POLITEKNIK MALAYSIA

KEMENTERIAN PENGAJIAN TINGGI

KOLEJ KOMUNITI MALAYSIA

SEMICONDUCTOR DEVICES

AZRINI IDRIS
MOHAMED ISA OSMAN
SARAH JEWAHID

DEPARTMENT OF ELECTRICAL ENGINEERING

Editor
Azrini Idris
Mohamed Isa Osman
Sarah Jewahid

Writer
Azrini Idris
Mohamed Isa Osman
Sarah Jewahid

Designer
Azrini Idris
Mohamed Isa Osman
Sarah Jewahid

First published 2021

Published by :

POLITEKNIK TUANKU SYED SIRAJUDDIN

Pauh Putra

02600 Arau

Perlis

ABSTRACT

This e-book aims at providing the students with the understanding of the basic operating principles of Semiconductor Devices and at the same time illustrates how the circuit have been derived from these principles. This e-book written based on the polytechnic syllabus for the Semiconductor Devices course taken by Electrical and Electronic Engineering students. The fundamental principles and applications of semiconductors are explained in this e-book to enable students to gain a good understanding of Semiconductor Devices and their applications.

The first chapter discusses the basic properties of semiconductors and introduces the characteristics of P-N junction. Chapter 2 discusses the characteristic of diode as a semiconductor device, the outlines of IV characteristics curve for silicon diode and the applications of the diode in other electronic circuit. Chapter 3 discusses the basic of Bipolar Junction Transistor (BJT), the characteristics and operation of BJT semiconductor, transistor configurations, DC operation, frequency response and their characteristic and the classes of amplifier. Tutorials are provided for all chapters to help students master the concepts covered by each topic. Answers are included at the end of the e-book.

ACKNOWLEDGEMENT

First of all, Alhamdulillah, thanks God Almighty for His guidance and blessing. We had succeeded in completing this Semiconductor Devices E-Book. We want to express our utmost gratitude to our Head Department of Electrical Engineering, Mr Shaffie Bin Husin, who supported us in grabbing this opportunity . Without his support, we would not be able to produce this E-Book. Not to forget the E-Learning team because it provides us with this opportunity and guides usin making this E-Book.

Besides, we also extend our gratitude to all friends and our lovely families for their kindness and sincere assistance in adding us to finish up this E-Book. Indeed, we have appreciated them. Again, thanks for everything.

Our hopes are, may this E-Book helps students out there, especially engineering students in polytechnic, ease them to understand about semiconductor devices. Nevertheless, we also need any comments from reads to help us improve our next debut. We hope this E-Book could ease everyone to understand and implement the technics and could fulfill everybody needs.

Thank you.

TABLE OF CONTENTS

UNIT 1
INTRODUCTION TO SEMICONDUCTOR

1.1 What Is Semiconductor?

A semiconductor device is an electronic component whose function is dependent on the electronic properties of a semiconductor material (most often silicon, germanium, and gallium arsenide, as well as organic semiconductors). Because of their dependability, compactness, and low cost, these devices have a wide range of applications such as illustrates in Figure 1.1. Discrete components, like as solid-state lasers, are employed in power devices, tiny optical sensors, and light emitters.

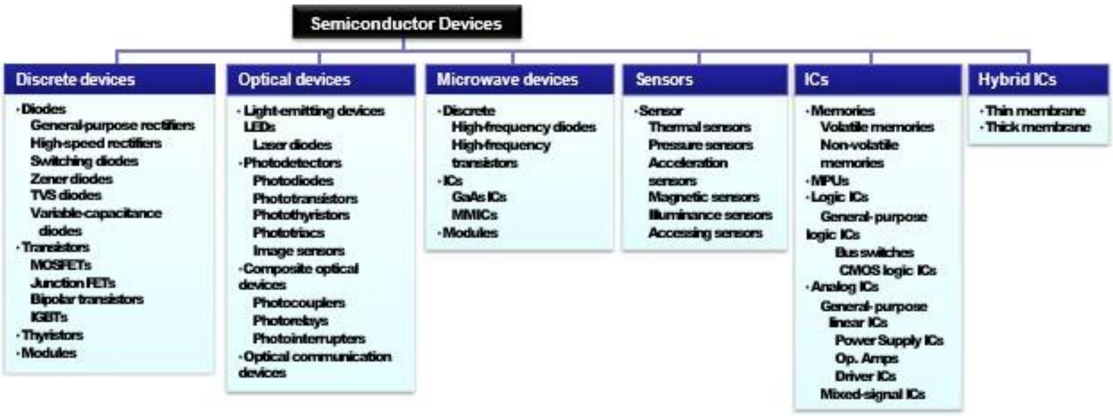


Figure 1.1 Application of semiconductor

1.2 Characteristics and electrical properties of semiconductors

- Semiconductors are materials that are neither conductors nor insulators. They have conductivity that is somewhere in the center of that of conductors and insulators.
- Examples of semiconductors are Germanium, Silicon, Carbon, and Selenium.
- Semiconductors have a resistivity range of 10^{-4} to 10^{8} Ω cm, whereas conductors have a resistivity range of 10^{8} to 10^{-4} Ω cm and insulators have a resistivity range of 10^{8} to 10^{18} Ω cm

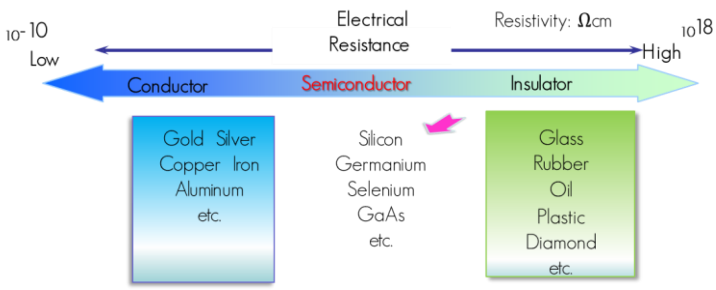


Figure 1.2 Resistivity range for different materials

1.2.1 Review of Basic Atomic Model

- Atoms are comprised of electrons, neutrons, and protons. Their characteristics are shown in Table 1.1.
- Electrons are found orbiting the nucleus of an atom at specific intervals, based upon their energy levels as in Figure 1.3.
- The outermost orbit is the valence orbit as shown in Figure 1.4. Valence band electrons are the furthest from the nucleus and have higher energy levels than electrons in lower orbits.
- The region beyond the valence band is called the conduction band. Electrons in the conduction band are easily made to be free electrons.

Table 1.1 Characteristics of atom

	Electron	Proton	Neutron
Size	Smallest and lightest particle	1800 times bigger than electron	Same size as proton
Charge	Negative	Positive	No charge

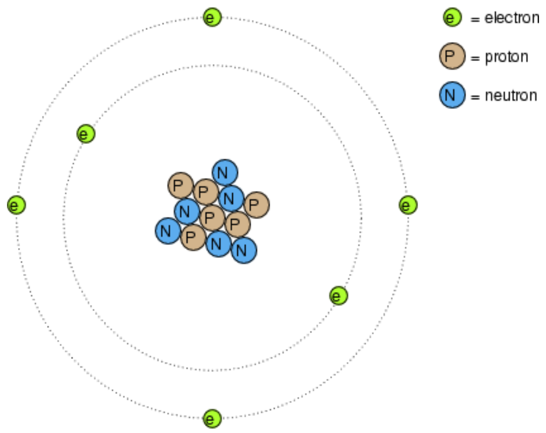


Figure 1.3 Atom orbit

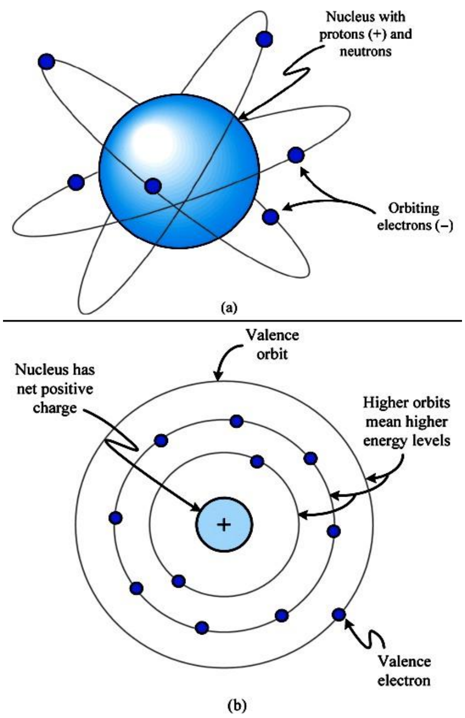


Figure 1.4 Atom layer

- Electron shells in an atom were formerly designated by letter rather than by number. Figure 1.5 illustrates multiple numbers of electron shells.
- The maximum number of electrons that any shell may hold is described by the equation $2n^2$, where "n" is the principal quantum number.
- The first shell (n=1) was labeled K, the second shell (n=2) L and so on as tabulated in Table 1.2.

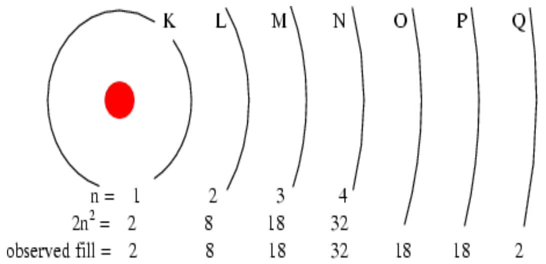


Figure 1.5 orbit/shell

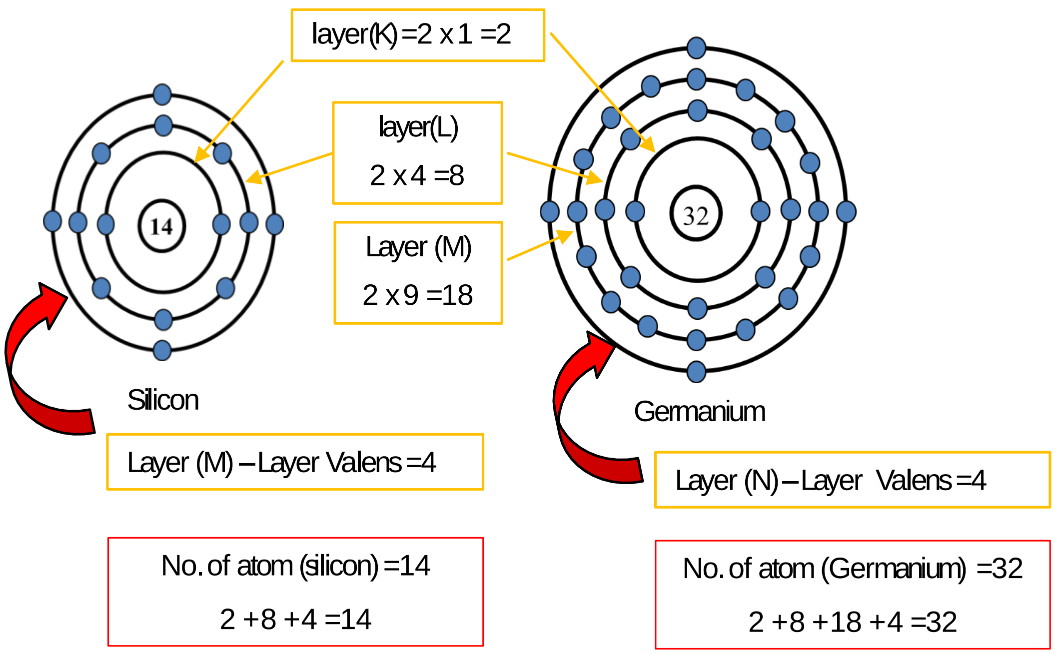
Table 1.2 Electron shells notation

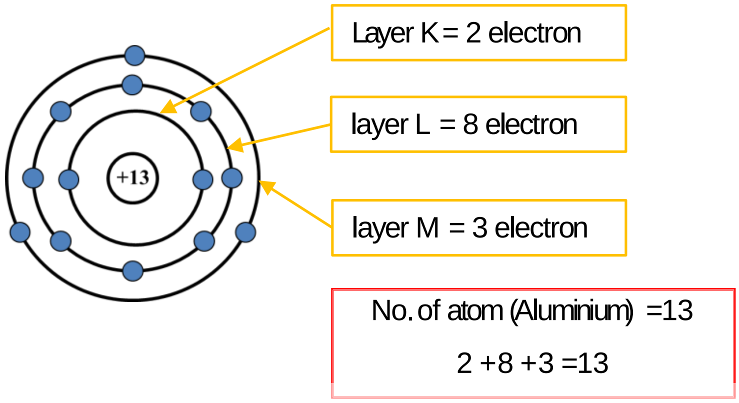
n	Shell	Maximum number of electrons
1	K	2
2	L	8
3	M	18
4	N	32
5	O	50
6	P	72
7	Q	98

Example 1.1

Determine number of atom for silicon, germanium and aluminium.

Solution :





1.2.2 Characteristics of Electron Valens Number

- The electrons in the outer most shell, or valence shell, are known as valence electrons.
- These valence electrons are responsible for the chemical properties of the chemical elements. The properties is tabulated as in Table 1.3.

Table 1.3 Properties of electron Valens

1-3 Valens electrons	5-8 Valens electrons	4 Valens electrons
Conductor	Insulator	Semiconductor
Conducts electricity	Does not conduct electricity	Electrical conductivity intermediate between insulator and conductor
Low resistivity. Atoms tend to release valence electrons	High resistivity. Atoms tend to accept electrons.	Does not easily release or accept electrons
Examples : gold, copper, silver, aluminium	Examples : glass, plastics, ceramics	Examples : silicon, germanium, carbon

1.2.3 Material

a) Conductor

- Support a generous flow of charge when a voltage source of limited magnitude is applied across its terminals. .
- Low resistance which permits electrons flow through easily. In other word, conductor allows electrical current flow.

b) Semiconductor

- Has a conductivity level somewhere between the extremes of an insulator and a conductor.
- Can allow or suppress electrical current flow.
- Can be conditioned to act as good conductors, or good insulators, or any thing in between.
- Silicon is the best and most widely used semiconductor.

c) Insulator

- Offers a very low level of conductivity under pressure from an applied voltage source.
- High resistance which suppresses electrical current flow so current does not flow in them .

1.2.4 Types of Semiconductor

Basically, semiconductor can be classified in two types as indicated in Figure 1.6.

a) Intrinsic Semiconductor

- pure semiconductors
- Example: Germanium (Ge) and Silicon (Si).

b) Extrinsic Semiconductor

- adding impurity to pure semiconductor through doping process to improve semiconductor conductivity.
- Two categories of impurity :
  a) Pentavalent impurity (N-type) – doped with extra electrons
  - Negative charge
  a) Trivalent impurity (P-type) – doped with material missing electrons that produce locations called holes
  - Positive charge

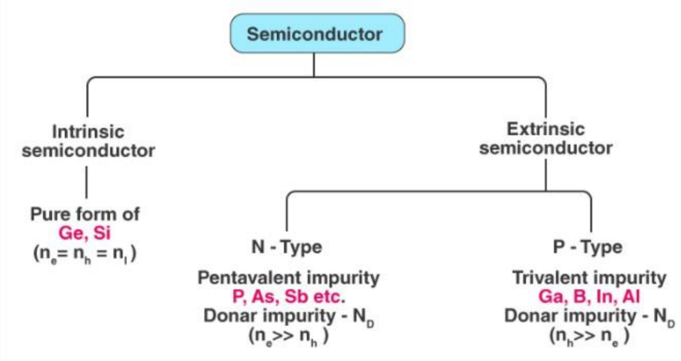


Figure 1.6 Classification of semiconductor

1.2.4 Types of Semiconductor

Basically, semiconductor can be classified in two types as indicated in Figure 1.6.

a) Intrinsic Semiconductor

- pure semiconductors
- Example: Germanium (Ge) and Silicon (Si).

b) Extrinsic Semiconductor

- adding impurity to pure semiconductor through doping process to improve semiconductor conductivity.
- Two categories of impurity :
  a) Pentavalent impurity (N-type) – doped with extra electrons
     - Negative charge
  a) Trivalent impurity (P-type) – doped with material missing electrons that produce locations called holes
     - Positive charge

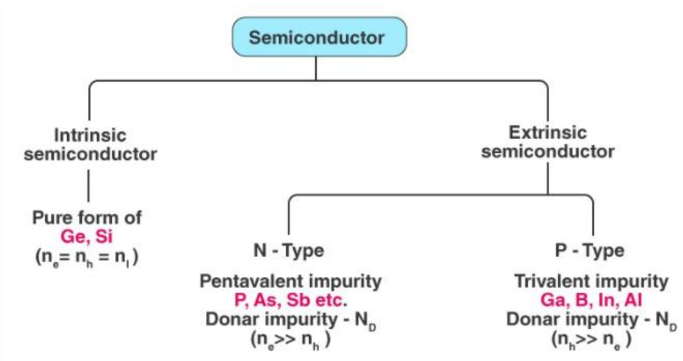


Figure 1.6 Classification of semiconductor

1.2.5 N-type Semiconductor

- An n-type semiconductor is an intrinsic semiconductor doped with phosphorus (P), arsenic (As), or antimony (Sb) as an impurity.
- Silicon of Group IV has four valence electrons and phosphorus of Group V has five valence electrons as shown in Figure 1.7. If a small amount of phosphorus is added to a pure silicon crystal, one of the valence electrons of phosphorus becomes free to move around (free electron*) as a surplus electron. When this free electron is attracted to the "+" electrode and moves, current flows.

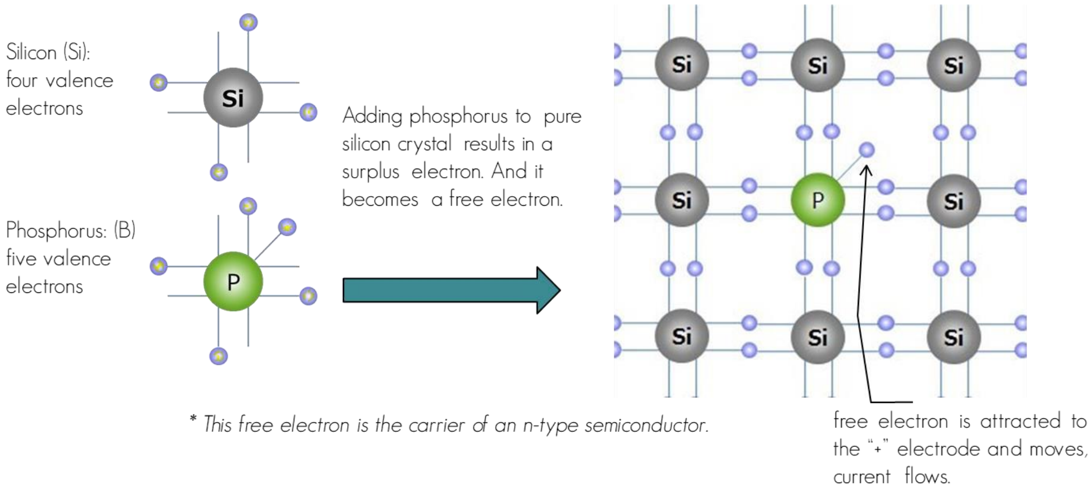


Figure 1.7 N-type semiconductor

1.2.6 P-type Semiconductor

- A p-type semiconductor is an intrinsic semiconductor doped with boron (B) or indium (In).
- Silicon of Group IV has four valence electrons and boron of Group III has three valence electrons as shown in Figure 1.8.
- If a small amount of boron is doped to a single crystal of silicon, valence electrons will be insufficient at one position to bond silicon and boron, resulting in holes* that lack electrons. When a voltage is applied in this state, the neighboring electrons move to the hole, so that the place where an electron is present becomes a new hole, and the holes appear to move to the "–" electrode in sequence.

