

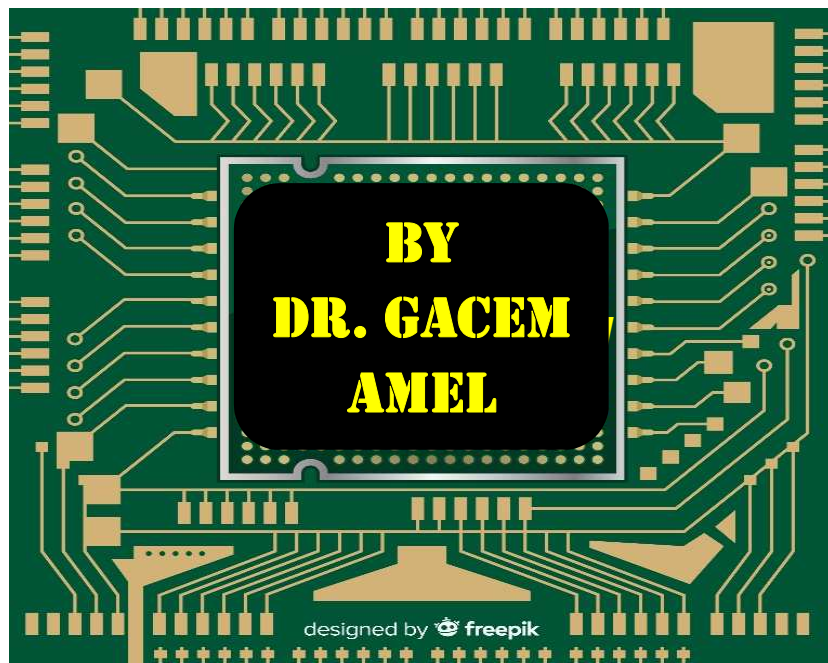
Ministère de l'Enseignement Supérieur
et de la Recherche Scientifique
Université 20 août 1955 - Skikda



وزارة التعليم العالي والبحث
العلمي
جامعة 20 أوت 1955 - سكيكدة

Electronics Component

Intended for Master 2 physics of materials



2024 - 2025

"التكنولوجيا مثل السحر؛ الجزء الذي تراه ليس دائماً ما يحرك العالم." - دانييل بيل

"Technology is like magic; the part you see is not always what moves the world. "

- Daniel Bell

Intitulé du Master : Physique des matériaux**Semestre : 03****Intitulé de l'UE : Méthodologie****Intitulé de la matière : Composants électroniques****Crédits : 05****Coefficients : 03****Objectifs de l'enseignement :**

La structure des semi-conductrice très importante.par le choix et le taux de dopage .Par ce procédé on peut changer les propriétés optoélectroniques des matériaux.L'application des semi-conducteurs dans circuits électroniques exige l'étude des interfaces entre un métal et un semi-conducteur et la jonction entre semi-conducteurs

Contenu de la matière :

- I. Diodes**
- II. Transistors :**
 - II.1. à jonctions**
 - II.2. à effet de champ**
 - II.3. régime dynamique**
- III. Amplificateurs à transistors**
- IV. Réaction dans les amplificateurs.**

Mode d'évaluation : 50% Continu, 50% examen.**Références :**

- 1- Physics of semiconductors devices, by J.P.Coling, Kluwer**
- 2- Physics of semiconductors devices, by S.M.Sze, Wiley, 2007.**
- 3- Semiconductor opto-electronic devices, by J.Piprek, 2003.**
- 4- Impurities in semiconductors, by V.I.Fistal, CRC press, 2004.**
- 5- Materials sciences in microelectronicsl, by E.S.Machlin, Elsevier, 2005.**

Foreword

Electronic components are the basic building blocks of electronic circuits, essential for controlling and manipulating electrical signals. Key components include resistors, which regulate current flow; capacitors, which store and release energy; diodes, which allow current to flow in one direction; transistors, used for amplification and switching; and inductors, which store energy in a magnetic field. These components work together in circuits to perform specific functions, such as signal processing, power management, and data transmission, forming the foundation of modern electronic devices like smartphones and computers.

This document is a course support for electronic components intended for students in the Master 2 in Physics of Materials, who wish to deepen their knowledge in the subject. This document aims particularly to support the personal work of the student and to make the professor's work more effective. The aim behind this course is to simplify the essential ideas contained in this course and to make them didactically simpler. Consequently, the emphasis will be placed on physical explanations, demonstrations, and examples when they are essential for the students' good understanding. In the context of this course, we are mainly interested in presenting the content of the subject of electronic components in accordance with the official program. The program is structured in the form of four chapters; these chapters allow the main concepts of electronic components to be introduced in a simple way.

The first chapter, entitled Diodes, is devoted to presenting basic notions on semiconductors as an introduction and more mainly to the in-depth study of PN junction diodes, their polarization, their modeling and their different functions.

The second chapter, entitled Transistors, will be dedicated to the study of the different types of junction and field effect transistors, their operating principle, their characteristics and their polarization in static and dynamic regime.

The third chapter, entitled Transistor Amplifiers ; is devoted to examining their operation, their equivalent diagrams, their main electrical characteristics and their applications in modern technology.

The last chapter deals with the different types of feedback in positive or negative amplifiers and their general properties. the study of their influence on gain fluctuations and input and output impedances in electrical circuits.

A large number of bibliographic references have been used to develop this document. Each chapter is preceded by the main part of a course followed by assessment questions with their indicators. I hope that this handout will serve as a valuable working tool for level License and Master in physics and electronics students.

Dr. Gacem Amel

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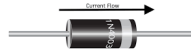
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Chapter I Diode

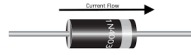


I.1. Introduction

Diodes are semiconductor devices from the late 1940s that control electrical current flow. They exhibit phenomena like biasing and de-biasing and have a constant voltage drop. They turn off quickly when in reverse-bias state. As electrical sources, diodes can switch multiple modes with minimal delay, providing a large variety of commercial uses. Their initial purpose was as a method of rectification in radio receivers. Nowadays, diodes are incorporated into many electronic and electrical components and devices, allowing the current flow through circuits to be controlled in an array of applications. Many improvements have continuously driven the power handling capabilities, switching speeds, and operating temperatures of diodes over the past century. Their role in the modern world has expanded significantly within consumer and commercial products. Newer devices such as diacs, unijunction transistors, and tunnel diodes have since evolved through integrating diode-type components. The improvement to efficiency and power handling capacity of the diodes has drastically increased through numerous improvements. Diodes have gradually become one of the more beneficial and fundamental types of electronic devices.

I.2. Overview of Metals, Insulators and Semiconductors

Metals, insulators, and semiconductors are often viewed as distinct classes of materials. For example, copper conducts electricity very well, whereas glass does not. Semiconductors, like germanium used in transistors, are intermediate in behaviour. There are, in fact, materials that cannot be classified neatly into any of these three classes. However, these are a minority, and the basic ideas about metals, insulators, and semiconductors are useful in understanding most of the materials with



which we are concerned in this document. Copper and glass have typically metal- and insulator-like behaviour. What is the origin of these differences? In the case of elemental solids, differences in their electrical properties are related to the nature of the bonds between atoms. The different types of bonds are illustrated by considering the elements. Every element, or at least most of them, can be assigned one of the following three categories: metals are elemental substances composed of atoms that bear a loose negative charge, distributed into all or part of the material. Metallic bonds are formed when metals have solid-state structure. The metal atoms share their outer electrons throughout the whole material. The atoms in insulators also share their outer electrons. However, they do not share them throughout the whole material. Instead, the atoms arrange themselves into spatial regions by themselves that encompass the various atoms. This spatial grouping is possible because the outer electrons in the insulator atoms are valence electrons involved in forming bonds. Semiconductors are somewhat like insulators.

Their atoms also fall into special regions with well-defined boundaries. However, in these materials, only some of the outer electrons are involved in forming groups. As a result, adjacent regions overlap. In this section, we explain these three types of atomic structure.

In the early stages of electronics development, metals were the primary focus with only a small role for insulators, as most metals have the properties needed to design a conductive path. If we consider a simple one-dimensional model, where a single electron can move along a path blocked by two energy barriers, the probability of the electron overcoming or tunnelling through these barriers can be expressed using the potential step.

It's then realized that the total probability, or current, decreases exponentially as the electron moves into the regions where it encounters potential barriers. For a simple potential barrier of positive energy approaching a barrier of height, we find the transmission coefficient by multiplying it with its complex-conjugate form, using the energy relationship to obtain the probability of the particle crossing to the other side.

The resulting behaviour for small barriers is that the probability is unity when the energy is less than the barrier's height, but drops to zero when it exceeds it - exactly as intuition would suggest.

To enable electrical current to flow over long distances, we need material properties that allow electrons to move over virtually all distances within a typical length of conducting wire.

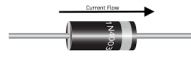


Table I.1 Periodic Table of Semiconductors

Periodic Table of the Elements

1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.06	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71 Lanthanides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.384	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine [209]	86 Rn Radon [222]
87 Fr Francium [223]	88 Ra Radium 226.025	89-103 Actinides	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Nh Nihonium [284]	114 Fl Flerovium [289]	115 Mc Moscovium [288]	116 Lv Livermorium [293]	117 Ts Tennessine [294]	118 Og Oganesson [294]
57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.242	61 Pm Promethium [145]	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.967			
89 Ac Actinium 227.033	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [252]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]			

Alkali Metal
Alkaline Earth
Transition Metal
Basic Metal
Semimetal
Nonmetal
Halogen
Noble Gas
Lanthanide
Actinide

- An insulator does not conduct electrical current under normal conditions. Most insulators are compounds and have very high resistivities. Valence electrons are tightly bound to the atoms and there are very few free electrons. Examples: rubber, plastics, glass, mica, quartz (Figure I.1 (a)).
- A conductor easily conducts electrical current. Most metals are good conductors. The best conductors are single-element materials, such as copper (Cu), silver (Ag), gold (Au), and aluminium (Al), characterized by atoms with one valence electron very loosely bound to the atom. These loosely bound valence electrons become free electrons (Figure I.1 (b)).
- A semiconductor in its pure (intrinsic) state is neither a good conductor nor a good insulator. Single-element semiconductors are (characterized by atoms with four valence electrons) antimony (Sb), arsenic (As), astatine (At), boron (B), polonium (Po), tellurium (Te), silicon (Si), and germanium (Ge). Compound semiconductors such as gallium arsenide, indium phosphide, gallium nitride, and silicon germanium are also commonly used. Silicon is the most commonly used semiconductor (Figure I.1 (c)).

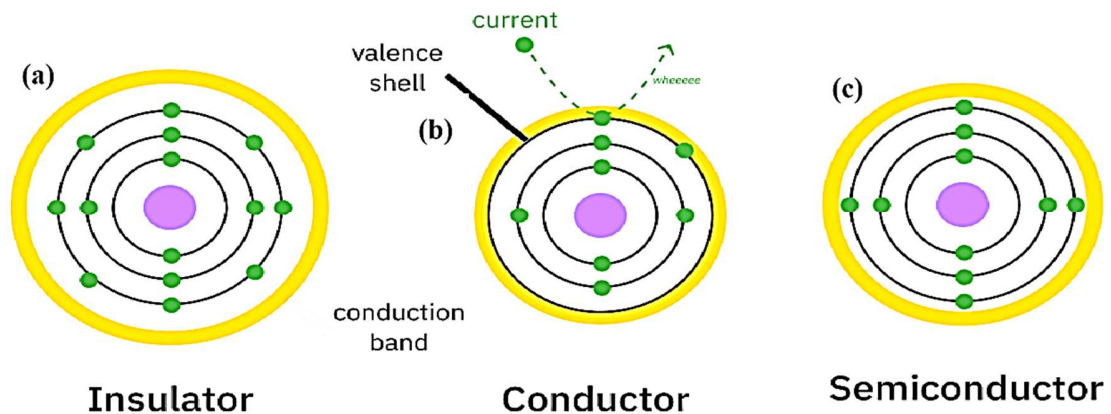
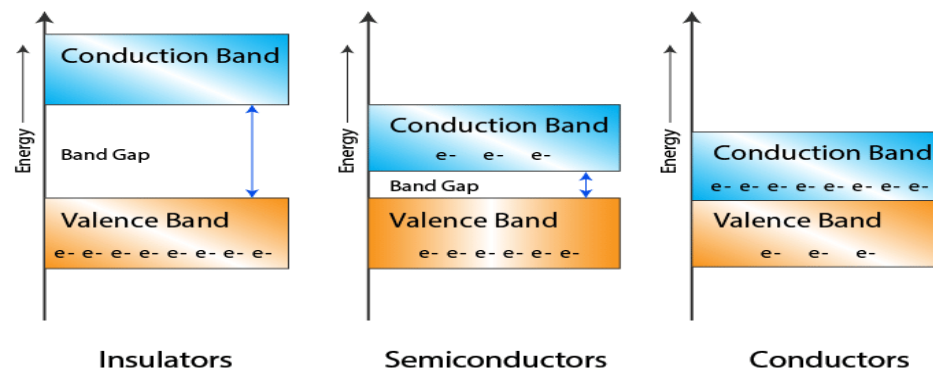


Figure I.1 Diagrams of Insulator (a), conductor (b) and semiconductor (c).

The energy difference between the valence band and the conduction band is the energy gap or band gap; the amount of energy that a valence electron must acquire to jump from the valence band to the conduction band. Once in the conduction band, the electron is free to move throughout the material. The band gap contains energy levels “not allowed” by quantum theory. It is a region in insulators and semiconductors where no electron states exist, although an electron can “jump” across it under certain conditions (Figure I.2).



In semiconductors, the band gap is smaller, allowing an electron in the valence band to jump into the conduction band if it absorbs a photon. The band gap depends on the semiconductor material. In conductors, the conduction band and valence band overlap, so there is no gap. Electrons in the valence band move freely into the conduction band, so there are always electrons available as free electrons.

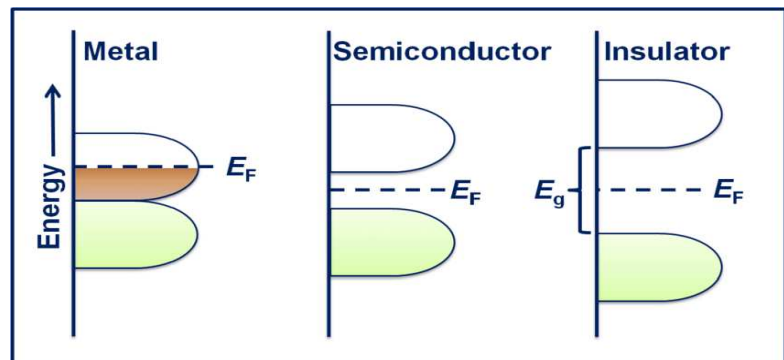


Figure 1.3 Schematic band diagram of metal, semiconductor and insulator.

I.3. Semiconductor materials

Semiconductors materials such as silicon (Si), germanium (Ge) and gallium arsenide (GaAs), have electrical properties somewhere in the middle, between those of a “conductor” and an “insulator”. They are not good conductors nor good insulators (hence their name “semi”-conductors). They have very few “free electrons” because their atoms are closely grouped together in a crystalline pattern called a “crystal lattice” but electrons are still able to flow, but only under special conditions. Semiconductor materials are the basic building blocks of all electronic devices from transistors, to phones, to computers, and to the internet. The ability of semiconductors to conduct electricity can be greatly improved by replacing or adding certain donor or acceptor atoms to this crystalline structure thereby, producing more free electrons than holes or vice versa. That is by adding a small percentage of another element to the base material, either silicon or germanium. On their own Silicon and Germanium are classed as intrinsic semiconductors, that is they are chemically pure, containing nothing but semi-conductive material. But by controlling the amount of impurities added to this intrinsic semiconductor material it is possible to control its conductivity. Various impurities called donors or acceptors can be added to this intrinsic material to produce free electrons or holes respectively.

This process of adding donor or acceptor atoms to semiconductor atoms (the order of 1 impurity atom per 10 million (or more) atoms of the semiconductor) is called Doping. The as the doped silicon is no longer pure, these donor and acceptor atoms are collectively referred to as “impurities”, and by doping these silicon material with a sufficient number of impurities, we can turn it into an N-type or P-type semi-conductor material. The most commonly used semiconductor basics material by far is silicon. Silicon has four valence electrons in its outermost shell which it shares with its neighbouring silicon atoms to form full orbital’s of eight electrons. The structure of the bond between the two silicon



atoms is such that each atom shares one electron with its neighbour making the bond very stable. As there are very few free electrons available to move around the silicon crystal, crystals of pure silicon (or germanium) are therefore good insulators, or at the very least very high value resistors. Silicon atoms are arranged in a definite symmetrical pattern making them a crystalline solid structure. A crystal of pure silica (silicon dioxide or glass) is generally said to be an intrinsic crystal (it has no impurities) and therefore has no free electrons.

But simply connecting a silicon crystal to a battery supply is not enough to extract an electric current from it. To do that we need to create a “positive” and a “negative” pole within the silicon allowing electrons and therefore electric current to flow out of the silicon. These poles are created by doping the silicon with certain impurities.

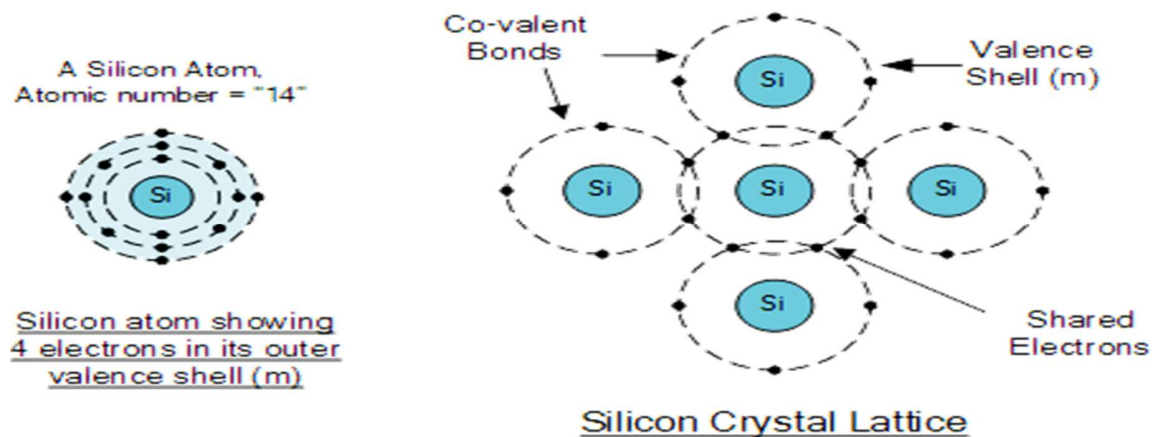
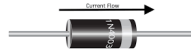


Figure I. 4 Diagram above shows the structure and lattice of a pure crystal of Silicon.

I.3.1. N-type Semiconductor

In order for our silicon crystal to conduct electricity, we need to introduce an impurity atom such as Arsenic, Antimony or Phosphorus into the crystalline structure making it extrinsic (impurities are added). These atoms have five outer electrons in their outermost orbital to share with neighbouring atoms and are commonly called “Pentavalent” impurities. This allows four out of the five orbital electrons to bond with its neighbouring silicon atoms leaving one “free electron” to become mobile when an electrical voltage is applied (electron flow). As each impurity atom “donates” one electron, pentavalent atoms are generally known as “donors”. Antimony (symbol Sb) as well as Phosphorus (symbol P), are frequently used as a pentavalent additive to silicon. Antimony has 51 electrons arranged in five shells around its nucleus with the outermost orbital having five electrons. The resulting semiconductor basic material has an excess of current-carrying electrons, each with a



negative charge, and is therefore referred to as an N-type material with the electrons called “Majority Carriers” while the resulting holes are called “Minority Carriers”. When stimulated by an external power source, the electrons freed from the silicon atoms by this stimulation are quickly replaced by the free electrons available from the doped Antimony atoms. But this action still leaves an extra electron (the freed electron) floating around the doped crystal making it negatively charged. Then a semiconductor material is classed as N-type when its donor density is greater than its acceptor density, in other words, it has more electrons than holes thereby creating a negative pole as shown. As illustrated in Figure I. 5 each pentavalent atom (antimony) forms covalent bonds with four adjacent silicon atoms, leaving one extra electron. This extra electron becomes a conduction electron.

- Because the pentavalent atom gives up an electron, it is often called a *donor atom*.
- A conduction electron created by this doping process does not leave a hole in the valence band because it is in excess of the number required to fill the valence band.
- The electrons are called the *majority carriers* in n-type material since most of the current carriers are electrons (the n stands for negative charge).
- There are a few holes created when electron-hole pairs are thermally generated. Holes in an n-type material are called *minority carriers*.

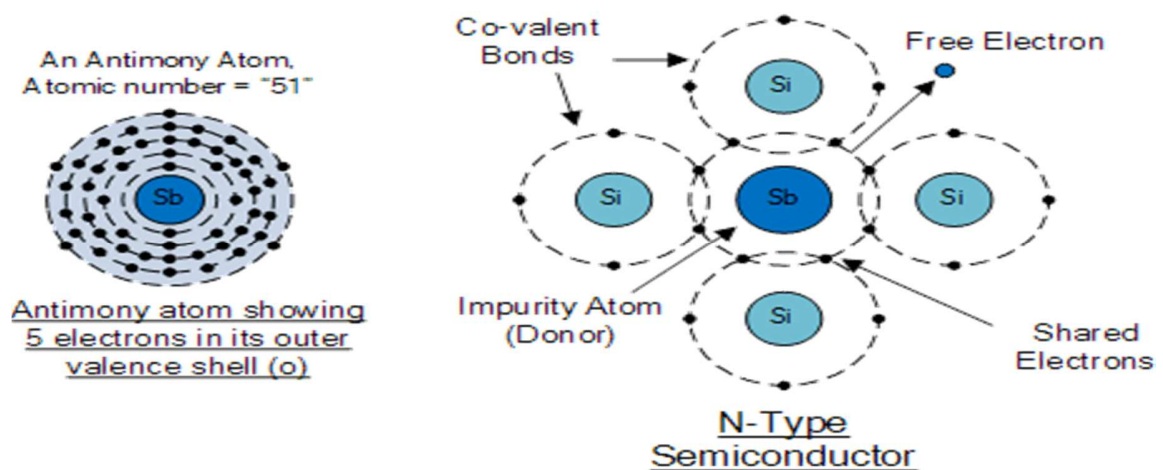


Figure I.5 Pentavalent impurity atom in a silicon crystal structure. An antimony (Sb) atom is shown in the center.



I.3.2. P-type Semiconductor

If we go the other way, and introduce a “Trivalent” (3-electron) impurity into the crystalline structure, such as Aluminium, Boron or Indium, which have only three valence electrons available in their outermost orbital, the fourth closed bond cannot be formed. Therefore, a complete connection is not possible, giving the semiconductor material an abundance of positively charged carriers known as holes in the structure of the crystal where electrons are effectively missing.

As there is now a hole in the silicon crystal, a neighbouring electron is attracted to it and will try to move into the hole to fill it. However, the electron filling the hole leaves another hole behind it as it moves. This in turn attracts another electron which in turn creates another hole behind it, and so forth giving the appearance that the holes are moving as a positive charge through the crystal structure (conventional current flow). This movement of holes results in a shortage of electrons in the silicon turning the entire doped crystal into a positive pole. As each impurity atom generates a hole, trivalent impurities are generally known as “Acceptors” as they are continually “accepting” extra or free electrons.

Boron (symbol B) is commonly used as a trivalent additive as it has only five electrons arranged in three shells around its nucleus with the outermost orbital having only three electrons. The doping of Boron atoms causes conduction to consist mainly of positive charge carriers resulting in a P-type material with the positive holes being called “Majority Carriers” while the free electrons are called “Minority Carriers”. As illustrated in Figure I.6, each trivalent atom (boron) forms covalent bonds with four adjacent silicon atoms. All three of the boron atom’s valence electrons are used in the bonds, and a hole results.

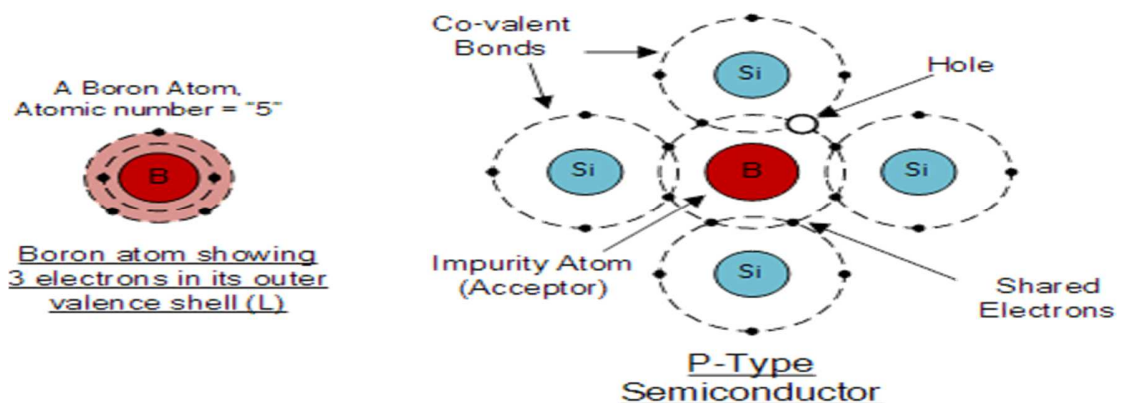
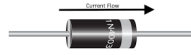


Figure I. 6 Trivalent impurity atom in a silicon crystal structure. A boron (B) impurity atom is shown in the center.



- Because the trivalent atom can take an electron, it is often referred to as an *acceptor atom*.
- A hole created by this doping process is not accompanied by a conduction (free) electron.
- The holes are the majority carriers in p-type material since most of the current carriers are holes.
- There are a few conduction-band electrons created when electron-hole pairs are thermally generated. Conduction-band electrons in p-type material are the minority carriers.

I.4. PN Junction Formation

The physical structure of the junction is depleted with a barrier insulating charge stripes and fields within doped semiconductors. Physically, the depletion region assembles physical distances within the junction that eliminates a mixture of carriers to any side.

The PN junction is formed when an N-type material is fused together with a P-type material creating a semiconductor diode, the PN junction theory shows that when silicon is doped with small amounts of Antimony, an N-type semiconductor material is formed, and when the same silicon material is doped with small amounts of Boron, a P-type semiconductor material is formed. Initially, any p-type and n-type semiconductor can be developed via an extrinsic impurity containing an electron-acceptor material used as a p-type semiconductor and a donor substance having electron supervisory capacity for establishing n-type material. Henceforth, these materials have to be combined to form PN junctions, intrinsically by the processes of preferment.

These preferment's could be accomplished via practicing doped semiconductors directly or intrinsic semiconductors developing excess carriers ready at the junction formation of p-n, comprising new supplies of electron holes. The designations of p-type are called holes' majority, and in n-type, as an electron's majority, are sustenance for the doped materials. Henceforth, carriers are endowed with charged carriers that include functionality within semiconducting.

There is a variation in hole and electron carriers' concentration, yet each semiconductor acquires additional charge carriers since impurities are numerous within the substrate. As a result, the charge density of the P-type along the junction is filled with negatively charged acceptor ions (N_A), and the charge density of the N-type along the junction becomes positive. This charge transfer of electrons and holes across the PN junction is known as diffusion. The width of these P and N layers depends on how heavily each side is doped with acceptor density N_A , and donor density N_D , respectively (Figure I.7).

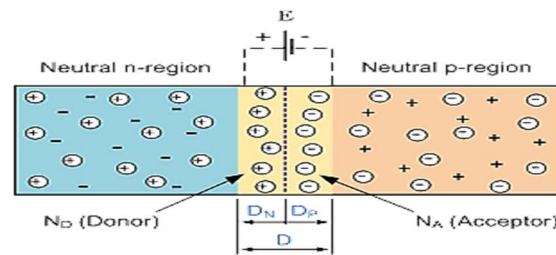


Figure I.7 PN junction formation showing the majority and minority carriers.

This process continues back and forth until the number of electrons which have crossed the junction have a large enough electrical charge to repel or prevent any more charge carriers from crossing over the junction. Eventually a state of equilibrium (electrically neutral situation) will occur producing a “potential barrier” zone around the area of the junction as the donor atoms repel the holes and the acceptor atoms repel the electrons.

Since no free charge carriers can rest in a position where there is a potential barrier, the regions on either sides of the junction now become completely depleted of any more free carriers in comparison to the N and P type materials further away from the junction. This area around the PN Junction is now called the Depletion Layer as shown in Figure I.8.

This is fine, but these newly doped N-type and P-type semiconductor materials do very little on their own as they are electrically neutral. However, if we join (or fuse) these two semiconductor materials together they behave in a very different way as they merge together producing what is generally known as a "PN Junction" allowing us to study the effect of PN junction theory.

When the N-type semiconductor and P-type semiconductor materials are first joined together, a very large density gradient exists between both sides of the PN junction. The result is that some of the free electrons from the donor impurity atoms begin to migrate across this newly formed junction to fill up the holes in the P-type material producing negative ions. However, because the electrons have moved across the PN junction from the N-type silicon to the P-type silicon, they leave behind positively charged donor ions (N_D) on the negative side and now the holes from the acceptor impurity migrate across the junction in the opposite direction into the region where there are large numbers of free electrons.

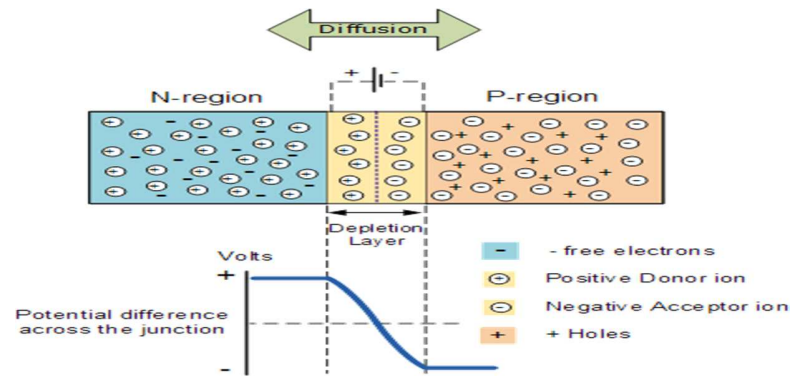


Figure I.8 PN junction forms and creation of depletion region.

The electric field created by the diffusion process has created a “built-in potential difference” across the junction with an open-circuit (zero bias) potential of:

$$E_0 = V_T \ln(N_D N_A / n_i^2)$$

Where:

E_0 is the zero bias junction voltage, V_T the thermal voltage of 26 mV at room temperature, N_D and N_A are the impurity concentrations and n_i is the intrinsic concentration.

A suitable positive voltage (forward bias) applied between the two ends of the PN junction can supply the free electrons and holes with the extra energy. The external voltage required to overcome this potential barrier that now exists is very much dependent upon the type of semiconductor material used and its actual temperature. Typically at room temperature the voltage across the depletion layer for silicon is about 0.6 – 0.7 volts and for germanium is about 0.3 – 0.35 volts at 25 °C.. This potential barrier will always exist even if the device is not connected to any external power source, as seen in diodes.

I.5. PN Junction Diode

The PN junction diode consists of a p-region and n-region separated by a depletion region where charge is stored. The effect described in the previous tutorial is achieved without any external voltage being applied to the actual PN junction resulting in the junction being in a state of equilibrium.

However, if we were to make electrical connections at the ends of both the N-type and the P-type materials and then connect them to a battery source, an additional energy source now exists to overcome the potential barrier.

The effect of adding this additional energy source results in the free electrons being able to cross the depletion region from one side to the other. The behaviour of the PN junction with regards to the



potential barrier's width produces an asymmetrical conducting two terminal device, better known as the PN Junction Diode. A PN Junction Diode is one of the simplest semiconductor devices around, and which has the electrical characteristic of passing current through itself in one direction only.

However, unlike a resistor, a diode does not behave linearly with respect to the applied voltage. Instead it has an exponential current-voltage (I-V) relationship and therefore we can't described its operation by simply using an equation such as Ohm's law. The *p* region is called the *anode* and is connected to a conductive terminal. The *n* region is called the *cathode* and is connected to a second conductive terminal. Figure I. 9 shows a DC voltage source connected by conductive material (contacts and wire) across a diode in the direction to produce forward bias.

The external bias voltage is designated as V_{BIAS} . The resistor limits the forward current to a value that will not damage the diode.

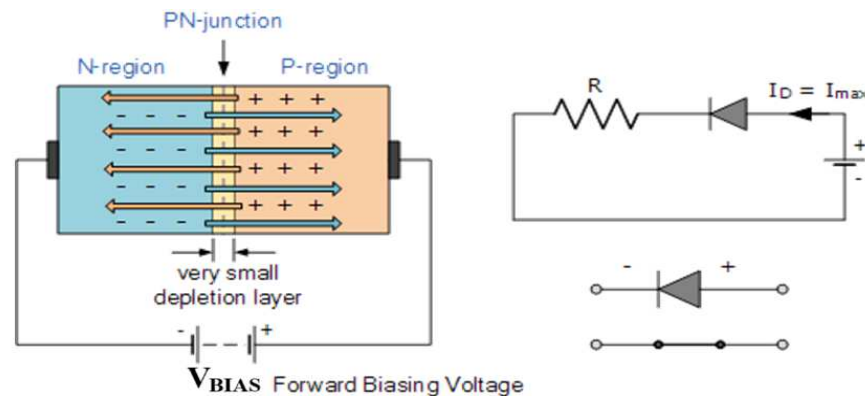


Figure I.9 Diode connected for forward bias.

- Requirements for forward bias:
 - The negative side of V_{BIAS} is connected to the *n* region of the diode and the positive side is connected to the *p* region.
 - V_{BIAS} must be greater than the barrier potential.
- The depletion region narrows due to the reduction in negative and positive ions as majority carriers move toward the PN junction.
- A voltage drop equal to the barrier potential (0.7 V for Silicon diode; 0.3 V for Germanium diode), is produced across the PN junction as electrons give up an amount of energy equivalent to the barrier potential when they cross the depletion region.
- Reverse Bias:
 - Reverse bias is the condition that prevents current through the diode.



- Figure I.10 shows a DC voltage source connected across a diode in the direction to produce reverse bias. This external bias voltage is designated as V_{BIAS} just as it was for forward

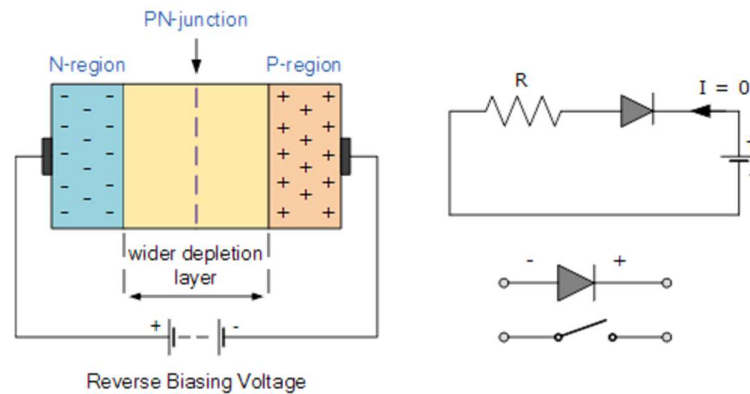


Figure I.10 A diode connected for reverse bias

The positive side of V_{BIAS} is connected to the n region of the diode and the negative side is connected to the p region. Note that the depletion region is shown much wider than in forward bias or equilibrium.

I.6. Basic Principles of Diodes

Diodes are arguably the most fundamental semiconductor devices due to their versatile applications and their utilization in electronic circuit building blocks. They are two-terminal devices that conduct current in one direction and block it in the opposite direction. They are commonly used in unpolarized and polarized rectifier configurations, in high-capacity reverse-current bypassing, in polarity inversion of signals or voltages, in polarity demodulation of modulated signals, in classical and high-speed switching, in signal clipping, in overstress protection, and many other applications. Consequently, an understanding of the dynamics of the forward and reverse states and their interaction is needed in order to tailor the performance characteristics to specific applications.

The most important diode types to date will be discussed, including some advanced applications that showcase the behavior of these devices at present and under adverse conditions. A diode is a nonlinear semiconductor that conducts in one direction and blocks in the opposite direction. It is formed by connecting a p-type and n-type region of a semiconductor. Its purpose is to form an exclusive electron or hole supply at the p-n type regions to enable conduction current within a certain voltage range. In diodes with high doping and small depletion



region widths, the generation and recombination of charge carriers in the margins of the space change the diffusion parameters of transport in both directions. Small-signal industry manuals provide a good starting material, containing important forward voltage drop, diffusion and lifetime parameters, and reverse polarization leakage (Figure I.11).

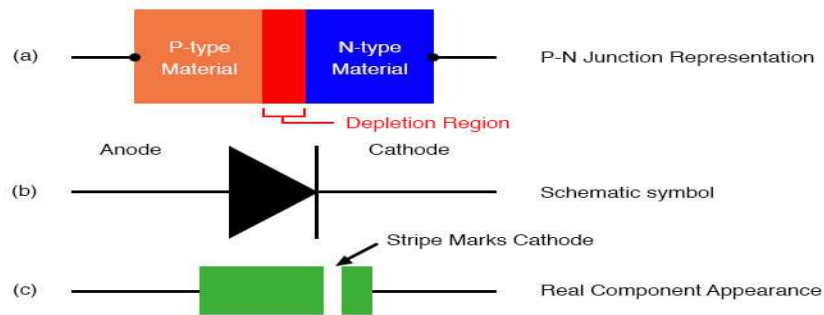


Figure I.11 Diode representations: PN junction model, schematic symbol, physical part.

However, they either do not fully describe or fully assess the fast and slow recovery states of their switching characteristics, repetitive voltage and current limits, or sustained reverse breakdown levels under outdated over-adjustment pulse techniques. Diode behavior is analogous to the behavior of a hydraulic device called a check valve. A check valve allows fluid flow through it in only one direction as in the figure below (Figure I.12).

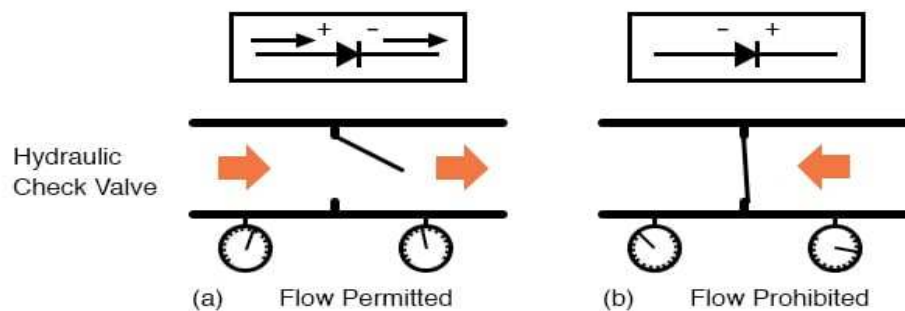
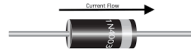


Figure I.12 Hydraulic check valve analogy: (a) Current flow permitted. (b) Current flow prohibited.

I.7. Fundamental Principles of Diode Operation

Diodes contribute powerfully to the world of electronics as they impart a wide range of functions in most circuits. They are typically seen in rectifiers and as freewheeling diodes. Understanding how diodes work and the way they react and change when a voltage or current is



applied can help us design and improve loudspeaker crossover networking, maintain proper voltage and current levels in power supplies, delve into high-tech gamma ray lasers and medical devices, and even get to the base of how diode rings and single phasing work in three-phase machinery.

A diode is made of an N-type semiconductor material and a P-type semiconductor material. The N-type material has abundant electric charge carriers that are negatively charged, while the opposite is true on the P-side. This means that the P-side contains an abundant amount of positive charge carriers, known as holes. Under normal conditions, the negative charge carriers of the N-side are constantly diffusing to the P-side due to the difference in charge carrying capacity between the P side and the N side. This creates negatively charged immobile ions on the P-side and leaves behind positively charged immobile ions on the N side, both of which are opposite to the side's current charge carriers. This creates what is called the 'Depletion Zone' or 'Space Charge Region' in between the P and N junctions where there are very few charge carriers. Silicon diodes have approximately 0.7 volts and germanium diodes have approximately 0.3 volts of potential difference across them when an N to P depletion zone is created. The diode is two terminal nonlinear device whose I-V characteristic besides exhibiting non-linear behavior is also polarity dependent. The non-linear, and polarity characteristics of the diode make for a very interesting and useful device albeit at the expense of added complexity of circuit design and analysis. The basic circuit symbol of the diode is shown on Figure 1. Unlike the resistor, whose two terminal leads are equivalent, the behavior of the diode depend on the relative polarity of its terminals. The conventional voltage polarity across the diode terminals and the current direction through the diode are also indicated on Figure I.13.

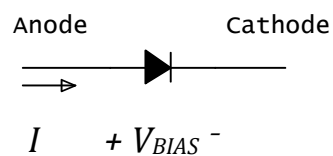


Figure I.13 Diode circuit model.

Depending on the polarity of the voltage, V_{BIAS} the diode is said to be:

- **Forward Biased**, ($V_{BIAS} > 0$), Anode voltage is greater than the Cathode voltage.
- **Reverse Biased**, ($V_{BIAS} < 0$), Cathode voltage is greater than the Anode voltage.



If a suitable positive voltage (forward bias) is applied between the two ends of the PN junction, it can supply free electrons and holes with the extra energy they require to cross the junction as the width of the depletion layer around the PN junction is decreased.

By applying a negative voltage (reverse bias) results in the free charges being pulled away from the junction resulting in the depletion layer width being increased. This has the effect of increasing or decreasing the effective resistance of the junction itself allowing or blocking the flow of current through the diodes PN junction. Then the depletion layer widens with an increase in the application of a reverse voltage and narrows with an increase in the application of a forward voltage.

This is due to the differences in the electrical properties on the two sides of the PN junction resulting in physical changes taking place. One of the results produces rectification as seen in the PN junction diodes static I-V (current-voltage) characteristics. Rectification is shown by an asymmetrical current flow when the polarity of bias voltage is altered as shown below.

I.8. Voltage- Current characteristic of Diode

I.8.1. Characteristic for Forward Bias

When a forward-bias voltage is applied across a diode, there is *forward current*; designated by I_F . Figure I.14 illustrates what happens as the forward-bias voltage is increased positively from zero volt.

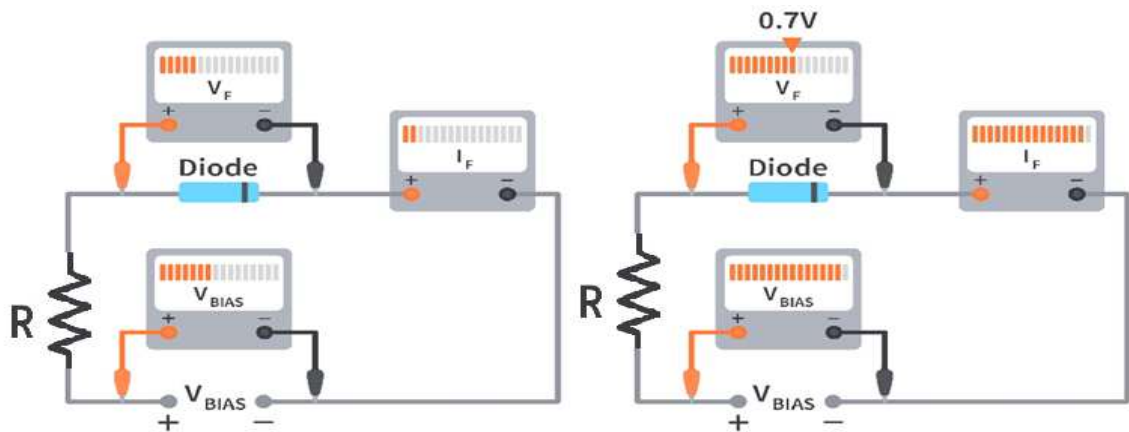
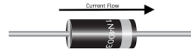


Figure I.14 Forward-bias measurements show general changes in forward voltage and forward current as bias voltage is increased.

With 0 V across the diode, $I_F = 0$ mA. As V_{BIAS} increases, I_F and the voltage across the diode (V_F) increases. A portion of V_{BIAS} is dropped across the limiting resistor.



When V_{BIAS} is increased to a value where V_F reaches approximately 0.7 V (barrier potential), I_F begins to increase rapidly. As V_{BIAS} continues to increase, I_F also increases very rapidly, but V_F increases only gradually above 0.7 V.

This small increase in V_F is due to the voltage drop across the internal resistance of the semiconductive material. In Figure I.15, V_F increases to the right along the horizontal axis, and I_F increases upward along the vertical axis. I_F increases very little until the forward voltage across the PN junction reaches approximately 0.7 V at the knee of the curve. After this point, the forward voltage remains nearly constant at approximately 0.7 V, but I_F increases rapidly.

As previously mentioned, there is a slight increase in V_F above 0.7 V. Point A corresponds to a zero-bias condition. Point B is when V_F is less than the barrier potential of 0.7 V. Point C is when V_F is approximately equal to the barrier potential. As V_{BIAS} and I_F continue to increase above the knee, V_F will increase slightly above 0.7 V. In reality, V_F can be as much as approximately 1-V, depending on the forward current.

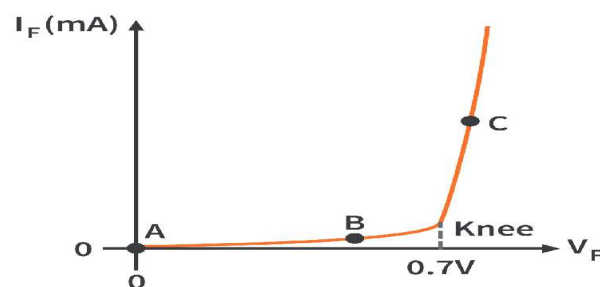
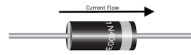


Figure I.15 Relationship of voltage and current in a forward-biased diode.

I.8.2. Characteristic for Reverse Bias

When a reverse-bias voltage is applied across a diode, there is only an extremely small reverse current (I_R) through the PN junction. With 0 V across the diode, $I_R = 0 \mu A$. As you gradually increase the reverse-bias voltage, there is a very small I_R and the voltage across the diode increases. When the applied bias voltage increases to a value where the reverse voltage across the diode (V_R) reaches the breakdown value (V_{BR}), I_R begins to increase rapidly.

As the bias voltage continues to increase, I_R also increases very rapidly, but the diode voltage increases very little above V_{BR} . Graphing the I-V Curve, V_R increases to the left along the horizontal axis, and I_R increases downward along the vertical axis (Figure I.16). There is very little I_R (usually) until V_R reaches approximately V_{BR} at the knee of the curve. After this point, V_R remains at approximately V_{BR} , but I_R increases very rapidly, resulting in overheating and possible damage if the



current is not limited to a safe level. V_{BR} depends on the doping level, which the manufacturer sets, depending on the type of diode.

A typical rectifier diode has a breakdown voltage of greater than 50 V. Some specialized diodes have a breakdown voltage that is only 5 V.

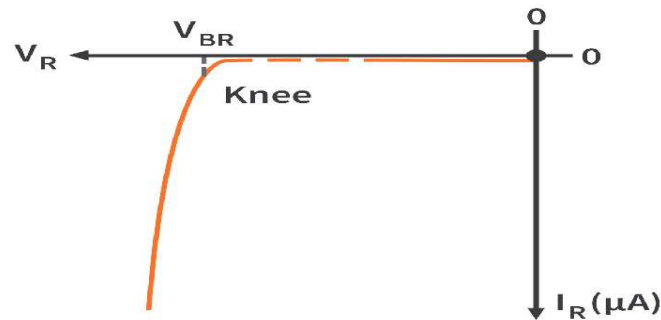


Figure I.16 I-V characteristic curve for a reverse-biased diode.

I.8.3. Complete I-V Characteristic Curve

Combine the curves for both forward bias and reverse bias, and you have the complete I-V characteristic curve for a diode. The current-voltage relationship in any component, especially a diode, is a crucial indicator. It shows how the current changes with the voltage across the device when the voltage is in the right direction for the current to flow (Figure I.17).

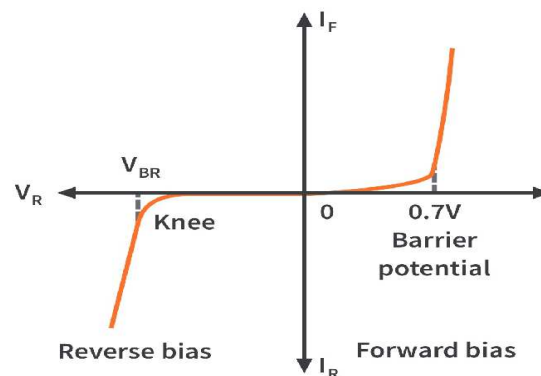
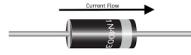


Figure I.17 Complete I-V characteristic curve for a diode.

The remarkably different voltage-current behaviors in these two polarities enable unique applications for the p-n junction diode. In the subsequent section, this differing diode behavior will be related to real-world applications. The p-n junction diode can permit current to flow unimpeded forward and present a large resistance in reverse. In other words, it unambiguously supports the movement of charge in one direction while blocking it in the other. This unidirectional action, inspired by the I-V



behavior, is why diodes are often called semiconductors with a “built-in gate.” With a small forward bias, the diode current increases almost unchecked as the forward voltage is increased. Just a little applied forward voltage is adequate to produce a significant increase in current flow through the diode. In reverse bias, the diode maintains a large resistance, presenting a formidable obstacle to the passage of any reverse current, small or large. Given this unidirectional behavior, the p-n junction diode sometimes serves to protect electric circuits by providing a path for “unwanted” current that is applied in a way as to present high impedance for desirable forward currents. A diode that serves this way is called a “protection diode.” Since diodes, effectively block or enable flow in one direction or the other, the action of the diode in a circuit is greatly influenced by the polarity and strength of the applied voltage. The application of a forward voltage to overcome the p-n junction potential results in the rapid increase of diode current with increasing voltage, given by the Shockley diode equation:

$$I = I_S (e^{V_{th}} - 1)$$

When the diode terminal is biased with a reverse voltage, the Shockley equation yields an immeasurably small reverse current. The characteristic curves of a p-n junction diode enable a closer look at the performance of the diode under both forward and reverse bias. In forward bias, the diode current increases to large values at modest forward voltages. Reverse bias results in a smaller knee current and a markedly reduced reverse current at less negative bias. The exponential behavior is a result of the reversible processes of thermionic emission and recombination in the diode, and gives important insights into its operation in signal and circuit design. In fact, for a forward-biased diode, as the temperature is increased, I_F increases for a given value of V_F . Conversely, for a given value of I_F , V_F decreases. Whereas, a reverse-biased diode, as temperature increases, I_R increases.

