deflection current. Hence the deflection in the meter will be half and it will read 5V. In this way the meter reads any voltage between 0 and 10V. Similarly, the galvanometer can be converted to a voltmeter of any range by connecting a suitable series resistor R_S.

Generally to extend the range of the voltmeter to a voltage V,

$$R_S = \frac{V}{I_g} - R_M$$

V → voltage to be measured

I_g → full scale deflection current

R_M → meter resistance

R_S is called the multiplier as it multiplies the voltage range. In a voltmeter, different voltage ranges are selected using a switch. The switch connects to different multipliers.

The above voltmeter can read DC voltages only. To read an AC voltage, a full wave rectifier is to be used along with the meter. When different AC voltages are to be measured, the rectifier produces proportional DC voltage and the meter produces corresponding deflection. We read this deflection in this scale as the corresponding AC voltage. Voltmeter must always be connected in parallel with the portion of the circuit across which the voltage is to be measured.

Check your progress:

You are given a galvanometer with full scale deflection current of 100 μA. Its resistance is 100 Ω. Determine the series resistance needed to convert it into a voltmeter with a range of 100V.

$$R_S = \frac{V}{I_g} - R_M$$

$$= \frac{100}{100\times10^{-6}} - 100 = 10^6$$

999.9 kΩ

11.3 AMMETER

Consider the same meter mentioned above having a full scale deflection current of 0.1mA and internal resistance of 500 Ω. This meter can measure a maximum current of 0.1 mA. For increasing the range of measurement, a resistor is to be connected in parallel with the meter to bypass the excess current. Suppose we want to convert this meter to read 0-0.5mA, then the excess 0.4mA should be bypassed through the parallel resistor.

Do you know how to calculate the value of this parallel (shunt) resistor? When maximum current to be measured which is 0.5 mA is given to the circuit, the current through the galvanometer should be only 0.1mA which is its full scale deflection current.

Voltage developed across the meter = $0.1\text{mA} \times R_M = 0.1\text{mA} \times 500 = 50\text{mV}$

The current to be bypassed through the shunt resistor R_{sh}.

$$I_{sh} = 0.4\text{mA}$$

Since the meter and R_{sh} are connected in parallel, their voltage drops will be the same.(see fig.11.3)

$$I_{sh} \times R_{sh} = 50\text{mV}$$

$$R_{sh} = 50\text{mV} / 0.4\text{mA} = 125\Omega.$$

Similarly, if 0.2mA is the maximum current to be measured, a 500 Ω resistor is connected in parallel with the meter and it bypasses 0.1mA.

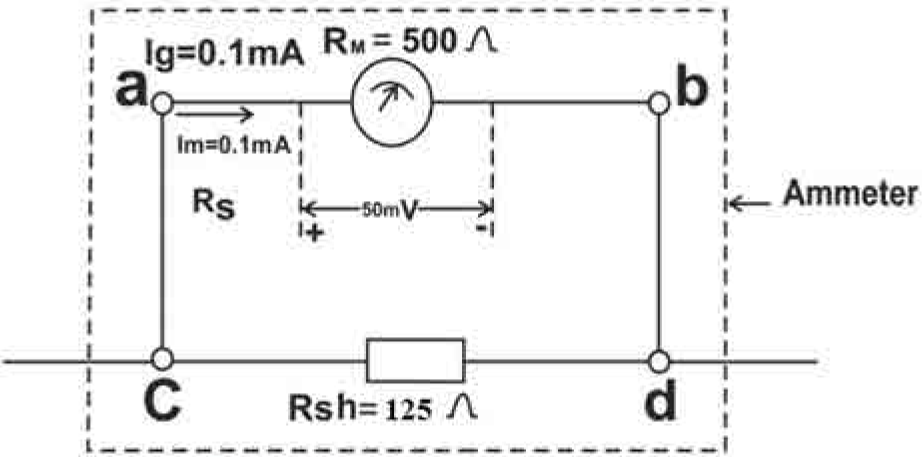


Fig. 11.3 Galvanometer as Ammeter

If larger current is to be measured, the resistor in parallel with the meter should be smaller so that this larger current passes through the parallel resistor. If I_{max} is the current to be measured, the current flowing through the resistor is

$$I_{max} - I_g$$

$$\text{ie, } I_{sh} = I_{max} - I_g$$

Since the meter and R_{sh} are connected in parallel, their voltage drops will be the same.