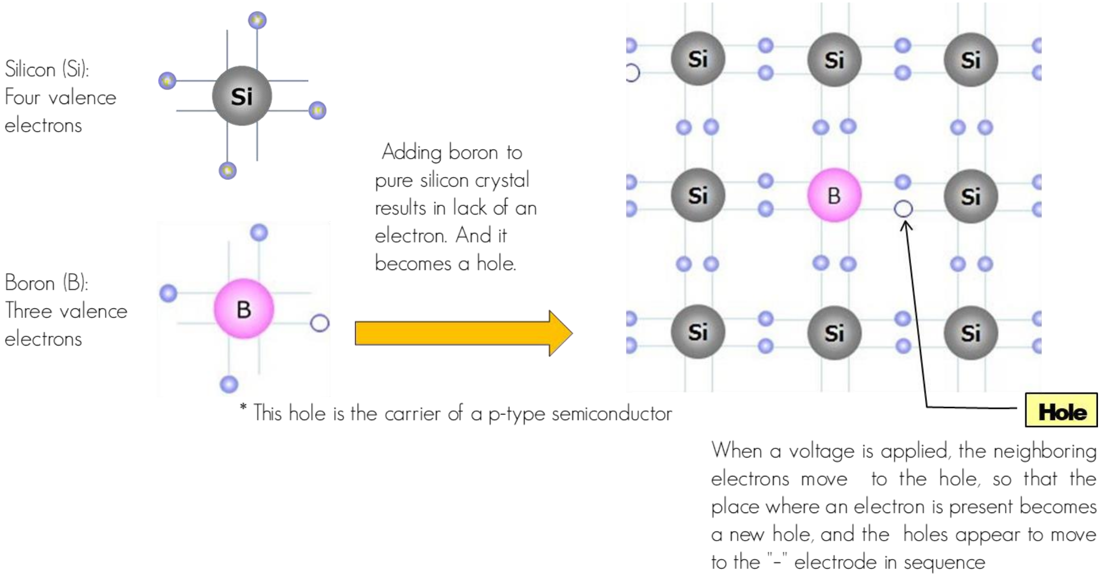


Figure 1.8 P-type semiconductor

1.3 Formation of Junction

- In semiconductor, the contact surface between a p-type and an n-type semiconductor is called a PN junction.

1.3.1 Free Electrons Mobility

- The basic concept of free electrons mobility is shown in Figure 1.9.

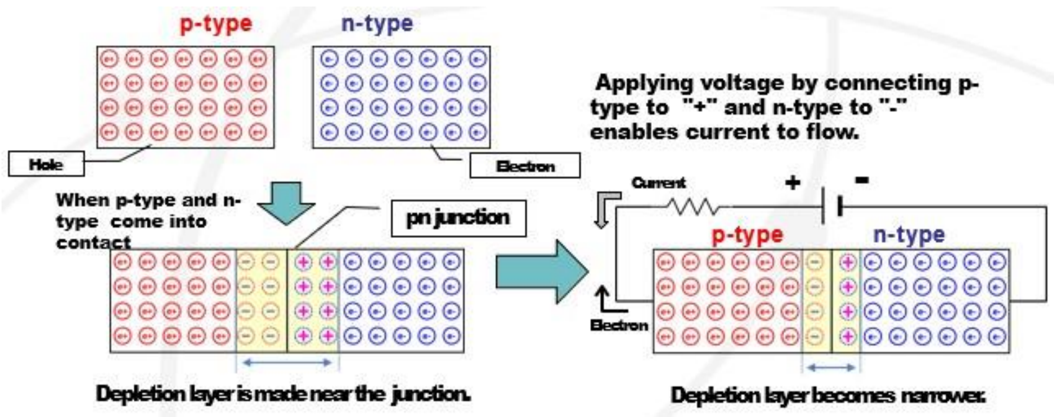


Figure 1.9 Free electrons mobility

1.3.2 Formation of depletion region and its properties

- An electric field is set up, between the donor and acceptor ions in the depletion layer of the p-n junction.
- The potential at the N-side is higher than the potential at P-side. Therefore electrons in the N-side are prevented to go to the lower potential of P-side.
- Similarly, holes in the P-side find themselves at a lower potential and are prevented to cross to the N- side.

1.3.3 Existence of threshold voltage and its values for silicon and germanium

- There is a barrier at the junction which opposes the movement of the majority charge carriers.
- Potential barrier is the difference of potential from one side of the barrier to the other side of the barrier
- In silicon, the potential is 0.6–0.7 V; in germanium, it is 0.2–0.3 V (Threshold Voltage).
- Width of the barrier is the distance from one side of the barrier to the other side which depends on the nature of the material.

1.4 Forward Bias and Reverse Bias

When a doped semiconductor has a voltage applied to it, current will flow from negative to positive, regardless of whether it is p- or n-type material. The current flow is radically different for the two types of material. There are namely forward bias and reverse bias.

1.4.1 Forward Bias

- Positive side of the voltage is connected to the p-type material, and the negative side to the n-type material.
- The 'holes' in the P-type region and the electrons in the N-type region are pushed towards the junction. This reduces the width of the depletion zone. The positive charge applied to the P-type block repels the holes, while the negative charge applied to the N-type block repels the electrons. As electrons and holes are pushed towards the junction, the distance between them decreases. This lowers the barrier in potential.

- With increasing bias voltage, eventually the no conducting depletion zone becomes so thin that the charge carriers can tunnel across the barrier, and the electrical resistance falls to a low value. The electrons which pass the junction barrier enter the P-type region (moving leftwards from one hole to the next, with reference to the above diagram).An electron starts flowing around from the negative terminal to the positive terminal of the battery. The thin depletion zone produces very little electrical resistance against the flow of electrons.

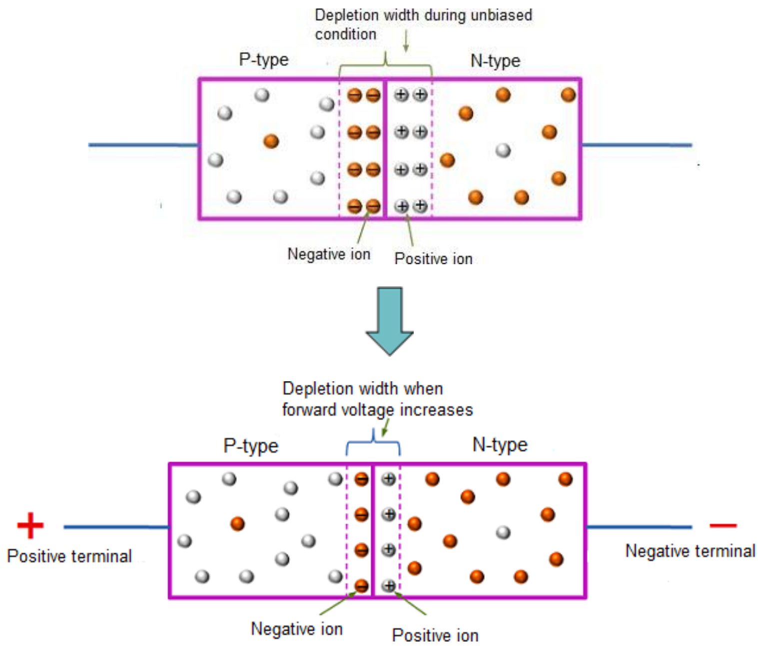


Figure 1.10 Forward Bias

1.4.2 Reverse Bias

- Connecting the P-type region to the negative terminal of the battery and the N-type region to the positive terminal.
- Because the P-type region is now connected to the negative terminal of the power supply, the 'holes' in the P-type region are pulled away from the junction, causing the width of the no conducting depletion zone to increase.
- Similarly, because the N-type region is connected to the positive terminal, the electrons will also be pulled away from the junction.
- This effectively increases the potential barrier and greatly increases the electrical resistance against the flow of charge carriers. For this reason, there will be minimal electric current across the junction.

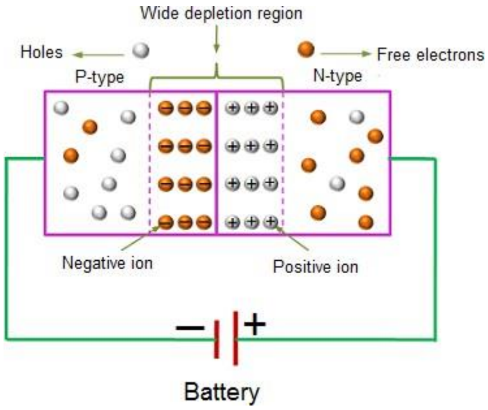


Figure 1.11 Reverse Bias

- When the voltage is further increased, the current is almost independent of the reverse voltage up to a certain critical value. This reverse current is known as the reverse saturation current or leakage current. This current is due to the minority charge carriers, which depends on junction temperature Ideally no current flow in reverse bias because the majority carrier ceases However, there is very small current produced by minority carriers. The current typically in the µA or nA p-region are "pushed" toward the PN junction by the negative terminal of bias voltage range.

OBJECTIVES QUESTIONS

1. "Materials which can conduct electricity better than insulator, but not as well as conductors". This is the definition of :
   a) Diode
   b) Semiconductor
   c) Conductor
   d) Insulator

2. Which of the following acts as a donor impurity in doping process?
   a) Arsenic
   b) Indium
   c) Gallium
   d) Boron

3. Which of these is an Example of Conductors?
   a) Wood
   b) Copper
   c) Glass
   d) Plastic

4. The forbidden energy gap for Germanium is of the order of:
   a) 0.7 eV
   b) 0.3 eV
   c) 1.1 eV
   d) 10 eV

5. The process of adding an impurity to an intrinsic semiconductor is called:
   a) Doping
   b) Ionization
   c) Recombination
   d) Atomic modification

6. The reverse saturation current in a PN Junction diode is only due to:
   a) majority carriers
   b) minority carriers
   c) acceptor ions

7. Donor ions Majority carriers of Ptype materials
   a) Neutrons
   b) Electrons
   c) Protons
   d) Holes

8. PN Junction diode formed
   a) Special fabrication technique of combining P and N -type material
   b) Pushing P and N- type material towards
   c) Welding of P and N type material

9. Resistance developed in the depletion region is
   10. Rforward >Rreverse
   11. Rforward <Rreverse
   12. Rforward =Rreverse

10. The depletion region contains
   a) Electrons
   b) Holes
   c) Immobilized charge carriers

STRUCTURED QUESTIONS

1. With the aid of a diagram, sketch and label the atomic structure of copper (Cu) which has 29 atomic number.

2. Silicon has 14 electrons. Draw the atomic structure for silicon.

3. List down THREE(3) types of material that are classified in semiconductor's family.

4. State TWO (2) semiconductor materials that are commonly used.

5. List THREE(3) types of electrical material classification.

6. State THREE (3) characteristics of semiconductor.

7. Explain how to produce N type semiconductor.

8. Explain TWO 92) types of doping materials which called an extrinsic semiconductor.

9. Differentiate TWO (2) between N-Type and P-Type material.

10. By using a suitable diagram, explain how p-type semiconductor can be constructed.

11. Describe TWO(2) of the differences between semiconductor and insulator.

12. State the value of the threshold voltage for germanium and Silicon.

13. State the process of adding to a pure semiconductor material, in order to increase its conductivity.

14. With the aid of a diagram, state the condition of depletion region when P-N Junction is in reverse biased.

15. Define semiconductor.

16. With the aid of a diagram, illustrate the effect of reverse biasing on the width of depletion region.

17. Discuss the operation of forward biased and the effect of depletion layer.

18. In semiconductor materials, atoms link together with one another sharing their outer electrons. These links are called covalent bonds. Draw the covalent bonds for silicon atoms.

19. Forward bias is the condition that allows current through the PN junction. Illustrate the connection of PN junction during forward bias and describe TWO (2) conditions that allow forward bias to occur.

20. With the aid of a diagram, illustrate the meaning of forward biased voltage and state condition of depletion region, junction resistance and current flow.

21. State TWO (2) semiconductor materials that are commonly used.

22. By using a suitable diagram, explain how P-type semiconductor can be constructed.

23. Illustrate with suitable diagram, the condition of P-N junction in forward bias and reverse bias.

24. Using a suitable diagram, illustrate the meaning of forward biased voltage across a P-N Junction.

25. With the aid of a diagram, illustrate the meaning of reverse biased voltage and state the condition of depletion region, junction resistance and current flown.

26. For a P-N Junction that is supplied with forward biased voltage:

    i) P-type material is connected to a __________terminal of the power supply

    ii) N-type material is connected to a __________terminal of the power supply

27. When a P-N Junction is supplied with reversed voltage:

    i) The resistances in the depletion region is ____________

    i) The current flow is __________

2.1 Introduction

Diode is a semiconductor device that conducts current only in one direction. The combination of PN junction creates a diode. Diodes come in a variety of sizes and shapes as shown in Figure 2.1. The design and structure is determined by what type of circuit they will be used in. Diode can be used in many application depending on their types as shown in Figure 2.2.

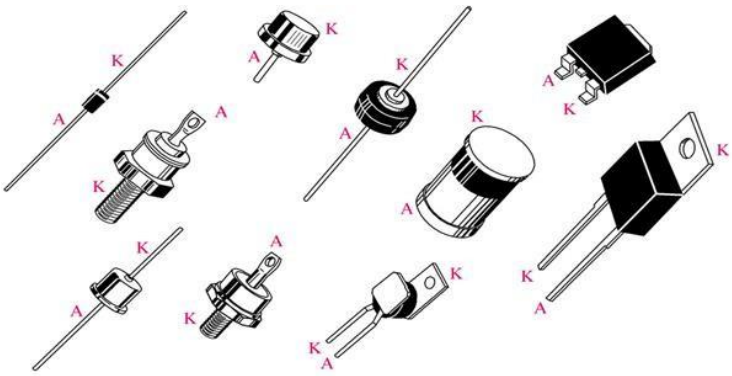


Figure 2.1 Diodes Package

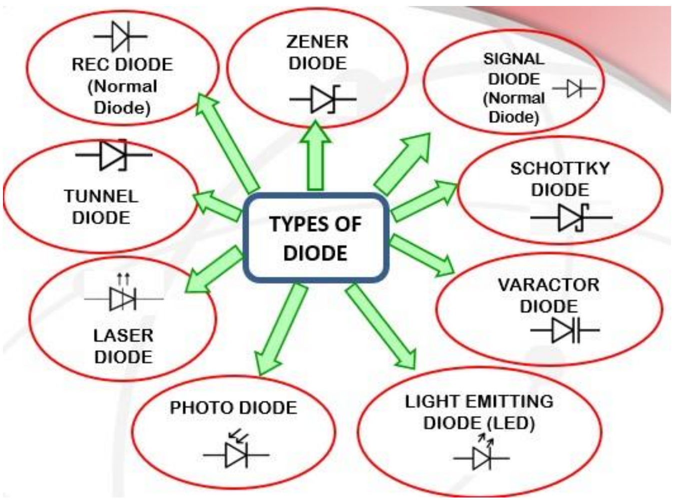


Figure 2.2 Types of diodes

2.2 Schematic diagram and physical structure of a diode

Diode is a device that conducts current only in one direction. n-type material and p-type material become extremely useful when joined together to form a p-n junction. before the p-n junction is formed , no net charge (neutral) since number of proton and electron is equal in both n-type and p-type. The physical structure and symbol of a diode is shown in Figure 2.3.

p region: holes (majority carriers), e- (minority carriers)
n region: e- (majority carriers), holes (minority carriers

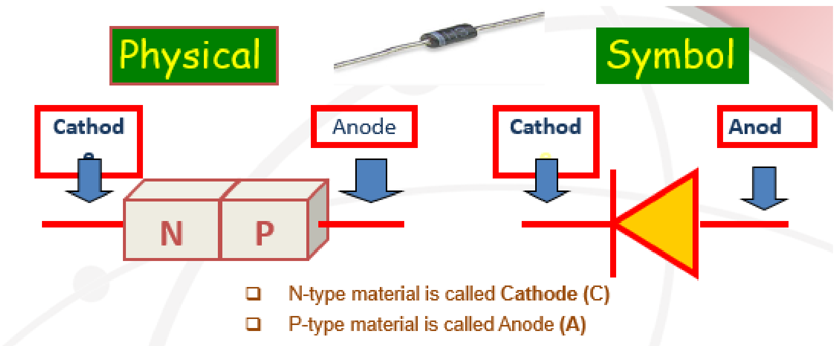


Figure 2..3 Physical structure and symbol of a diode

2.3 Forward bias and reverse bias

a) Forward bias

- P junction is connected to positive terminal and n junction is connected to negative terminal.
- Bias voltage >barrier potential (Ge=0.3V or Si=0.7V).
- The depletion region narrows due to reduction in positive and negative ions.

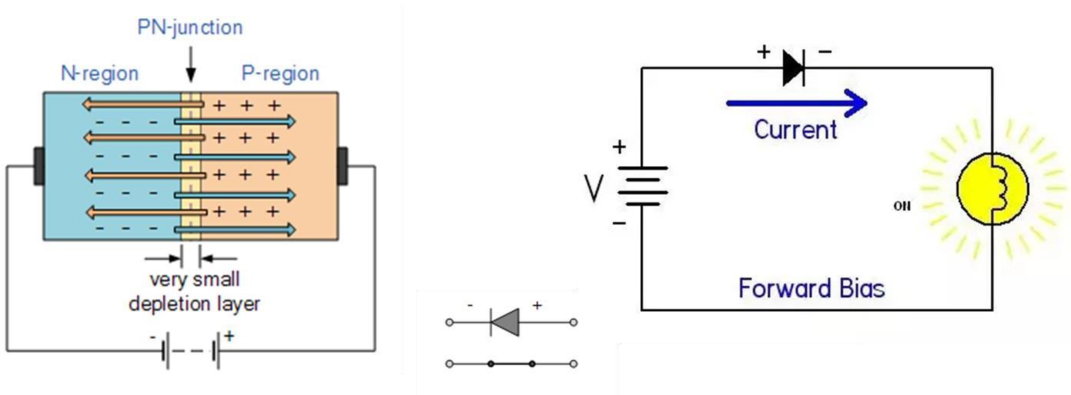


Figure 2.4 Diode in forward bias

b) Reverse bias diode

- P junction is connected to negative terminal and n junction is connected to positive terminal.
- The depletion region widens due to additional positive ions are created.

