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SCHOOL OF BIO AND CHEMICAL ENGINEERING

DEPARTMENT OF BIOMEDICAL ENGINEERING

UNIT – I – BASIC ELECTRONIC DEVICES, CIRCUITS AND ITS APPLICATIONS – SBMA1305

1.1 PN Junction diode

-Semi-conductor material P-type and N-type

-Impurity doped

-P-type- high concentration of holes

-N-type- high concentration of electrons -Free electrons move towards positive and holes towards negative side and form a barrier

- Induced electric field across deletion layer is called potential barrier, junction barrier, diffusion potential, or contact potential Vo

-It varies with doping levels and temperature - Vo for Germanium 0.3V and 0.72 V for silicon

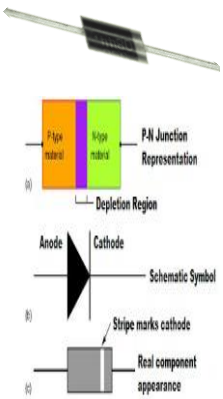


Figure 1. PN Junction diode

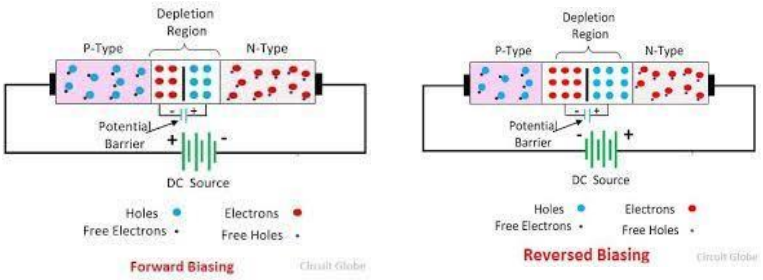


Figure 2.Biasing of a PN Junction diode

1.2 VI Characteristics

The PN junction as a practical device or as a rectifying device we need to firstly bias the junction, that is connect a voltage potential across it. On the voltage axis above, "Reverse Bias" refers to an external voltage potential which increases the potential barrier. An external voltage which decreases the potential barrier is said to act in the "Forward Bias" direction.

There are two operating regions and three possible "biasing" conditions for the standard Junction Diode and these are:

- **1. Zero Bias – No external voltage potential is applied to the PN junction diode.**
- **2. Reverse Bias – The voltage potential is connected negative, (-ve) to the P-type material and positive, (+ve) to the N-type material across the diode which has the effect of Increasing the PN junction diode's width.**
- **3. Forward Bias – The voltage potential is connected positive, (+ve) to the P-type material and negative, (-ve) to the N-type material across the diode which has the effect of Decreasing the PN junction diodes width.**

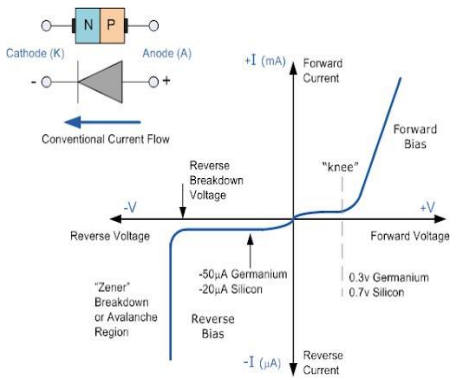


Figure 3.VI Characteristics of a PN Junction diode

1.3 Diffusion And Transient Capacitance

-In a PN junction diode when it is REVERSE biased, the width of PN region becomes SMALL the capacitance of this PN junction is called TRANSITION capacitance

-In a PN junction diode when it is FORWARD biased, the width of PN region becomes LARGE the capacitance of this PN junction is called DIFFUSION capacitance

-Diffused capacitance is always smaller than transition capacitance, -few tens of pico farads

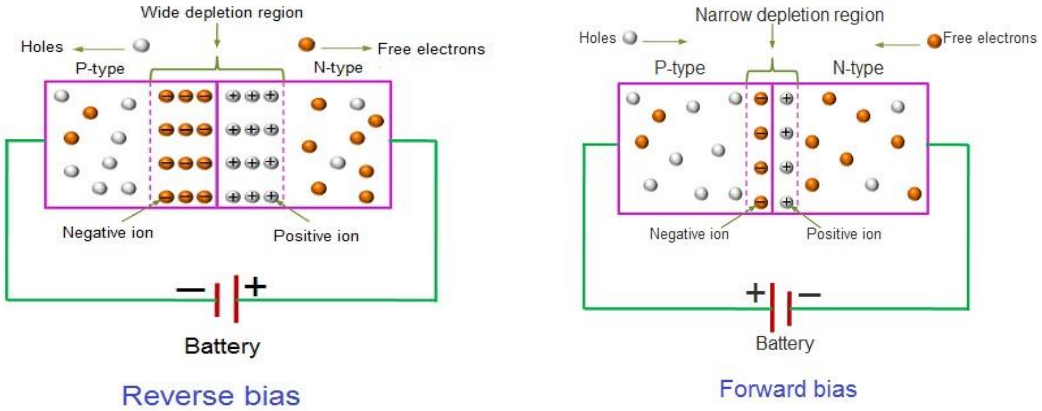


Figure 4.VI Characteristics of a PN Junction diode

Transient Capacitance

- **With the increase of magnitude of reverse bias, majority carriers move away from the junction i.e. the width W of the depletion layer increases.**
- **These uncovered immobile charge on the two sides of the junction constitute a capacitor of incremental capacitance C_T given by,**

$$C_T = \left|\frac{dQ}{dV}\right|$$

- **dQ -increase in the charge resulting from an increase dV in voltage.**
- **voltage change dV in the time interval dt will result in a current i given by,**

$$i = \frac{dQ}{dt} = C_T \frac{dV}{dt}$$

C_T -Transition Capacitance

- **A junction is said to be step graded if there is an abrupt change from acceptor ion density on the P-side to donor ion density on the N-side.**
- **Such a junction gets formed in alloyed junction (or Fused Junction) diode.**
- **the acceptor density N_A and the donor density N_D are kept unequal. The transition capacitance C_T is then given by,**

$$C_T = \frac{\epsilon A}{W}$$

- **is a absolute permittivity of the semiconductor medium, A is the cross-sectional area of the junction and W is the of the depletion layer and is given by**

$$W^2 = [\frac{2\epsilon V_j}{q}][\frac{1}{N_A} + \frac{1}{N_D}]$$

- **If $N_A >> N_D$**

$$W = (\frac{2\epsilon V_j}{N_D q})\frac{1}{2}$$

$$C_T = A(\frac{N_D}{V_j})\frac{1}{2} \times (\frac{q\epsilon}{2})\frac{1}{2}$$

- **Thus, in a step graded junction, C_T is inversely proportional to square root of junction voltage V_j where V_j is given by,**

$$V_j = V_0 - V_d$$

- **Where Vd is a negative number indicating the applied reverse bias and V0 is the contact potential.**

C_T in a Linear Graded Junction

- **A junction is said to be linear graded if there is a linear variation of net charge density with distance in the transition region.**

- **The transition capacitance is given by,**

$$C_T = \frac{\epsilon A}{W}$$

- **Assuming NA = ND, the width W of the depletion layer is given by,**

$$W = \left(\frac{6\epsilon V_j}{qN_D}\right)^{\frac{1}{2}}$$

$$C_T = A\left(\frac{N_D}{V_j}\right)^{\frac{1}{2}} \times \left(\frac{q\epsilon}{6}\right)^{\frac{1}{2}}$$

- **C_T is inversely proportional to the square root of V_j**

Diffusion Capacitance or Storage Capacitance C_D

- **In the forward biased diode, the potential barrier at the junction gets lowered.**
- **Holes get injected from the P-side to the N-side and electron get injected from the N-side to the P-side.**
- **These injected charges get stored near the junction just outside the depletion layer, holes in the N-region and electrons in the P-region.**
- **Due to charge storage, the voltage lags behind the current producing the capacitance effect.**
- **Such a capacitance is called diffusion capacitance or storage capacitance C_D.**
- **The diffusion capacitance C_D may be defined as the rate of change of injected charge with voltage**

$$C_D = \frac{dQ}{dV}$$

- **A forward biased diode with one region say P-region very heavily doped relative to the other region (N region), current (I) is mainly due to holes**

$$I = \frac{Q}{\tau_p}$$

- **Where Q is the stored charge and is the mean lifetime of hole and is given by,**

$$T_p = \frac{L_p^2}{D_p}$$

- **L_P is the diffusion length for holes, and D_P is the diffusion constant for holes**

$$C_D = \tau \frac{dI}{dV} = \frac{\tau}{r}$$

- **But from equation of dynamic resistance**

$$r \approx \frac{\eta V_T}{I}$$

- **Substituting this value of r we get**

$$C_D = \frac{\tau I}{\eta V_T}$$

- **Diffusion constant C_D is caused by diffusion of both the holes in the n-regions and electrons in the P-region, resulting in diffusion capacitance C_{Dp} and C_{Dn} respectively. The total diffusion capacitance C_D is the sum of C_{Dp} and C_{Dn}.**
- **C_D value ---- few thousand of pF. This time constant C_D.**
- **r mainly limits the frequency response of certain semiconductor devices when used in high frequency applications.**
- **In a forward biases diode, there are present both the diffusion capacitance C_D and the transition capacitance C_T, but $C_D >> C_T$. Typically, C_D is more than a million times greater than C_T. Hence, in a forward biased diode, C_T may be neglected and we need consider only C_D.**
- **Similarly, in reverse biased diode, these are present both C_D and C_T. But $C_D << C_T$. Hence, in a reverse biased diode, we may neglect C_D and we need consider only C_T.**

1.4 Rectifiers

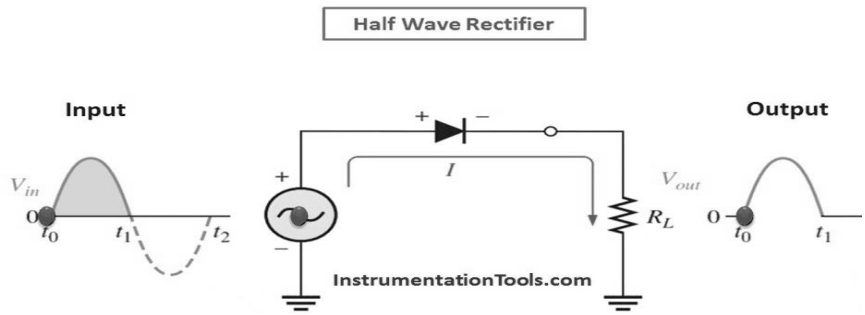
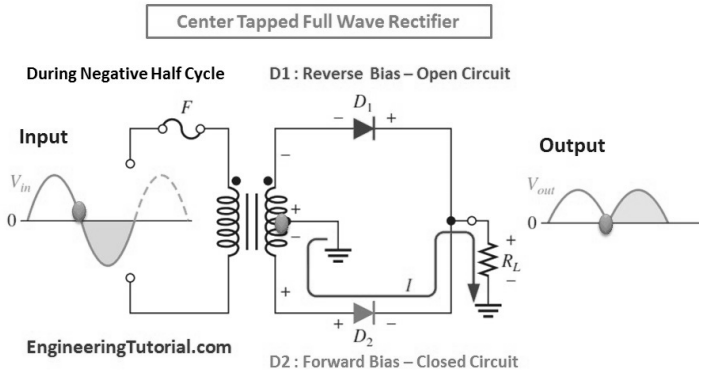
- **A rectifier is an electrical device that converts alternating current (AC), which periodically reverses direction, to direct current (DC), which flows in only one direction.**
- **Half-wave Rectifier**
- **Fullwave Rectifier**
- **Half wave rectifier only converts half of the AC wave into DC signal whereas Full wave rectifier converts complete AC signal into DC.**
- **Bridge rectifier is the most commonly used rectifier in electronics and this report will deal with the working and making of one. Simple bridge rectifier circuit is the most popular method for full wave rectification.**
- 

Figure 5.Halfwave Rectifier

Full-wave rectifier



- **A full wave rectifier converts both positive and negative half cycles of the AC (alternating current) into DC (direct current). It provides double output voltage compared to the halfwave rectifier**
- **A full wave rectifier is made up of more than one diode.**
- **There are two types of full wave rectifier.**
- **Bridge Rectifier**
- **Center-Tap Rectifier**

Bridge rectifiers

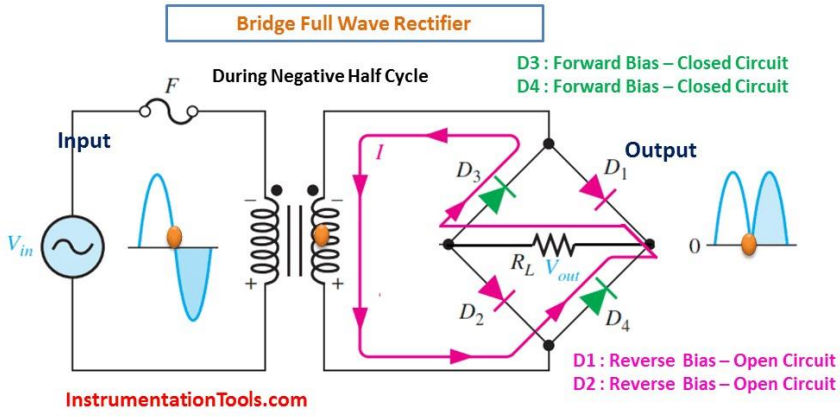


Figure 6.Halfwave Rectifier

- **A bridge rectifier uses four diodes to convert both half cycle of the input AC into DC output.**
- **From the circuit diagram it is apparent that the diodes are connected in a particular fashion. This unique arrangement gives the converter its name. In bridge rectifier, voltage that is given as the input can be from any source. It can be from a transformer that is used to step up or down the voltage or it can be from the mains of our domestic power supply. In this article, we are using a 6-0-6 centre tapped transformer for providing AC voltage.**
- **In the first phase of working of the rectifier, during the positive half cycle, diodes D3-D2 get forward biased and conducts. Diodes D1-D4 gets reversed biased and do not conduct in this half cycle, acting as open switches. Thus, we get a positive half cycle at the output. Conversely, in the negative half cycle, diodes D1-D4 get forward biased, and start conducting whereas diodes D3-D2 gets reversed biased and do not conduct in this half cycle.**
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Rectifier with filter

The filter is a device that allows passing the dc component of the load and blocks the ac component of the rectifier output. Thus the output of the filter circuit will be a steady dc voltage.

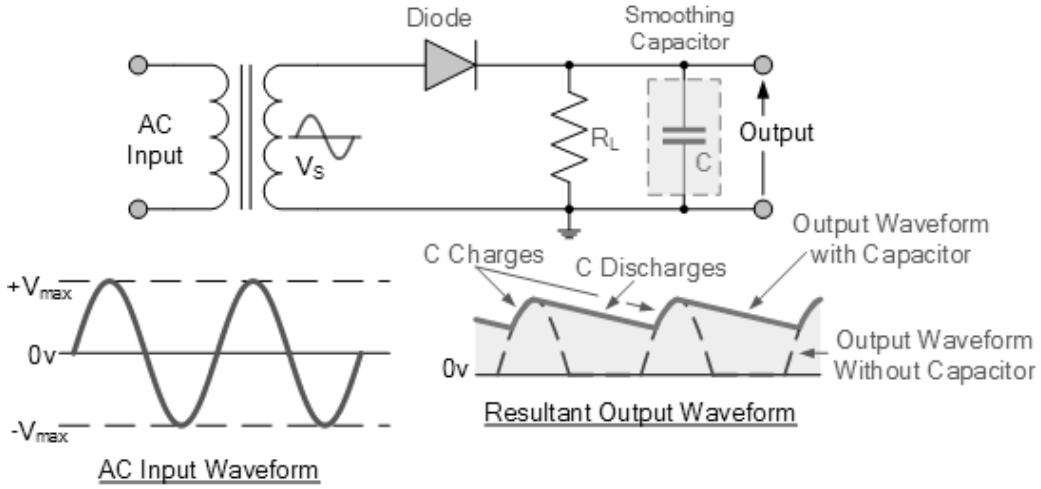


Figure 7. Halfwave Rectifier with filter

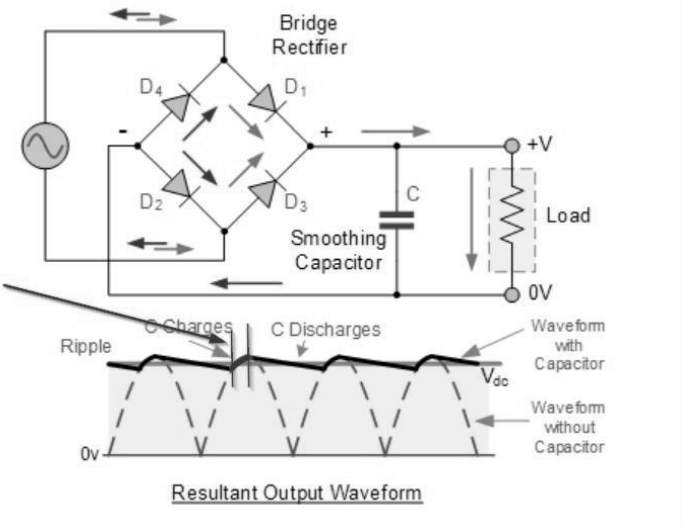
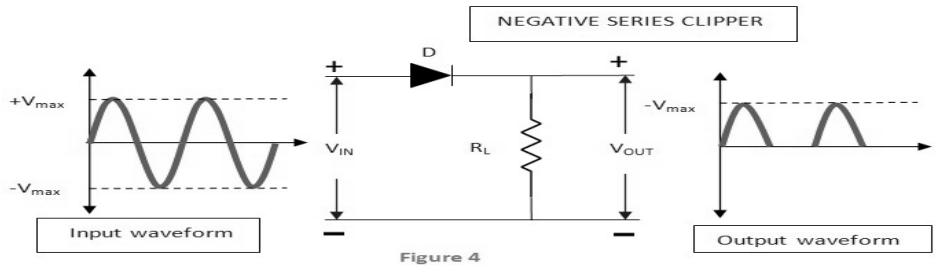


Figure 8. Halfwave Rectifier with filter

Applications of Diodes

Clipper Circuit



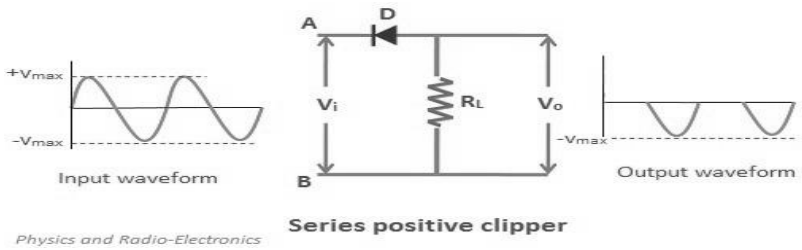


Figure 9. Positive and Negative Clipper

Clamper

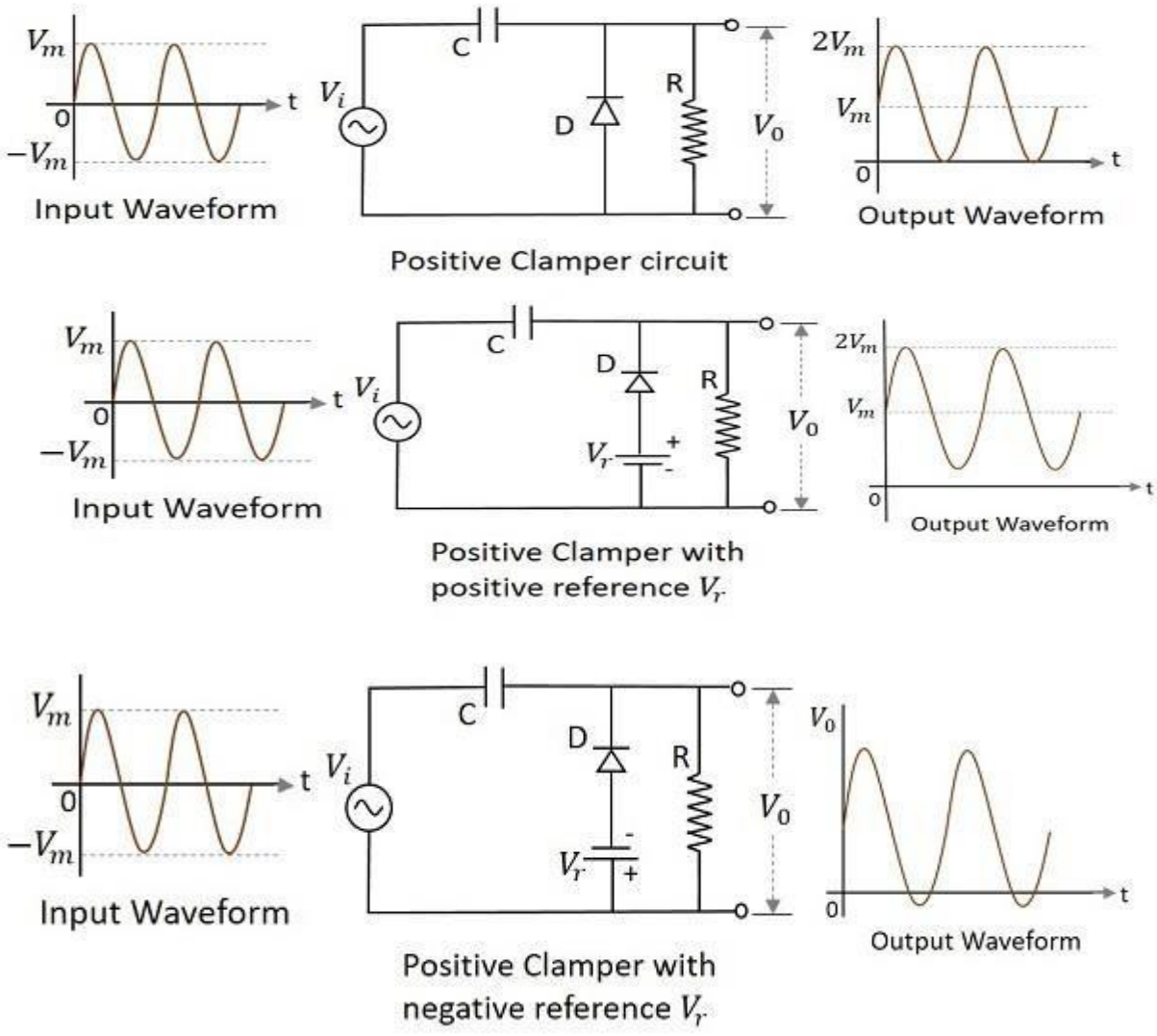


Figure 10. Positive Clamper

Clamper

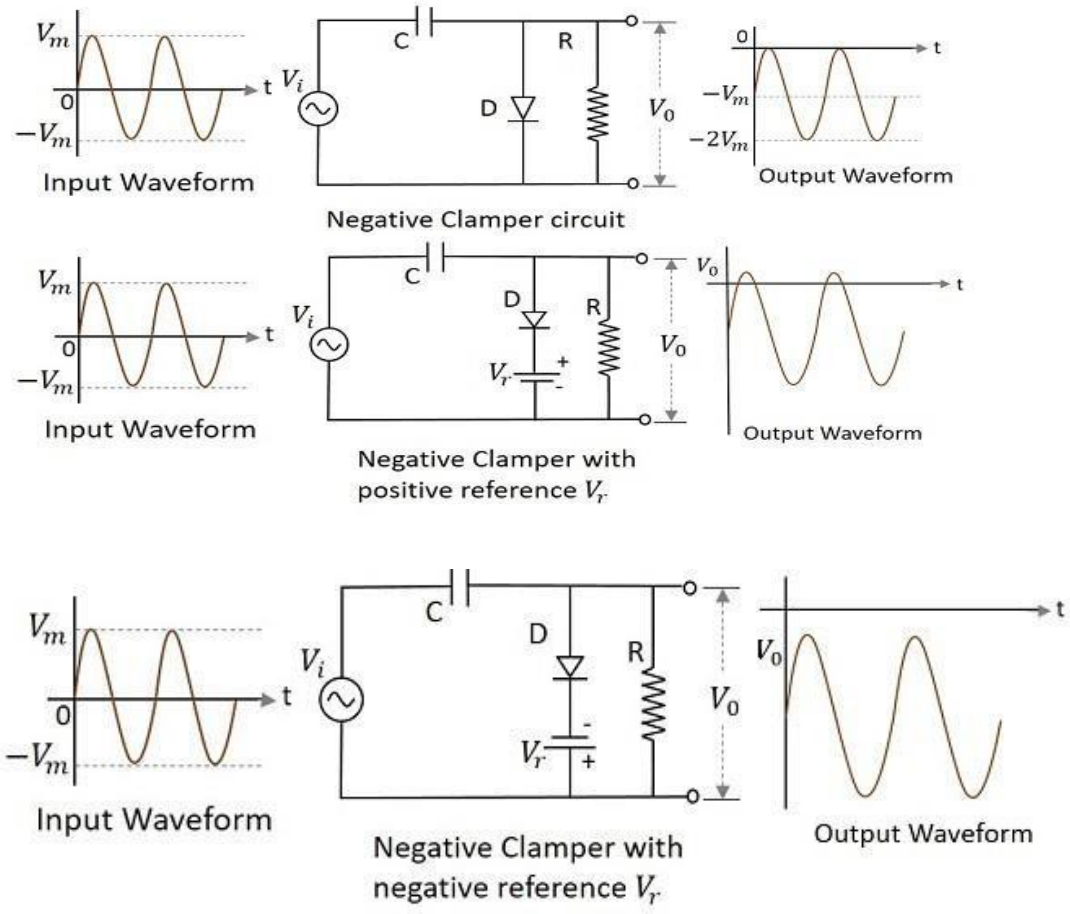


Figure 11. Negative Clamper

Applications of Clippers and Clampers

There are many applications for both Clippers and Clampers such as

Clippers

- **Used for the generation and shaping of waveforms**
- **Used for the protection of circuits from spikes**
- **Used for amplitude restorers**
- **Used as voltage limiters**
- **Used in television circuits**
- **Used in FM transmitters**