I.9. Diode Models

I.9.1. Ideal Diode Model

The ideal diode model is the simplest representation of a diode. According to the ideal diode model, a diode is an electronic device that operates as a perfect conductor when it is in forward bias and as a perfect insulator when it is in reverse bias. The three most important properties of a perfect conductor are: zero resistance, zero voltage drop, infinite current handling capability. And the three most important properties of a perfect insulator are: maximum resistance, infinite voltage drop (or zero current), zero current handling capability. Based on this, the ideal diode model is characterized by: zero



forward resistance, zero forward drop in potential across its terminals, zero forward voltage, maximum reverse resistance, minimum reverse leakage current (Figure I.18).

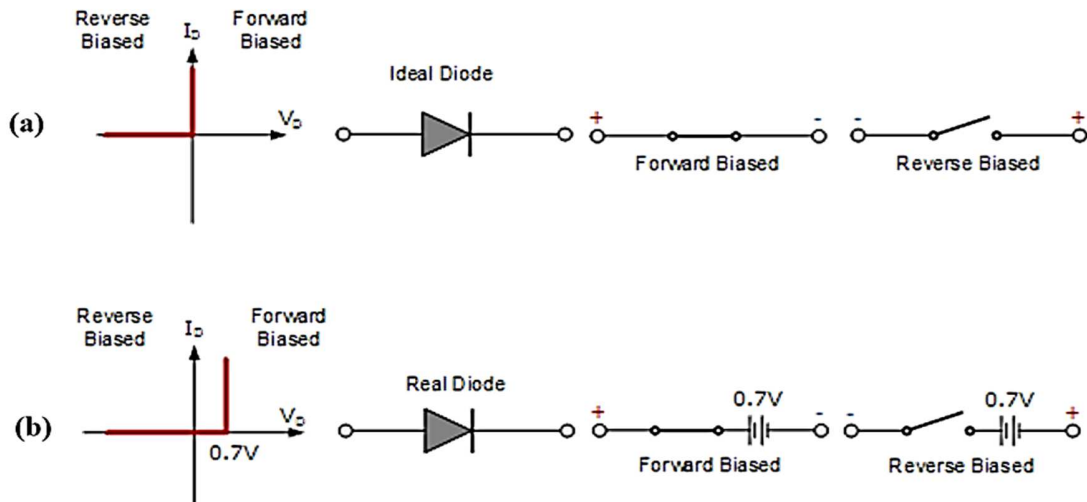


Figure I.18 (a) The ideal diode and (b) the real diode.

The diode is assumed to be an ideal electronic device for a number of reasons. The primary reason is that this simplified model is used for circuit analysis as well as for design purposes, as this helps to predict and understand output by gross approximations and changes due to large variations in parameters like temperature. Second, we are mainly interested in the forward bias condition of a PN junction diode; hence, we will be using this ideal diode model with respect to forward bias only. Here, it is notable that a real-world diode may not meet all of the above assumptions exactly in practice. It can act as a near ideal only under the following conditions. Unless you see any major deviations from the desired ideal behavior, you may assume these ideal characteristics of the diode in the circuits. The least accurate approximation; can be represented by a simple switch, forward-biased: diode acts like a closed (ON) switch; reverse-biased: diode acts like an open (OFF) switch, as shown in Figure I.18.

Although the barrier potential, the forward dynamic resistance, and the reverse current are all neglected, this model is adequate for most troubleshooting to determine if the diode is working properly. The diode is assumed to have a zero voltage across it when forward-biased: $V_F = 0$ V.

The forward current is determined by the bias voltage and the resistor R using Ohm's law.

$$I_F = V_{BIAS}/R$$

Since the reverse current is neglected, its value is assumed zero: $I_R = 0$ A.

The reverse voltage equals the bias voltage: $V_R = V_{BIAS}$.



I.9.2. Practical Diode Model

In Forward-biased, diode is equivalent to a closed switch in series with a small equivalent voltage source (V_F) equal to the barrier potential (0.7 V) with the positive side toward the anode. When conducting, a voltage drop of 0.7 V appears across the diode.

In Reverse-biased, diode is equivalent to an open switch just as in the ideal model. The barrier potential does not affect reverse bias. Since the barrier potential is included and the dynamic resistance is neglected, the diode is assumed to have a voltage across it when forward-biased: $V_F = 0.7 \text{ V}$.

The forward current is determined by first applying Kirchoff's voltage law to Figure I.19 :

$$I_F = (V_{BIAS} - V_F)/R$$

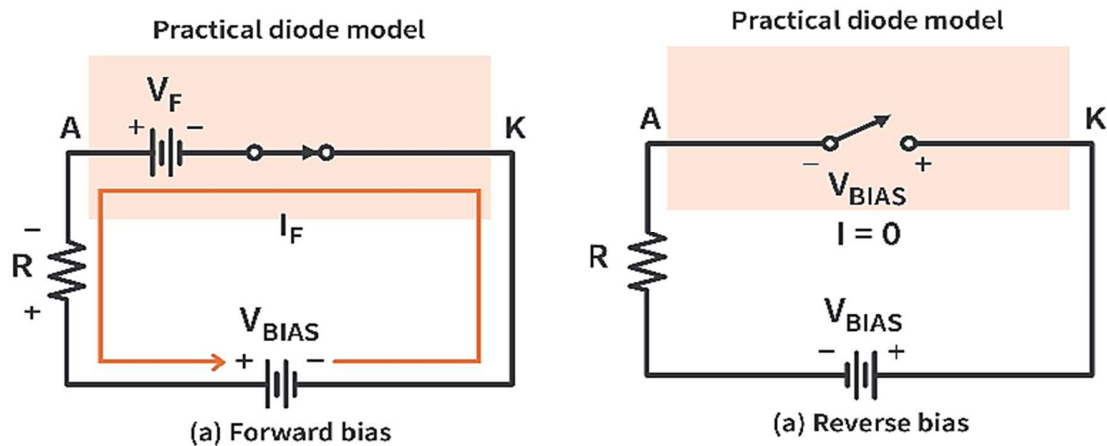
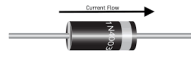


Figure I.19 The practical model of a diode.

The diode is assumed to have zero reverse current: $I_R = 0 \text{ A}$, $V_R = V_{BIAS}$. The practical model is useful when troubleshooting in lower-voltage circuits. In these cases, the 0.7 V drop across the diode may be significant and should be taken into account.

I.9.3. Complete Diode Model

The most accurate approximation; includes the barrier potential, small forward dynamic resistance (r'_d) and large internal reverse resistance (r'_R). In Forward-biased: diode acts as a closed switch in series with the equivalent barrier potential voltage (V_B) and r'_d . In Reverse-biased: diode acts as an open switch in parallel with r'_R . The barrier potential does not affect reverse bias (Figure I.20).



The diode is assumed to have a voltage across it when forward-biased. This voltage (V_F) consists of V_B plus the small voltage drop across the dynamic resistance. The voltage drop due to dynamic resistance increases as the current increases. For the complete model of a silicon diode, the following formulas apply:

$$V_F = 0.7 V + I_F r'_d$$

$$I_F = (V_{BIAS} - 0.7V)/(R + r'_d)$$

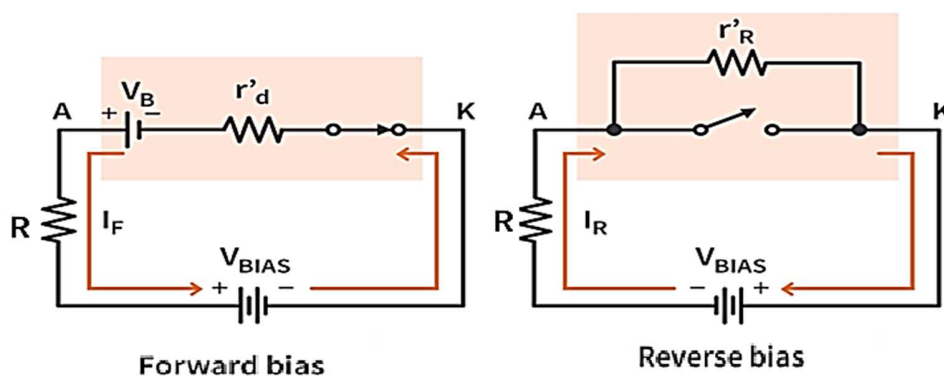


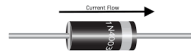
Figure I.20 The complete model of a diode

I.10. Types of Diodes

The standard PN junction diode, although the focus of design and analysis for much of the previous content, is not the only kind of diode used in modern electronic systems. Specialized diode technologies have been developed to fit into specific applications. This section will explore these specialized types of diodes, what makes them unique, and when they are used.

I.10.1. Light Emitting Diodes (LEDs)

Light Emitting Diodes are a special class of diodes that can produce visible light while passing electric current. The phenomenon by which LEDs work is called electroluminescence, which produces light in semiconductors. In detail, when charge carriers move between different energy bands in semiconductors and a radiative combination of one electron-hole pair happens, resulting in the emission of the photon. Generally, the energy bands of silicon and germanium are not sufficient to excite light because of their bandgap. The exact choice of the semiconductor material used will determine the overall wavelength of the photon light emissions and therefore the resulting colour of the light emitted.



The LED symbol is the standard symbol for a diode, with the addition of two small arrows denoting the emission of light (Figure I.21).

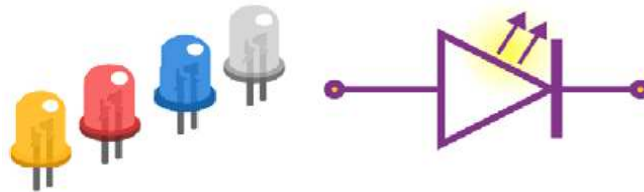


Figure I.21 The LED symbol.

Thus, the actual color of a light emitting diode is determined by the wavelength of the light emitted, which in turn is determined by the actual semiconductor compound used in forming the PN junction during manufacture and not by the coloring of the LEDs plastic body although these are slightly colored to both enhance the light and indicate its color when its not be used. Light emitting diodes are available in a wide range of colors with the most common being Red, Amber, Yellow and Green and are thus widely used as visual indicators and as moving light displays.

The color of an LED is determined by the material used in the semiconducting element. The two primary materials used in LEDs are aluminum gallium indium phosphide alloys and indium gallium nitride alloys. Aluminum alloys are used to obtain red, orange and yellow light, and indium alloys are used to get green, blue and white light.

Slight changes in the composition of these alloys change the color of the emitted light. When the diode is forward biased, the minority electrons are sent from $p \rightarrow n$ while the minority holes are sent from $n \rightarrow p$. At the junction boundary, the concentration of minority carriers increases. The excess minority carriers at the junction recombine with the majority charges carriers.

The energy is released in the form of photons on recombination. In standard diodes, the energy is released in the form of heat. But in light-emitting diodes, the energy is released in the form of photons. We call this phenomenon electroluminescence.

Electroluminescence is an optical phenomenon, and electrical phenomenon where a material emits light in response to an electric current passed through it.

As the forward voltage increases, the intensity of the light increases and reaches a maximum (Figure I.22).

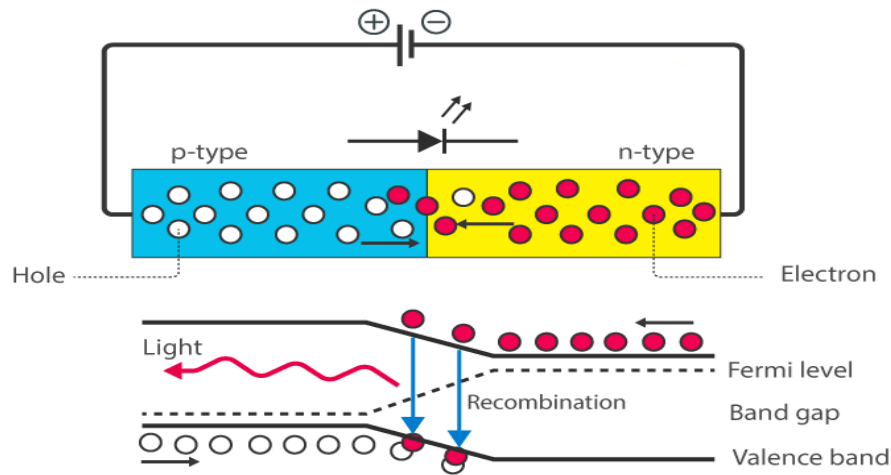
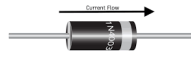


Figure I.22 Principle work of LED.

Like conventional PN junction diodes, LEDs are current-dependent devices with its forward voltage drop V_F , depending on the semiconductor compound (its light colour) and on the forward biased LED current. The point where conduction begins and light is produced is about 1.2V for a standard red LED to about 3.6V for a blue LED. The exact voltage drop will of course depend on the manufacturer because of the different dopant materials and wavelengths used. The voltage drop across the LED at a particular current value, for example 20mA, will also depend on the initial conduction V_F point. As an LED is effectively a diode, its forward current to voltage characteristics curves can be plotted for each diode colour as shown below (Figure I. 23).

Before a light emitting diode can "emit" any form of light it needs a current to flow through it, as it is a current dependant device with their light output intensity being directly proportional to the forward current flowing through the LED. As the LED is to be connected in a forward bias condition across a power supply it should be current limited using a series resistor to protect it from excessive current flow.

Never connect an LED directly to a battery or power supply as it will be destroyed almost instantly because too much current will pass through and burn it out. From the table I.2 above we can see that each LED has its own forward voltage drop across the PN junction and this parameter which is determined by the semiconductor material used, is the forward voltage drop for a specified amount of forward conduction current, typically for a forward current of 20mA. In most cases LEDs are operated from a low voltage DC supply, with a series resistor, R_S used to limit the forward current to a



safe value from say 5mA for a simple LED indicator to 30mA or more where a high brightness light output is needed.

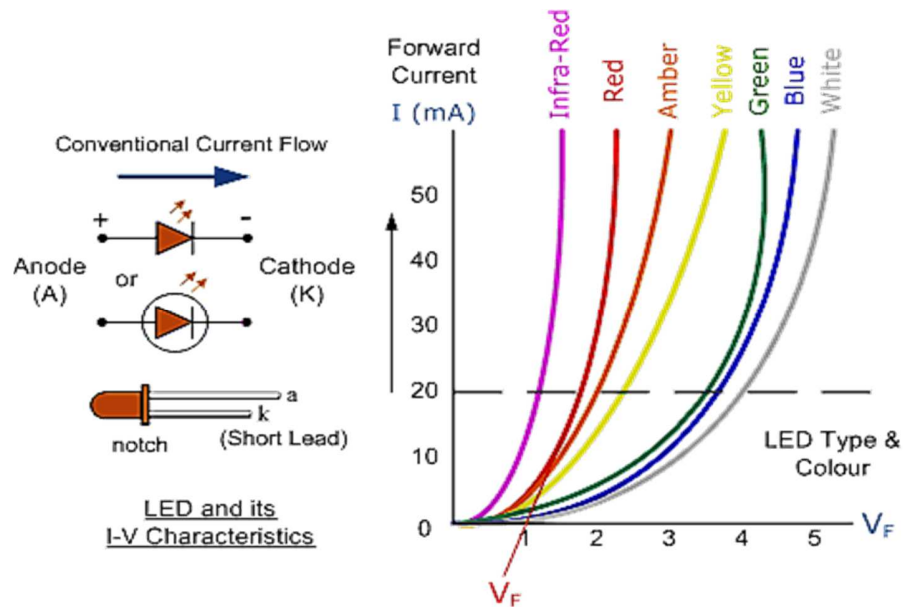
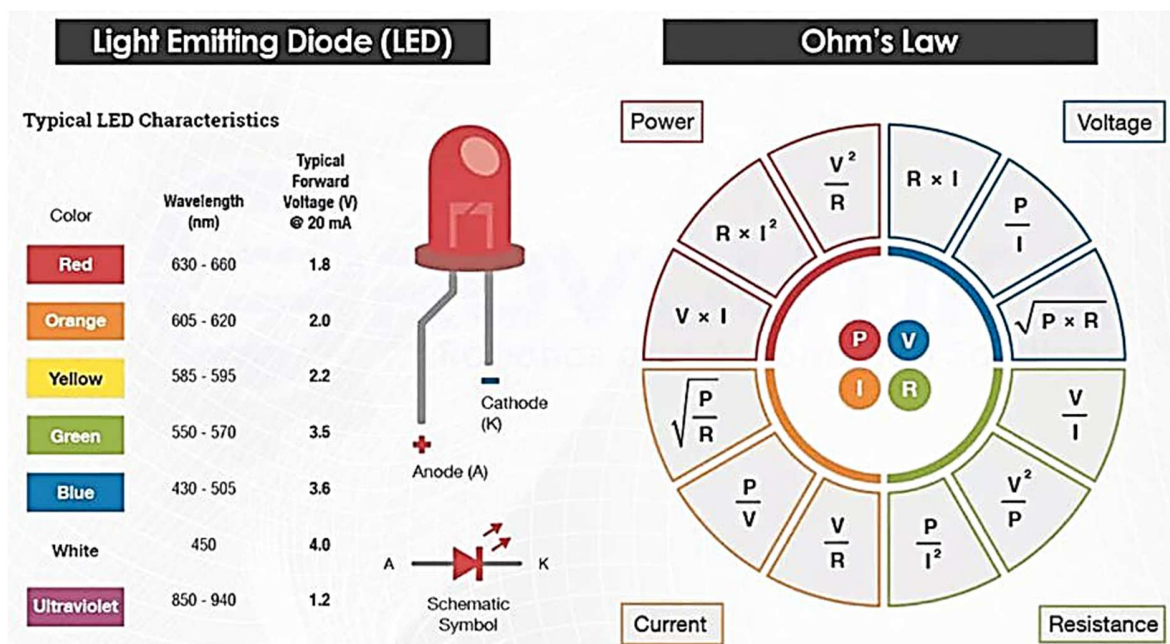


Figure I.23 Schematic symbol of LED and its I-V Characteristics.

Table I.2 Characteristics of Light emitting diodes.





LEDs find applications in various fields, including optical communication, alarm and security systems, remote-controlled operations, robotics, etc. It finds usage in many areas because of its long-lasting capability, low power requirements, swift response time, and fast switching capabilities. Below are a few standards LED uses in: back-lighting, displays, Automotive and the dimming of lights.

I.10.2. Zener Diodes

Zener diode is a silicon PN junction device that allows current to flow not only in the forward direction, but also in the reverse direction if the voltage is greater than the breakdown voltage known as the Zener knee voltage/Zener voltage. Zener diodes are unique in the sense that they can conduct current in the reverse direction when a specific voltage has been applied.

Once a forward threshold has been surpassed, they regulate the voltage, and thus they are a type of voltage regulator used in numerous electronic circuits.

The most common use for Zener diodes is within simple voltage regulation functions such as shunt regulators and protection devices, though there are numerous other applications for this type of diode. Zener diodes come in various packaging options, depending on their power dissipation requirements. Some are designed for high-power applications, while others are available in surface mount formats. The most commonly used Zener diode is packaged in a small glass enclosure, with a distinctive band indicating the cathode side of the diode (Figure I.24).

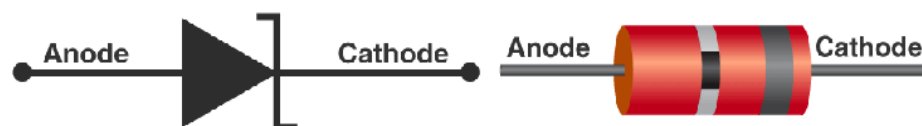


Figure I. 24 Zener diode symbol.

Zener diode is a device which works in the Zener breakdown region. When these diodes are forward-biased, they act like a p-n junction diode.

These diodes have a very thin depletion region as they are heavily doped, allowing more electric current than regular p-n junction diodes. The I-V characteristic of Zener diode is given in Figure I. 25.

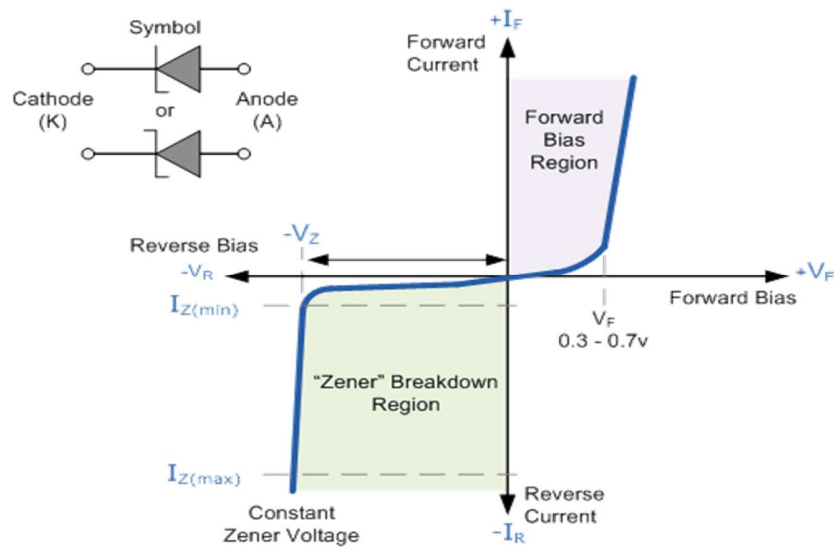
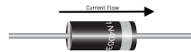


Figure I. 25 Zener Diode I-V Characteristics.

The Zener Diode is used in its "reverse bias" or reverse breakdown mode, i.e. the diodes anode connects to the negative supply. From the I-V characteristics curve above, we can see that the zener diode has a region in its reverse bias characteristics of almost a constant negative voltage regardless of the value of the current flowing through the diode and remains nearly constant even with large changes in current as long as the Zener diodes current remains between the breakdown current $I_{Z(\min)}$ and the maximum current rating $I_{Z(\max)}$. This ability to control itself can be used to great effect to regulate or stabilise a voltage source against supply or load variations. The fact that the voltage across the diode in the breakdown region is almost constant turns out to be an important application of the zener diode as a voltage regulator. The function of a regulator is to provide a constant output voltage to a load connected in parallel with it in spite of the ripples in the supply voltage or the variation in the load current and the Zener diode will continue to regulate the voltage until the diodes current falls below the minimum $I_{Z(\min)}$ value in the reverse breakdown region.

Zener diodes are designed to operate in the breakdown region. it operating in breakdown acts as a voltage regulator because it maintains a nearly constant voltage, which is equal to the Zener voltage, across its terminals over a specified range of reverse-current values (Figure I. 26).

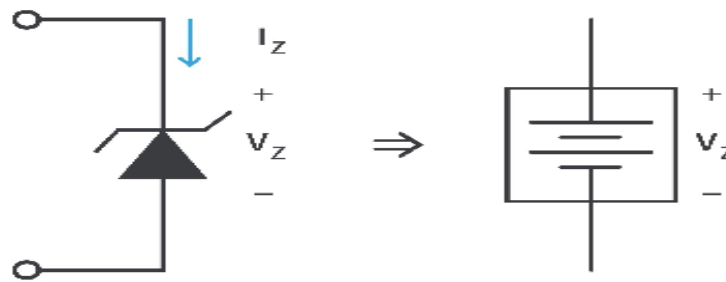
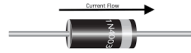


Figure I. 26 Zener diode operating in the breakdown region.

The first quadrant in the graph represents the forward characteristics of a Zener diode. From the graph, we understand that it is almost identical to the forward characteristics of PN junction diode. When a reverse voltage is applied to a Zener voltage, a small reverse saturation current I_0 flows across the diode. This current is due to thermally generated minority carriers. As the reverse voltage increases, at a certain value of reverse voltage, the reverse current increases drastically and sharply. This is an indication that the breakdown has occurred. We call this voltage breakdown voltage or Zener voltage, and V_Z denotes it. Zener diodes are specially designed to work in the reverse breakdown region and exhibit the unique characteristic of maintaining a reverse voltage across the diode at a constant level even as the current through the diode can vary. Because of this, Zener diodes are incorporated into voltage level-shifting circuits that prevent capacitor digitalization at undesired voltage levels. An additional characteristic of Zener diodes is their high energy efficiency. In comparison to standard rectifier and light-emitting diodes that require a specific voltage to turn on, Zener diodes only conduct a small amount of current when this 'Zener' voltage is reached. Although the exact value of the Zener voltage for the Zener diode depends on its manufacture and its material composition, most off-shelf Zener diodes are available in the range of 3V to 30V. In circuit designs making use of cascaded Zener diodes with differing values, the designer can obtain a summed Zener voltage greater than 30V.

The Zener diode can be used to produce a stabilised voltage output with low ripple under varying load current conditions. By passing a small current through the diode from a voltage source, via a suitable current limiting resistor (R_S), the Zener diode will conduct sufficient current to maintain a voltage drop of V_{out} .

We remember from the previous tutorials that the DC output voltage from the half or full-wave rectifiers contains ripple superimposed onto the DC voltage and that as the load value changes so to does the average output voltage. By connecting a simple Zener stabiliser circuit as shown below across the output of the rectifier, a more stable output voltage can be produced (Figure I. 27) .

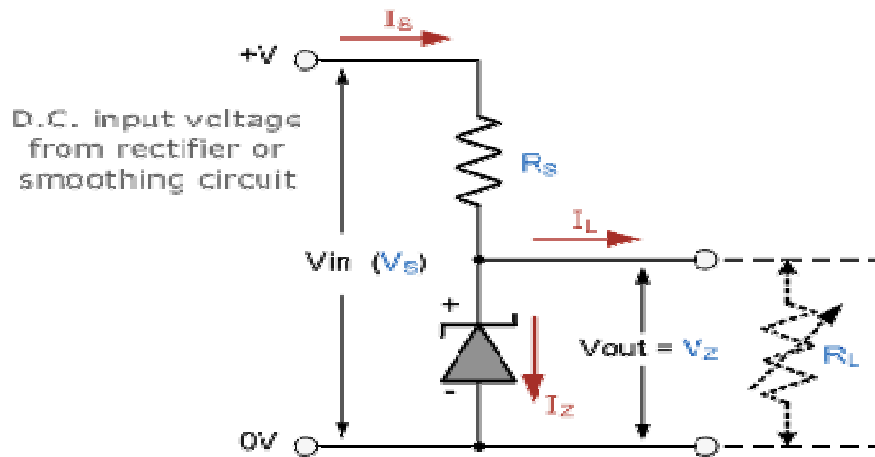


Figure I. 27 Zener Diode Regulator.

The resistor, R_S is connected in series with the Zener diode to limit the current flow through the diode with the voltage source, V_S being connected across the combination. The stabilised output voltage V_{out} is taken from across the Zener diode.

The Zener diode is connected with its cathode terminal connected to the positive rail of the DC supply so it is reverse biased and will be operating in its breakdown condition. Resistor R_S is selected so to limit the maximum current flowing in the circuit.

❖ Example

A 5 V stabilised power supply is required to be produced from a 12V DC power supply input source. The maximum power rating P_Z of Zener diode is 2W. Using the Zener regulator circuit above calculate:

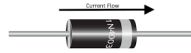
- a) The maximum current flowing through the Zener diode:

$$I_{max} = P/V = \frac{2}{5} = 0.4 \text{ A}$$

- b) The minimum value of the series resistor:

$$R_S = \frac{V_S - V_Z}{I_Z} = \frac{12 - 5}{0.4} = 17.5 \Omega$$

- c) The load current I_L if a load resistor of $1k\Omega$ is connected across the Zener diode:



$$I_L = \frac{V_Z}{R_L} = \frac{5}{1000} = 5 \text{ mA}$$

d) The total supply current I_S at full load :

$$I_S = I_Z + I_L = 400 + 5 = 405 \text{ mA}$$

Following are the applications of Zener diode:

- The Zener diode is used as a Shunt voltage regulator for regulating voltage across small loads. The Zener diode is connected parallel to the load to make it reverse bias, and once the Zener diode exceeds knee voltage, the voltage across the load will become constant. The breakdown voltage of Zener diodes will be constant for a wide range of currents.
- The Zener diode in over-voltage protection, When the input voltage is higher than the Zener breakage voltage, the voltage across the resistor drops resulting in a short circuit, this can be avoided by using the Zener diode.
- Zener diode is used for modifying AC waveform clipping circuits by limiting the parts of either one or both the half cycles of an AC waveform.

I.10.3. Schottky Diodes

The characteristic features of Schottky diodes are lower forward voltage drop, about 0.3 volts less than the normal p-n junction diode, and faster switching speed, which is useful in various high-frequency applications. Schottky diodes, in some cases, are also used to replace normal diodes. However, Schottky diodes also have some disadvantages. They have a higher reverse leakage current when compared to normal diodes and are also less rugged. The Schottky diode is formed by a direct metal-semiconductor contact. When the metal-like tungsten, molybdenum, or platinum is placed in electrical contact with a moderately doped layer of semiconductor-like n-type silicon, the resulting metal-semiconductor contact is called Schottky contact. The Schottky diode is a unipolar device. It has only majority carriers called hot electrons. It switches off quickly because of the low minority carrier concentration. The contact between the silicon region and a noble metal such as silver, gold, aluminium, platinum, or molybdenum is called a Schottky contact. The contact is such that current flows unencumbered in only one direction when forward biased. While forming the metal-semiconductor junction, the magnitude of the forward voltage required is generally less than for similar p-n diode current ratings. The characteristics shown by the Schottky barrier diodes are basically different from



those of p-n junction diodes. When negligible stored charge is produced in forward-biasing after the junction converts from conducting to off state, the Schottky barrier diode exhibits fast switching characteristics. Compared to p-n junction diodes, the Schottky barrier has a higher current rating.

Figure I. 28 illustrates the simplified construction and symbol of a Schottky diode in which a lightly doped n-type silicon semiconductor is joined with a metal electrode to produce what is called a "metal-semiconductor junction". The width, and therefore the electrical characteristics, of this *metal-semiconductor junction* will depend greatly on the type of metal compound and semiconductor material used in its construction, but when forward-biased, electrons move from the n-type material to the metal electrode allowing current to flow. Thus current through the Schottky diode is the result of the drift of majority carriers. Since there is no p-type semiconductor material and therefore no minority carriers (holes), when reverse biased, the diodes conduction stops very quickly and changes to blocking current flow, as for a conventional PN junction diode. Thus for a Schottky diode there is a very rapid response to changes in bias and demonstrating the characteristics of a rectifying diode. The operation relies on the principle that the electrons in different materials have different potential energy. N-type semiconductors have higher potential energy than electrons of metals. When these two are brought into contact, there is a flow of electrons in both directions across the metal-semiconductor interface. A voltage is applied to the Schottky so that the metal is positive when compared to the semiconductor. The voltage opposes the built-in potential and makes the current flow easy.

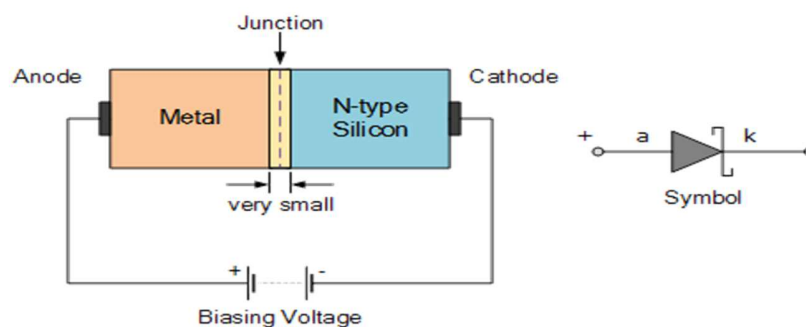


Figure I. 28 Schottky diode construction and symbol.

The I-V characteristics of Schottky diodes are very much similar to the PN junction diode. Current is the dependent variable while voltage is the independent variable in the Schottky diode. The forward voltage drop of the Schottky diode is low between 0.2 to 0.3 volts (Figure I.29) .

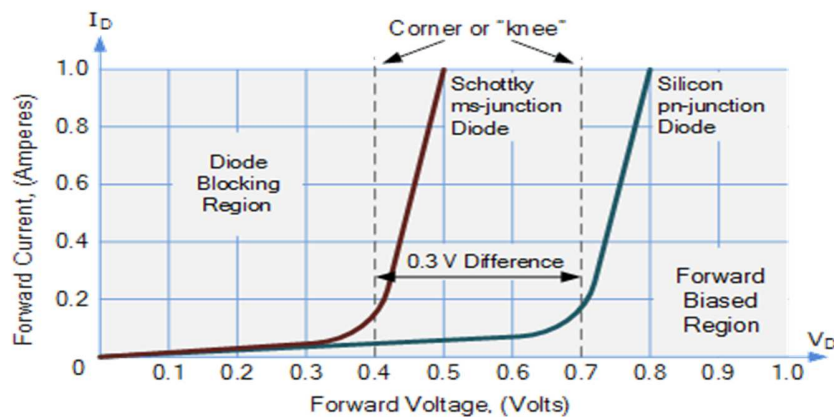
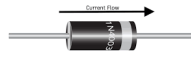


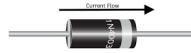
Figure 1.29 Schottky diode I-V characteristics.

As we can see, the general shape of the metal-semiconductor Schottky diode I-V characteristics is very similar to that of a standard PN junction diode, except the corner or knee voltage at which the PN junction diode starts to conduct is much lower at around 0.4 volts.

This lower power loss makes the Schottky diode a good choice in low-voltage and high-current applications such as solar photovoltaic panels where the forward-voltage, V_F drop across a standard PN junction diode would produce an excessive heating effect. However, it must be noted that the reverse leakage current, I_R for a Schottky diode is generally much larger than for a PN junction diode. Note however that if the I-V characteristics curve shows a more linear non-rectifying characteristic, then it is an Ohmic contact. Ohmic contacts are commonly used to connect semiconductor wafers and chips with external connecting pins or circuitry of a system. For example, connecting the semiconductor wafer of a typical logic gate to the pins of its plastic dual-in-line (DIL) package.

Due to this lower value, the forward current of a silicon Schottky diode can be many times larger than that of a typical PN junction diode, depending on the metal electrode used. Remember that Ohms law tells us that power equals volts times amps, ($P = V I$) so a smaller forward voltage drop for a given diode current, I_D will produce lower forward power dissipation in the form of heat across the junction.

This lower power loss makes the Schottky diode a good choice in low-voltage and high-current applications such as solar photovoltaic panels where the forward-voltage, V_F drop across a standard PN junction diode would produce an excessive heating effect. However, the I-V characteristics curve shows a more linear non-rectifying characteristic, then it is an Ohmic contact. Ohmic contacts are commonly used to connect semiconductor wafers and chips with external connecting pins or circuitry of a system. For example, connecting the semiconductor wafer of a typical logic gate to the pins of its plastic dual-in-line (DIL) package.

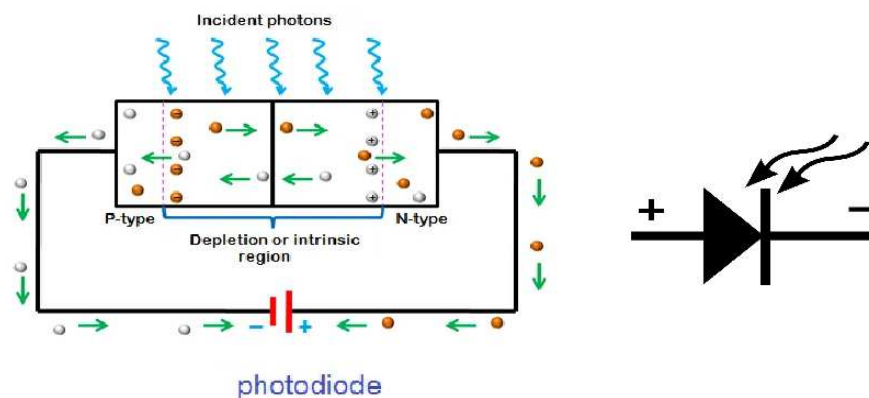


Schottky diodes have been useful for the industry of electronics that has spotted many applications in diode rectifiers because of its unique properties. Here are some major areas where it is widely used. Following are the applications of Schottky diode:

- **RF mixer and detector diode:** The Schottky diode consists of its radio frequency functions owing to its switching speed at the highest level and top frequency capability. The Schottky barrier diodes come handy for diode ring mixers with high performance.
- **Power rectifier:** The Schottky barrier diodes also have functions with high power as rectifiers. The high density of current and voltage drop with low forward shows that the wastage of power is lesser than the normal PN junction diodes.
- **Power OR circuits:** This diode would be useful for functions where two different power supplies drive a load like in battery supply. It is important that the power coming from supply should not mix with the others.
- **Solar Cell Applications:** As we know, the solar cells are usually linked to the batteries that are rechargeable, mostly batteries with lead-acid since power supply must be necessary round the clock. Solar cells would not support the applied charge in reverse and thus, a diode would be used in a proportional pattern of the solar cells.

I.10.4. Photodiodes

Photodiodes are different from normal p-n junction diodes called photodiodes. They are specially designed to operate in the reverse breakdown region to respond to a large flux of light energy. Photodiodes operate like normal p-n junction diodes. When the terminal end of photodiodes, a lower level of applied reverse bias voltage than a normal p-n junction diode, the increase in reverse current starts as voltage is applied to the photodiode. It will cause the internal field to increase and create more electron-hole pairs (Figure I.30).



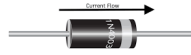


Figure I.30 Photodiode construction and symbol.

When the photodiode is exposed to light, the temperature of the junction will increase. The electrons and holes will get separated from each other. The electrons in the n side will get attracted towards the positive terminal of the battery, and the holes in the p side will get attracted to the (-) terminal of the battery.

As a result, a high amount of reverse current gets generated through the junction. When the light intensity increases, more carriers are generated and flow through the photodiodes.

Hence, a large current is produced. In the I-V characteristic graph of photodiodes, the x-axis represents the reverse applied voltage, and the y-axis represents the current that flows through the device on the application of reverse voltage (Figure I.31).

As we have already discussed in the workings, a small reverse current will flow through the device, and this current is known as dark current (represented on the x-axis). When the junction is illuminated, the current will increase and become independent of the applied reverse voltage. Hence the carriers will flow only due to the radiation intensity with the increase in temperature, and the reverse bias condition will not play any role in this situation.

There are three regions of operation for a photodiode: photoconductive, proportional, and saturation. These act and respond much as p-n junction diodes, causing photodiodes to exhibit similar properties.

Photodiodes are graded from 1 MHz to GHz and are used extensively in communication systems, in applications related to race, industry, and medicine. The I-V (Voltage-Current) characteristics of a photodiode provide valuable insights into how the device behaves under different conditions of light and biasing. A photodiode's performance is influenced by the intensity of light, the applied voltage, and the inherent properties of its semiconductor material.

A photodiode typically operates in reverse bias mode, where a reverse voltage is applied across the p-n junction. The current through the photodiode, known as photocurrent, is a function of the incident light intensity. In the absence of light, a small reverse current known as dark current flows through the diode due to the thermal generation of charge carriers.

When light falls on the depletion region, the photodiode generates electron-hole pairs, which lead to a noticeable increase in current.

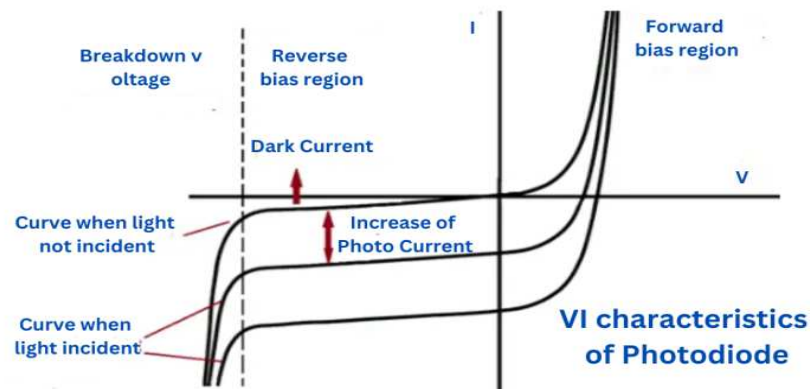


Figure I. 31 Photodiode IV characteristics.

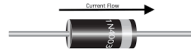
Photodiodes are widely used in applications where light detection or measurement is crucial. Common applications include:

- Optical Communication: To convert light signals into electrical signals in fiber optic networks.
- Light Meters: Used in cameras and environmental sensors to measure light intensity.
- Solar Cells: Large photodiodes are used in solar panels to convert light into electrical energy.
- Smoke Detectors: To detect smoke particles by measuring light absorption.
- Medical Devices: Used in pulse oximeters and medical imaging devices to monitor light absorption.

I.11. Applications of Diodes in Electronic Circuits

I.11.1. Rectification Circuits

Rectification circuits play an extremely important role in the realm of electronics. As our home electrical appliances are now required to run on direct current (DC), rectifiers are used to convert alternating current (AC) into DC. DC is a steady-state energy source the direction of which remains the same, but an AC energy source reverses the direction of the flow of electricity many times per second. Thus, rectifiers are extensively used in the design of power supply circuits. In the charging system of a battery, for most power supplies, and for the host of domestic electronics, the use of rectifiers is inevitable. Different kinds of rectification methods are deployed for specific applications based on their performance. This text focuses on different kinds of rectification circuits that can be designed using diodes. There are two primary types of rectification: half-wave and full-wave rectification. Half-wave rectification is the simplest form of rectification. When a diode is integrated into the circuit, allowing the flow of current for the positive half-cycle and blocking the negative half-cycle, a single diode rectification circuit is designed. An output waveform is thus obtained, which resembles the shape of a



half-sinusoidal wave, and it is followed by a DC level. If a diode with a different or opposite orientation is integrated into the half-wave rectifier, then conversion of the negative half-cycle into positive is done, and a single diode works as a rectifier.

The obtained waveform is a series of half sine waves. A half-wave rectifier can be configured to make the negative side of the waveform accessible. It disposes of the negative side but results in reduced output voltage as only one positive half-cycle of the input AC wave is transformed into DC. In a full-wave rectifier, the whole of the input AC waveform gets converted into direct current. These circuits are further wrapped by applying a couple of diodes and transformers. These are essentially of two types: the bridge rectifier and the center-tap full rectifier.

I.11.2. Half wave rectifier

Basic rectification is the process of allowing only one-half cycle waveform. It utilizes a diode as its basic component. The diodes allow the current to flow in one direction (forward biased) and stop it in the other direction (reverse biased). The name itself suggests that the half-wave rectifier conducts only during one half-cycle of the AC input voltage. The output voltage has the same waveform as the input voltage (magnitude is different).

In practical applications, the half-wave rectifier has a wide variety of uses in low-power devices, such as in signal and event detection, medical devices, low-power motor controllers, numeric analyzers, emission headers, interference testing, signal detectors, and communication receivers.

Low power, being highly simple in design, cost-effective, and highly reliable, plays a main part in these devices.

It is possible to get output frequency in terms of half-wave, but due to the greater harmonic content, it is less than that of the full-wave rectifier. The significant limitations of the half-wave rectifier are the presence of high ripples in the output DC voltage, which greatly reduces the efficiency. When compared with the full-wave center-tapped rectifier, the half-wave application is significantly smaller.

Let's start with the circuit shown. We will analyze this circuit assuming that the diode is ideal. The input voltage V_{in} has the sinusoidal form shown on Figure I.32.

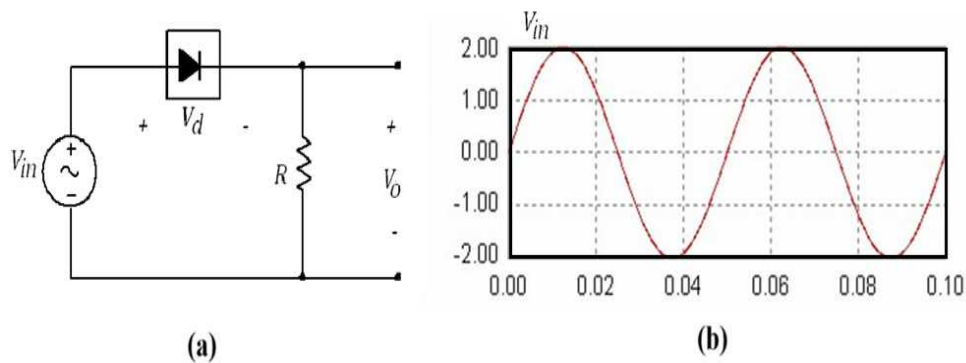


Figure I.32 (a) Diode circuit and (b) Sinusoidal signal V_{in} .

We see that during the time when $V_{in} > 0$ the diode is forward biased and so the voltage across this “ideal” diode is zero. This observation is also represented by the equivalent circuit shown on Figure I.33 (a), which clearly indicates that the output voltage V_o is equal to the input voltage V_{in} . Similarly during the time when $V_{in} < 0$, the diode is reverse biased and so the current flowing through the diode is zero, see equivalent circuit on Figure I.33 (b), and the output voltage is zero.

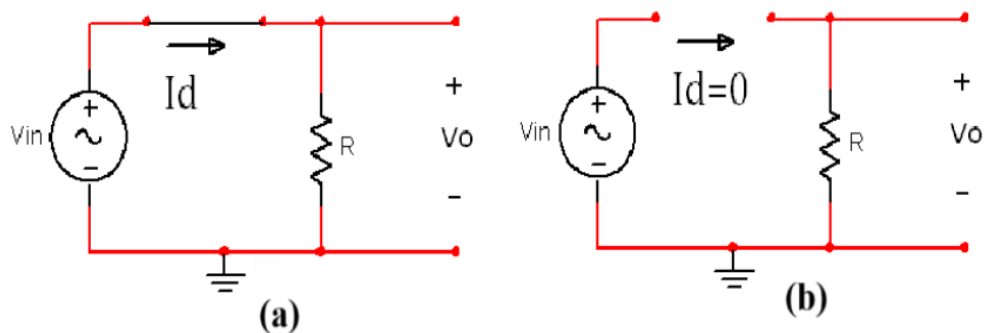


Figure I.33 Equivalent circuits (a) $V_{in} > 0$ and (b) $V_{in} < 0$ for ideal diode.

The total response of the circuit to the input signal V_{in} is shown on Figure I.34. Note that the presence of the diode alters the output signal in a profound way: it converts an AC (alternating current) input voltage, whose average value over time is zero, into an output voltage whose polarity does not change over time, and which has a non-zero average value. This type of voltage signal is called DC (direct current) since the direction of the current does not change over time. We have just taken the first step in the design of an AC to DC converter.

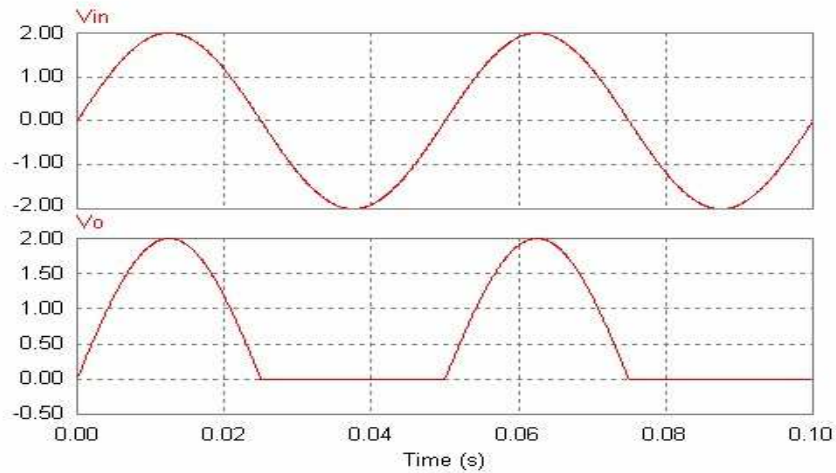
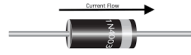


Figure I.34 Input signal (top) and equivalent rectified signal.

The output signal V_o is a rectified signal of the input V_{in} and the circuit that generated this signal, Figure I.31(a), is called Rectifier circuit. Furthermore, since it passes only half of the input signal it is called a Half Wave Rectifier Circuit. Let's now again analyze the behavior of the rectifier circuit with the offset diode model. The circuit is shown on Figure I.35.

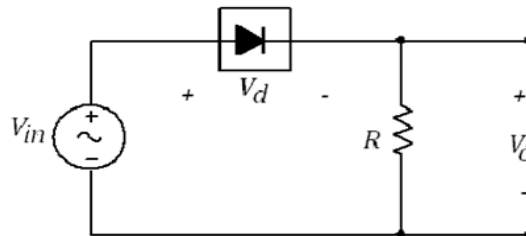


Figure I.35 Half wave rectifier circuit.

Application of Kirchhoff's voltage law to the circuit of Figure I.35 gives:

$$V_o = V_{in} - V_d$$

The voltage transfer curve for this circuit is shown on Figure I.36 and it is derived from the I - V characteristic of the diode model and Kirchhoff's voltage law.

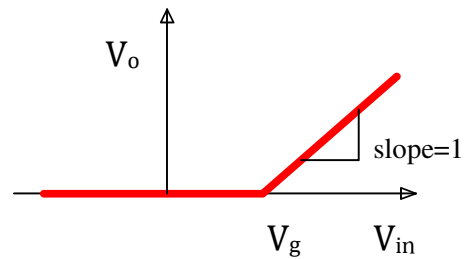
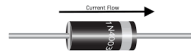


Figure I.36 Voltage transfer characteristic of the rectifier circuit.