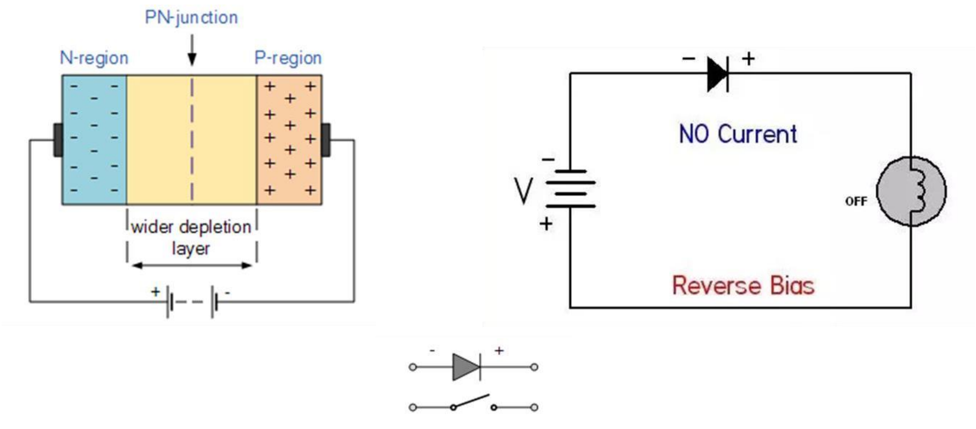


Figure 2.5 Diode in reverse bias

2.4 I-V characteristic curve for silicon diode

The current and voltage characteristics of silicon diode is illustrate as in Figure 2.6 while the description of the respective characteristics is represented in Table 2.1

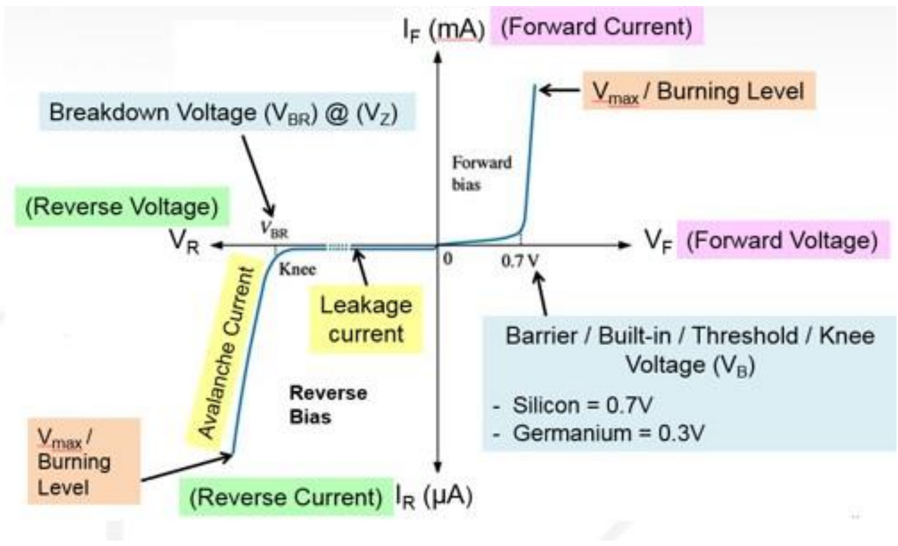


Figure 2..6 IV characteristics curve for silicon diode

Table 2.1 IV Characteristic curve for silicon diode

IV Characteristic	Function
Knee Voltage (Threshold Voltage)	• Voltage level where the increment of current happens. • When the applied forward biased voltage reaches the barrier voltage. • Knee voltage for Si=0.7V and Ge=0.3V.
Forward current (Id) (Miliampere)	• Amount of current that can be handled safely when the forward voltage is supplied and measured in miliampere (mA).
Reverse current (Microampere)	• Very small current or leakage current when the diode is reversed biased and measured in micro ampere.
Breakdown voltage	• Voltage level where the increment of reverse current happens (in microampere). • Big current value exceeds the breakdown level can burn the p-n junction and damage it.
Burning Level (when Id, Vd exceeds P max)	• Power (P) that exceeds the max power of the diode during forward biased. • P max is produced from Id and Vd. Vd is a constant. Normally • P is represented by maximum current (Id)

2.5 Diode in rectifiers

- A rectifier is an electrical device that transforms alternating current to direct current
- It only allows for one-way electric charge passage (one direction only) by using a semiconductor diode.
- Basically there are two types of rectifier : half-wave rectifier and full-wave rectifier.

2.5.1 Half-wave rectifier

Half-wave rectifier use only one diode in the circuit to produce output voltage at one cycle only. The operation and equation of half rectifier is tabulated in Table 2.2 and Table 2.3.

Table 2.2 Half-wave rectifier operation

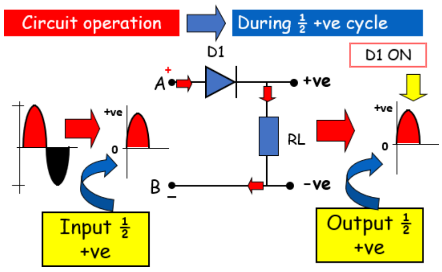
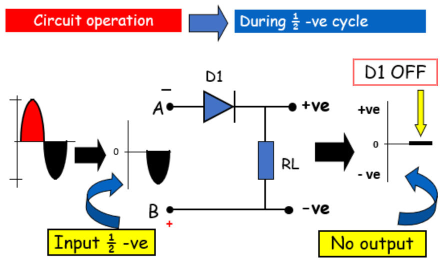
	Half positive cycle	Half negative cycle
Circuit		
Terminal A	Positive	Negative
Terminal B	Negative	Positive
D1	Forward bias	Reverse bias
Output voltage, Vo	$V_O = V_{AB} - 0.7$	$V_O = 0$

Table 2.3 Half-wave rectifier equations

Characteristics	Equation
Vout	$V_{out} = V_{in} - 0.7V$
Average voltage	$V_{avg} = \frac{V_{out}}{\pi} = V_{DC}$
Averag e current	$I_{avg} = \frac{I_m}{\pi}$
RMS voltage	$V_{rms} = \frac{V_m}{\sqrt{2}}$
RMS current	$I_{rms} = \frac{I_m}{\sqrt{2}}$

2.5.2 Half-wave rectifier with transformer- coupled input voltage

Transformer coupling allows the input voltage to be stepped up or down and to electrically isolated the rectifier. The half-wave rectifier with transformer coupled circuit is shown in Figure 2.7.

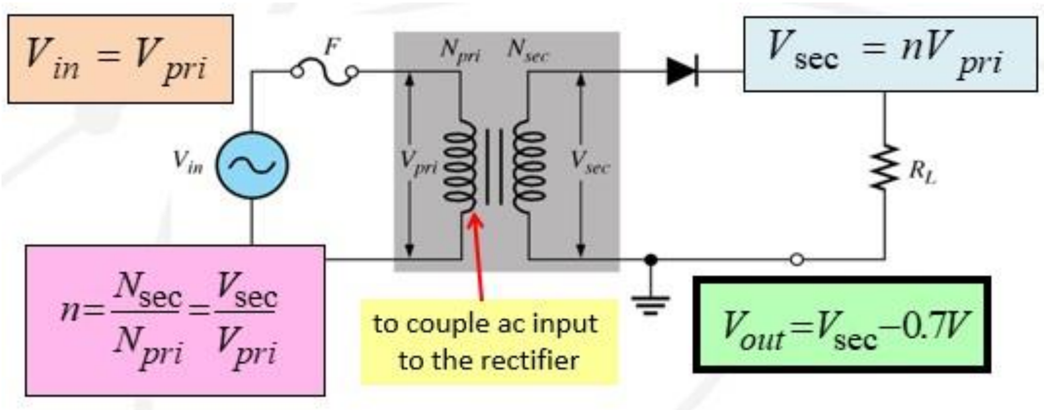


Figure 2.7 Half-wave rectifier with transformer coupled

2.5.3 Full-wave rectifier

Figure 2.8 illustrates the full-wave rectifier connected to a center tap transformer. Full wave rectifier use two diodes to produce output voltage at both positive and negative cycle. The operation and equation of full-wave rectifier is tabulated in Table 2.4 and Table 2.5..

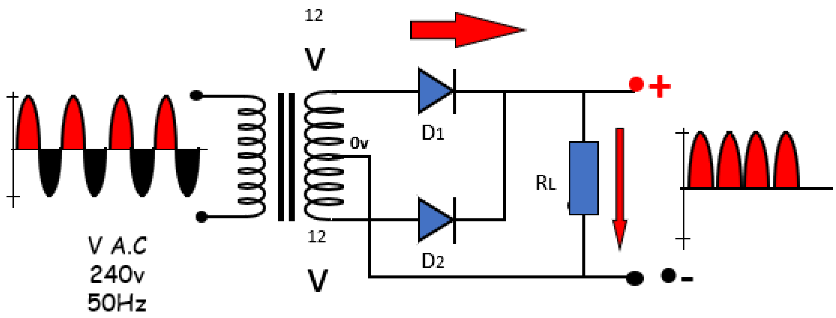


Figure 2.8 Full-wave rectifier circuit

Table 2.4 Half-wave rectifier operation

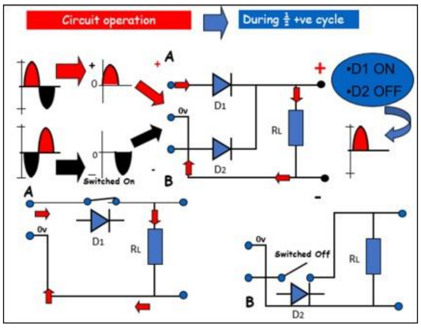
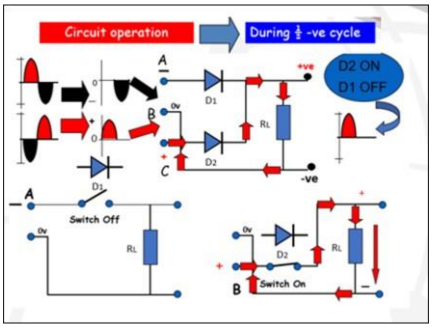
	Positive half cycle	Negative half cycle
Circuit		
Terminal A	Positive	Negative
Terminal B	Negative	Positive
D1	Forward bias	Reverse bias
D2	Reverse bias	Forward bias
Output voltage, Vo	$V_O = V_{AB} - 0.7$	$V_O = V_{AB} - 0.7$

Table 2.3 Fulll-wave rectifier equations

Characteristics	Equation
Vout	$V_{out} = V_{in} - 0.7V$
Averag e voltage	$V_{avg} = \frac{2V_m}{\pi} = V_{DC}$
Averag e current	$I_{avg} = \frac{2I_m}{\pi}$
RMS voltage	$V_{rms} = \frac{\sqrt{V_m}}{2}$
RMS current	$I_{rms} = \frac{\sqrt{I_m}}{2}$

2.5.4 Bridge rectifier

Bridge rectifier consists four diodes as shown in Figure 2.9 while the operation of the circuit is as indicated in Table 2.4 while the formula is tabulated in Tale 2.5.

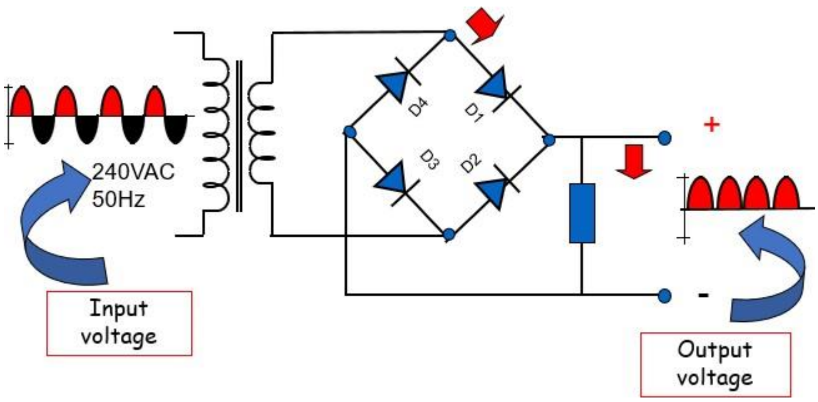


Figure 2.9 Bridge rectifier

Table 2.4 Bridge rectifier circuit

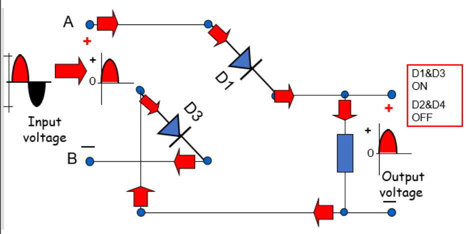
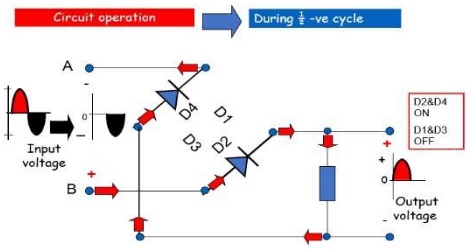
	Positive half cycle	Negative half cycle
Circuit		
Terminal A	Positive	Negative
Terminal B	Negative	Positive
D1, D3	Forward bias	Reverse bias
D2, D4	Reverse bias	Forward bias
Output voltage, Vo	$V_O = V_{AB} - 1.4$	$V_O = V_{AB} - 1.4$
Output frequency	2 x input frequency	

Table 2.5 Bridge rectifier equations

Characteristics	Equation
Vout	$V_{out} = V_{in} - 1.4V$
Averag e voltage	$V_{avg} = \frac{2V_m}{\pi}$
Averag e current	$I_{avg} = \frac{2I_m}{\pi}$
RMS voltage	$V_{rms} = \frac{V_m}{\sqrt{2}}$
RMS current	$I_{rms} = \frac{I_m}{\sqrt{2}}$

Example 2.1

An a.c supply of 230 V is applied to a half-wave rectifier circuit through a transformer of turn ratio 10 : 1. Find the output d.c. voltage.

Solution :

$$\frac{N_1}{N_2} = 10$$

Vprimary=230Vrms

Vm (max),

$$V_m = \sqrt{2}\ X\ V_{rms}$$
$$V_m = \sqrt{2}\ X\ 230$$
$$V_m = 325.3V$$

$$I_{av} = \frac{I_m}{\pi}$$

$$V_{dc} = \frac{I_m}{\pi} X R_L = \frac{V_{sm}}{\pi} = \frac{32.53}{\pi} = 10.36V$$

Example 2.2

In the center-tap circuit shown in Figure 2.10 below, the diodes are assumed to be ideal i.e., having zero internal resistance. Find : d.c. output voltage and average current

.

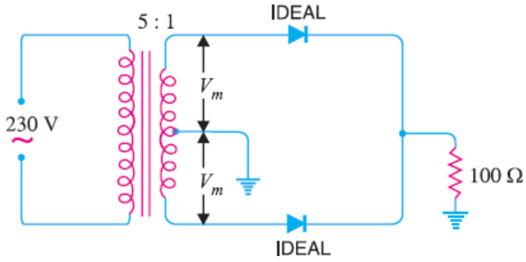


Figure 2.10

Solution :

Vprimary=230Vrms

Vsecondary=230 X (1/5) =46Vrms

Vm (secondary)= 46 X $\sqrt{2}$ *=65V*

Vm (across half secondary winding) =65/2 =32.5V

$$\frac{2V_m}{\pi R_L} = \frac{2X32.5}{\pi \ X \ 100} = 0.207A$$

Example 2.3

In the bridge type circuit shown in Figure 2.11, the diodes are assumed to be ideal. Find :

(i) d.c. output voltage

(ii) peak inverse voltage, PIV

(iii) output frequency.

Assume primary to secondary turns to be 4.

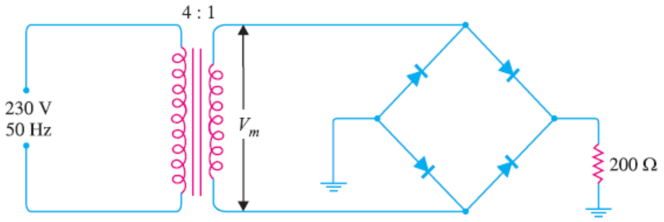


Figure 2.11

Solution :

$$\frac{N_1}{N_2} = 4$$

V primary = 230Vrms

V secondary = 230 (N_2/N_1) = 230 X (1/4) = 57.5Vrms

Vm = 57.5 x $\sqrt{2}$ = 81.3V

(i) $I_{dc} = \frac{2V_m}{\pi R_L} = \frac{2X81.3}{\pi\ X\ 200}$ = *0.26A*

(ii) PIV = 81.3V

(iii) fout = 2 X fin = 2 X 50 = 100Hz

2.5.5 AC voltage and current in rectifier circuits

- AC voltmeter is an instrument used to measure AC voltage.
- DC voltages are measured by the DC voltmeter through a rectifier-based AC voltmeter.
- Diode polarity can be determined using an Ohmmeter and the VDC measuring function in multimeter.

2.6 Application of diode in electronic circuit application.

Diode can be used in many electronic circuit application depending on the design requirement.

2.6.1 Clipper

- Clipper or limiter is a circuit which limits/clips the portion of signal voltage above or below certain level by limits positive or negative amplitude, or both.
- Prevent either or both polarities of a wave form exceeding a specific amplitude level.
- The operation of series clipper and parallel clipper is shown in Table 2.6. and Table 2.7.

Table 2.6 Series clipper operation

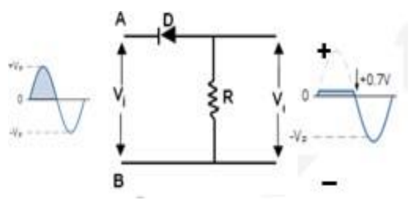
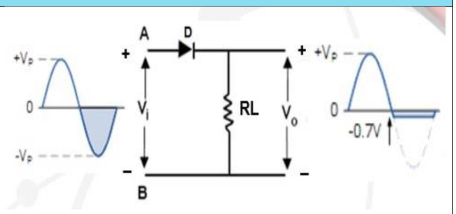
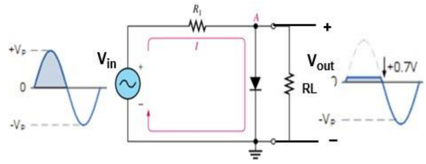
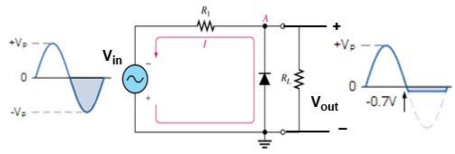
	Positive series clipper	Negative series clipper
Circuit		
Positive amplitude is clipped-off	• diode in reverse biased • open circuit • Vout = 0V	• diode in forward biased • closed circuit • Vout = VRL
Negative amplitude is clipped-off	• diode in forward biased • closed circuit • Vout = VRL	• diode in reverse biased • open circuit • Vout = 0V

Table 2.7 Parallel clipper operation

	Positive parallel clipper	Negative parallel clipper
Circuit		
Positive amplitude is clipped-off	• diode in foward biased • open circuit • Vout = 0V	• diode in reverse biased • closed circuit • Vout = VRL
Negative amplitude is clipped-off	• diode in reverse biased • closed circuit • Vout = VRL	• diode in foward biased • open circuit • Vout = 0V

2.6.2 Clamper

- Clamper "clamps" a signal to at a desired DC level.
- A diode clamper adds a DC level to an AC voltage so the AC signal will be offset up (positive) or down (negative).
- Capacitor and diode position will determine either it is positive clamper or negative clamper. Figure 2.12 shows the clamper voltage waveform.