Clampers

- **Used as direct current restorers**
- **Used to remove distortions**
- **Used as voltage multipliers**
- **Used for the protection of amplifiers**
- **Used as test equipment**
- **Used as base-line stabilizer**

1.5 Zener Diode

- **Zener diode is basically like an ordinary PN junction diode but normally operated in reverse biased condition**
- **A Zener diode is a specially designed, highly doped PN junction diode.**

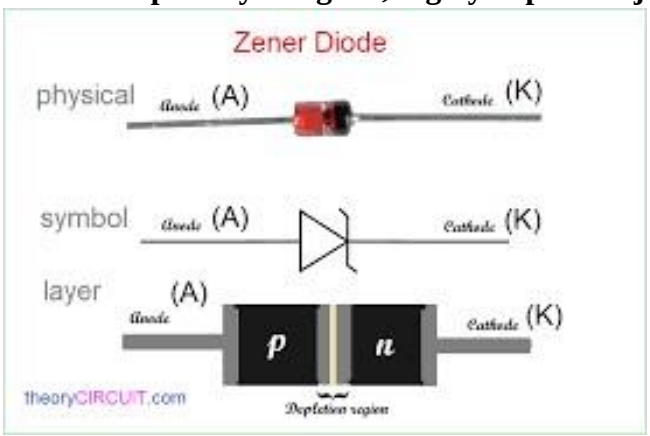


Figure 13. Zener Diode

V-I charecteristics of zener diode

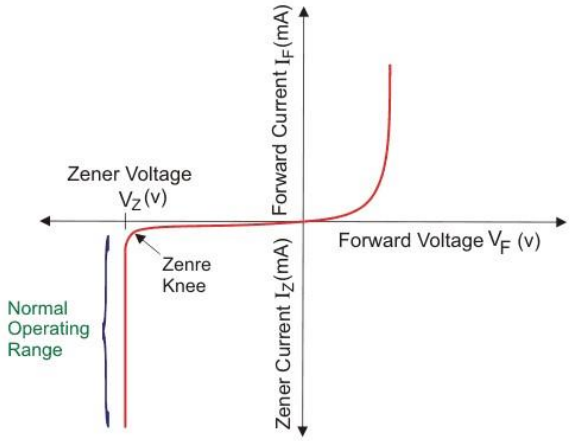


Figure 14. Zener Diode

V-I characteristics of a Zener diode

- **The V-I characteristics of a Zener diode can be divided into two parts as follows:**

(i) **Forward Characteristics**

(ii) **Reverse Characteristics**

Forward Characteristics

- **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 any other P-N junction diode.**

Reverse Characteristics

- **When a reverse voltage is applied to a Zener voltage, initially a small reverse saturation current Io flows across the diode. This current is due to thermally generated minority carriers.**

- **As the reverse voltage is increased, 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 it is denoted by Vz.**

Break down voltage

- **Avalanche breakdown**
  - **The avalanche breakdown occurs in both normal diodes and Zener diodes at high reverse voltage. When a high reverse voltage is applied to the p-n junction diode, the free electrons (minority carriers) gains a large amount of energy and accelerated to greater velocities.**
  - **This sudden increase in electric current may permanently destroy the normal diode.**

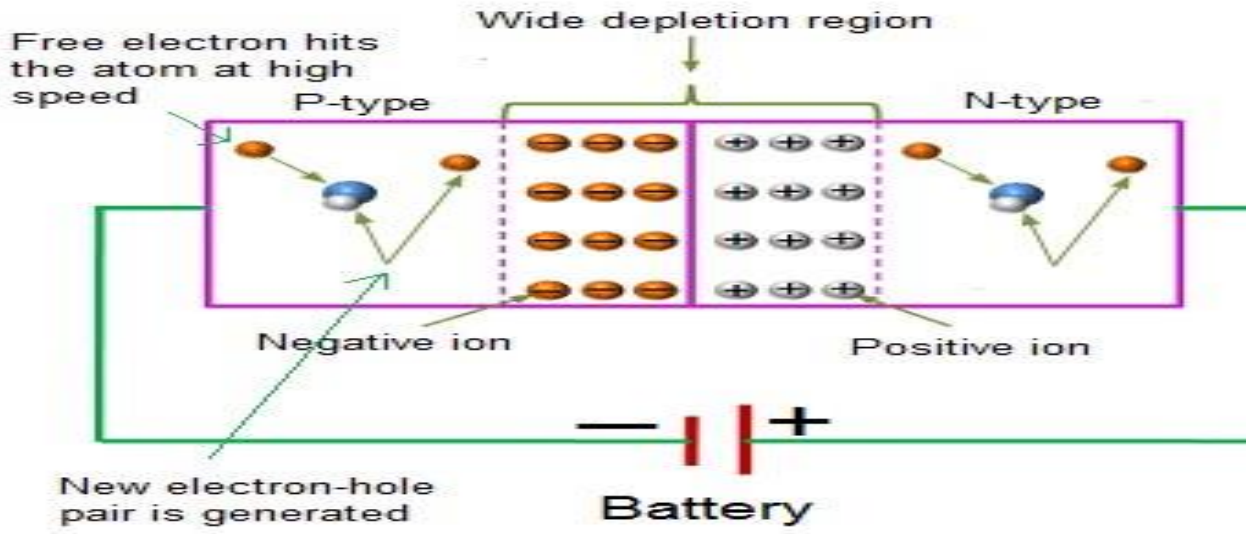


Figure 15. Zener break down voltage

- **The Zener breakdown occurs in heavily doped p-n junction diodes because of their narrow depletion region. When the reverse biased voltage applied to the diode is increased, the narrow depletion region generates a strong electric field.**
- **The Zener breakdown occurs in heavily doped p-n junction diodes because of their narrow depletion region.**
- **At the Zener breakdown region, a small increase in voltage will rapidly increase the electric current.**
- **Zener breakdown occurs at low reverse voltage whereas avalanche breakdown occurs at high reverse voltage.**
- **Zener breakdown occurs in Zener diodes because they have very thin depletion region.**
- **Breakdown region is the normal operating region for a Zener diode.**
- **Zener breakdown occurs in Zener diodes with Zener voltage (Vz) less than 6V.**

Zener diode as voltage regulator

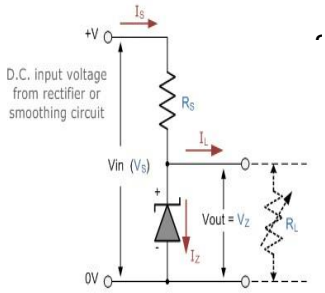


Figure 16. Voltage regulator

Resistor, R is connected in series with the zener diode to limit the current flow through the diode with the voltage source, V_S

•The stabilised output voltage V_{out} is taken from across the load is connected in parallel with the zener diode •voltage across R_L is always the same as the zener voltage ($V_R = V_Z$)

1.6 Light Emitting Diode

A light-emitting diode is a two-lead semiconductor light source. It is a p–n junction diode that emits light when activated. When a suitable voltage is applied to the leads, electrons are able to recombine with electron holes within the device, releasing energy in the form of photons. This effect is called electroluminescence, and the color of the light (corresponding to the energy of the photon) is determined by the energy band gap of the semiconductor.

Working Principle of LED

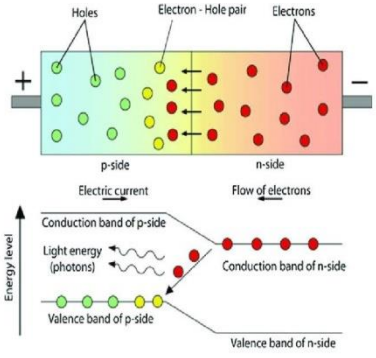


Figure 17. Working of LED

- **The material used in LEDs is basically aluminum-gallium-arsenide (AlGaAs). In its original state, the atoms of this material are strongly bonded. Without free electrons, conduction of electricity becomes impossible here.**

- **By adding an impurity, which is known as doping, extra atoms are introduced, effectively disturbing the balance of the material.**

- **These impurities in the form of additional atoms are able either to provide free electrons (N-type) into the system or suck out some of the already existing electrons from the atoms (P-Type) creating "holes" in the atomic orbits. In both ways the material is rendered more conductive. Thus in the influence of an electric current in N-type of material, the electrons are able to travel from anode (positive) to the cathode (negative) and vice versa in the P-type of material. Due to the virtue of the semiconductor property, current will never travel in opposite directions in the respective cases.**

- **From the above explanation, it's clear that the intensity of light emitted from a source (LED in this case) will depend on the energy level of the emitted photons which in turn will depend on the energy released by the electrons jumping in between the atomic orbits of the semiconductor material.**

- **We know that to make an electron shoot from lower orbital to higher orbital its energy level is required to be lifted. Conversely, if the electrons are made to fall from the higher to the lower orbitals, logically energy should be released in the process.**

- **In LEDs, the above phenomena is well exploited. In response to the P-type of doping, electrons in LEDs move by falling from the higher orbitals to the lower ones releasing energy in the form of photons i.e. light. The farther these orbitals are apart from each other, the greater the intensity of the emitted light.**

- **Different wavelengths involved in the process determine the different colors produced from the LEDs. Hence, light emitted by the device depends on the type of semiconductor material used.**
  Infrared light is produced by using Gallium Arsenide (GaAs) as a semiconductor. Red or yellow light is produced by using Gallium-Arsenide-Phosphorus (GaAsP) as a semiconductor. Red or green light is produced by using Gallium-Phosphorus (GaP) as a semiconductor.

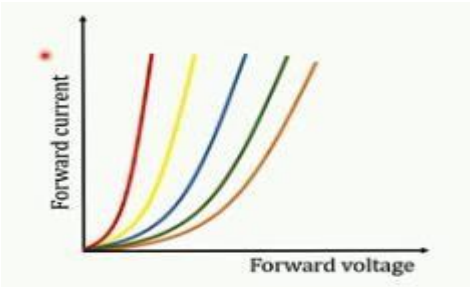
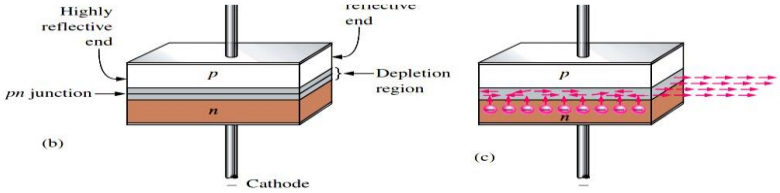
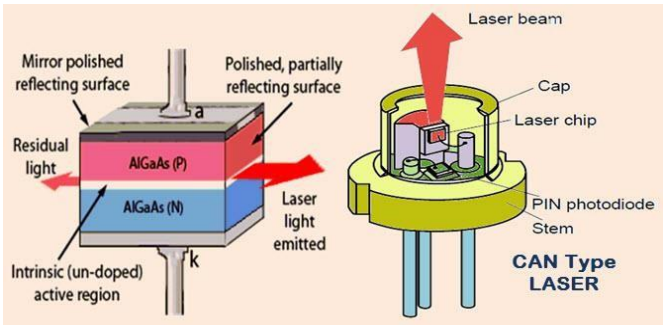


Figure 18. VI characteristics of LED





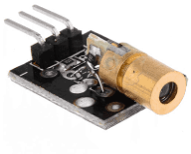


Figure 19 LASER Diode internal structure

1.7 LASER DIODE

- **Absorption**
  In absorption, the electrons at lower energy levels jump to higher energy level i.e. from valence band to conduction band when the electrons are provided with an external source of energy. Now, there are holes at lower energy level i.e. valence band and electrons at higher energy level i.e. conduction band.
- **Spontaneous Emission**
  Now, if the electrons in higher energy level are unstable then they will tend to move to the lower energy level in order to achieve stability. But if they will move from higher energy level to lower energy levels they will definitely release the energy which will be the energy difference between these two levels. The energy released will be in the form of light and thus photons will be emitted. This process is called spontaneous emission.
  Stimulated Emission
- **In stimulated emission, the photons strike electrons at higher energy level and these photons are supplied from an external light energy source. When these photons strike the electrons, electrons gain energy and they recombine with holes and release an extra photon. Thus, one incident photon stimulates another photon to release. Thus, this process is called stimulated emission.**
- **Population inversion**
  The density of electrons at energy levels is the population of electrons and it is more in valence band or lower energy band and less in the conduction band or higher energy level. If the population of electrons increases at higher energy level or the lifetime of higher energy states is long then stimulated emission will increase. This increase of population at higher energy level is termed as population inversion.

Advantages of Laser Diode

- **Low power Consumption device.**
- **Economical as its cost of manufacturing and operation is low.**
- **It can be operated for a long time.**
- **Portable due to its small size and internal architecture.**
- **Highly reliable and highly efficient.**

Disadvantages of Laser Diode

- **These are temperature dependent and thus its operation is affected by the change in operating temperature.**
- **It is not suitable for high power application.**

Applications of Laser diode

- **Fibre optical communication system.**
- **Barcode readers.**
- **Laser Printing and laser scanning.**
- **Rangefinders.**
- **In medical fields in surgical instruments.**
- **In CD players and DVD recorder.**

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UNIT – II- BASIC ELECTRONIC DEVICES, CIRCUITS AND ITS APPLICATIONS – SBMA1305

2.1 BJT

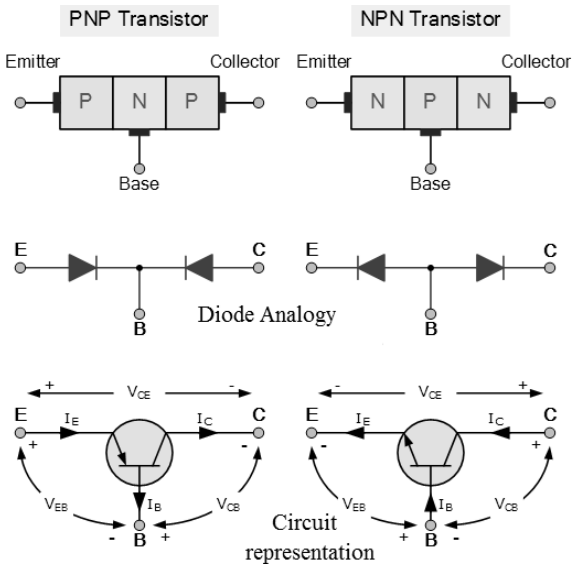
- Semiconductor device which can be used for switchingor amplification
- The fusion of these two diodes produces a three layer, two junction, three terminal device forming the basis of a **Bipolar Junction Transistor.**
- Act as either an insulator or a conductor by the application ofa small signal voltage.
- Three regions of operation

Active Region–the transistor operates as an amplifier and Ic = β*Ib

Saturation–the transistor is "Fully-ON" operating as a switch and Ic = I(saturation)

Cut-off the transistor is "Fully-OFF" operating as a switch and Ic = 0

- Types-PNP and NPN
- Terminals-Emitter (E), the Base (B) and the Collector (C)



- Figure 1. PNP and NPN Transistors

Bipolar Transistor Configurations

- Three possible ways to connect it within an electronic circuit with one terminal being common to both the input and output.
- Each method of connection responding differently to its input signal within a circuit as the static characteristics of the transistor vary with each circuit arrangement.
- Common Base Configuration– has Voltage Gain but no Current Gain.
- Common Emitter Configuration–has both Current and Voltage Gain.
- Common Collector Configuration–has Current Gain but no Voltage Gain

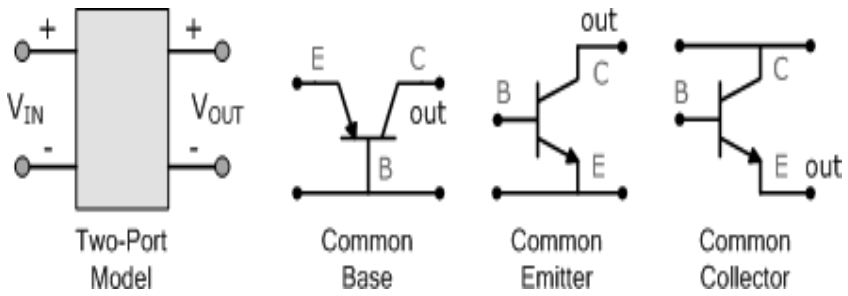


Figure 2. Configuration BJT

2.1.1The Common Base (CB) Configuration

- BASE connection is common to both the input signal AND the output signal

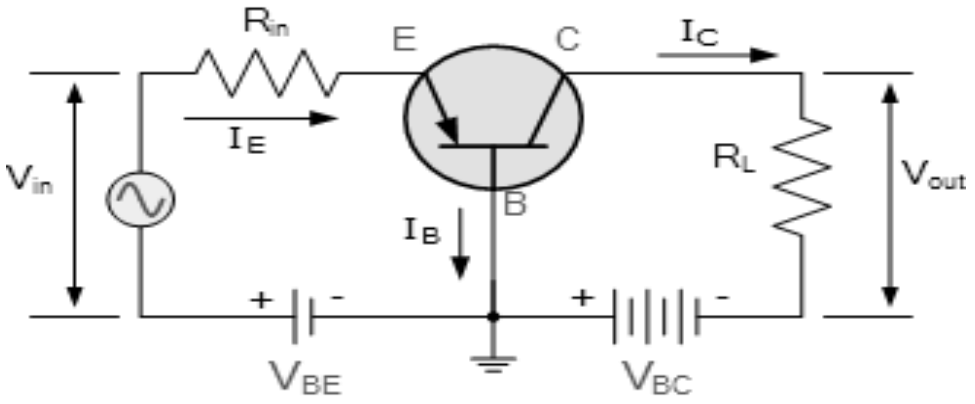


Figure 3. Common Base configuration

Vin and Vout are “in-phase”.

Has a high ratio of output (RL) to input resistance (Rin) -Resistance Gain”.

Voltage gain is given by

Ic/Ie is the current gain, alpha (α)

Application

- Commonly used only in single stage amplifier circuits such as microphone pre- amplifier or radio frequency (R*f*) amplifiers due to its very good highfrequency response.

$$A_V = \frac{Vout}{Vin} = \frac{I_C \times R_L}{I_E \times R_{IN}}$$

2.1.2 The Common Emitter (CE) Configuration

- **The input signal** is applied between the base and the emitter, while the output is taken from between the collector and the emitter
- The common emitter amplifier configuration produces the highest current and power gain of all the three bipolar transistor configurations.
- High gain due to input impedance is LOW as it is connected to a forward biased PN-junction, while the output impedance is HIGH as it is taken from a reverse biased PN-junction.
- current flowing out of the transistor must be equal to the currents flowing into the transistor as the emitter current is given as Ie = Ic + Ib

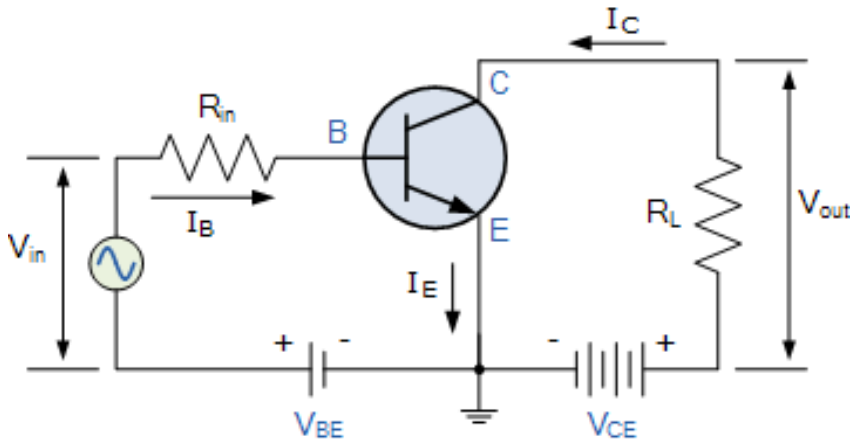


Figure 4. Common Emitter configuration

- As the load resistance (R_L) is connected in series with the collector, the current gain of the common emitter transistor configuration is quite large as it is the ratio of Ic/Ib.
- Small change in the base current (Ib), will result in a much larger change in the collector current (Ic).
- Beta has a value between 20 and 200 for most general purpose transistors.
- ie.. if a transistor has a Beta value of 100, then one electron will flow from the base terminal for every 100 electrons flowing between the emitter- collector terminal.
- output signal has a 180^o phase-shift with regards to the input voltage signal.

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

$$I_E = I_B + I_C \ldots\ldots \text{(KCL)} \quad \text{and} \quad \frac{I_C}{I_E} = \alpha$$

$$\text{Thus:} \quad I_B = I_E - I_C$$

$$I_B = I_E - \alpha I_E$$

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

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

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

$$\alpha = \frac{\beta}{\beta+1} \quad \text{or} \quad \alpha = \beta(1-\alpha)$$

$$\beta = \frac{\alpha}{1-\alpha} \quad \text{or} \quad \beta = \alpha(1+\beta)$$

$$\text{If} \quad \alpha = 0.99 \qquad \beta = \frac{0.99}{0.01} = 99$$

2.1.3 The Common Collector (CC) Configuration

- The input signal is connected directly to the base terminal, while the output signal is taken from across the emitter load resistor as shown.
- Commonly known as a **Voltage Follower** or **Emitter Follower** circuit.

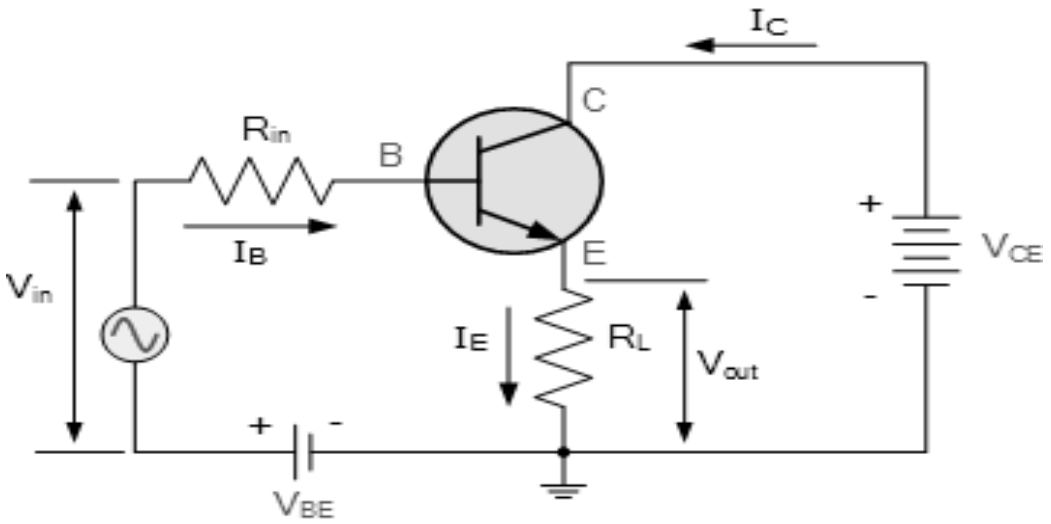


Figure 5. Common Collector configuration

- The load resistance of the common collector transistor receives both the base and collector currents giving a large current gain
- provides good current amplification with very little voltage gain

- Application
- The common collector, or emitter follower configuration is very useful for impedance matching applications because of its very high input impedance, in the region of hundreds of thousands of Ohms while having a relatively low output impedance.