Or $$R_{sh}(I_{max} - I_g) = I_g \times R_M$$

$$\therefore R_{sh} = \frac{R_M \times I_g}{I_{max} - I_g}$$

So the galvanometer can be converted into an ammeter to read any range of values if we connect the required resistor in parallel.

The ammeter is always connected in series with the path in which the current is to be measured.

Check your progress:

A galvanometer with a full scale deflection current of 100µA and internal resistance of 100Ω is required to measure a maximum current of 10 mA. Determine the shunt resistance needed.

From the fig. 11.3.

$$R_{sh} = \frac{R_M \times I_g}{I_{max} - I_g}$$

$$= \frac{100 \times 100 \times 10^{6}}{(10 \times 10^{3} - 100 \times 10^{6}}$$

$$= 1.01\ \Omega$$

Now the meter is able to measure a maximum current of 10mA allowing 100µA to flow through the galvanometer and the rest through the shunt resistance. If we give 5mA to the ammeter, only 50µA flows through the galvanometer and it shows half of the maximum deflection and we read this current as 5mA.

A **multimeter** is an instrument that integrates the functions of voltmeter, ammeter and ohmmeter into a single unit and hence all these quantities can be measured with it.

11.4 CATHODE RAY OSCILLOSCOPE

This is the most important and versatile instrument used in laboratories. It gives a visual presentation of a signal waveform. It is used for trouble shooting in radio and television receivers and for laboratory measurements. The oscilloscope can measure voltage, amplitude, frequency and phase shift. In fact, an oscilloscope works as an 'eye for electronic engineers'.

A CRO is basically a very fast X-Y plotter. It plots the given signal waveform on a fluorescent screen.

Block diagram of a CRO

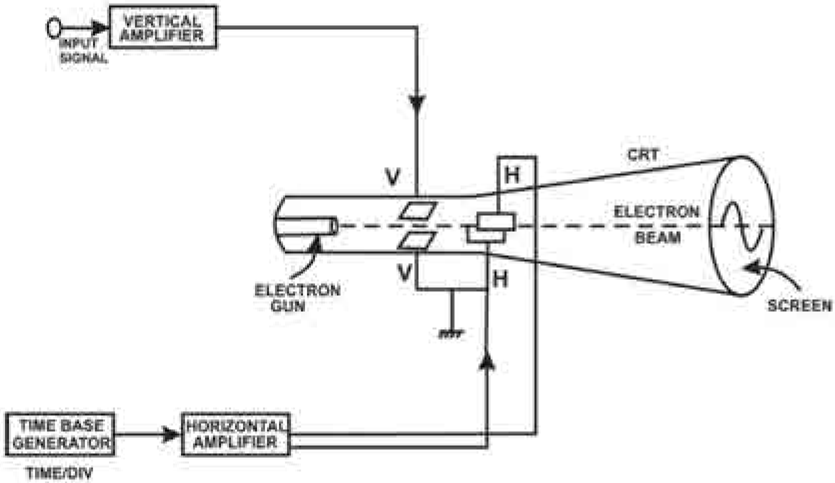


Fig 11.4 Block diagram of CRO

The important sub-systems of a general purpose CRO are shown in Fig 11.4. This figure does not show all the sub-systems but these are the minimum stages required.

(i) Cathode ray tube

The heart of the oscilloscope is the Cathode Ray Tube (CRT), on the screen of which a visible spot moves according to the variation of a signal. The rest of the instrument consists of the circuit which is necessary to operate the CRT.