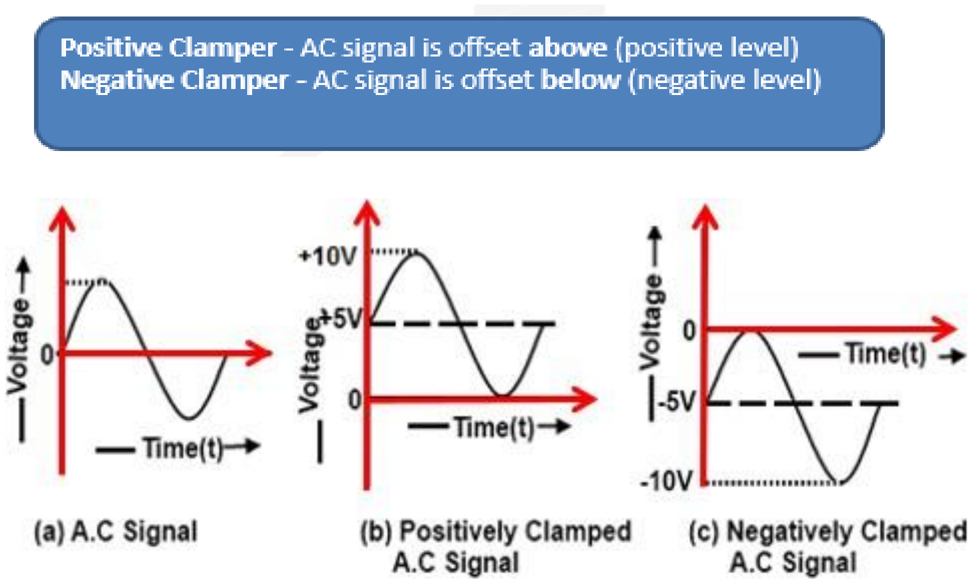
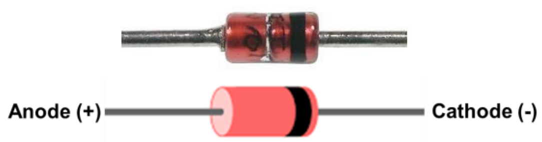


Figure 2.12 Clamper voltage waveform

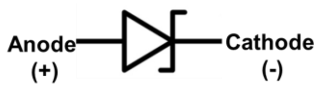
2.7 Zener diode

- Zener diode is a special kind of diode that is designed for operation in the reverse biased mode.
- It permits current to flow in forward and reverse direction.
- It is placed in the circuit in reverse bias and operates in reverse breakdown.
- It is used to produce a stabilized voltage output (voltage regulator) for use in power supply, voltmeter and other equipment.
- The physical structure and symbol of zener diode is shown in Figure 2.13.



(a) Physical structure

(b) Schematic diagram



(c) Symbol

Figure 2..13 Physical structure and symbol of zener diode

- Zener diode could operate in the reverse biased mode because of its low reverse breakdown voltage (zener voltage).
- When diode reached reverse breakdown (Vz), reverse voltage remains constant even though reverse current increase drastically as shonn in Figure 2.14.

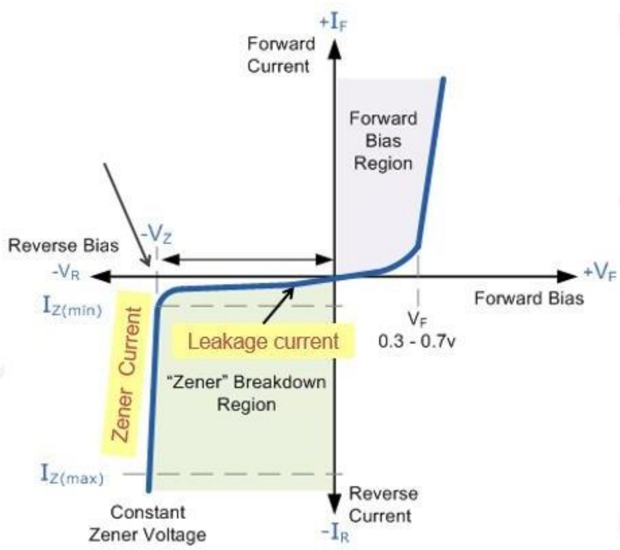
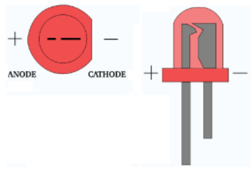
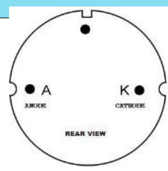
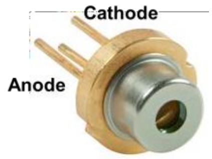
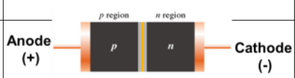
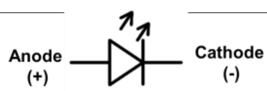
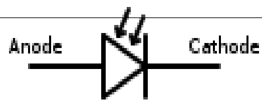
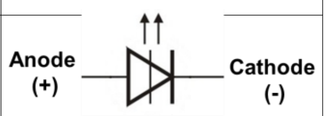


Figure 2..14 I-V characteristics curve for zener diode

2.8 Other type of diodes

Diode can be used in many applications depending on the type of diode itself as shown in Table 2.8.

Table 2.8 Types of diode

	Light Emitting Diode (LED)	Photodiode	Laser diode
Physical structure	 	 	 
Schematic			
Symbol			
Characteristics	• operates when receives forward bias voltage. • operating at low voltage (1 to 4V) and let current 10mA to 40mA flow. • Breakdown voltage (3 to 5V). • The color of light depends on the material of LED	• Able to convert light into current or voltage	• Produces coherent radiation in the visible or infrared spectrum when current passed through it.
Application	• Lighting	• Photoconductor, photodetectors, charge-couple devices, etc.	• Optical fibre systems, compact disc, laser printer, etc.

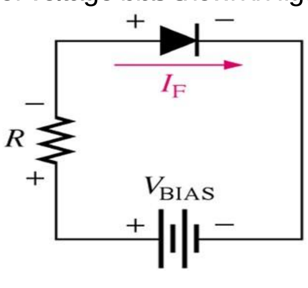
OBJECTIVES QUESTIONS

1. If a 12V supply connected in forward bias, using a silicon diode and 370Ω resistor in series. Calculate the value of voltage dropped across the diode.
   a) 0.3V
   b) 0.9V
   c) 1.4V
   d) 0.7V

2. State the value of threshold voltage for silicon.
   a) 0.3V
   b) 0.5V
   c) 0.7V
   d) 0.9V

3. For a silicon atom, identify the number of electrons in the second orbit. (Atomic No. of silicon=14)
   a) 2
   b) 8
   c) 10
   d) 14

4. Name the type of voltage bias shown in figure below.



   a) Zero biased
   b) Depletion biased
   c) Reverse biased
   d) Forward biased

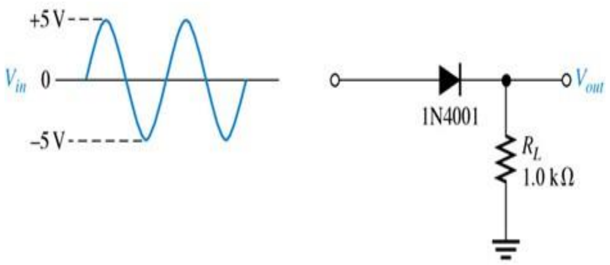
5. A component X is a special kind of diode which permits current to flow in the forward direction as normal, but will also allow it to flow in the reverse direction when the voltage is above certain value. What is component X?

a) LED
b) Photodiode
c) Zener diode
d) Laser diode

6. The depletion region in PN junction is caused by

a) Drift of hole
b) Diffusion of charge carriers
c) Migration of charge carriers
d) Drift of electron

7. Based to the figure below, the peak value of input to a half-wave rectifier is 10V. Calculate approximate peak value of the output voltage if silicon diode is used.



a) 9.3V
b) 10.7V
c) 20V
d) 19.3V

8. State the barrier potential for silicon.

a) 0.1V
b) 0.3V
c) 0.5V
d) 0.7V

9. State the barrier potential for silicon.
   a) 0.1V
   b) 0.3V
   c) 0.5V
   d) 0.7V

ESSAY QUESTIONS

1. Sketch a center-tapped full-wave rectifier circuit with the direction of current flow. The load resistor is 2kΩ and the diode resistance is neglected. If the peak to peak voltage across the secondary winding is 220V, calculate output voltage, average voltage and average current.

2. A full-wave rectifier (bridge) operates with a silicon diode. Draw the circuit and explain the operation of the circuit.

3. With the aid of a diagram, explain the I-V characteristic curve and properties of silicon diode about the forward and reverse biased with respect to the current and voltage.

4. The most popular application of diode is rectification. Rectifier is a circuit that converts the AC voltage to DC voltage. Draw three types of rectifier circuits complete with input and output waveform.

UNIT 3
BIPOLAR JUNCTION TRANSISTORS (BJT)

3.1 Introduction

- Transistor is a three terminal device whose output current, voltage and power are controlled its input and commonly used in amplifiers, logic gates, microprocessors and etc.
- Two basic type of transistor:
    a) Bipolar Junction Transistor (BJT)
    b) Field Effect Transistor (FET)
- Typical packaging for BJT is as shown in Figure 3.1.

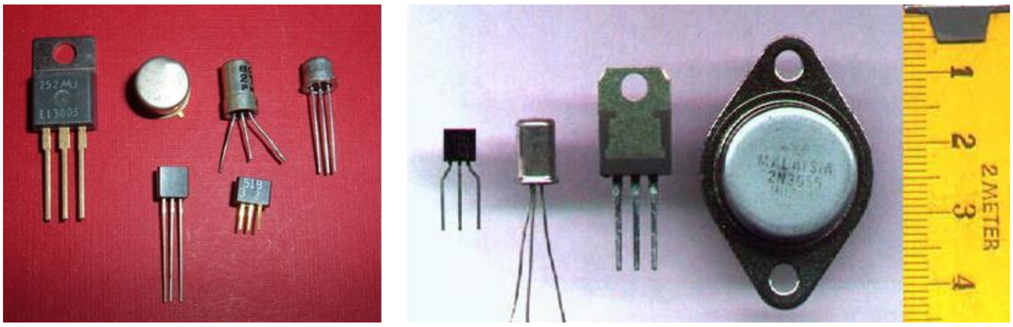


Figure 3.1 Diodes Package

3.1.1 BJT vs FET

Table 3.1 Comparison between BJT and FET

JFET	BJT
Unipolar device (current conduction is only due to one type of majority carrier either electron or hole)	Bipolar device (current condition, by both types of carriers)
The operation depends on the control of a junction depletion width under reverse bias	The operation depends on the injection of minority carriers across a forward biased junction.
Voltage driven device. The current through the two terminals is controlled by a voltage at the third terminal (gate).	Current driven device. The current through the two terminals is controlled by a current at the third terminal (base)

Table 3.1 Comparison between BJT and FET (cont.)

JFET	BJT
Low noise level	High noise level
High input impedance (due to reverse bias)	Low input impedance (due to forward bias)
Gain is characterised by transconductance.	Gain is characterized by voltage gain.
Better thermal stability.	Less thermal stability.

3.1.2 Physical structure and schematic symbols for BJT

- The NPN and PNP transistor are shown in Figure 3.2.
- The collector and emitter are made of the same material and the base is made of the other.
- The arrow on the schematic symbol identifies the emitter terminal and the type of component

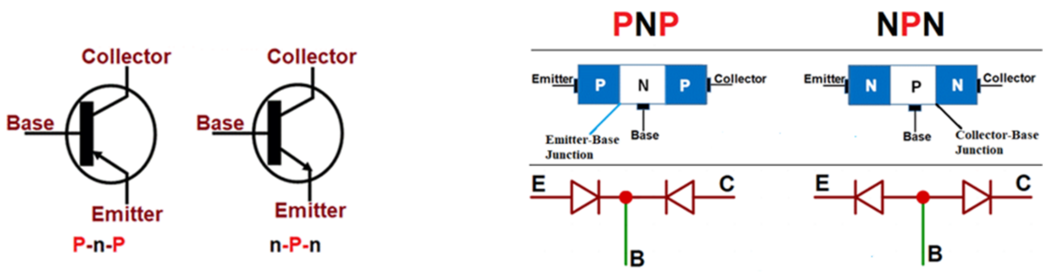


Figure 3.2 Schematic and construction of transistor

3.1.3 BJT schematic representation

- The BJT schematic representation is shown in Figure 3.3. .

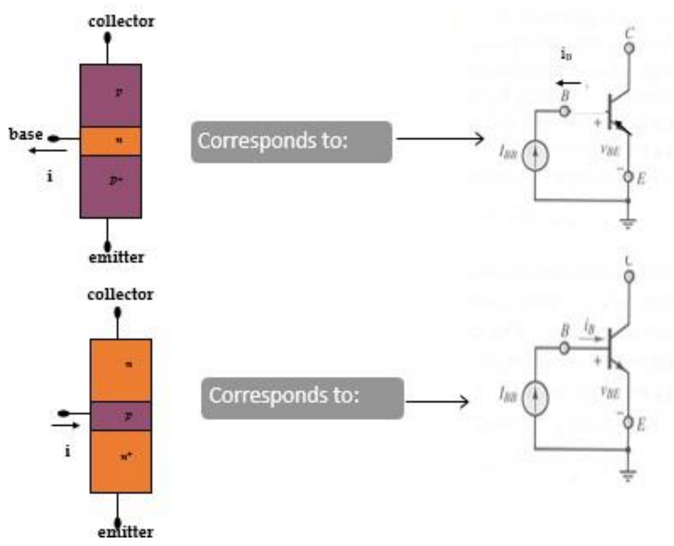


Figure 3.3 BJT schematic representation

3.1.4 BJT structure

- BJT has three layers which are:
  - a) Collector
  - b) Base
  - c) Emitter
- BJT can be classified into two types:
  - a) PNP – operates with outgoing base current
  - b) NPN – operates with incoming base current

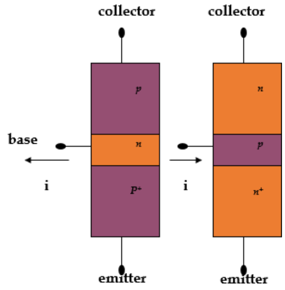


Figure 3.4 PNP and NPN transistor

3.1.5 BJT terminal current

- Transistor terminal current flow is shown in Figure 3.5.
- I_E is normally has the greatest value, followed closely by I_C.
- The BJT is a current controlled device. The value of I_C is normally some multiple of value I_B.

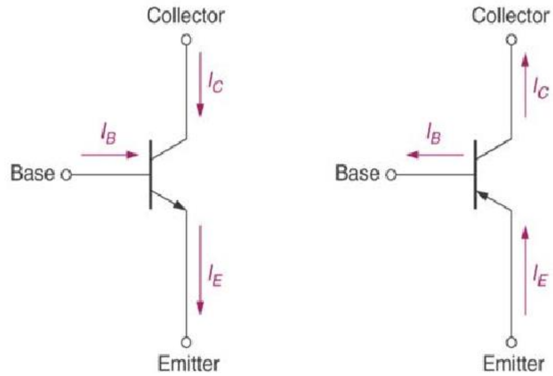


Figure 3.5 Transistor terminal current

- Transistor terminal current :

The emitter current (IE) is the sum of the collector current (IC) and the base current (IB)

$$I_E = I_B + I_C$$

Transistor is a current-controlled device ; the value of collector and emitter currents are determined by the value of base current.

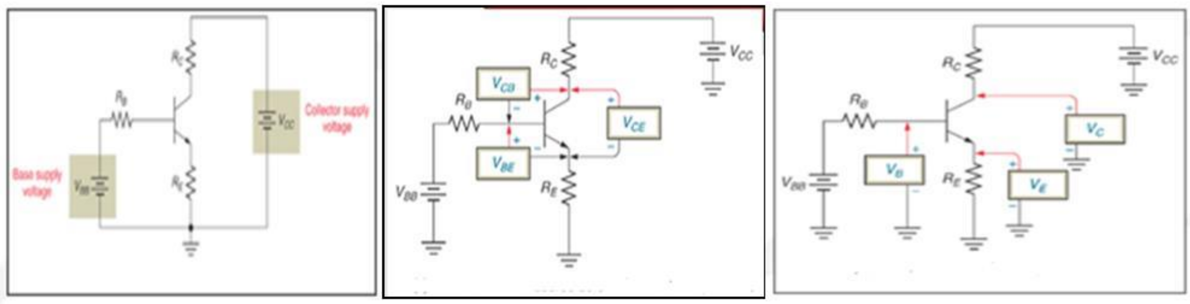
IB ≪ IE or IC

An increase or decrease in value of I_B causes similar change in values of I_C and I_E.

Current gain (β) → factor by which current increases from base of transistor to its collector.

$$I_C = \beta_{DC} I_B$$

- Transistor terminal voltage:



V_{CC}, V_{BB}, and V_{EE} are power supply voltages, each connected (directly or indirectly) to the identified terminal.

V_{CE}, V_{BE} and V_{CB} are inter terminal voltages, each measured from the first identified terminal to the second.

V_C, V_B and V_E are terminal voltages , each measured from the identified terminal to ground.

3.1.6 Basic transistor operation

A PNP transistor is typically connected as in Figure 3.6. The operation of the PNP transistor is as below:

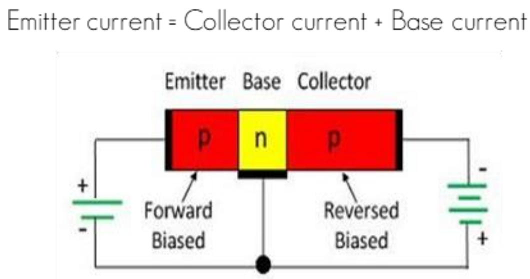


Figure 3.6 PNP transistor

The emitter-base junction of PNP is connected in forward biased while the collector-base junction is connected in reverse bias.

The emitter-base junction pushes the majority charge carrier toward the base, thus established the emitter current.

The hole in the p-type material combines with the n-type material hence constitute the base current. The remaining hole reaches across the negatively biased collector-base region and collected by the collector due to which collector current develops.

Thus, complete emitter current flows through the collector circuit.

A NPN transistor is typically connected as in Figure 3.7. The operation of the NPN transistor is as below:

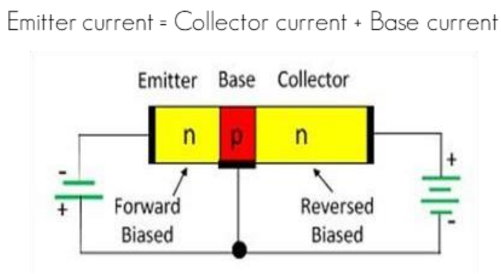


Figure 3.7 NPN transistor

The emitter-base region of the transistor is in forward biasing and the collector base region is connected in reverse bias.

→ The voltage of the reverse bias is considerably smaller as compared to the reversed biased.

→ The emitter-base junction is in forward biasing due to which a large number of electrons is reached to the base. This develops the emitter current.

↓ The electron in the base region combined with the holes. But the base is very thin and lightly doped, thus only small holes combined with the electrons and constitute the base current.