Table 1 Charecteristics of BJT

Characteristic	Common Base	Common Emitter	Common Collector
Input Impedance	Low	Medium	High
Output Impedance	Very High	High	Low
Phase Shift	0^o	180^o	0^o
Voltage Gain	High	Medium	Low
Current Gain	Low	Medium	High
Power Gain	Low	Very High	Medium

2.1.4Biasing of BJT

- Biasing is the process of providing DC voltage which helps in the functioning of the circuit.
- A transistor is biased in order to make the emitter base junction forward biased and collector base junction reverse biased, so that it maintains in active region, to work as an amplifier.
- If a signal of very small voltage is given to the input of BJT, it cannot be amplified. For BJT, to amplify a signal, two conditions have to be met.
  - The input voltage should exceed **cut-in voltage** for the transistor to be **ON**.
  - The BJT should be in the **active region**, to be operated as an **amplifier**.
  - If appropriate DC voltages and currents are given through BJT by external sources, so that BJT operates in active region and superimpose the AC signals to be amplified, then this problem can be avoided.
  - The given DC voltage and currents are so chosen that the transistor remains in active region for entire input AC cycle. Hence DC biasing is needed.

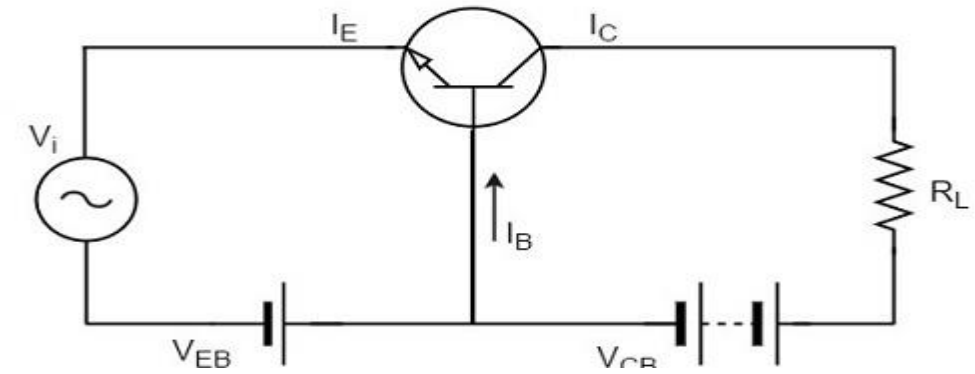


Figure 6. Common Collector configuration

2.2 JFET

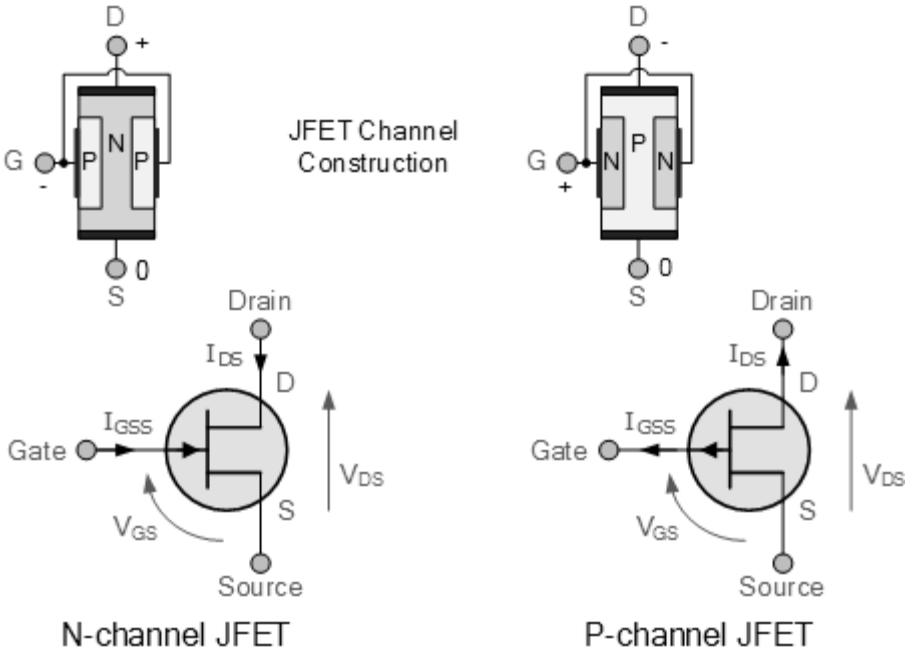


Figure 7. JFET

- BJT "CURRENT" operated device (Beta model) as a smaller current can be used to switch a larger load current.
- **Field Effect Transistor** a "VOLTAGE" operated device since their operation relies on an electric field (hence the name field effect) generated by the input Gate voltage.
- Advantages of FET over BJT
  -high efficiency, instant operation, robust and cheap
  -can be used in most electronic circuit applications to replace their equivalent BJT

  It provides
- Fast switching.
- For low frequency operation, source and drain can be interchanged.
- Gate **voltage** that controls drain current.
- Single majority carrier.
- Small in size.
- High "Z" input.

2.2.1 Two basic configurations

– 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 in the form of electrons.

– P-channel JFET's channel is doped with acceptor impurities meaning that the flow of current through the channel is positive (hence the term P-channel) in the form of holes.

– N-channel JFET's have a greater channel conductivity (lower resistance) than their equivalent P-channel types, since electrons have a higher mobility through a conductor compared to holes.

N-channel JFET's a more efficient conductor compared to their P-channel counterparts.

- 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.
- 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 (ie, 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).

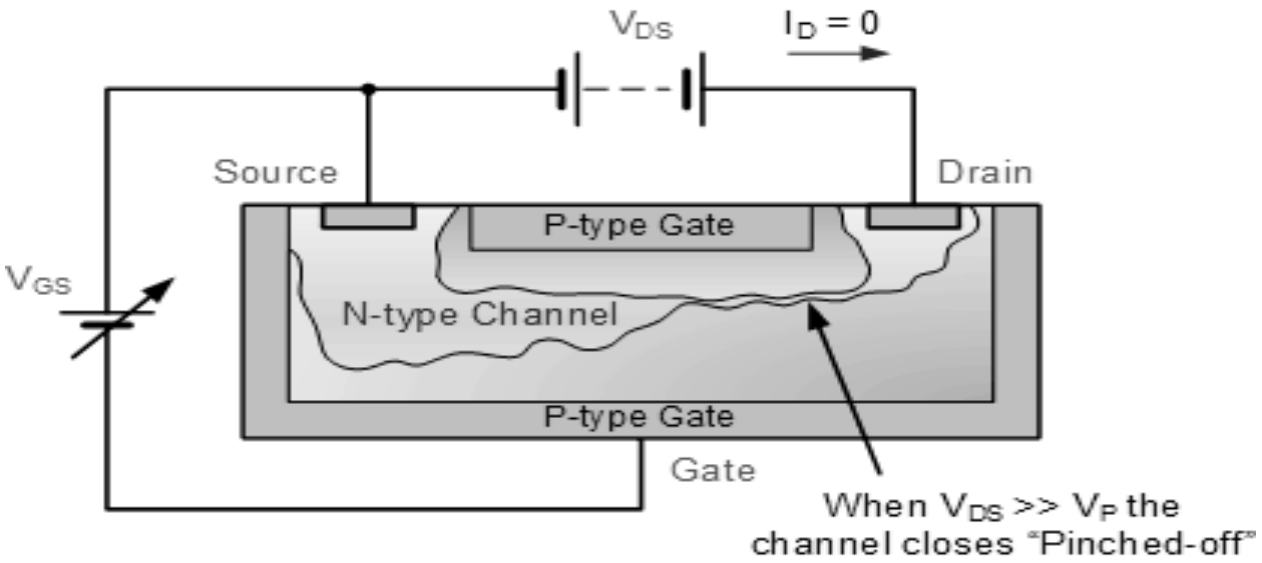


Figure 8. PNP JFET

The P-channel **Junction Field Effect Transistor** operates exactly the same as the N-channel above, with the following exceptions: 1). Channel current is positive due to holes,

2). The polarity of the biasing voltage needs to be reversed.

2.2.3 Output Characteristics

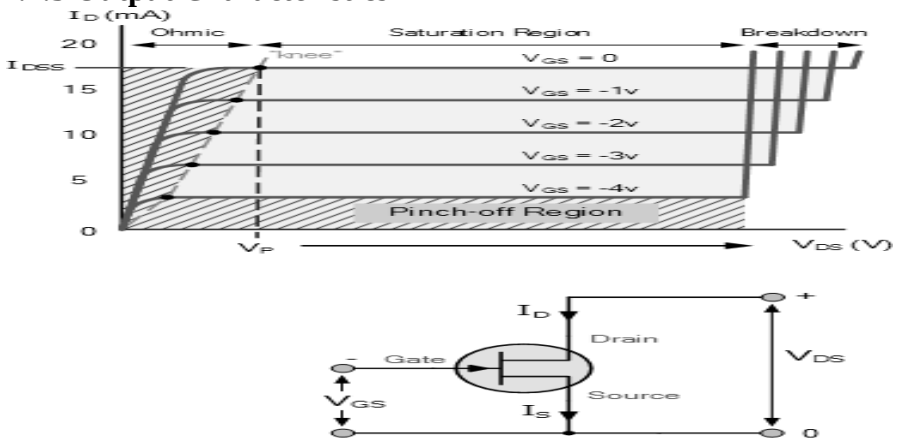


Figure 9. Output Characteristics

- The voltage V_{GS} applied to the Gate controls the current flowing between the Drain and the Source terminals.
- JFET 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 above, 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.

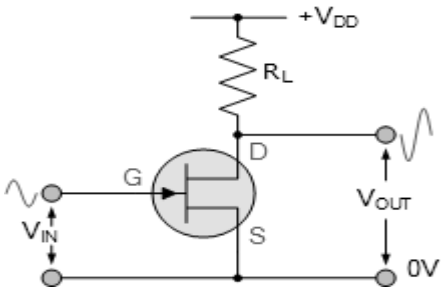


Figure 10. Common Source

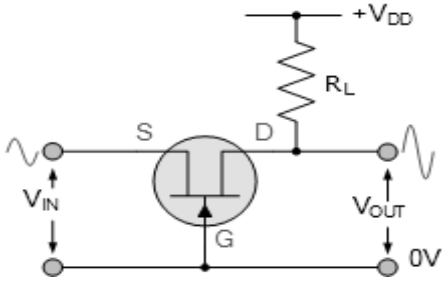


Figure 11. Common Gate Configuration

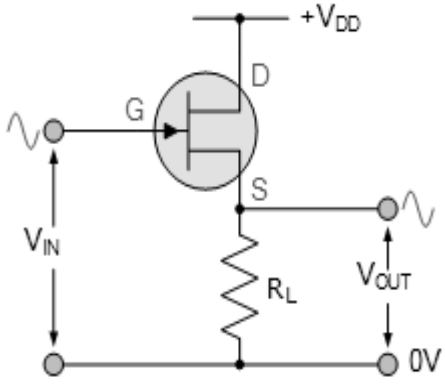


Figure 12. Common Source Configuration

2.2.4 Biasing of JFET Amplifier

- Common source (CS) amplifier circuit is biased in class "A" mode by the voltage divider network formed by resistors R1 and R2.
- The voltage across the Source resistor R_S is generally set to be about one quarter of V_{DD}, (V_{DD} /4) but can be any reasonable value.
- The required Gate voltage can then be calculated from this R_S value. Since the Gate current is zero, ($I_G = 0$) we can set the required DC quiescent voltage by the proper selection of resistors R1 and R2.

$$V_S = I_D R_S = \frac{V_{DD}}{4}$$

$$V_S = V_G - V_{GS}$$

$$V_G = \left| \frac{R_2}{R_1 + R_2} \right| V_{DD}$$

$$I_D = \frac{V_S}{R_S} = \frac{V_G - V_{GS}}{R_S}$$

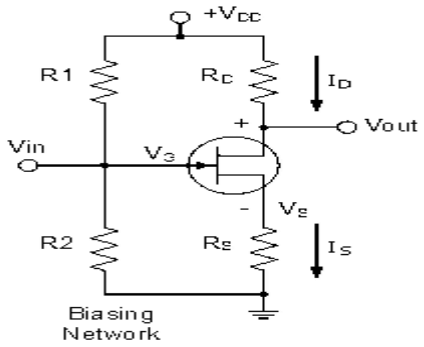


Figure 13. Common Source Configuration

2.3 MOSFET

- MOSFET's operate the same as JFET's but have a gate terminal that is electrically isolated from the conductive channel

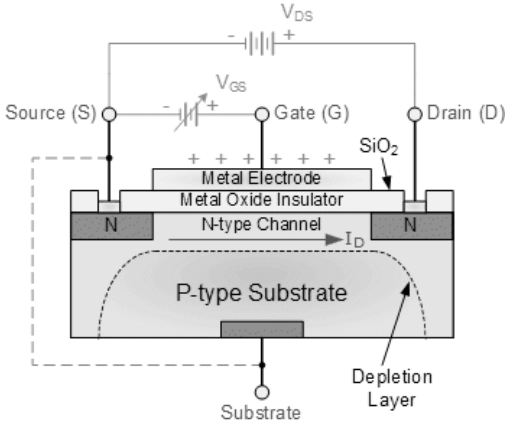


Figure 14. Common Source Configuration

- The **IGFET** or **MOSFET** is a voltage controlled field effect transistor that differs from a JFET in that it has a “Metal Oxide” Gate electrode which is electrically insulated from the main semiconductor n-channel or p-channel by a very thin layer of insulating material usually silicon dioxide, commonly known as glass.
- MOSFETs are three terminal devices with a Gate, Drain and Source and both P-channel (PMOS) and N-channel (NMOS) MOSFETs are available. The main difference this time is that MOSFETs are available in two basic forms:
- **Depletion Type** – the transistor requires the Gate-Source voltage, (V_{GS}) to switch the device “OFF”. The depletion mode MOSFET is equivalent to a “Normally Closed” switch.
- **Enhancement Type** – the transistor requires a Gate-Source voltage, (V_{GS}) to switch the device “ON”. The enhancement mode MOSFET is equivalent to a “Normally Open” switch.

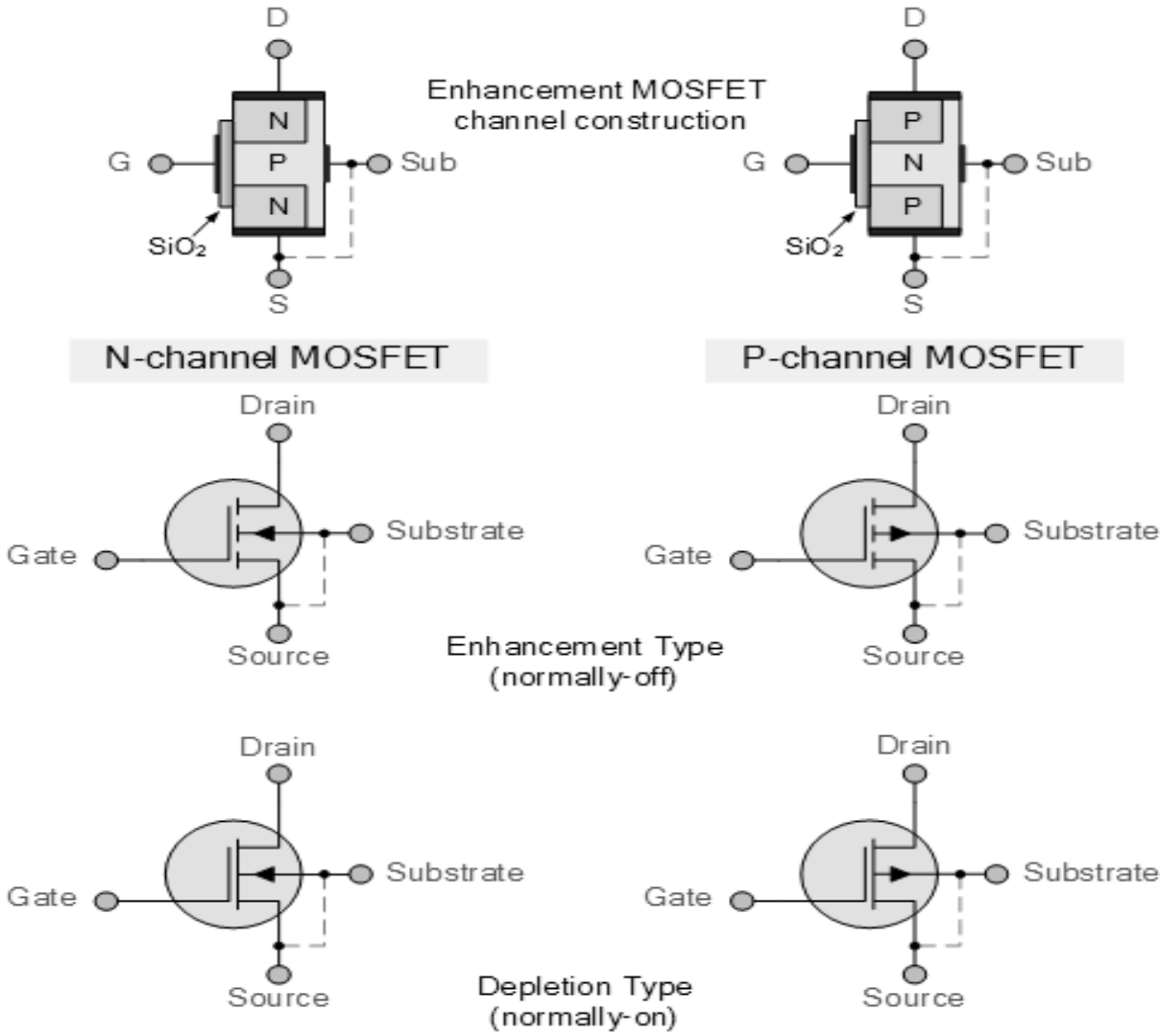


Figure 15. MOSFET

additional terminal called the **Substrate** and is not normally used as either an input or an output connection but instead it is used for grounding the substrate.

2.3.1 Depletion-mode MOSFET

- The Depletion-mode MOSFET, which is less common than the enhancement mode types is normally switched "ON" (conducting) without the application of a gate bias voltage. That is the channel conducts when $V_{GS} = 0$ making it a "normally-closed" device. The circuit symbol shown above for a depletion MOS transistor uses a solid channel line to signify a normally closed conductive channel.
- For the n-channel depletion MOS transistor, a negative gate-source voltage, $-V_{GS}$ will deplete (hence its name) the conductive channel of its free electrons switching the transistor "OFF". Likewise for a p-channel depletion MOS transistor a positive gate-source voltage, $+V_{GS}$ will deplete the channel of its free holes turning it "OFF".
- -for an n-channel depletion mode MOSFET: $+V_{GS}$ means more electrons and more current. While a $-V_{GS}$ means less electrons and less current. The opposite is also true for the p-channel types. Then the depletion mode MOSFET is equivalent to a "normally-closed" switch**.**

2.3.2 Enhancement-mode MOSFET

- The more common Enhancement-mode MOSFET or eMOSFET, is the reverse of the depletion-mode type. Here the conducting channel is lightly doped or even undoped making it non-conductive. This results in the device being normally "OFF" (non-conducting) when the gate bias voltage, V_{GS} is equal to zero.
- For the n-channel enhancement MOS transistor a drain current will only flow when a gate voltage (V_{GS}) is applied to the gate terminal greater than the threshold voltage (V_{TH}) level in which conductance takes place making it a transconductance device.
- The application of a positive (+ve) gate voltage to a n-type eMOSFET attracts more electrons towards the oxide layer around the gate thereby increasing or enhancing (hence its name) the thickness of the channel allowing more current to flow. It is called an enhancement mode device as the application of a gate voltage enhances the channel.
- Increasing this positive gate voltage will cause the channel resistance to decrease further causing an increase in the drain current, I_D through the channel. In other words, for an n-channel enhancement mode MOSFET: $+V_{GS}$ turns the transistor "ON", while a zero or $-V_{GS}$ turns the transistor "OFF". Thus the enhancement-mode MOSFET is equivalent to a "normally-open" switch.
- The reverse is true for the p-channel enhancement MOS transistor. When $V_{GS} = 0$ the device is "OFF" and the channel is open. The application of a negative (-ve) gate voltage to the p-type eMOSFET enhances the channels conductivity turning it "ON". Then for an p-channel enhancement mode MOSFET: $+V_{GS}$ turns the transistor "OFF", while $-V_{GS}$ turns the transistor "ON".

- The MOSFETs ability to change between these two states enables it to have two basic functions: "switching" (digital electronics) or "amplification" (analogue electronics). Then MOSFETs have the ability to operate within three different regions:
- 1. **Cut-off Region** – with $V_{GS} < V_{threshold}$ the gate-source voltage is much lower than the

transistors threshold voltage so the MOSFET transistor is switched "fully-OFF" thus, $I_D = 0$, with the transistor acting like an open switch regardless of the value of V_{DS}.

- 2. **Linear (Ohmic) Region** – with $V_{GS} > V_{threshold}$ and $V_{DS} < V_{GS}$ the transistor is in its constant resistance region behaving as a voltage-controlled resistance whose resistive value is determined by the gate voltage, V_{GS} level.
- 3. **Saturation Region** – with $V_{GS} > V_{threshold}$ and $V_{DS} > V_{GS}$ the transistor is in its constant current region and is therefore "fully-ON". The Drain current I_D = Maximum with the transistor acting as a closed switch.

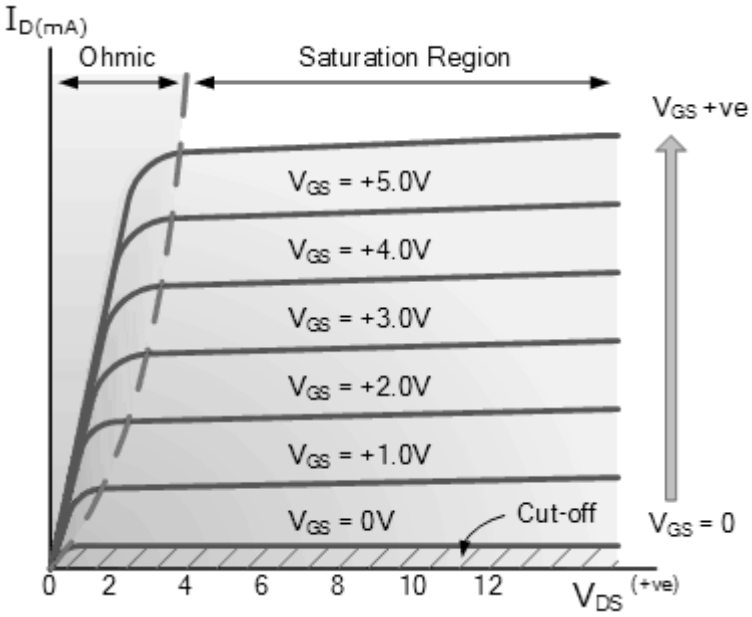


Figure 16. MOSFET output characteristics

Table 2. MOSFET Voltages

MOSFET type	V_{GS} = +ve	V_{GS} = 0	V_{GS} = -ve
N-Channel Depletion	ON	ON	OFF
N-Channel Enhancement	ON	OFF	OFF
P-Channel Depletion	OFF	ON	ON
P-Channel Enhancement	OFF	OFF	ON

2.3..3 Biasing of MOSFET

- DC gate voltage will be set by the bias circuit. Then the total gate-source voltage will be the sum of V_{GS} and V_i.
- The DC characteristics and therefore Q-point (quiescent point) are all functions of gate voltage V_{GS}, supply voltage V_{DD} and load resistance R_D.
- The MOS transistor is biased within the saturation region to establish the desired drain current which will define the transistors Q-point. As the instantaneous value of V_{GS} increases, the bias point moves up the curve as shown allowing a larger drain current to flow as V_{DS} decreases.
- Likewise, as the instantaneous value of V_{GS} decreases (during the negative half of the input sine wave), the bias point moves down the curve and a smaller V_{GS} results in a smaller drain current and increased V_{DS}.
- Then in order to establish a large output swing we must **bias the transistor well above threshold level to ensure that the transistor stays in saturation over the full sinusoidal input cycle.** However, there is a limit on the amount of gate bias and drain current we can use. To allow for **maximum voltage swing of the output, the Q-point should be positioned approximately halfway between the supply voltage V_{DD} and the threshold voltage V_{TH}.**
- So for example, lets assume we want to construct a single stage NMOS common-source amplifier. The threshold voltage, V_{TH} of the eMOSFET is 2.5 volts and the supply voltage, V_{DD} is +15 volts. Then the DC bias point will be 15 – 2.5 = 12.5v or 6 volts to the nearest integer value.