From the voltage transfer curve we observe the following:

$$a) \text{ for } V_{in} \geq V_g \Rightarrow V_o = V_{in} - V_g$$

$$b) \text{ for } V_{in} < V_g \Rightarrow V_o = 0 \text{ (Open circuit).}$$

When the sinusoidal input voltage (V_{in}) goes positive, the diode is forward-biased and conducts current through the load resistor (Figure I.37).

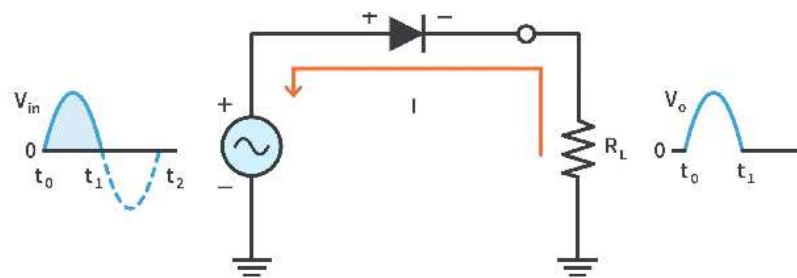


Figure I.37 During the positive alternation of V_{in} .

The output voltage looks like the positive half of the input voltage. The current path is through the ground back to the source (Figure I.38).

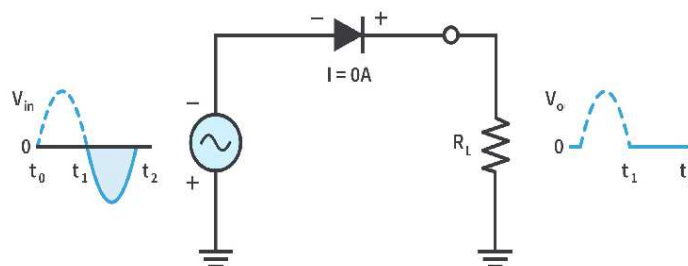
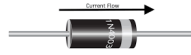


Figure I.38 During the negative alternation of V_{in} .



When the input voltage goes negative, the diode is reverse-biased. There is no current, so the voltage across the load resistor is 0 V. The net result is that only the positive half-cycles of the AC input voltage appear across the load. Since the output does not change polarity, it is a pulsating DC voltage with a (standard) frequency of 60 Hz. The average value of the half-wave rectified output voltage (V_{in}) is the value measured on a DC voltmeter. Mathematically, it is the area under the curve over a full cycle, divided by the number of radians in a full cycle:

$$V_{AVG} = \frac{V_P}{\pi}$$

Where V_O is the peak value of voltage. When the practical diode model is used with the barrier potential of 0.7 V, V_{in} must overcome the barrier potential before the diode becomes forward-biased. This results in a half-wave output with a peak value that is 0.7 V less than the peak value of the input. The expression for the peak output voltage is:

$$V_{P(O)} = V_{P(in)} - 0.7$$

The peak inverse voltage (PIV) is the peak value of the input voltage, and the diode must be capable of withstanding this amount of repetitive reverse voltage.

$$PIV = V_{P(in)}$$

The PIV occurs at the peak of each half-cycle of the input voltage when the diode is reverse-biased. A diode should be rated at least 20% higher than the PIV.

I.11.3. Full wave rectifier

Rectifiers are used extensively in the conversion of AC signals to DC. In such a circuit the half wave rectifier is not efficient since it "wastes" half of the signal. A circuit that overcomes this problem is the full wave rectifier which uses four diodes as shown on Figure I.39. The diodes are arranged in a bridge configuration. The output voltage is taken across the resistor R .

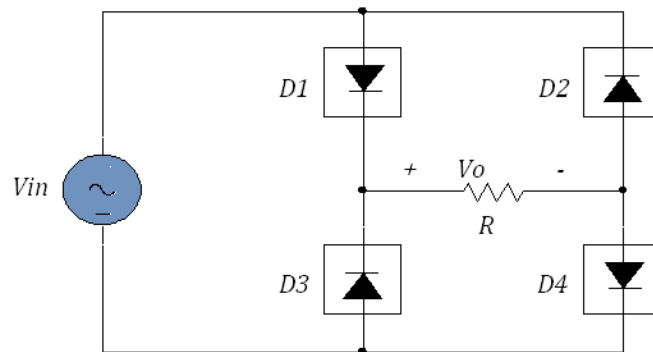
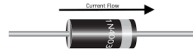


Figure I.39 Full wave rectifier circuit.

First let's consider the response of this circuit using the ideal diode model. We will apply a sinusoidal input signal and detect the output. Let's consider the example with the sinusoidal input signal V_{in} shown on Figure I.40. In order to understand the behavior of this circuit we will look at the direction of current flow during the positive and the negative swing of the input voltage.

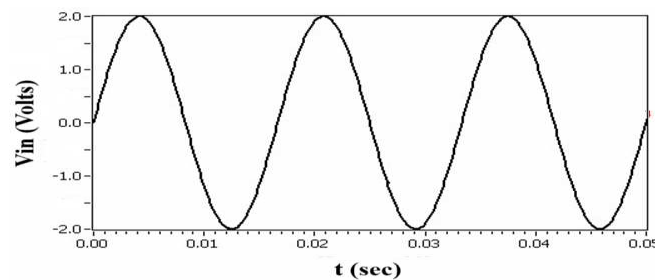


Figure I.40 Input signal to a full wave rectifier.

When V_{in} is positive, diodes D_1 and D_4 are forward biased and diodes D_2 and D_3 are reverse biased and the direction of the current is shown on Figure I.41 (a). During the negative part of the cycle, diodes D_2 and D_3 are forward biased and diodes D_1 and D_4 are reverse biased and the current flow is indicated on Figure I.41 (b).

Note that the current through the resistor R is in the same direction during the entire cycle. This is the basis for the behavior of the full wave rectifier circuit.

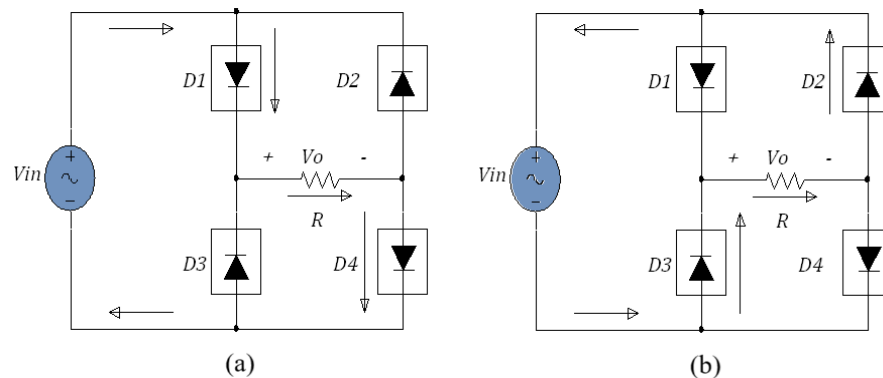
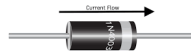


Figure I.41 the full wave rectifier circuit (a) V_{in} is positive and (b) During the negative part.

A full-wave rectifier allows unidirectional (one-way) current through the load during the entire input cycle. The result of full-wave rectification is an output voltage V_0 with a frequency twice the input frequency and that pulsates every half-cycle of the input V_{in} (Figure I.42).

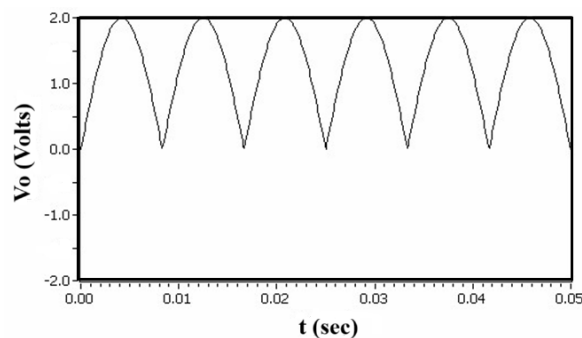


Figure I.42 Output signal of a full wave rectifier with ideal diodes.

Now let's consider the more realistic scenario represented by the full diode model. In this case the direction of the current during the positive and the negative cycle is the same as before (Figure I.43).

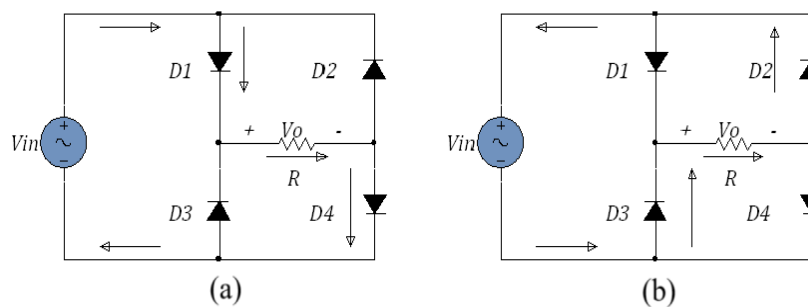
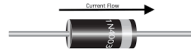


Figure I.43 Direction of current in the full wave rectifier during :



(a) the positive cycle of V_{in} and (b) during the negative cycle of V_{in} .

The difference in the response becomes apparent by considering the circuit equivalent of the offset model of the diode as shown on Figure I.44 for the positive and negative portions of the input signal V_{in} . From Kirchhoff's voltage law we see that :

$$V_o = V_{in} - 2V_g$$

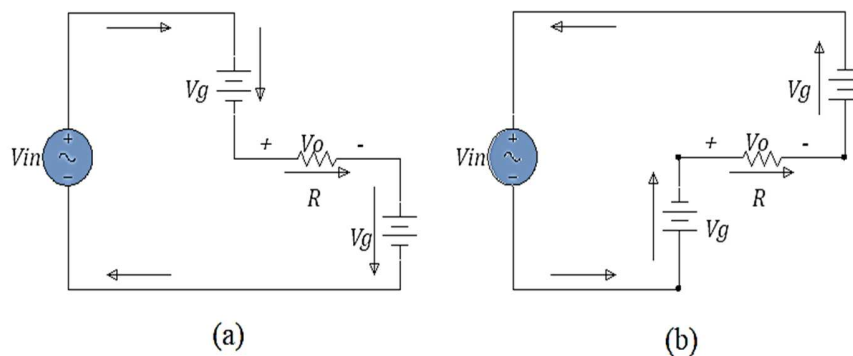


Figure I.44 Equivalent model of the full wave rectifier during (a) the positive and (b) negative portions of the cycle.

The resulting output is rectified during the positive and the negative cycle of the signal V_{in} and it has the form shown on Figure I.45 for a silicon diode characterized by $V_g = 0.7$ Volts. For V_{in} that have a small amplitude (not much greater than the offset voltage V_g) the rectified signal may only be a small fraction of the input signal. Later in the term we will improve this circuit by designing a "super diode" which will have $V_g=0$ and thus the rectified signal will resemble the one obtained by the ideal diode model.

For obtaining the operating point, the current I_d , when $V_{in} \geq V_g$, is :

$$\triangleright I_d = \frac{V_{in} - V_d}{R} \rightarrow \text{(This is the load line equation for this circuit)}$$

$$\triangleright I_d = I_s(e^{V_d/V_t} - 1) \rightarrow \text{(the I-V characteristic curve)}$$

The intersection of the load line and the I-V characteristic curve for the device is the operating point for the diode. This operating point is also called the quiescent point or Q-point and it gives the value of the current through the diode and the voltage across the diode. For $R = 100 \Omega$, and $V_{in} = 2V$, the load line and resulting operating point is shown on Figure I.46.

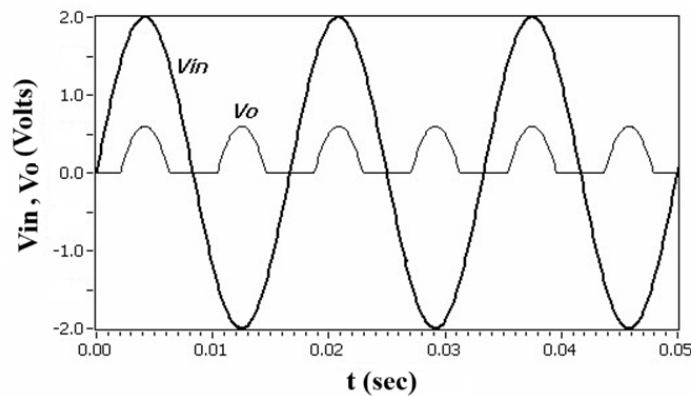


Figure I.45 Input and output signals for the full wave rectifier.

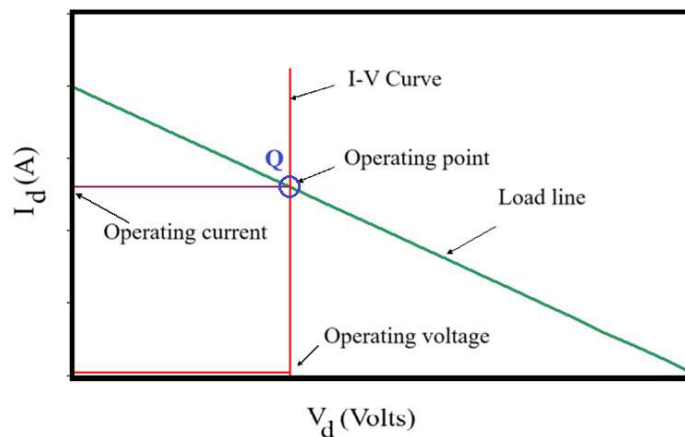


Figure I.46 Load line and operating point of diode in a rectifying circuit.

A full-wave rectifier allows unidirectional (one-way) current through the load during the entire input cycle. The result of full-wave rectification is an output voltage with a frequency twice the input frequency and that pulsates every half-cycle of the input (Figure I.47). The number of positive alternations that make up the full-wave rectified voltage is twice that of the half-wave voltage for the same time interval. V_{AVG} for a full-wave rectified sinusoidal voltage is twice that of the half-wave:

$$V_{AVG} = \frac{V_P}{\pi}$$

Where, V_{AVG} is approximately 63.7% of V_p for a full-wave rectified voltage.

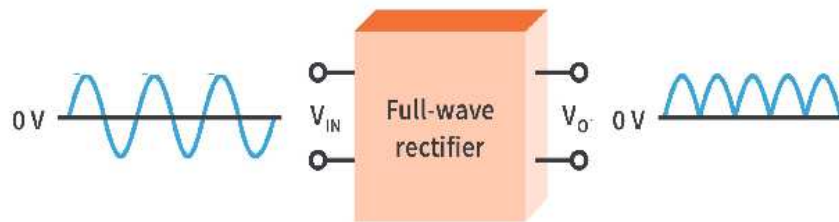


Figure I.47 Full-wave rectification.

A center-tapped rectifier is a type of full-wave rectifier that uses two diodes connected to the secondary of a center-tapped transformer. During positive half-cycles, D_1 is forward-biased and D_2 is reverse-biased. The current path is through D_1 and the load resistor R_L . During negative half-cycles, D_2 is forward-biased and D_1 is reverse-biased. The current path is through D_2 and R_L . Because the output current during both the positive and negative portions of the input cycle is in the same direction through the load, the output voltage developed across the load resistor is a full-wave rectified DC voltage. The output voltage of a center-tapped full-wave rectifier is always one-half of the total secondary voltage less the diode drop.

$$V_O = \frac{V_{SEC}}{2} - 0.7$$

- The Peak Inverse Voltage (PIV) is given by :

$$PIV = VP(O) + 0.7$$

I.11.4. Bridge Full-Wave Rectifier

Many electronic circuits require a rectified DC power supply to power various electronic basic components from the available AC mains supply. Rectifiers are used to convert an AC power to a DC power. Among the rectifiers, the bridge rectifier is the most efficient rectifier circuit. We can define bridge rectifiers as a type of full-wave rectifier that uses four or more diodes in a bridge circuit configuration to efficiently convert alternating (AC) current to a direct (DC) current. In the next few sections, let us learn more about its construction, working, and more. The construction of a bridge rectifier is shown in the figure below. The bridge rectifier circuit is made of four diodes D_1 , D_2 , D_3 , D_4 , and a load resistor R_L . The four diodes are connected in a closed-loop configuration to efficiently convert the alternating current (AC) into Direct Current (DC). The main advantage of this configuration is the absence of the expensive centre-tapped transformer. Therefore, the size and cost are reduced. The bridge rectifier uses four diodes connected as shown in Figure I.48.

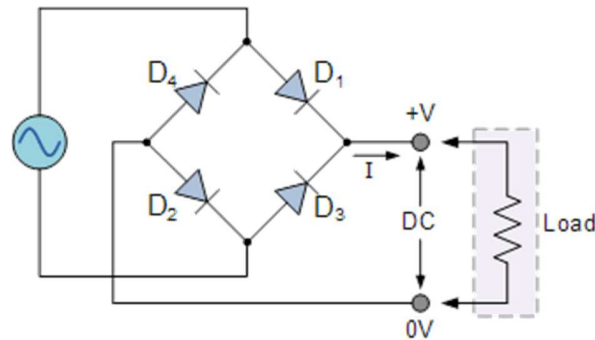
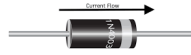


Figure I.48 A bridge rectifier circuit.

During the positive half cycle of the supply, diodes D_1 and D_2 conduct in series while diodes D_3 and D_4 are reverse biased and the current flows through the load as shown below (Figure I.49 (a)). During the negative half cycle of the supply, diodes D_3 and D_4 conduct in series, but diodes D_1 and D_2 switch "OFF" as they are now reverse biased. The current flowing through the load is the same direction as before (Figure I.49 (b)).

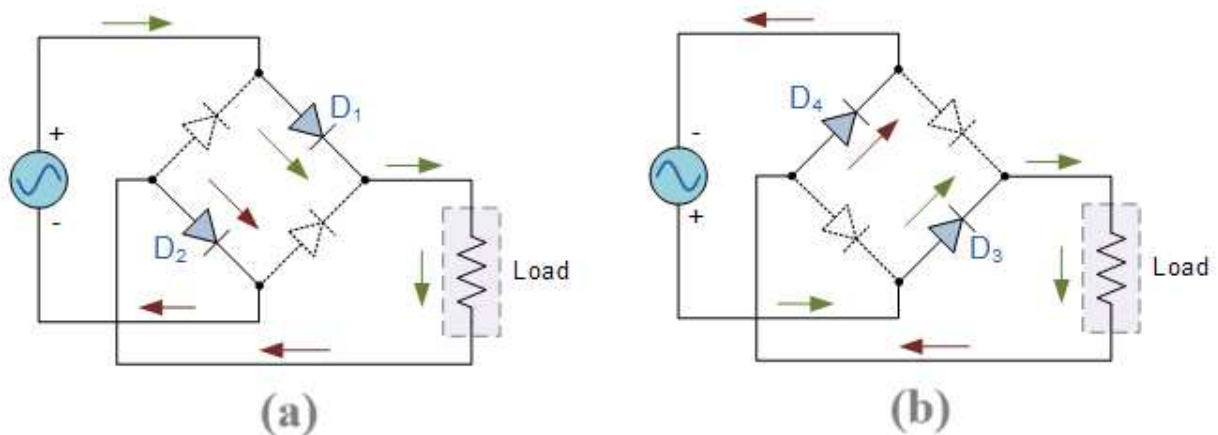


Figure I.49 (a) positive half cycle and (b) negative half cycle of the supply.

Two diodes are always in series with the load resistor during both the positive and negative half-cycles. Taking diode drops into account, the output voltage is :

$$V_{P(O)} = V_{P(SEC)} - 1.4$$

Since the output voltage is ideally equal to the secondary voltage :

$$PIV = V_{P(O)}$$

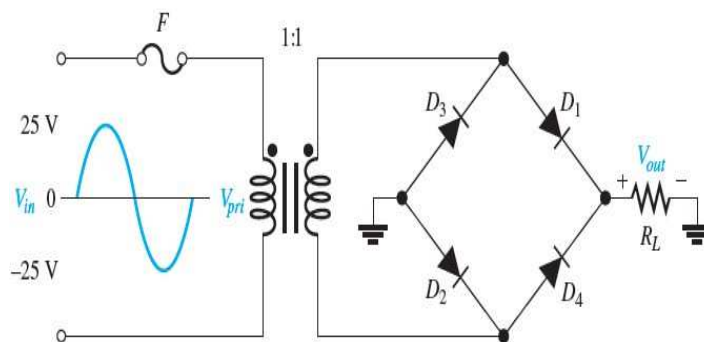


If the diode drops of the forward-biased diodes are included, the peak inverse voltage across each reverse-biased diode in terms of $V_{p(o)}$ is:

$$PIV = V_{p(o)} + 0.7$$

If the diode drop is neglected, the bridge rectifier requires diodes with half the PIV rating of those in a center-tapped rectifier for the same output voltage.

- **Example**



a) Determine the peak output voltage $V_{p(o)}$, $V_{p(RL)}$ and V_{AVG} for the bridge rectifier in Figure I.50.

b) What is the minimum PIV rating required for the diodes? $V_{P(RL)}$.

Figure I. 50 Full-Wave Bridge Rectifier.

- **Solution**

$$a) V_{p(o)} = V_{p(sec)} = nV_{p(in)} = (1) 25 V = 25 V$$

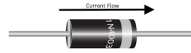
$$V_{p(RL)} = V_{p(o)} - 2(V_B) = 23.6 V$$

$$V = 2V_{p(RL)}\pi = (47.2)(3.14) = 15 V$$

$$b) PIV = V_{p(sec)} = V_{p(o)} = 25 V$$

I.12. Recent Advances and Future Trends in Diode Technology

The recent technological advances for diodes have generally been on the same lines as those of the other semiconductor components, i.e., smaller size, lower cost, and greater facilities. Chiefly as a result of improved methods of production, diodes are now obtainable in a wider range of types and ratings than previously. As well as being made more cheaply, the improved equipment and greater experience of the semiconductor industry have generally resulted in increased reliability. Experiments are known to have been undertaken to determine the feasibility of using diodes as active elements in

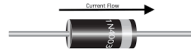


large and very high power applications, an early and fairly obvious field for the application of semiconductor power devices. Devices having working voltage ratings in the region of about 3 kV have been produced and are readily available. Such diodes generally consist of several parallel connected units encapsulated in a single package providing series connections between electrodes and function solely or predominantly in the reverse resistive mode.

The advantages of a widely used voltage rating standard may be lost as technology advances. A case in point is the voltage doubling capability of many diodes used in low voltage threshold level shifting and high-speed modulation circuits. For a long time, drive circuit designers, taught the intrinsic and parasitic capacitances of such diodes, have kept the input risetime and dynamic distortion cost of diode switching to a minimum. However, the processes by which power MOSFETs are approaching on-state design limits and the recent appearance of sub-100 V catalytic PN junctions will enable diode equipped, GaAs MESFET terrace drivers to challenge conventional wisdom in high-speed, low threshold, low voltage switcher design. The concurrent development of silica-clad photonic integrated circuits has positioned external cavity diode lasers to be widely deployed across multiple device platforms and to share the control and monitor costs associated with technology. A restated diode laser success will increase the capital, process simplification, and rapid testing advantage of a direct bandgap, photon-controlled device technology.

I.12.1. Nanotechnology in Diodes

Nanotechnology contributes effective advances for the production of nanodiodes that bring important advantages when compared to other devices that only make use of the emission of electrons, as is the case of the photovoltaic cell, which loses much energy when electrons are pulled from the absorbent material and those that absorb much more energy than necessary and those that remain loose. Such diodes are produced by depositing nanoscopic debris on the surface of the semiconductor material and using the same laser effect of the major damages caused by electric impulse to return the free electrons to their source. It is a simple device and, with the inevitable industrialization process, it will even surpass photovoltaic cells in the issue of energy usage efficiency. These are the initial dispositions that must take the layers and the debris that will be used, at the time of their deposit, on the surface of the semiconductor, in relation to the direction of incidence of the light. Small blocks can be used, which can be cubes, octahedra, or other geometric figures. The principle of operation is based on an increase in the spatial occupation of the displacement of free electron species in the interior nano-surface structure, which is immediately below the surface of the gap in the semiconductor, causing potential mechanical deformations with the appearance of elastic deformations and electronic excitation. In



certain conditions of increasing the ability to relax these structures, free charges can be organized to form electric and/or electronic dipoles. These dipoles become associated with self-associative vibratory movements of the original ions in a vacuum, beyond the production of zwitterionic polar structures. The resulting structures are characterized because they appear as non-linear electronic conductors accompanied by non-ohmic freedom, similar to those of junctions formed by the junction of metallic conductors with semiconductors.

I.12.2. Emerging Diode Technologies

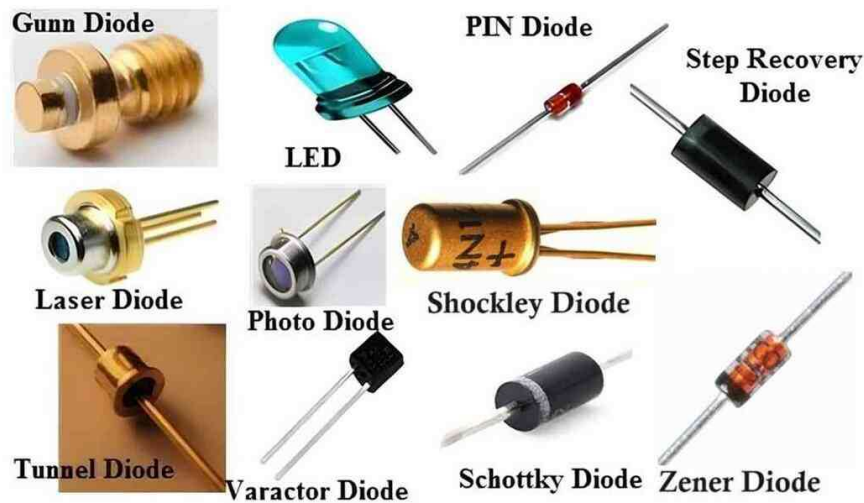
We have looked at various types of diodes, which are defined as electronic devices with two electrodes or connections. Most standard diodes are made of semiconductor materials, such as silicon, and may either be inorganic silicon diodes, organic diodes, polymer or molecular diodes, multi-layer or zinc oxide diodes, and so on in a variety of forms. We also find that the performance of diodes is typically characterized by the relationship between current and voltage when the diode is in forward or reverse bias. Initially, the current-voltage characteristics of most of the diodes would not be pronounced, but it would change dramatically as the diodes were in use. One of the emerging diode technologies that is seeing increasing application is that of organic diodes. Also known as plastic diodes, they are made by combining organic and inorganic compounds, many of which are hydrocarbon-based, and have a wide range of applications from solar panels, lighting, photodetectors, and logic gates to radio-frequency identification tags. The organic diodes have the advantage of being lighter, cheaper, and easier to process than standard diodes. They are available in a wide range of colors, and combined with different materials, they exhibit the ability to rectify both direct and alternating current.

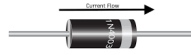
I.13. Conclusion and Summary

The various applications of diodes in electronic circuits are so many and diverse that they seem more like utility elements rather than active elements. It is clearly impossible to make a complete survey of all the ways diodes are used in modern electronics, but an attempt has been made to cover a representative selection of uses. Yet it is clear that there is much repetition of what amounts to the basic diode functions of rectification and clipping. So the selection of applications was biased towards functions that at least used these basic functions in more sophisticated ways for signal isolation, power tool protection, etc. The specific devices of PIN diodes and varactor chips usually have hyperextensions of these basic functions or somewhat different basic functions for specific usages. No attempt to quantify the application functions was made, but for future work in this area it would be interesting to



have a clear idea of the extent to which the two hyperextended functions or the somewhat different functions become important in relation to the basic function of power rectification. What is worth emphasizing about the diode is that the wrinkles in its fundamental current–voltage curve that give rise to these exotic functions is that all the necessary information for using the diode as a signal detector or signal isolator is already present in the standard IV curve. This is not necessarily the case for the exotic and peculiar behaviour of a vacuum tube or a power FET, and while these two devices have their own advantages, in terms of complexity and information density the diode has them both beaten hands down.





Questions & Answers

1. What happens when the battery voltage is increased in a forward-biased P-N junction?

The current through the junction increases when the battery voltage is increased in a forward-biased P-N junction.

2. What happens when a P-N junction is reverse biased?

The holes and electrons tend to move away from the junction.

3. What are the two breakdown mechanisms of the P-N junction? And the static resistance of a diode?

The two breakdown mechanisms are Zener breakdown and Avalanche breakdown. Static resistance of a diode is defined as the ratio of the DC voltage applied across the diode to the DC current flowing through the diode.

4. What is the dynamic resistance of a diode?

Dynamic resistance of a diode is defined as the ratio of change in voltage to the change in current.

5. What is reverse resistance?

Reverse resistance is defined as the resistance offered by the P-N junction diode when it is reverse biased.

6. What is a semiconductor?

A semiconductor is a material whose conductivity stays between an insulator and a conductor.

7. What are the two types of semiconductors?

N-type semiconductors and p-type semiconductors are the two types of semiconductors.

8. What are n-type semiconductors?

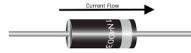
N-type semiconductors are intrinsic semiconductors doped with antimony (Sb), phosphorus (P), or arsenic (As) as doping impurities.

9. What is meant by doping?

In semiconductor technology, doping is the process of intentional infliction of impurities into intrinsic semiconductors for the objective of remodelling their optical, structural, and electrical properties.

10. What is a diode?

A diode is an electrical device that enables the current to flow only in one direction. In an electrical circuit diagram, a diode is denoted by a triangle symbol with a line along one vertex.

**11. What are the main types of diodes?**

Light-emitting diode, avalanche diode, laser diode, Schottky diode, photodiode, p-n junction diode, and Zener diode are the main types of diodes.

12. What are the three regions in which diodes function?

Forward bias, zero bias and reverse bias are the three regions in which diodes function.

13. Give one application of P-N junction diodes.

P-N junction diodes are used as rectifiers in numerous electric circuits. They are also used as voltage-controlled oscillators in varactors.

14. How do you define Zener diode?

Zener diode is a semiconductor device that enables the flow of current in both forward and reverse directions.

15. Why is Zener Diode used a regulator?

Zener diode is utilized as a shunt voltage regulator. It is connected in parallel with the load, operating in reverse bias. Once the Zener diode exceeds its knee voltage, it maintains a constant voltage across the load.

16. Does Zener Diode exhibit a controlled breakdown?

Yes, Zener Diode does exhibit a controlled breakdown.

17. Does Zener Diode work in forward-biased mode?

No, a Zener diode does not function in forward-biased mode. It is designed to operate in reverse bias for its intended applications.

18. Which are the materials used in the fabrication of diodes?

Silicon and Germanium are the semiconductor materials used in the construction of the diode.

19. State true or false: in the Zener breakdown, the increase in temperature increases the breakdown voltage.

False. In Zener breakdown, the increase in temperature decreases the breakdown voltage.

20. In which type of diode avalanche breakdown takes place?

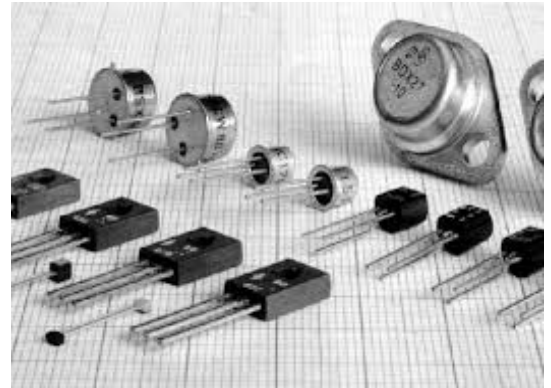
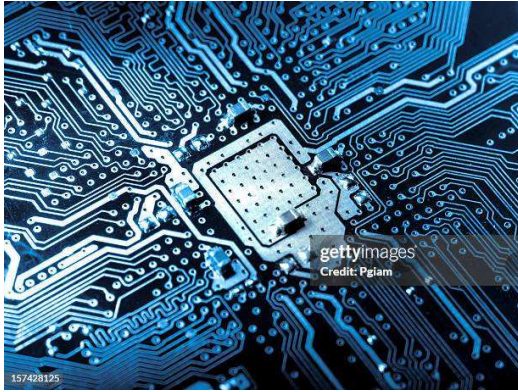
It occurs in diodes that are lightly doped.

21. What happens in avalanche breakdown when the increase in temperature takes place?

When the temperature increases, the breakdown voltage also increases. Once you know V , you can find the voltages and currents in the circuit.



Chapter II Transistors



II.1. Introduction

Modern electronics would not be possible without transistors, tiny devices that convert low-power input into the highly efficient electric current that powers our computers, smartphones, televisions, and countless other parts of our modern world. Typically, a transistor itself contains fewer than ten critical layers. These layers may each be thinner than one-thousandth the width of a human hair. The functionality of these devices lies on the border between linear amplifiers and high-speed switches. As amplifiers, digital transistors are often used in mixers and amplifiers, a critical element of the wireless infrastructure in applications ranging from Wi-Fi to cell phones to GPS. In switch mode, they shuttle digital information throughout a device, allowing only 0 and 1 to pass, which is a critical building block in synchronous digital electronics.

There are many types of transistors, and the transistor used in a specific chip design depends in large part on the application the chip is to perform. For example, as wireless communication systems have moved to higher frequencies, so too have silicon transistor technologies. The overwhelming driver in silicon advanced transistor technologies is lower power operation, because lower power means less heat, less demand for cooling, and longer battery life. In the abstract, a transistor is just a semiconductor device with at least three terminals. There are various possible designs for such devices, and there have been several different dominant transistor technologies in the sixty or so years since the invention of the first transistor. At its heart, a transistor is a switch, able to allow or not allow current to flow depending on the instantaneous state of some other part of the circuit. Transistors can also function as amplifiers, multiplying the voltage level of a signal. We will walk through the general operational



principles, but this work is a broad look at how we got to modern transistors from the semiconductors available in the early twentieth century.

II.2. Historical Development of Transistors

The development of transistors can be traced back to the efforts to develop semiconductor amplifiers made during the 1930s. Several laboratory experiments were performed in a number of institutions in the 1930s to show that semiconductor materials exhibited rectification and amplified signals. These early studies showed that a great deal of patience and time with high precision was needed to obtain semiconductor devices that worked as desired. The solid-state, which led to the development of the first point-contact and doubly diffused alloy junction transistors inside of a few months, was a loose coalition coming from many technical backgrounds and experiences, limited funding, and paperwork that reflected a great deal of multitasking. The definite history of solid-state research was coupled with a changing set of contracts and employment opportunities, most of which could not have been foreseen. The methods to grow suitable materials were developed entirely in support of the radar effort. The long history of semiconductor optics had produced a body of optical knowledge that led directly to the basic chemistry needed to produce some kinds of point-contact transistors. Research in nanostructured materials began to yield new materials, such as quantum dot transistors and molecular transistors, with unusual electrical properties. Large-scale integration involves the use of transistor gauges to create integrated circuits with thousands of transistors on a single wafer. Advances from these fields influence the future of digital electronic development.

II.3. Types of Transistors

A transistor is an electronic device that controls the flow of current in a circuit, acting either as an amplifier to increase the intensity of a weak input signal or as a switch to convert an input into high or low values. There are many types of transistors, but the two main categories are:

➤ **Bipolar Junction Transistors (BJTs):** These are made of semiconductor materials such as silicon that have been specially treated to change their basic electrical characteristics. BJTs are described as "bipolar" because the flow of current across a BJT is carried by both negatively charged electrons and positively charged holes. BJTs have a very high current or power gain, which makes them very useful in analog circuits where voltage amplification is required. For this reason, they are commonly used in power amplifiers.

➤ **Field-Effect Transistors (FETs):** In contrast to BJTs, field-effect transistors contain no holes, and the charge carriers flow across the device between the source and drain using an electric field that



permeates the entire transistor. FETs are known as unipolar devices because current conduction is carried either by electrons or holes but not by both as is in the BJT. With this simple structural difference, field-effect transistors do not draw input current but induce current conduction between their input and output through electric field induction. This has two distinct advantages over bipolar transistors: higher input impedance and less power consumption. These features make FETs ideal for use as integrated circuit components.

In the case of these two transistors, the main characteristics include how transistors work, such as how BJTs use an applied voltage to control the current flow between two of their three terminals and how FETs use an applied electric field to control the flow of current between their terminals. The application of these two transistors in relation to the above characteristics is explained. It should also be noted that it is important to choose the appropriate transistor type and number according to these features and applications.

II.4. Bipolar Junction Transistors (BJTs)

Bipolar Junction Transistors (BJTs) are three-layer (either NPN or PNP) semiconductor devices with a p-type base sandwiched between n-type emitter and collector regions. The flow of current in an emitter-base junction, or base-collector junction, will cause the current in the other junction to vary correspondingly. BJTs can function as current amplifiers while operating. A small change in input current alters the output current. A small electric signal on the input controls the large energy flow from the output. The large current and voltage relationship is constant provided the collector-base junction is not in breakdown.

The BJT is constructed with three doped semiconductor regions (emitter, base, and collector) separated by two pn junctions (Figure II.1). One type consists of two n regions separated by a p region (nnp), and the other type consists of two p regions separated by an n region (pnp). The term bipolar refers to the use of both holes and electrons as current carriers in the transistor structure.

The pn junction joining the base region and the emitter region is called the *base-emitter junction*. The pn junction joining the base region and the collector region is called the *base-collector junction*. A wire lead connects to each of the three regions. The leads are labelled E, B, and C for emitter, base, and collector, respectively. The base region is lightly doped and very thin compared to the heavily doped emitter and the moderately doped collector regions. Figure II.2 shows the schematic symbols for the npn and pnp bipolar junction transistors.

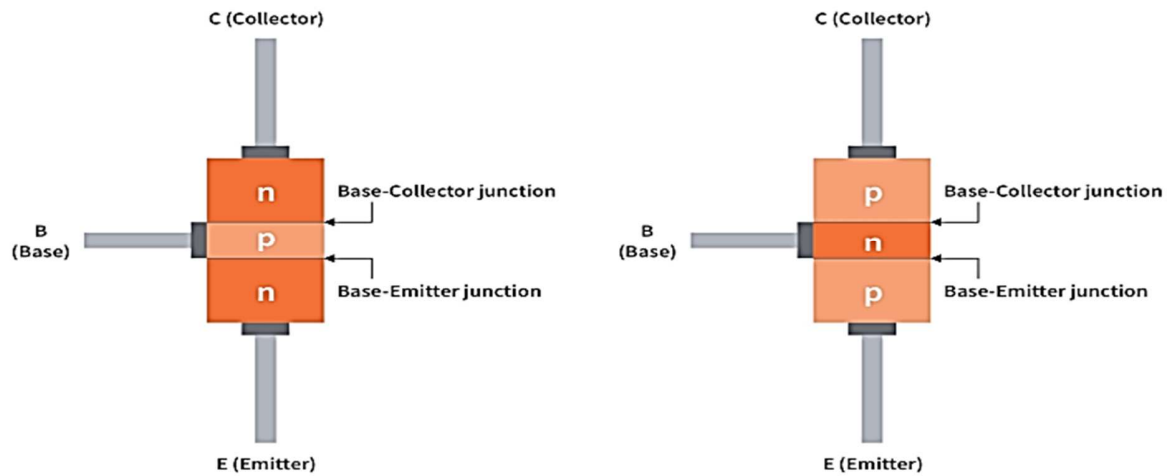


Figure II.1 Bipolar Junction Transistors (BJTs) structures.

The PN junction joining the base region and the emitter region is called the *base-emitter junction*. The PN junction joining the base region and the collector region is called the *base-collector junction*. A wire lead connects to each of the three regions. The leads are labelled E, B, and C for emitter, base, and collector, respectively. The base region is lightly doped and very thin compared to the heavily doped emitter and the moderately doped collector regions. Figure II.2 shows the schematic symbols for the **npn** and **pnp** bipolar junction transistors.

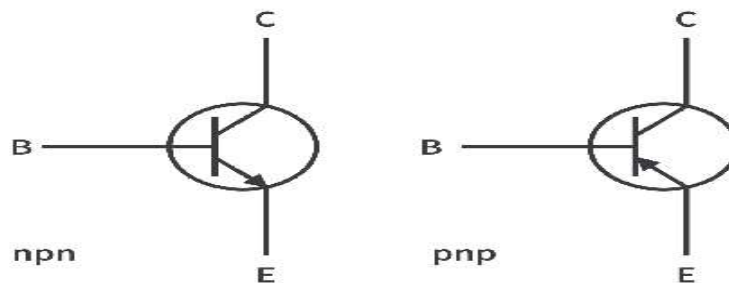


Figure II.2 Bipolar Junction Transistors (BJT) symbols.

There are three types of configuration, which are common base (CB), common collector (CC) and common emitter (CE) (Figure II.3).

- In common base (CB) configuration, the base terminal of the transistor is common between input and output terminals (Figure II.3(a)).
- In common collector (CC) configuration, the collector terminals are common between the input and output terminals (Figure II.3(b)).
- In common emitter (CE) configuration, the emitter terminal is common between the input and the output terminals (Figure II.3(c)).

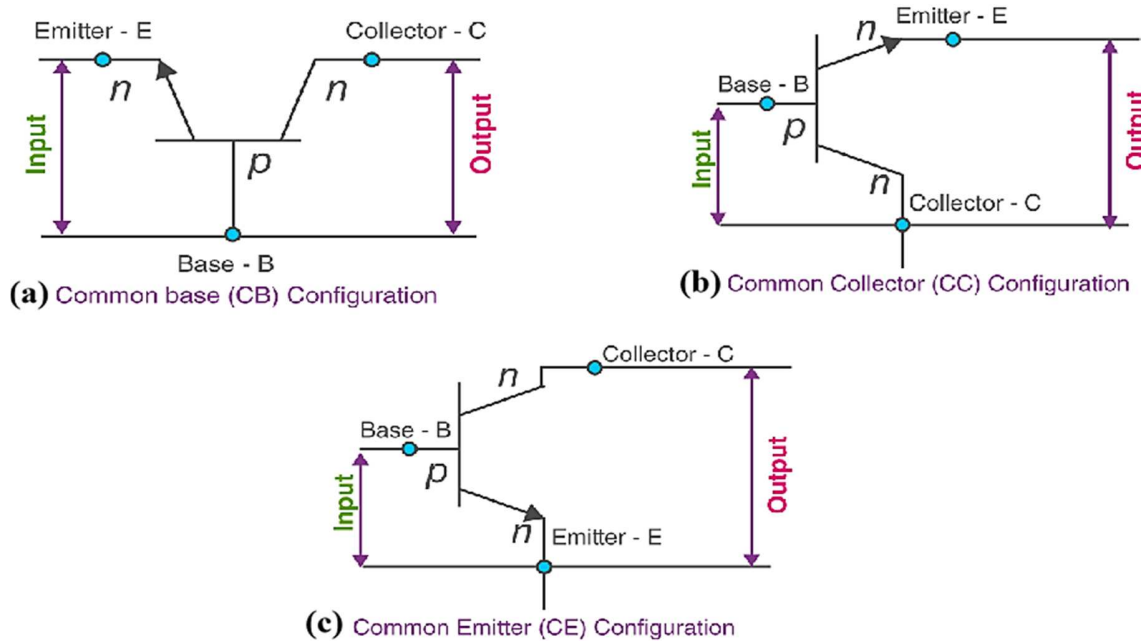


Figure II.3 Types of Bipolar Junction Transistors (a) common base (CB), (b) common collector (CC) and (c) common emitter (CE).

Figure II.4 shows a bias arrangement for both npn and pnp BJTs for operation as an amplifier. In order for a BJT to operate properly, the two pn junctions must be correctly biased with external DC voltages. In both cases the base-emitter (BE) junction is forward-biased and the base-collector (BC) junction is reverse-biased. This condition is called forward-reverse bias.

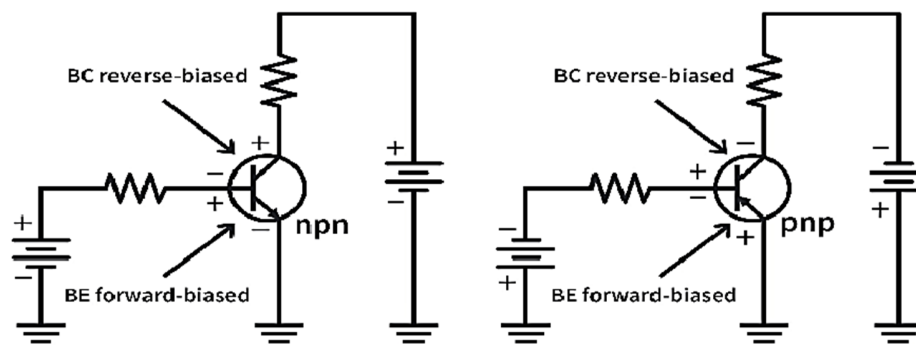


Figure II.4 Forward-reverse bias of a BJT.

II.4.1. Transistor Currents

The directions of the currents in both npn and pnp transistors and the schematic symbols are as shown in Figure II.5.

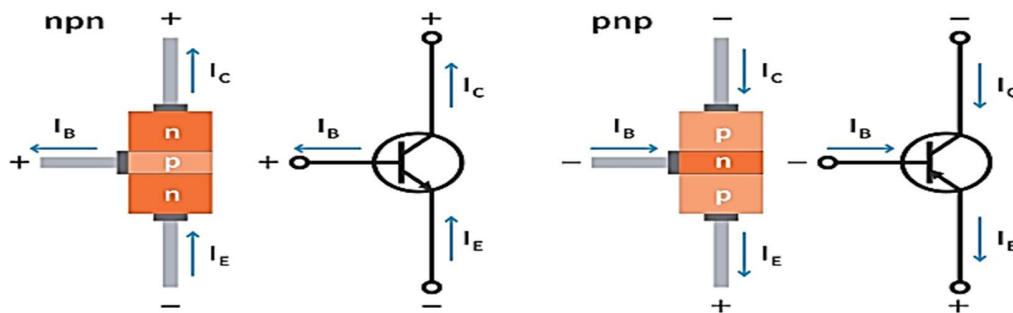


Figure II.5 Transistor currents.

The heavily doped n-type emitter region has a very high density of conduction-band (free) electrons. These free electrons easily diffuse through the forward-biased BE junction into the lightly doped and very thin p-type base region. The base has a low density of holes, which are the majority carriers. A small percentage of the total number of free electrons injected into the base region recombine with holes and move as valence electrons through the base region and into the emitter region as hole current. The construction and terminal voltages for a bipolar NPN transistor are shown above. The voltage between the Base and Emitter (V_{BE}), is positive at the Base and negative at the Emitter because for an NPN transistor, the Base terminal is always positive with respect to the Emitter. The Collector supply voltage must also be more positive with respect to the Emitter (V_{CE}). Therefore, for a bipolar NPN transistor to conduct correctly, the Collector must always more positive with respect to both the Base and the Emitter terminals (Figure II.6).

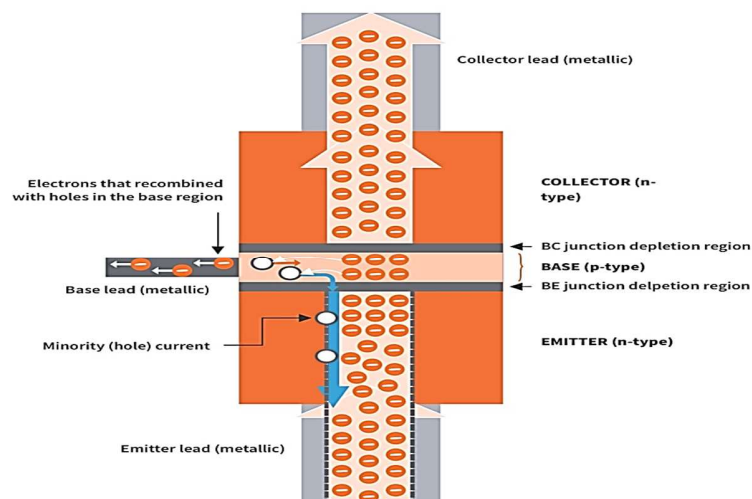


Figure II.6 BJT operation showing electron flow.



A change in output current from changes in the base to emitter current creates a parameter called the current gain (β) of the BJT and is given by the ratio I_C/I_B . The current gain (β) is typically constant. The bipolar junction transistor (BJT) is currently one of the most important components in electronic systems. For this reason, it is imperative that the student has a sound understanding of the transistor and its characteristics. To begin this understanding, it is imperative that the student first understands what is meant by a BJT. Additionally, in understanding the transistor, one must first understand how the transistor is physically configured to form the two pn-junctions that are present in the transistor.

Then the voltage sources are connected to an NPN transistor as shown. The Collector is connected to the supply voltage V_{CC} via the load resistor, R_L which also acts to limit the maximum current flowing through the device. The Base supply voltage V_B is connected to the Base resistor R_B , which again is used to limit the maximum Base current. So in a NPN Transistor it is the movement of negative current carriers (electrons) through the Base region that constitutes transistor action, since these mobile electrons provide the link between the Collector and Emitter circuits. This link between the input and output circuits is the main feature of transistor action because the transistors amplifying properties come from the consequent control which the Base exerts upon the Collector to Emitter current (Figure I.7).

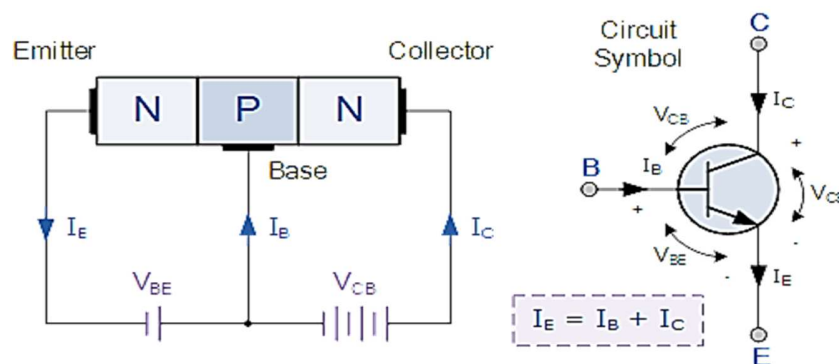


Figure II.7 Bipolar NPN Transistor Configuration.