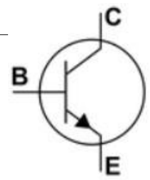
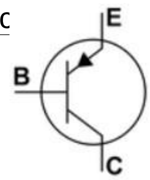
← The remaining electrons reach across the collector base region and develop the collector current.

→ The entire emitter current flows through the collector circuit.

3.1.7 Difference between NPN and PNP transistor

NPN and PNP has their own characteristics that difference from each other as indicated in Table 3.2.

Table 3.2 Difference between NPN and PNP transistor

Basis for comparison	NPN Transistor	PNP Transistor
Definition	Transistor in which two n- type layer are separated by ne P-type layer	Two blocks of p-types semiconductors are separated by one thin block of n-type semic
Symbol		
Full form	Negative Positive and Negative	Positive Negative and Positive
Direction of current	Collector to Emitter	Emitter to Collector
Turn-on	When electrons enters into the base	When holes enter into the base
Inside current	Develop because of varying position of electrons	Originate because of varying position of holes
Outside current	Current develop because of the flow of holes	Current develop because of the flow of electrons
Majority charge carrier	Electron	Hole
Switching Time	Faster	Slower
Minority charge carrier	Hole	Electron
Positive voltage	Collector terminal	Emitter terminal
Forward biased	Emitter Based Junction	Emitter Base Junction
Reverse Biased	Collector Base Junction	Collector Base Junction
Small current	Flows from emitter-to-base	Base to emitter
Ground signal	Low	High

3.2 Characteristics and operations of BJT

BJT is commonly used in electronic circuits as an amplifier or switching devices.

3.2.1 BJT as an amplifier

Amplification is the process of increasing the amplitude of an electrical signal. The circuits used to provide the amplificat0io2n are referred to as amplifiers as shown in Figure 3.8.

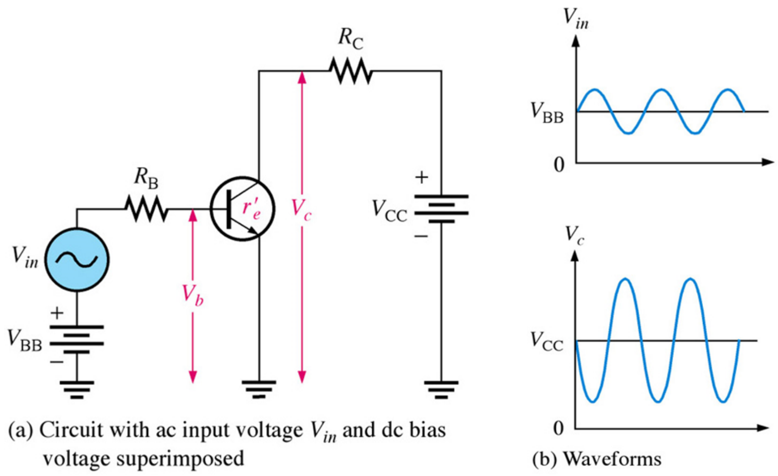


Figure 3.8 Basic transistor amplifier circuit

3.2.2 BJT as a switching devices

- If the base-emitter junction is not forward-biased, the BJT is in the cutoff (switched off) and there is an open circuit between collector and emitter, as shown in Figure 3.9 (a).
- If the base-emitter junction and base-collector junction are forward-biased, the BJT is in the saturation (switched on). There is a short circuit between collector and emitter, as shown in Figure 3.9 (b).

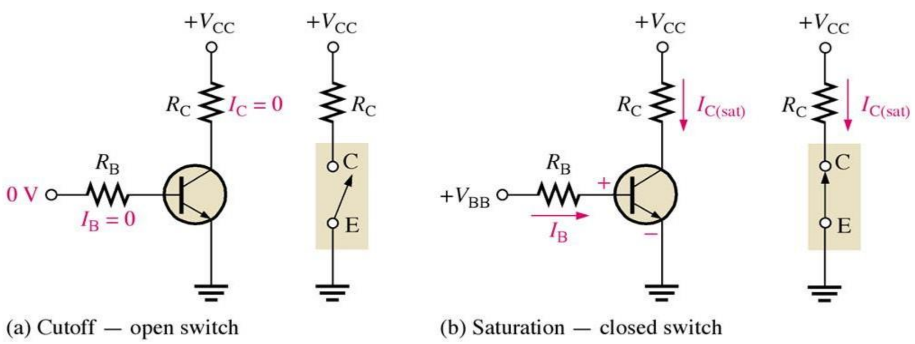


Figure 3.9 Basic transistor amplifier circuit

Table 3.3 Operation mode of BJT

Operation mode	Biasing polarity B-E junction	Biasing polarity B-C junction
Active	Forward	Reverse
Saturation	Forward	Forward
Cut-off	Reverse	Reverse

3.3 Basic transistor configurations

BJT can be connected in three ways as such as in Figure 3.10 while the characteristics is as in Table 3.4 .

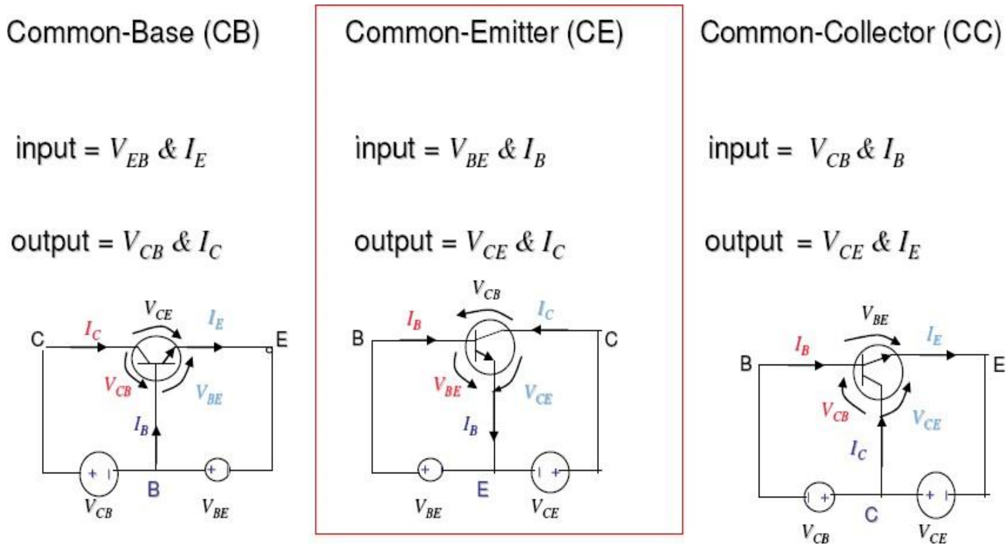


Figure 3.10 Basic transistor configurations

Table 3.4 Characteristics of the transistor configurations

Characteristic	Common Base	Common Emitter	Common Collector
Input impedance	Low	Medium	High
Output impedance	Very high	High	Low
Phase shift	0°	180°	0°
Voltage gain	High	Medium	Low
Current gain	Low	Medium	High
Power gain	Low	Very high	Medium

According to Kirchhoff's current law, the current leaving a component must equal the current entering the component. By formula,

$$I_E = I_C + I_B \tag{3-1}$$

Since I_B is normally much less than I_C, I_C and I_E are approximately equal, expressed as follows:

$$I_C \cong I_E \tag{3-2}$$

The value of I_C is normally some multiple of the value of I_B. The factor by which current increases from base to collector is referred to as dc current gain (β_{DC}) of a transistor.

$$I_E = I_B(\beta_{DC} + 1) \tag{3-3}$$

If we combine this Eq.3-3 with Eq.3-1, we get

$$I_C = \beta_{DC} I_B \tag{3-4}$$

β_{DC} is usually designated as an equivalent hybrid parameter, h_{FE}.

$$h_{FE} = \beta_{DC} \tag{3-5}$$

The ratio of the dc collector current (I_C) to the dc emitter current (I_E) is a dc alpha (α_{DC})

$$\alpha_{DC} = \frac{I_C}{I_E} \tag{3-6}$$

Using the relationships of Eq.3-1 and 3-6, we can calculate base current as

$$I_B = I_E(1 - \alpha) \tag{3-7}$$

The relationship between alpha and beta:

$$\alpha_{DC} = \frac{\beta_{DC}}{\beta_{DC} + 1} \tag{3-8}$$

3.5 DC operations of BJT

- Initially, BJT will operate when DC supply is given. The operation of BJT is influence by its operating current, voltage and several characteristics.

3.5.1 DC Beta (β_{DC}) and DC Alpha (α_{DC})

- The ratio of the dc collector current (Ic) to the dc base current (IB) is the dc beta (β_{DC}) =dc current gain of transistor.
- Range value : 20< β_{DC}<200. It is usually designed as an equivalent hybrid (h)Parameter.

The ratio of the dc collector current (Ic) to the dc emitter current (IE) is the dc alpha less used .

$$\beta_{DC} = \frac{I_C}{I_B}$$ $$h_{FE} = \beta_{DC}$$ $$\alpha_{DC} = \frac{I_C}{I_E}$$

3.5.2 BJT characteristics and parameters

- The current and voltage in Figure 3.11 can be identified as follow :

a) Current:

- dc base current, I_B
- dc base current, I_B
- dc base current, I_C

b) Voltage

- dc voltage at base with respect to emitter, V_{BE}
- dc voltage at base with respect to base, V_{CB}
- dc voltage at base with respect to emitter, V_{CE}

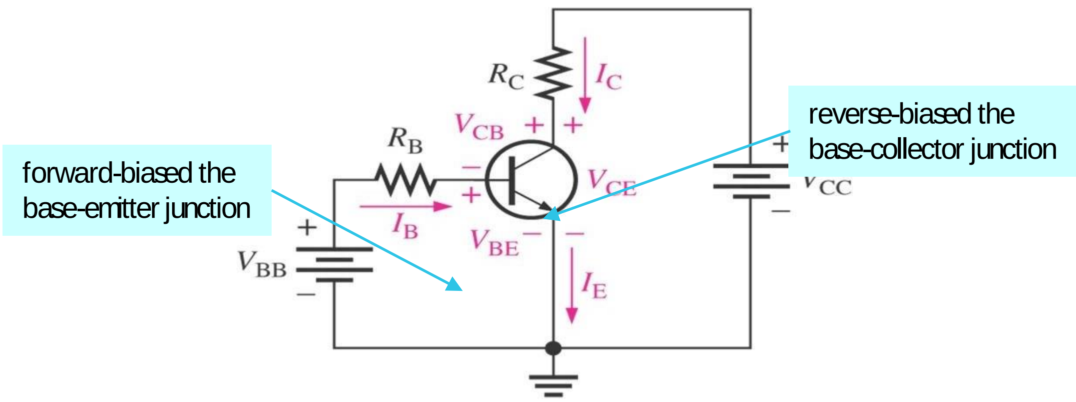


Figure 3.11 Transistor current and voltage

3.5.3 Current and voltage analysis

When the BE junction is forward-biased, $V_{BE} \cong 0.7V$

Since the emitter is at ground (0V), by Kirchhoff's voltage law, the voltage across R_B is:

$$V_{R_B} = V_{BB} - V_{BE} \quad (3\text{-}9)$$

Also, by Ohm's law :

$$V_{R_B} = I_B R_B \quad (3\text{-}10)$$

From equation (3-9) and (3-10):

$$V_{BB} - V_{BE} = I_B R_B$$

Therefore, the dc base current is :

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} \quad (3\text{-}11)$$

The voltage at the collector with respect to the grounded emitter is :

$$V_{CE} = V_{CC} - V_{R_C} \quad (3\text{-}12)$$

Since the drop across R_C is $V_{RC} = I_C R_C$,

The dc voltage at the collector with respect to the emitter is:

$$V_{CE} = V_{CC} - I_C R_C \quad (3\text{-}13)$$

Where, $I_C = \beta_{DC} I_B$

The dc voltage at the collector with respect to the base is:

$$V_{CB} = V_{CE} - V_{BE} \quad (3\text{-}14)$$

i) Biasing technique -RE

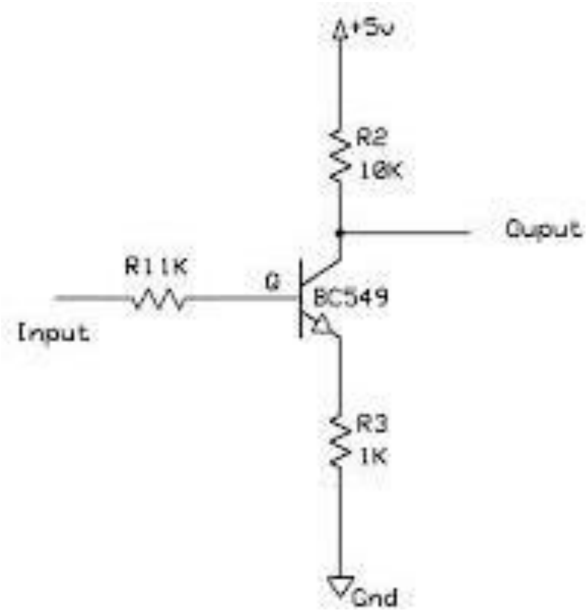


Figure 3.12

$$I_\beta = \frac{V_{CC}}{R_B + (\beta + 1)R_E}$$

$$I_C = \beta . I_\beta$$

$$V_{CE} = V_{CC} - I_C (R_C + R_E)$$

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

$$V_E = V_C - V_{CE} @ I_E R_E$$

ii) Voltage divider calculation

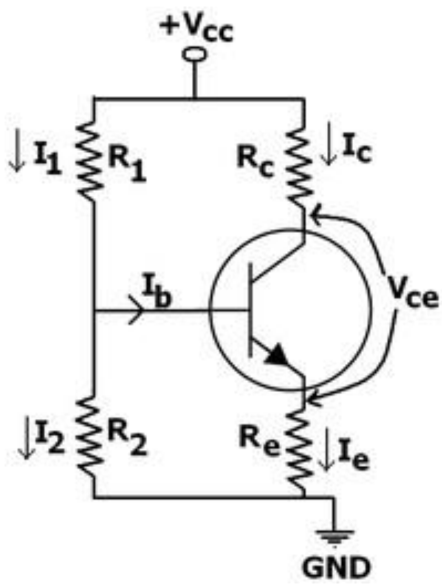


Figure 3.13

$$R_{TH} = R_1 // R_2$$

$$R_{TH} = \frac{R_1 R_2}{R_1 + R_2}$$

$$V_{TH} = \frac{R_2}{R_1 + R_2} \times V_{CC}$$

$$I_E = (\beta + 1) I_B$$

$$I_B = \frac{V_{TH} - V_{BE}}{(RTH + (\beta+1)R_E)}$$

$$V_{CE} = V_{CC} - I_C (R_C + R_E)$$

$$V_B = V_{TH}$$

$$V_E = V_B - V_{BE}$$

Example 3.1

Determine I_B, I_C, I_E, V_{CE} and V_{CB} in the circuit in Figure 3.14. The transistor has a β_{DC}=150

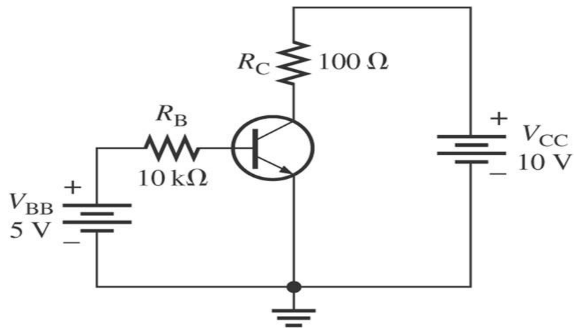


Figure 3.14

Solution:

When BE junction is FB, act as normal diode. So, V_{BE}=0.7V

The base current,

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5 - 0.7}{10k\Omega} = 430\mu 3$$

Collector current,

$$I_C = \beta_{DC} I_B = 150(430\mu 50 = 64.5mA$$

Emitter current,

$$I_E = I_C + I_B = 64.5mA + 430\mu 3 = 64.9mA$$

Solve for V_{CE} and V_{CB},

$$V_{CE} = V_{CC} - I_C R_C = 10V - (64.5mA)(100\Omega 0 = 3.55V$$

$$V_{CB} = V_{CE} - V_{BE} = 3.55 - 0.7 = 2.85V$$

3.5.4 Transistor operating region

Transistor has three operating region which are saturation region, active region and cut-off region as illustrated in Figure 3.15.

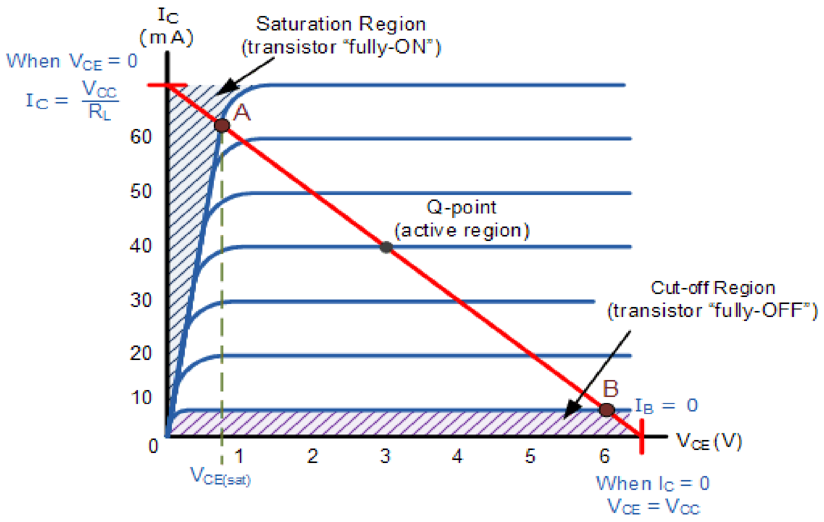


Figure 3.15 Transistor operating region

3.5.5 Cut-off

Cutoff is a non-conducting state of a transistor. This occurs when the base lead opens, and the base current is zero. There is only a very small amount of collector *leakage current* , I_{CEO},(as shown in Figure 3.16) caused by thermally produced carriers. However, it will usually be neglected so that $V_{CE} = V_{CC}$. In the cutoff, neither the base-emitter nor the base-collector junctions are forward biased.

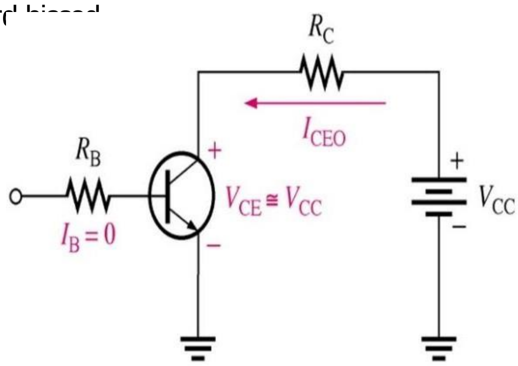


Figure 3.16 Transistor circuit

3.5.6 Saturation

- Saturation is the state of a BJT in which the collector current has reached a maximum and is independent of the base current.
- Note that saturation value of I_C can be determined by application of Ohm's law. When V_{CE} reaches its saturation value ($V_{CE(sat)}$) =0, we obtain,

$$I_{Csat} = \frac{V_{CC}}{R_C} \quad (3\text{-}15)$$

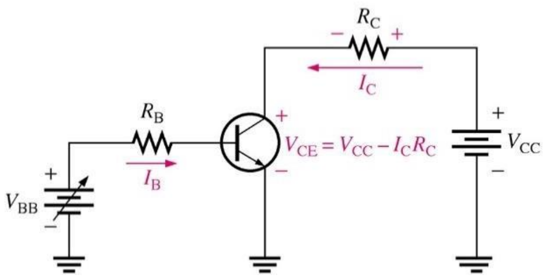


Figure 3.17 Transistor circuit

a) NPN transistor in cut-off mode (Figure 3.18).