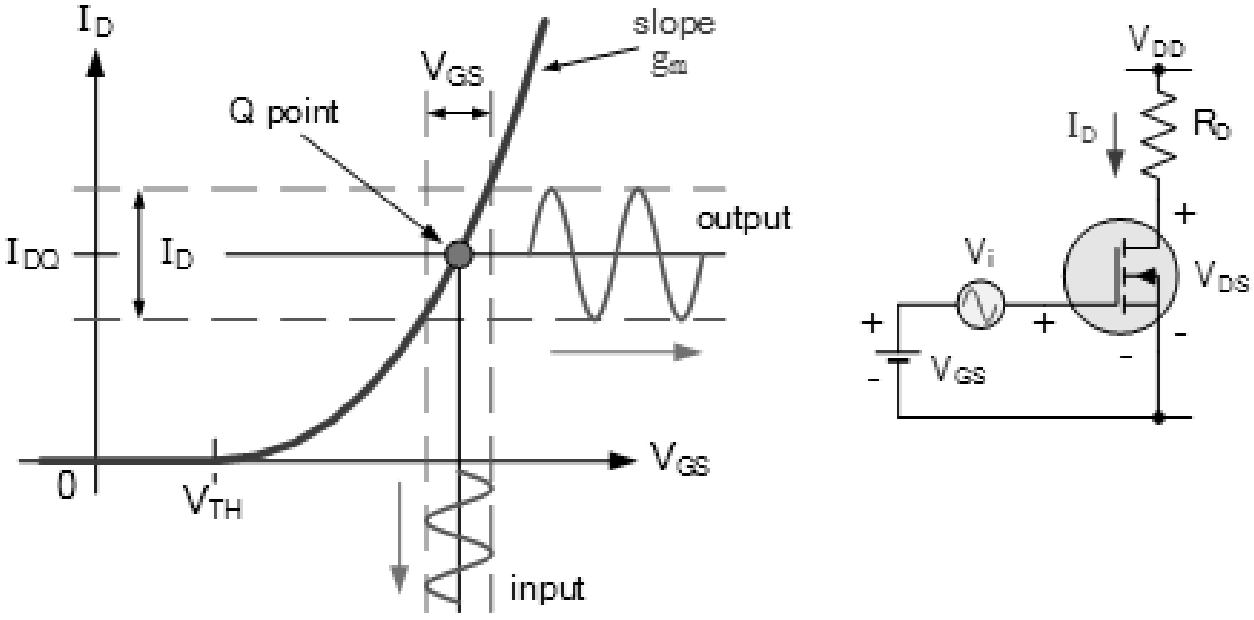


Figure 17. MOSFET Biasing

2.4. Uni-junction transistor(UJT)

A unijunction transistor is a three-lead electronic semiconductor device with only one junction that acts exclusively as an electrically controlled switch.

2.4.1 Output Characteristics

Cutoff

Cutoff region is the area where the UJT doesn't get sufficient voltage to turn on. The applied voltage hasn't reached the triggering voltage, thus making transistor to be in off state.

Negative Resistance Region

When the transistor reaches the triggering voltage, V_{TRIG}, UJT will turn on. After a certain time, if the applied voltage increases to the emitter lead, it will reach out at V_{PEAK}. The voltage drops from V_{PEAK} to Valley Point even though the current increases (negative resistance).

Saturation

Saturation region is the area where the current and voltage raises, if the applied voltage to emitter terminal increases.

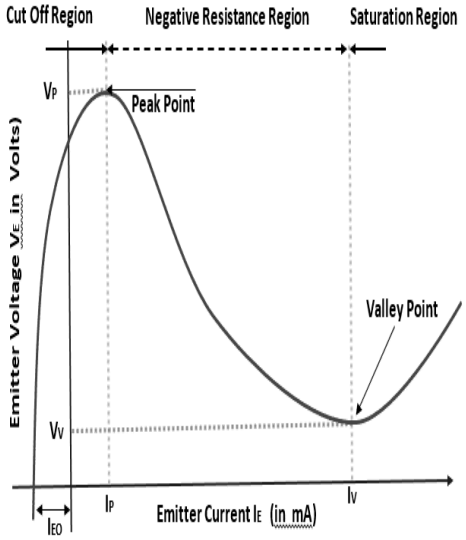


Figure 18. UJT

2.5 Insulated Gate Bipolar Transistor(IGBT)

Insulated Gate Bipolar Transistor is semiconductor switching device that has the **output characteristics of a bipolar junction transistor**, BJT, but is **controlled like a metal oxide field effect transistor, MOSFET.**

- One of the main advantages of the IGBT transistor is the simplicity by which it can be driven "**ON**" by applying a **positive gate voltage**, or switched "**OFF**" by making the gate signal zero or slightly negative allowing it to be used in a variety of switching applications. It can also be **driven in its linear active region for use in power amplifiers.**
- With its lower on-state resistance and conduction losses as well as its ability to switch high voltages at high frequencies without damage makes the **Insulated Gate Bipolar Transistor** ideal for driving inductive loads such as coil windings, electromagnets and DC motors.

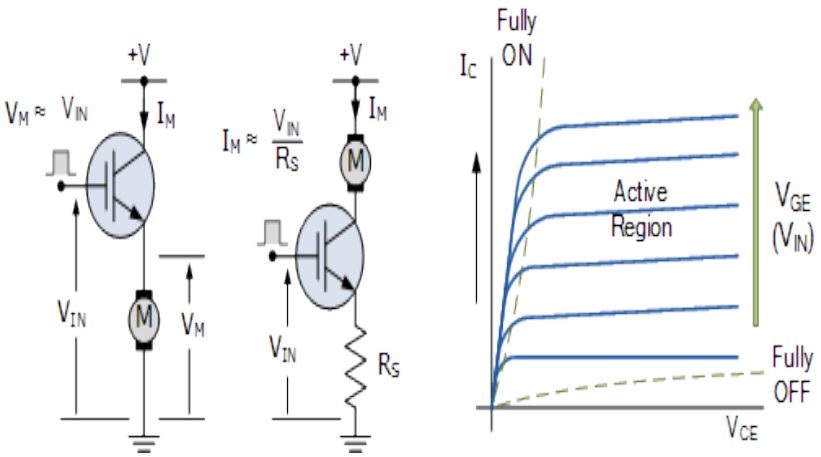


Figure 19 IGBT

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SCHOOL OF BIO AND CHEMICAL ENGINEERING

DEPARTMENT OF BIOMEDICAL ENGINEERING

UNIT – III – BASIC ELECTRONIC DEVICES, CIRCUITS AND ITS APPLICATIONS – SBMA1305

3.1 HYBRID PARAMETERS

- **Hybrid parameters or h-parameters are used to determine amplifier characteristic parameters such as voltage gain, current gain, input and output resistance etc.,**
- **h-parameters are easy to measure and the procedure followed to obtain is quite simple and easy to understand**
- **They are real numbers at audio frequencies**
- **They can be easily obtained from the static characteristics of the transistor itself**
- **Hybrid model is an equivalent model used in small signal analysis i.e low frequency applications**
- **h stands for hybrid consisting mixed parameters.**
- **h_{11} - input impedance**
- **h_{21} - forward current gain**
- **h_{22} - output admittance**
- **h_{12} - reverse voltage gain**

$$h_{11} = \left.\frac{V_1}{I_1}\right|_{V_2=0}$$

$$h_{21} = \left.\frac{I_2}{I_1}\right|_{V_2=0}$$

$$h_{22} = \left.\frac{I_2}{V_2}\right|_{I_1=0}$$

$$h_{12} = \left.\frac{V_1}{V_2}\right|_{I_1=0}$$

$$V_1 = h_{11} I_1 + h_{12} V_2$$
$$I_2 = h_{21} I_1 + h_{22} V_2 \cdot$$

While Analyzing Small Signal amplifiers we need to draw an equivalent circuit of BJT and that circuit is called Small signal model of BJT

In Small Signal Analysis we can do AC and DC analysis separately

Small-signal analysis assumes that the transistor is correctly biased and concentrates on the linear behavior for small signals

In Active Region the transistor shows linear behavior

Small-signal modeling is a common analysis technique in electronics engineering which is used to approximate the behavior of electronic circuits containing nonlinear devices with linear equations

Step 1:

Short Circuit all the Capacitors and DC power Supplies. Draw the Hybrid model of given circuit and Replace the Series Combination of Resistors into Parallel in an equivalent Circuit

Step 2:

Apply the Approximate Model Conditions and get the Simplified equivalent circuit

Step 3:

Draw the Small signal equivalent Circuit

Step 4:

Assume Rs=0 and Find the Parameters Input Impedance (Zi), Voltage Gain (Av), Output Impedance (Zo)

Step 5:

Case 1. Find the Overall Current Gain (Ai) [without

neglecting any of the resistors]

Case 2. Let Rs =0 and Find the Current Gain

Case 3. Let RL=0 and Find the Current Gain

Case 4. Let RL=0, Rs=0 and Find the Current Gain

3.2 Small signal Analysis of Common Emitter configuration

An Equivalent model is the combination of circuit elements properly chosen to best represent the actual behaviour of the device under specific operating conditions

Step 1: Draw the equivalent hybrid model of the circuit

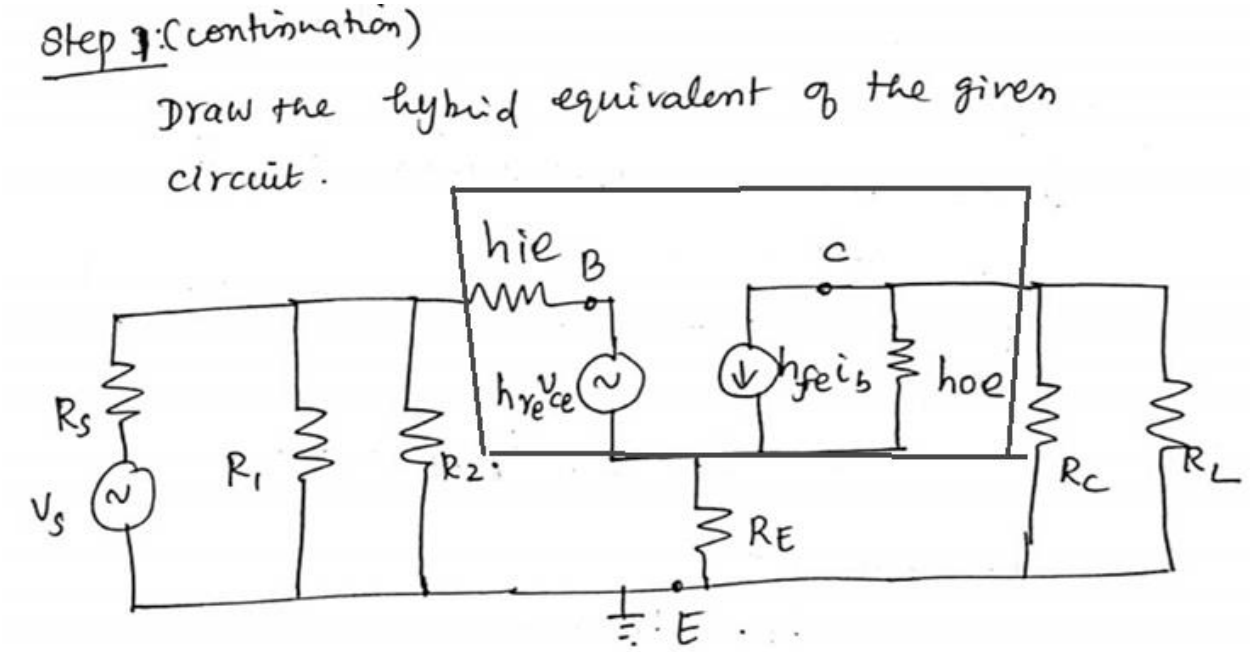


Figure 1. Equivalent Circuit for common emitter configuration

Step 2: Apply the Approximate Model Conditions and get the Simplified equivalent circuit

Step 2

Draw the small signal equivalent model (applying approximate model conditions).

Small signal model is

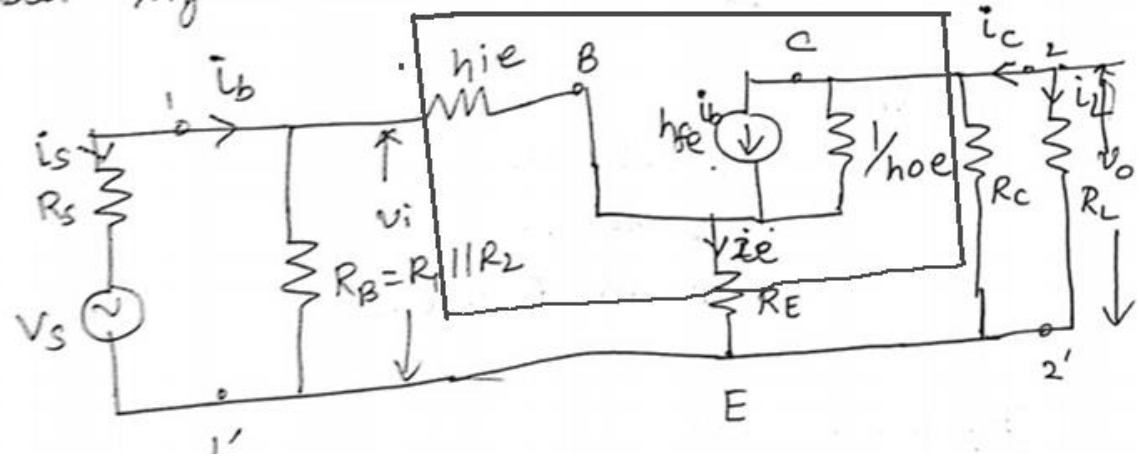


Figure 2. Equivalent Circuit for common emitter configuration

Step 3 :

(i) Calculation of input impedance Z_i

Let us assume $R_s = 0$.

The input voltage v_i across the input port is given by

$$v_i = i_b h_{ie} + i_e R_E \rightarrow (1).$$

We know that,

$$I_E = I_B + I_C.$$

(or)

$$i_e = i_b + i_c \quad \text{(ac analysis)}.$$

and also the current gain $\beta = \dfrac{i_c}{i_b}$.

$$\beta = \frac{I_C}{I_B} \quad (\text{or}) \quad I_C = \beta I_B .$$

$$\therefore I_E = I_B + \beta I_B$$

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

(ie) $i_e = i_b(1+\beta)$.

substituting this in eqn (1)

$$v_i = i_b h_{ie} + i_b(1+\beta) R_E$$

Dividing by i_b

$$\frac{v_i}{i_b} = \frac{i_b h_{ie} + i_b(1+\beta) R_E}{i_b}$$

$$\Rightarrow z_i = h_{ie} + (1+\beta) R_E .$$

$$\boxed{z_i = h_{ie} + (1+\beta) R_E}$$

(ii) Calculation of output impedance (Z_o)

The output voltage across the load R_L is v_o and it is expressed by

$$v_o = i_L R_L$$

But $$i_L = -i_2 = -i_c$$

$$\therefore v_o = -i_c R_L$$

(or) $$v_o = -i_c (R_L \| R_c)$$

$$v_o = -i_c (R_c \| R_L)$$

$$\frac{v_o}{-i_c} = \frac{v_o}{i_L} = R_c \| R_L .$$

$$\Rightarrow z_o = R_c \| R_L$$

(iii) Calculation of voltage gain (A_V)

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

$$V_o = -i_c(R_C \| R_L)$$

$$V_i = i_b h_{ie} + i_e R_E$$

$$\therefore \frac{V_o}{V_i} = \frac{-i_c(R_C \| R_L)}{i_b h_{ie} + i_e R_E}$$

Converting these in terms of i_c

$$A_V = \frac{-i_c(R_C \| R_L)}{\frac{i_c}{\beta} h_{ie} + (i_b + i_c) R_E}$$

WKT $\beta = \frac{i_c}{i_b}$ (or) $i_b = \frac{i_c}{\beta}$

$$\Rightarrow \frac{-i_c(R_C \| R_L)}{i_c/\beta \cdot h_{ie} + \left(\frac{i_c}{\beta} + i_c\right) R_E}$$

$$= \frac{-i_c(R_C \| R_L)}{\frac{i_c}{\beta} \cdot h_{ie} + i_c\left(\frac{1}{\beta} + 1\right) R_E}$$

$$A_V = \frac{-(R_C \| R_L)}{h_{ie} + \left(1 + \frac{1}{\beta}\right) \cdot R_E}$$

3.3 Small Signal Analysis of Common Collector (CC)BJT Amplifier

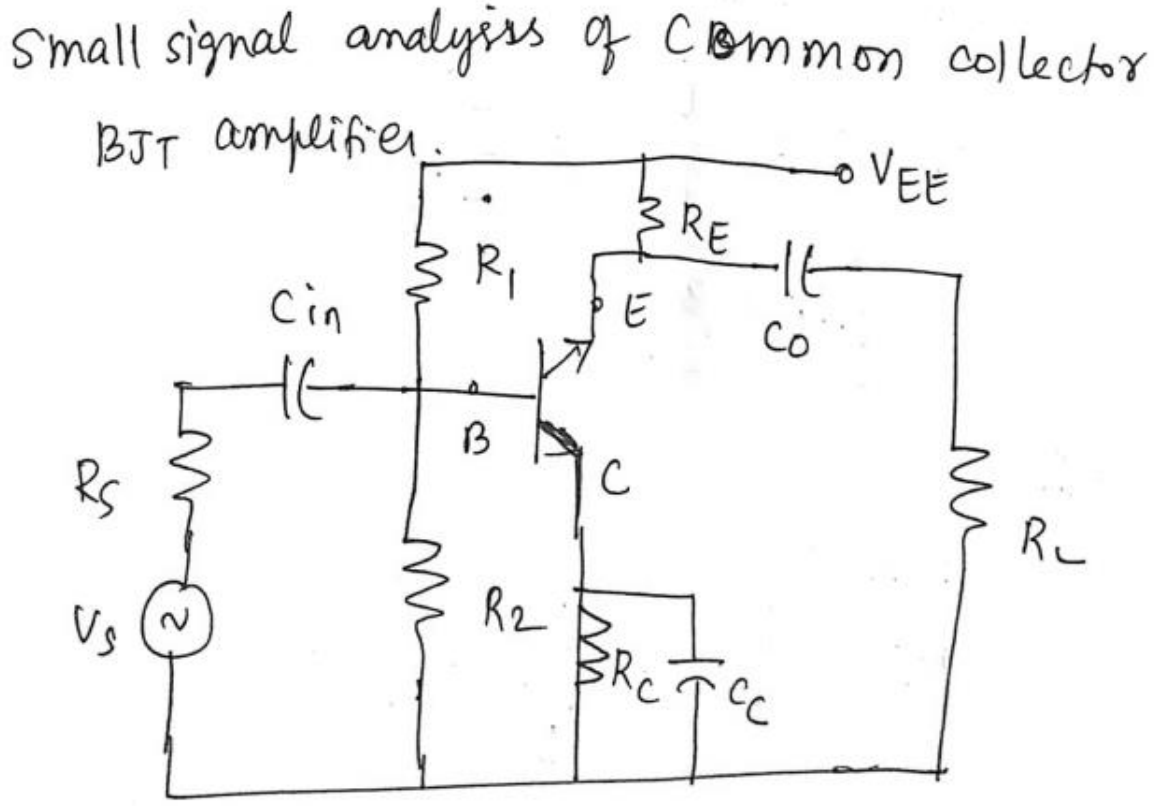


Figure 2. Common Collector Configuration

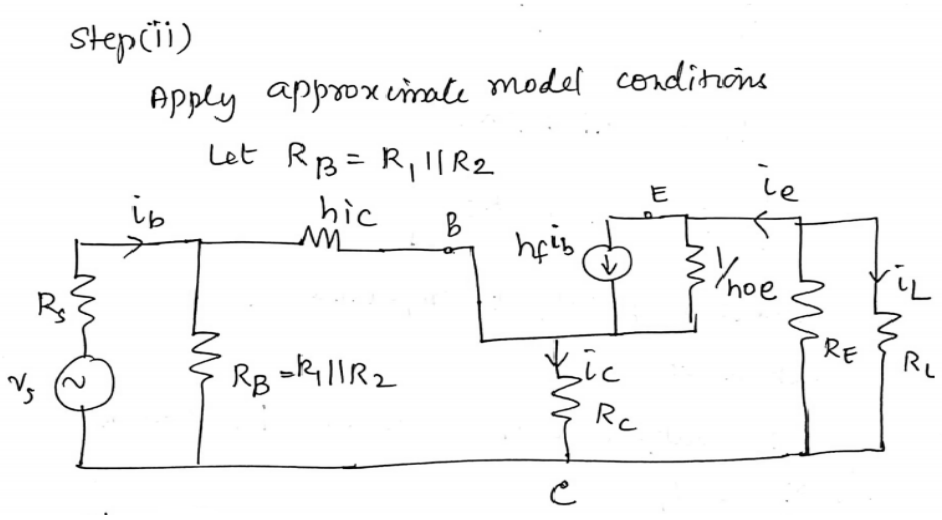


Figure 4. Equivalent Circuit for common collector configuration

step (iii)

Calculation of input impedance (Z_i)

Let $R_S = 0$. The input voltage v_i across the input ports be,

$$v_i = i_b h_{ic} + i_c R_c$$

We know that

$$\beta = \frac{i_c}{i_b}$$

$$i_c = \beta \cdot i_b$$

$$\therefore v_i = i_b h_{ic} + \beta i_b R_c$$

$$\Rightarrow v_i = i_b h_{ic} + \beta i_b R_c$$

$\div$ by i_b

$$\frac{v_i}{i_b} = \frac{i_b h_{ic} + \beta i_b R_c}{i_b}$$

$$Z_i = h_{ic} + \beta R_c$$

$$\boxed{Z_i = h_{ic} + \beta R_e}$$

3) Calculation of voltage gain (A_V)

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

$$V_o = -i_e (R_E \| R_L)$$

$$V_i = i_b h_{ic} + i_c R_c$$

$$\therefore \frac{V_o}{V_i} = \frac{-i_e (R_E \| R_L)}{i_b h_{ic} + i_c R_c}$$

Wkt $I_E = I_c + I_B$ and $\frac{I_c}{I_B} = \beta$.

$$\Rightarrow \frac{V_o}{V_i} = \frac{-i_e (R_E \| R_L)}{i_b h_{ic} + i_c R_c}$$

and

$$I_E = I_B + \beta I_B$$

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

$$\therefore \frac{V_o}{V_i} = \frac{-I_B \cdot (1+\beta)\,(R_E \| R_L)}{I_B h_{ic} + \beta I_B}$$

For ac analysis,

$$\therefore \frac{V_o}{V_i} = \frac{-i_b (1+\beta)\,(R_E \| R_L)}{i_b h_{ic} + \beta i_b}$$

$$\Rightarrow A_V = \frac{-(1+\beta)\,(R_E \| R_L)}{h_{ic} + \beta}$$

step 4 :

Calculation of current Gain (A_I)