Then we can see that the transistor is a current operated device (Beta model) and that a large current (I_C) flows freely through the device between the collector and the emitter terminals when the transistor is switched "fully-ON". However, this only happens when a small biasing current (I_B) is flowing into the base terminal of the transistor at the same time thus allowing the Base to act as a sort of current control input. The current in a bipolar NPN transistor is the ratio of these two currents (I_C/I_B), called the DC Current Gain of the device and is given the symbol Beta, β . The value of β can be large up to 200 for standard transistors, and it is this large ratio between I_C and I_B that makes the bipolar NPN



transistor a useful amplifying device when used in its active region as I_B provides the input and I_C provides the output. Note that Beta has no units as it is a ratio. Also, the current gain of the transistor from the Collector terminal to the Emitter terminal, I_C/I_E , is called Alpha, (α), and is a function of the transistor itself (electrons diffusing across the junction)

As the emitter current I_E is the sum of a very small base current plus a very large collector current, the value of alpha (α), is very close to unity, and for a typical low-power signal transistor this value ranges from about 0.950 to 0.999.

$$\beta = \frac{\text{Output Current}}{\text{Input Current}} = \frac{I_C}{I_B}$$

$$I_E = I_B + I_C \quad \text{and} \quad \frac{I_C}{I_E} = \alpha$$

$$I_B = I_E - I_C$$

$$I_B = I_E - \alpha I_E$$

$$I_B = (1 - \alpha)I_E$$

$$\beta = \frac{I_C}{I_B} = \frac{I_C}{(1-\alpha)I_C} = \frac{\alpha}{1-\alpha}$$

II.4.2. BJT Circuit Analysis

Consider the basic transistor bias circuit in Figure II.8. However, V_{BE} is DC voltage at base with respect to emitter, V_{CB} is DC voltage at collector with respect to base and V_{CE} is DC voltage at collector with respect to emitter.

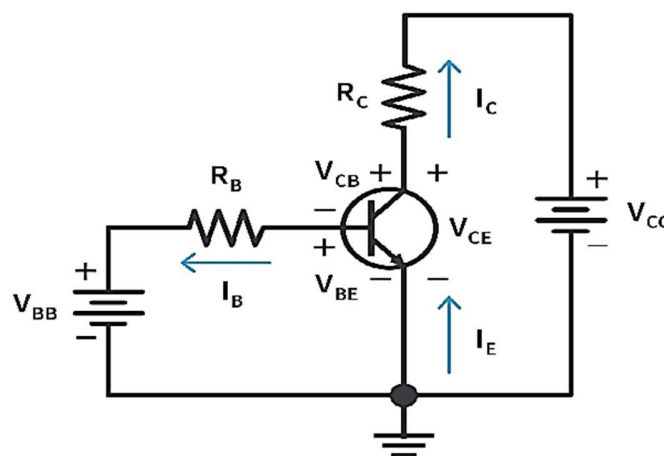


Figure II.8 Transistor currents and voltages.



V_{BB} forward-biases the base-emitter junction, and V_{CC} reverse-biases the base-collector junction. When the base-emitter junction is forward-biased where:

$$V_{BE} \approx 0.7 \text{ V}$$

Although V_{BE} can be as high as 0.9 V in an actual transistor and is dependent on current, 0.7 V is used to simplify the analysis of the basic concepts. The characteristic of the base-emitter junction is the same as a normal diode curve. Since the emitter is at ground (0 V), by Kirchhoff's voltage law, the voltage across R_B is :

$$V_{RB} = V_{BB} - V_{BE}$$

By Ohm's law, $V_{RB} = I_B R_B$. Substituting for V_{RB} and solving for I_B given by:

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

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

$$V_{RB} = V_{CC} - V_{RC}$$

Since the drop across R_C is $V_{RC} = I_C R_C$, V_{CE} can be written as:

$$V_{CE} = V_{CC} - I_C R_C \quad \text{Where, } I_C = \beta I_B$$

The voltage across the reverse-biased collector-base junction is :

$$V_{CB} = V_{CE} - V_{BE}$$

II.4.3. Collector Characteristic Curves

Using a circuit like that shown in Figure II.9, a set of collector characteristic curves can be generated that show how I_C varies with V_{CE} , for specified values of I_B . Both V_{BB} and V_{CC} are variable sources of voltage. V_{BB} is assumed to be set to produce a certain value of I_B and V_{CC} is zero.

Thus, both the base-emitter junction and the base-collector junction are forward-biased because the base is at approximately 0.7 V while the emitter and the collector are at 0 V. I_B is through the base-emitter junction because of the low impedance path to ground and, therefore, I_C is zero.



When both junctions are forward-biased, the transistor is in the *saturation* region of operation. Saturation is the state of a BJT in which I_C has reached a maximum and is independent of I_B . As V_{CC} is increased, V_{CE} increases as I_C increases.

This is the portion between points A and B in Figure II.10. I_C increases as V_{CC} is increased because V_{CE} remains less than 0.7 V due to the forward-biased base-collector junction. When V_{CE} exceeds 0.7 V, the base-collector junction becomes reverse-biased and the transistor goes into the active, or linear, region of operation. I_C increases very slightly for a given I_B as V_{CE} increases due to widening of the base-collector depletion region. This causes a slight increase in β .

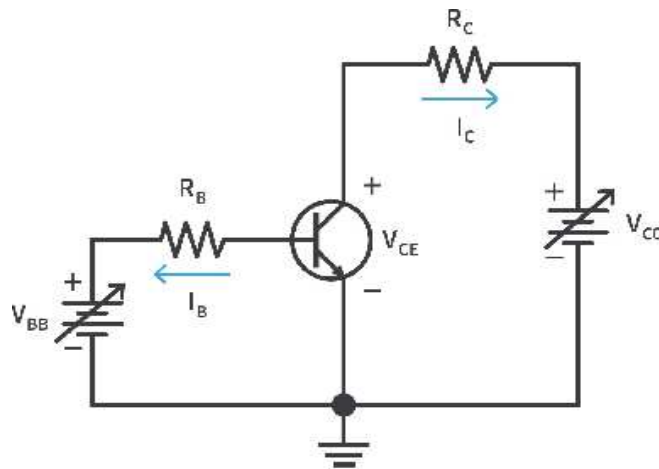


Figure II.9 BJT circuit.

This is the portion between points B and C in Figure II.10. I_C in this portion is determined only by $I_C = \beta I_B$. When V_{CE} reaches a sufficiently high voltage, the base-collector junction goes into **breakdown**; and I_C increases rapidly, shown by the portion to the right of point C. A transistor should never be operated in this region. A family of curves is produced when I_C versus V_{CE} is plotted for values of I_B . When $I_B = 0$ A, the transistor is in the **cutoff region**. Cutoff is the nonconducting state of a transistor. The most important factor to notice is the effect of V_{CE} upon the collector current I_C when V_{CE} is greater than about 1 volts.

We can see that I_C is largely unaffected by changes in V_{CE} above this value and instead it is almost entirely controlled by the base current, I_B . When this happens, we can say then that the output circuit represents that of a "Constant Current Source". It can also be seen from the common emitter circuit above that the emitter current I_E is the sum of the collector current, I_C and the base current, I_B , added together so we can also say that $I_E = I_C + I_B$ for the common emitter (CE) configuration.

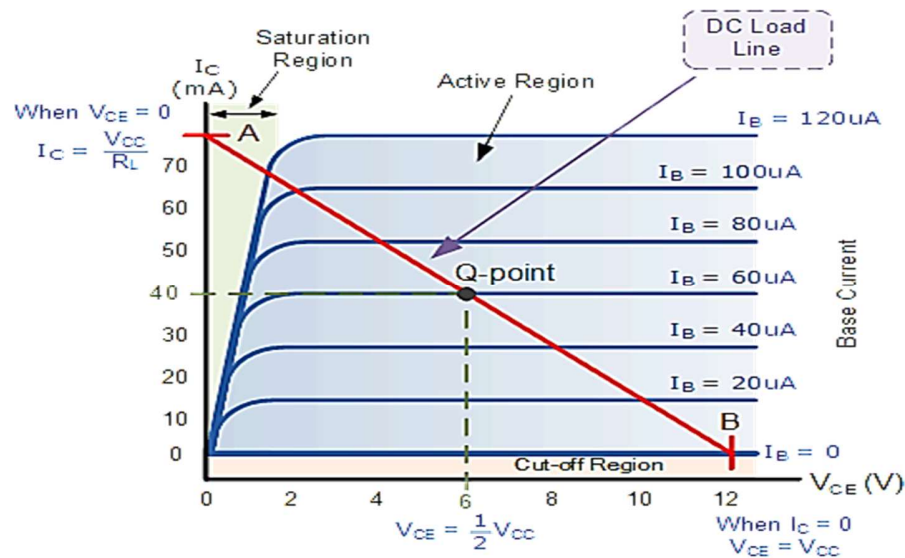


Figure II.10 Collector characteristic curves.

By using the output characteristics curves in our example above and also Ohm's Law, the current flowing through the load resistor, (R_L), is equal to the collector current, I_C entering the transistor which in turn corresponds to the supply voltage, (V_{CC}) minus the voltage drop between the collector and the emitter terminals, (V_{CE}) and is given as:

$$I_C = \frac{V_{CC} - V_{CE}}{R_L}$$

Also, a straight line representing the Dynamic Load Line of the transistor can be drawn directly onto the graph of curves above from the point of "**Saturation**" (A) when $V_{CE} = 0$ V, to the point of "**Cut-off**" (B) when $I_C = 0$ A, thus giving us the "**Operating**" or Q point of the transistor. These two points are joined together by a straight line and any position along this straight line represents the "**Active Region**" of the transistor. The actual position of the load line on the characteristics curves can be calculated as follows:

$$\text{While : } V_{CE} = 0 \text{ V} \Rightarrow I_C = \frac{V_{CC} - 0}{R_L} \Rightarrow I_C = \frac{V_{CC}}{R_L}$$

$$\text{Whereas : } I_C = 0 \text{ A} \Rightarrow 0 = \frac{V_{CC} - V_{CE}}{R_L} \Rightarrow V_{CC} = V_{CE}$$

Then, the collector or output characteristics curves for Common Emitter NPN Transistors can be used to predict the Collector current, I_C , when given V_{CE} and the Base current, I_B .

A Load Line can also be constructed onto the curves to determine a suitable Operating or Q point which can be set by adjustment of the base current. The slope of this load line is equal to the reciprocal of the load resistance which is given as: $(-1/R_L)$.



Then we can define a NPN Transistor as being normally "OFF" but a small input current and a small positive voltage at its Base (B) relative to its Emitter (E) will turn it "ON" allowing a much large Collector-Emitter current to flow.

NPN transistors conduct when V_C is much greater than V_E . Cutoff and saturation can be illustrated in relation to the collector characteristic curves by the use of a load line (Figure II.11). The bottom of the load line is at ideal cutoff where $I_C = 0$ A, and $V_{CE} = V_{CC}$. The top of the load line is at saturation where $I_C = I_{C(sat)}$ and $V_{CE} = V_{CE(sat)}$. In between cutoff and saturation along the load line is the active region of the transistor's operation.

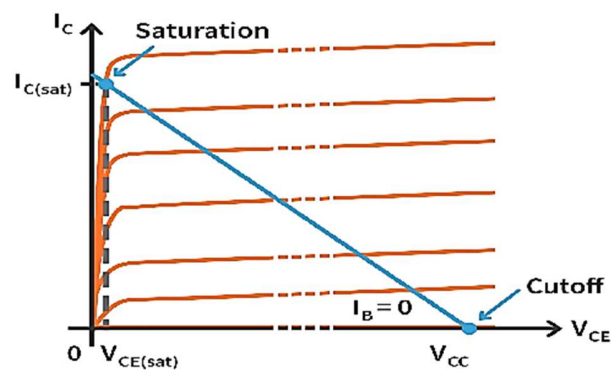


Figure II.11 DC load line on a family of collector characteristic curves.

II.4.4. Transistor Amplifiers

Transistor amplifiers are widely employed for amplifying various signals, from very weak audio frequency signals to radio frequency signals. Amplification is based on the principle that a transistor can control the magnitude of output current, voltage, or power from the transistor input signal. The amplification of a weak input signal and its amplification properties mainly depend on the choice of transistor and its mode of operation, voltage ratings, and current ratings. Hence, the choice of transistor in relation to a particular amplifier requirement is decided based on the amplification and power amplification stages. In turn, a further processing or transmission stage can be used for the purpose of a given application. Signal processors, starting with transistor amplifiers, find applications in audio systems and communication systems like AM, FM, pulse width modulation, and stereo systems. Typical examples include consumer electronics like AM/FM radios, audio tapes, compact disc music systems, public address or sound systems, and televisions. There are mainly three basic configurations of transistor amplifiers, namely common emitter, common collector, and common base. Of these configurations, the most widely used are the common emitter configurations as far as power amplification is involved. Here, however, other configurations are used as input or voltage amplifiers



to feed into a common emitter configuration. The common collector transistor amplifiers find application in impedance matching networks, emitter followers, etc. The advantages and disadvantages of these configurations of transistor amplifiers will be discussed along with the theory of their operation. The various factors connected with an amplifier, such as its gain, linearity, bandwidth, input, and output impedance, are also discussed at appropriate places. The factors governing the performance of real amplifiers, distortion, and feedback in amplifiers are also discussed in other paragraphs. Other applications, such as modulators and mixers, are briefly explained in this section for the purpose of clarity on site signals and their processing.

A transistor amplifies current because I_C is equal to I_B multiplied by the current gain, β . I_B is very small compared to I_C and I_E . Because of this:

$$I_C \approx I_E$$

An AC voltage, V_S , is superimposed on the DC bias voltage V_{BB} as shown in Figure II.12. The DC bias voltage V_{CC} is connected to the collector through R_C .

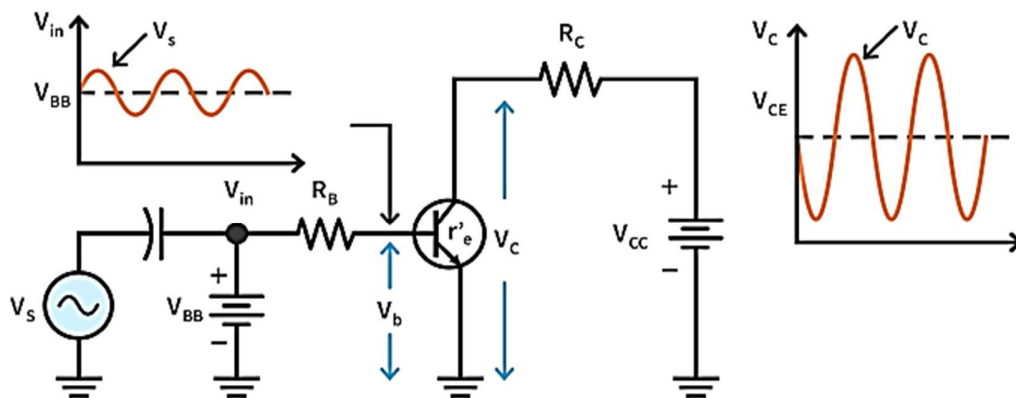


Figure II.12 Basic transistor amplifier circuit.

I_b , I_c and I_e are the AC transistor currents. V_b , V_c and V_e are AC voltages from the transistor terminals to the ground. The AC V_{in} produces an AC I_B , which results in a much larger AC I_C . The AC I_C produces an ac voltage across R_C , producing an amplified, but inverted, reproduction of the ac input voltage in the active region of operation. The forward-biased base-emitter junction presents a very low resistance to the ac signal. This internal AC emitter resistance (r'_e) appears in series with R_B . The AC base voltage is:

$$V_b = r'_e I_e$$

The AC collector voltage, V_c , equals the AC voltage drop across R_C :



$$V_C = I_C R_C$$

Since $I_c \approx I_e$, the AC collector voltage is:

$$V_C \approx I_e R_C$$

V_b can be considered the transistor AC input voltage where $V_b = V_S - I_b R_B$. V_C can be considered the transistor AC output voltage. Since *voltage gain* is defined as the ratio of the output voltage to the input voltage, the ratio of V_C to V_b is the AC voltage gain, A_v , of the transistor.

$$A_v = \frac{V_C}{V_b}$$

Substituting $I_e R_C$ for V_C and $I_e r'_e$ for V_b , so:

$$A_v \approx \frac{I_e R_C}{I_e r'_e} \cong \frac{R_C}{r'_e}$$

II.5. Transistor Switching Circuits

In this section, we look at switch circuits with transistors. These are the circuits where transistors are extremely popular to use. In fact, this is their most important application. The concept of transistors working as switches is studied in every part of the world in the field of electronics and communication. Thus, our clear concept in the topic of the operation of transistors as switches is another vital topic in the study of transistors. When a transistor is used as a switch, it is operated in the extreme region. The operating point is taken to be the extreme value of the characteristic curve of the transistor. In this condition, there are two states of operation. One state operates the switch, which is the ON state, and the other is the OFF state. The continuous operation of the transistor in alternate ON state and OFF state is useful in digital technology. The system consists of two states of transistor switched circuits known as logic circuits.

The logic circuits process binary numbers, and all modern digital computers are built with the combinational and sequential logic circuits, which consist of transistors as basic building blocks. Looking at the future of transistors as switches, the transistors have a low cost. They consume low current. They are simple to use and easily available in bulk on the market. In the switching operation, the on and off operation of the transistors is very quick. The transistor switches are widely used in control circuits, digital to analog and analog to digital integrated circuits, data storage purposes, data processing circuits, and in multiplexers, registers, counters, memory devices, and many more applications. Data multiplexing and demultiplexing operations can be completed just by attending to



the servo sequence period when the load devices are not connected. The logic gates' inputs A and B always have a greater digital voltage drop compared to the G terminal of the transistor. Similarly, the universal gates have resistance output capability.

In Figure II.13 (a), the transistor is in the cutoff region because the base-emitter junction is not forward-biased. There is, ideally, an *open* between collector and emitter. Whereas, concerning Figure II.13 (b), the transistor is in the saturation region because the base-emitter junction and the base-collector junction are forward-biased. I_B is made large enough to cause I_C to reach its saturation value. There is, ideally, a *short* between collector and emitter. A small voltage drop across the transistor of up to a few tenths of a volt normally occurs, which is the saturation voltage, $V_{CE(sat)}$.

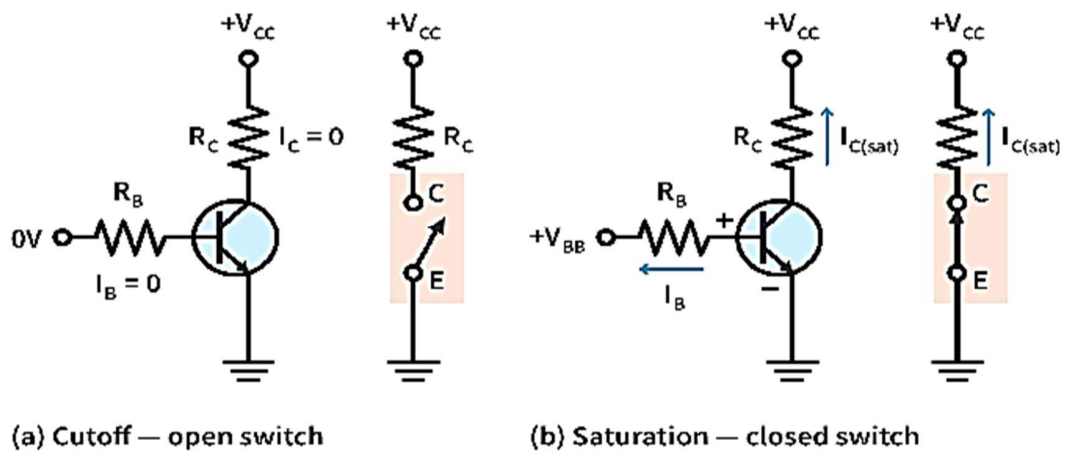


Figure II.13 Switching action of an ideal transistor.

When used as an AC signal amplifier, the transistors Base biasing voltage is applied in such a way that it always operates within its “active” region, that is the linear part of the output characteristics curves are used. However, both the NPN & PNP type bipolar transistors can be made to operate as “ON/OFF” type solid state switch by biasing the transistors Base terminal differently operating the transistor as a switch. Solid state switches are one of the main applications for the use of transistor to switch a DC output “ON” or “OFF”.

Some output devices, such as LED’s only require a few milliamps at logic level DC voltages and can therefore be driven directly by the output of a logic gate. However, high power devices such as motors, solenoids or lamps, often require more power than that supplied by an ordinary logic gate so transistor switches are used. If the circuit uses the Bipolar Transistor as a Switch, then the biasing of the transistor, either NPN or PNP is arranged to operate the transistor at both sides of the I-V characteristics curves we have seen previously (Figure II.14).



The areas of operation for a transistor switch are known as the Saturation Region and the Cut-off Region.

This means then that we can ignore the operating Q point biasing and voltage divider circuitry required for amplification, and use the transistor as a switch by driving it back and forth between its "fully-OFF" (cut-off) and "fully-ON" (saturation) regions as shown below.

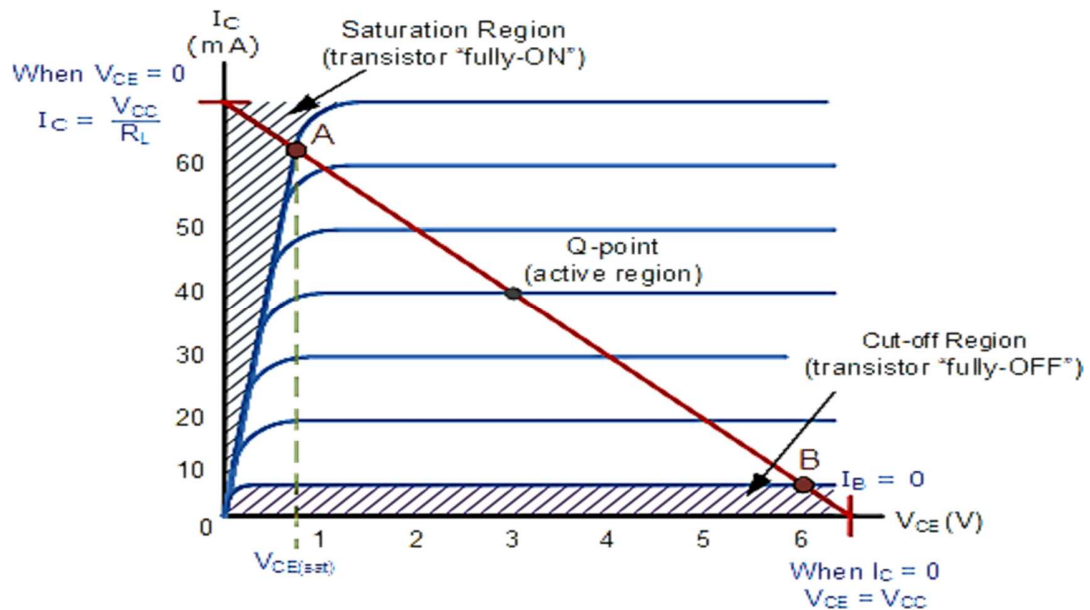


Figure II.14 The areas of operation for a transistor switch are known as the Saturation Region and the Cut-off Region.

➤ **Conditions in Cutoff :**

The base-emitter junction is not forward-biased. Neglecting leakage current, all of the currents are zero, and $V_{CE} = V_{CC}$, when:

$$V_{CE(\text{cutoff})} = V_{CC}$$

Here the operating conditions of the transistor are zero input base current (I_B), zero output collector current (I_C) and maximum collector voltage (V_{CE}) which results in a large depletion layer and no current flowing through the device. Therefore the transistor is switched "Fully-OFF".

➤ **Conditions in Saturation:**

The base-emitter junction is forward-biased and there is enough I_B to produce a maximum I_C . The collector saturation current is :

$$V_{C(\text{sat})} = \frac{V_{CC} - V_{CE(\text{sat})}}{R_C}$$



Since $V_{CE(sat)}$ is very small compared to V_{CC} , it can usually be neglected. The minimum value of I_B needed to produce saturation is :

$$I_{B(min)} = \frac{I_{C(sat)}}{\beta}$$

Normally, I_B should be significantly greater than $I_{B(min)}$ to ensure that the transistor is saturated.

II.6. Transistor Bias Circuit

The transistor in Figure II.15(a) is biased with V_{CC} and V_{BB} to obtain certain values of I_B , I_C , I_E , and V_{CE} . The collector characteristic curves for this transistor are shown in Figure II.15(b); which graphically illustrate the effects of DC bias. We assign three values to I_B and observe what happens to I_C and V_{CE} .

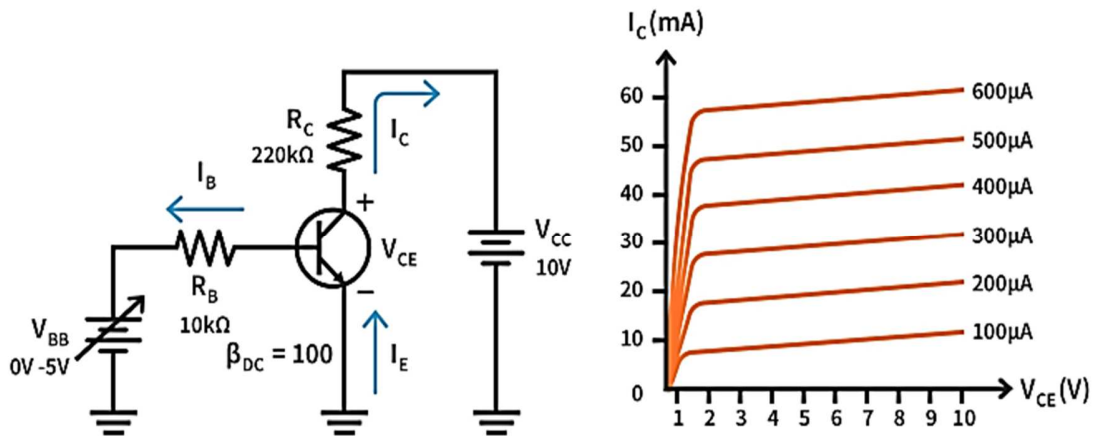


Figure II.15 The variable bias voltage and the collector characteristic curves.

First, V_{BB} is adjusted to produce an I_B of 200 A as shown in Figure II.16(a). Since $I_C = \beta I_B$, the collector current is 20 mA as indicated, when:

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

$$V_{CE} = 10 - (20)(220) = 5.6 \text{ V}$$

Next, as shown in Figure II.16(b), V_{BB} is increased to produce an I_B of 300 A and an I_C of 30 mA, as:

$$V_{CE} = 10 - (30)(220) = 3.4 \text{ V}$$



Finally, V_{BB} is increased to give an I_B of $400 \mu\text{A}$ and an I_C of 40 mA (Figure II.16(c)), while:

$$V_{CE} = 10 - (40)(220) = 1.2 \text{ V}$$

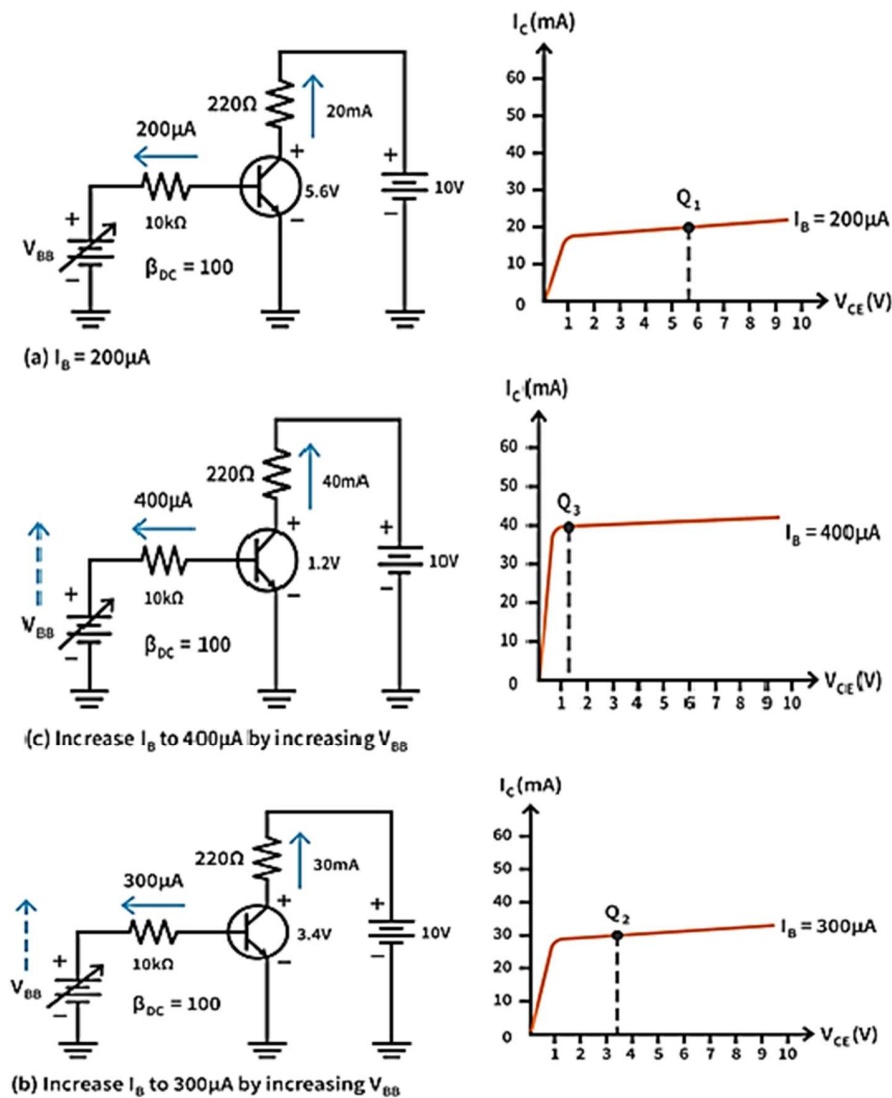


Figure II.16 Illustration of Q point adjustment of BJT transistor.

➤ Describes graphically the DC operation of a transistor circuit, a straight line drawn on the characteristic curves from the saturation value where $I_C = I_{C(sat)}$ on the y-axis to the cutoff value where $V_{CE} = V_{CC}$ on the x-axis, as shown in Figure II.17(a). The equation for I_C is:

$$I_C = \frac{V_{CC} - V_{CE}}{R_C} = -\left(\frac{1}{R_C}\right)V_{CE} + \frac{V_{CC}}{R_C}$$

This is the equation of a straight line with a slope of $-1/R_C$, an x intercept of $V_{CE} = V_{CC}$, and a y intercept of V_{CC}/R_C , which is $I_{C(sat)}$. The point at which the load line intersects a characteristic curve



represents the Q-point for that particular value of I_B . Figure II.17(b) illustrates the Q point on the load line for each value of I_B in Figure II.16.

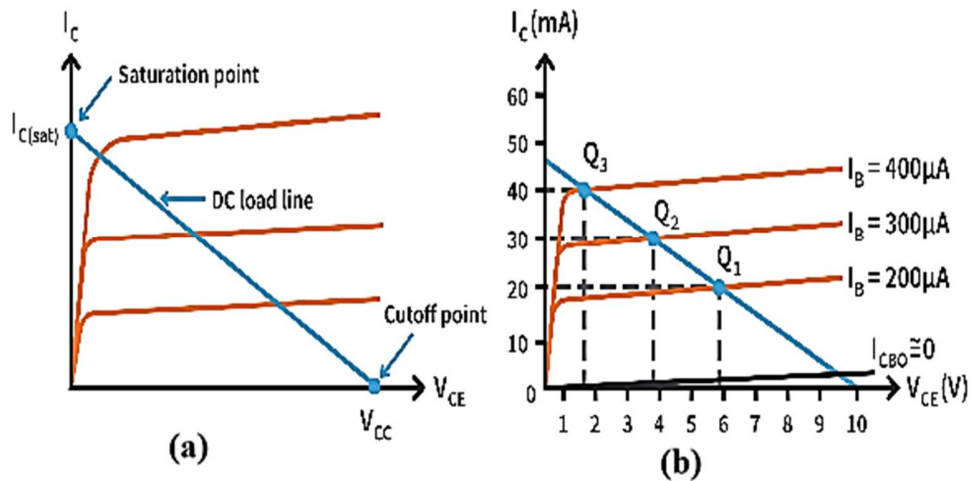


Figure II.17 The direct current load line.

II.6.1. Transistor with emitter bias

Emitter bias provides excellent bias stability in spite of changes in or temperature. It uses both a positive and a negative supply voltage. In an NPN circuit shown in Figure II.18, the small I_B causes V_B to be slightly below ground. V_E is one diode drop less than this.

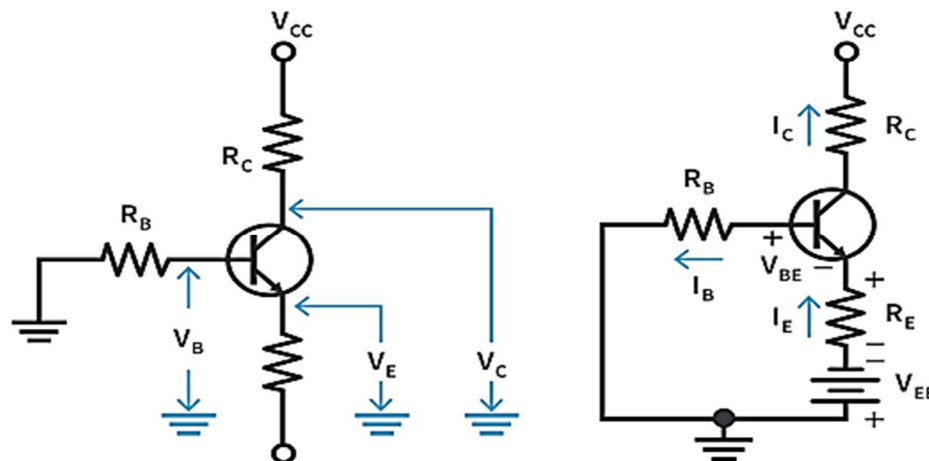


Figure II.18 NPN transistor with emitter bias.

The combination of the small drop across R_B and V_{BE} forces the emitter to be at approximately $I-V$. Using this approximation, I_E is given by:

$$I_E = \frac{-V_{CE} - 1}{R_E}$$

You can apply the approximation that $I_C \approx I_E$ to calculate V_C :



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

The approximation that $V_E \approx -IV$ is useful for troubleshooting to circumvent detailed calculations. Kirchhoff's voltage law can be applied to develop a more accurate formula for I_E for detailed analysis. Kirchhoff's voltage law applied around the base-emitter circuit in Figure II.18, which has been redrawn in part (b) for analysis, gives:

$$V_{EE} + V_{RB} + V_{BE} + V_{RE} = 0$$

Substituting $I_B \approx I_E / \beta$, we obtain :

$$\left(\frac{R_E}{\beta}\right)R_B + I_E R_E + V_{BE} = -V_{EE}$$

$$I_E = -\frac{V_{EE} - V_{BE}}{R_E + \frac{R_B}{\beta}}$$

• Voltages with respect to ground are indicated by a single subscript. V_E with respect to ground is:

$$V_E = V_{EE} + I_C R_C$$

• V_B with respect to ground is:

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

• V_C with respect to ground is:

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

II.6.2. Transistor with base bias

This method of biasing is common in switching circuits. The analysis of this circuit for the linear region shows that it is directly dependent on β (Figure II.19). Starting with Kirchhoff's voltage law around the base circuit, we obtain:

$$V_{CC} - V_{RB} - V_{BE} = 0$$

Substituting $I_B R_B$ for V_{RB} and solving for I_B , so:

$$I_B = \frac{V_{CC} - V_{BE}}{R_B}$$

Kirchhoff's voltage law applied around the collector circuit in Figure II.19 gives the equation: $V_{CC} - I_C R_C - V_{CE} = 0$. Solving for V_{CE} , where:

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



Substituting the expression for I_B into $I_C = \beta I_B$ yields, thus:

$$I_B = \beta \left(\frac{V_{CC} - V_{BE}}{R_B} \right)$$

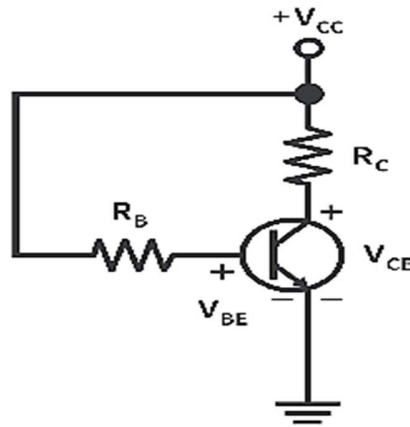


Figure II.19 NPN transistor with emitter bias.

II.7. Field Effect Transistor

Field-effect transistors (FETs) are current-operated, voltage-controlled devices, or voltage amplifiers. FETs are also characterized by being controlled by the electric field associated with the input terminal (gate for the MOSFETs and base for BJTs), as well as the shunt connection of the current carriers across two other terminals: source and drain in the FET and emitter and collector in the BJT. In contrast to the BJTs discussed earlier, the transconductance of the FETs is not primarily determined by the carriers' injection from the "source" to the "drain" or "collector." Rather, the field-effect transistors are operated based on the influence of the input terminal's electric field on the conductivity of the two shunt terminals situated closely to each other.

A three-terminal structure represented by the gate (G), source (S), and drain (D) is shown. The gate-source shunt connection enables the flow of the charge carriers through the gate dielectric into the thick-channel body that bridges the source and drain regions.

The Junction Field Effect Transistor, or JFET, is a voltage controlled three terminal unipolar semiconductor device available in N-channel and P-channel configurations. The field effect transistor is a three terminal device that is constructed with no PN-junctions within the main current carrying path between the Drain and the Source terminals.

These terminals correspond 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. As their name implies, Bipolar Transistors are “Bipolar” devices because they operate with both types of charge carriers, holes and electrons.

The Field Effect Transistor on the other hand is a “Unipolar” device that depends only on the conduction of electrons (N-channel) or holes (P-channel).

The Field Effect Transistor has one major advantage over its standard bipolar transistor cousins, in that their input impedance, (R_{in}) is very high, (thousands of Ohms), while the BJT is comparatively low. This very high input impedance makes them very sensitive to input voltage signals, but the price of this high sensitivity also means that they can be easily damaged by static electricity. There are two basic configurations of junction field effect transistor, the N-channel JFET and the P-channel JFET. The N-channel JFET’s channel is doped with donor impurities meaning that the flow of current through the channel is negative (hence the term N-channel) in the form of electrons.

II.7.1. Symbols of FETs

The symbols and basic construction for both configurations of JFETs are shown in Figure II.20. The semiconductor “channel” of the Junction Field Effect Transistor is a resistive path through which a voltage V_{DS} causes a current I_D to flow and as such the junction field effect transistor can conduct current equally well in either direction.

As the channel is resistive in nature, a voltage gradient is thus formed down the length of the channel with this voltage becoming less positive as we go from the Drain terminal to the Source terminal.

The result is that the PN-junction therefore has a high reverse bias at the Drain terminal and a lower reverse bias at the Source terminal.

This bias causes a “depletion layer” to be formed within the channel and whose width increases with the bias.

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 a reverse-biased. In an N-channel JFET this Gate voltage is negative while for a P-channel JFET the Gate voltage is positive.

The main difference between the JFET and a BJT device is that when the JFET junction is reverse-biased the Gate current is practically zero, whereas the Base current of the BJT is always some value greater than zero.

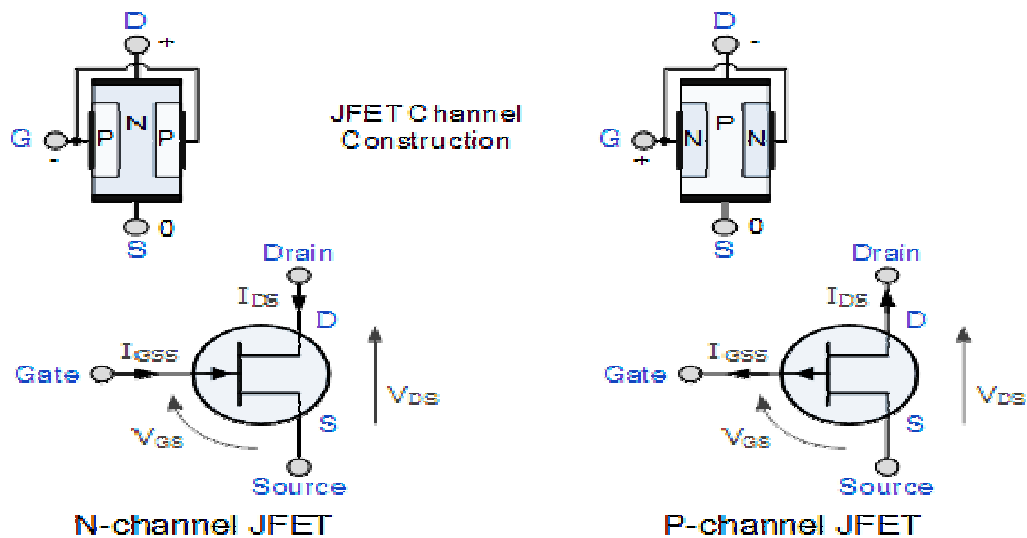


Figure II.20 Symbol of the Junction Field Effect Transistor.

II.7.2. Biasing of an N-channel Junction Field Effect Transistor

Figure II.21 shows an N-type semiconductor channel with a P-type region called the Gate diffused into the N-type channel forming a reverse biased PN-junction and it is this junction which forms the *depletion region* around the Gate area when no external voltages are applied. JFETs are therefore known as depletion mode devices. This depletion region produces a potential gradient which is of varying thickness around the PN-junction and restrict the current flow through the channel by reducing its effective width and thus increasing the overall resistance of the channel itself. Then we can see that the most-depleted portion of the depletion region is in between the Gate and the Drain, while the least-depleted area is between the Gate and the Source. Then the JFET's channel conducts with zero bias voltage applied (the depletion region has near zero width).

With no external Gate voltage ($V_G = 0$), and a small voltage (V_{DS}) applied between the Drain and the Source, maximum saturation current (I_{DSS}) will flow through the channel from the Drain to the Source restricted only by the small depletion region around the junctions. If a small negative voltage ($-V_{GS}$) is now applied to the Gate the size of the depletion region begins to increase reducing the overall effective area of the channel and thus reducing the current flowing through it, a sort of "squeezing" effect takes place.

So by applying a reverse bias voltage increases the width of the depletion region which in turn reduces the conduction of the channel. Since the PN-junction is reverse biased, little current will flow into the gate connection. 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 voltage at which the channel closes is called the "pinch-off voltage", (V_P).

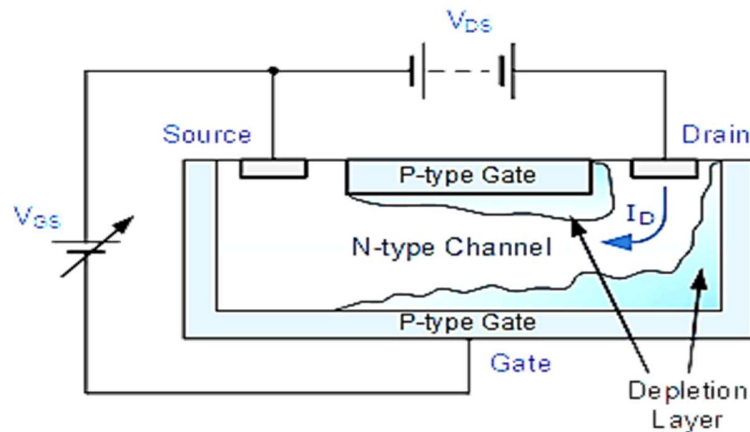


Figure II.21 Bias connection for n-channel JFET.

II.7.3. FET Characteristics and Parameters

Figure II.22 shows the drain current characteristics of a JFET for gate-to-source voltage equal to 0V. i.e. $V_{GS} = 0$. Between point A and B, it is the ohmic region of the JFET. It is the region where the voltage and current relationship follows ohm's law. At point B, the drain current is at maximum for $V_{GS} = 0$ condition and is defined as I_{DSS} . It is the pinch-off point, where there is no increase of current as drain-to-source voltage V_{DS} is further increased. The V_{DS} voltage at this point is called **pinch-off voltage** V_P . It is also the voltage point where drain-to-gate voltage V_{DG} produces enough depletion thickness to narrow the channel so that the resistance of the channel will increase significantly. Since $V_{GS} = 0$, V_{DS} is also equal to V_{DG} . Thus, in general the pinch-off voltage V_P is :

$$V_P = V_{DS(P)} - V_{GS}$$

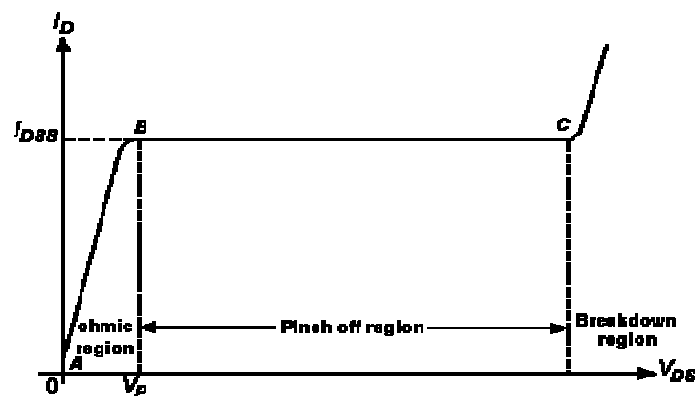


Figure II.22 JFET drain characteristics curve for $V_{GS} = 0V$.



Where $V_{DS(P)}$ is the pinch-off drain-to-source voltage for a V_{GS} value. I_{DSS} and V_P are constant values listed by the manufacturer for a given JFET type, which are the drain current and pinch-off voltage at gate-to-source voltage $V_{GS} = 0V$. At point C, the JFET begins to breakdown where the I_D increases rapidly and it is an irreversible breakdown. Different value of V_{GS} produces different drain characteristic curve. For n channel JFET, as V_{GS} decreases, I_D current and $V_{DS(P)}$ decreases (Figure II.23). There is a V_{GS} value that no drain current I_D is registered irrespective of the drain-source voltage V_{DS} . This gate-to-source voltage V_{GS} is the cutoff gate-to-source voltage $V_{GS(off)}$. Since there is no I_D current, V_{DS} must be zero. Thus $V_{GS} = -V_P$. We can also now be written as $V_{DS(P)} = V_{GS} - V_{GS(off)}$.

In the drain ohmic region, the characteristic curve for the N-channel type follows the following equation:

$$I_D = AqN_D\mu_n E_x = 2bqN_D\mu_n \left(\frac{W}{L}\right) V_{DS}$$

Where A is the effective cross sectional area of the channel for a given V_{GS} voltage and b is the effective channel width for a given gate-to-source voltage and zero drain current. At gate-to-source voltage equals to zero volt. $V_{GS} = 0$ volt, the effective channel width b is equal to h . Thus, the *channel on-resistance* is defined as:

$$r_{DS(on)} = \frac{1}{2hqN_D\mu_n} \cdot \frac{L}{W}$$

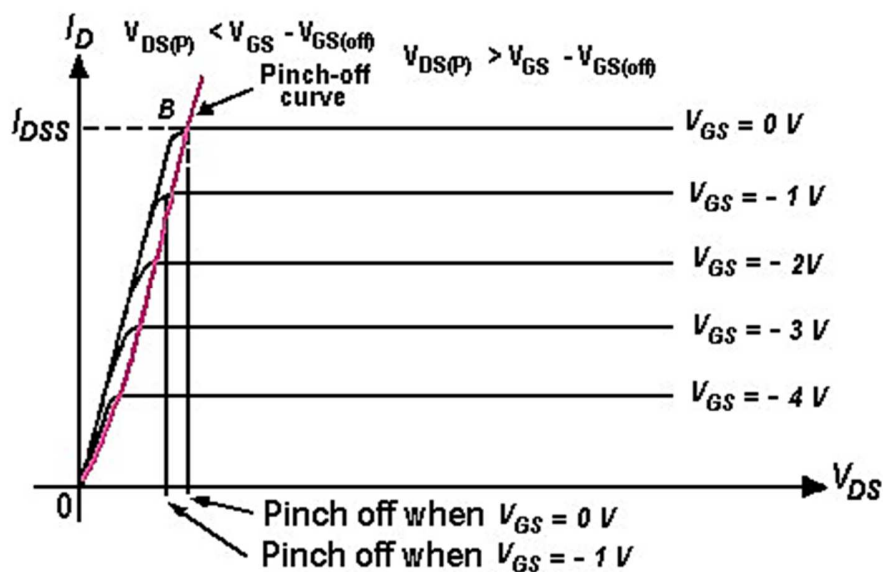


Figure II.22 Drain characteristics of n -channel JFET of different V_{GS} .



The pinch-off curve follows equation, which is:

$$I_D = I_{DSS} \left[1 - \frac{V_{GS}}{V_P} \right]^2$$

For obtaining cut-off condition whereby the drain current I_D is equal to zero (Figure II.23).

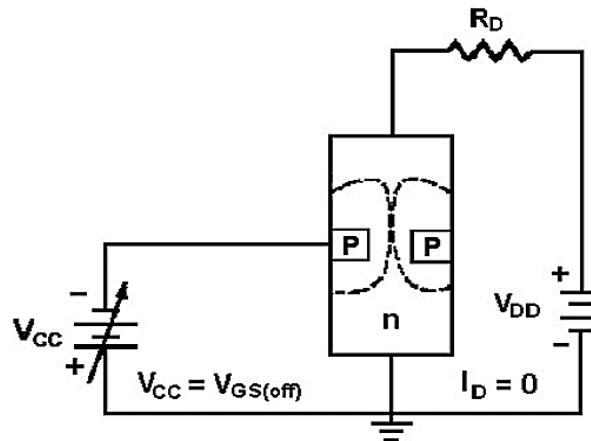
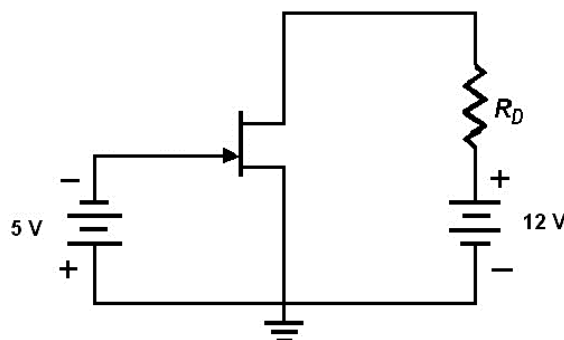


Figure II.23 Condition for cutoff of an n-channel JFET.