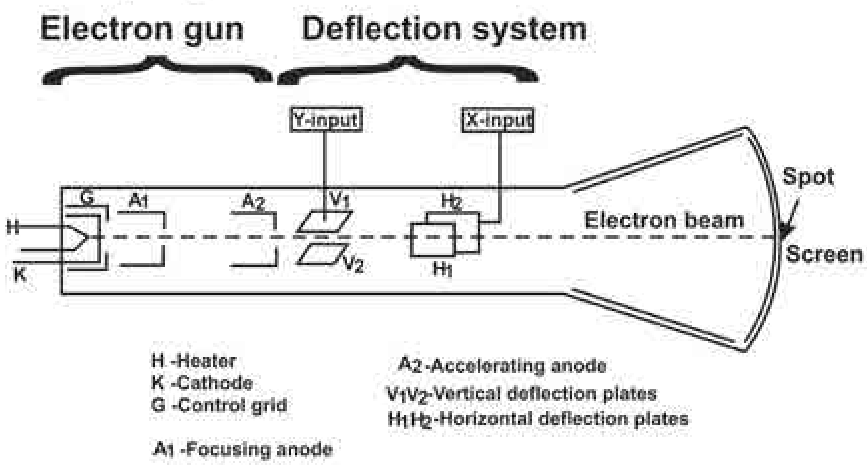


Fig 11.5 Internal diagram of CRT

CRT is a vacuum tube of special geometrical shape enclosed within a glass envelope. It converts an electrical signal into a visible one. Fig 11.5 shows the schematic diagram of a cathode ray tube along with its control circuits. There is a cathode which is heated by a heater. The cathode emits electrons. The electrons are accelerated to a high velocity and finally focused on to the screen which is coated with some fluorescent material. A spot of bright light is obtained on the screen where the electron beam strikes. The electron beam from the cathode is deflected by a suitable circuitry on its journey towards the screen. As a result a visual wave form is obtained on the screen.

The main parts of a CRT are described below.

a) The fluorescent screen

This is the inside face of the tube and is coated with some fluorescent materials such as zinc oxide, phosphor etc. This material emits light when high velocity electrons strike it, converting the energy of the electrons into visible light. Hence the name fluorescent screen. Depending upon the phosphor material used in the fluorescent screen it is possible to have green, orange or white light. This spot of bright light can be moved on the screen in horizontal and vertical directions with the help of controls.

b) The electron gun

The electron gun gets its name because it fires electrons at a very high speed. It consists of cathode (a metallic cylinder with one end closed and a heating filament inside), control grid (a metallic wire mesh) and focusing and accelerating anodes (metallic cylinders). Cathode is an electrode which is kept at a negative potential. When it is heated indirectly, it emits a large number of electrons. The control grid controls the beam current and consequently controls the intensity (or brightness) of the phosphorescent spot. Therefore, the knob controlling the grid voltage is labelled as intensity control. The electron beam is focused to a very small dot on the screen by the focusing anode. The accelerating anode gives the required acceleration to the electron beam.

c) Deflection plates

The electron beam passes through two pairs of parallel plates – Y-deflection plate and X-deflection plate.

The Y-deflection plates (also called vertical deflection plates) are placed horizontally in the tube. Any voltage applied to this set of plates moves the electron beam up or down. The bright spot on the screen will move along the Y-axis.

The X-deflection plates (or horizontal deflection plates) are kept vertically. Any voltage applied to this set of plates moves the spot on the screen to the left or to the right (along the X-axis).

If no voltage is applied externally to either set of plates, the spot should be located at the centre of the screen.

(ii) Vertical deflection system

This section is mainly used to supply the input signal to the vertical deflection plates with sufficient voltage to deflect the electron beam. The gain of the vertical deflection section can be controlled by adjusting the Volt/ Div control on the front panel of the CRO.

(iii) Horizontal deflection system

It consists of a number of amplifier stages and a time base generator or saw tooth oscillator. The time base generator provides the voltage for moving the electron beam horizontally. The horizontal amplifier increases the amplitude of this voltage. While we are adjusting the Time/Div control on the front panel of the CRO, we are changing the frequency of this time base generator.

Displaying waveform

As you know, CRO has horizontal and vertical deflection plates. If we apply a DC voltage to the X- plate, the spot at the centre of the screen shifts horizontally. Instead, if we apply a voltage waveform which has the shape of sawtooth to the X- plate, what will happen?

A sawtooth waveform has a linearly increasing voltage part and a suddenly decreasing votage part. It is shown in fig. 11.6.

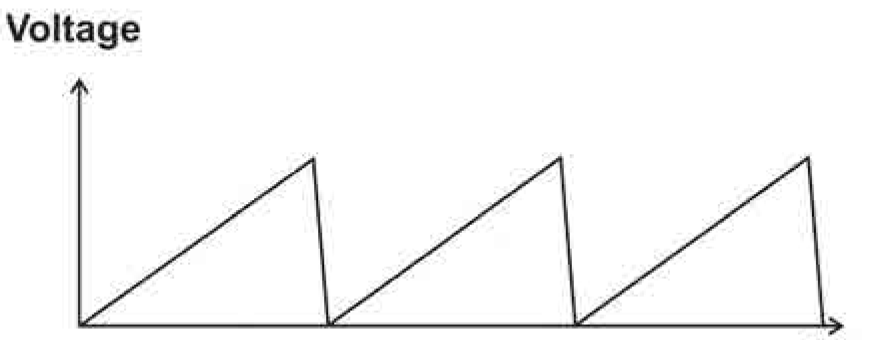


Fig 11.6 Sawtooth waveform

Now the electron beam will move fast horizontally forward and backward continuously so that we will see a horizontal line instead of a spot.