Case (i)

overall current Gain

$$A_I = \frac{I_L}{I_S} = \frac{-I_E}{-I_B} = \frac{I_E}{I_B}$$

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

$$A_I = \frac{I_B(1+\beta)}{I_B}$$

$$\boxed{A_I = (1+\beta)}$$

$$\boxed{A_I = (1+\beta)}$$

Case (ii)

Let $R_S = 0$

$$\therefore A_I = \frac{I_L}{I_B} = -\frac{I_E}{I_B}$$

$$A_I = -(1+\beta)$$

3. 4 Small Signal Model CS – MOSFET

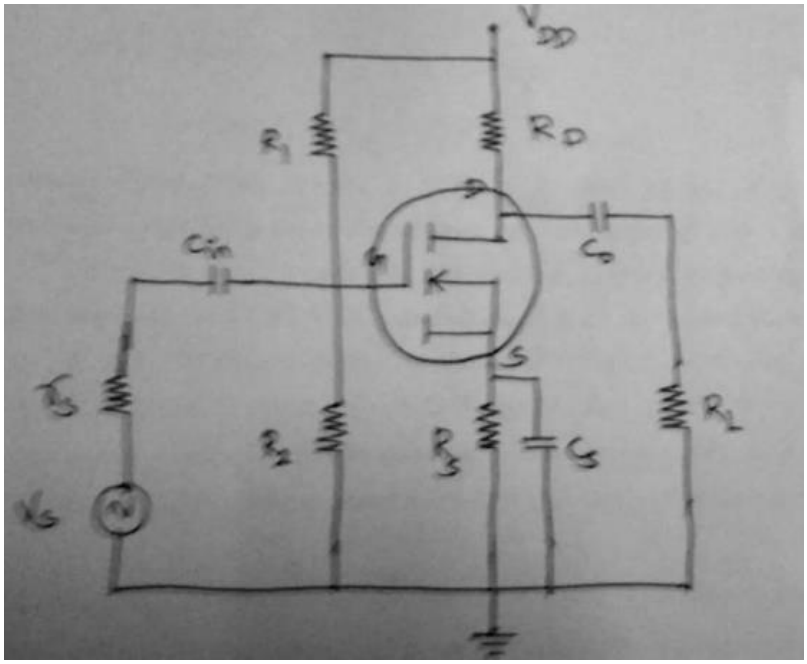


Figure 5. Equivalent Circuit for common emitter configuration

Small Signal Model – CS MOSFET

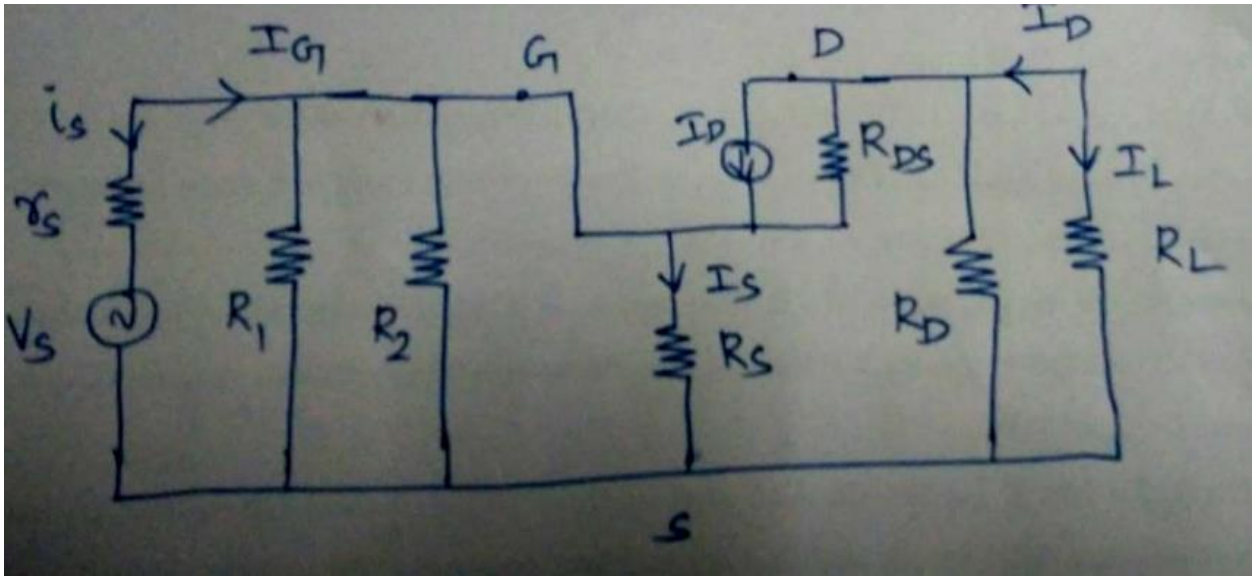


Figure 6. Equivalent Circuit for common source configuration

Calculation of Input Impedance (Z_i)

Let $\gamma_s = 0$

The i/p voltage across the potential divider R_G is given by

$$V_i = I_G R_G + I_S R_S$$

÷ by I_G

$$\frac{V_i}{I_G} = \frac{I_G R_G + I_S R_S}{I_G}$$

$$= R_G + \frac{I_S R_S}{I_G}$$

3.5 High Frequency of BJT

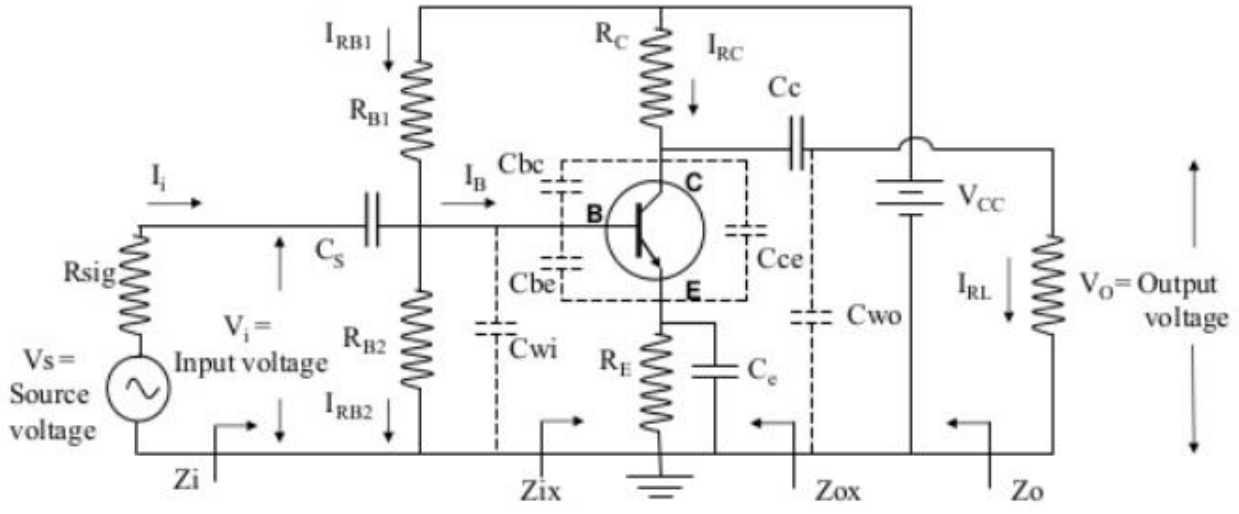


Figure 7 High frequency Response of BJT

Cbe = capacitance between the base and emitter of transistor
Cce = capacitance between collector and emitter of transistor
Cbc = capacitance between base and collector of transistor
Cwi = wiring capacitance at input of amplifier
Cwo = wiring capacitance at output of amplifier

- At the high frequency end, the ***high cutoff frequency (-3 db) of BJT*** circuits is affected by:
  - ***Network capacitance*** (***parasitic and induced***)
  - ***Frequency dependence of the current gain hfe***

- At high frequencies, the ***high cutoff frequency*** of a BJT circuit is affected by:
  - the ***interelectrode capacitance*** between the ***base and emitter***, ***base and collector***, and ***collector and emitter.***
  - ***Wiring capacitance*** at the ***input and output*** of the BJT.

- At ***high frequencies***, the reactance of the interelectrode and wiring capacitance become ***significantly low***, resulting to a ***"shorting" effect*** across the capacitances.
- The ***"shorting" effect*** at the input and output of an amplifier causes a ***reduction in the gain*** of the amplifier.

Input and output capacitances are given by

$$Ci = Cwi + Cbe + C_{Mi}$$

$$Co = Cwo + Cce + C_{Mo}$$

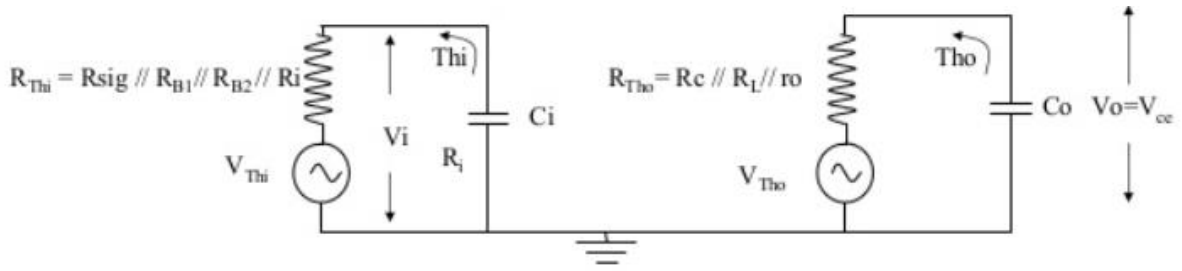


Figure 8. High frequency Response – Ci capacitance

- For the ***input side***, the ***-3db high cutoff frequency*** can be computed as:

$$f_{Hi} = \frac{1}{2\pi R_{Thi} C_i} = \text{higher cut off frequency for the input side (-3db frequency)}$$

$$R_{THi} = Rsig // R_{B1} // R_{B2} // Ri = Rsig // R_{B1} // R_{B2} // (\beta + 1)re$$
$$= \text{Thevenin equivalent resistance at input side}$$

$$C_i = C_{wi} + C_{be} + C_{Mi} = C_{wi} + C_{be} + (1 - Av)C_{bc} = \text{input capacitance of circuit}$$

- At the ***high frequency end***, the ***reactance of capacitance Ci*** will decrease as frequency increases, resulting to ***reduction in the total impedance*** at the input side.
  - This will result to ***lower voltage across Ci,*** resulting to ***lower base current, and lower voltage gain***.

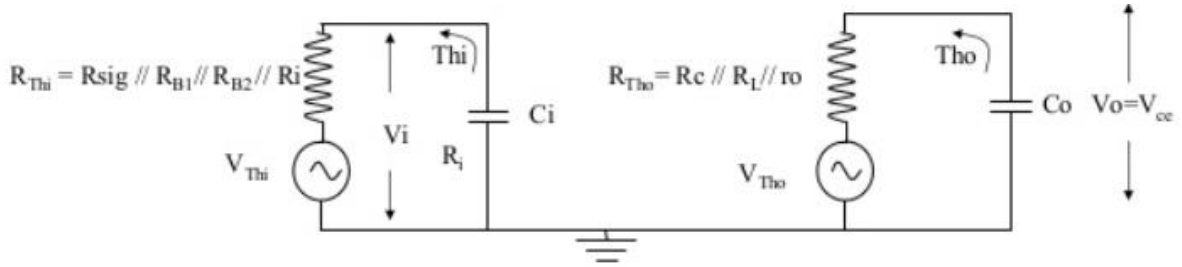


Figure 9. High frequency Response – Co capacitance

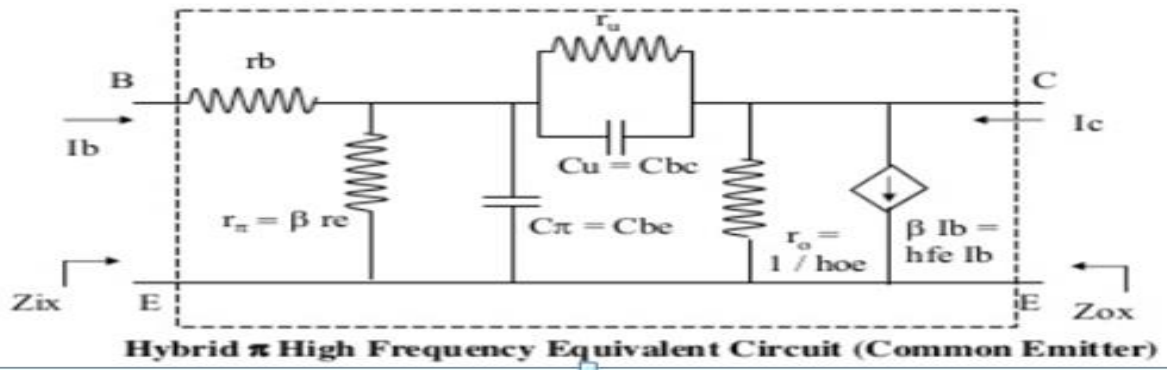
- For the ***output side***, the ***-3db high cutoff frequency*** can be computed as:

$$f_{Ho} = \frac{1}{2\pi R_{Tho} C_o} = \text{higher cut off frequency for the output side (-3db frequency)}$$

$$R_{THo} = R_c \,//\, R_L // r_o = \text{Thevenin equivalent resistance at output side}$$

$$C_o = C_{wo} + C_{ce} + C_{Mo} = C_{wo} + C_{ce} + \left[1 - \frac{1}{A_V}\right] C_{bc} = \text{output capacitance of circuit}$$

- At the ***high frequency end***, the ***reactance of capacitance Co*** will decrease as frequency increases, resulting to ***reduction in the total impedance*** at the output side.
  - This will result to ***lower output voltage Vo***, resulting to ***lower voltage and power gain***.



Hybrid π High Frequency Equivalent Circuit (Common Emitter)

Figure 10. High frequency Response – Hybrid pi Model

- The ***Hybrid π (or Giacolleto) high frequency equivalent circuit*** for ***common emitter*** is shown below.
- The ***resistance rb*** includes the ***base contact resistance*** (due to actual connection to the base) , ***base bulk resistance*** (resistance from external base terminal to the active region of transistor), and ***base spreading resistance*** (actual resistance within the active region of transistor).
- The ***resistances*** r_π, r_o, and r_u are the ***resistances between the indicated terminals*** when the BJT is in the ***active region***.
- ***Cbe and Cbc*** are the capacitances between the indicated terminals.

- At the ***high frequency end, hfe*** of a BJT will be reduced as frequency increases.
- The ***variation of hfe (or β)*** with frequency can approximately be computed as:

$$hfe = \frac{hfe_{mid}}{1 + j\frac{f}{f_\beta}} = \text{hfe at frequency f}$$

$hfe_{mid} = \beta_{mid} =$ hfe at middle frequency (the one usually given at specs sheet)

$$f_\beta = f_{hfe} = \frac{1}{2\pi\, r_\pi\,(C\pi + Cu)} = \frac{1}{hfe_{mid}} \frac{1}{2\pi\, re\,(C\pi + Cu)}$$

$$f_\beta \cong \frac{1}{\beta_{mid}} \frac{1}{2\pi\, re\,(C\pi + Cu)}$$

$$r_\pi = \beta_{mid}\, r_e = (hfe_{mid})(r_e)$$

$$r_e = \frac{26mV}{I_E}$$

I_E = DC emitter current of transistor

- Since r_e is a function of the DC emitter current I_E, and f_β is a function of r_e, ***f_β is a function of the bias condition of the circuit***.
  - The ***upper cutoff frequency of the entire system*** (upper limit for the bandwidth) ***is lower than the lowest upper cutoff frequency*** (lowest among f_{Hi}, f_{Ho}, and f_β)
  - The ***lowest upper cutoff frequency*** has the ***greatest impact on the bandwidth of the system***. It ***defines a limit*** for the bandwidth of the system.
  - The ***lower is the upper cut off frequency***, the ***greater is its effect*** on the bandwidth of the entire system.

GAIN BANDWIDTH PRODUCT :

The Gain-Bandwidth of the circuit (usually amplifier) is the product of the bandwidth and the gain at which the bandwidth is measured. For an operational amplifier, the gain-bandwidth product for one configuration will always equal the gain-bandwidth product for any other configuration of the same amplifier.

- The ***gain-bandwidth product of a transistor*** is defined by the following ***condition***:

$$hfe = \left|\frac{hfe_{mid}}{1 + j\frac{f}{f_\beta}}\right| = 1 \qquad \text{and} \quad hfe_{db} = 20\log\left|\frac{hfe_{mid}}{1 + j\frac{f}{f_\beta}}\right| = 20\log 1 = 0\,db$$

The frequency at which hfe_{db} is equal to 0db is denoted by f_T, and the magnitude of hfe when ($f_T >> f_\beta$) is computed as :

$$\frac{hfe_{mid}}{\sqrt{1 + \left(\frac{f_T}{f_\beta}\right)^2}} \cong \frac{hfe_{mid}}{\frac{f_T}{f_\beta}} = 1$$

$$f_T \cong (hfe_{mid})(f_\beta) = (\beta_{mid})(f_\beta) = \text{gain bandwidth product, since } \beta_{mid} = \text{gain and } f_\beta \cong \text{bandwidth}$$

$$f_\beta \cong \frac{f_T}{\beta_{mid}} \cong \text{bandwidth}$$

$$f_T \cong (\beta_{mid})(f_\beta) = (\beta_{mid})\left[\frac{1}{\beta_{mid}}\frac{1}{2\pi\, re\,(C\pi + Cu)}\right]$$

$$f_T \cong \frac{1}{2\pi\, re\,(C\pi + Cu)} = \text{gain bandwidth product}$$

3.5 MOSFET FREQUENCY RESPONCE

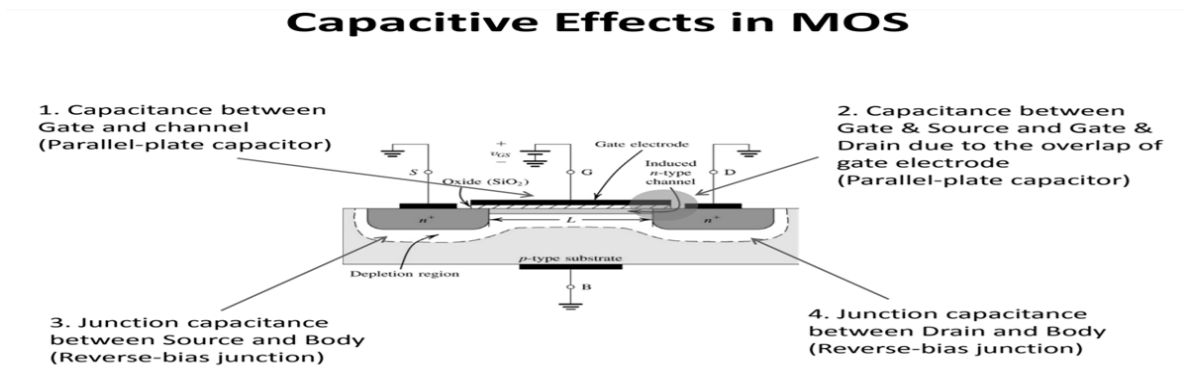


Figure 11. Equivalent Circuit for common emitter configuration

1) MOS "internal" capacitors are shown "outside" of the transistor to see their impact.
2) All MOS capacitors contribute to f_H (v_o is reduced when $f \to \infty$ or caps short circuit)
3) For $f \to \infty$, all coupling (C_{c1} and C_{c2}) and by-pass capacitors are short circuit

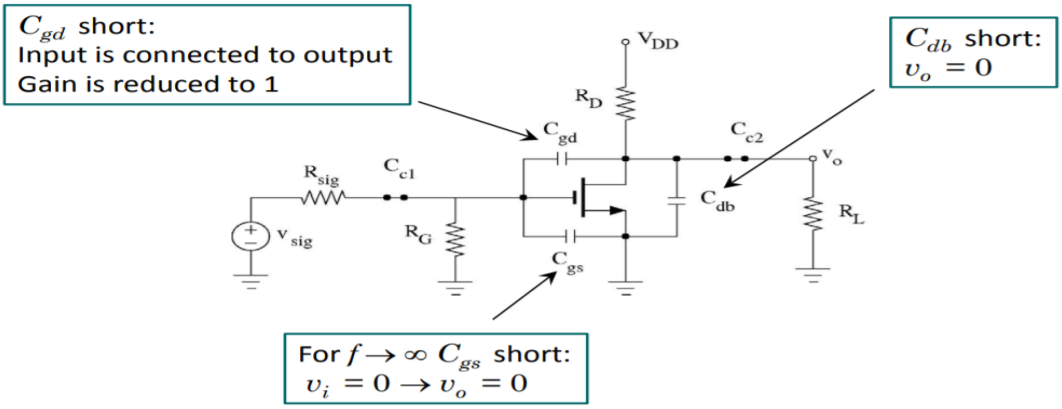
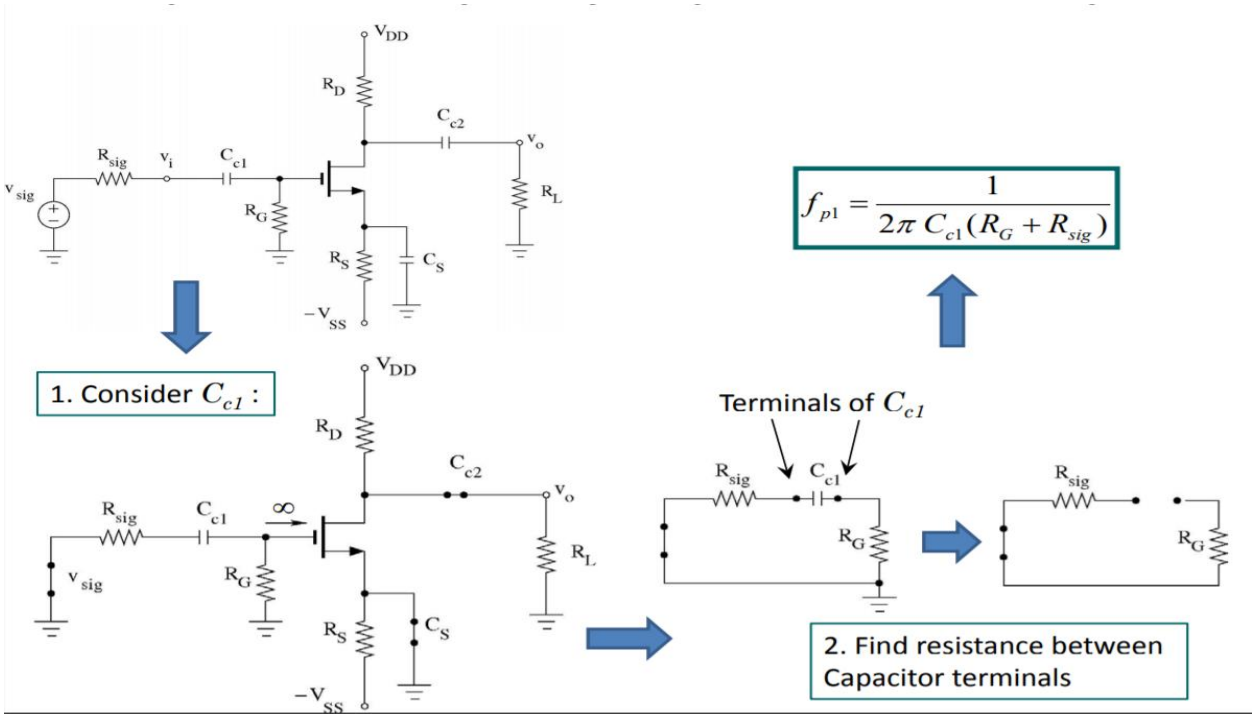
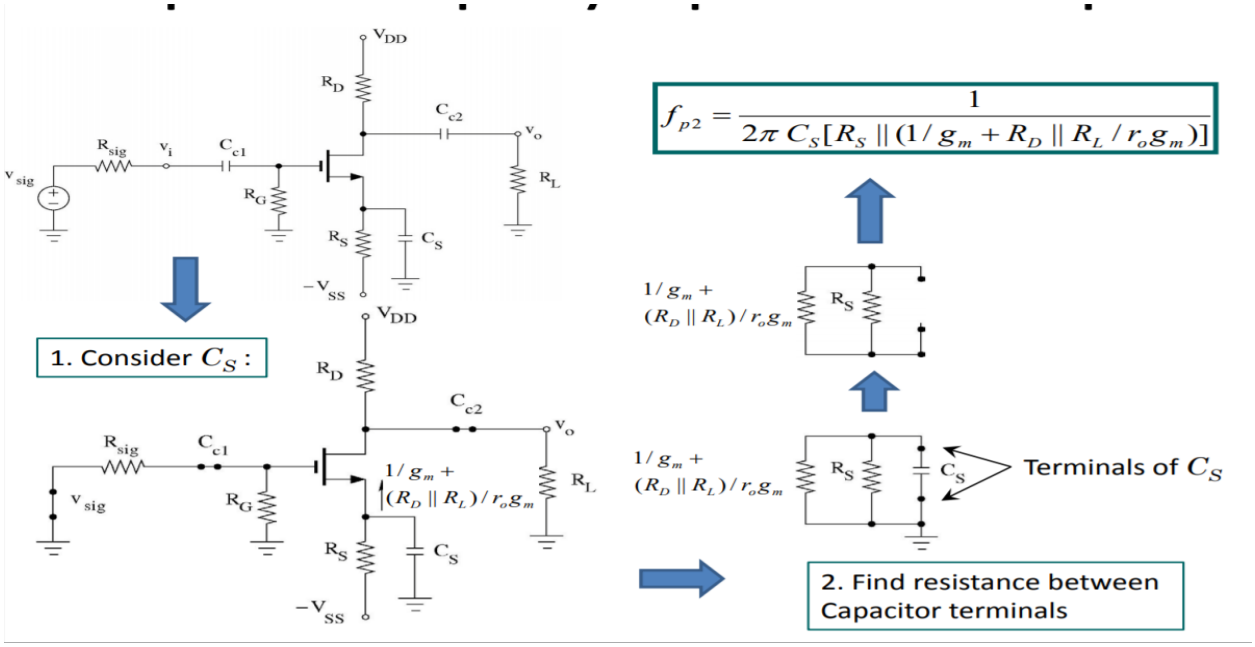
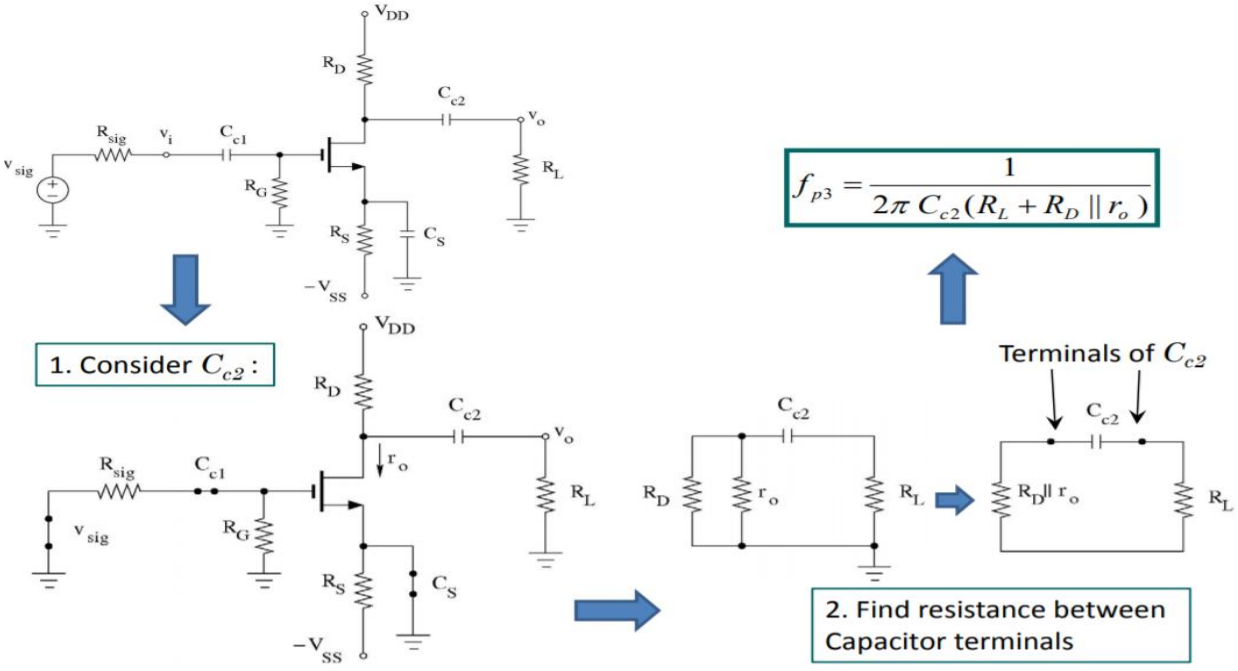