➤ **Example :** For the JFET circuit shown in the figure, $V_P = 8.0V$ and $I_{DSS} = 12.0mA$. (a) Determine the value of V_{DS} when pinch-off begins. (b) If the gate is grounded, what is the value of I_D for $V_{DD} = 12.0V$ when V_{DS} is above pinch-off?



➤ **Solution :** From the circuit, $V_{GS} = -5V$ and apply equation $V_{DS(P)} = V_{GS} - V_{GS(off)}$,

$$V_{DS(P)} = V_P + V_{GS} = 8V + (-5V) = 3V$$

The V_{DS} voltage when pinch-off occurred is 3.0 V. When the gate is grounded, $V_{GS} = 0V$, the drain current I_D is equal to $I_{DSS} = 12$ mA. For any value of drain-to-source voltage V_{DS} above pinch-off voltage of 8V, the drain current I_D remains as $I_{DSS} = 12.0$ mA. This is true as long as the drain-to-source voltage V_{DS} is below breakdown voltage.



II.7.4. Characteristic I-V curves of junction FET

The voltage V_{GS} applied to the Gate controls the current flowing between the Drain and the Source terminals. V_{GS} refers to the voltage applied between the Gate and the Source while V_{DS} refers to the voltage applied between the Drain and the Source (Figure II.24(a)). Because a Junction Field Effect Transistor is a voltage controlled device, “NO current flows into the gate!” then the Source current (I_S) flowing out of the device equals the Drain current flowing into it and therefore ($I_D = I_S$). The characteristics curves example shown in Figure II.24(b), shows the four different regions of operation for a JFET and these are given as:

- Ohmic Region ; When $V_{GS} = 0$ the depletion layer of the channel is very small and the JFET acts like a voltage controlled resistor.
- Cut-off Region : This is also known as the pinch-off region were the Gate voltage, V_{GS} is sufficient to cause the JFET to act as an open circuit as the channel resistance is at maximum.
- Saturation or Active Region :The JFET becomes a good conductor and is controlled by the Gate-Source voltage, (V_{GS}) while the Drain-Source voltage, (V_{DS}) has little or no effect.
- Breakdown Region : The voltage between the Drain and the Source, (V_{DS}) is high enough to causes the JFET’s resistive channel to break down and pass uncontrolled maximum current.

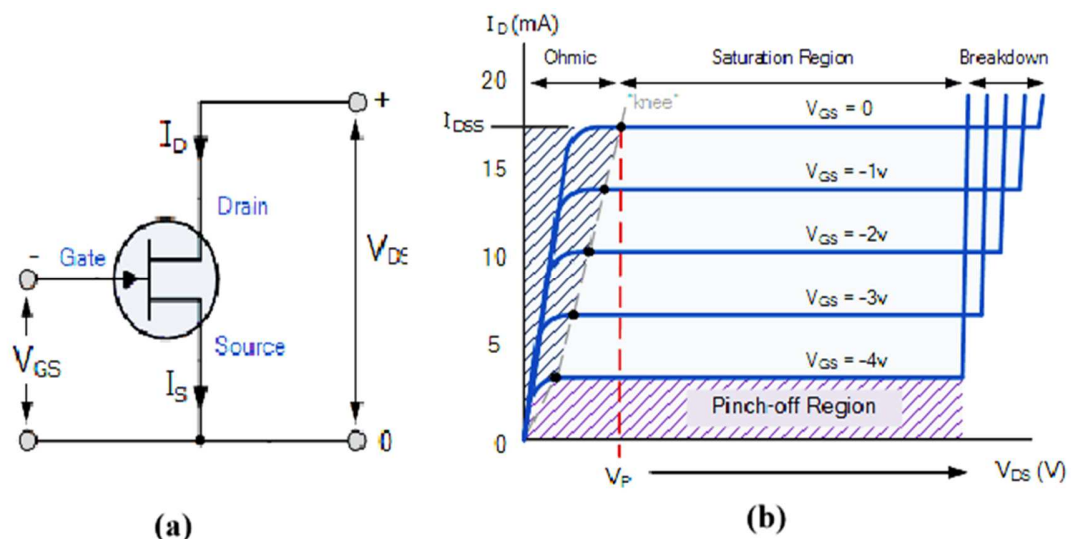


Figure II.24 (a) Symbol of Field Effect Transistor and (b) Characteristic I-V curves.

The transfer characteristic of an n -channel JFET is shown in Figure II.25. At gate to-source voltage $V_{GS} = 0$, the drain current I_D is equal to I_{DSS} and at gate-to source voltage $V_{GS(off)}$, drain current $I_D = 0$.

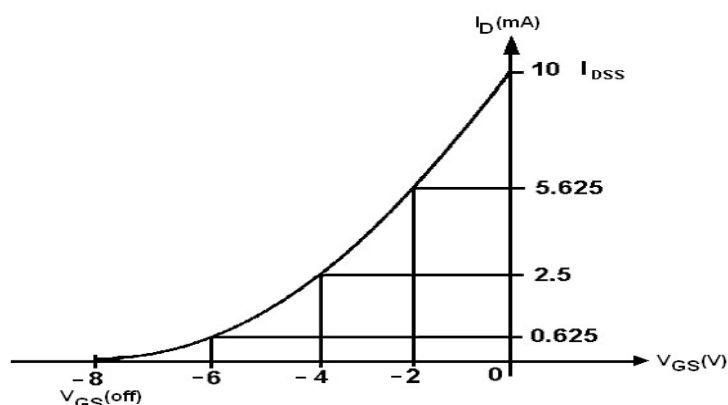


Figure II.25 Transfer characteristics curve of an *n*-channel JFET.

The curve is a parabolic curve, which can be expressed mathematically as :

$$I_D = I_{DSS} \left[1 - \frac{V_{GS}}{V_P} \right]^2$$

The Drain current is zero when $V_{GS} = V_P$. For normal operation, V_{GS} is biased to be somewhere between V_P and 0. Then we can calculate the Drain current, I_D for any given bias point in the saturation or active region. The characteristics curves for a P-channel junction field effect transistor are the same as those above, except that the Drain current I_D decreases with an increasing positive Gate-Source voltage, V_{GS} . Note that the value of the Drain current will be between zero (pinch-off) and I_{DSS} (maximum current).

II.7.5. Forward Transconductance

The forward transconductance g_m of the JFET is defined as the change of drain current for a given change in gate-source voltage V_{GS} and it is expressed as :

$$g_m = \frac{\Delta I_D}{\Delta V_{GS}}$$

From the transfer characteristic curve, one will realize that the transconductance of the device is at maximum when V_{GS} is at zero voltage. The value of g_m at $V_{GS} = 0$ is always given in the manufacturer data sheet of the device, which is denoted as g_{m0} . If g_{m0} is given, g_m for a given V_{GS} can be calculated from equation :

$$g_m = g_{m0} \left[1 - \frac{V_{GS}}{V_{GS(off)}} \right]$$

By differentiating drain current with respect to gate-to-source voltage dI_D/dV_{GS} ,



$$g_m = \frac{dI_D}{dV_{GS}} = -\frac{2I_{DSS}}{V_{GS(Off)}} \left[1 - \frac{V_{GS}}{V_{GS(off)}} \right]$$

Thus, given the values of I_{DSS} and $V_{GS(off)}$, the transconductance of the device at $V_{GS} = 0$ can be expressed as :

$$g_m = g_{m0} \sqrt{I_D / I_{DSS}}$$

Thus, the transconductance g_m of JFET for a given drain current I_D value, can be obtained. Since the gate of JFET is reverse-biased, the input impedance is very high. This is one advantage of JFET over bipolar junction transistor. In JFET data sheet, the input impedance is given by gate reverse current I_{GSS} for a given gate-source voltage V_{GS} . Thus, input impedance can be expressed as:

$$R_{DS} = \frac{\Delta V_{DS}}{\Delta I_D} = \frac{1}{g_m}$$

By knowing the Drain current I_D and the Drain-Source voltage V_{DS} the resistance of the channel (R_{DS}) is given as:

II.7.6. Modes of FET

Like the bipolar junction transistor, the field effect transistor being a three terminal device is capable of three distinct modes of operation and can therefore be connected within a circuit in one of the following configurations.

➤ **Common Source (CS) Configuration:** In the Common Source configuration (similar to common emitter), the input is applied to the Gate and its output is taken from the Drain as shown (Figure II.26 (a)). This is the most common mode of operation of the FET due to its high input impedance and good voltage amplification and as such Common Source amplifiers are widely used. The common source mode of FET connection is generally used audio frequency amplifiers and in high input impedance pre-amps and stages. Being an amplifying circuit, the output signal is 180° “out-of-phase” with the input.

➤ **Common Gate (CG) Configuration:** In the Common Gate configuration (similar to common base), the input is applied to the Source and its output is taken from the Drain with the Gate connected directly to ground (0 v) as shown (Figure II.26 (b)). The high input impedance feature of the previous connection is lost in this configuration as the common gate has a low input impedance, but a high output impedance. This type of FET configuration can be used in high frequency circuits or in impedance



matching circuits where a low input impedance needs to be matched to a high output impedance. The output is “in-phase” with the input.

➤ **Common Drain (CD) Configuration:** In the Common Drain configuration (similar to common collector), the input is applied to the Gate and its output is taken from the Source (Figure II.26 (c)). The common drain or “source follower” configuration has a high input impedance and a low output impedance and near-unity voltage gain so is therefore used in buffer amplifiers. The voltage gain of the source follower configuration is less than unity, and the output signal is “in-phase”, 0° with the input signal. This type of configuration is referred to as “Common Drain” because there is no signal available at the drain connection, the voltage present, $+V_{DD}$ just provides a bias. The output is in-phase with the input.

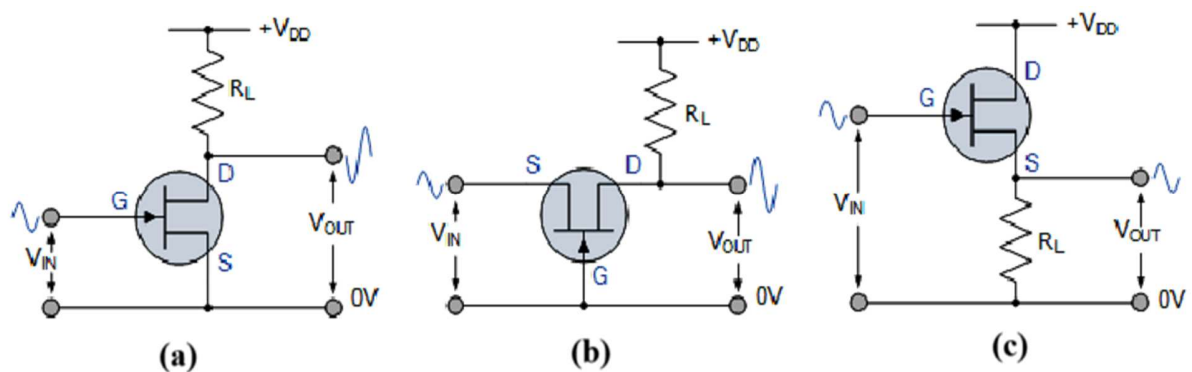


Figure II.26 (a) Common Source, (b) Common Gate and (c) Common Drain configuration.

II.8. Transistor in Dynamic Regime

In a transistor amplifier, the DC sources establish currents and DC voltages. The AC source produces fluctuations in the transistor currents and voltages. To analyze more simply the action of transistor circuits, the analysis is divided into two parts: an analysis for the continuous quantities and the other for the alternative sizes. In other words, transistor circuits can be analyzed by applying the superposition theorem of electrical states. Instead of taking one source at a time, we take all the DC sources at the same time and find the DC currents and voltages using the usual methods in the section on the polarization of bipolar transistors. We then take all the AC sources at the same time and calculate the AC currents and voltages. By adding these DC and AC currents and voltages, we obtain the total currents and voltages.



II.8.1. Coupling and decoupling capacitors

We remind that a transistor assembly includes a direct current circuit and an alternating current circuit. Thanks to the capacitors, we will be able to superimpose the alternating current circuit on the bias circuit without the latter, this modifies direct currents and voltages.

a) Coupling capacitors

A coupling capacitor transmits an alternating signal from one point that is not grounded to another point that is also not grounded. In the circuit of Figure II.26, the voltage alternative point A appears in B provided that the impedance Z_C of the capacitor is low compared to those of the resistors. On the other hand, the direct current will not be able to pass from A in B.

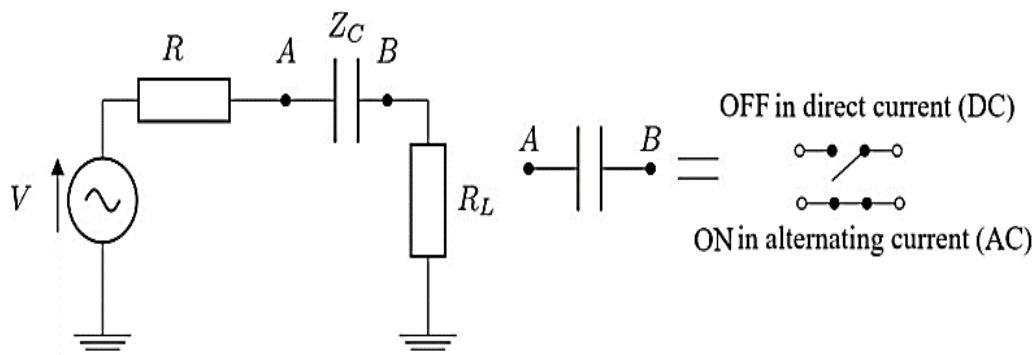


Figure II.26 Coupling capacitor.

Impedance Z_C is : $Z_C = 1 / C \times 2\pi \times f$

where f is the frequency of the superimposed AC signal. So Z_C will be all the greater as f will be small. To have a low coupling capacitor impedance compared to the ohmic resistances of the circuit, we can use the following approximation:

$$RC = \frac{1}{f} \Rightarrow \frac{1}{10} = 10 \cdot 10^3 \cdot C \Rightarrow C = 10 \mu F$$

Or f is the lowest frequency of use and R the resistance of the mesh in series with the capacitance. This is the minimum value of the capacity to be employed. By its action, such a capacity allows to transfer an alternating signal of a transistor stage to another without disturbing the DC bias of each stage.

b) Decoupling capacitors

A decoupling capacitor is similar to a coupling capacitor that is coupled to ground (creation of a virtual mass). These capabilities introduce the concept of ground in AC. On the circuit from figure II.27, the point A is shorted to ground in AC. The direct current in A will not be disturbed since the



capacitance does not allow the direct current to pass. To determine the value of the capacitor, we use the approximation of the previous paragraph.

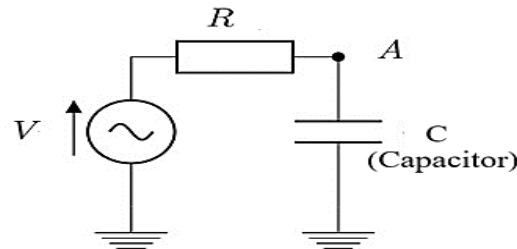


Figure II.27 Decoupling capacitor.

II.8.2. Equivalent circuits in direct and alternating currents

Here's how to apply superposition to transistor circuits.

(i) Reduce all AC sources to zero; open all capacitors. The remaining circuit is all we are interested in for currents and continuous tensions. We call it the equivalent circuit in direct current. From this circuit, we calculate the direct currents and voltages that interest us. Reduce all DC sources to zero. Short-circuit all coupling and decoupling capacitors. The remaining circuit is all that interests us for AC currents and voltages. This is called circuit the equivalent circuit in alternating current. It is the circuit to use for calculating alternating currents and voltages. The total current in each branch is equal to the sum of the direct current and the alternating current in that branch. Similarly, the total voltage between the terminals of a any branch is equal to the sum of the direct voltage and the alternating voltage between the terminals of this branch.

Here is how to apply the superposition theorem to the amplifier at circuit transistor from Figure II.28.

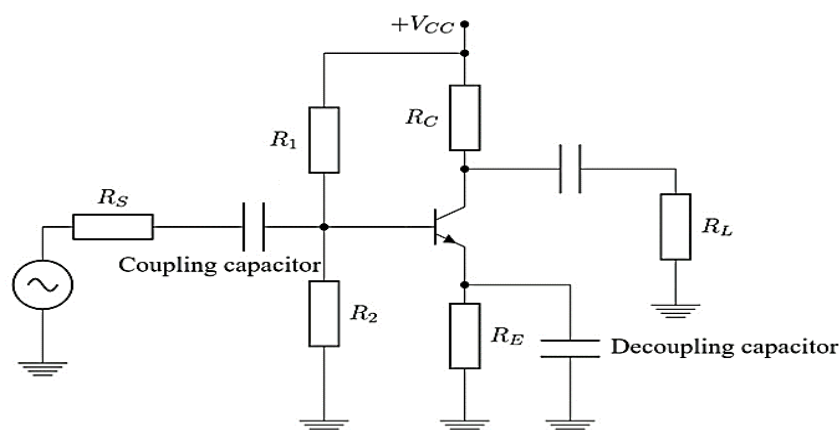


Figure II.28 Transistor-based amplifier circuit.



All first, cancel all sources alternatives and open all the capacitors. Then only the circuit remains Figure II.29 which is the equivalent circuit in direct current. This is whatever interests us because with this circuit, we can calculate any direct current and any direct voltage that interests us.

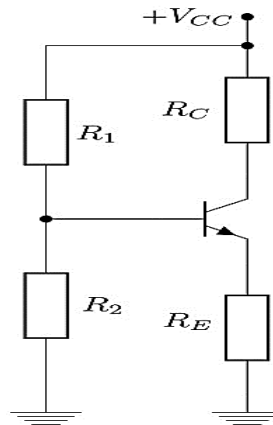


Figure II.29 Direct current equivalent circuit.

Next, cancel all DC sources and short-circuit all coupling and decoupling capacitors. Then only the AC equivalent circuit remains (Figure II.30). Reducing a voltage source to zero is equivalent to the short-circuit. That's why R_1 and R_C are shorted to ground in alternating current through source V_{CC} . The decoupling capacitor puts the emitter of the circuit of Figure II.30 current and alternating voltage that we will need.

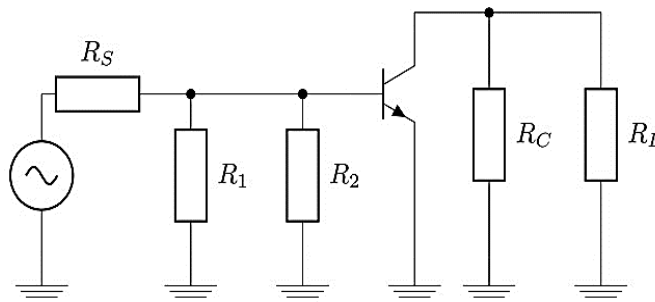


Figure II.30 Equivalent circuit in alternating current.

II.8.3. Dynamic model of the transistor

Equivalent model of a transistor in alternating mode or dynamic is introduced which is simple to use. The equation of the real characteristics is generally complicated and we do an approximation, which consists of replacing the curves of the real characteristics by pieces of straight lines. In the vicinity of the polarization point, the characteristics are replaced by their tangents at this point. This approximation is called small signal.



$$\begin{pmatrix} V_1 \\ I_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix} \cdot \begin{pmatrix} I_1 \\ V_2 \end{pmatrix}$$

The quadropole shown in Figure II.31(a) can then be replaced by the following linear elements presented in figure II.31(b):

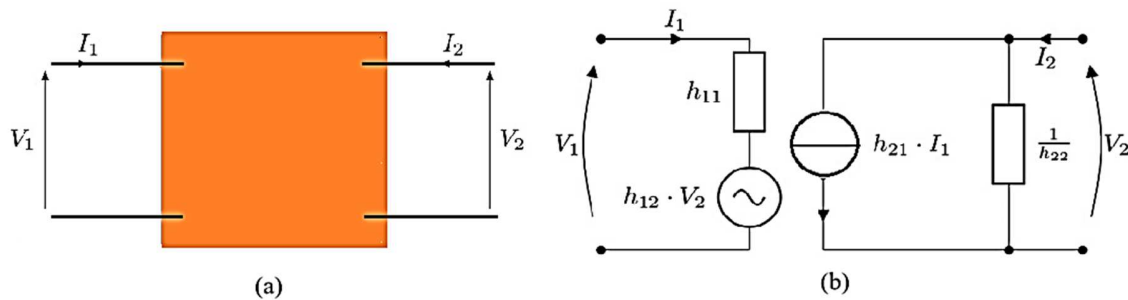


Figure II.31 (a) Quadropole and (b) Equivalent diagram of a linear quadropole .

The common emitter transistor can be considered as a quadropole as shown in Figure II.32.

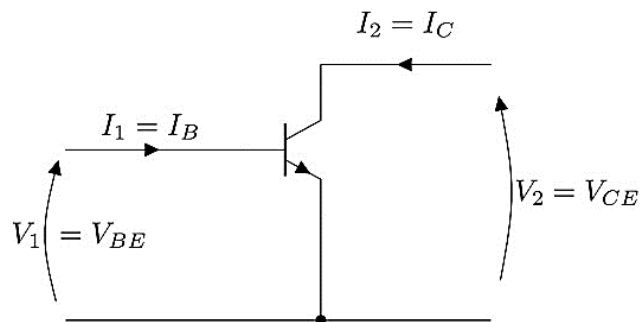


Figure II.32 Common emitter quadropole.

If we use the quadropole theory, we have:

$$V_{BE} = f_1(I_B, V_{CE})$$

$$I_C = f_2(I_B, V_{CE})$$

We have seen that currents and voltages are composed of a continuous quantity and a dynamic quantity (alternative):

$$V_{CE} = \underbrace{V_{CE0}}_{\text{tension continue}} + \underbrace{v_{ce}}_{\text{tension alternative}}$$

If we apply the hypothesis small signals, by their limited development to the 1st order, assuming that these functions are differentiable and we know that :



$$I_B = I_0 e^{\frac{4v_{BE}}{kT}}$$

Because the base and emitter form forward biased diode, one finds that:

$$h_{11} = \frac{kT}{qI_B} \approx \frac{25mV}{I_B}$$

Because, at 25°C, kT/q is almost equal to 25mV. On the other hand $h_{12} = 0$, we know that $I_C = \beta \cdot I_{B0}$, therefore: $h_{21} = \beta$.

On the other hand, complex calculations will give:

$$\frac{\partial f_2}{\partial V_{CE}}(I_{B0}, V_{CE0}) = h_{22}$$

$\frac{1}{h_{22}}$ is still noted ρ $\frac{1}{h_{22}}$ is homogeneous to a resistance. This resistance is generally very high value (0.1 MΩ) and therefore, placed in parallel with another resistance, it will be negligible in front of the latter. By replacing the hybrid parameters with their values in Figure II.31(b), we obtain a simple equivalent diagram of the transistor in dynamic mode, as shown in Figure II.33.

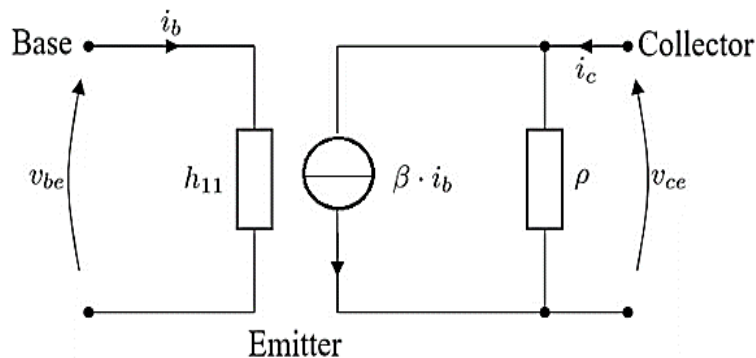


Figure II.33 Dynamic transistor model for small signals.

II.8.4. Physical interpretation

The polarization point being at Q on the basic characteristic of Figure II.34 (a), we apply a small variation in base-emitter voltage. The operating point moves from Q to A, then from A to Q, then to B and back to Q. This movement is repeated in the next cycle. Since A and B are close to Q, only a small arc of the diode characteristic is described. If we use only a small part of a curve, the operation is approximately linear, meaning that the arc between A and B are related to a straight line. Therefore, the variations in voltage and current are directly proportional to each other. We will therefore have:



$$\Delta V_{BE} = K \cdot \Delta I_B \Rightarrow h_{11} = \left(\frac{\Delta V_{BE}}{\Delta I_B} \right)_{V_{CE} \text{ constante}}$$

where Δ is variation) and K is the constant of proportionality which is equal to:

$$K = \frac{kT}{qI_{B0}} = \frac{25mV}{I_{B0}}$$

It therefore appears that K is homogeneous to a resistance. This resistance models the base emitter diode in small signals, it is noted r_e or h_{11} . For the polarization point Q in the collector characteristic, indicated in Figure 2.17, we will proceed in the same way as before. If we apply a small voltage variation ΔV_{CE} , the operating point moves from A to B . Since we use a small part of the curve, the operation is approximately linear. We can notice that, this approximation is better than the previous one because the shape of the curve is almost linear. We have:

$$\Delta V_{CE} = \rho \cdot \Delta I_C$$

With ρ homogeneous to a high value resistance ($10^5 \Omega$). We can therefore give an equivalent diagram of the transistor which is illustrated in Figure II.34 (b).

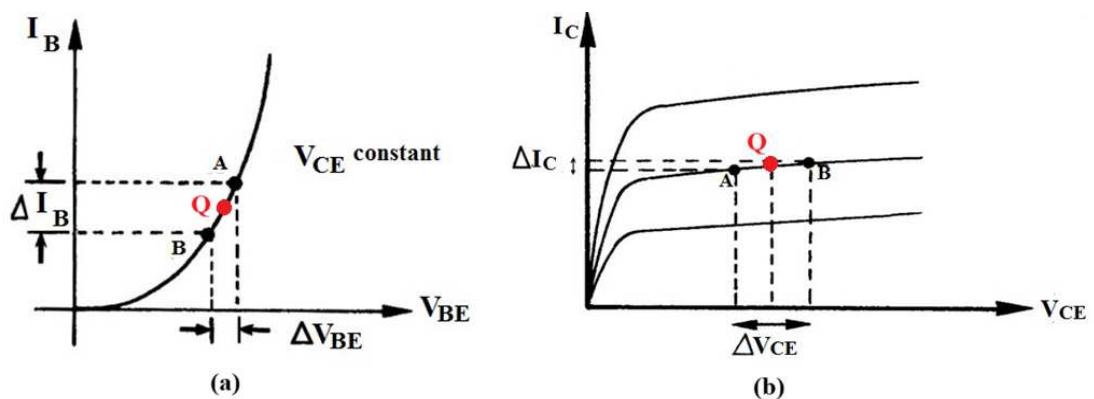


Figure II.34 (a) Graphic meaning of h_{11} and (b) Graphical meaning of β .

II.9. Applications of Transistors

The variety of fields that apply the abilities of transistors reveals the diverse features of this component. While the earliest applications were in computers and we first explored using them in computer memories, real-world applications quickly broadened. A relatively complete list would include: Audio High-fidelity audio amplifiers use them for low distortion and high gain. For example, power transistors are used in the output stages of high-quality audio amplifiers. CD recording can be controlled to keep distortion down. Digital First as switches in some digital logic circuits in applications such as desktop publishing for laser printers, then in all digital circuits, and then alone, completely



replacing all other switching devices in digital circuits. RF Of course, the first use in digital logic circuits meant that these circuits could be used to modulate and demodulate radio frequency carriers. Quite recently, simple short-range radios have been built solely with a digital printer I/O board that connects the radio inside their printers. Power Control Of course, power transistors are used in the circuitry that makes the rolling of heating wax random. They are a major component of the power control circuit that addresses these problems. A dynamic arc compensator that utilizes thyristors has a more direct relevance to this chapter. Lasers have made the production of short-run bestsellers a viable business option. Given the importance of controlling heating in digital printers, it is not surprising that the greatest use of power transistors is helping to control laser output. Power transistors are used in comparison for solid-state lasers. Transistors, including power transistors, are used in the amplifiers of the pulse forming network in class free-electron lasers.

II.9.1. Audio Amplification

A very important task that transistors, particularly bipolar transistors, perform is that of amplifying audio signals before they finally reach the loudspeaker that converts them into sound (Figure II.35). Without amplification, the signal emerging from the receiver stage is far too small to drive the speaker without drowning in hiss and noise. The nature of the operation of bipolar and FET transistors offers itself to the convenient amplification of such weak signals. We need to know, then, the limitations that are imposed on our use of transistors from a consideration of their properties in relation to their application as audio amplifiers.

From the beginning of electronic audio amplification in the late 1920, it was recognized that some bias voltage had to be applied to the inherent diode of the triode tube in order to drive it deep into the linear region of its transconductance characteristic in order to achieve an efficient amplifier. Various configurations of the two-transistor amplifier have been devised in order to get the most from the benefits of applying bias voltages to the transistors.

These amplifiers are found in all professional and consumer electronics stereo systems and commercial amplifiers bridging the full frequency range from 20 Hz to 20 kHz. The newer design trend in audio today is fitting stereo systems and amplifiers with a host of digital audio signal processing, such as surround sound, echo, reverb, psycho-acoustic effects, room ambiance, and dynamic range control, but they all still rely on a transistor sound amplification stage to reproduce sound at the required level of quality. The challenging task in transistor audio today is to reduce the THD from the current 0.5% or so to 0.05%, where the traditional two-transistor cyclic amplification sequence will find a formidable challenge.

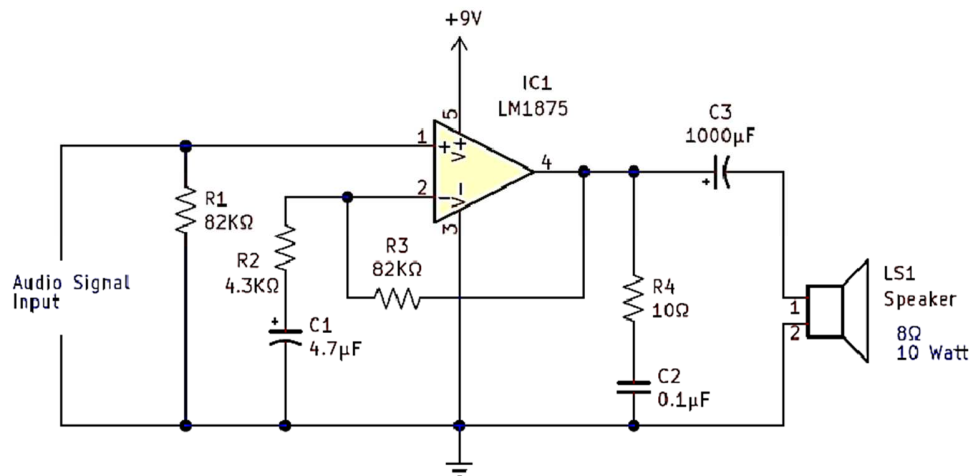


Figure II.35 Audio Amplification circuit.

II.9.2. Digital Logic Circuits

Transistors form the basis of the digital logic circuits that are the foundation of modern computing. They are useful in digital circuits because their two stable states allow them to readily implement binary logic. For example, two transistors can be arranged in such a way that a voltage may be present at the output of a circuit if and only if both transistors are in the on state. Such an arrangement is called a logic AND gate, and two others are called OR gates and NOT gates (Figure II.36). Such transistors with a full "complement" of digital logic gates enable the implementation of digital systems, including digital flip-flops that can maintain a state of a digital signal. In addition, when two logical inverters are connected in a loop, while in the most common technology, CMOS, the gate dissipates very little power when in its stable state, further enabling the realization of large digital systems capable of performing complex tasks. There is therefore a "chain of logic" that links the physics of transistor devices to our modern digital devices. Digital computers, calculators, and a large variety of other digital electronic devices are typically designed and constructed out of the digital logic circuits described above. Among the most important features of transistors for such applications are their high reliability, speed, and low cost. As a result, the integration of digital transistors into larger systems has been the main driving force as they have been "scaled" into modern CMOS technology. The ability to maintain the high performance of the digital devices as more transistors are incorporated into the chip without significant "collateral" effects is a key question that determines the likely evolution of future digital logic. In particular, digital transistors are of great practical interest to the extent that they are able to operate correctly and independently of the "activity" of the millions of other transistors within which they are situated. Finally, while the digital devices of "classical" logic gates are usually utilized one at



a time, the emerging quantum digital devices transistors are being combined into huge arrays in hopes of performing many tasks simultaneously.

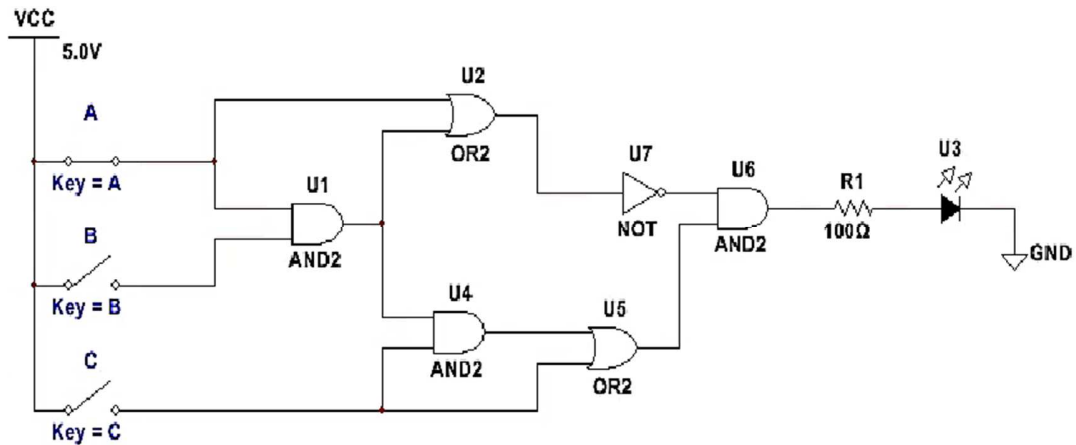


Figure II.36 Digital Logic Circuits.

II.9.3. Radio Frequency (RF) Circuits

In wireless communication systems, the process of transferring baseband signals onto RF carriers, modulation, and low-noise amplification hierarchically consume a significant amount of RF energy. Generally, transistors can operate at RF frequencies above a few MHz, which makes them favourable devices for designing signal modulators and RF low-noise amplifiers. In wireless communication systems, a signal modulator (transmitter) and an RF low-noise amplifier circuit are mandatory modules in order to rectify and, in turn, demodulate the transmitted data from an RF signal. It is practically possible by using a transistor since it has the ability to change a comparatively low input baseband signal to an efficient RF modulated signal using efficient modulation techniques. In a transmitter, the transistor first operates as a variable resistor, effectively changing the impedance of the RF/antenna port using the transmitted baseband signal. As a result, the device will be either modulating amplitude or modulating frequency of the signals in addition to varying its phase. Possessing different characteristic parameters, the ideal performance of a transistor will also vary with frequency/wavelength. Parasitic capacitors and an inductor will become ineffective or fail to operate in ideal situations. Real parts of transistors, such as transconductance, gain, and input/output resistance, tend to change with frequency. The interest of researchers mainly lies in the characterization of transistors either in their full data-scattering parameters or small signal measurements. A primary transistor characteristic in RF design indicates the ability of a transistor to amplify the signals. Moreover, the transconductance gain of a transistor directly reveals the strength of amplification in a



transistor. For a power amplifier (an element in an RF system that boosts the power level of the RF signal), a transistor with a high gain value is of prime interest (Figure II.37).

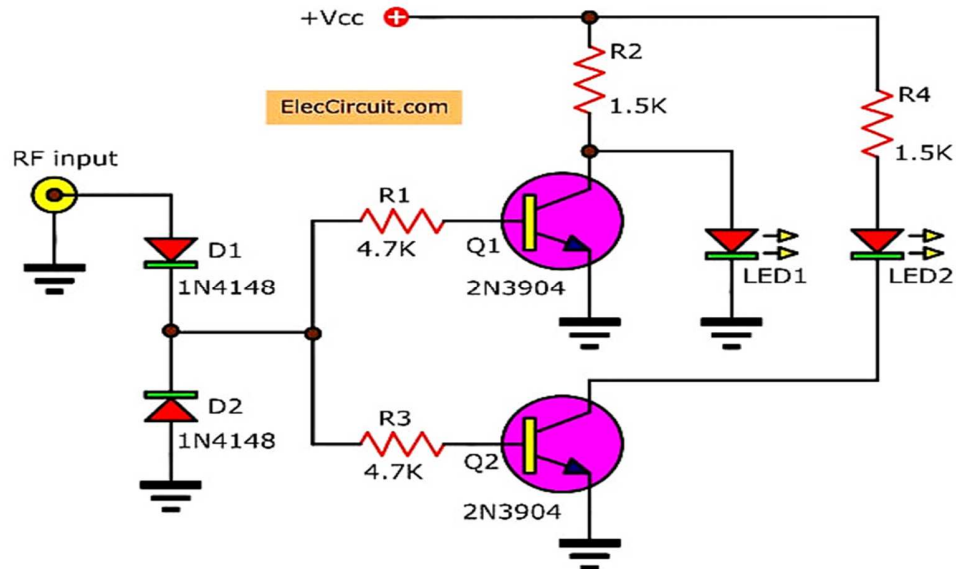


Figure II.37 Radio Frequency (RF) Circuits.

II.9.4. Power Control Circuits

Power control circuits regulate the amount of electrical energy employed in a variety of contexts (Figure II.38). The primary variable of interest is typically voltage or current, and the goal of the regulation is generally one of efficiency, stability, or safety. A fuse, for example, is a rudimentary power control component that interrupts current flow should the value of current exceed a predefined maximum. In high-power consumer systems, power transistors can be used to manage the power distribution. As the name implies, a power transistor is simply a transistor assembled in a large, high-power package. In many cases, as much as tens of amperes and hundreds of volts may be controlled. An equally important issue is heat management. The power transistors themselves will generate a substantial amount of power in the form of heat. They must therefore be mounted to a heat sink, which will conduct the heat away from the device and into the surrounding air. Various thermal enhancement considerations will be made in the packaging of the device and mounting to the heat sink. A typical example of a power electronics application is the controllers of your central heating. These usually drive a pump or a blower to circulate hot water or air to warm certain parts of your house. They have to dissipate hundredths of watts to kilowatts of power, depending on the size of your house and the climate. It is not economically reasonable to make them too efficient, but still, the voltage drop and power dissipation need to be regulated. One of the most common power control circuits is the voltage



regulator. Its main task is to deliver constant voltage from a varying input voltage. Quite often, depending on local requirements, these converters are split into input and output stages, which are in a majority of cases DC-DC converters. If the power needed is above a few tens of watts, too much heat has to be dissipated within the device, which may damage it. Complex protection circuitry can be added, but special care is paid to the design in order to withstand larger currents. Also, current transients related to IR drop have to be given special attention for useful operation.

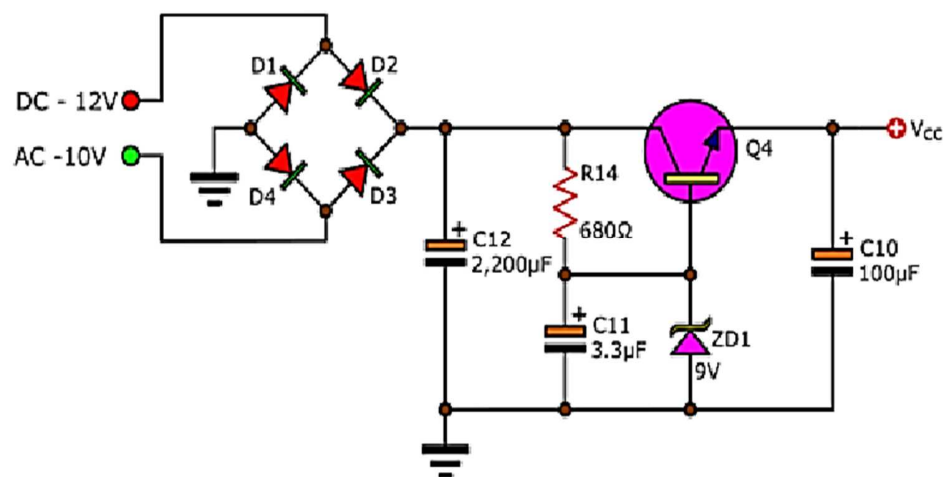


Figure II.38 Power Control Circuits.

II.10. Conclusion and Summary

Transistor is the most important part of many electronic devices, it plays a central role in modern electronics and is widely used in radio, television, computer, mobile phones, and many other small electronics. The development and production of different types of transistors is encouraged as per their applications. This support will help graduate students to bring new elemental technologies in electronics and advancement. Low-cost analog electronic devices have a variety of applications based on field-effect electrolyte-oxide-semiconductor transistors, which have exhibited significant potential in current research. The expression of competing device attributes and cost requirement drives evolution among electrolytes, electrodes, and their mode of interactions. In recent years, the transistors technological challenges become very interesting due to their potential applications in cutting-edge devices such as wearable smart devices, biomedical devices, etc. This chapter discussed and introduced the transistors and defines the transistors structure and the different kinds of applications, and aims to present the advancement of current research about transistors development for postgraduation, researchers, and professors.



Questions & Answers

1. What is a transistor?

A transistor is an electrical device that regulates voltage or current flow and also behaves as a gate or switch for electronic signals.

2. Who proposed the idea of a field-effect transistor?

Julius Edgar Lilienfeld proposed the idea of a field-effect transistor.

3. What are the important uses of transistors?

The fundamental use of transistors includes switching applications or both switching and amplification.

4. What are the main types of transistors?

Bipolar transistors, insulated-gate bipolar transistors and field-effect transistors are the main types of transistors.

5. What are the two types of field-effect transistors?

Junction field-effect transistors and metal oxide semiconductor field-effect transistors are two types of field-effect transistors.

6. Which type of transistor is called a unipolar transistor?

FET transistors are also called unipolar transistors since they undergo the operation of a single-carrier type.

7. Who invented BJT?

BJT was invented by W.H Brattin, Bardeen, and William Shockley.

8. What are the operating regions of BJT?

The operating regions of BJT are:

- Forward active or active region
- Reverse active or inverted region
- Saturation
- Cut-off

9. What are the applications of BJT?

Following are the applications of Bipolar Junction Transistor:

- It is used as an amplifier
- It is used as an oscillator



- It is used as a demodulator

10. What happens if the transistor is not biased properly?

Following is the list of consequences if the transistor is not biased properly:

- The work efficiency of the transistor reduces
- There will be a distortion in the output signal
- The operating point may shift
- Transistor parameters will change

11. Why is there a maximum limit for the collector supply voltage for a transistor?

There is a maximum limit for the collector supply voltage for a transistor because when the collector current is increased rapidly there are chances of transistor getting damaged. To avoid this, the voltage in the collector should have a maximum limit.

12. How does a transistor work as an amplifier?

A transistor works as an amplifier by taking in a very small weak signal through the base junction and raising the strength of the weak signal. This amplified signal is released through the collector.

13. What are the functions of a transistor?

A transistor is a device used for amplifying, controlling and generating electrical signals.

14. What are the uses of transistors?

Transistors are used in cameras, hearing aids, watches, cell phones, power regulators, etc.

15. What is the advantage of JFET over BJT?

JFET (junction field-effect transistor) has advantages over BJT (bipolar junction transistor) including high input impedance, voltage-controlled operation, low noise, thermal stability, simplified biasing, and zero input current.

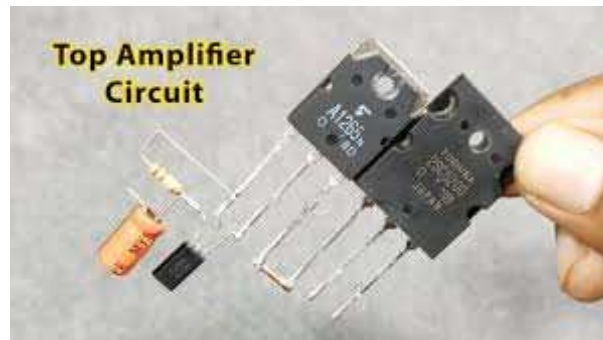
16. When V_{GS} of a p-channel JFET is increased from 1 to 3 V,

Causes the depletion region to widen, leading to an increase in channel resistance. This is due to the enhanced reverse bias that pushes majority carriers away from the gate junction. Thus, both changes are linked to the fundamental operation of JFETs.



Chapter III

Transistor Amplifiers



III.1. Introduction

Amplifiers, and more specifically transistor amplifiers, represent one of the most popular properties of transistors. Almost every person makes use of amplifiers in some form or another, even if it is just to amplify the sound in a simple stereo system. With advances in technology, these amplifiers have shrunk to a level where miniature integrated amplifiers may be found on chips that can almost fit on a pinhead. However, it is vital to understand that these miniature amplifiers may not perform the way simple transistor amplifiers perform. A thorough grounding in basic principles will make the understanding and design of amplifiers much easier. Transistor amplifiers may be used in various applications such as in hi-fi systems, audio recording systems, personal music systems, telephones, TV sets, radio sets, and many more. A transistor amplifier may be incorporated into another system to efficiently process signals. An amplifier may take a weak signal as input and provide a comparable output. The output is changed in amplitude, while other parameters may remain the same. It is important to note that an amplifier does not change the frequency or distortion of the signal. Although the output signal is larger in amplitude compared to the input signal (Figure III.1), an ideal amplifier does not add power to the signal; it only redistributes power from the power supply to the signal. Amplifier is the generic term used to describe a circuit which produces an increased version of its input signal. Amplifier circuits are different and they are classified according to their circuit configurations and modes of operation. Generally, amplifiers can be sub-divided into two distinct types depending upon their power or voltage gain. One type is called the Small Signal Amplifier which include pre-amplifiers, instrumentation amplifiers etc. Small signal amplifiers are designed to amplify very small



signal voltage levels of only a few micro-volts (μV) from sensors or audio signals. The other type are called Large Signal Amplifiers such as audio power amplifiers or power switching amplifiers. Large signal amplifiers are designed to amplify large input voltage signals or switch heavy load currents as you would find driving loudspeakers. In general the classification of an amplifier depends upon the size of the signal, large or small, its physical configuration and how it processes the input signal.

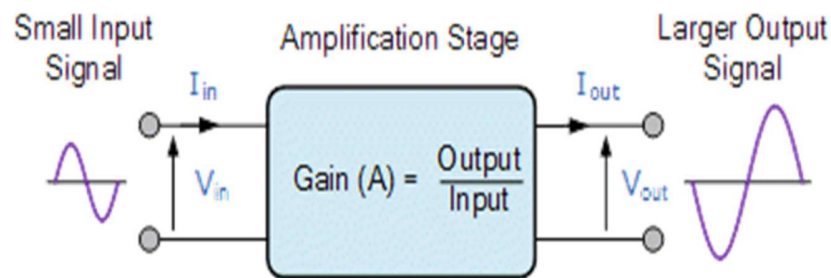


Figure III.1 representative diagram of an amplifier.

III.2. Transistor Amplifier Configurations

The transistor amplifier configurations, their characteristics and applications, are briefly introduced. There are three differently configured basic amplifiers such as Common Emitter, Common Collector and Common Base amplifiers. Each configuration has its own characteristics to suit the requirements of different applications. In the Common Emitter amplifier configuration, the input is applied between base and emitter and the output is taken between collector and emitter. The Common Emitter amplifier is the most popular amplifier configuration because it provides a high voltage gain. Therefore, it is widely used in audio applications as well as in radiofrequency applications. When a transistor is used in the Common Emitter mode, there is a phase shift of 180 degrees between input and output signals. This configuration is usually designed to provide a maximum voltage swing to minimize distortion in the amplified output. In the Common Collector amplifier configuration, the input is applied between base and collector and the output is taken between emitter and collector. The Common Collector amplifier configuration is also known as an Emitter Follower amplifier.

The Common Collector configuration is widely used when a high current gain is to be achieved because the current gain is $(\beta + 1)$ in this configuration. In other words, the CC amplifier configuration is used when the load has to be driven directly from a high gain stage. Also, this configuration is used for impedance matching purposes since it has a very high input resistance and low output resistance. In the Common Base amplifier configuration, the input is applied between emitter and base and the output is taken between collector and base.



The Common Base amplifier configuration is very rarely used because it has a low input impedance and a high output impedance. The most significant feature of the Common Base amplifier is that it has a unique input-output relationship compared to the other configurations. The input signal is applied to the emitter terminal and the output is obtained at the collector terminal. As a result, this configuration is sometimes used to process RF signals which are received through an incoming antenna. A comparative study of the three configurations has been included to show the relative merits and demerits of each configuration. These three configurations are widely used in practical applications in widely used electronic devices such as radios, televisions, microphones, etc. Each of these configurations exhibit certain characteristics that make them more desirable in certain circuit applications than the others. A qualitative comparison of these three configurations is shown below in Table III.1.

Table III.1 Qualitative BJT Amplifier Comparison.

	Common-emitter	common-base	common-collector
Input Impedance	Medium	Low	High
Output Impedance	Medium	High	Low
Current Gain	High(β)	Low(α)	High
Voltage Gain	High	High	Low
Power Gain	High	Medium	Low

Generally, the common-emitter and common-collector have a lower frequency bandwidth than the common-base. This can be attributed to such effects caused by the intrinsic device capacitances and how the transistor is configured in relation to these capacitances. A common cause of the loss of bandwidth is the Miller effect, which is covered in most analog electronics textbooks.