- The input and Base are grounded (0V)
- Base-Emitter voltage, V_{BE} <0.7V
- Based-Emitter junction is reverse biased
- Based-Collector junction is reverse biased
- Transistor is "fully-OFF" (Cut-off region)
- No Collector current flows (I_C=0)
- V_{OUT}=V_{CE}=V_{CC}="1"
- Transistor operates as an "open switch"

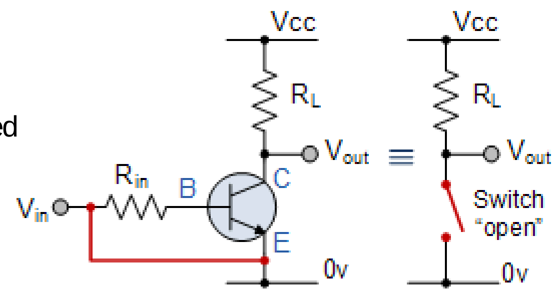


Figure 3.18 Cut-off mode

b) NPN transistor in saturation mode (Figure 3.19).

- The input and Base are connected to Vcc
- Base-Emitter voltage, V_{BE} >0.7V
- Based-Emitter junction is forward biased
- Based-Collector junction is forward biased
- Transistor is "fully-ON" (saturation region)
- Max Collector current flows (ideal saturation)
- V_{OUT}=V_{CE}="0"
- Transistor operates as a "closed switch"

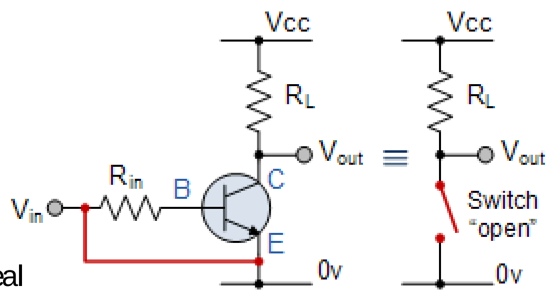


Figure 3.19 Saturation mode

3.5.8 DC load line

- DC load line graphically illustrates Ic(sat) and cutoff for a transistor as in Figure 3.20.
- The bottom of the load line is at ideal cutoff where $I_C = 0$ and $V_{CE} = V_{CC}$.
- The top of the load line is at saturation where $I_C = I_{C(sat)}$ and $V_{CE} = V_{CE(sat)}$.
- Along the load line is the *active region* of the transistor's operation.

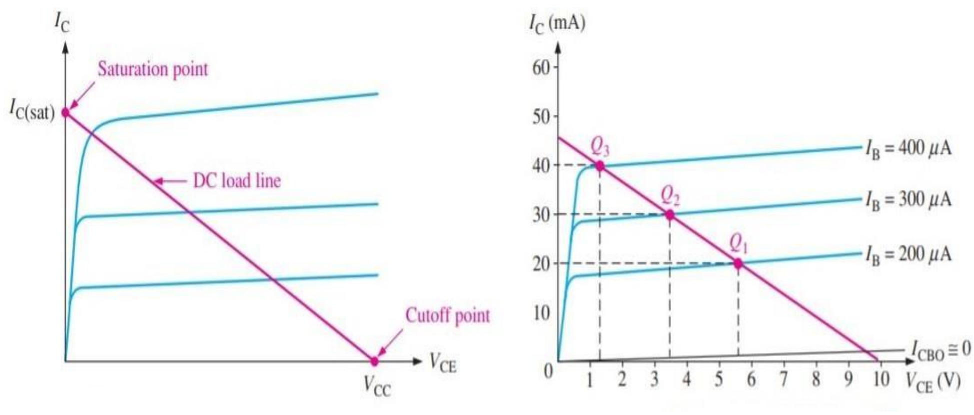


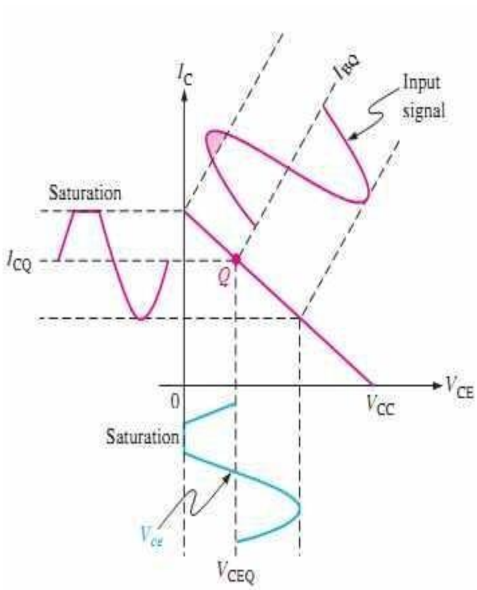
Figure 3.20 DC load line

3.5.8 Q-Point (Static Operation Point)

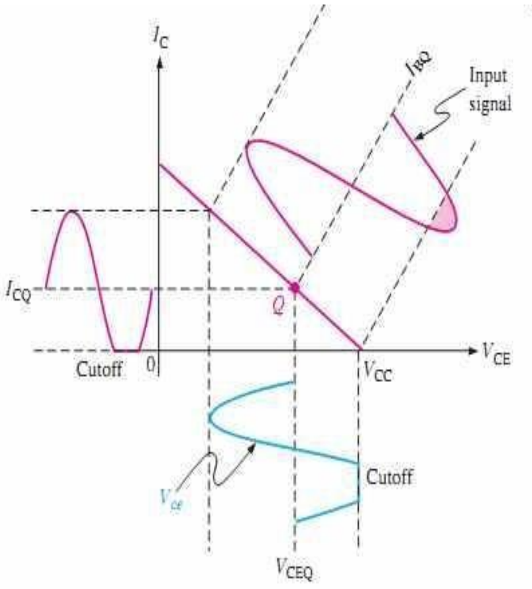
- Q point or the operating point of a device, also known as a bias point, or quiescent point is the steady-state DC voltage or current at a specified terminal of an active device such as a diode or transistor with no input signal applied.

3.5.9 DC biasing and AC signal

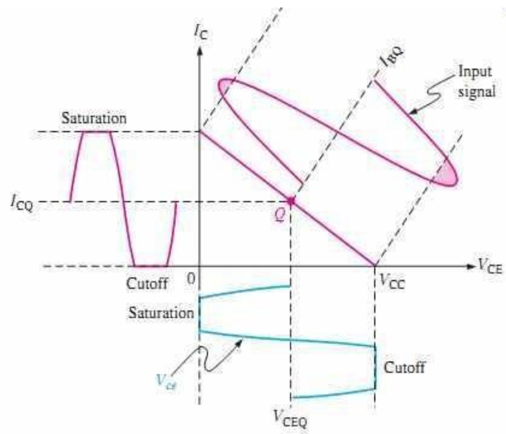
- When an ac signal is applied to the base of the transistor, I_C and V_{CE} will both vary around their *Q*-point values.
- When the *Q*-point is centered, I_C and V_{CE} can both make the maximum possible transitions above and below their initial dc values.
- When the *Q*-point is above the center on the load line, the input signal may cause the transistor to saturate. When this happens, a part of the output signal will be *clipped* off.
- When the *Q*-point is below midpoint on the load line, the input signal may cause the transistor to cutoff. This can also cause a portion of the output signal to be clipped.



(a) Transistor is driven into saturation because the Q-point is too close to saturation for the given input signal.



(b) Transistor is driven into cut-off because the Q-point is too close to cut-off for the given input signal.

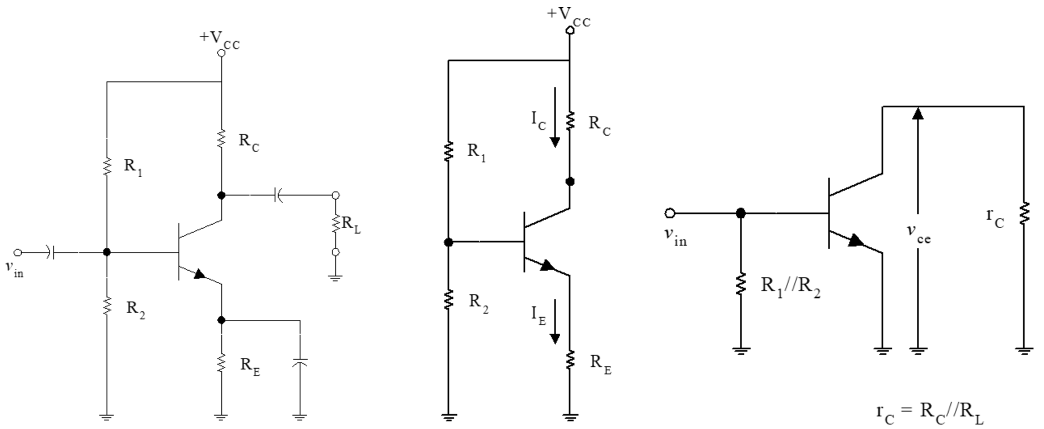


(c) Transistor is driven into both saturation and cut-off because the input signal is too large.

Figure 3.21Transistor operating region

3.5.10 DC and AC equivalent circuits

Transistor can be represented as an equivalent circuit as shown in Figure 3.22.



(a) Bias current (b) DC equivalent circuit (c) AC equivalent circuit

Figure 3.22 Transistor equivalent circuit

3.5.11 Q-Point (Static Operation Point)

- Q point or the operating point of a device, also known as a bias point, or quiescent point is the steady-state DC voltage or current at a specified terminal of an active device such as a diode or transistor with no input signal applied.

3.5.12 DC biasing and AC signal

- When an ac signal is applied to the base of the transistor, I_C and V_{CE} will both vary around their *Q*-point values.
- When the *Q*-point is centered, I_C and V_{CE} can both make the maximum possible transitions above and below their initial dc values.
- When the *Q*-point is above the center on the load line, the input signal may cause the transistor to saturate. When this happens, a part of the output signal will be *clipped* off.
- When the *Q*-point is below midpoint on the load line, the input signal may cause the transistor to cutoff. This can also cause a portion of the output signal to be clipped.

3.5.13 AC load line

- The ac load line is used to tell you the maximum possible output voltage swing for a given common-emitter amplifier.
- In other words, the ac load line will tell you the maximum possible peak-to-peak output voltage (V_{pp}) from a given amplifier.
- This maximum V_{pp} is referred to as the compliance of the amplifier (AC Saturation Current $I_{c(sat)}$, AC Cutoff Voltage $V_{CE(off)}$).
- The ac load line of a given amplifier will not follow the plot of the dc load line.
- This is due to the dc load of an amplifier is different from the ac load.
- Ac load line, saturation current and cut-off voltage are shown in Figure 3.23 and Figure 3.24.

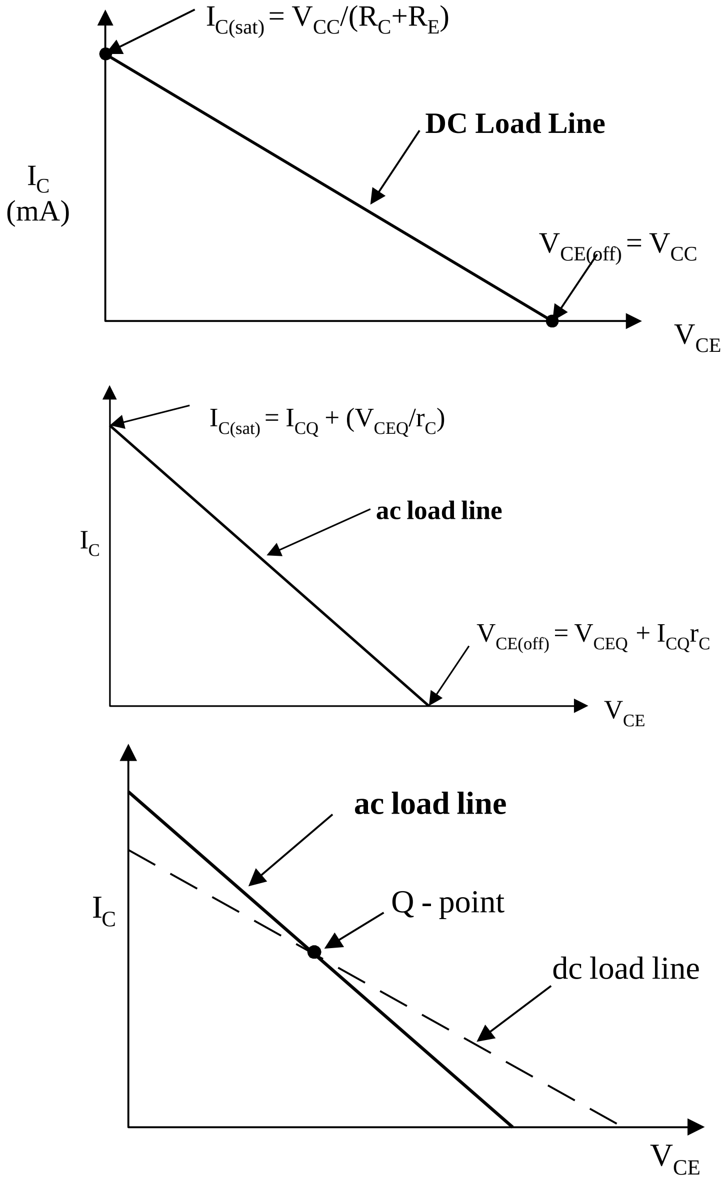


Figure 3.23 AC load line

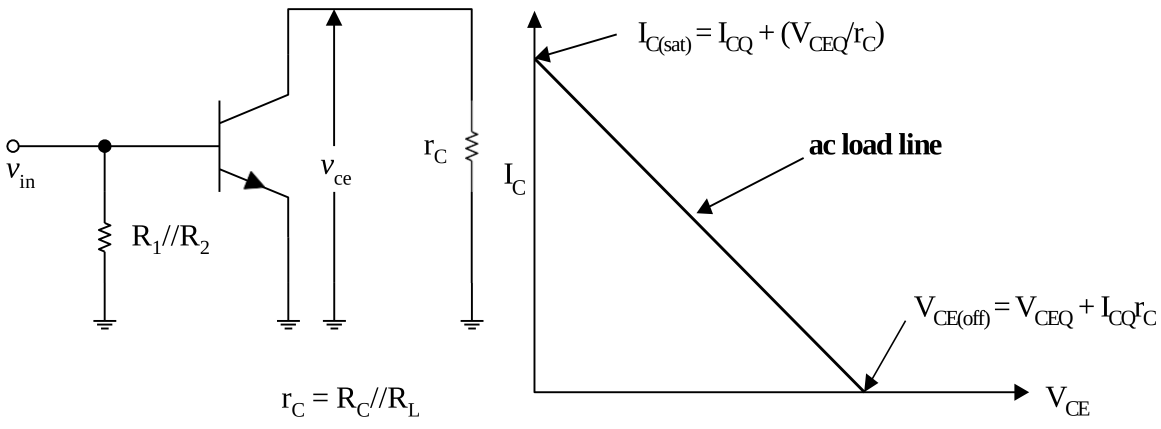


Figure 3.24 AC saturation current and AC cut-off voltage

3.5.14 Amplifier compliance

- The ac load line is used to tell the maximum possible output voltage swing for a given common-emitter amplifier. In another words, the ac load line will tell the maximum possible peak-to-peak output voltage (V_{PP}) from a given amplifier. This maximum V_{PP} is referred to as the compliance of the amplifier.
- The compliance of an amplifier is found by determine the maximum possible of I_C and V_{CE} from their respective values of I_{CQ} and V_{CEQ}.

3.5.15 Maximum undistorted output signal amplitude

- The maximum possible transition for V_{CE} is equal to the difference between $V_{CE(off)}$ and V_{CEQ}.
- Since this transition is equal to $I_{CQ}r_C$, the maximum peak output voltage from the amplifier is equal to $I_{CQ}r_C$.
- Two times this value will give the maximum peak-to-peak transition of the output voltage:

V_{PP} =the output compliance, in peak-to-peak voltage

I_{CQ} =the quiescent value of I_C

r_C =the ac load resistance in the circuit

$$V_{PP} = 2I_{CQ}r_C$$

3-15

- When $I_C = I_{C(sat)}$, V_{CE} is ideally equal to 0V. When $I_C = I_{CQ}$, V_{CE} is at V_{CEQ}.
- Note that when I_C makes its maximum possible transition (from I_{CQ} to $I_{C(sat)}$), the output voltage changes by an amount equal to V_{CEQ}.
- Thus, the maximum peak-to-peak transition would be equal to twice this value:

$$V_{PP} = 2V_{CEQ} \tag{3-16}$$

- Equation 3-15 sets the limit in terms of $V_{CE(off)}$. If the value obtained by this equation is exceed, the output voltage will try to exceed $V_{CE(off)}$, which is not possible. This is called cutoff clipping, because the output voltage is clipped off at the value of $V_{CE(off)}$.
- Equation 3-16 sets of the limit in terms of $I_{C(sat)}$. If the value obtained by this equation is exceed, the output will experience saturation clipping.