Figure 12. Circuit for common Source configuration

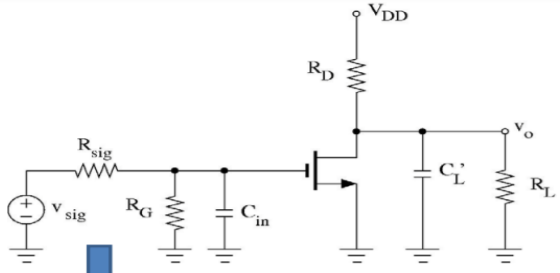
MOSFET LOW FREQUENCY COMMON SOURCE RESPONSE



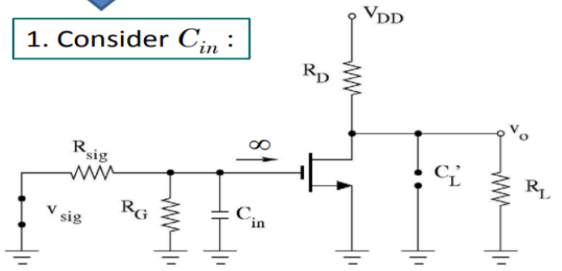




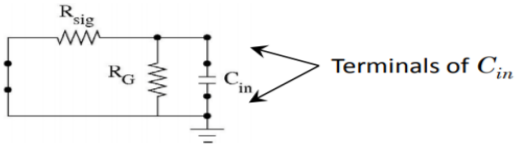
CS High-Frequency Response –MOSFET



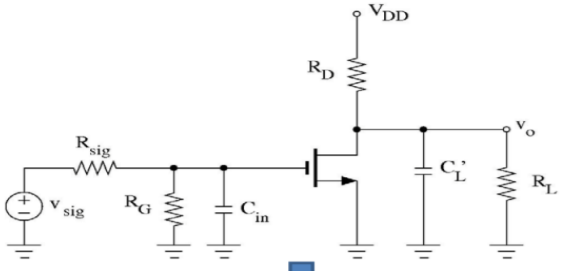
1. Consider C_{in} :



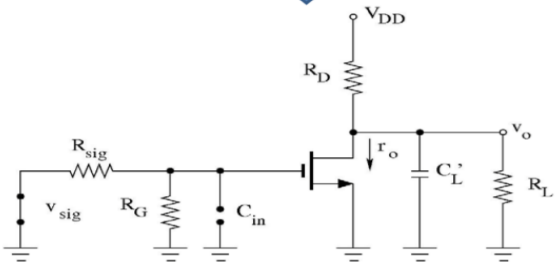
$$f_{p1} = \frac{1}{2\pi\, C_{in}(R_G \parallel R_{sig})}$$



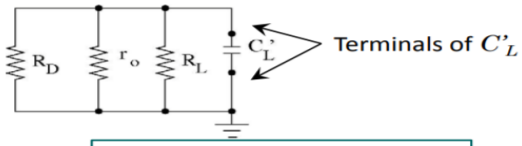
2. Find resistance between Capacitor terminals



1. Consider C'_L :



$$f_{p2} = \frac{1}{2\pi\, C'_L(r_o \parallel R_D \parallel R_L)}$$



2. Find resistance between Capacitor terminals

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4.1 Multistage Amplifiers

- The performance obtainable from a single stage amplifier is often insufficient for many applications.
- Several stages may be combined forming a multistage amplifier. These stages are connected in cascade,

i.e. output of the first stage is connected to form input of second stage, whose output becomes input of third stage, and so on.

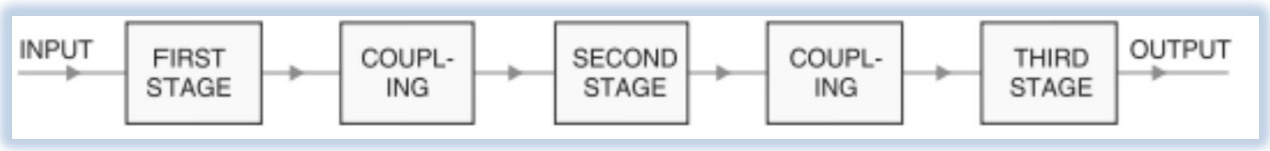


Figure 4.1 Block Diagram of Multistage Amplifier

- Single amplifier is inadequate for practical purposes.
- Additional amplification over two or three stages is necessary. To achieve this, the output of each amplifier stage is coupled in some way to the input of the next stage. The resulting system is referred to as **multistage amplifier**.

(OR)

A transistor circuit containing more than one stage of amplification is known as multistage transistor amplifier.Ex: Transistor radio receiver- Number of amplification stages may be six or more.

4.2 CASCADING

- In Multi-stage amplifiers, the output of first stage is coupled to the input of next stage using a coupling device. These coupling devices can usually be a capacitor or a transformer. This process of joining two amplifier stages using a coupling device can be called as Cascading.
- The following figure shows a two-stage amplifier connected in cascade.

The overall gain is the product of voltage gain of individual stages.

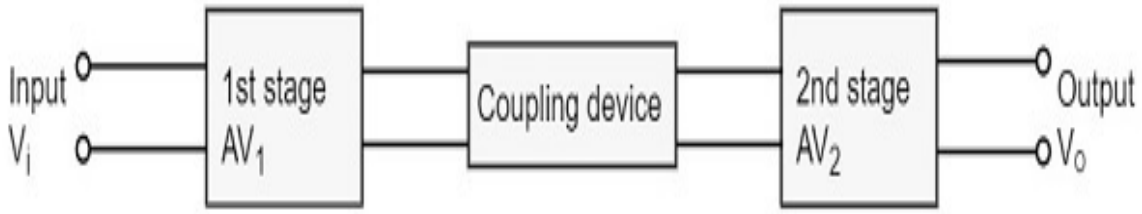


Figure 4.2 Two-stage amplifier

Where A_V = Overall gain

A_{V1} = Voltage gain of 1st stage

A_{V2} = Voltage gain of 2nd stage

$$A_V = A_{V1} \times A_{V2} = \frac{V_2}{V_1} \times \frac{V_0}{V_2} = \frac{V_0}{V_1}$$

4.3 MULTISTAGE AMPLIFIERS:

- Overall gain of an ac signal will get increased.
- Calculated by simply multiplying each gain together.

The overall gain of a multistage amplifier is the product of the gains of the individual stages,

Gain (A) = A1* A2*A3*A4*... *An

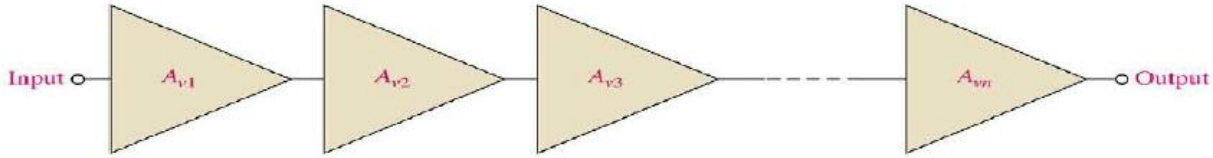


Figure 4.3 Multistage Amplifier

NEED FOR MULTISTAGE AMPLIFIERS:

- To transfer the AC from the output of one stage to the input of next stage.
- To block the DC to pass from the output of one stage to the input of next stage, which means to isolate the DC conditions

- To amplify extremely weak signals to sufficient level, so that it can travel to a large distance.
- The distortion can be reduced by changing the signal within stages.

To understand the working of multistage amplifiers, the following terms need to be known

1. **Gain**
2. **Decibel gain**
3. **Frequency response**
4. **Bandwidth**

Gain

The ratio of the output electrical quantity to the input of the amplifier is called its gain. It can be current gain or voltage gain or power gain.

The gain of a multistage amplifier is equal to the product of gains of individual stages.

E.g. G1, G2 and G3 are the individual voltage gains of a three- stage amplifier, then total voltage gain G is given by

$$G = G1 \times G2 \times G3$$

Decibel gain

The gain of an amplifier can be expressed in unit as decibel (db).

The common logarithm (log to the base 10) of power gain is known as db power gain i.e.

$$\text{Power gain} = 10 \log_{10} \frac{P_{out}}{P_{in}} db \longrightarrow 1$$

$$P_{in} = \frac{V_{in}^2}{R} = I_{in}^2 R$$

$$P_{out} = \frac{V_{out}^2}{R} = I_{out}^2 R$$

From equation 1,

$$\text{Voltage gain in } db = 10 \log_{10} \frac{V_{out}^2 / R}{V_{in}^2 / R} = 20 \log_{10} \frac{V_{out}}{V_{in}}$$

$$\text{Current gain in } db = 10 \log_{10} \frac{I_{out}^2 R}{I_{in}^2 R} = 20 \log_{10} \frac{I_{out}}{I_{in}}$$

Decibel gain

Advantages:

The following are the advantages of expressing the gain in db :

(a) The unit db is a logarithmic unit. Our ear response is also logarithmic i.e. loudness of sound heard by ear is not according to the intensity of sound but according to the log of intensity of sound.

Thus if the intensity of sound given by speaker (i.e. power) is increased 100 times, our ears hear a doubling effect ($\log_{10} 100 = 2$).Hence, this unit tallies with the natural response of our ears.

(b) When the gains are expressed in db, the overall gain of a multistage amplifier is the sum of gains of individual stages in db.

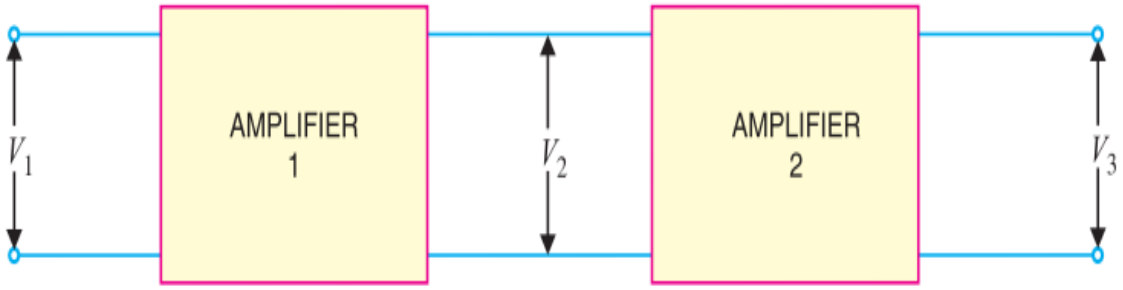


Figure 4.5 Two stage Amplifier

$$\text{Gain as number} = \frac{V_2}{V_1} \times \frac{V_3}{V_2}$$

$$\text{Gain in } db = 20 \log_{10} \frac{V_2}{V_1} \times \frac{V_3}{V_2}$$

$$= 20 \log_{10} \frac{V_2}{V_1} + 20 \log_{10} \frac{V_3}{V_2}$$

$$= \text{1st stage gain in } db + \text{2nd stage gain in } db$$

$G_1(db) + G_2(db)$

Frequency response

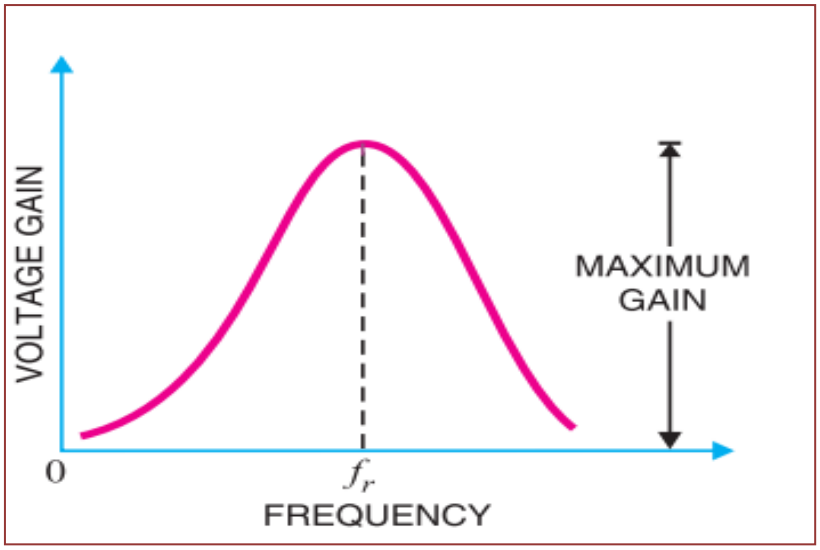


Figure 4.6 Frequency Response curve

The curve between voltage gain and signal frequency of an amplifier is known as frequency response.

- The voltage gain of an amplifier varies with signal frequency.
- It is because reactance of the capacitors in the circuit changes with signal frequency and hence affects the output voltage and voltage gain.
- The gain of the amplifier increases as the frequency increases from zero till it becomes maximum at f_r, called **Resonant frequency**.
- If the frequency of signal increases beyond f_r, the gain decreases.

Bandwidth

The range of frequency over which the voltage gain is equal to or greater than 70.7%(3db) of the maximum gain is known as bandwidth.

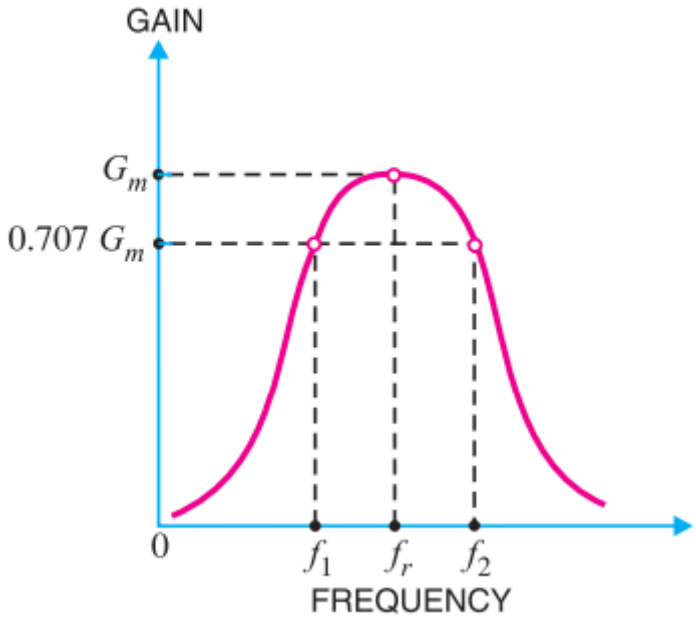


Figure 4.7 Bandwidth $f_2 - f_1$

1. Draw the 3db line from the maximum value and find f_1 and f_2 from the graph.

2. The (f 1) is called lower cut-off frequency & (f 2) is known as upper cut-off frequency

3. Therefore, $f_2 - f_1$ is the bandwidth. (i.e. Upper cutoff frequency – Lower cutoff frequency)

5. For distortionless amplification, it is important that signal frequency range must be within the bandwidth of the amplifier.

   Bandwidth of an amplifier is the range of frequency at the limits of which its voltage gain falls by 3 db from the maximum gain.

The frequency f 1 or f 2 is also called 3-db frequency or half-power frequency.

Half Power Bandwidth

In amplifier analysis, half power gain is found out as follows:

$$\text{Half power gain in dB} = 10 \log_{10} \frac{P_{\text{output max}}/2}{P_{\text{output max}}}$$

$$= 10 \log_{10}\left(\frac{1}{2}\right)$$

$$= 10 \log_{10}(0.5)$$

$$= -3 \text{ dB}$$

4.4 Types of multistage amplifier

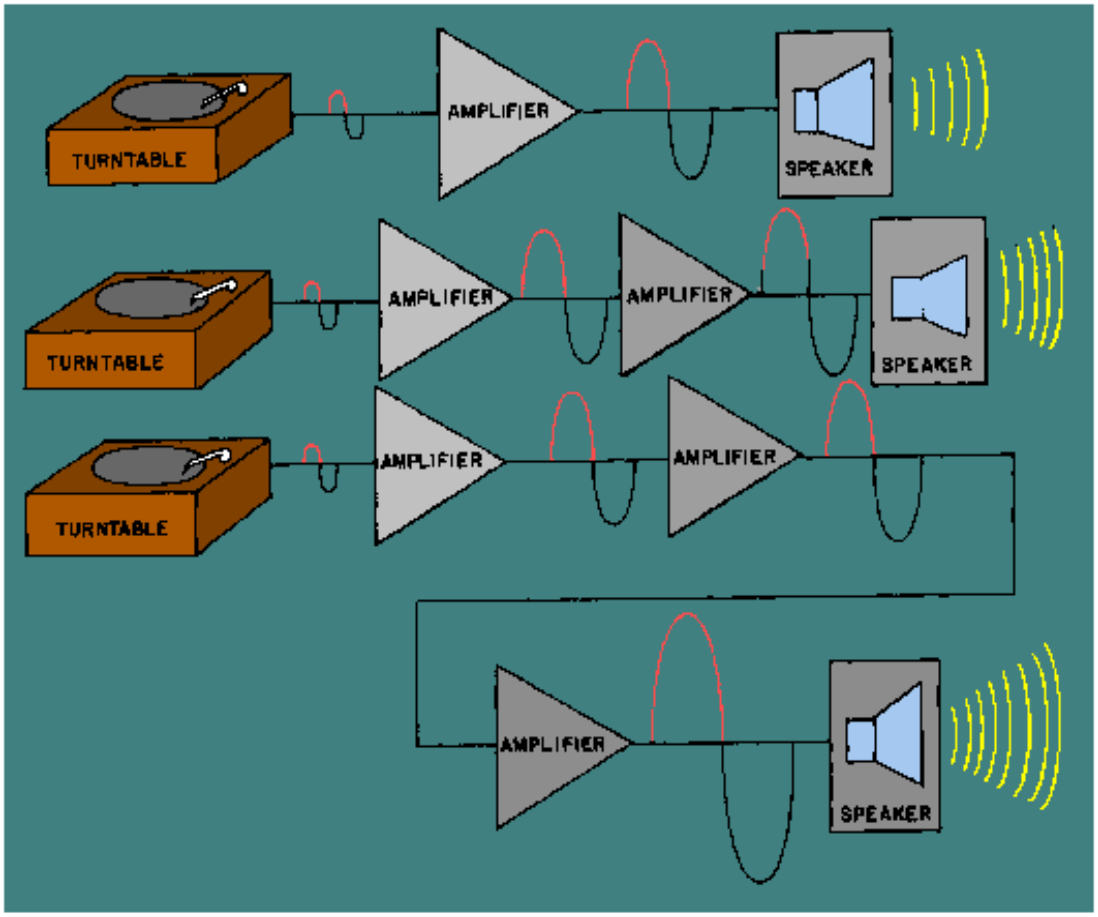


Figure 4.8 Multistage Amplifiers

The output of first stage is coupled to the input of next stage using a coupling device. The process of transferring energy between circuits is known as COUPLING.

There are various ways of coupling signals into and out of amplifier circuits.

Common methods of amplifier coupling

- **RC Coupled Amplifier**
- **Transformer Coupled Transistor Amplifier**
- **Direct Coupled Amplifier**

(i) In RC coupling, a capacitor is used as the coupling device. The capacitor connects the output of one stage to the input of the next stage in order to pass the a.c. signal on while blocking the d.c. bias voltages.

(ii) In transformer coupling, transformer is used as the coupling device. The transformer coupling provides the same two functions (viz. to pass the signal on and blocking d.c.) but permits in addition impedance matching.