III.2.1. Common Emitter Amplifier

Emphasis is primarily placed on the Common Emitter Amplifier, a configuration of transistor amplifier considered to be the most widely used of all amplifier configurations. Despite some limitations, it is the most popular transistor amplifier configuration due to its versatility and wide application in single-ended amplification. The output can be taken across either a resistor or a bypass capacitor parallel to the emitter. As a voltage amplifier, it may be RC coupled, transformer coupled, or directly coupled. A Common Emitter transistor amplifier provides high voltage gain, high power gain, and high input resistance and is able to drive either a resistive load or an inductive load. Basic operation



is explained with the help of a typical circuit and input-output characteristics. Regarding phase inversion, it is discussed how, at low frequencies, the input circuit of the transistor amplifier sees AC signals taking ground as a reference point. Therefore, there are input and output voltages with respect to ground which result in the Common Emitter transistor amplifier phase inverting the input signal. Additionally, an explanation on the different reasons for the Common Emitter Amplifier's popularity is provided. After the basic operation of a common emitter amplifier is covered, the potential limitations of this configuration are examined. As with any other amplifier, it suffers from limitations in bandwidth. Also, at very low input signal levels, distortion results from the approach to the cut-off regions of operation.

Circuit design considerations apply to biasing as it is necessary to set the Q-point for proper operation under no-signal conditions. With common emitter amplifiers, this is done using resistor biasing which may involve circuit components other than just the transistor. It is clarified the component selection regarding the required overall voltage gain, the load-driven design, and the effect of transistor current gain on amplifier performance.

A good simple approximation of the AC input and output resistances is provided as well. Finally, as real world applications, the use of common emitter amplifiers in consumer audio amplification and telecommunication signal processing is discussed.

The common-emitter (CE) configuration has the emitter as the common terminal, or ground, to an AC signal. CE amplifiers exhibit high voltage gain and high current gain.

Figure III.2 shows a CE amplifier with voltage-divider bias and coupling capacitors C_1 and C_3 , and a bypass capacitor, C_2 . V_{in} is capacitively coupled to the base terminal and V_{out} is capacitively coupled from the collector to the load. The amplified output is 180° out of phase with the input. Since the AC signal is applied to the base as the input and taken from the collector as the output, the emitter is common to both the input and output signals. There is no signal at the emitter because C_2 shorts the emitter to the ground at the signal frequency. The DC bias values must first be determined and DC equivalent circuit is developed by removing the capacitors because they appear open in DC bias. This also removes R_L and the signal source.

The DC equivalent circuit of Figure III.2(a) is shown in Figure III.2(b).

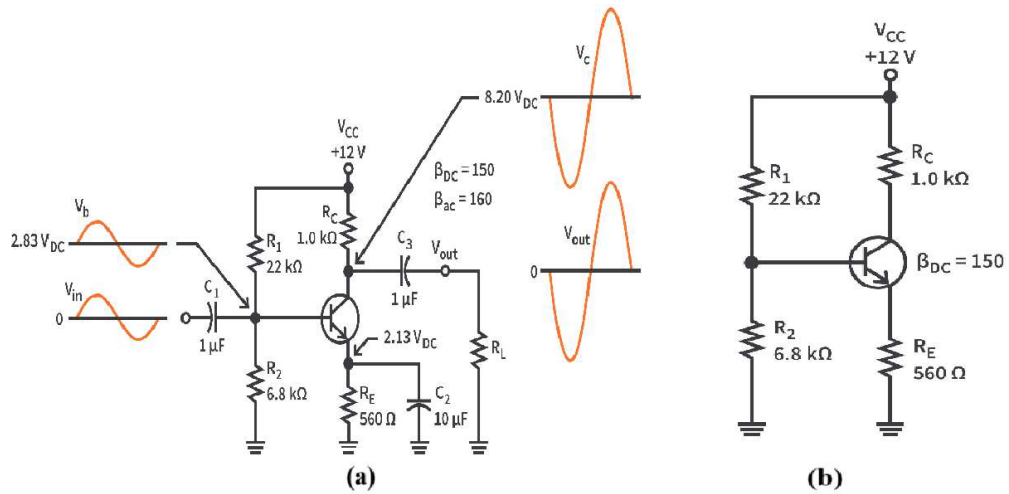


Figure III.2(a) A common-emitter amplifier and (b) DC equivalent circuit for the amplifier.

However, the E/B junction is forward-biased by V_{BB} and C/B junction is reversed-biased by V_{CC} (in fact, same battery V_{CC} can provide dc power for both base and collector. working condition is determined by V_{CC} together with R_B and R_C , when:

Input Resistance given by the equation $r_{in} = \beta r_e$, output resistance is $r_o = R_C$ where $r_o = R_C \parallel R_L$, current Gain is $A_V = \beta$ and voltage gain is $A_V = \frac{R_o}{R_e}$. Using Thevenin's theorem, the bias circuit and applying Kirchoff's voltage law to the base-emitter circuit,

$$V_{TH} = \frac{R_1 + R_2}{R_1 + R_2} = 5.19 \text{ K}\Omega$$

$$V_{TH} = \left(\frac{R_1}{R_1 + R_2} \right) V_{CC} = 2.83 \text{ V}$$

$$I_E = \frac{V_{TH} - V_{BE}}{R_E - R_{TH}/\beta} = 3.85 \text{ mA}$$

$$I_C \cong I_B = 3.85 \text{ mA}$$

$$V_E = R_E I_E = 2 \text{ V}$$

$$V_B + 0.7 = 2.7 \text{ V}$$

$$V_C = V_{CC} - R_C I_C = 8.42 \text{ V}$$

$$V_{CE} = V_C - V_E = 6.42 \text{ V}$$



In AC equivalent circuit is developed as follows: The capacitors are replaced by effective shorts because their values are selected so that X_C is negligible at the signal frequency. The DC source is replaced by ground. If the internal resistance of the AC source is 0 then all of the source voltage appears at the base terminal. If the AC source has a nonzero internal resistance, three factors must be taken into account in determining the actual signal voltage at the base: the source resistance (R_s), the bias resistance ($R_1 \parallel R_2$) and AC input resistance at the base of the transistor ($R_{in(base)}$). This is illustrated in Figure III. 3 and is simplified by combining R_1 , R_2 and $R_{in(base)}$ in parallel to get the total input resistance, $R_{in(tot)}$.

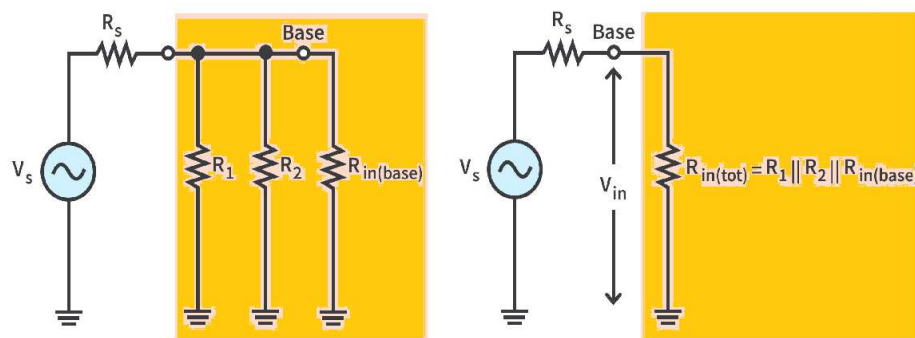


Figure III.3 AC equivalent of the base circuit.

The source voltage, V_s is divided down by R_s and $R_{in(tot)}$ so that the signal voltage at the base of the transistor is found by the voltage-divider formula:

$$V_b = \left(\frac{R_{in(tot)}}{R_s + R_{in(tot)}} \right) V_s$$

Input Resistance at the Base is:

$$R_{in(base)} = \frac{V_{in}}{I_{in}} = \frac{V_b}{I_b}$$

The output resistance of the common-emitter amplifier is the resistance looking in at the collector. Actually, $R_{out} = R_C \parallel r'_c$ but since the internal AC collector resistance, r'_c is typically much larger than R_C , the approximation is usually valid. The AC voltage gain expression for the common-emitter amplifier is developed using the model circuit in Figure III.4.

$$A_v = \frac{V_{out}}{V_{in}} = \frac{V_c}{V_b}$$



Where, $V_c = \alpha_{ac} I_e R_C \approx I_e R_C$ and $V_b = I_e r'_e$. Thus, we obtain

$$A_v = \frac{R_C}{r'_e}$$

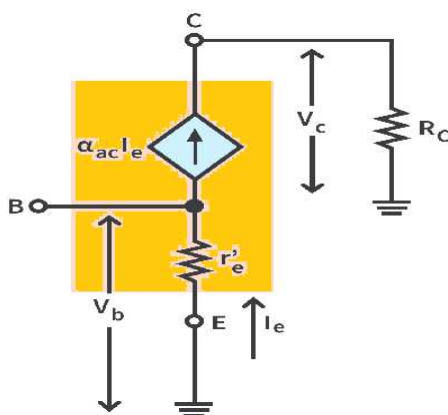


Figure III.4 Model circuit for obtaining ac voltage gain.

Though, with the bypass capacitor, the gain of a given amplifier is maximum and equal to R_C/r'_e , and Without the bypass capacitor, the emitter is no longer at AC ground. R_E is seen by the AC signal between the emitter and ground and adds to r'_e in the voltage gain formula.

$$A_v = \frac{R_C}{r'_e + R_E}$$

The effect of R_E is to decrease the AC voltage gain. *Effect of a Load on the Voltage Gain* When a resistor, R_L , is connected to the output through the coupling capacitor C_3 (Fig. 9), it creates a load on the circuit. The collector resistance at the signal frequency is effectively R_C in parallel with R_L . The total AC collector resistance is:

$$R_c = R_C || R_L$$

The voltage gain expression becomes:

$$A_v = \frac{R_C || R_L}{r'_e} = \frac{R_C R_L}{R_C + R_L} \frac{1}{r'_e}$$

Stability is a measure of how well an amplifier maintains its design values over changes in temperature or for a transistor with a different β . There is a stability problem because the AC voltage gain is dependent on r'_e which in turn depends on I_E and temperature. Then r'_e increases, the gain decreases and vice versa. *Swamping r'_e to Stabilize the Voltage Gain* *Swamping* is used to minimize the effect of r'_e without reducing the voltage gain to its minimum value. This method “swamps” out the effect on the voltage gain; a compromise between having a bypass capacitor across R_E and having



no bypass capacitor at all. The total external emitter resistance, R_E , is formed with two emitter resistors, R_{E1} and R_{E2} . In Figure III.5, R_{E2} is bypassed and R_{E1} is not.

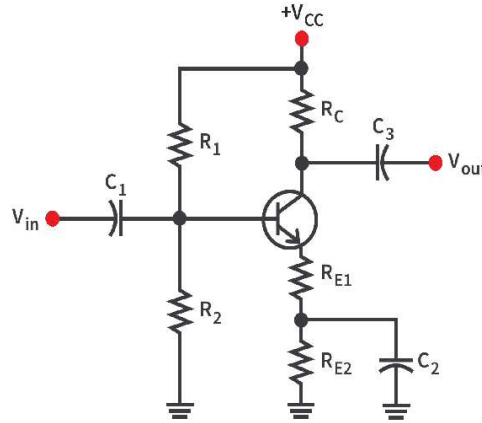


Figure III.5 Swamped amplifier with a partially bypassed emitter resistance.

$$A_v = \frac{R_C}{r'_e + R_{E1}}$$

If R_{E1} is at least ten times larger than r'_e then the effect of r'_e is minimized and the approximate voltage gain for the swamped amplifier is:

$$A_v \cong \frac{R_C}{R_{E1}}$$

The Effect of Swamping on the Amplifier's Input Resistance. The AC input resistance, looking in at the base of a common-emitter amplifier with R_E completely bypassed is $R_{in} = \beta_{ac} r'_e$. When the emitter resistance is partially by passed,

$$R_{in(base)} = \beta_{ac}(r'_e + R_{E1})$$

The current gain from base to collector is I_c/I_b or β . The overall current gain of the common-emitter amplifier is :

$$A_i = \frac{I_c}{I_s} \text{ where } I_s = \frac{V_s}{R_s + R_{in(tot)}}$$

The overall power gain is the product of the overall voltage gain (A_v') and the overall current gain (A_i) is:

$$A_p = A_v' A_i \text{ where } A_v' = \frac{V_c}{V_s}$$

a) Amplifier Coupling Capacitors

In Common Emitter Amplifier circuits, capacitors C_1 and C_2 are used as Coupling Capacitors to separate the AC signals from the DC biasing voltage(Figure III.6). This ensures that the bias condition



set up for the circuit to operate correctly is not affected by any additional amplifier stages, as the capacitors will only pass AC signals and block any DC component. The output AC signal is then superimposed on the biasing of the following stages. Also a bypass capacitor, C_E is included in the Emitter leg circuit. This capacitor is effectively an open circuit component for DC biasing conditions, which means that the biasing currents and voltages are not affected by the addition of the capacitor maintaining a good Q-point stability. However, this parallel connected bypass capacitor effectively becomes a short circuit to the Emitter resistor at high frequency signals due to its reactance. Thus only R_L plus a very small internal resistance acts as its load increasing voltage gain to its maximum. Generally, the value of the bypass capacitor, C_E is chosen to provide a reactance of at most, 10^{-1} the value of R_E at the lowest operating signal frequency.

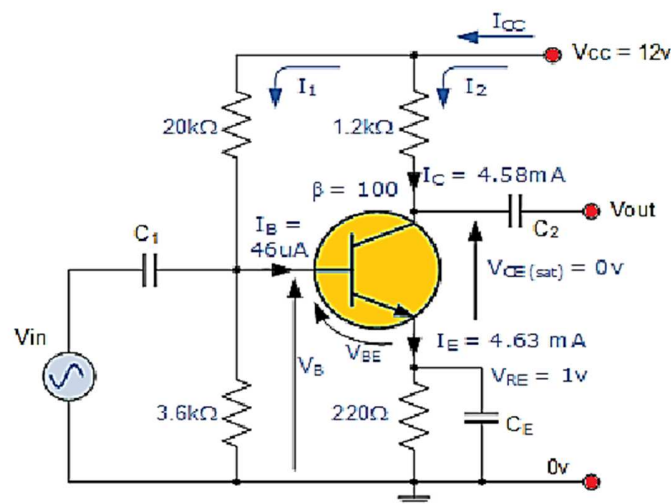


Figure III.6 Completed Common Emitter Circuit.

b) Output Characteristics Curves

We can now construct a series of curves that show the Collector current, I_c against the Collector/Emitter voltage, V_{ce} with different values of Base current, I_b for our simple common emitter amplifier circuit. These curves are known as the "Output Characteristic Curves" and are used to show how the transistor will operate over its dynamic range (Figure III.7). A static or DC load line is drawn onto the curves for the load resistor R_L of 1.2 k Ω to show all the transistor's possible operating points. When the transistor is switched "OFF", V_{ce} equals the supply voltage V_{cc} and this is point "B" on the line. Likewise, when the transistor is fully "ON" and saturated the Collector current is determined by the load resistor, R_L and this is point "A" on the line.

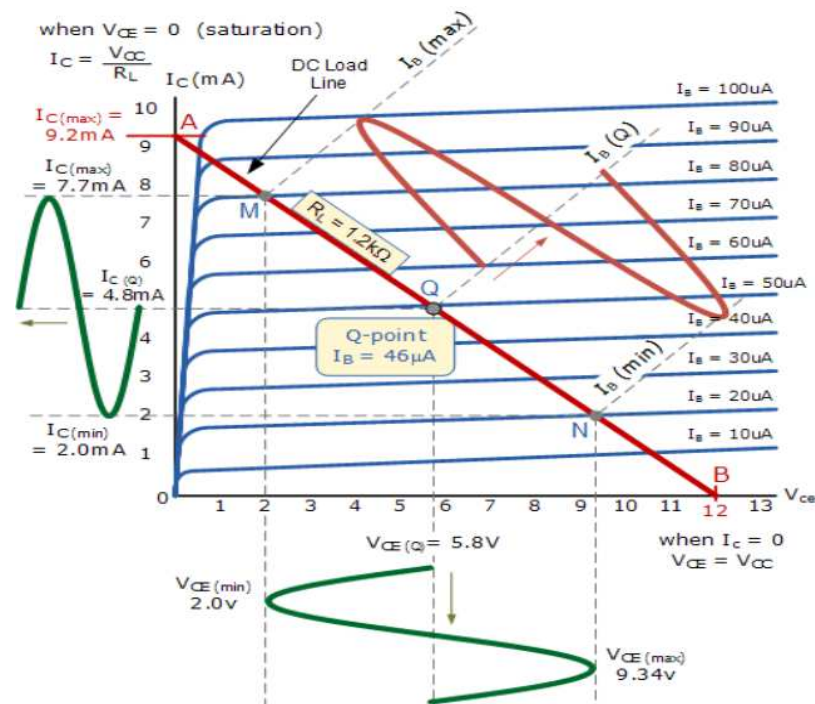


Figure III.7 Output Characteristics Curves.

We calculated before from the DC gain of the transistor that the Base current required for the mean position of the transistor was $45.8\ \mu\text{A}$ and this is marked as point Q on the load line which represents Q-point of the amplifier. We could quite easily make life easy for ourselves and round off this value to $50\ \mu\text{A}$ exactly, without any effect to the operating point. We can now construct a series of curves that show the Collector current, I_c against the Collector/Emitter voltage, V_{ce} with different values of Base current, I_b for our simple common emitter amplifier circuit. These curves are known as the "Output Characteristic Curves" and are used to show how the transistor will operate over its dynamic range. A static or DC load line is drawn onto the curves for the load resistor R_L of $1.2\ \text{k}\Omega$ to show all the transistor's possible operating points. When the transistor is switched "OFF", V_{ce} equals the supply voltage V_{cc} and this is point "B" on the line. Likewise, when the transistor is fully "ON" and saturated the Collector current is determined by the load resistor, R_L and this is point "A" on the line. We calculated before from the DC gain of the transistor that the Base current required for the mean position of the transistor was $45.8\ \mu\text{A}$ and this is marked as point Q on the load line which represents the Quiescent point or Q-point of the amplifier. We could quite easily make life easy for ourselves and round off this value to $50\ \mu\text{A}$ exactly, without any effect to the operating point.

Point Q on the load line gives us the Base current Q-point of $I_b = 45.8\ \mu\text{A}$ or $46\ \mu\text{A}$. We need to find the maximum and minimum peak swings of Base current that will result in a proportional change to the Collector current, I_c without any distortion to the output signal. As the load line cuts through the



different Base current values on the DC characteristics curves we can find the peak swings of Base current that are equally spaced along the load line. These values are marked as points "N" and "M" on the line, giving a minimum and a maximum Base current of $20\ \mu\text{A}$ and $80\ \mu\text{A}$ respectively. These points, "N" and "M" can be anywhere along the load line that we choose as long as they are equally spaced from Q. This then gives us a theoretical maximum input signal to the Base terminal of $60\ \mu\text{A}$ peak-to-peak. As the Base current I_b changes in a positive direction from $50\ \mu\text{A}$ to $80\ \mu\text{A}$, the Collector-emitter voltage, which is also the output voltage decreases from its steady state value of 5.8 volts to 2.0 volts. Then a single stage Common Emitter Amplifier is also an "Inverting Amplifier" as an increase in Base voltage causes a decrease in V_{out} and a decrease in Base voltage produces an increase in V_{out} . In other words, the output signal is 180° out-of-phase with the input signal.

III.2.2. Common Collector Amplifier (Emitter-Follower)

Among the various transistor amplifiers configurations, the Common Collector Amplifier is probably the most well-known and widely used after the Common Emitter Amplifier. It is famous for its impedance transformation properties: the input impedance is high and the output impedance is low. This configuration is also known as Emitter Follower since the output signal follows the input signal and is connected to the Emitter terminal of the transistor. This configuration provides a high current gain while keeping a low output impedance. Its greatest advantage is as a load driving stage. The output stage of most audio power amplifiers is usually a complimentary push-pull Common Collector/Emitter Follower pair used to drive a low impedance load like a speaker. However, the output current drive ability may sometimes come at the expense of the class of amplifier biasing design, overheating issues, and low quiescent current conditions. Moreover, since the output stage is a Common Collector configuration, the voltage gain of this particular transistor configuration is about 1 (unity gain) which means it cannot amplify a weak signal voltage. But it still has its uses and some advantages over its Common Emitter counterpart especially in signal buffering applications where the input and output signals are AC coupled as a insulated DC level difference is maintained. This configuration is rather simple, widely used in practice, and very useful to know because understanding this configuration will make it clearer how to match circuit elements with different impedances since all these matching network circuits apply the same principle as this transistor configuration. Also, this configuration is so widely used that even some ICs have it internally for input signal processing, reducing the need for an external amplifier stage circuitry. To illustrate the principle of this configuration, the input and output signals are taken at the Base and Emitter respectively. This is a Basic Common Collector Transistor Amplifier with the input signal V_{in} AC coupling through to Base B and the output signal V_{out} taken on



Emitter E. The transistor is biased with properly selected resistors as to maintain an appropriate Q point DC operating level. Consider a small signal AC voltage is injected at the Base. Since the input signal is an AC signal, the effect of the DC bias voltage is ignored, thus considering only the small AC signal represented as v_{in} . An emitter-follower circuit with voltage-divider bias is shown in Figure III.8. The input signal is capacitively coupled to the base, the output signal is capacitively coupled from the emitter, and the collector is at ac ground. There is no phase inversion, and the output is approximately the same amplitude as the input.

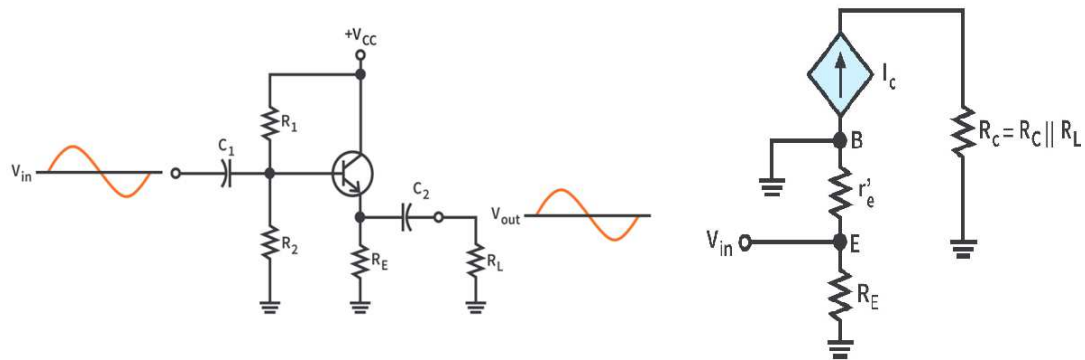


Figure III.8 Emitter follower with voltage-divider bias.

Capacitive reactance's are assumed to be negligible at the frequency of operation.

$$A_v \simeq 1$$

Since the output voltage is at the emitter, it is in phase with the base voltage, there is no inversion from input to output. Because there is no inversion and because the voltage gain is approximately 1, the output voltage closely follows the input voltage in both phase and amplitude; thus the term emitter-follower. The emitter-follower is characterized by a high input resistance; this is what makes it a useful circuit.

If $R_E \gg r'_e$, $R_{in(base)}$ is equal to:

$$R_{in(base)} \cong \beta_{ac} R_e \quad \text{where } R_e = R_E || R_L$$

$$R_{in(base)} \cong \beta_{ac} R_e$$

It can be used as a buffer to minimize loading effects when a circuit is driving a low-resistance load. The bias resistors in Figure III.7 appear in parallel with $R_{in(base)}$, looking from the input source; and just as in the common-emitter circuit, the total input resistance is:

$$R_{in(tot)} = R_1 // R_2 // R_{in(base)}$$



With the load removed, the output resistance, looking into the emitter of the emitter-follower, is approximated as:

$$R_{out} \cong \left(\frac{R_s}{\beta_{ac}} \right) // R_e$$

Where R_s is the resistance of the input source. The common-collector power gain is the product of the voltage gain and the current gain. For the emitter-follower, the power gain is approximately equal to the current gain because the voltage gain is approximately 1: $A_p = A_v A_i$. Since $A_v \approx 1$, the power gain is:

$$A_p \approx A_i$$

III.2.3. Common Base Amplifier

Another configuration with unique properties is the Common Base Amplifier (CBA). This configuration is not as widely used as common emitter or common collector but has its specific applications. As the name suggests, the Base terminal is common to the input and output. The vast majority of the amplifiers discussed so far have used the same principle of operation. However, the common base amplifier is fundamentally different from all the other transistor amplifiers discussed. Although it is a current control device, it does not have voltage gain, meaning that the input voltage and output voltage are in a fixed ratio of less than one (< 1). Thus, the common base amplifier steps down the voltage while greatly amplifying the current. This means that the output current is much greater than the input current and by a fixed ratio. Such a configuration is used when an application needs a step-up current gain as well as a standard voltage gain. The common base amplifier is characterized by a highly favorable current gain. The common base configuration is also known as a transconductance stage because it takes a voltage signal and produces a current output. This amplifier has better high-frequency performance due to the internal transistor capacitance structure and is often used in integrated circuit designs.

However, it has disadvantages: Low input impedance, which is a function of the emitter resistor and the transistor current gain; It is hard to design; Biasing is difficult since it requires two biasing resistors, similar to the common emitter arrangement. This amplifier works on class A mode similar to common emitter and common collector. As the Websimulator does not allow defining the input/output impedance, a predefined analysis with the default parameter values will be shown first. The input/output characteristics, which show the relationship between the input voltage and output current, will be plotted, and then the design consideration will be discussed.



The input voltage and input current are V_{in} and I_{in} , and the output voltage and output current are V_{out} and I_{out} . The phase relationship between the input and output can be shown as both characteristics share the same direction; thus, the input voltage and output current are in phase, while the input current and output voltage are out of phase. A typical common-base amplifier is shown in Figure III.9. The base is the common terminal and is at AC ground because of capacitor C_2 . The input signal is capacitively coupled to the emitter. The output is capacitively coupled from the collector to a load resistor.

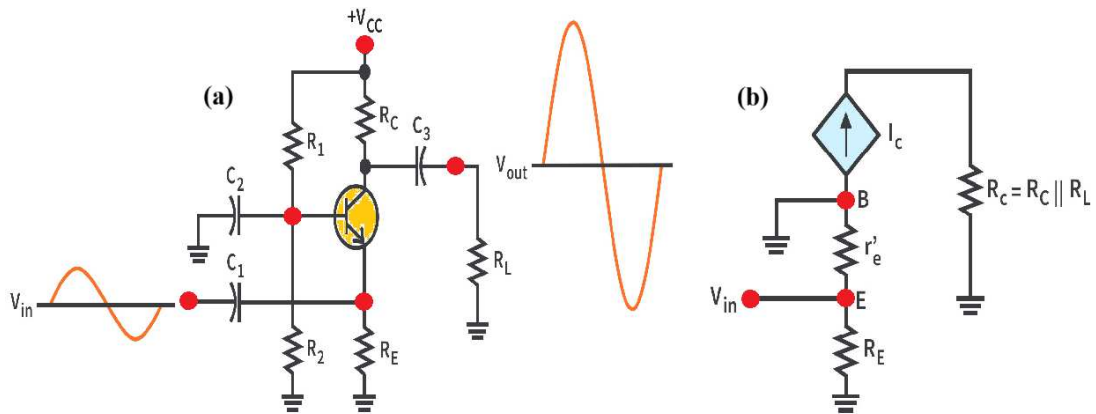


Figure III.9 (a) Common base amplifier with voltage divider bias and (b) AC equivalent model.

The voltage gain A_v from emitter to collector is developed as follows :

$$V_{in} = V_e, \quad V_{out} = V_c$$

$$A_v = \frac{V_{out}}{V_{in}} = \frac{V_c}{V_e} = \frac{I_c R_c}{I_e (r'_e \parallel R_E)} \cong \frac{I_e R_c}{I_e (r'_e \parallel R_E)}$$

If $R_E \gg r'_e$, then :

$$A_v \cong \frac{R_c}{r'_e} \quad \text{where } R_c = R_C \parallel R_L$$

The input resistance, R_{in} , looking in at the emitter, is:

$$R_{in(emitter)} = \frac{V_{in}}{I_{in}} = \frac{V_e}{I_e} = \frac{I_e (r'_e \parallel R_E)}{I_e}$$

If $R_E \gg r'_e$, then :



$$R_{in(emitter)} = r'_e$$

Looking into the collector, the AC collector resistance, r'_c , appears in parallel with R_C . Typically, r'_c is much larger than R_C , so an approximation for the output resistance R_{out} is :

$$R_{out} \approx R_C$$

I_c is the AC output current, and I_e is the AC input current. Since $I_c \approx I_e$, the current gain A_i is approximately 1, where:

$$A_i \approx 1$$

Since the current gain is approximately 1 for the common-base amplifier and $A_p = A_v A_i$, the power gain A_p is approximately equal to the voltage gain, thus:

$$A_p \approx A_v$$

III.3. Operational Amplifiers

Operational Amplifiers, or Op-Amps, are arguably the most widely used building blocks in all of analog electronics. Their versatility allows them to be used in a variety of applications, making them the backbone of countless electronic circuits. Almost any job involving the processing of analog signals can be handled by an Op-Amp circuit. Consumer, industrial, and scientific electronics all use Op-Amps in one form or another. terminal four port active element. The symbol of the op-amp with the associated terminals and ports is shown on Figure III.10 (a) and (b).

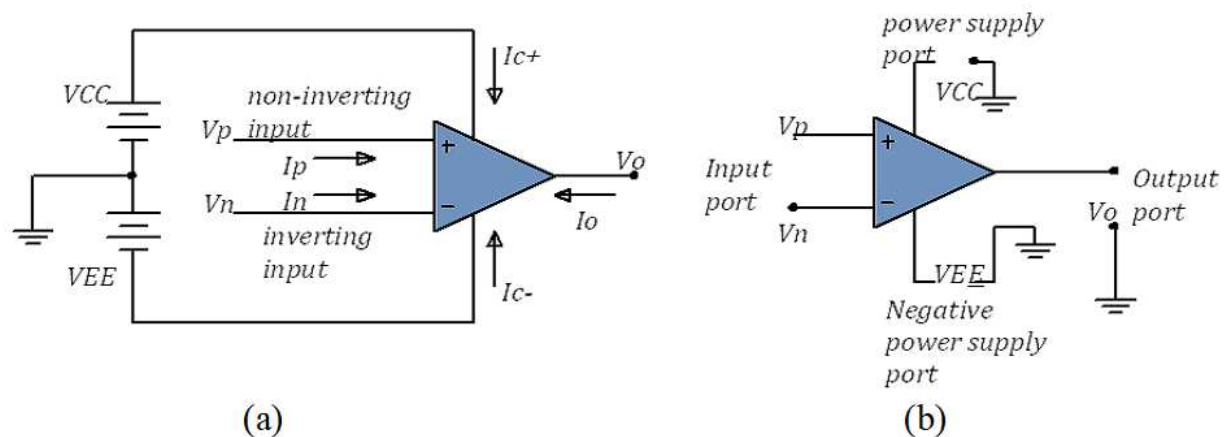


Figure III.10 (a) Symbol and (b) associated notation of op-amp.

The operational amplifier (op-amp) is a voltage controlled voltage source with very high gain. It is a five terminal four port active element. The symbol of the op-amp with the associated terminals and ports The power supply voltages V_{CC} and V_{EE} power the operational amplifier and in general define



the output voltage range of the amplifier. The terminals labeled with the “+” and the “-” signs are called non-inverting and inverting respectively. The input voltage V_p and V_n and the output voltage V_o are referenced to ground. The five terminals of the op-amp form one (complicated) node and if the currents are defined as shown on Figure III.10 (a) requires that :

$$I_n + I_p + I_{c-} + I_o = 0$$

Therefore for current balance we must include all currents. This is what defines an active element. If we just consider the signal terminals then there is no relationship between their currents. In particular,

$$I_n + I_p + I_o \neq 0$$

The equivalent circuit model of an op-amp is shown on Figure III.11 (a). The voltage V_i is the differential input voltage $V_i = V_p - V_n$. R_i is the input resistance of the device and R_o is the output resistance. The gain pa configuration of an op-amp is defined as an op-amp circuit without any circuit loops that connect the output to any of the inputs. In the absence of any load at the output, the output voltage is :

$$V_o = AV_i = A V_p (-V_n)$$

Which indicates that the output voltage V_o is a function of the difference between the input voltages V_p and V_n . For this reason op-amps are difference amplifiers. For most practical op-amps the open loop DC gain A is extremely high. Figure III.11 (b) relates the output voltage to the input voltage is called the voltage transfer curve and is fundamental in designing and understanding amplifier circuits.

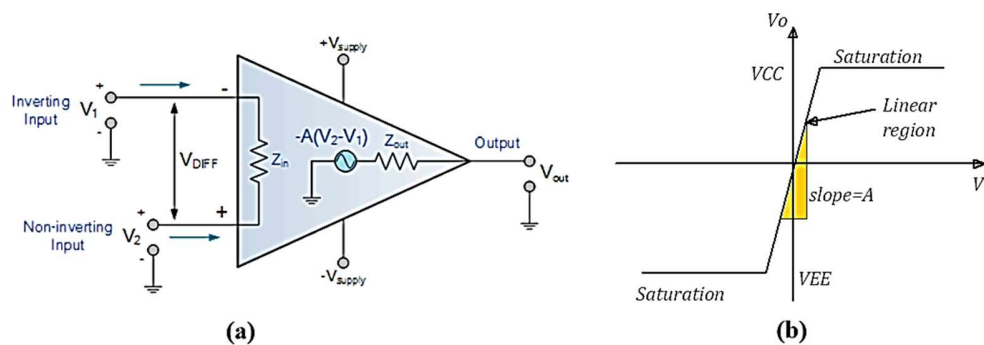


Figure III.11 (a) Equivalent circuit model and (b) Op-amp voltage transfer characteristics.

Note the two distinct regions of operation: one around $V_i=0V$, the linear region where the output changes linearly with respect to input, and the other at which changes in V_i has little affect on V_o , the



saturation region (non-linear behavior). Circuits with operational amplifiers can be designed to operate in both of these regions. In the linear region the slope of the line relating V_o to V_i is very large, indeed it is equal to the open loop gain A . For a op-amp powered with $V_{CC} = +10V$ and $V_{EE} = -10V$, V_o will saturate (reach the maximum output voltage range) at about $\pm 10V$. With an $A=200$ saturation occurs with an input differential voltage of $10/200 = 50\mu V$, a very small voltage.

III.4. Classification of Power Amplifiers

Transistor power amplifiers handle large signals. Many of them are driven so hard by the input large signal that collector current is either cut-off or is in the saturation region during a large portion of the input cycle. Therefore, such amplifiers are generally classified according to their mode of operation i.e. the portion of the input cycle during which the collector current is expected to flow. On this basis, they are classified as: (i) class A power amplifier (ii) class B power amplifier and (iii) class C power amplifier.

III.4.1. Class A Power Amplifier

A class A amplifier is biased such that it always operates in the linear region where the output signal is an amplified replica of the input signal (Figure III.12). For a small-signal amplifier, the AC signal moves over a small percentage of the total AC load line. For a large-signal amplifier, the output signal is larger and approaches the limits of the AC load line. Both large-signal and small-signal amplifiers are considered to be class A if they operate in the linear region at all times.

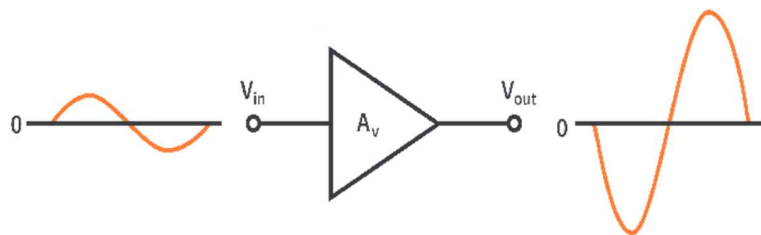


Figure III.12 Class A amplifier operation.

If the collector current flows at all times during the full cycle of the signal, the power amplifier is known as class A power amplifier. Power devices must dissipate a large amount of internally generated heat. For BJT power transistors, the collector terminal is the critical junction:

- ✓ The transistor's case is always connected to the collector terminal. The case is designed to provide a large contact area between it and an external heat sink.
- ✓ Heat from the transistor flows through the case to the heat sink and then dissipates in the surrounding air.



✓ Heat sinks vary in size, number of fins, and type of material. Their size depends on the heat dissipation requirement and the maximum ambient temperature of transistor operation

DC and AC load lines intersect at the Q point (Figure III.13(a)). When the Q point is at the center of the AC load line, the maximum class A signal can be obtained. This graph shows the AC load line with the Q point at its center. I_C can vary from its Q point value, I_{CQ} , up to its saturation value, $I_{C(sat)}$, and down to its cutoff value of zero. V_{CE} can swing from its Q-point value, V_{CEQ} , up to its cutoff value, $V_{ce(cutoff)}$, and down to its saturation value of near zero. This operation is indicated in Figure III.13 (b). The peak value of I_C equals I_{CQ} , and the peak value of V_{CE} equals V_{CEQ} in this case. This signal is the maximum that can be obtained from the class A amplifier.

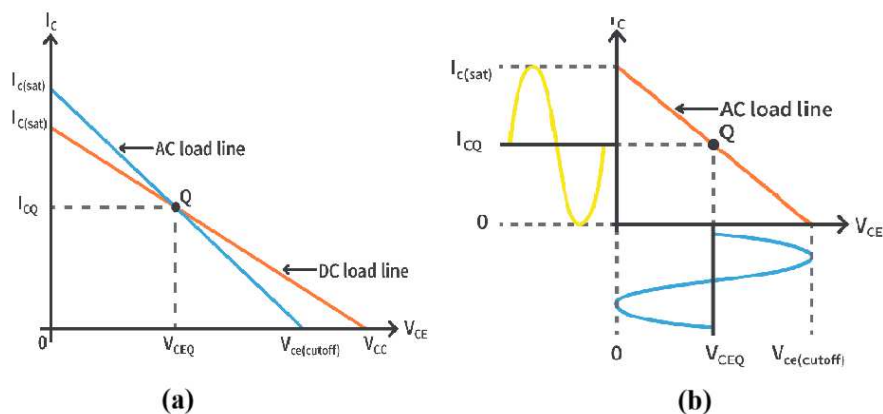


Figure III.13 Maximum class A output occurs when the Q point is centered on the AC load line.

Figure III.14 shows an AC load line with the Q point moved away from center toward saturation. The output variation is limited by saturation. I_C can only swing up to near saturation and an equal amount below I_{CQ} . V_{CE} can only swing down to its saturation value and an equal amount above V_{CEQ} . This situation is illustrated in Figure III.14(a). If the amplifier is driven any further, it will "clip" at saturation, as shown in Figure III.14(b).

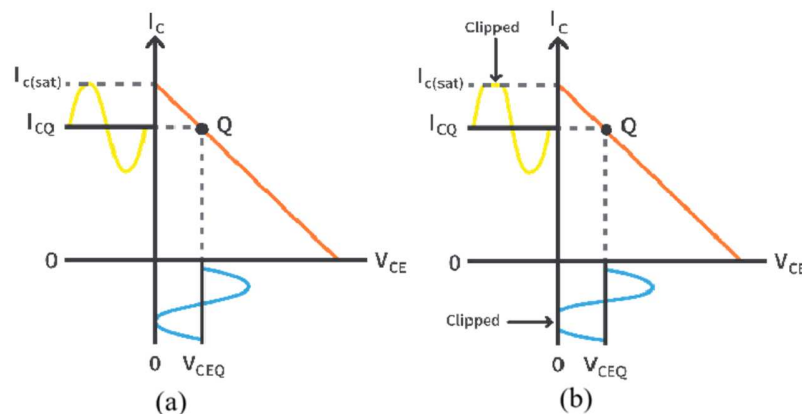


Figure III.14 Q point closer to saturation.



Class A Amplifier operation is where the entire input signal waveform is faithfully reproduced as the transistor is perfectly biased within its active region. This means that the switching transistor is never driven into its cut-off or saturation regions. The result is that the AC input signal is perfectly “centred” between the amplifiers upper and lower signal limits as shown below (Figure III.15).

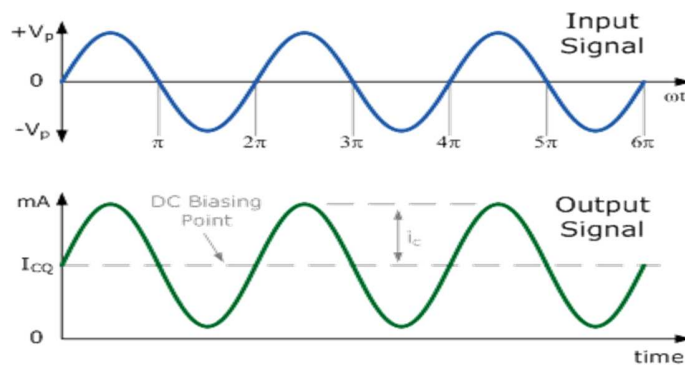


Figure III.15 Class A Amplifier Output Waveform.

The power gain of an amplifier is the ratio of the output power (power delivered to the load) to the input power. In general, power gain is:

$$A_p = \frac{P_L}{P_{in}}$$

Where A_p is the power gain, P_L is signal power delivered to the load, and P_{in} is signal power delivered to the amplifier. The power gain can be computed by any of several formulas, depending on what is known. Frequently, the easiest way to obtain power gain is from input resistance, load resistance, and voltage gain:

$$A_p = \frac{V_L^2}{V_{in}^2} \left(\frac{R_{in}}{R_L} \right)$$

Since $V_L/V_{in} = A_v$, thus:

$$A_p = A_v^2 \left(\frac{R_{in}}{R_L} \right)$$

III.4.2. Class A Power Amplifier

The class B operation is illustrated in Figure III.16, where the output waveform is shown relative to the input in terms of time (t).

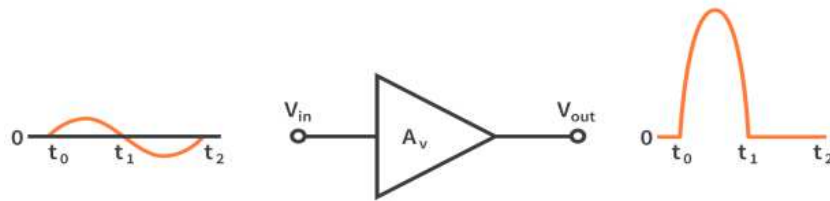


Figure III.15 Basic class B amplifier operation.

The Q Point Is at Cutoff, The class B amplifier is biased at the cutoff point so that $I_{CQ} = 0$, $V_{CEQ} = V_{CE(cutoff)}$. It is brought out of cutoff and operates in its linear region when the input signal drives the transistor into conduction. This is illustrated in Figure III.16 with an emitter-follower circuit where the output is not a replica of the input.

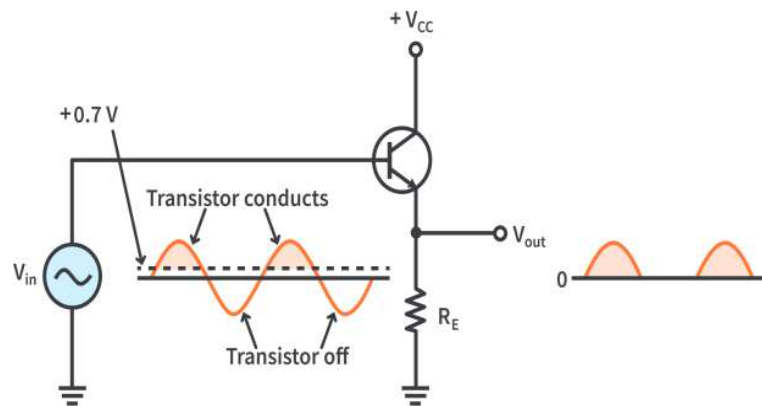


Figure III.16 Common-collector class B amplifier.

The combination of two class B amplifiers working together is called push-pull operation. To amplify the entire cycle in Figure III.17, it is necessary to add a second class B amplifier that operates on the negative half. There are two common approaches for using push-pull amplifiers: via transformer coupling and via complementary symmetry transistors; a matching pair of npn/pnp BJTs.

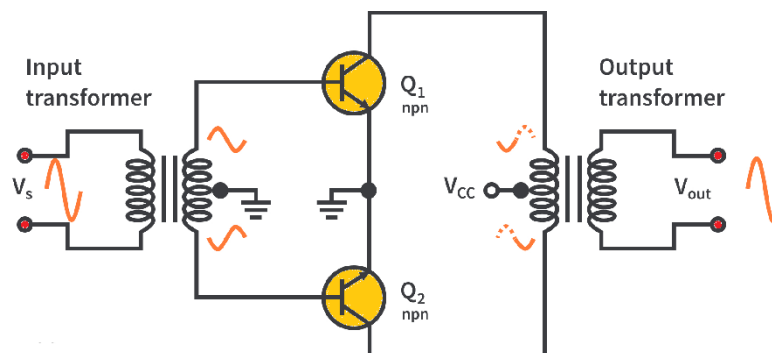


Figure III.17 Transformer-coupled push-pull amplifiers.



Consider the AC load line for Q_1 in Figure III.18. The Q point is slightly above cutoff. The AC cutoff voltage for a two-supply operation is at V_{CC} with an I_{CQ} as given earlier. $I_{c(sat)}$ for a two-supply operation with a push-pull amplifier is:

$$I_{c(sat)} = \frac{V_{CC}}{R_L}$$

The saturation current for DC is the current if the collector to emitter is shorted on both transistors. This assumed short across the power supplies obviously would cause maximum current from the supplies and implies the DC load line passes almost vertically through the cutoff. Operation along the DC load line, such as caused by thermal runaway, could produce such a high current that the transistors are destroyed.

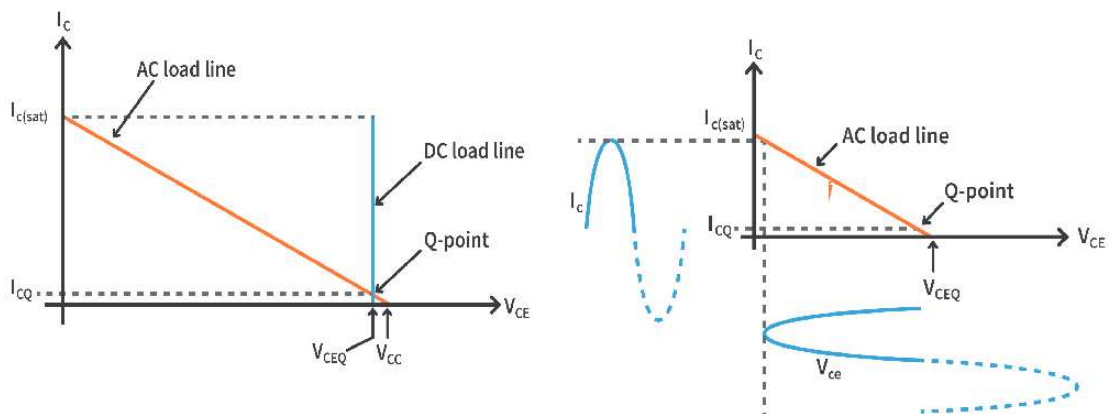


Figure III.18 Load lines for a complementary symmetry push-pull amplifier.

One transistor conducts for only one-half of the signal waveform while the other conducts for the other or opposite half of the signal waveform. This means that each transistor spends half of its time in the active region and half its time in the cut-off region thereby amplifying only 50% of the input signal (Figure III. 19).

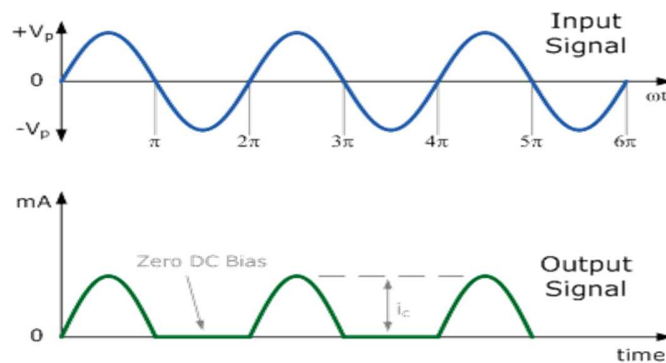


Figure III.19 Class B Amplifier Output Waveform.



III.4.3. Class C Power Amplifier

The basic concept of class C operation is illustrated in Figure III.20. These amplifiers are biased so that conduction occurs for much less than 180° , and are more efficient than either class A or push-pull class B and class AB; more output power can be obtained from class C operation.

The output amplitude is a nonlinear function of the input, so class C amplifiers are not used for linear amplification. They are generally used in radio frequency (RF) applications, such as oscillators that have a constant output amplitude, and modulators, where a high-frequency signal is controlled by a low-frequency signal.

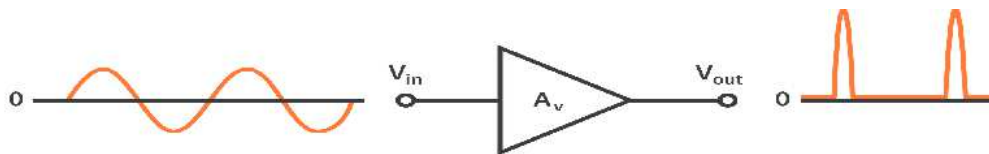


Figure III.20 Basic class C amplifier operation (noninverting)

A common-emitter class C amplifier with a resistive load is shown in Figure 21(a). It is biased below cutoff with the negative V_{BB} supply. The AC source voltage has a peak value that is slightly greater than $|V_{BB}| + V_{BE}$ so that the base voltage exceeds the base-emitter barrier potential for a short time near the positive peak of each cycle, as shown in Figure 21(b).

During this short interval, the transistor is turned on. When the entire AC load line is used, as shown in Figure 21(c), the ideal maximum collector current is $I_{c(sat)}$, and the ideal minimum collector voltage is $V_{ce(sat)}$.