Meanwhile, if we apply another signal to the Y plate of the CRO, it will move the horizontally moving electron beam vertically too. So the earlier horizontal line will be modified in the shape of the signal applied to the vertical plate.

Usually in a CRO, the horizontal deflection plate is supplied with an internally generated sawtooth waveform and the signal to be displayed is given to the vertical plate. As an example if a sine wave is given to the Y plate , we see a sine wave on the screen.

Measurements using CRO

A CRO can be used for measuring voltage and the time period of a signal directly. We can measure the current indirectly. The screen of the CRO is a graph; the variable along the Y - axis is the voltage and the variable along X- axis is the time. Usually, the CRO has two input channels and you can input the signal through either of these input channels. Otherwise, you can input two different signals simultaneously to CRO through these input channels and can observe the two signals on the screen at the same time. The device has a "volts/ division" knob for each input channel and a common "time/division" knob. The voltage pointed by the mark on the volts/div knob indicates the voltage of one main division along Y-axis. Similarly the time pointed by the mark on the time/div knob indicates the time of one main division along X-axis.

a) Voltage measurement

At first the ground level is adjusted to lie on the X-axis by varying the Y-level adjusting the knob. Now the signal whose voltage is to be measured is input to the CRO and the signal is seen on the screen. The height of this signal is calculated in terms of the number of divisions along Y-axis. This number of divisions multiplied by the reading indicated by the volts/div knob gives the voltage of the signal. The device can measure both DC and AC voltages equally well.

b) Current measurement

In a CRO, we cannot measure current directly since this is basically a voltage measuring instrument. So to measure the current, we take a standard value resistance and allow this current to flow through this resistance. The voltage developed across this resistor can be measured using a CRO. Now the current is calculated by using the equation, I= V/R.

c) Time period / frequency measurement

The signal whose time period is to be measured is given to the input of the CRO and the waveform is observed on the screen. Now the time of one cycle is to be measured to get the time period. The number of divisions along X-axis within one cycle is counted and it is multiplied by the time indicated by the mark of the time/div knob. This gives the time period of the signal. The frequency of the signal is obtained by taking the reciprocal of the time period.

11.5 SEVEN SEGMENT DISPLAY

The Light Emitting Diode (LED) finds its place in many applications in the modern electronic fields. One of them is the Seven Segment Display. Seven segment display is a form of electronic display device for displaying decimal numerals.

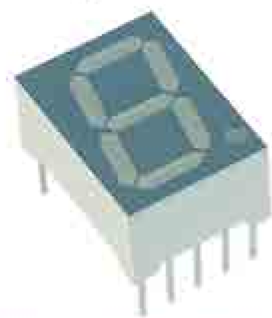


Fig 11.7 A single digit 7 segment display

The name seven segment comes because it contains 7 segments. The segments are arranged as shown in the fig. 11.7. Seven segment displays may use a liquid crystal display or LED for each segment. Seven segment displays are widely used in digital clock, electronic meters and other electronic devices for displaying numerical information. Here in this figure the segments are named from A to G. The purpose of arranging it in this style is that, all the digits can be displayed using this by selectively making the LEDs ON and OFF (see the last column of table 11.1).

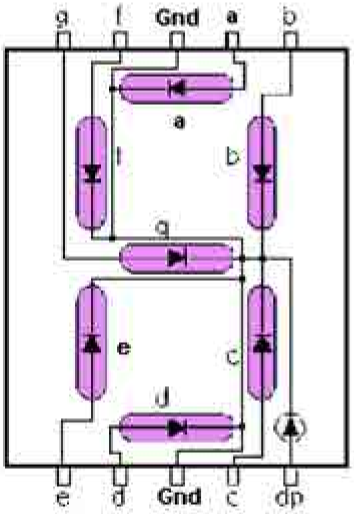


Fig 11.8 Arrangement of segments in seven segment display

Binary Coded Decimal (BCD) to Seven Segment conversion

The fig 11.9 shows a typical interface to a seven segment display. First we have to convert the decimal into BCD. Then the binary numbers for each decimal is given to the converter. The converter gives the output word (a,b,c,d,e,f,g). If a bit in that word is 1, it will turn on the corresponding light and if the output bit is 0, it will turn off.