(iii) In direct coupling or d.c. coupling, the individual amplifier stage bias conditions are so designed that the two stages may be directly connected without the necessity for d.c. isolation

RC Coupled Amplifier

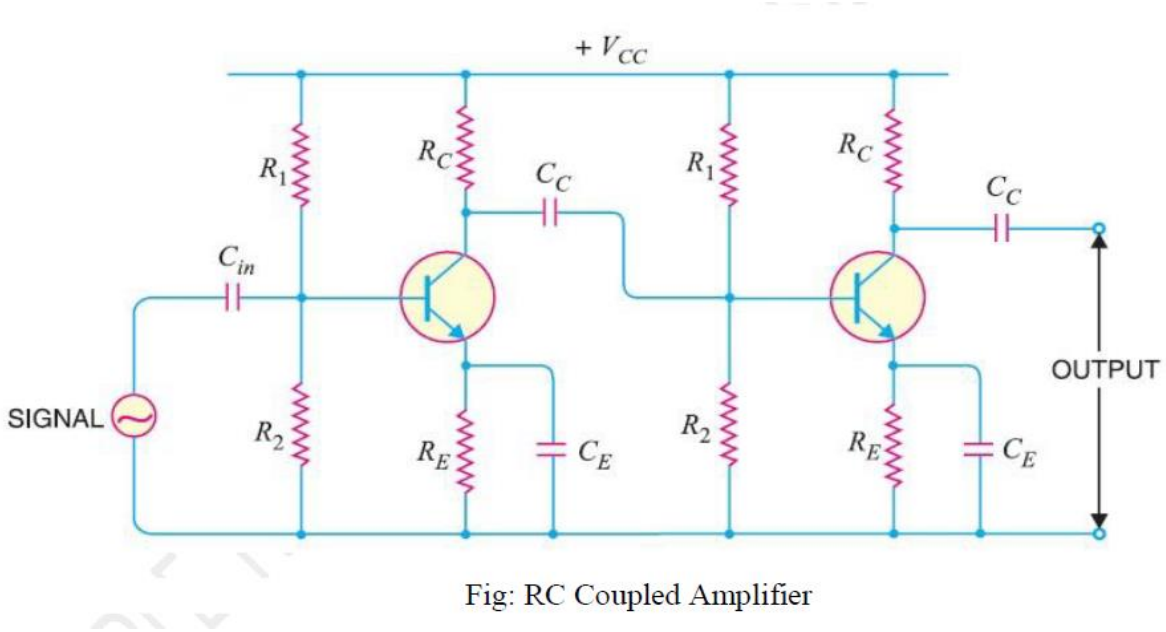


Fig: RC Coupled Amplifier

Figure 4.9 RC coupled Amplifier

- As the coupling from one stage to next is achieved by a coupling capacitor (C_C) followed by a connection to a shunt resistor, therefore, such amplifiers are called Resistance - Capacitance coupled amplifiers.
- R_1, R_2 and R_E – used for biasing and stabilisation of network.
- C_E- emitter bypass capacitor offers low reactance path to the signal. Without it, the voltage gain of each stage would be lost.
- C_C transmits a.c. signal but blocks d.c. This prevents d.c. interference between various stages and the shifting of operating point

Operation:

- It may be mentioned here that total gain is less than the product of the gains of individual stages. It is because when a second stage is made to follow the first stage, the effective load resistance of first stage is reduced due to the shunting effect of the input resistance of second stage. This reduces the gain of the stage which is loaded by the next stage.
- For instance, in a 3-stage amplifier, the gain of first and second stages will be reduced due to loading effect of next stage. The overall gain shall be equal to the product of the gains of three stages.

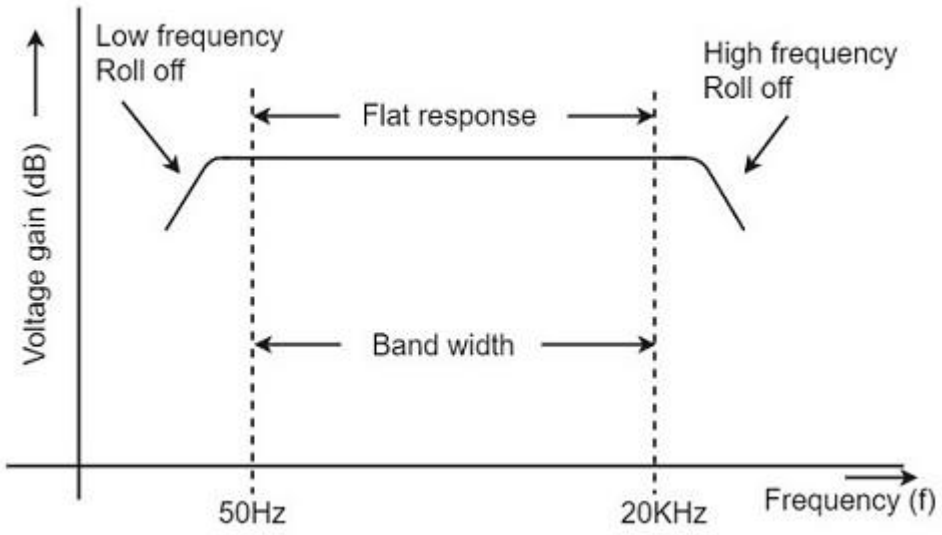


Figure 4.10 Frequency Response

The frequency response of a typical RC coupled amplifier :

(i) At low frequencies (< 50 Hz): two factors cause a falling of voltage gain

- ✓ Reactance of coupling capacitor CC is quite high - very small part of signal will pass from one stage to the next stage.
- ✓ CE cannot shunt the emitter resistance RE effectively because of its large reactance at low frequencies.

ii) At mid-frequencies (50 Hz to 20 kHz): the voltage gain of the amplifier is constant.

- ✓ Thus, as the frequency increases in this range, reactance of CC decreases which tends to increase the gain.
- ✓ However, at the same time, lower reactance means higher loading of first stage and hence lower gain.
- ✓ These two factors almost cancel each other, resulting in a uniform gain at mid-frequency.

(iii) At high frequencies (> 20 kHz): two reasons causes the voltage gain drops off

- ✓ Reactance of CC is very small and it behaves as a short circuit- increases the loading effect of next stage and serves to reduce the voltage gain.
- ✓ Capacitive reactance of base-emitter junction is low which increases the base current. This reduces the current amplification factor β.

Advantages :

(i) It has excellent frequency response.

(ii) The gain is constant over the audio frequency range which is the region of most importance for speech, music etc.

(iii) It has lower cost since it employs resistors and capacitors which are cheap.

(iv) The circuit is very compact as the modern resistors and capacitors are small and extremely light.

Disadvantages :

(i) The RC coupled amplifiers have low voltage and power gain.

(ii) They have the tendency to become noisy with age, particularly in moist climates.

(iii) Impedance matching is poor.

Applications:

- The RC coupled amplifiers have excellent audio fidelity over a wide range of frequency.
- Therefore, they are widely used as voltage amplifiers e.g. in the initial stages of public address system.

Note:

- If other type of coupling (e.g. transformer coupling) is employed in the initial stages, this results in frequency distortion which may be amplified in next stages.
- However, because of poor impedance matching, RC coupling is rarely used in the final stages.

- ❖ RC coupling- used in initial stages
- ❖ Transformer coupling- used in final stages

Transformer-Coupled Amplifier

In RC coupled amplifier, the effective load of each stage is decreased due to the low resistance and the voltage and power gain also gets decreased.

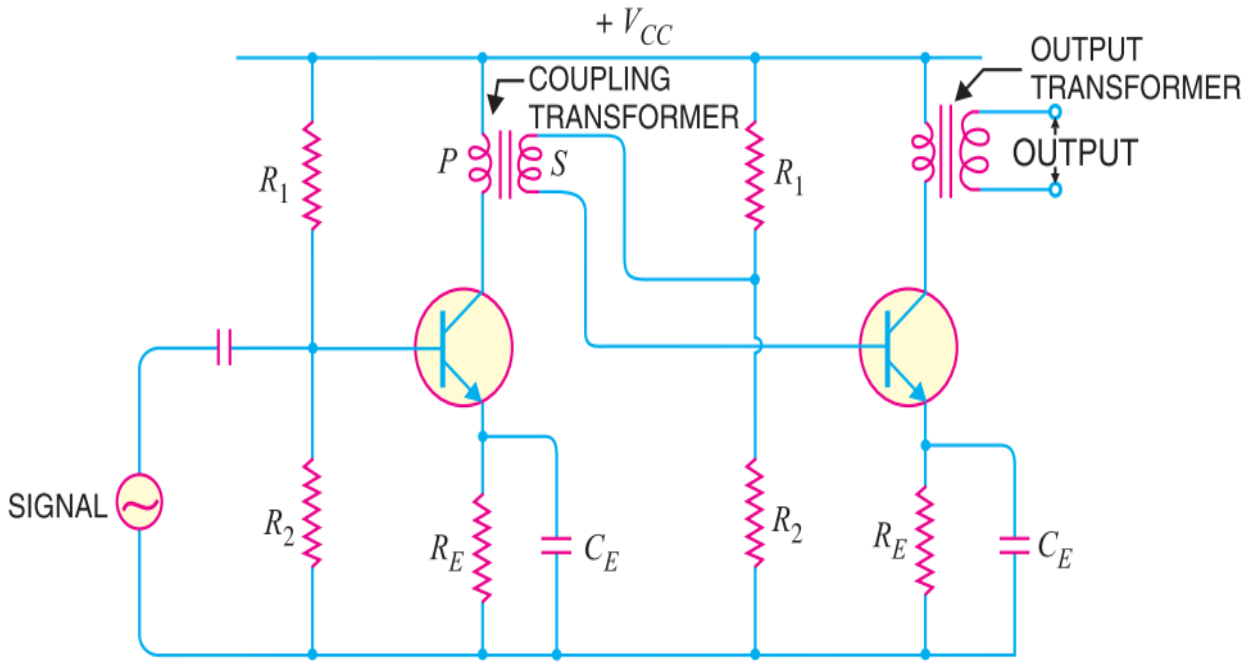


Fig 4.11 Transformer coupled Amplifier

- R1 & R2 resistors provide the biasing and stabilization for the circuit.
- Cin isolates DC and allows only AC components from the input signal to the circuit.
- The emitter capacitor provides a low reactance path to the signal and offers stability to the circuit.
- The first stage of output is connected as an input to the second stage through secondary windings of the primary transformer.
- It is mostly used for power amplification.
- When an a.c. signal is applied to the base of first transistor, it appears in the amplified form across primary P of the coupling transformer.
- The voltage developed across primary is transferred to the input of the next stage by the transformer secondary S. The second stage renders amplification in an exactly similar manner.
- Impedance matching - By this property, low resistance of one stage can be reflected as high load resistance to the previous stage. Therefore the voltage at primary windings can be forwarded according to the ratio of secondary windings of the transformer.

Frequency response

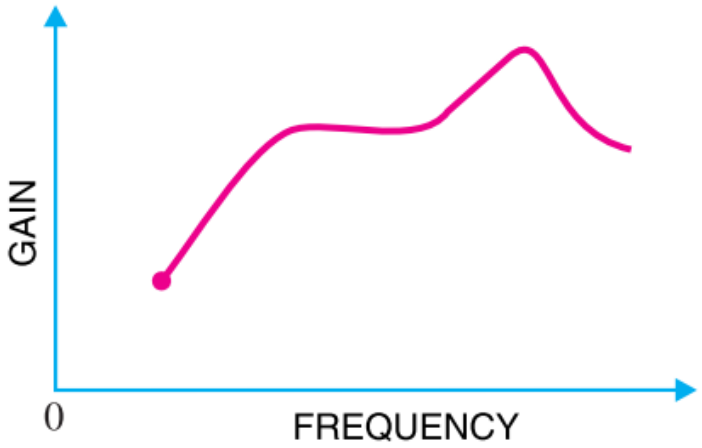


Figure 12 Frequency Response

- It is clear that frequency response is rather poor i.e. gain is constant only over a small range of frequency.
- At low frequencies, the reactance of primary begins to fall, resulting in decreased gain.
- At high frequencies, the capacitance between turns of windings acts as a bypass condenser to reduce the output voltage and hence gain.
- Hence, transformer-coupled amplifier introduces frequency distortion. It is possible to achieve a fairly constant gain over the audio frequency range.
- Transformer coupled that achieves a frequency response may cost 10 to 20 times expensive than the RC coupled amplifier.

Advantages

(i) No signal power is lost in the collector or base resistors.

(ii) An excellent impedance matching can be achieved in a transformer coupled amplifier

(iii) Due to excellent impedance matching, transformer coupling provides higher gain.

(iv) As a result, a single stage of properly designed transformer coupling can provide the gain of two stages of RC coupling.

S. No	Particular	*RC* coupling	Transformer coupling	Direct coupling
1.	*Frequency response*	Excellent in the audio frequency range	Poor	Best
2.	*Cost*	Less	More	Least
3.	*Space and weight*	Less	More	Least
4.	*Impedance matching*	Not good	Excellent	Good
5.	*Use*	For voltage amplification	For power amplification	For amplifiying extremely low frequencies

4.5 Single tuned amplifier

- **An amplifier circuit with a single tuner section being at the collector of the amplifier circuit is called as Single tuner amplifier circuit.**

Construction

- **A simple transistor amplifier circuit consisting of a parallel tuned circuit in its collector load, makes a single tuned amplifier circuit. The values of capacitance and inductance of the tuned circuit are selected such that its resonant frequency is equal to the frequency to be amplified.**
- **The output can be obtained from the coupling capacitor C_C as shown above or from a secondary winding placed at L.**

Operation

- **The high frequency signal that has to be amplified is applied at the input of the amplifier. The resonant frequency of the parallel tuned circuit is made equal to the frequency of the signal applied by altering the capacitance value of the capacitor C, in the tuned circuit.**
- **At this stage, the tuned circuit offers high impedance to the signal frequency, which helps to offer high output across the tuned circuit. As high impedance is offered only for the tuned frequency, all the other frequencies which get lower impedance are rejected by the tuned circuit. Hence the tuned amplifier selects and amplifies the desired frequency signal.**

Frequency Response

- **The parallel resonance occurs at resonant frequency f_r when the circuit has a high Q. the resonant frequency f_r is given by**

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

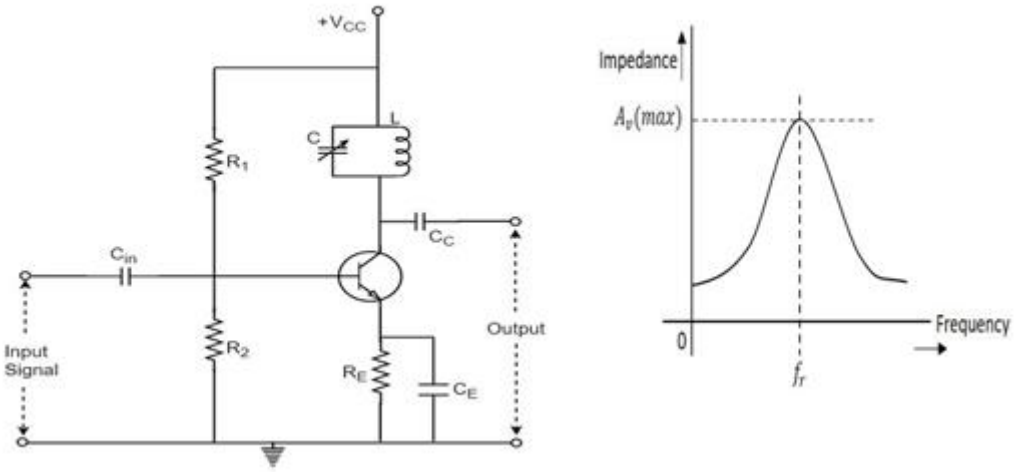


Figure 13. Single tuned amplifier

At resonant frequency f_r the impedance of parallel tuned circuit is very high and is purely resistive. The voltage across R_L is therefore maximum, when the circuit is tuned to resonant frequency. Hence the voltage gain is maximum at resonant frequency and drops off above and below it. The higher the Q, the narrower will the curve be.

4.6 Neutralization

- **It is the process by which feedback can be cancelled by introducing a current that is equal in magnitude but 180o out of phase with the feedback signal at the input of the active device. The two signals will cancel and the effect of feedback will be eliminated. This technique is termed as neutralization.**

Types of neutralization

- **Hazeltine neutralization**

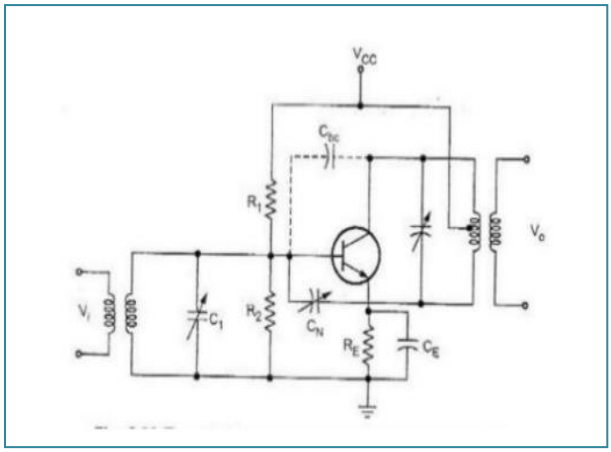


Figure 14. Hazeltine Neutralization

- **Rice neutralization**

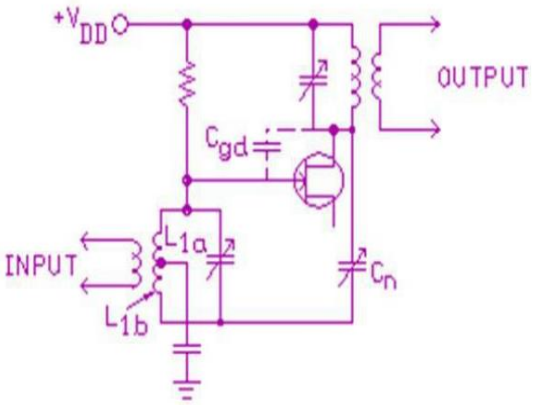


Figure 14. Rice Neutralization

- **Neutrodyne neutralization**

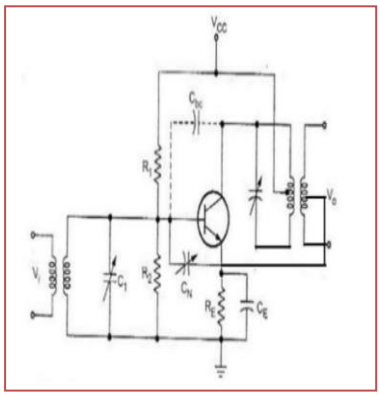
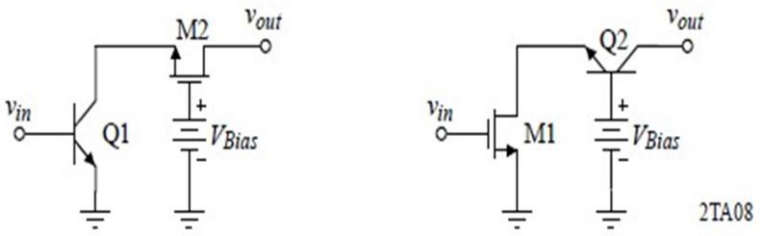


Figure 15. Neutrodyne Neutralization

4.7 BiCMOS Cascode Amplifier

BiCMOS Cascode Amplifier

Circuits:



Comparison:

Larger voltage gain	Infinite input resistance
Smaller input resistance	Smaller voltage gain
Q1 voltage gain greater than -1V/V	M1 voltage gain less than -1V/V
High output resistance	High output resistance
Requires input current	Does not require input current

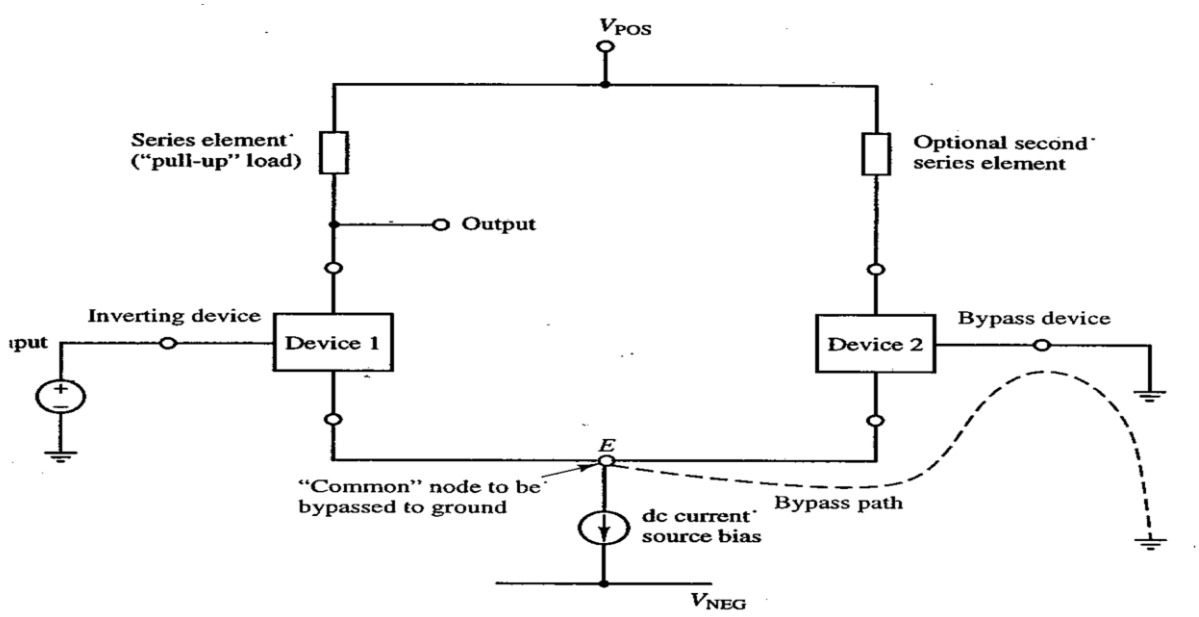
Differential amplifiers are pervasive in analog electronics

- **Low frequency amplifiers**
- **High frequency amplifiers**
- **Operational amplifiers – the first stage is a differential amplifier**
- **Analog modulators**
- **Logic gates**

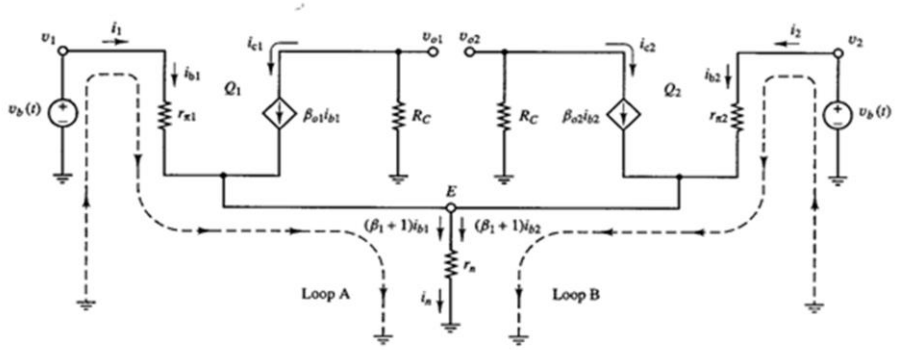
Advantages

- **Large input resistance**
- **High gain**
- **Differential input**
- **Good bias stability**
- **Excellent device parameter tracking in IC implementation**

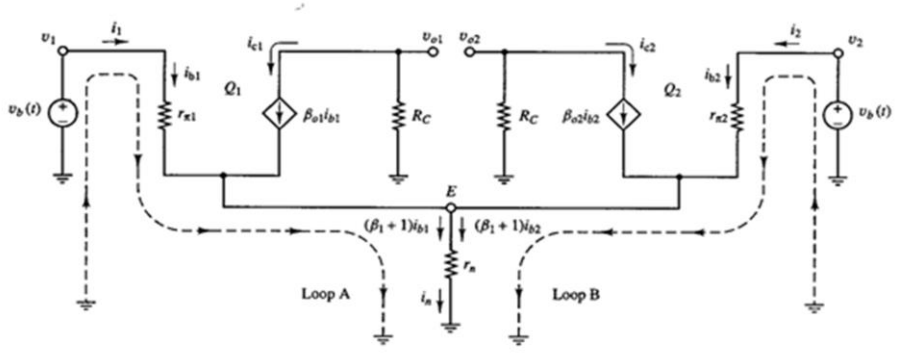
- **In contrast to the single device common-emitter (common-source) amplifier with negative feedback bias resistor of the previous slide, the differential circuit shown at left provides a better bypass scheme.**
- **Device 2 provides bypass for active device 1,Bias provided by dc current source Device 2 can also be used for input, allowing a differential input**
- **Load devices might be resistors or they might be current sources (current mirrors)**