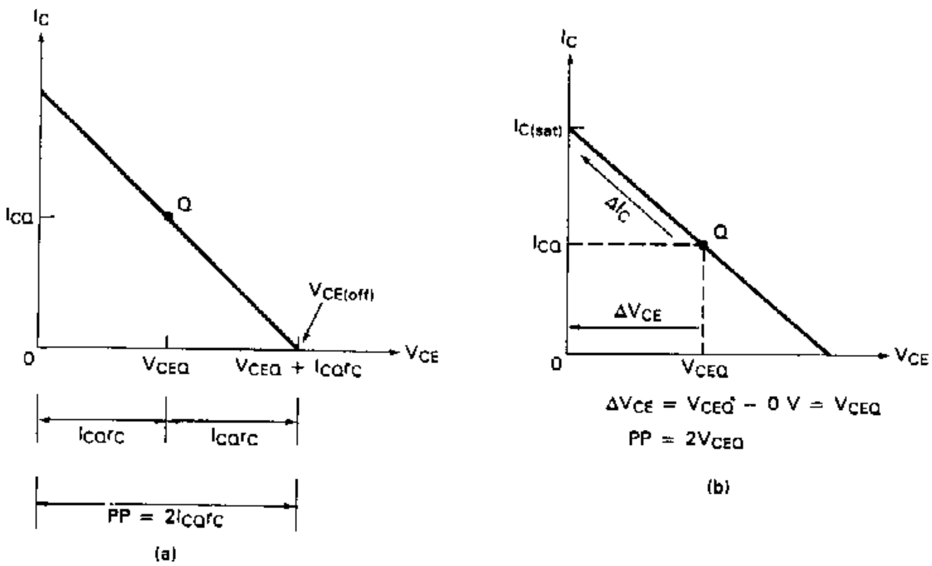


Figure 3.25 Maximum possible compliance

3.5.16 Cut-off and saturation clipping

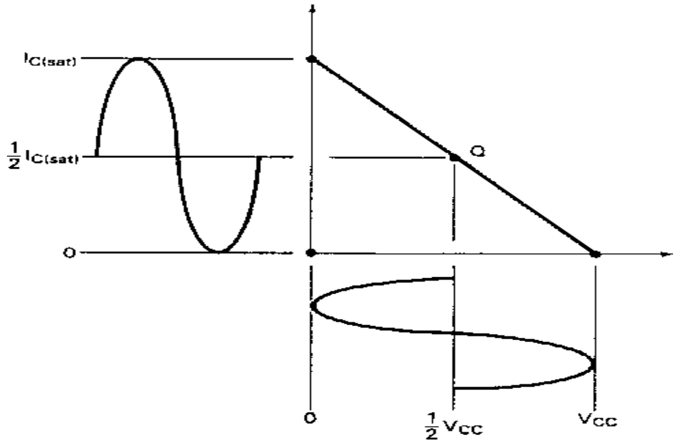


Figure 3.26 Centered Q-Point for an ideal amplification

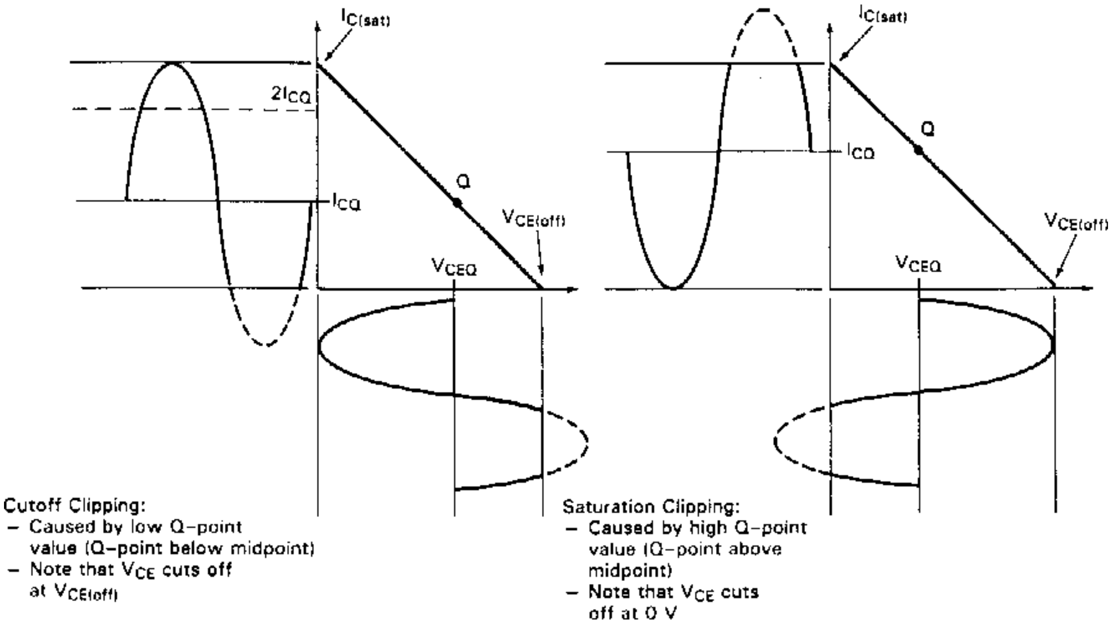


Figure 3.27 Cutoff and saturation clipping

3.6 Frequency response

- Most amplifiers have a limited frequency range in which they can function.
- The behavior of amplifiers also rely on the input signal frequency which is known as frequency response.
- The frequency response is affected by the selection of components during designing stage of amplifier.
- A frequency response of an amplifier can be represented as frequency response as shown in Figure 3.28.

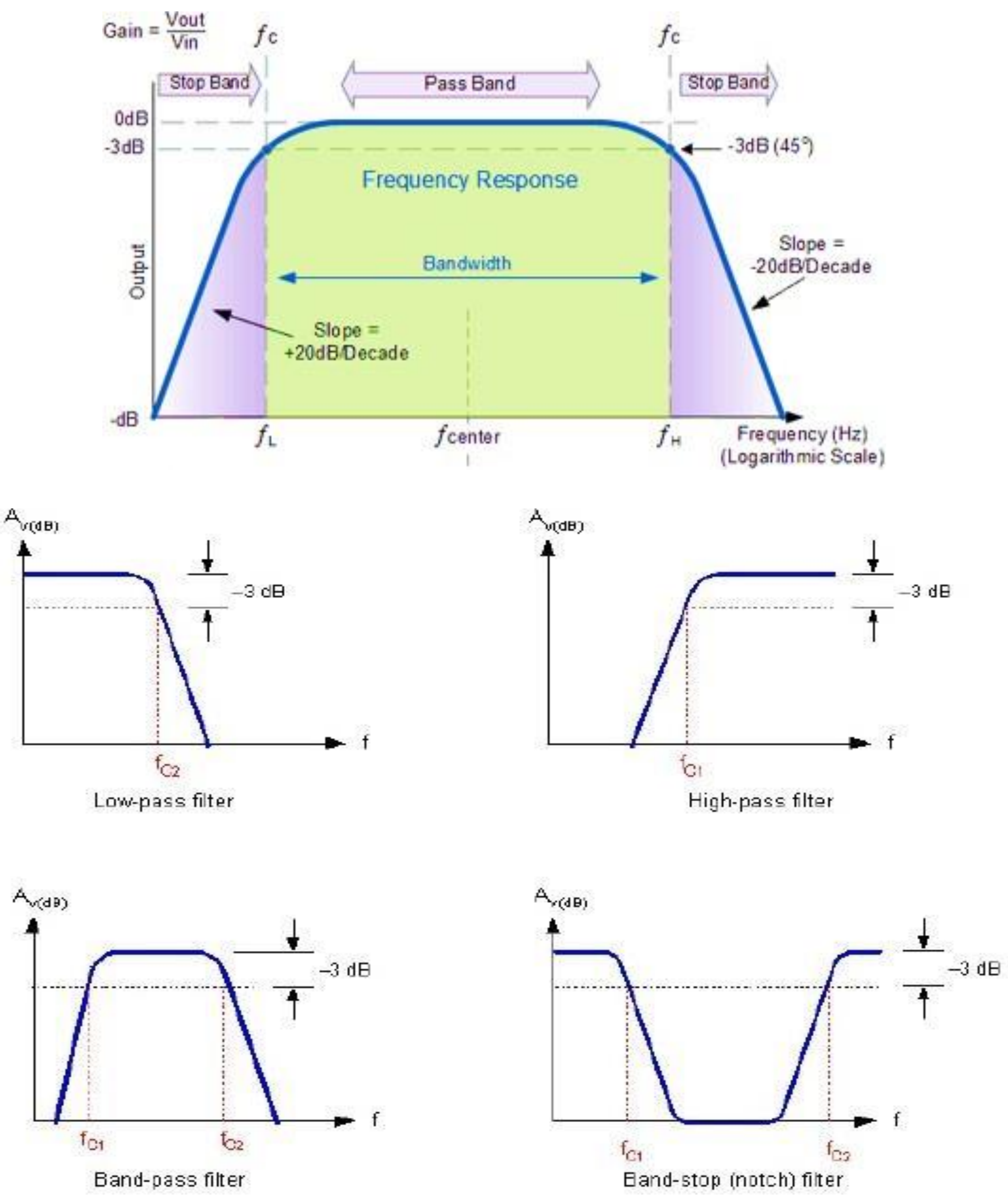


Figure 3.28 Frequency response curve

The decibel is a common unit of measurement of voltage gain and frequency response. It is a logarithmic measurement of the ratio of one power to another or one voltage to another. The formulas below are used for calculation of decibels for power gain and voltage gain.

$$A_{p(db)} = 10 \log A_p$$
$$A_{v(db)} = 20 \log A_v \quad \text{3-16}$$

Example 3.2

Express each of the following ratios in dB:

(a) $\frac{P_{out}}{P_{in}} = 250$ (b) $\frac{P_{out}}{P_{in}} = 100$ (c) Av = 10

(d) $A_p = 0.5$ (e) $\frac{V_{out}}{V_{in}} = 0.707$

Solution:

(a) $A_{p(dB)} = 10 \log(250) = 24$ dB

(b) $A_{p(dB)} = 10 \log(100) = 20$ dB

(c) $A_{v(dB)} = 20 \log(10) = 20$ dB

(d) $A_{p(dB)} = 10 \log(0.5) = -3$ dB

(e) $A_{v(dB)} = 20 \log(0.707) = -3$ dB

3.7 Frequency response characteristics of an amplifier

- Characteristics of an amplifier can be identified by referring to the respective frequency response curve.

1. The critical frequency

- The critical frequency also known as the cutoff frequency is the frequency at which the output power drops by 3 dB, which represents one-half of its midrange value.
- An output voltage drop of 3 dB represents about a 70.7% drop from the midrange value. Power is often measured in units of dBm.
- This is decibels with reference to 1mW of power. This means that 0 dBm = 1mW.

Example 3.3

A certain amplifier has a midrange rms output voltage of 10 V. What is the rms output voltage for each of the following dB gain reductions with a constant rms input voltage?

(a) –3 dB (b) –6 dB (c) –12 dB (d) –24 dB

Solution:

Multiply the midrange output voltage by the voltage gain corresponding to the specified dB value in Table.

(a) At –3 dB, $V_{out} = 0.707(10\ V) = 7.07\ V$
(b) At –6 dB, $V_{out} = 0.5(10\ V) = 5\ V$
(c) At –12 dB, $V_{out} = 0.25(10\ V) = 2.5\ V$
(d) At –24 dB, $V_{out} = 0.0625(10\ V) = 0.625\ V$

2. Low frequency amplifier response

- The roll-off is the decrease in voltage gain with frequency. A decade is defined as a tenfold increase in frequency.
- The dB/decade is the attenuation measured in decibels at each decade.
- The relationship can be seen in Figure 3.29 of dB Av vs frequency. Roll-off is sometimes stated as dB/octave, which is a frequency doubling or halving.

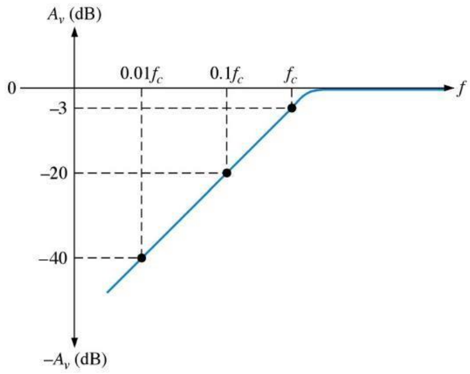


Figure 3.29 dB voltage gain versus frequency for the input RC circuit.

3. High frequency amplifier response

- Figure 3.30 shows a high-frequency ac equivalent circuit for the BJT amplifier.
- The coupling and bypass capacitors are viewed as effective shorts in the equivalent circuit and do not show.
- The internal capacitances, Cbe and Cbc, are shown in the diagram, but they are only significant at high frequencies.

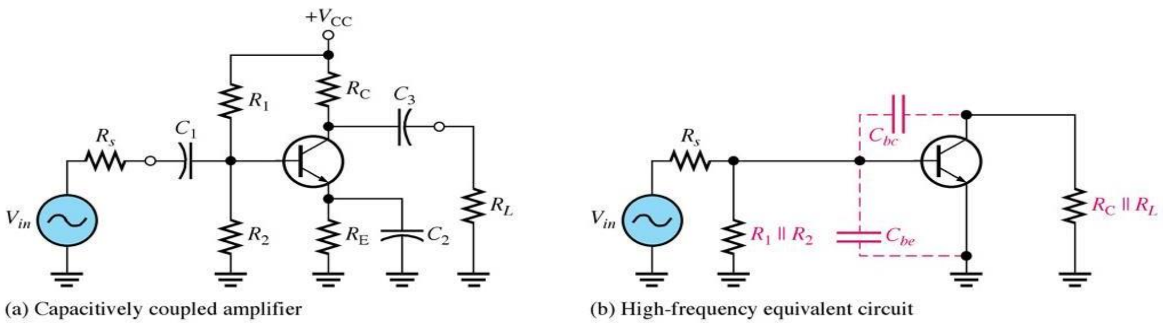


Figure 3.30 Capacitively coupled amplifier and its high-frequency equivalent circuit.

4. Total amplifier frequency response

- A generalized ideal response curve (Bode plot) for the BJT amplifier described in Figure 3.31 (a) is shown in Figure 3.31 (b).
- The three low-frequency RC circuits established by the coupling and bypass capacitors produce the three break points at the lower critical frequencies (fc1, fc2, and fc3). The two high-frequency RC circuits established by the transistor's internal capacitances produce the break points at the upper critical frequencies, fc4 and fc5.

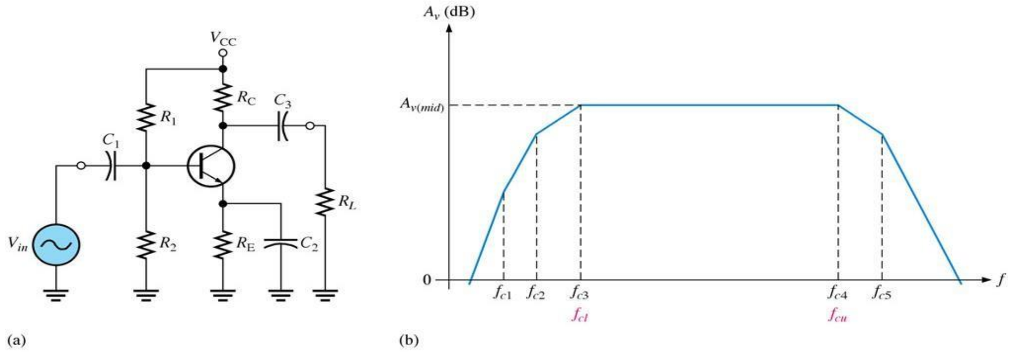


Figure 3.31BJT amplifier circuit and response curve

3.7.5 Total amplifier frequency response-Bandwidth

An amplifier normally operates with signal frequencies between f_{cl} and f_{cu}. The range (band) of frequencies lying between f_{cl} and f_{cu} is defined as the bandwidth of the amplifier, as illustrated in Figure. The amplifier's bandwidth is expressed in units of hertz as:

$$BW = f_{cu} - f_{cl} \quad (3\text{-}17)$$

3.8 Classification of amplifier

Amplifier can be classified to several class based with their own operating characteristics and frequency response.

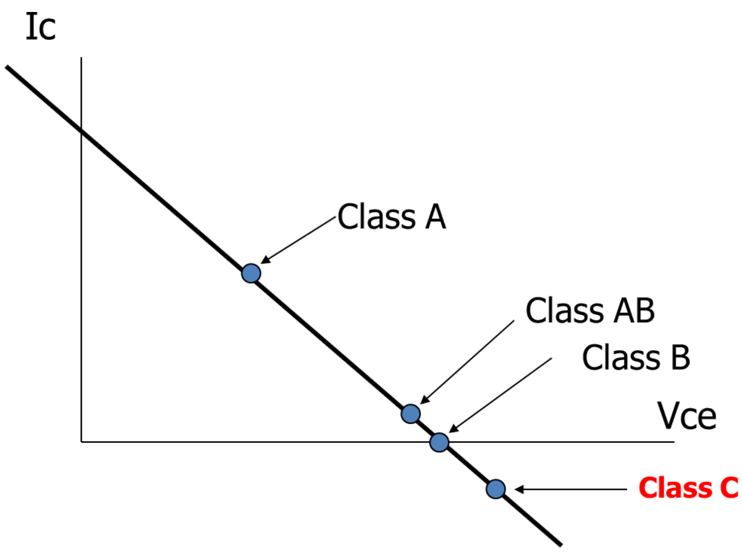
3.8.1 Amplifier types

Class A
- The amplifier conducts through the full 360°of the input.
- The Q-point is set near the middle of the load line.

Class B
- The amplifier conducts through 180°of the input.
- The Q-point is set at the cutoff point.

Class AB
- This is a compromise between the class A and B amplifiers.
- The amplifier conducts somewhere between 180°and 360°.
- The Q-point is located between the mid-point and cutoff.

Class C
- The amplifier conducts less than 180 of the input.
- The Q-point is located below the cutoff level.



3.8.2 Class A amplifier

- The amplifier conducts through the full 360°of the input. The Q-point is set near the middle of the load line.
- The class A amplifier as in Figure 3.32 has the characteristics of good FIDELITY and low EFFICIENCY.
- Fidelity means that the output signal is just like the input signal in all respects except amplitude. It has the same shape and frequency.
- Since class A amplifiers operate (have current flow) for 360º of input signal, they are low in efficiency.
- Application: e.g Small-signal stages or for low-power applications (such as driving headphones).

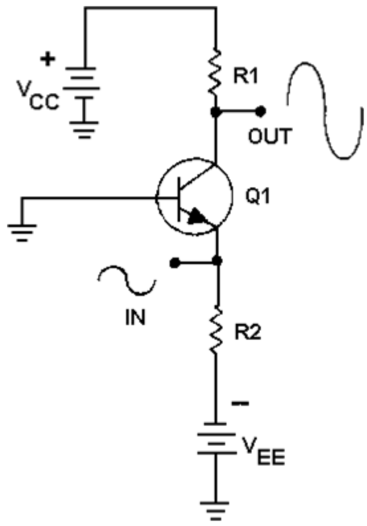


Figure 3.32 Class A amplifier

3.8.3 Class B amplifier

The Class B amplifier is biased at cutoff, in other words there is no bias. The amplifier relies on the input signal to bias the transistor. The first 0.7 volts of the signal in is lost A class B amplifier operates for 50% of the input signal. Amplifier is very efficient but provides 'crossover distortion'. Class B amplifiers are twice as efficient as class A amplifiers. Application: e.g., RF Power Amplifier where the distortion levels are less important.

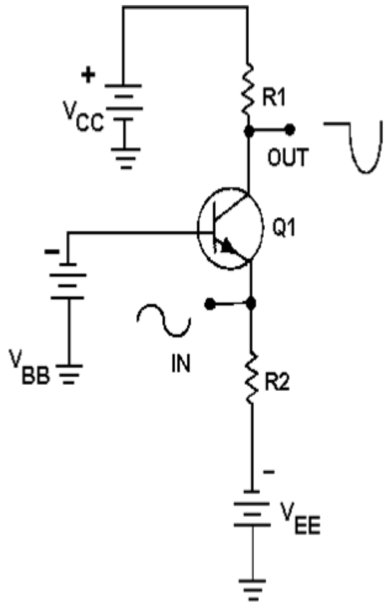


Figure 3.33 Class B amplifier

3.8.4 Class AB amplifier

- Current flows in the device for 51%- 99% of the input signal. Class AB amplifiers have better efficiency and poorer fidelity than class A amplifiers.
- Notice that the output signal in Figure 3.34 is distorted. Any further increase in input signal will not cause an increase in output signal voltage.