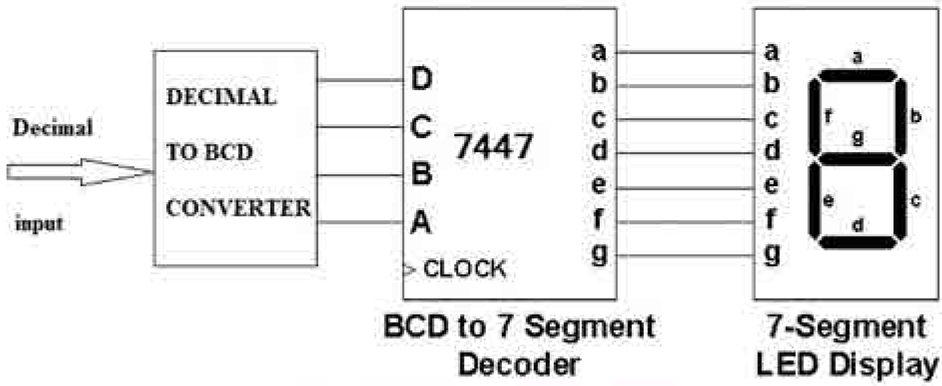


Fig 11.9 BCD to 7 segment converter

Seven Segment Display Table

The table 11.1 shows the combination of BCD inputs and their corresponding outputs. If the output bit is 1 the corresponding segment glows. The table is written in such a way that the corresponding decimal number is displayed when the selected LEDs glow.

BCD means binary coded decimal. The number system is decimal, but each digit is coded as binary. For example $(24)_{10}$ in BCD is 00100100.

BCD input				Segment outputs							Display
D	C	B	A	a	b	c	d	e	f	g	
0	0	0	0	1	1	1	1	1	1	0	0
0	0	0	1	0	1	1	0	0	0	0	1
0	0	1	0	1	1	0	1	1	0	1	2
0	0	1	1	1	1	1	1	0	0	1	3
0	1	0	0	0	1	1	0	0	1	1	4
0	1	0	1	1	0	1	1	0	1	1	5
0	1	1	0	1	0	1	1	1	1	1	6
0	1	1	1	1	1	1	0	0	1	0	7
1	0	0	0	1	1	1	1	1	1	1	8
1	0	0	1	1	1	1	1	0	1	1	9

Table 11.1 BCD to 7 segment conversion table

Activity 1

List out the devices in which the seven segment display is used.

11.6 DOT MATRIX DISPLAY

You might have noticed the display boards in railway stations and airports. It uses a dot matrix display. A dot matrix display is used to display information in machines, clocks, railway departure indicators and many other devices requiring a simple display device of limited resolution. The display consists of a matrix type arrangement of lights or mechanical indicators arranged in a rectangular configuration (other shapes are also possible, although not common) such that by switching ON or OFF selected lights, text or graphics can be displayed. Each dot in a matrix can also be a LED. The dot LED can be separately turned on or off to obtain the required display. The fig. 11.10 shows a LED dot matrix display in a bus indicating the route of journey.

Fig 11.10 Dot matrix display on KSRTC bus

A dot matrix display system consists of a dot matrix converter which converts instructions from a processor into signal which turns on or off the light in the matrix so that the required display is produced.

Fig 11.11 Single digit dot matrix display

0	1	1	1	0
1	0	0	0	1
1	0	0	0	1
1	0	0	0	1
1	1	1	1	1
1	0	0	0	1
1	0	0	0	1
1	0	0	0	1

Fig 11.12 Letter A displayed on dot matrix

Usually 5×7 dot matrix display is used to display alphanumeric characters in the display system. Fig. 11.11 shows the arrangement of lights in a 5×7 matrix. The 5×7 dot matrix display format contains 5 horizontal dots and 7 vertical dots. If each of the dot position corresponds to a source of light, the off lamp corresponds to logic zero and on lamp corresponds to logic1. Fig. 11.12 Shows a 5x8 dot matrix display for the letter A.

Activity 2

By drawing a 5×7 dot matrix indicate the first letter of your name.

Now a days dot matrix bicolor LED display information board features high resolution and gentle color and offers four different selections. These are used for advertisement boards in cities, display scores in stadium etc.

Fig 11.13 Dot matrix score board

A bigger dot matrix display can be constructed by using large sized matrix which may contain several thousands of dots of LEDs. The quality of the picture or text depends on the resolution of the dot matrix display. The resolution can be improved by increasing the number of dot per area.