The Class AB Amplifier is a compromise between the Class A and the Class B configurations above. While Class AB operation still uses two complementary transistors in its output stage a very small biasing voltage is applied to the Base of each transistor to bias them close to their cut-off region when no input signal is present (Figure III.22).

An input signal will cause the transistor to operate as normal within its active region, eliminating any crossover distortion which is always present in the class-B configuration. A small biasing Collector current (I_{CQ}) will flow through the transistor when there is no input signal present, but generally it is much less than that for the Class A amplifier configuration. Thus each transistor is conducting, "ON" for a little more than half a cycle of the input waveform. The small biasing of the Class AB amplifier configuration improves both the efficiency and linearity of the amplifier circuit compared to a pure Class A configuration above.

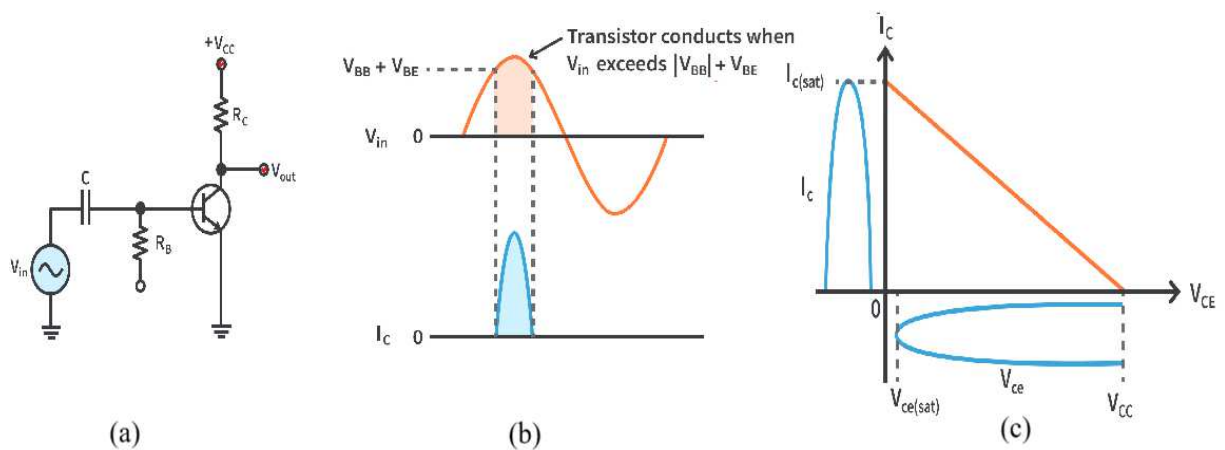


Figure III.21 Basic class C operation.

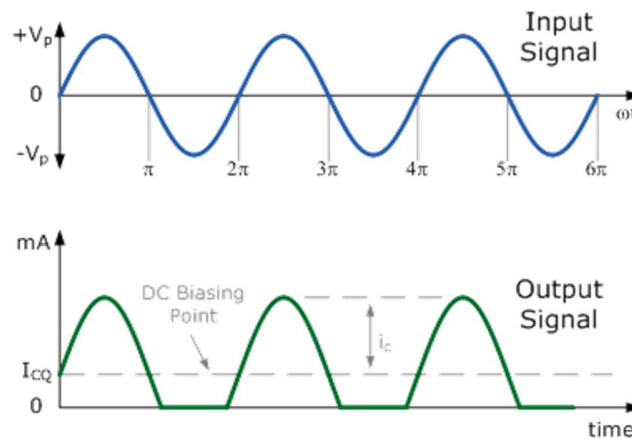


Figure III.22 Class AB Amplifier Output Waveform.

We can make a comparison between the most common types of amplifier classifications in the table III.2. Amplifiers may also require larger power transistors, more expensive heat sinks, cooling fans, or even an increase in the size of the power supply required to deliver the extra wasted power required by the amplifier. Power converted into heat from transistors, resistors or any other component for that matter, makes any electronic circuit inefficient and will result in the premature failure of the device. So why use a Class A amplifier if its efficiency is less than 40% compared to a Class B amplifier that has a higher efficiency rating of over 70%. Basically, a Class A amplifier gives a much more linear output meaning that it has, Linearity over a larger frequency response even if it does consume large amounts of DC power.)



Table III.2 Power Amplifier Classes.

Class	A	B	C	AB
Conduction Angle	360°	180°	Less than 90°	180 to 360°
Position of Q point	Centre Point of the Load Line	Exactly on the X-axis	Below the X-axis	In between the X-axis and the Centre Load Line
Overall Efficiency	Poor 25 to 30%	Better 70 to 80%	Higher than 80%	Better than A but less than B 50 to 70%
Signal Distortion	None if Correctly Biased	At the X-axis Crossover Point	Large Amounts	Small Amounts

III.5. MOSFET Amplifiers

MOSFET amplifiers are a subclass of amplifiers that use MOSFET technology to process digital signals with less power. MOSFET's are used in amplification processes because they have high input impedance and low output impedance, allowing for high voltage gain. Today, MOSFET amplifiers are the design choice for 99% of the world's microchips. The simple circuit diagram of a MOSFET amplifier is shown in the Figure III.23, in which the drain voltage (V_D), drain current (I_D), gate-source voltage (V_{GS}), and the positions of the gate, source, and drain are indicated by the letters "G", "S", and "D".

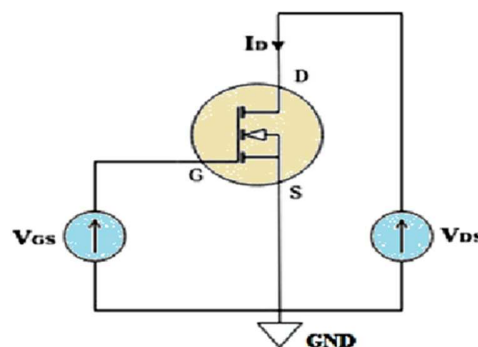


Figure III.23 MOSFET amplifier circuit.

In general, MOSFETs operate in the linear/ohmic, cut-off, and saturation regions. In these three regions, when MOSFETs are used as amplifiers, they should operate in the ohmic region, where the



current flowing through the device increases as the applied voltage increases. In this section, the basic configurations of MOSFET amplifiers will be studied similar to that of BJT. Previously, it has been shown that with the transistor DC biased at the appropriate point (Q point or operating point), linear relations can be derived between the small voltage signal and current signal.

III.5.1. Common Source MOSFET amplifier

The common source (CS) MOSFET amplifier is the analogue of the common emitter amplifier for BJT. Its popularity arises from its high gain, and that by cascading a number of them, larger amplification of the signal can be achieved. Figure III.23(a) shows the small-signal model for the common-source amplifier. Here, R_D is considered part of the amplifier and is the resistance that one measures between the drain and the ground. The small-signal model can be replaced by its hybrid- π model as shown in Figure III.23(b). Then the current induced in the output port is : $i = -g_m v_{gs}$ as indicated by the current source. Thus:

$$v_o = -g_m v_{gs} R_D$$

By inspection, one sees that:

$$R_{in} = \infty, \quad v_i = v_{sig}, \quad v_{gs} = v_i$$

Thus the open-circuit voltage gain is :

$$A_{vo} = \frac{v_o}{v_i} = -g_m R_D$$

One can replace a linear circuit driven by a source by its Thevenin equivalence. Then from the equivalent circuit model in Figure III.23(b) and the test current method by setting $v_i = 0$, the output resistance, which is the Thevenin resistor is : $R_o = R_D$.

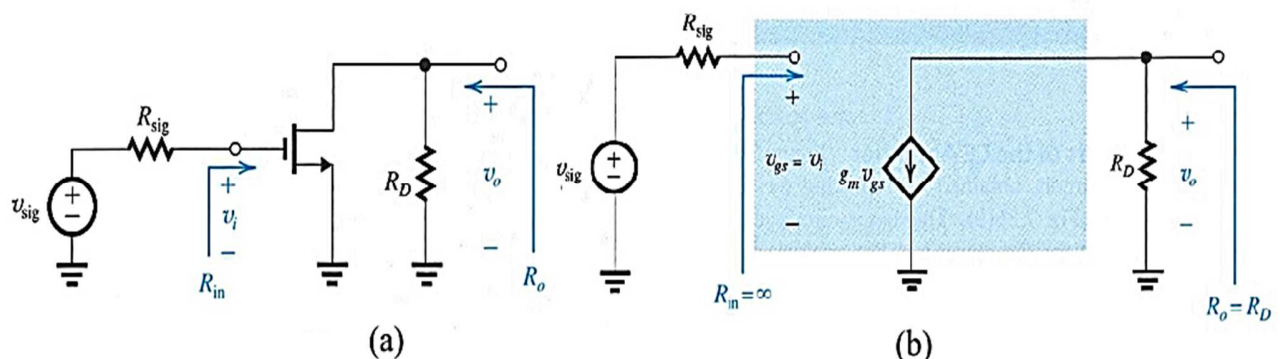


Figure III.23 (a) Small-signal model for a common source MOSFET amplifier and (b) The model for the common source amplifier.



If now, a load resistor, R_L is connected to the output across R_D , then the voltage gain proper (also called terminal voltage gain), by the voltage divider formula, is :

$$A_v = A_{vo} \frac{R_L}{R_L + R_o} = -g_m \frac{R_D R_L}{R_L + R_D} = -g_m (R_D \parallel R_L)$$

From the fact that $R_{in} = \infty$, then $v_i = v_{sig}$. The overall voltage gain, G_v , is the same as the voltage gain proper, A_v , namely:

$$G_v = -g_m (R_D \parallel R_L)$$

The CS MOSFET amplifiers has infinite input impedance (draws no current at DC), and a moderately high output resistance (easier to match), and a high voltage gain (a desirable feature of an amplifier). Reducing R_D reduces the output resistance of a CS amplifier, but unfortunately, the voltage gain is also reduced. Alternate design can be employed to reduce the output resistance (to be discussed later). CS amplifier suffers from poor high frequency performance, as most transistor amplifiers do.

III.5.2. Common Source Amplifier with a Source Resistance

As shown in Figure III.24, a T model is used for the equivalent circuit for simplicity. It is seen that the input resistance of the circuit is infinite because no gate current flows.

As a consequence, $v_i = v_{sig}$. However, because of the existence of the source resistance, less of the input voltage is divided to v_{gs} , by the voltage divider formula. Thus:

$$v_{gs} = v_i \frac{1/g_m}{1/g_m + R_s} = \frac{v_i}{1 + g_m R_s}$$

It is seen that R_s can be used to make v_{gs} small so that there is less nonlinear distortion as the small signal approximations will become better. The output voltage is generated by the controlled current source yielding:

$$v_o = -iR_D$$

The current i can be found by:

$$i = \frac{v_i}{1/g_m + R_s} = \frac{g_m}{1 + g_m R_s} v_i$$

Thus the open-circuit voltage gain (assume that R_D is part of the amplifier) is:



$$A_{vo} = \frac{v_o}{v_i} = -\frac{g_m R_D}{1 + g_m R_s} = -\frac{R_D}{1/g_m + R_s}$$

The above shows that including the source resistance reduces the amplifier gain by a factor of $1 + g_m R_s$, but linearity and bandwidth performance (to be shown later) will improve. This is called negative feedback because when the input voltage v_i or v_{gs} attempts to increase, the voltage drop across R_s increases reducing v_{gs} . The source resistance is also called source-degeneration resistance.

Since this is a linear circuit, the Thevenin equivalence of the amplifier looking in from the right can be easily found. The open-circuit voltage allows us to easily find the equivalent Thevenin voltage source. The equivalent Thevenin resistor is R_o which is just R_D in this case. When a load resistor R_L is added, then the voltage gain proper (also called terminal voltage gain)

$$A_v = -\frac{g_m (R_D \parallel R_L)}{1 + g_m R_s} = -\frac{R_D \parallel R_L}{1/g_m + R_s}$$

Because the input resistance is infinite, hence $v_i = v_{sig}$ and the overall voltage gain $G_v = A_v$.

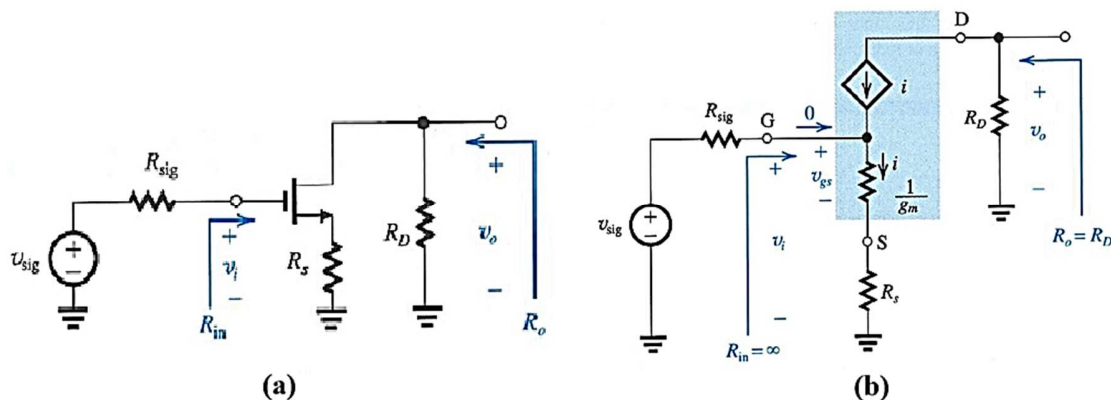


Figure III.24 (a) CS Amplifier with a source resistance and (b) equivalent circuit T model.

Summary of the CS Amplifier with Source Resistance:

The input resistance R_{in} is infinite, The open-circuit voltage gain, A_{vo} , is reduced by a factor of $1 + g_m R_s$, for the same nonlinear distortion, the input signal can be increased by a factor of $1 + g_m R_s$ compared to without R_s and as shall be shown later, the high-frequency response of this design is improved.

III.5.3. Common Gate (CG) Amplifier

The small-signal and a T-model equivalent-circuit common-gate (CG) amplifier is shown in Figure III.25. By inspection, the input resistance R_{in} is given by:



$$R_{in} = \frac{1}{g_m}$$

Which is typically a few hundred ohms, a low input impedance. The output voltage is:

$$i = -\frac{v_i}{1/g_m} = -g_m v_i$$

Hence the open-circuit voltage gain is:

$$A_{vo} = \frac{v_o}{v_i} = g_m R_D$$

Which is similar to that of the CS amplifier save for a sign change. The output resistance (or the Thevenin equivalent resistor) of the circuit is :

$$R_o = R_D$$

When a load resistor R_L is connected to the output, the voltage gain proper (terminal voltage gain) is then :

$$A_v = g_m R_D R_L$$

Thus the overall voltage gain is:

$$G_v = \frac{1/g_m}{R_{sig} + 1/g_m} g_m (R_D \parallel R_L) = \frac{R_D \parallel R_L}{R_{sig} + 1/g_m}$$

As the input impedance is low, it is good for matching sources with a low input impedance due the maximum power theorem, but it draws more current, implying high power consumption from the signal source.

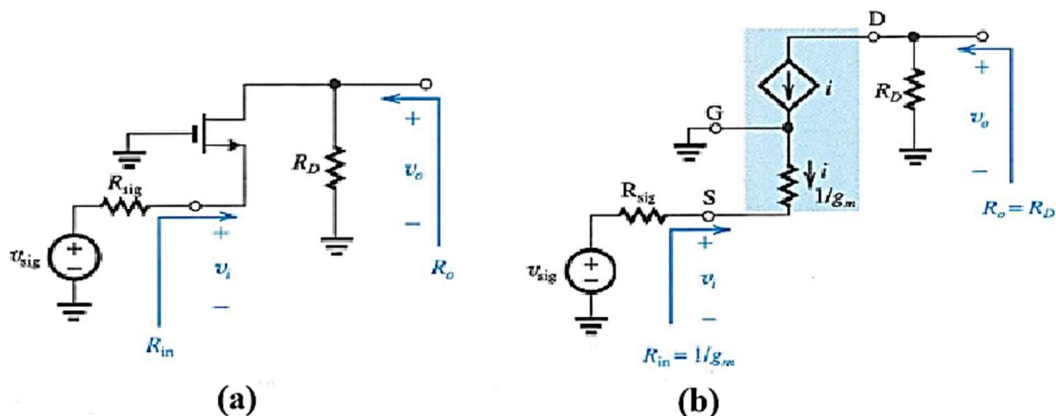


Figure III.25 (a) Small-signal model for a common-gate amplifier and (b) The T model equivalent.



This is similar to the emitter follower for the BJT, which is used as a voltage buffer. It is a unit-gain amplifier with a very large input impedance but a smaller output impedance. Therefore it is good for matching a high-impedance circuit to a low-impedance circuit. The input source is represented by a Thevenin equivalent voltage v_{sig} and resistor R_{sig} . A load resistor is connected to the output between the source and ground.

Since the gate current is zero for this circuit,

$$R_{in} = \infty$$

Using the voltage divider formula, it is seen that voltage gain proper or terminal voltage gain is :

$$A_v = \frac{v_o}{v_i} = \frac{R_L}{R_L + 1/g_m}$$

For the open-circuit voltage gain, $R_L = \infty$ and $A_{vo} = 1$, the output resistance is obtained by replacing the proper part of the amplifier with a Thevenin equivalence. To this end, with the use of the test current method, the value of $v_i = 0$, and thus :

$$R_o = 1/g_m$$

Because of the infinite input impedance R_{in} , then $v_i = v_{sig}$, and the overall voltage gain G_v (also called the total voltage gain) is the same as the voltage gain proper A_v (also called terminal voltage gain)

$$G_v = A_v = \frac{R_L}{R_L + 1/g_m}$$

Since $1/g_m$ is typically small, with large R_L , the gain is less than unity, but is close to unity. Hence, this is a source follower.

The following concluding points are in order for the MOSFET and BJT amplifiers.

- MOS amplifiers have high input impedance (except for CG amplifiers). This is an advantage over BJT amplifiers.
- BJT's have higher transconductance g_m than MOSFET's giving BJT amplifiers higher gains.
- Discrete-circuit amplifiers, e.g., circuits assembled on printed-circuit board (PCB), BJT's are prevalent because of their longer history and wider commercial availability.
- Because of easier fabrication, integrated circuit (IC) amplifiers are dominated by MOSFET's.



- The CS and CE configurations are best suited for gain amplifiers because of their larger than unity gain. A cascade of them can be used to increase the gain.
- The addition of R_s in a CS amplifier improves the linearity of the circuit and better high frequency performance.

III.6. Applications of Amplifiers

An amplifier is a circuit that increases the value of a physical quantity, particularly a voltage or current. Signal amplifiers increase the power of weak electrical signals to make them suitable for further processing or use, such as in radio receivers, audio equipment, and computers. In an electronic amplifier, one electrical quantity controls another quantity. Amplification can be realized using various components, including vacuum tubes, transistors, operational amplifiers, and integrated circuit amplifiers. Small signal amplifiers accept small input signals and amplify them without significantly changing their shape. The transistor configurations used for small signal amplifiers include common emitter, common base, and common collector. Large signal amplifiers accept large input signals, and the transistor is driven into cutoff or saturation, resulting in a distortion of the input signal shape. Class A, B, AB, and C configurations are used for large signal amplifiers.

III.6.1. Audio Amplifiers

The simplest arrangements of coupled transistors will yield voltage amplifiers providing an audio range bandwidth of more than 50 Hz with reasonable gain figures. A Darlington emitter follower configuration with a transistor pair can yield a current gain of 10^3 , and yet have a bandwidth extending well into the MHz range. Transistor hybrids in ceramic packages with multiplier. Most low-noise wide bandwidth integrated audio preamplifiers can be assembled using low-cost discrete transistors.

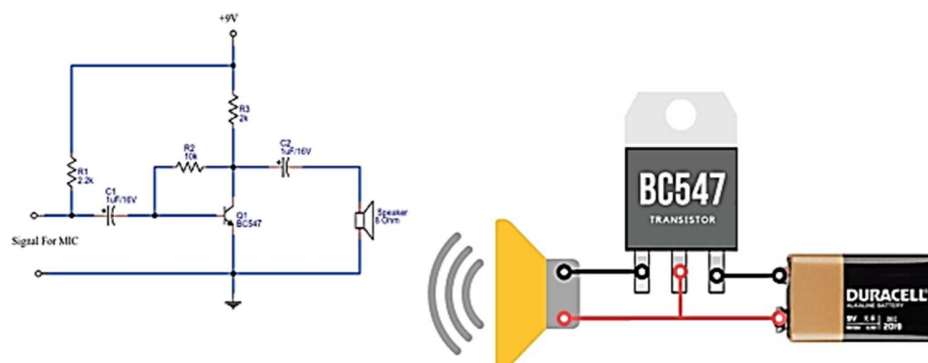


Figure III.26 Audio Amplifiers.

Successful audio amplifier designs must strive for high performance figures, but also take into account parameters important to consumer end products. Cost constraints will severely limit package



size, and hence cross-sectional area, which compromises heat sinking. Consequently, the output stage is often a class B arrangement. Transistor selection is critical, as high h_{FE} , low $V_{CE(sat)}$ devices are required. Even with these, careful attention to symmetry in the differential pair, current mirror output configuration. A good compromise design must accommodate parameters such as h_{FE} temperature coefficient, T , package V_{BE} variation, input and output node capacitance, and class B output cross-over conduction delay. Added to these must be included considerations routing of input nodes and power supply decoupling, even to the degree of input transistor location relative to the package sealing weld to avoid interference.

III.6.2. Radio Frequency (RF) Amplifiers

Low level RF amplifiers are used to increase the signal level for proper treatment and manipulation. The relevant standard specifications used to qualify the performance of small signal amplifiers are: Temperature range usually from $-40\text{ }^{\circ}\text{C}$ to $+125\text{ }^{\circ}\text{C}$; DC supply voltage nominal value and maximum variation; DC power consumption maximum power at DC supply line; Transistor technology type; number of transistors and packages used; Frequency range from DC to $> 10\text{ GHz}$, multi-decades covered by a single device; Output level maximum power at the amplifier output; Gain and gain flatness ratio between the output and input levels, typically expressed in dB; 1 dB compression point output level corresponding to a 1 dB reduced gain; Noise figure ratio between the input and output signal-to-noise ratios; Dynamic range potential excursion of the output level; Two-tone third-order intercept point measures the amplifier linearity; Input/output or return loss measure of the input/output matching characteristics of the amplifier. Nowadays, solid-state technology is used for low/medium power applications, up to $\approx 10\text{ GHz}$. For higher power application, vacuum tube technology still holds.

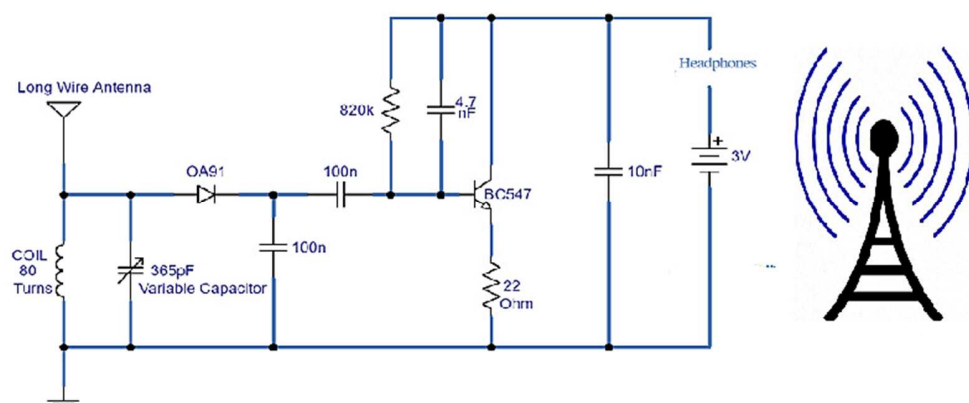


Figure III.26 Radio Frequency (RF) Amplifiers.



Active devices used in solid-state RF amplifiers are bipolar transistors, and low temperature grown. Small signal amplifiers generally operate in class A since power efficiency is not an issue in this context. Transformers are widely used in RF electronics. They are effective to match lines of different impedance with negligible insertion loss, de-couple ground while transmitting RF signals, and connect balanced and unbalanced circuits.

III.6.3. Instrumentation Amplifiers

Instrumentation amplifiers (in-amps) are a special type of differential amplifiers with additional buffering stages at the input. They have three basic characteristics that make them suitable for low level differential signal amplification: a very high input impedance, a gain that can be precisely set with a single resistor, and a high common mode rejection ratio (Figure III.27). Because of these important characteristics, they are commonly used in low level sensor applications, for example, thermocouples or RTD sensors and strain gauges. Since sensor signals are typically very low and susceptible to noise, amplifier front-end design becomes critical to system performance. Instrumentation amplifiers can be designed using either three op-amps or two op-amps with instrumentation input stages. Using two op-amps, the in-amp architecture requires an additional active device to provide high input impedance, which is typically done using a buffer stage. The three op-amp topology is considered classic and is the simplest implementation of an instrumentation amplifier. Op-amp A3 is configured as a differential stage and provides summation.

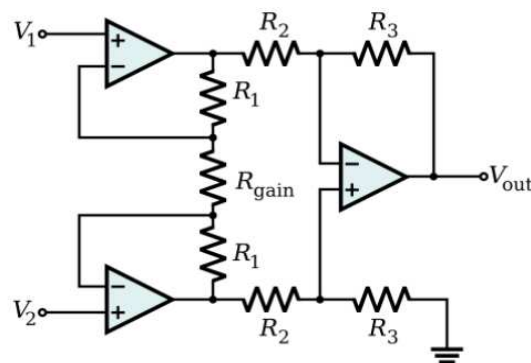


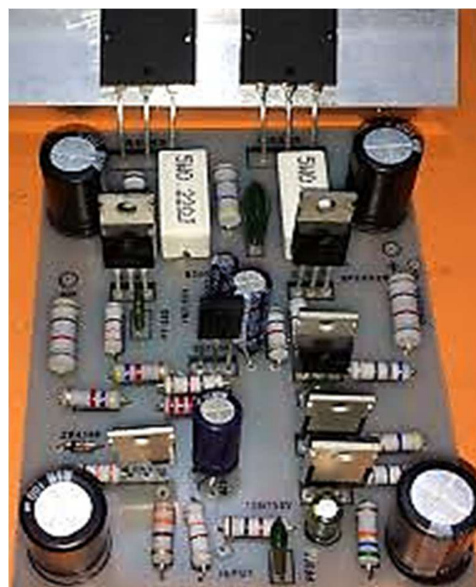
Figure III.27 Instrumentation Amplifiers.

The two other op-amps, A₁ and A₂, buffer the input signals. The three op-amp in-amp provides precise gain matching with a simple resistor configuration. A single resistor R_G sets the gain, and the input resistor of the difference amplifier stage is designed with an equivalent value. Because of the feedback network's topology, resistors R₅, R₆, and R_G must also satisfy the matching condition, R₅ = R₆, or else the gain would differ and would result in poor performance.



III.7. Conclusion and Summary

Amplifiers form the crux of many electronic systems with a broad range of consumer and industrial applications. The basic concepts of amplifiers, as well as the types of amplifiers, were discussed and explained with illustrations. Most amplifiers can be categorized as voltage, current, or transconductance amplifiers based on the type of input and output signals processed. Similarly, amplifiers can be classified as unidirectional or differential amplifiers based on the input signal configuration. The operational principles of several commonly used amplifiers were reviewed. The important amplifier performance parameters, including gain, bandwidth, slew rate, input impedance, and output impedance, were discussed. The influence of performance parameters on amplifier design was also highlighted. The small-signal and large-signal equivalent models of bipolar junction transistors (BJTs) and MOSFETs were investigated. The small-signal equivalent models were used to derive the performance parameters of some commonly used amplifiers. The performance evaluation results were compared with the theoretical predictions. Amplifiers form an integral part of many consumer and industrial electronic systems. The importance of amplifiers was highlighted through some system-level examples. The different types of amplifiers were discussed with detailed operational principles and applications. The importance of performance parameters such as gain, bandwidth, slew rate, and impedance was highlighted with a few design examples. The evolution of amplifier technology from discrete transistors to integrated circuit solutions and the current state-of-the-art was discussed. The significance of amplifiers in modern electronic systems was highlighted. Amplifiers will continue to play an important role in advanced electronic systems with applications in emerging areas such as biomedical, automotive, and space exploration.





Questions & Answers

1. Define an Amplifier.

An amplifier is defined as the device which increases the magnitude of the input signal and produces a larger electrical output.

2. Define small signal amplifier.

The amplifier which operates on small signal is called small signal amplifier small signal indicates that the input signal is very small in the range of few mV.

3. What do you mean by hybrid parameter?

- The input current i_1 and the output voltage V_2 are taken as independent variables.
- The input voltage V_1 and the output current i_2 are expressed in terms of i_1 and V_2 .
- The units of these four parameters are completely different from each other, these parameters are called hybrid parameters.

4. What are the factors affecting h-parameters?

Transistor type, transistor configuration, operating point, frequency and temperature.

5. What are the advantages of h-parameter?

Easy to measure from static characteristics of transistor; simple conversion from one configuration to other; can be used up to radio frequencies and convenient for circuit analysis and design.

6. List the steps involved in small signal analysis of amplifier.

Draw the ac equivalent circuit of the amplifier, draw the hybrid equivalent circuit, calculate the input impedance, output impedance, current gain and voltage gain.

7. How ac equivalent circuit is obtained?

- Replace the dc voltage source by short circuit
- Replace coupling and bypass capacitor by short circuit.

8. Write the characteristics of CE amplifier.

- Good voltage gain
- Output voltage is 180° out of phase with input
- Good current gain and power gain

9. List the characteristics of CB amplifier.

- Provides voltage gain and power gain
- High output impedance and very low input impedance



- No current gain

10. List the characteristics of CC amplifier.

- Provides current gain and power gain
- High input impedance and very low output impedance 3. No voltage gain

11. Why common drain amplifier is called source follower?

The input signal is applied to the gate terminal and the output terminal is taken from the source terminal. The source exactly follows the input signal. Hence it is called as source follower.

12. Write the properties of common source amplifier.

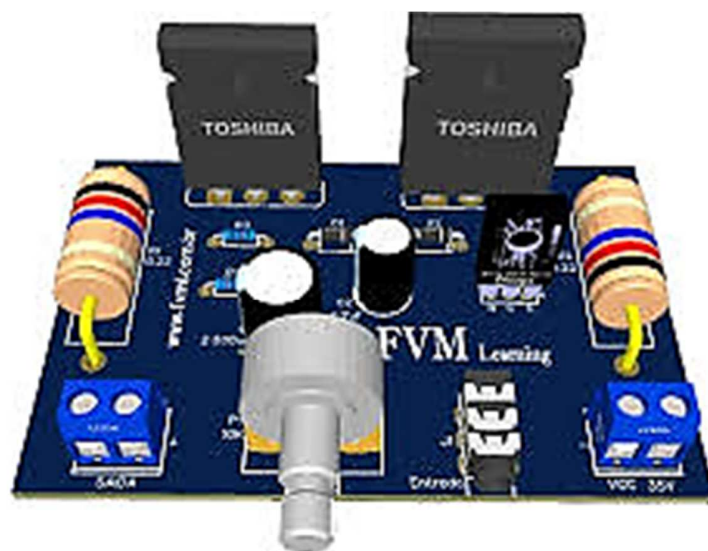
- High input and output impedance
- Relatively high small-signal voltage gain.
- Very high small-signal current gain.

13. List the properties of common drain amplifier.

- Non inverting amplifier
- Very large input impedance
- Small output impedance
- Voltage gain $A_V < 1$
- Large small-signal current gain

14. Define voltage gain of the cascaded amplifier.

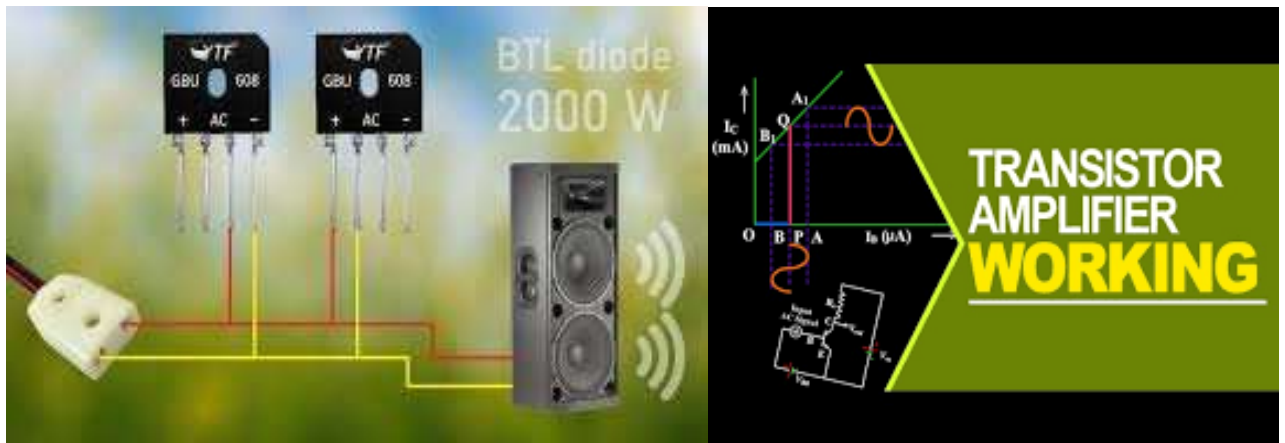
The voltage gain of the cascaded amplifier is defined as the product of the individual voltage gain of each stage.





Chapter IV

Reactions in Amplifiers



IV.1. Introduction

Amplifier circuits, in their simplest form, consist of an active two-port device combined with passive components. These devices perform some of the most fundamental linear transformations encountered in electronics. Given their centrality, amplifiers have been the focus of many analyses, both empirical and mathematical. As with most linear systems, the performance of basic amplifier circuits was well understood long before integrated circuit technology became dominant. The challenge then lay in how to replicate amplifier performance in small and low power integrated circuits. This led to major advances in both the finesse of the amplifier circuits themselves, as well as the associated design techniques. An amplifier is characterized by a number of parameters, but the most important parameters are gain, bandwidth, input impedance, and output impedance. Input impedance is the output impedance of the previous stage as seen from the input terminals of the amplifier. Output impedance is the output impedance of the amplifier as seen from the output terminals. For the successful and desired operation of signal processing from one stage to another, these impedances play a major role. In amplifiers, "reactions" can refer to several different concepts, including feedback mechanisms, phase shifts, and the interaction of different components within the circuit.



IV.2. Importance of Stability and Reactivity in Amplifiers

In the context of amplifiers, reactions are understood as changes in amplifier output caused by fluctuations in influenced characteristics. Influenced characteristics may include temperature alterations and fluctuations in supply voltages, bias determination resistors, input or output signal levels, or the internal gain of the amplifier. The important notion of stability in amplifiers relates directly to reactivity, as stable amplifiers will exhibit less reactivity compared to unsteady amplifiers. For a desirable and useful operation of amplifiers, stability is of extreme importance. Stability in amplifiers is defined as an amplifier's ability to maintain the same operating state without self-generated oscillations despite alterations in influenced characteristics. Generally, oscillations want to occur more readily in amplifiers with higher internal gain and phase shift, and these conditions must be avoided for a stable operation of amplifiers. Nevertheless, inspired by the ability of amplifiers to propagate signals, feedback within amplifiers may be used to create oscillators that regularly regenerate the same signal. An understanding of stability is crucial for amplifier applications in communications, where the propagation of certain frequencies is desired and oscillations at unwanted frequencies will degrade the performance. Therefore, it is necessary to have amplifiers designed with considerations that ensure a stable operation, even in practical implementations that involve external components and characteristics.

Reactivity in amplifiers is generally understood as a phase shift between the conditioned input and output signals of the amplifier. A typical amplifier's output voltage is determined by an internal gain multiplied by an input voltage. Since the input and output voltages are conditioned by the same internal gain, a phase difference occurs as internal gains usually involve phase shift elements. Amplifiers may also actively mitigate the effects of some inputs on the outputs, which is implemented using feedback. Phase shifts inevitably accompany all propagation elements and will affect the output states of the amplifiers. This causes a change in output states given a change in input states and results in undesired oscillations if the changes are on a similar time scale. This highlights the importance of stability and reactivity, thus providing a basis for further discussion of the involved phase shift and feedback in amplifiers. Additionally, it is noted that reactive components are often used in amplifiers to tune the desired performance and stability margins.

IV.3. Feedback in Amplifiers.

If a portion of the output of an amplifier is fed back to its input, the amplifier is said to have feedback. Feedback can be either negative or positive. If the feedback tends to reduce the effect of the input signal on output, it is referred to as negative feedback. If the feedback tends to increase the effect



of the input signal on output, it is referred to as positive feedback. In most applications, amplifiers employ negative feedback. A negative feedback amplifier has good frequency stability. It can also stabilize gain against variations in temperature and device parameters. Such an amplifier has reduced distortion. In addition to these advantages, a feedback amplifier can be designed to have a specific input or output impedance. A feedback amplifier can also be used to increase the bandwidth of cascading stages. Power amplifiers without feedback tend to be non-linear for large input signals. Such amplifiers have harmonic distortion at the output. Using feedback in these amplifiers linearizes the output characteristics. Amplifiers are widely used in various electronic applications to increase signal levels. As the states of transistors in wearable devices change, amplifiers must be designed to adapt to these changes. Thus, feedback is a vital concept that addresses how the output of an amplifier influences its input. Feedback profoundly affects the stability and performance of amplifiers. It is broadly categorized into two types: negative and positive feedback. Negative feedback involves returning a portion of the output in an inverted form to the input, while positive feedback returns a portion of the output in a non-inverted form. The two feedback types have profoundly different effects on amplifiers, which are detailed in this chapter. Negative feedback reduces distortion in amplifiers and expands the bandwidth of amplifiers. However, negative feedback should be carefully applied in the design process since it has been found that applying too much negative feedback can make amplifiers inoperable.

From the perspective of closed-loop gain in amplifiers, negative feedback is analyzed concerning its impact on gain stability. Negative feedback reduces the gain sensitivity of an amplifier, which means amplifier gain is less affected by variations in amplifier parameters. Positive feedback applies gain enhancement to amplify inaudible signals. Still, it also produces other unwanted effects, such as circuit oscillation, as designers find out in their transistor amplifier designs. In the regard of gain, positive feedback might be useful for amplifier designs in the vicinity of circuit oscillation. However, for most amplifier designs, positive feedback should be avoided. Considering the practical implications of feedback, simple circuit examples are shown to understand it better.

The first two examples illustrate the negative feedback effect in amplifiers. The last two examples depict how positive feedback is utilized in design, one for gain enhancement and the other for resistance enhancement. Illustrating these mechanisms practical applications found in real designs highlights how feedback greatly impacts amplifiers. The process of injecting a fraction of output energy of some device back to the input is known as feedback. A feedback amplifier is one in which a fraction of the amplifier output is fed back to the input circuit.



a) For an ordinary amplifier i.e. one without feedback, the voltage gain is given by the ratio of the output voltage V_o (or V_0) and input voltage V_s . As shown in the block diagram of Figure IV.1, the input voltage V_s is amplified by a factor of A to the value V_o of the output, where:

$$A = V_o/V_s$$

b) A feedback amplifier generally consists of two parts. They are the amplifier and the feedback circuit.

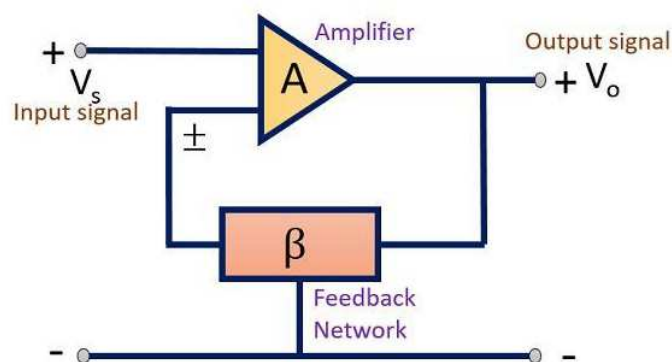


Figure IV.1 Diagram of feedback amplifier.

Depending on the changes in the output signal when a feedback is applied, we have two different types of feedback, namely (i) positive or regenerative feedback and (ii) negative or degenerative feedback.

When the feedback energy (voltage or current) is in phase with the input signal and thus aids it, it is called positive feedback. Both amplifier and feedback network introduce a phase shift of 180° . The result is a 360° phase shift around the loop. When the feedback energy (voltage or current) is out of phase with the input signal and thus opposes it, it is called negative feedback the amplifier introduces a phase shift of 180° into the circuit while the feedback network is so designed that it introduces no phase shift if the feedback signal is of opposite polarity to the input signal, as shown in Fig.1, negative feedback results.

While negative feedback results in reduced overall voltage gain, a number of improvements are obtained, among them being: Higher input impedance, lower output impedance, better stabilized voltage gain, improved frequency response, reduced noise and more linear operation.



IV.3.1. Positive Feedback

In an amplifier circuit with positive feedback (Figure IV.2), an increase in input always results in an increase at the output, and there are always conditions to ensure it functions as an amplifier. However, amplifiers may not take input as it is and may unintentionally alter its nature. They might just work as oscillators and disregard any form of input signal. Only one feedback system must be ensured when designing positive feedback amplifiers, which is there must be only one point of negativity in the system. Everything must ensure this point remains stable. It is also important to note that the gain from external inputs is insignificant relative to internal gains. The feedback in which the feedback energy (voltage or current) is in phase with the input signal and thus aids, it is called as Positive feedback. Positive feedback increases the gain of the amplifier and it is also called regenerative feedback. However, it has the disadvantages of increased distortion and instability. Therefore, positive feedback is seldom employed in amplifiers. One important use of positive feedback is in oscillators. As we shall see in the next chapter, if positive feedback is sufficiently large, it leads to oscillations. As a matter of fact, an oscillator is a device that converts DC power into AC.

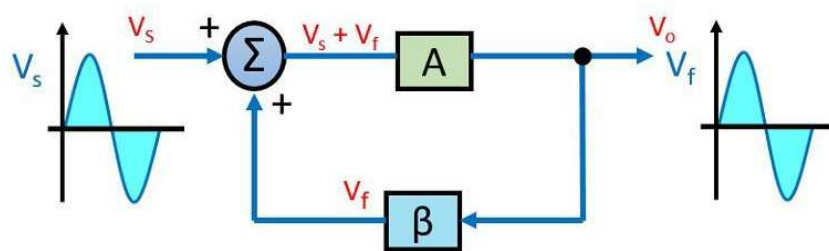


Figure IV.2 Positive Feedback operation.

So, the gain of the amplifier is given as :

$$A_{vf} = \frac{A}{1 - \beta A}$$

This is the gain for a positive feedback amplifier. Moving further when we talk about negative feedback amplifier, the source signal and the feedback signal are out of phase with respect to each other. Thus the mixer circuit will resultantly produce the difference between the two signal in case of a negative feedback amplifier.



IV.3.2. Negative Feedback

Negative Feedback is one of the most powerful techniques available to the designer of amplifiers. It consists in feeding back a portion of the output signal to the input, in such a way that the signal fed back counteracts the input signal (Figure IV.3). Thus if there is an increase in the output signal, a corresponding feedback signal is applied to reduce it, and vice versa. In this way, any change in the output which would tend to change the gain will be counteracted by negative feedback. Negative feedback can therefore be used to make the gain of an amplifier far less sensitive to other parameters which may vary greatly. If at one time a particular design and value of gain is chosen, it will remain virtually unchanged for all foreseeable variations in the parameters. In addition to this main property of making the gain stable, negative feedback has a number of advantages. First, it will be shown that negative feedback reduces the non-linear distortion created by an amplifier. The presence of distortion in the output signal means that there is a non-linear relationship between the input and output, and therefore between the desired signal and the unwanted terms which it creates. Negative feedback counteracts this non-linearity by acting on the output signal, minimising the difference between the input and the output. Second, it will be shown that the bandwidth of an amplifier is increased by negative feedback. In the simple model of an amplifier as a gain which gradually rolls off with frequency, negative feedback compensates for this roll off.

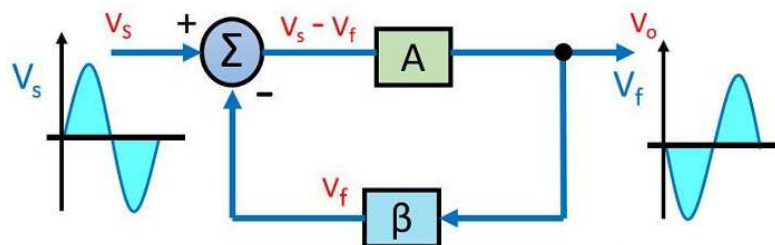


Figure IV.3 Positive Feedback operation.

So, in this case, the gain of the amplifier is given as :

$$A_{vf} = \frac{A}{1 + \beta A}$$

For a negative feedback, the value of denominator is always greater than 1, this will decrease the overall gain of the system by the factor $1 + A\beta$. In case of a positive feedback system, the value of denominator is always less than 1, this will resultantly increase the overall gain by $1 - A\beta$. For an ideal system, the gain of the amplifier is infinite. Thus, for a smaller input, we will have a much higher value



as output. So, such a large gain is not desirable in the circuit. The system becomes stable only when its gain is small. Hence, by decreasing the gain the stability of the system increases and vice-versa. So to have a stable system, the gain of the amplifier must be small and it is achieved by employing negative feedback in the circuit.

IV.3.3. Unity Feedback system

Let us now discuss the case where no any feedback network is employed in the amplifier circuit but feedback is provided in the circuit by some physical connection (Figure IV.4).

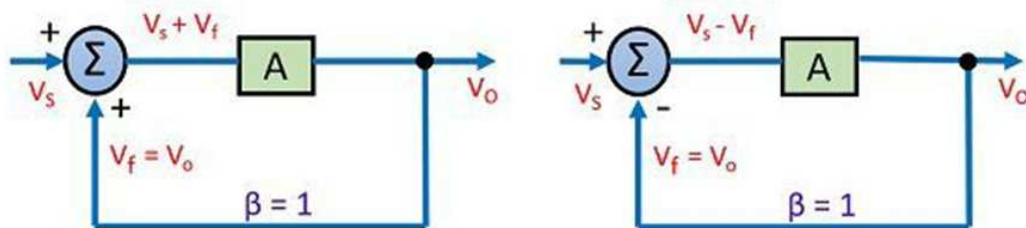


Figure IV.4 Unity feedback system with (a) positive and (b) negative feedback.

Here, we will have $\beta = 1$. So, for positive feedback amplifier:

$$A_{vf} = \frac{A}{1 - \beta A}$$

And in case of the negative feedback amplifier:

$$A_{vf} = \frac{A}{1 + \beta A}$$

Hence we can say that the gain of an amplifier depends on the type of feedback employed in the circuit. From the above discussion, we can conclude that a negative feedback is much better than positive feedback. However, it is possible to increase the bandwidth with respect to the roll-off frequency of the amplifier's gain itself. The feedback, in which the feedback energy (voltage or current) is 180° out of phase with the input and thus opposes it, is called as negative feedback. Negative feedback reduces the gain of the amplifier and it is also called degenerative feedback. Advantages of Negative Feedback are:

- **Stability of gain is improved :** The output of an ordinary amplifier is easily changed due to variations in ambient temperature, frequency and signal amplitude. This changes the gain of the amplifier, resulting in distortion. However, by applying negative voltage feedback, voltage gain of



the amplifier is stabilized or accurately fixed in value. This can be easily explained. Suppose the output of a negative voltage feedback amplifier has increased because of temperature change or due to some other reason. This means more negative feedback since feedback is being given from the output. This tends to oppose the increase in amplification and maintains it stable. The same is true should the output voltage decrease. Consequently, the circuit stability is considerably increased.

- Reduction in distortion (amplitude, frequency, phase and harmonic) : A large signal stage has non-linear distortion because its voltage gain changes at various points in the cycle. The negative voltage feedback reduces the nonlinear distortion in large signal amplifiers. It is clear that by applying negative voltage feedback to an amplifier, distortion is reduced by a factor $1 + A\beta$.
- Increase in input impedance : It is clear that by applying negative voltage feedback, the input impedance of the amplifier is increased by a factor $1 + A\beta$. As $A\beta$ is much greater than unity, therefore, input impedance is increased considerably. This is an advantage, since the amplifier will now present less of a load to its source circuit.
- Decrease in output impedance : It is clear that by applying negative feedback, the output impedance of the amplifier is decreased by a factor $1 + A\beta$, This is an added benefit of using negative voltage feedback. With lower value of output impedance, the amplifier is much better suited to drive low impedance loads. However, it is because of these advantages negative feedback is frequently employed in amplifiers. Finally, a disadvantage of negative feedback should also be mentioned. For reasons that will become clear, too much feedback will result in instability. It is actually the case that all practical systems have some amount of instability. In the case of negative feedback amplifiers, they will oscillate if the gain exceeds approximately 40 dB. For this reason closed-control systems and feedback amplifiers should be designed so that they are stable, as a feedback amplifier will oscillate if it is too well designed.

IV.4. Feedback Connection Types

There are four basic ways of connecting the feedback signal. Both voltage and current can be fed back to the input either in series or parallel. Specifically, there can be: Voltage-series feedback (Figure IV.5(a)). Voltage-shunt feedback (Figure IV.5(b)). Current-series feedback (Figure IV.5(c)). Current-shunt feedback (Figure IV.5(d)). In the list above, voltage refers to connecting the output voltage as input to the feedback network; current refers to tapping off some output current through the feedback network. Series refers to connecting the feedback signal in series with the input signal voltage; shunt refers to connecting the feedback signal in shunt (parallel) with an input current source. Generally, series feedback connections tend to increase the input resistance, while shunt feedback connections



tend to decrease the input resistance. Voltage feedback tends to decrease the output impedance, while current feedback tends to increase the output impedance.