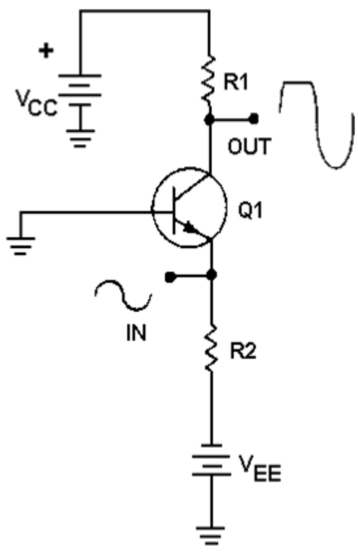


Figure 3.34 Class AB amplifier

3.8.5 Class C amplifier

- The Class C amplifier has a negative voltage at the base, and zero volts at the emitter. The Base-Emitter junction is reverse biased.
- Notice that only a small portion of the input signal is present in the output signal. It also has the worst fidelity.
- The transistor will turn on at a signal voltage of 4.7V. The transistor will only conduct a small pulse through to the collector output. Amplifier is very efficient but has very little usefulness.
- Application: e.g., RF Transmitters, where the distortion can be vastly reduced by using tuned loads on the amplifier stage.

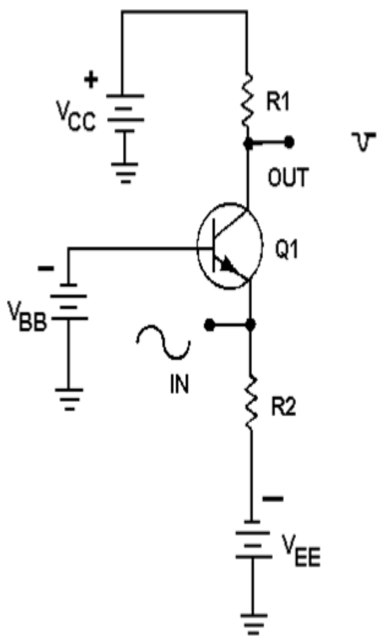


Figure 3.35 Class B amplifier

3.8.6 Class C application

- Collector resonant circuit responds to an impulse by 'ringing' at its resonant frequency. This is like pushing someone on a swing.
- A sharp short push each trip allows the swing to oscillate back and forth at its resonant frequency.
- Collector impulses occur by design at the resonant frequency of the tank circuit. Resonant circuit continues to ring and restores the sine wave at the output.
- Class C Amplifier is used in radio/RF applications and is also called a 'tuned' amplifier.

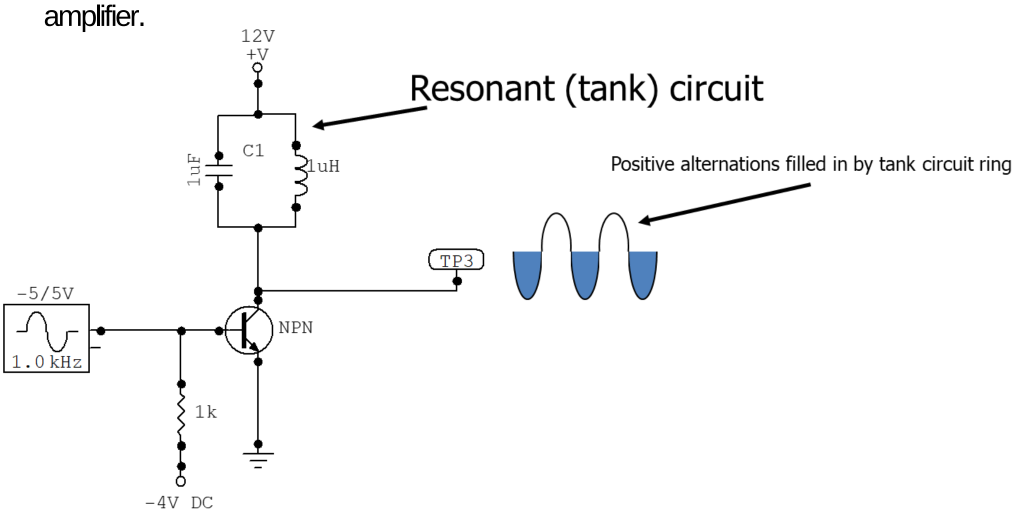


Figure 3.36 Class C amplifier

Table 3.6 Summary of amplifier class

Class	A	AB	B	C
Conduction Angle	360°	180 to 360°	180°	Less than 90°
Position of the Q-point	Centre Point of the Load Line	Forward (Near Cutoff)	Zero (at Cutoff)	Reverse (Beyond Cutoff)
Overall Efficiency	Poor, 25 to 30%	Better than A but less than B 50 to 70%	Better, 70 to 80%	Higher than 80%
Signal Distortion	Low	Moderate	High	Extreme
Applications	Practically all small signal amplifiers. A few moderate power amplifiers in audio	High power stages in both audio and radio frequency applications.	High power stages- generally no used in audio applications due to	Generally limited to radio frequency applications. Tuned circuits remove much of the

3.9 Feedback

Feedback is a technique where a proportion of the output of a system (amplifier) is fed back and recombined with input as in Figure 3.37. the various signal "x" can be either current or voltage.

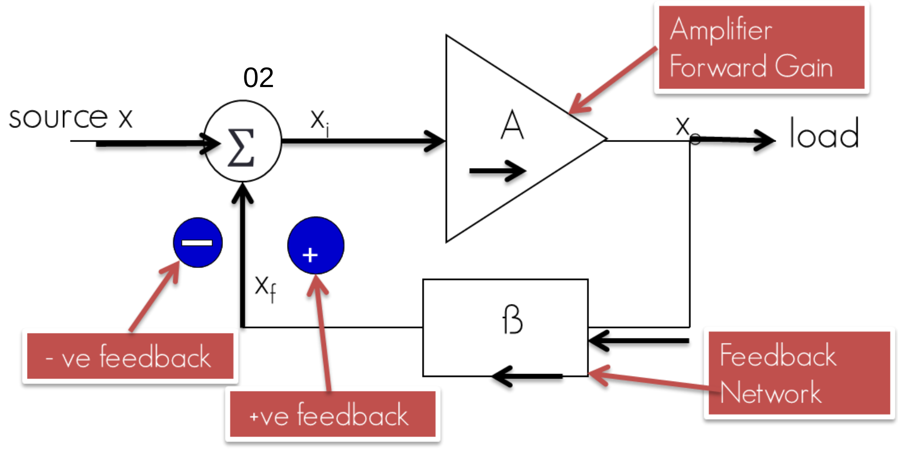
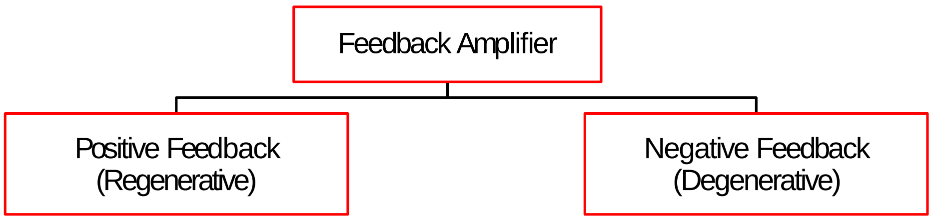


Figure 3.37 Feedback block diagram

- It is used most commonly in an amplifier. Part of the output from the amplifier is fed back to the input and this concept is called feedback.
- When the input signal of amplifier and part of the output are In-phase with each other, it is called as Positive feedback.
- When the input signal of amplifier and part of the output are Out-phase with each other, it is called as Negative feedback.
- The concept of positive feedback results in oscillations, so they are used to generate oscillations of particular frequency as required. Such circuits are called as Oscillators.

3.9.1 Amplifier types



- Positive feedback occurs when the feedback signal is in phase with the input signal.
- Application – used in Oscillator circuits

- Negative feedback occurs when the feedback signal is out of phase with the input signal.
- Application - used in Amplifier Circuits.

3.9.2 Positive and negative feedback

Negative feedback is when the output is subtracted from the input. In this case, the feedback signal is out of phase with the input signal. This means that the feedback signal will subtract from or "degenerate" the input signal. This results in a lower amplitude output signal than would occur without the feedback.

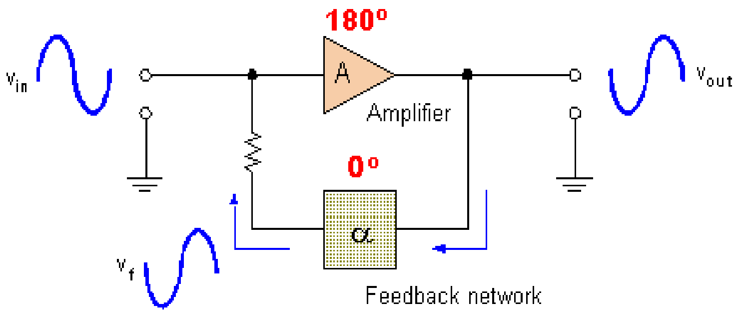


Figure 3.38 Negative feedback

Positive feedback is the process when the output is added to the input, amplified again, and this process continues. Notice that the feedback signal is in phase with the input signal. This means that the feedback signal will add to or "regenerate" the input signal. The result is a larger amplitude output signal than would occur without the feedback.

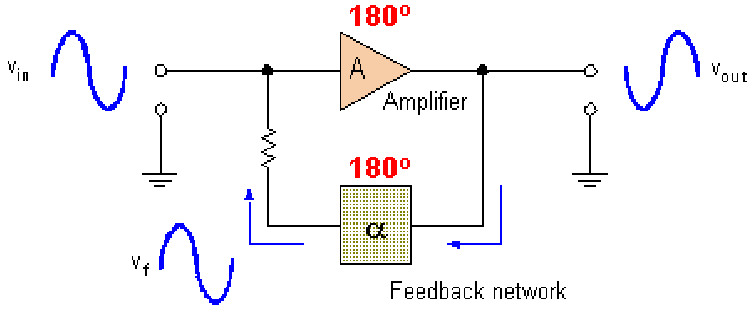


Figure 3.39 Positive feedback

3.9.3 Difference between positive and negative feedback

As indicated, each type of feedback has their own parameter and characteristic as tabulated in Table 3.7.

Table 3.7 Difference between positive and negative feedback

Parameter	Positive Feedback	Negative Feedback
Overall Phase Shift	0 or 360^0	180^0
Input &Output Voltage, noise	Increases due to Feedback	Decreases due to Feedback
Feedback Signal & Input Signal	In phase	Out of phase
Stability	Becomes poor	Becomes better
Applications	Oscillators	Amplifiers

3.9.4 Advantage and disadvantage of negative feedback

As indicated, each type of feedback has their own parameter and characteristic as tabulated in Table 3.7.

Table 3.8 Negative feedback advantages and disadvantages

Advantages	Disadvantages
Desensitize the gain make the value of the gain less sensitive to variations in the values of circuit components, such as might be caused by changes in temperature.	▪ Circuit Gain - The overall amplifier gain, with negative feedback, is reduced compared to the basic amplifier used in the circuit.
Bandwidth extension, The bandwidth of a circuit that incorporates negative feedback is large than that of the basic amplifier.	▪ Stability - There is a possibility that the feedback circuit may become unstable (oscillate) at high frequencies
Noise sensitivity, Negative feedback may reduce the noise level in amplifier and increase the single-to-noise ratio (SNR)	

Table 3.8 Negative feedback advantages and disadvantages (cont.)

Advantages	Disadvantages
Reduction of non-linear distortion. since transistors have nonlinear characteristics, distortion may appear in the output signals, especially at large signal levels. Negative feedback reduces this distortion.	
Control of impedance levels. The input and output impedances can be increased and decreased with proper type of negative feedback circuits.	

1. Describe physical structure and symbols for BJT.
2. Describe basic transistor operation mode.
3. Compare their input signal different A, B, AB and C classes Amplifiers.
4. Express the following voltage gains in dB:
   i. 12
   ii. 50
   iii. 100
   iv. 2500
5. Express the following voltage gains in dB as standard voltage gains:
   i. 3 dB
   ii. 6 dB
   iii. 10 dB
   iv. 20 dB
   v. 40 dB

6. Compare THREE (3) advantages and disadvantages of negative feedback
7. Explain THREE (3) characteristic negative and positive feedback
8. According to Figure 3.40 below :

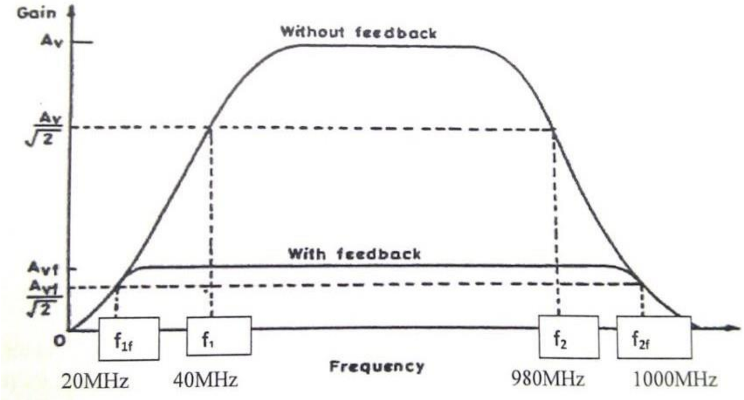


Figure 3.40

   i. Calculate the bandwidth for a frequency response without Feedback and with Feedback.
   ii. If an electronic system produces a 24mV output voltage when a 12mV signal is applied, calculate the decibel value of the system output voltage.

9. Figure 3.41 shows transistor with β_{DC} =120.

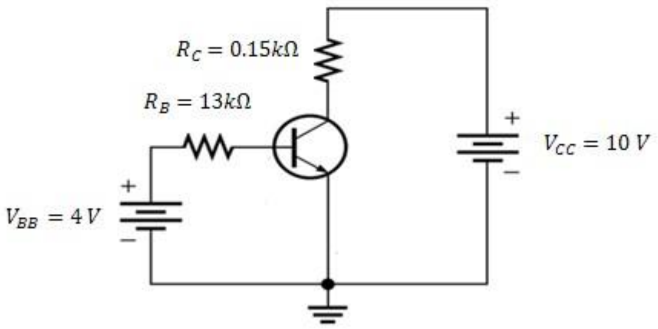


Figure 3.41

Determine:

i. Base current,

ii. Collector current,

i. Emitter current,

iv. Base-to-emitter voltage,

v. Collector-to-emitter voltage,

vi. Collector-to-base voltage,

vii. Draw the DC load line

10. Refer to Figure 3.42. Given the value of β =60 and V_{BE}=0.7V.

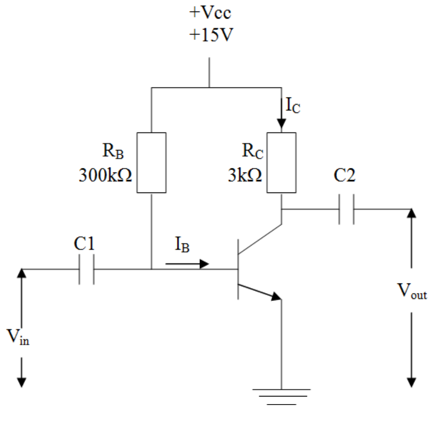


Figure 3.42

Determine:

i. I_B, I_{CQ}, V_{CQ}, saturation point, cut-off point, and

ii. Draw the DC load line

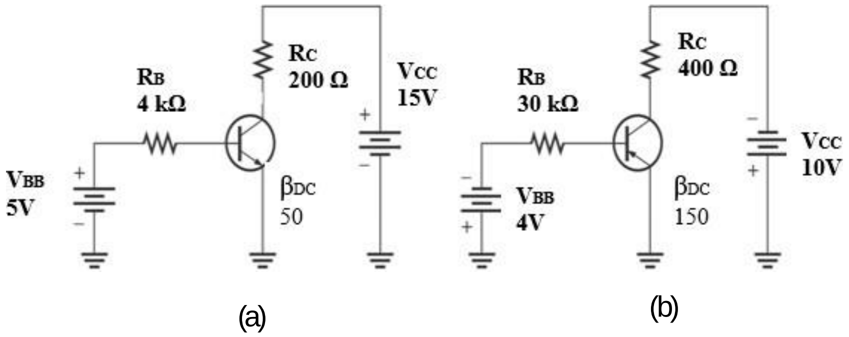


Figure 3.43

11. For both circuits in Figure 3.43 (a) and (b), determine:
   i. VCE,
   ii. VBE,
   iii. VCB, and
   iv. whether or not the transistors are saturated?

12. With reference to Figure 3.44, calculate the value of:

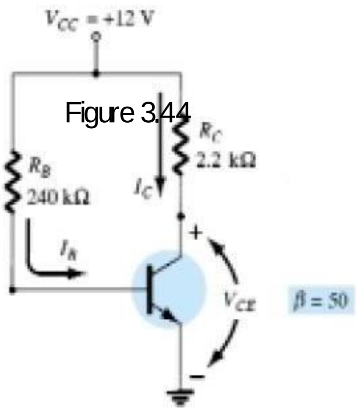


Figure 3.44

   i. I_B ,
   ii. I_C ,
   iii. V_{RC} ,
   iv. V_C ,
   v. Saturation Point , and
   vi. Cut-off point

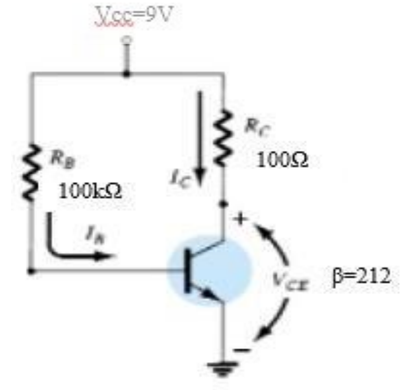


Figure 3.45

13. Determine the following for the fixed-bias configuration of Figure 3.45.

    i. I_B and I_C ,

    ii. V_{CE} ,

    iii. V_B and V_C , and

    iv. VBC

Boylestad, R.L.,& Nashelsky, L.(2013). *Electronic Devices and Circuit Theory* (Eleventh ed.). Pearson.

Byjus. (2021). Retrieved from Semiconductors: https://byjus.com/jee/semiconductors/

Fundamentals of Electrical Engineering (2 ed.). (1996). New York: Oxford UP.

Grahn, H.T.(1996). *Electronic Semiconductor.* Berlin. doi:https://doi.org/10.1142/3631

Nave, R(2013). *P-Type, N-Type Semiconductors.* California: LibreTexts.

Physics and Radio Electronics. (n.d.). Retrieved from Forward biased p-n junction diode: https://www.physics-and-radio-electronics.com/electronic-devices-and-circuits/semiconductor-diodes/forwardbiasedpnjunctionsemiconductordiode.html

Semiconductor Devices and Circuits, Applications. (n.d.). Retrieved from Elcoprus: https://www.elprocus.com/semiconductor-devices-types-and-applications/

Understanding the difference between n and p type semiconductors. (n.d.). Retrieved from Power and Beyond: https://www.power-and-beyond.com/understanding-the-difference-between-n-and-p-type-semiconductors-a-905805/

what is electron hole pair in semiconductor. (n.d.).Retrieved from Radiation Dosimetry: https://www.radiation-dosimetry.org/what-is-electron-hole-pair-in-semiconductors-definition/

Terbitan

POLITEKNIK MALAYSIA
TUANKU SYED SIRAJUDDIN

e ISBN 978-967-2258-48-3

9 7 8 9 6 7 2 2 5 8 4 8 3