The dynamic dot matrix display displays running displays or movies. This is obtained by turning the dots in the display ON and OFF very fast. A better dynamic display can be constructed using LED matrix since the switching time of LED is very small.

Let us sum up

A galvanometer is used to detect small electric current flowing through a circuit. It consists of an iron coil mounted within the field of a permanent magnet, it deflects. A galvanometer can be converted to a voltmeter to measure a high value of voltage by connecting a high resistance in series. The value of series resistance required can be calculated by using the equation $Rs = V/I_g - R_M$. To convert a galvanometer to an ammeter, a low resistance should be connected in parallel. The required shunt resistance can be calculated using the formula $R_{sh}=R_M x I_g/(I_{max}-I_g)$. Where I_{max} is the maximum current to be measured and I_g is the full scale deflection current of the galvanometer. Cathode ray oscilloscope (CRO) gives a visual indication of a signal wave form. It is used for trouble shooting in radio and TV receivers and for laboratory measurements. It can measure voltage amplitude, frequency and phase. Cathode ray tube is the heart of a CRO. The electron beam from the cathode is deflected by a suitable circuitry on its journey towards the screen. Seven segment display is used for displaying decimal numerals. It uses LCD or LED for each segment and it is used in digital clock, electronic meters etc. A BCD to seven segment converter converts binary to corresponding output word. Dot matrix display is a simple display device of limited resolution used in machines, clocks, railway departure indicators etc. It consists of a matrix type arrangement of lights. A 5x7 matrix display is an example of a display device used to display alphanumeric characters.

Learning outcomes

The learner is able to

- Explain the significance of measuring instruments like voltmeter, ammeter, multimeter etc.
- Explain how to convert a galvanometer into ammeter and voltmeter.
- List out the applications of CRO.
- Explain the constructional details of CRO.
- Measure current, voltage, frequency and time period using CRO.
- Explain the principle of operation and uses of the Seven segment display.
- Point out the principle of operation and the uses of Dot matrix display.

Evaluation items

Multiple choice questions

1. Which of the following instrument is used to measure the phase of a signal?

   a) Voltmeter b) Ammeter c) Multimeter d) CRO

2. Which of the following quantity can be measured directly by a CRO?

   a) Voltage b) Current c) Frequency d) Resistance

3. A galvanometer can be converted into a voltmeter by connecting............

   a) a large value resistance in parallel
   b) a large value resistance in series
   c) a small value resistance in parallel
   d) a small value resistance in series

4. A galvanometer can be converted into an ammeter by connecting............

   a) a large value resistance in parallel
   b) a large value resistance in series
   c) a small value resistance in parallel
   d) a small value resistance in series

5. If a DC voltage is applied to both X and Y deflection plates of a CRO, you will see.............on the screen

   a) a horizontal line
   b) a vertical line
   c) a spot at the centre of the screen
   d) a spot shifted away from the centre

6. The measurement using a CRO is very accurate because............

   a) the quantity is displayed
   b) the CRO draws no current
   c) the voltage and time range can be changed.
   d) none of these

7. A seven segment display contains...........

   a) seven different LEDs
   b) one single LED having seven segments
   c) any number of LEDs
   d) LEDs arranged as the number seven

8. A seven segment display is of...........

   a) LEDs b) LCDs c) lamps d) both a and b

9. The resolution of a dot matrix display can be increased by...........

a) increasing the number of LEDs
b) closely arranging the LEDs
c) both a and b
d) none of these

10. A dynamic dot matrix display is possible because...........

a) LEDs can produce different intensity light.
b) LEDs can be switched ON and OFF very fast
c) LEDs can be produced in different colors
d) LEDs can be made very small in size

Answers key

1.d 2.a 3.b 4.c 5.d 6.b 7.a 8.d 9.c 10.b

Descriptive type questions

1. How voltmeters of different ranges are produced?
2. What are the quantities measured by a voltmeter?
3. Write the need of a sawtooth waveform applied to the horizontal deflection plate of a CRO.
4. Explain the measurement of voltage, current and frequency using a CRO.
5. List the devices where you see a dot matrix display and a seven segment display.
6. You are given a galvanometer with internal resistance of 500Ω and a full scale deflection current of $100\mu A$. How will you convert this meter into a voltmeter of a range of 0-10V?
7. How will you convert the above galvanometer into an ammeter of 0-10mA?

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