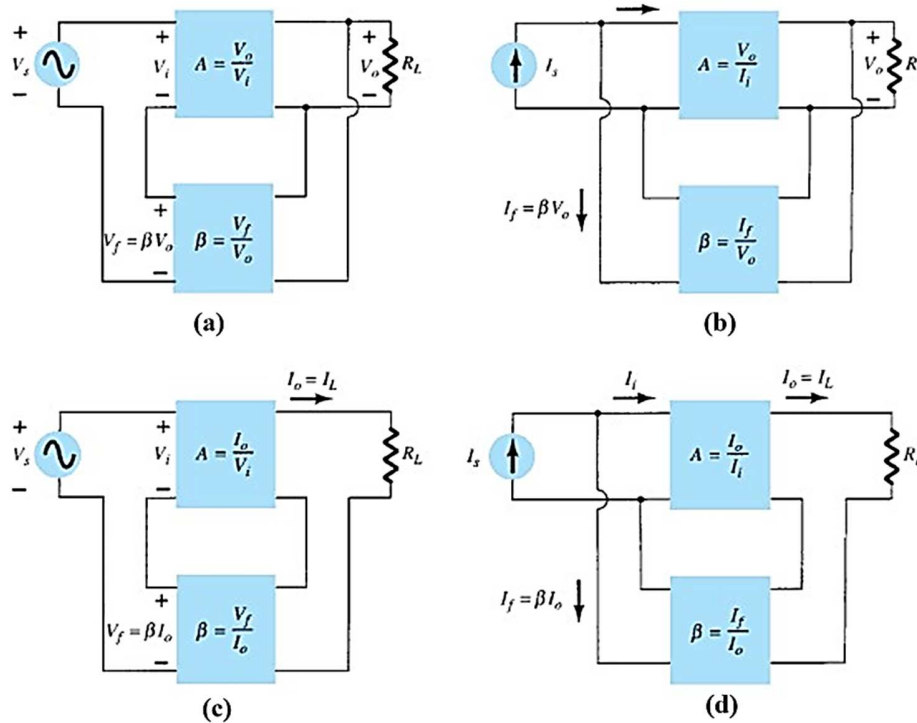


Figure IV.5 Feedback Connection Types (a) Voltage-series feedback , (b) Voltage-shunt feedback, (c) Current-series feedback and (c) Current-shunt feedback (Figure IV.5(d)).

The gain without feedback, A , is that of the amplifier stage. With feedback, β , the Overall gain of the circuit is reduced by a factor $(1 + \beta A)$, as detailed below. A summary of the gain, feedback factor, and gain with feedback of Figure IV.5 is provided for reference in Table IV.1.

- **Voltage-Series Feedback:** From Figure IV.5(a) and Table IV.1, the gain A_f is:

$$A_f = \frac{V_o}{V_s} = \frac{V_o}{V_i + V_f} = \frac{V_o}{V_i + \beta V_o} = \frac{AV_i}{V_i + \beta AV_i},$$

The gain with feedback is:

$$A_f = \frac{V_o}{V_s} = \frac{A}{1 + \beta A}$$

- **Voltage-Shunt Feedback:** From Figure IV.5(b) and Table IV.1, the gain A_f is:



$$Af = \frac{V_o}{I_s} = \frac{V_o}{I_i + I_f} = \frac{V_o}{I_i + \beta V_o} = \frac{AI_i}{I_i + \beta AI_i}$$

The gain with feedback is:

$$A_f = \frac{V_o}{I_s} = \frac{A}{1 + \beta A}$$

- **Current-Series Feedback:** From Figure IV.5(c) and Table IV.1, the gain A_f is:

$$Af = \frac{I_o}{V_s} = \frac{I_o}{V_i + V_f} = \frac{I_o}{V_i + \beta I_o} = \frac{AV_i}{V_i + \beta AV_i}$$

The gain with feedback is:

$$A_f = \frac{I_o}{V_s} = \frac{A}{1 + \beta A}$$

- **Current-Shunt Feedback:** From Figure IV.5(d) and Table IV.1, the gain A_f is:

$$Af = \frac{I_o}{I_s} = \frac{I_o}{I_i + I_f} = \frac{I_o}{I_i + \beta I_o} = \frac{AI_i}{I_i + \beta AI_i}$$

The gain with feedback is:

$$A_f = \frac{I_o}{I_s} = \frac{A}{1 + \beta A}$$

Table IV.1 Parameters of feedback types.

Parameters		Feedback Types			
		Voltage series	Voltage- shunt	Current series	Current-shunt
Gain without feedback	A	$\frac{V_o}{V_i}$	$\frac{V_o}{I_i}$	$\frac{I_o}{V_i}$	$\frac{I_o}{I_i}$
Feedback	β	$\frac{V_f}{V_o}$	$\frac{I_f}{V_o}$	$\frac{V_f}{I_o}$	$\frac{I_f}{I_o}$
Gain with feedback	A_f	$\frac{V_o}{V_s}$	$\frac{V_o}{I_s}$	$\frac{I_o}{V_s}$	$\frac{I_o}{I_s}$



IV.4.1. Input Impedance with Feedback

The input impedance for the connections of Figure IV.5 is dependent on whether series or shunt feedback is used. For series feedback, the input impedance is increased, while shunt feedback decreases the input impedance.

- **Series Feedback:** From Figure IV.6 with voltage-series feedback; where:

$$Z_{if} = \frac{V_s}{I_i} = \frac{V_i + V_f}{I_i} = \frac{V_i + \beta V_o}{I_i} = \frac{V_i + \beta A V_i}{I_i} = Z_i + (\beta A) Z_i,$$

$$Z_{if} = Z_i(1 + \beta A)$$

The input impedance with series feedback is seen to be the value of the input impedance without feedback multiplied by the factor $(1 + \beta A)$ and applies to both voltage-series (Figure IV.5(a)) and current-series (Figure IV.5(c)) configurations.

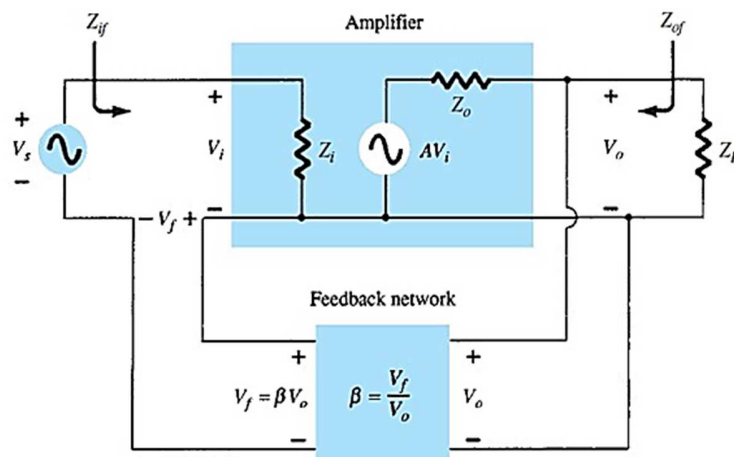


Figure IV.6 voltage-series feedback.

- **Shunt Feedback:** From Figure IV.7 with voltage-shunt feedback; so:

$$Z_{if} = \frac{V_i}{I_s} = \frac{V_i}{I_i + I_f} = \frac{V_i}{I_i + \beta V_o} = \frac{\frac{V_i}{I_i}}{\frac{I_i}{I_i} + \frac{\beta V_o}{I_i}},$$

$$Z_{if} = \frac{Z_i}{1 + \beta A}$$

This reduced input impedance applies to the voltage-shunt connection of Figure IV.5(b) and the current-shunt connection of Figure IV.5(d).

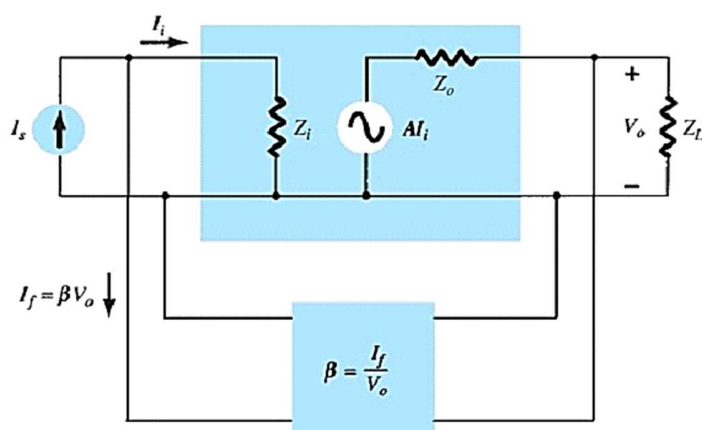


Figure IV.7 Voltage shunt feedback.

IV.4.2. Output Impedance with Feedback

The output impedance for the connections of Figure IV.5 is dependent on whether voltage or current feedback is used. For voltage feedback, the output impedance is decreased, while current feedback increases the output impedance.

- **Voltage Feedback:** For the voltage-series feedback circuit of Figure IV.6, the output impedance is determined by applying a voltage, V , resulting in a current, I , with V_s shorted out ($V_s = 0$). The voltage V is then :

$$V = IZ_o + AV_i,$$

$$V_i = -V_f \text{ for } V_s = 0,$$

$$V = IZ_o - AV_f = IZ_o - A(\beta V) \Rightarrow V + A(\beta V) = IZ_o,$$

$$Z_{of} = \frac{V}{I} = \frac{Z_o}{1 + \beta A}$$

The above equation shows that with voltage feedback the output impedance is reduced from that without feedback by the factor $(1 + \beta A)$.

- **Current Feedback:** From Figure IV.8 with current series feedback, therefore:

$$V_i = V_f \text{ for } V_s = 0,$$

$$I = \frac{V}{Z_o} - AV_i = \frac{V}{Z_o} - AV_f = \frac{V}{Z_o} - A\beta I \Rightarrow Z_o(1 + \beta A)I = V,$$

$$Z_{of} = \frac{V}{I} = Z_o(1 + \beta A)$$

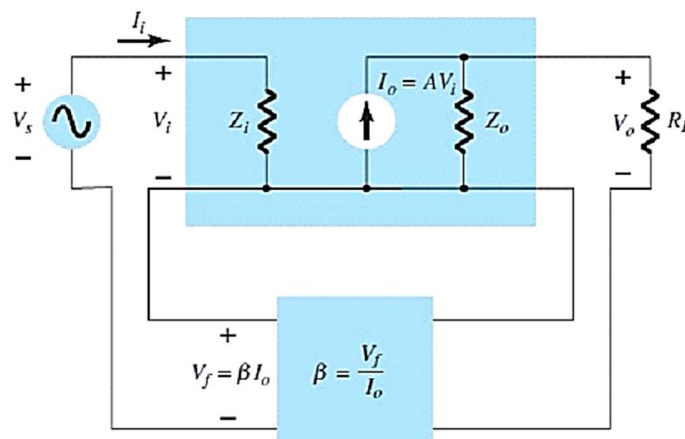


Figure IV.8 Current series feedback.

IV.4.3. Gain Stability with Feedback

The fractional change in amplification with feedback divided by the fractional change without feedback is called the *sensitivity* of the gain. If the equation $A_f = A/(1 + \beta A)$ is differentiated with respect to A , the absolute value of resulting equation is:

$$\left| \frac{dA_f}{A} \right| = \frac{1}{|1 + \beta A|} \left| \frac{dA}{A} \right|$$

Hence the sensitivity is $|1 + \beta A|$. This shows that magnitude of the relative change in gain with feedback is reduced by the $|1 + \beta A|$ compared to that without feedback. The reciprocal of sensitivity is called the *desensitivity* D , or :

$$D = 1 + \beta A$$

The fractional change in gain without feedback is divided by the *desensitivity* D when feedback is added. In particular, if $|\beta A| \gg 1$, then :

$$A_f = \frac{A}{1 + \beta A} \approx \frac{A}{\beta A} = \frac{1}{\beta}$$

And the gain may be made to depend entirely on the feedback network. The worst offenders with respect to stability are usually the active devices (transistors) involved. If the feedback network contains only stable passive elements, the improvement in stability may indeed be pronounced. Table IV.2



summarizes the above procedure and should be referred to when carrying out the analyses of the feedback circuits.

IV.4.4. Bandwidth with Feedback

Amplifier with negative feedback has more bandwidth (β_f) than the amplifier without feedback (β). The feedback amplifier has a higher upper 3 dB frequency and smaller lower 3 dB frequency (Figure IV.9).

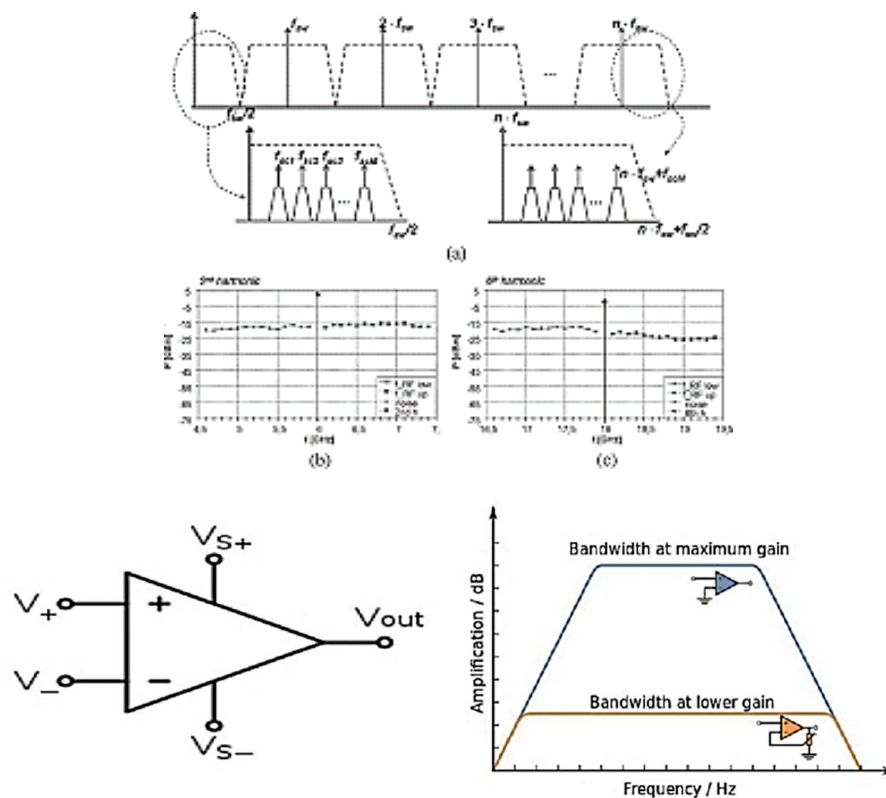


Figure IV.9 Amplifier gain bandwidth.

It is desirable to separate the feedback amplifier into two blocks, the basic amplifier A and the feedback network β , because with a knowledge of A and β , we can calculate the important parameters of the feedback amplifier, namely, A_f , Z_{if} , and Z_{of} . The basic amplifier configuration without feedback but taking the loading of the β network into account is obtained by applying the following rules:

- **To find the input circuit:** Set $V_o = 0$ for voltage feedback (sampling). In other words, short the output node. Set $I_o = 0$ for current feedback (sampling). In other words, open the output loop.
- **To find the output circuit:** Set $V_i = 0$ for shunt feedback. In other words, short the input node, and set $I_i = 0$ for series feedback. In other words, open the input loop.



Table IV.2 summarizes the above procedure the analyses of the feedback circuits.

Parameters	Feedback Types			
	Voltage-series	Voltage-shunt	Current-series	Current-shunt
Sampled signal X_o	Voltage (shunt)	Voltage (shunt)	Current (series)	Current (series)
Feedback signal X_f	Voltage (series)	Current (shunt)	Voltage (series)	Current (shunt)
To find input loop, set	$V_o = 0$	$V_o = 0$	$I_o = 0$	$I_o = 0$
To find output loop, set	$I_i = 0$	$V_i = 0$	$I_i = 0$	$V_i = 0$
Signal source	Thevenin	Norton	Thevenin	Norton
$A = X_o/X_i$	$A_v = V_o/V_i$	$A_z = V_o/I_i$	$A_g = I_o/V_i$	$A_i = I_o/I_i$
$\beta = X_f/X_o$	$\beta_v = V_f/V_o$	$\beta_g = I_f/V_o$	$\beta_z = V_f/I_o$	$\beta_i = I_f/I_o$
$D = 1 + \beta A$	$1 + \beta_v A_v$	$1 + \beta_g A_z$	$1 + \beta_z A_g$	$1 + \beta_i A_i$
A_f	A_v/D	A_z/D	A_g/D	A_i/D
Z_{if}	$Z_i D$	Z_i/D	$Z_i D$	Z_i/D
Z_{of}	Z_o/D	Z_o/D	$Z_o D$	$Z_o D$

IV.5. Frequency Response of Amplifiers

One of the most important aspects of any amplifier is its frequency response. This is also one of the most important basic considerations in regard to amplifier performance. As the name implies, the frequency response of an amplifier tells how the amplifier responds to signals of different frequency components. Understanding the frequency response of amplifiers is essential for the successful design and proper use of amplifiers in practice.

Any practical signal will contain many different frequency components, and an amplifier will behave differently with respect to different frequency components.

The importance of frequency considerations in amplifier design is often neglected by novices because of insufficient real world experience. After reading the chapter, it will be understood how the low-frequency response, high-frequency response, or both of an amplifier circuit can be modified by



the addition of different components in a particular configuration. The bandwidth is defined. Then the concepts of cutoff frequency and gain variation are introduced.

These concepts are essential to understand practical use of amplifiers. There are different types of frequency response: flat, peaking, low-frequency roll-off, high-frequency roll-off, and band-pass. The basic idea is given to classify amplifier performance as flat or peaking. Considerations of frequency response in amplifier design are usually focused on flat response due to low-frequency roll-off, high frequency roll-off, or both. As signal frequency increases, cutoff frequency is defined as the frequency at which the response drops 3 dB down from its nominal value, and the importance of gain variation for frequency response (flat, peaking, or otherwise) is discussed.

Simple calculations to find the nominal gain and cutoff frequency of some basic circuits are given as examples. In addition to basic design problems, frequency response may need to be adjusted to meet certain specifications in circuit design. Therefore, techniques to modify frequency response characteristics by adding components to the circuit are discussed.

Initially, the problem is considered as a single-stage amplifier with low-frequency roll-off and how bandwidth may be improved by the addition of a circuit paralleled with a component. Then, the relationship between frequency response and amplifier stability is discussed, how this problem might arise in multi-stage amplifiers, and what precautions need to be taken.

IV.5.1. Effect of Coupling Capacitors

Coupling capacitors are in series with the signal and are part of a high-pass filter network. They affect the low-frequency response of the amplifier. For the circuit shown in Figure IV.10(a), the equivalent circuit for C_1 is a high-pass filter, C_3 and $(R_C + R_L)$ form another high-pass filter.

With FETs, the input coupling capacitor is usually smaller because of the high input resistance. The output capacitor may be smaller or larger depending on the drain and load resistor size. For the circuit shown in Figure IV.10(b), the equivalent low-pass filter for the input is simply C_1 in series with R_G because the gate input resistance is so high.

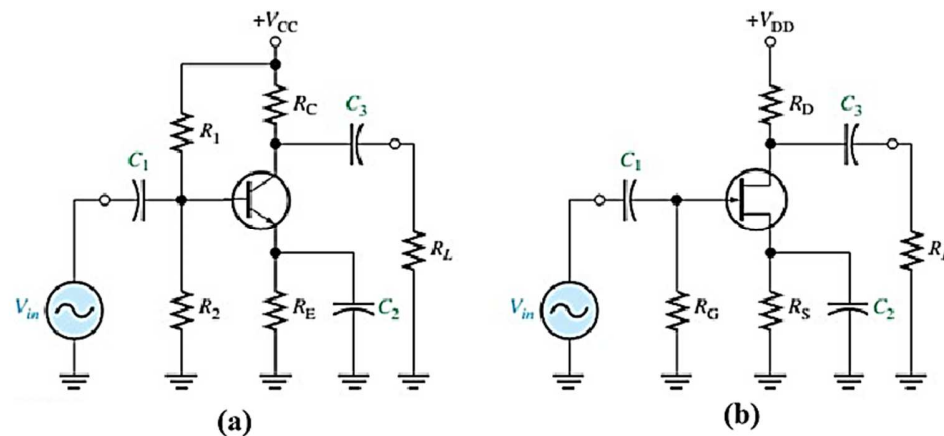


Figure IV.10 Examples of capacitively coupled (a) BJT and (b) FET amplifiers.

IV.5.2. Effect of Bypass Capacitors

A bypass capacitor causes reduced gain at low frequencies and has a high-pass filter response (Figure IV.11). The resistors “seen” by the bypass capacitor include R_E , r'_e , and the bias resistors. For example, when the frequency is sufficiently high $X_C \cong 0\Omega$ and the voltage gain of the CE amplifier is $A_v = R_C/r'_e$. At lower frequencies, $X_C \gg 0\Omega$ and the voltage gain $A_v = R_C/(r'_e + Z_e)$.

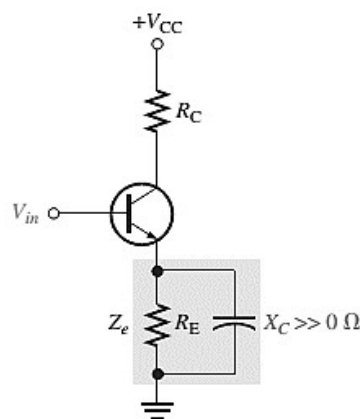


Figure IV.11 Nonzero reactance of the bypass capacitor in parallel with R_E creates an emitter impedance (Z_e), which reduces the voltage gain.

The high frequency response of an amplifier is determined by internal junction capacitances. These capacitances form low-pass filters with the external resistors. Sometimes a designer will add an external parallel capacitor to deliberately reduce the high frequency response (Figure IV.12).

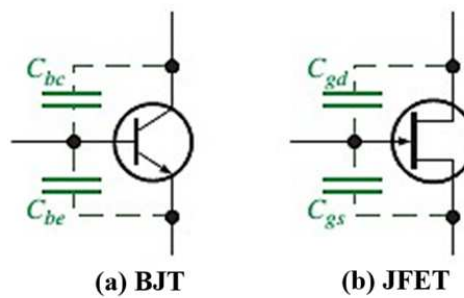


Figure IV.12 Internal transistor capacitances.

Miller's theorem states that, for inverting amplifiers, the capacitance between the input and output is equivalent to separate input and output capacitances to ground (Figure IV.13).

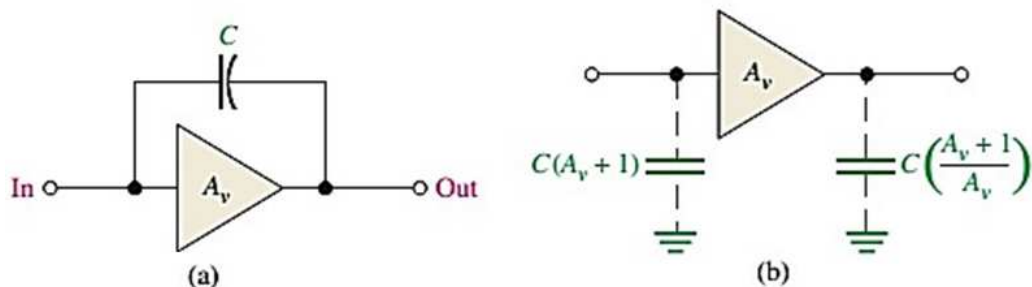


Figure IV.13 General case of Miller input and output capacitances, C represents C_{bc} or C_{gd} .

A_v is the absolute value of the gain. For the input capacitance, the gain has a large effect on the equivalent capacitance, which is an important consideration when using inverting amplifiers. Notice that the effect of Miller's theorem is an equivalent capacitance to ground, which shunts high frequencies to ground and reduces the gain as frequency is increased (Figure IV.14).

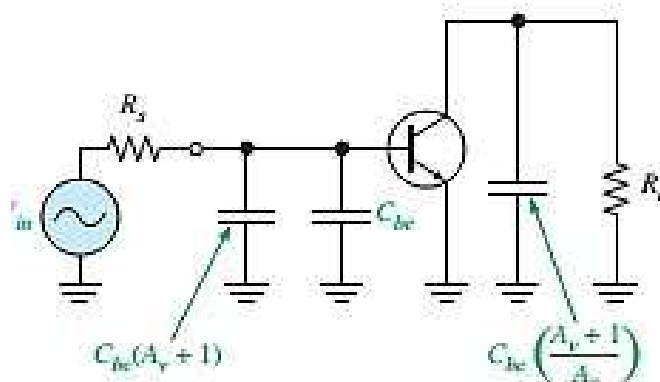


Figure IV.14 Amplifier ac equivalent circuits showing internal and effective Miller capacitances.

**Example:**

What is the input capacitance for a 2N3904 inverting amplifier with a gain of 25? Assume the values of $C_{bc}= 4\text{pF}$ and $C_{be}= 6\text{pF}$.

Solution:

$$C_{in} = C_{bc}(A_v + 1) + C_{be}$$

$$C_{in} = 4(25 + 1) + 6 = 110 \text{ pF}$$

The decibel is a logarithmic ratio of two power levels and is used in electronics work in gain or attenuation measurements. Decibels can be expressed as a voltage ratio when the voltages are measured in the same impedance. To express power gain in decibels, the formula is:

$$A_{p(dB)} = 10 \log A_p$$

Sometimes, 0 dB is assigned as a convenient reference level for comparison. Then, other power or voltage levels are shown with respect to 0 dB.

IV.5.3. Low Frequency Response

In capacitively coupled amplifiers, the coupling and bypass capacitors affect the low frequency cutoff. These capacitors form a high-pass filter with circuit resistances. A typical BJT amplifier has three high pass filters. For example, the input coupling capacitor forms a high pass filter with the input resistance of the amplifier is illustrated in Figure IV.15.

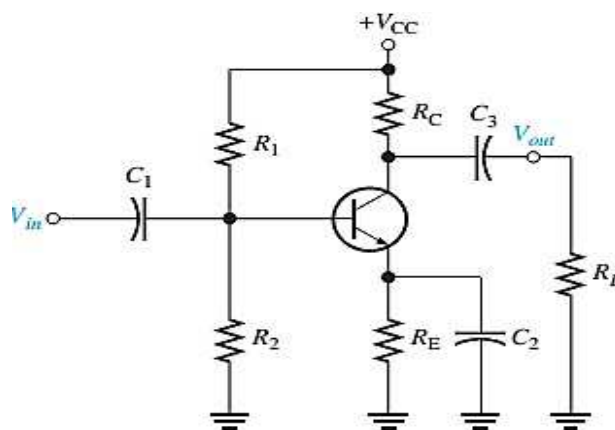


Figure IV.15 Capacitively coupled BJT amplifier.

The input RC circuit for the BJT amplifier in Figure IV.15 is formed by C_1 and the amplifier's input resistance and is shown in Figure IV.16.



The total input resistance is expressed by the following formula:

$$R_{in(tot)} = R_1 // R_2 // R_{in(base)}$$

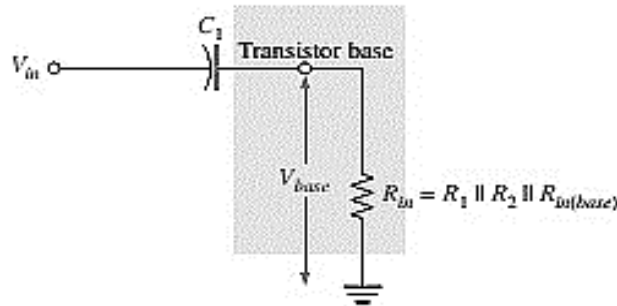


Figure IV.16 Input RC circuit formed by the input coupling capacitor.

The output RC circuit is composed of the series combination of the collector and load resistors with the output capacitor. The cutoff frequency due to the output circuit is :

$$f_c = 1 / 2\pi(RC + RL)C_3$$

Example:

For the circuit in the Figure IV.17, calculate the lower critical frequency due to the input RC circuit. Assumed $r'_e = 9.6\Omega$ and $\beta=200$. Notice that a swamping resistor, R_{E1} , is used (Figure IV.17).

Solution:

The input resistance is

$$R_{in} = R_1 // R_2 // (\beta(r'_e + R_{E1})) = 68\Omega // 22\Omega // (200(9.6\Omega + 33\Omega)) = 5.63 \text{ k}\Omega$$

The lower critical frequency is :

$$f_{ci(input)} = 1/2\pi R_{in} C_1 = 1/2\pi(5.63)(0.1) = 282 \text{ Hz}$$

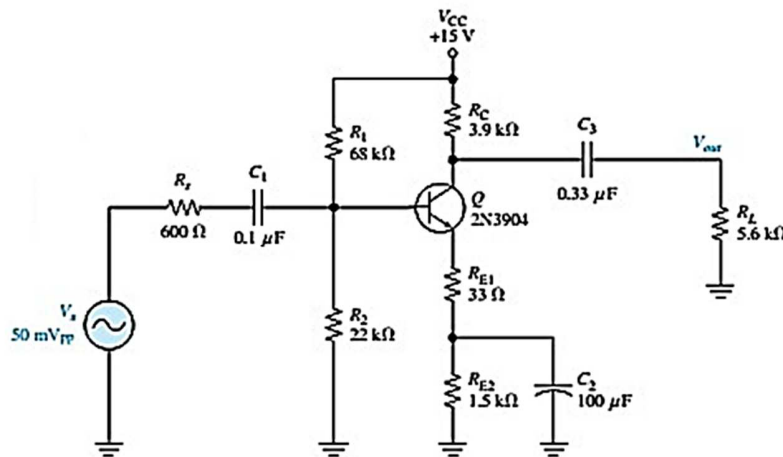


Figure IV.17

IV.5.4. High-Frequency Response

The high frequency response of inverting amplifiers is primarily determined by the transistor's internal capacitance and the Miller effect. The equivalent high-frequency ac circuit is shown for a voltage-divider biased CE amplifier with a fully bypassed emitter resistor (Figure IV.18).

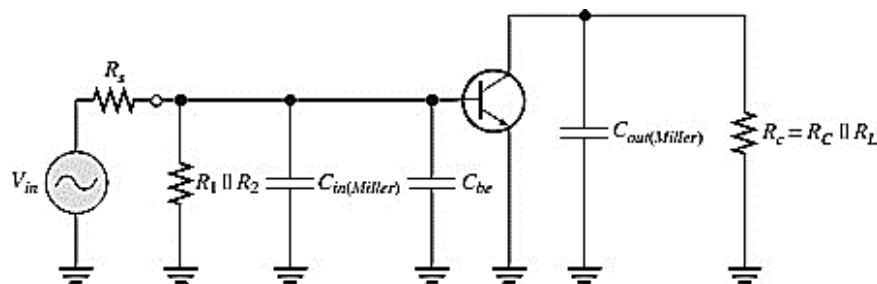


Figure IV.18 High-frequency equivalent circuit after applying Miller's theorem.

If there is an unbypassed emitter resistor, such as R_{E1} it is shown in the emitter circuit and acts to increase f_c and thus reduce f_c . At high frequencies, the input circuit is as shown in Figure IV.19(a), where $\beta_{ac}r_e$ is the input resistance at the base of the transistor because the bypass capacitor effectively shorts the emitter to ground. By combining C_{be} and $C_{in(Miller)}$ in parallel and repositioning, you get the simplified circuit shown in Figure IV.19(b). Next, by thevenizing the circuit to the left of the capacitor, as indicated, the input RC circuit is reduced to the equivalent form shown in Figure IV.19(c).

If there is an unbypassed emitter resistor (R_{E1} in this case), the Thevenin resistance is modified to $R_{th} = R_s // R_1 // R_2 // \beta_{ac}(r_e + R_{E1})$. The high frequency analysis of FETs is similar to that of BJTs. Like the CE amplifier, the CS amplifier inverts the signal, so the Miller effect must be taken into account.



You may see special circuits such as cascode connections in very high frequency applications to minimize the Miller effect. A high frequency ac model of a CS amplifier shown in figure IV.20.

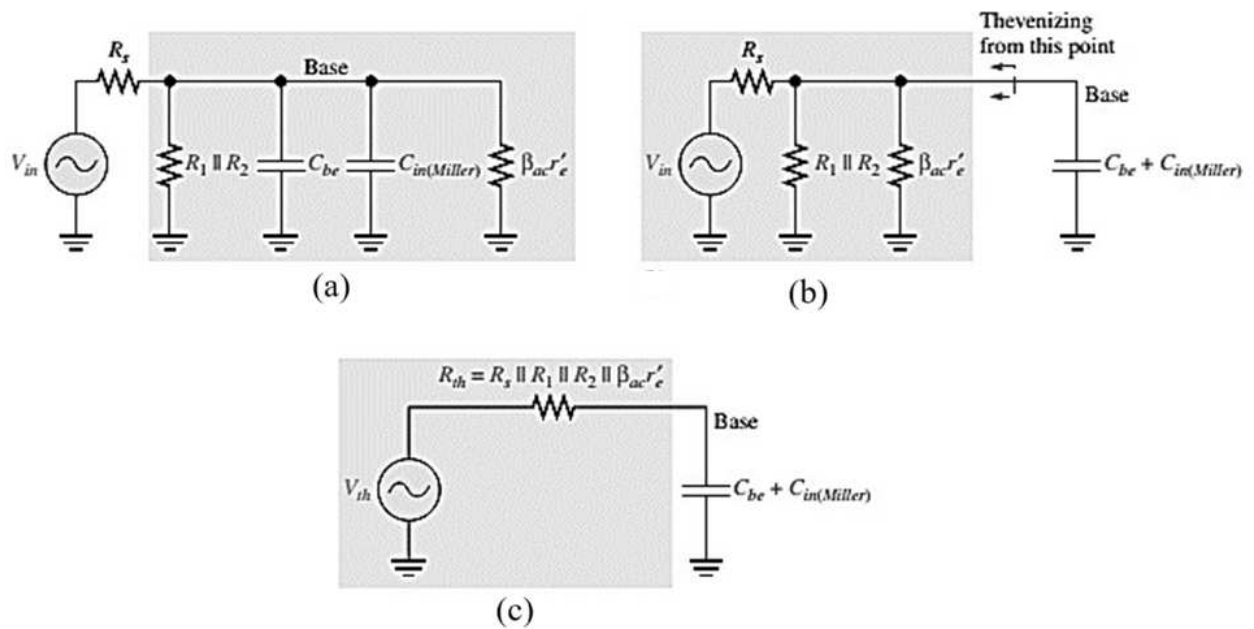


Figure IV.19 Development of the equivalent high-frequency input RC circuit.

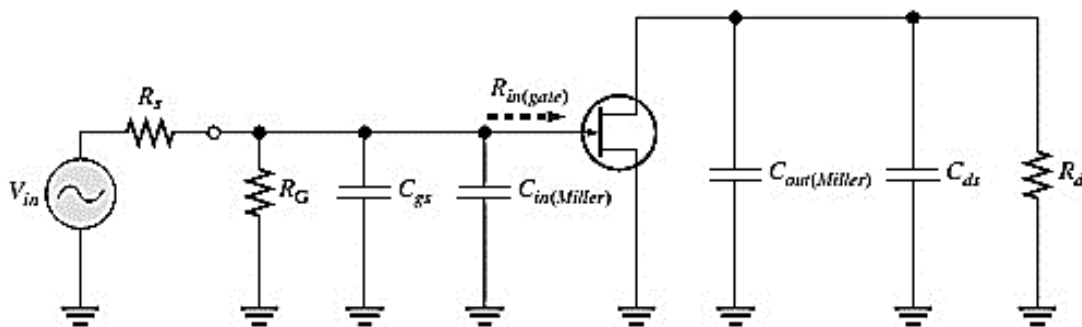
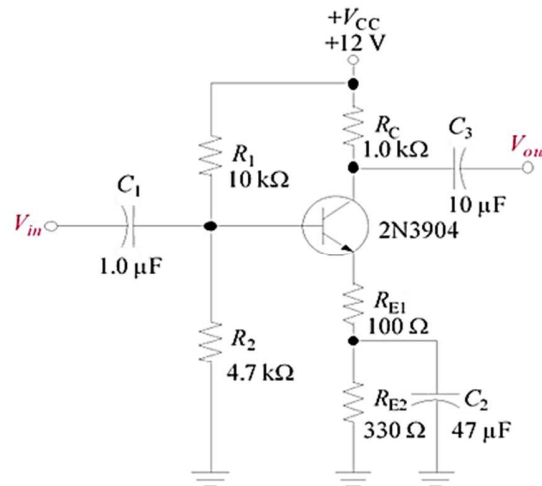


Figure IV.20 High-frequency equivalent circuit after applying Miller's theorem.

C_{gs} simply appears as a capacitance to ac ground in parallel with $C_{in(Miller)}$, as shown in Figure 12. Looking in at the drain, C_{gd} effectively appears in the Miller output capacitance from drain to ground in parallel with R_d ,

**Example:**

What is the upper cutoff frequency due to the input circuit? Assume $R_S=600\Omega$, $r_e=3.5\Omega$, $\beta=200$, $C_{be}=6\text{ pF}$, $C_{bc}=3.5\text{ pF}$, and $A_v=9.7$ (Figure IV.21).

**Figure IV.21.****Solution:**

$$R_{th} = R_S // R_1 // R_2 // \beta(r_e + R_{E1})$$

$$= 600\Omega // 10\text{ k}\Omega // 4.7\text{ k}\Omega // 200(3.5 + 100) = 493\Omega$$

$$C_{in(tot)} = C_{be} + C_{Miller} = C_{be} + C_{bc}(A_{v(mid)} + 1)$$

$$= 6 + 3.5(9.7 + 1) = 43\text{ pF}$$

$$f_c = 1/2\pi R_C = 7.4\text{ MHz}$$

IV.5.5. Total Amplifier Frequency Response

The overall frequency response is the combination of three lower critical frequencies due to coupling and bypass capacitors and two upper critical frequencies due to internal capacitances. Figure IV.22 shows a generalized ideal response curve (Bode plot) for the BJT amplifier. The three break points at the lower critical frequencies (f_{cl1} , f_{cl2} , and f_{cl3}) are produced by the three low-frequency RC circuits formed by the coupling and bypass capacitors. The break points at the upper critical frequencies, f_{cu1} and f_{cu2} , are produced by the two high-frequency RC circuits formed by the transistor's internal capacitances..

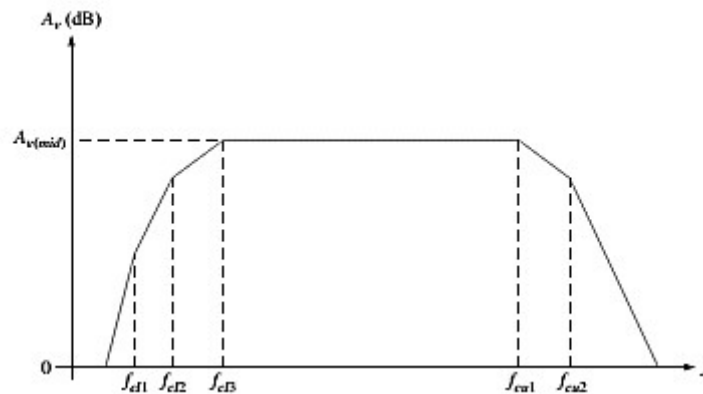


Figure IV.22 BJT amplifier and its generalized ideal response curve (Bode plot).

For multistage amplifiers, the individual stages have an effect on the overall response. In general, with different cutoff frequencies, the dominant *lower* cutoff frequency is equal to the *highest* f_{cl} ; the dominant *upper* critical frequency is equal to *lowest* f_{cu} . When the critical frequencies for multistage amplifiers are equal, the lower critical frequency is higher than any one as given by:

$$f'_{cl} = \frac{f_{cl}}{\sqrt{2^{1/n} - 1}}$$

And the upper critical frequency is given by:

$$f'_{cu} = f_{cu} \sqrt{2^{1/n} - 1}$$

IV.6. Measurement and Testing Techniques

The measurement and testing techniques used to evaluate amplifier performance are critical to verifying the correctness of designs. In any signal chain, an amplifier is usually the most critical component, controlling distortion and noise performance. Therefore, accurate measurement techniques are necessary to determine an amplifier's distortion and noise and ensure the integrity of the processed signal. This section outlines the most common testing techniques, such as Total Harmonic Distortion (THD) and Signal to Noise Ratio (SNR); these techniques can be used as benchmarks to evaluate the quality of amplifiers in a variety of applications, from audio to RF. To facilitate future reference, the discussion includes standard test setups and procedures used to obtain repeatable and reliable results. Emerging measurement technologies that greatly enhance precision and efficiency in gauging amplifier performance are also discussed. A basic understanding of testing techniques is essential for designers who wish to refine their designs effectively. Specifics of these measurements and techniques will be discussed in the following subsections. Testing amplifiers is both a simple and a complicated task.



Simplicity arises from the fact that measuring distortion and noise can be done completely with off-the-shelf test equipment. Usually, a signal generator, a voltmeter or oscilloscope, and a load resistance are all that is needed to perform the most simple measurements. Complications arise because, although in principle measuring distortion and noise can be done with just a few pieces of equipment, to get accurate and meaningful results often requires elaborate setups and an understanding of the pitfalls and potential for misleading results. The simplest amplifier measurements that can be performed are gain and linearity, and they can be done with an arbitrary function generator and an oscilloscope. Most modern amplifiers, however, have non-zero output impedance; hence, measuring input/output waveforms without loading the amplifier would require a device with infinite input impedance.

IV.6.1. THD Measurement

A measurement that is essential and performed for every amplifier tested, regardless of design or application, is total harmonic distortion (THD). THD is a key indicator of performance, quantifying how far an amplifier output deviates from an ideal signal. In purely mathematical terms, an ideal amplification of a signal can be understood in a Fourier analysis sense as preserving the amplitude, phase, and frequency of the input signal's sinusoidal components. If an amplifier reacts non-ideally regarding these parameters, it is said to have distortion. Other reactions of the amplifier will be classified as non-ideal behaviour and they will also mean the output signal has distortion, albeit of a different kind. Nevertheless, such a situation is still conceivable where an amplifier's transfer function does not exhibit any distortion and correctly interprets the input signal, but the output signal still deviates from the input. With importance for music reproduction, this might indicate that although the output has no mean distortion, it could still have significant harmonic distortion, meaning that new sinusoidal components have been generated at the output whose frequencies are integer multiples of the input signal's frequency. This is exactly what THD measures, in percentage, the extent of such harmonic distortion in the output (Figure IV.23).

Aside from oscilloscopes and FFT analyzers, a simple one-tone signal sweep through the bandwidth of the amplifier, with simultaneous measuring and plotting of the output/input gain vs. frequency, is a great way to inspect for known problems, irregularities in the response, and passive component miscalculations. If the input range is sufficiently large, this can also help expose non-linearities, as at low frequencies the THD will grow, indicating that the ratio of harmonics in respect to the fundamental is increasing. Of course, THD can also be measured in the frequency domain using a precision FFT analyzer, a method often preferred by audio companies because it gives a clearer overview of the performance over the entire bandwidth. High-end audio equipment typically has a THD



of 0.01 % or better, and levels this low are difficult to measure accurately without expensive gear. It is important to note any THD results must be interpreted with respect to sound quality and fidelity, as there are amplifiers exhibiting very low THD and yet sound unlistenable, while others with THD a hundred times greater can sound wonderfully clear. To achieve a good compromise between arguably conflicting objectives, great care must be taken in selecting and designing each component. How to go about minimizing THD, generally speaking, will now be briefly outlined, starting with the most important component, the transistor.

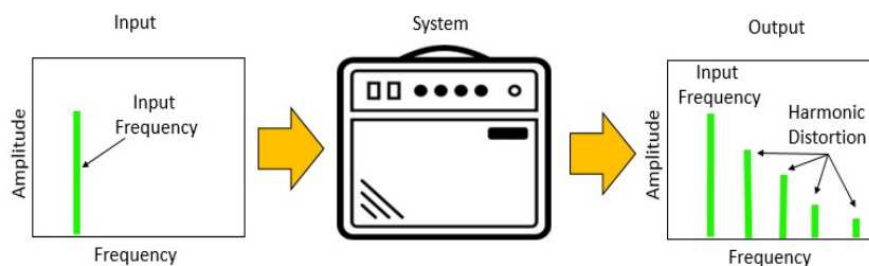


Figure IV.23 Total harmonic distortion.

IV.6.2. SNR Measurement

Signal-to-Noise Ratio (SNR) measurement is examined here as one of the most important performance metrics when it comes to amplifiers. Simply put, SNR defines the relationship between a desired signal and background noise, hence trying to quantify the clearness of the output. The higher the SNR level, the clearer the signal is. Because system noise can be an unwanted addition to the output audio, SNR becomes vital when taking into account the overall quality of the application. This is especially true for more sensitive applications, such that a higher quality microphone would have a more difficult time trying to reject noise from outside a desired audio pickup zone. On the contrary, a lower SNR would result in more audible noise paired with the desired signal, degrading performance. Consequently, all baseline and testing amplifiers under examination would be thoroughly measured for SNR levels. Equipment and techniques necessary to adequately measure SNR levels are examined. The measurements will rely strongly on the use of a digital audio workstation (DAW) with an audio interface that possesses high-quality preamps for inputting audio. The DAW allows for easier playback of audio files, as well as recording, monitoring, and providing visualization tools to observe the audio collected from the amplifiers. The primary visual monitoring tool will be the FFT display built into the DAW. It provides a live frequency-domain view of the audio signal and will help ensure recordings are free of clipping/distortion. Because the amplifiers under consideration are single-channel devices, SNR measurements will be a per-channel measurement taken using a two-step process. First, the amplifier



is fed a quantifiable desired signal and the output is recorded. Then, a silent audio file is played to collect a measurement of the background noise floor. These two audio files can then be post-processed within the DAW to determine the SNR. Ultimately, continuous SNR measurements on the testing platform will lead to a better understanding of how design choices impact the performance of an amplifier. Not only this, but high SNR could also be used as a selling point for the module as end users take notice of amplifiers that can better maintain signal fidelity. Finally, it should be noted that SNR measurement is not common practice within currently reported audio amplifier testing.

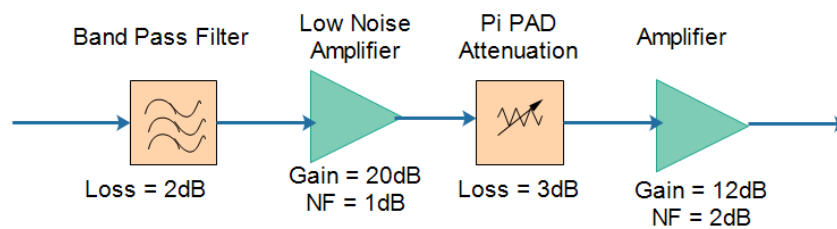


Figure IV.24 Signal-to-Noise Ratio (SNR) measurement.

IV.7. Conclusion and Future Developments

In conclusion, research on the design and performance of wideband amplifier using transconductance boosting techniques is presented. It begins with a detailed analysis of the limitations of conventional amplifier topologies designed with transconductance boosting techniques. To help designers avoid these limitations, a new approach that employs a differential pair with a wide input common-mode range is proposed. Then, transconductance boosting techniques are used to design wideband amplifiers in modern technologies. Finally, experimentally verified amplifier circuit implementations designed with transconductance boosting techniques are shown, considering the constraints imposed by the technological process used and the target application. Future developments in operational amplifiers (amplifiers) and amplifier-less circuits will include advances in exploitable techniques for low-power designs that achieve high performance. A focus will be made on improved voltage gain (A) by exploiting new gain-enhancement techniques, on new compensation schemes for high-frequency stability (f_T), and on transconductance (g_m) stabilization techniques against process, voltage variations. These improvements will maintain the essential low-power character of the amplifiers and amplifier-less circuits being developed.



Questions & Answers

1. What is meant by feedback?

A portion of the output signal is taken from the output of the amplifier and is combined with the normal input signal. This is known as feedback. Feedback is a part of output is sampled and feedback to the input of the amplifier.

2. Give the different types of feedbacks used in amplifier circuits.

Positive feedback, and Negative feedback.

3. Define the positive feedback.

When input signal and part of the output signal are in phase, the feedback is called Positive feedback.

4. Define negative feedback.

When input signal and part of the output signal are in out of phase, the feedback is called negative feedback.

6. Give classification of amplifiers.

The amplifiers can be classified into four broad categories: voltage, current, Transconductance and Transresistance amplifiers.

7. What is node sampling?

When the output voltage is sampled by connecting the feedback network in shunt across the output, the connection is referred to as voltage or node sampling.

8. What is loop sampling?

When the output current is sampled by connecting the feedback network in series with the output, the connection is referred to as current or loop sampling.

9. Define feedback factor or feedback ratio.

The ratio of the feedback voltage to output voltage is known as feedback factor or feedback ratio.

10. What is the purpose of mixer network in feedback amplifier?

The mixer network is used to combine feedback signal and input at input of an amplifier.

11. What are the advantages of introducing negative feedback?

- Input resistance is very high.
- Output resistance is low.
- The transfer gain A_f of the amplifier with feedback can be stabilized against variations of the h parameters or hybrid π parameters of the transistors or the Parameters of the others active devices used in the amplifiers.



- It improves the frequency response of the amplifiers.
- There is a significant improvement in the linearity of operation of the feedback.

12. What is loop gain or return ratio.

A path of a signal from input terminals through basic amplifier, through the feedback network and back to the input terminals forms a loop. The gain of this loop is the product $-A\beta$. This gain is known as loop gain or return ratio.

13. What is sensitivity of the transfer gain?

The fractional change in amplification with feedback divided by the fractional change without feedback is called the sensitivity of the transfer gain.

14. What is desensitivity?

The reciprocal of the sensitivity is called the desensitivity D . it is given as $D = 1 + A\beta$

15. What is the effect of lower cut-off frequency with negative feedback?

Lower cutoff frequency with feedback is less than lower cutoff frequency without feedback by factor $(1 + A\beta)$

16. What is the effect of upper cut-off frequency with negative feedback?

Upper cutoff frequency with feedback is greater than upper cutoff frequency without feedback by factor $(1 + A\beta)$

19. What is the effect of negative feedback on bandwidth?

Bandwidth of amplifier with feedback is greater than bandwidth of amplifier without feedback.

Benefits of Implementing Negative Feedback in Bandwidth Control





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