- The figure below is the small-signal model for the diff amp with common-mode inputs
  - $v1 = v2 = v_b(t)$ and $v_{icm} = \frac{1}{2}(v1 + v2) = v_b(t)$
- The common-mode currents from both inputs flow through r_n as shown by the two loops
  - $i_n = 2(\beta_o + 1)\, i_{b1} = 2(\beta_o + 1)\, i_{b2}$
  - and therefore, $v_b = i_b r_\pi + 2(\beta_o + 1) i_b r_n$ or $i_b = v_b/[r_\pi + 2(\beta_o + 1) r_n]$
- The collector voltages can be found as
  - $v_{01} = v_{02} = -\beta_o R_C v_b/[r_\pi + 2(\beta_o + 1) r_n] = \sim -g_m R_C v_b/[1 + 2g_m r_n]$
- The common-mode gain with single-ended output is given by
  - $A_{cm\text{-}se1} = A_{cm\text{-}se2} = v_{o1}/v_{icm} = v_{o2}/v_{icm} = -\mathbf{g_m R_C/[1 + 2g_m r_n]} = \sim -\mathbf{R_C/2r_n}$
- The common-mode gain with differential output is $A_{cm\text{-}diff} = (v_{o1} - v_{o2})/v_{icm} = 0$



- The figure below is the small-signal model for the diff amp with common-mode inputs
  - $v1 = v2 = v_b(t)$ and $v_{icm} = \frac{1}{2}(v1 + v2) = v_b(t)$
- The common-mode currents from both inputs flow through r_n as shown by the two loops
  - $i_n = 2(\beta_o + 1)\, i_{b1} = 2(\beta_o + 1)\, i_{b2}$
  - and therefore, $v_b = i_b r_\pi + 2(\beta_o + 1) i_b r_n$ or $i_b = v_b/[r_\pi + 2(\beta_o + 1) r_n]$
- The collector voltages can be found as
  - $v_{01} = v_{02} = -\beta_o R_C v_b/[r_\pi + 2(\beta_o + 1) r_n] = \sim -g_m R_C v_b/[1 + 2g_m r_n]$
- The common-mode gain with single-ended output is given by
  - $A_{cm\text{-}se1} = A_{cm\text{-}se2} = v_{o1}/v_{icm} = v_{o2}/v_{icm} = -\mathbf{g_m R_C/[1 + 2g_m r_n]} = \sim -\mathbf{R_C/2r_n}$
- The common-mode gain with differential output is $A_{cm\text{-}diff} = (v_{o1} - v_{o2})/v_{icm} = 0$



- In a differential amplifier we typically want to amplify the differential input while, at the same time, rejecting the common-mode input signal
- A figure of merit ***Common Mode Rejection Ratio*** is defined as

  $$\mathbf{CMRR} = |A_{dm}|/|A_{cm}|$$

  - where A_{dm} is the differential mode gain and A_{cm} is the common mode gain
- For a bipolar diff amp with differential output, the CMRR is found to be

  $$\text{CMRR} = |A_{dm\text{-}diff}|/|A_{cm\text{-}diff}| = |-\, g_m R_C| \;/\; 0 = \textbf{infinity}$$

- In the case of the bipolar diff amp with single-ended output, CMRR is given by

  $$\text{CMRR} = |A_{dm\text{-}se}|/|A_{cm\text{-}se}| = |\, \tfrac{1}{2} g_m R_C| \;/\; |\, \beta_o R_C/[r_\pi + 2(\beta_o + 1) r_n]|$$
  $$= [r_\pi + 2(\beta_o + 1) r_n]/2r_\pi = \sim \beta_o r_n/r_\pi = g_m r_n = I_C r_n/\eta V_T$$
  $$= \mathbf{I_o r_n/2\eta V_T}$$

  - since $\beta_o = g_m r_\pi$ and V_T is defined as kT/q
- CMRR is often expressed in decibels, in which case the definition becomes
  - $\text{CMRR} = 20 \log (|A_{dm}|/|A_{cm}|)$

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5.1 Feedback Amplifiers

In a Feedback System, all or part of the output signal either positive or negative is fed back to the input

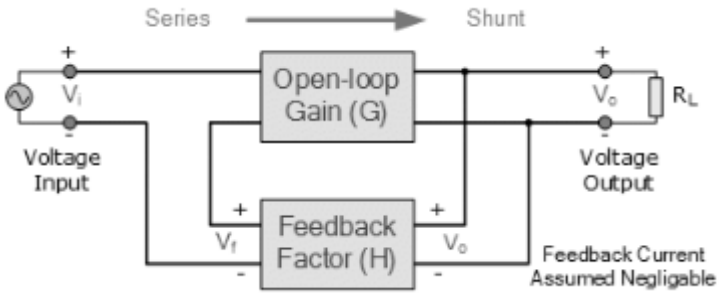

Figure 1. Feed back Network

Feedback Systems process signals and as such are signal processors. The processing part of a feedback system may be electrical or electronic, ranging from a very simple to a highly complex circuits.

Simple analogue feedback control circuits can be constructed using individual or discrete components, such as transistors, resistors and capacitors, etc, or by using microprocessor-based and integrated circuits (IC's) to form more complex digital feedback systems.

As we have seen, open-loop systems are just that, open ended, and no attempt is made to compensate for changes in circuit conditions or changes in load conditions due to variations in circuit parameters, such as gain and stability, temperature, supply voltage variations and/or external disturbances. But the effects of these "open-loop" variations can be eliminated or at least considerably reduced by the introduction of **Feedback**.

A feedback system is one in which the output signal is sampled and then fed back to the input to form an error signal that drives the system. In the previous tutorial about Closed-loop Systems, we saw that in general, feedback is comprised of a sub-circuit that allows a fraction of the output signal from a system to modify the effective input signal in such a way as to produce a response that can differ substantially from the response produced in the absence of such feedback.

Feedback Systems are very useful and widely used in amplifier circuits, oscillators, process control systems as well as other types of electronic systems. But for feedback to be an effective tool it must be controlled as an uncontrolled system will either oscillate or fail to function. The basic model of a feedback system is given as:

Feedback System Block Diagram Model

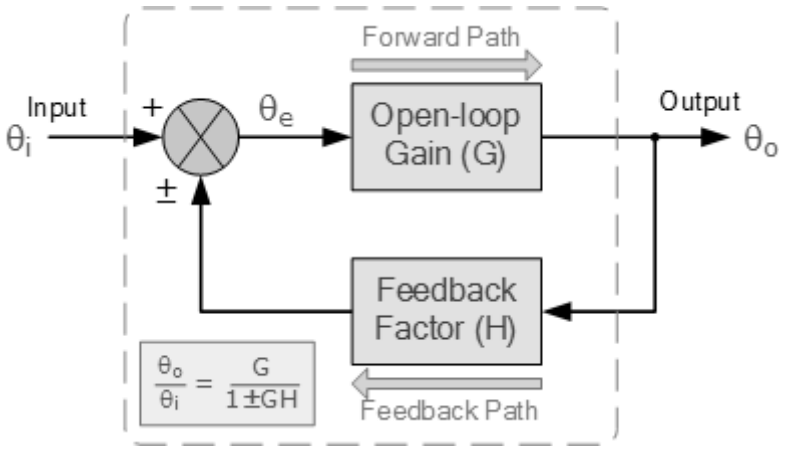

Figure 2. System with Feedback

This basic feedback loop of sensing, controlling and actuation is the main concept behind a feedback control system and there are several good reasons why feedback is applied and used in electronic circuits:

- Circuit characteristics such as the systems gain and response can be precisely controlled.
- Circuit characteristics can be made independent of operating conditions such as supply voltages or temperature variations.
- Signal distortion due to the non-linear nature of the components used can be greatly reduced.
- The Frequency Response, Gain and Bandwidth of a circuit or system can be easily controlled to within tight limits.

Whilst there are many different types of control systems, there are just two main types of feedback control namely: **Negative Feedback** and **Positive Feedback**.

5.2 Positive Feedback Systems

In a “positive feedback control system”, the set point and output values are added together by the controller as the feedback is “in-phase” with the input. The effect of positive (or regenerative) feedback is to “increase” the systems gain, i.e, the overall gain with positive feedback applied will be greater than the gain without feedback. For example, if someone praises you or gives you positive feedback about something, you feel happy about yourself and are full of energy, you feel more positive.

However, in electronic and control systems to much praise and positive feedback can increase the systems gain far too much which would give rise to oscillatory circuit responses as it increases the magnitude of the effective input signal.

5.3 Voltage / current, series / shunt feedback

Negative feedback in an amplifier is the method of feeding a portion of the amplified output to the input but in opposite phase. The phase opposition occurs as the amplifier provides 180^o phase shift whereas the feedback network doesn't.

While the output energy is being applied to the input, for the voltage energy to be taken as feedback, the output is taken in shunt connection and for the current energy to be taken as feedback, the output is taken in series connection.

There are two main types of negative feedback circuits. They are −

- Negative Voltage Feedback
- Negative Current Feedback

Negative Voltage Feedback

In this method, the voltage feedback to the input of amplifier is proportional to the output voltage. This is further classified into two types −

- Voltage-series feedback
- Voltage-shunt feedback

Negative Current Feedback

In this method, the voltage feedback to the input of amplifier is proportional to the output current. This is further classified into two types.

- Current-series feedback
- Current-shunt feedback

Let us have a brief idea on all of them.

Voltage-Series Feedback

In the voltage series feedback circuit, a fraction of the output voltage is applied in series with the input voltage through the feedback circuit. This is also known as **shunt-driven series-fed** feedback, i.e., a parallel-series circuit.

The following figure shows the block diagram of voltage series feedback, by which it is evident that the feedback circuit is placed in shunt with the output but in series with the input.

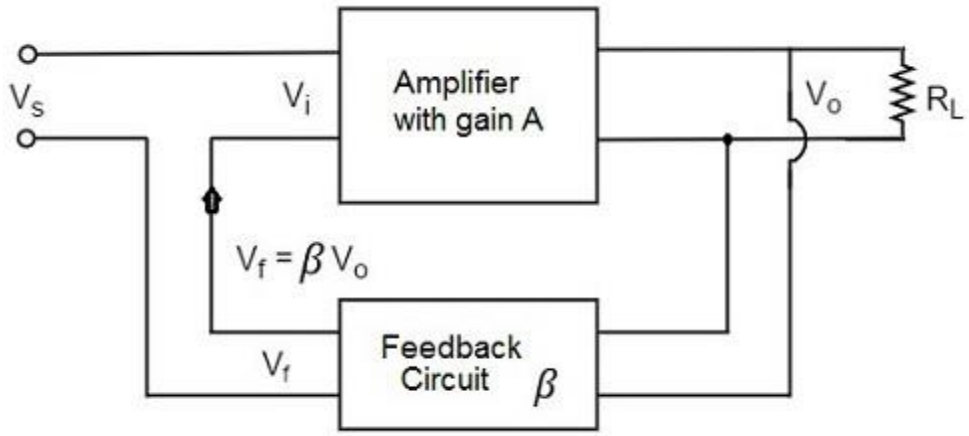

Figure 3 Voltage Feedback

As the feedback circuit is connected in shunt with the output, the output impedance is decreased and due to the series connection with the input, the input impedance is increased.

Voltage-Shunt Feedback

In the voltage shunt feedback circuit, a fraction of the output voltage is applied in parallel with the input voltage through the feedback network. This is also known as **shunt-driven shunt-fed** feedback i.e., a parallel-parallel proto type.

The below figure shows the block diagram of voltage shunt feedback, by which it is evident that the feedback circuit is placed in shunt with the output and also with the input.

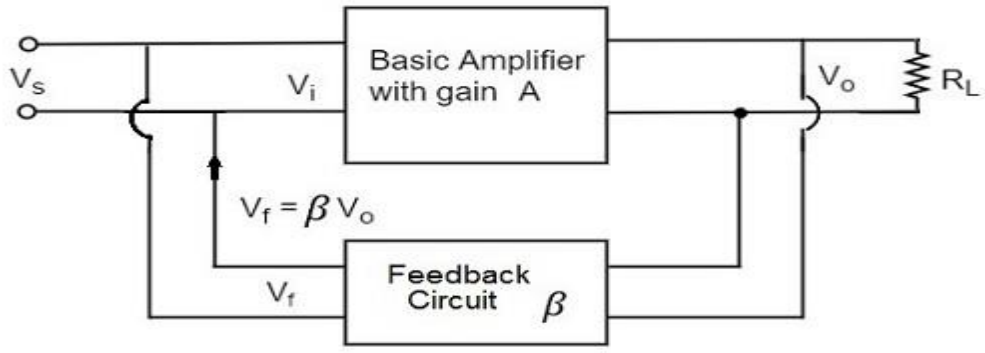

Figure 4 Shunt feedback

As the feedback circuit is connected in shunt with the output and the input as well, both the output impedance and the input impedance are decreased.

Current-Series Feedback

In the current series feedback circuit, a fraction of the output voltage is applied in series with the input voltage through the feedback circuit. This is also known as **series-driven series-fed** feedback i.e., a series-series circuit.

The following figure shows the block diagram of current series feedback, by which it is evident that the feedback circuit is placed in series with the output and also with the input.

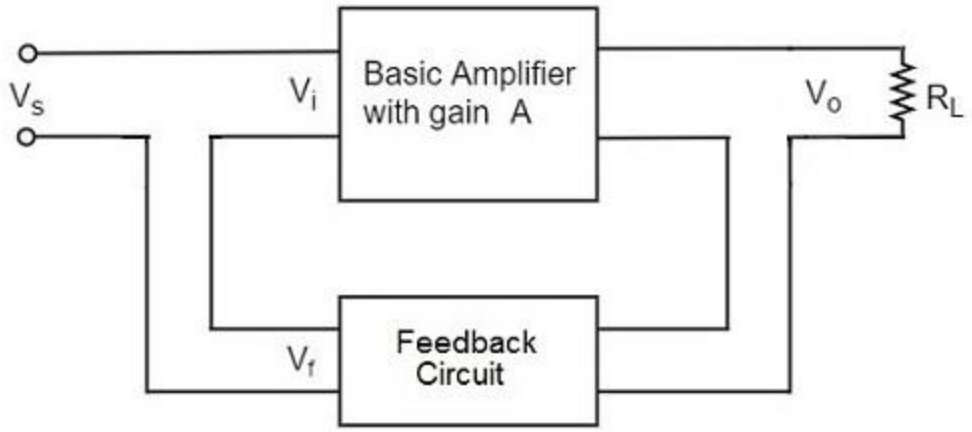

Figure 5 Series Feedback

As the feedback circuit is connected in series with the output and the input as well, both the output impedance and the input impedance are increased.

Current-Shunt Feedback

In the current shunt feedback circuit, a fraction of the output voltage is applied in series with the input voltage through the feedback circuit. This is also known as **series-driven shunt-fed** feedback i.e., a series-parallel circuit.

The below figure shows the block diagram of current shunt feedback, by which it is evident that the feedback circuit is placed in series with the output but in parallel with the input.

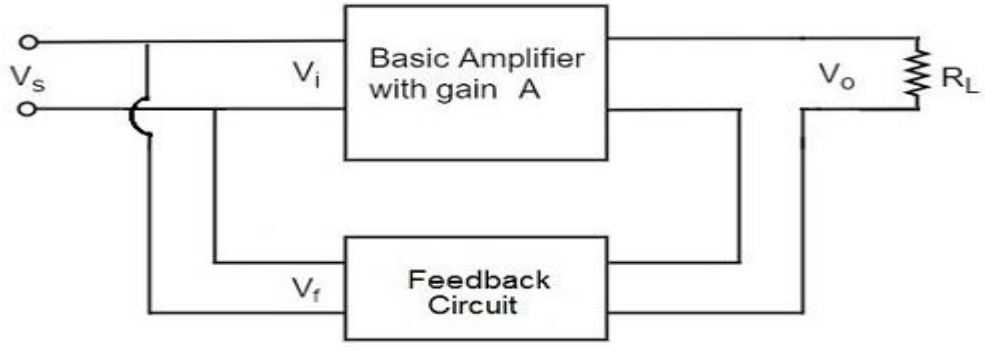

Figure 6 Shunt Feedback

As the feedback circuit is connected in series with the output, the output impedance is increased and due to the parallel connection with the input, the input impedance is decreased.

Let us now tabulate the amplifier characteristics that get affected by different types of negative feedbacks.

Characteristics	**Types of Feedback**			
	Voltage-Series	**Voltage-Shunt**	**Current-Series**	**Current-Shunt**
Voltage Gain	Decreases	Decreases	Decreases	Decreases
Bandwidth	Increases	Increases	Increases	Increases
Input resistance	Increases	Decreases	Increases	Decreases
Output resistance	Decreases	Decreases	Increases	Increases
Harmonic distortion	Decreases	Decreases	Decreases	Decreases
Noise	Decreases	Decreases	Decreases	Decreases

5.4 Oscillators

Types

- RC oscillator
- Wein bridge oscillator
- Hartley Oscillator
- Colpitts Oscillator
- Crystal Oscillator

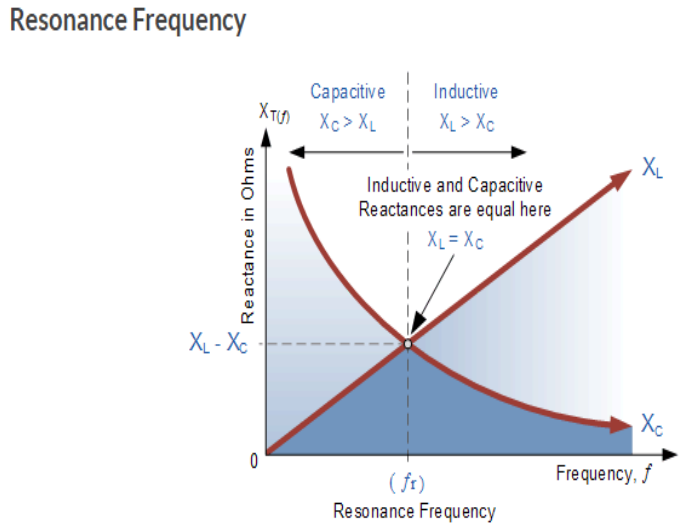

Figure 7 Condition for Oscillation

5.4.1 HARTLEY OSCILLATOR

- A very popular local oscillator circuit that is mostly used in radio receivers is the Hartley Oscillator circuit
- The resistors R1, R2 and Re provide necessary bias condition for the circuit
- The capacitor Ce provides a.c. ground thereby providing any signal degeneration. This also provides temperature stabilization.
- The capacitors Cc and Cb are employed to block d.c. and to provide an a.c. path
- The radio frequency choke offers very high impedance to high frequency currents which means it shorts for d.c. and opens for a.c. Hence it provides d.c. load for collector and keeps a.c. currents out of d.c. supply source

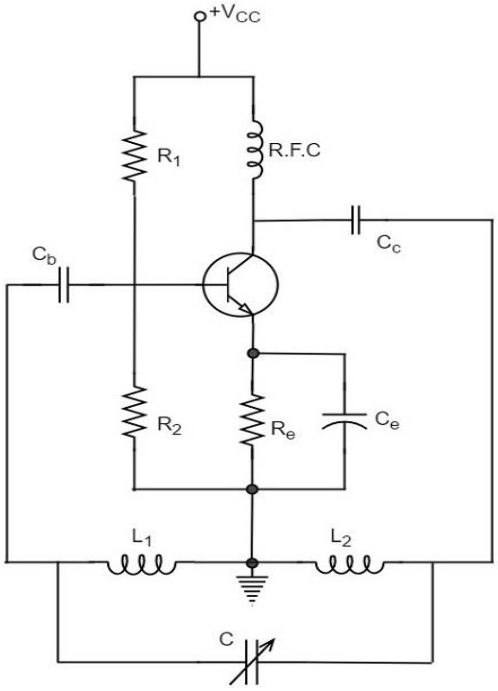

Figure 8 Hartley Oscillator

Tank Circuit

- The frequency determining network is a parallel resonant circuit which consists of the inductors L1 and L2 along with a variable capacitor C.
- The junction of L1 and L2 are earthed. The coil L1 has its one end connected to base via Cc and the other to emitter via Ce.
- So, L2 is in the output circuit. Both the coils L1 and L2 are inductively coupled and together form an Auto-transformer.
- The tank circuit is shunt fed in this circuit. It can also be a series-fed.

Operation

- When the collector supply is given, a transient current is produced in the oscillatory or tank circuit. The oscillatory current in the tank circuit produces a.c. voltage across L1.
- The auto-transformer made by the inductive coupling of L1 and L2 helps in determining the frequency and establishes the feedback.
- As the CE configured transistor provides 180 degree phase shift, another 180 degree phase shift is provided by the transformer, which makes 360o phase shift between the input and output voltages.

- This makes the feedback positive which is essential for the condition of oscillations. When the loop gain |βA| of the amplifier is greater than one,
- oscillations are sustained in the circuit.

Frequency

- The equation for frequency

LT = L1 + L2 + 2M

L1 and L2 represent inductances of 1st and 2nd coils; and M represents mutual inductance

$$f = \frac{1}{2\pi\sqrt{L_T C}}$$

A **Hartley Oscillator** circuit having two individual inductors of 0.5mH each, are designed to resonate in parallel with a variable capacitor that can be adjusted between 100pF and 500pF. Determine the upper and lower frequencies of oscillation and also the Hartley oscillators bandwidth.

Hartley Oscillator Lower Frequency

$$f_L = \frac{1}{2\pi\sqrt{1mH \times 500pF}} = \frac{1}{6.283\sqrt{5\times10^{-13}}} = 225050Hz$$

$$\therefore f_L = 225kHz$$

Hartley Oscillator Bandwidth

$$Bandwidth = f_H - f_L$$

$$= 503 - 225 = 278kHz$$

$$f_r = \frac{1}{2\pi\sqrt{L_T C}}$$

The circuit consists of two inductive coils in series, so the total inductance is given as:

$$L_T = L_1 + L_2 = 0.5mH + 0.5mH = 1.0mH$$

Hartley Oscillator Upper Frequency

$$f_H = \frac{1}{2\pi\sqrt{1mH \times 100pF}} = \frac{1}{6.283\sqrt{1\times10^{-13}}} = 503228Hz$$

$$\therefore f_H = 503kHz$$

- Mutual inductance is calculated when two windings are considered.

Advantages

- Instead of using a large transformer, a single coil can be used as an auto-transformer.
- Frequency can be varied by employing either a variable capacitor or a variable inductor.
- Less number of components are sufficient.
- The amplitude of the output remains constant over a fixed frequency range.

Disadvantages

- It cannot be a low frequency oscillator.
- Harmonic distortions are present.

Applications

- The applications of Hartley oscillator are
- It is used to produce a sinewave of desired frequency.
- Mostly used as a local oscillator in radio receivers.

It is also used as R.F. Oscillator.

5.4.2 Colpitts oscillator

- A Colpitts oscillator looks just like the Hartley oscillator but the inductors and capacitors are replaced with each other in the tank circuit.
- The resistors R1, R2 and Re provide necessary bias condition for the circuit. The capacitor Ce provides a.c. ground thereby providing any signal degeneration. This also provides temperature stabilization.
- The capacitors Cc and Cb are employed to block d.c. and to provide an a.c. path. The radio frequency choke offers very high impedance to high

frequency currents which means it shorts for d.c. and opens for a.c. Hence it provides d.c. load for collector and keeps a.c. currents out of d.c. supply

source.

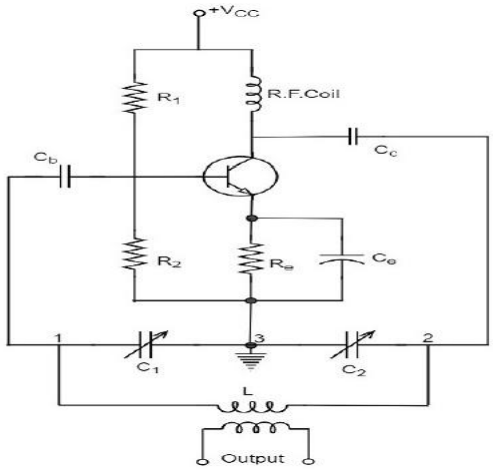

Figure 9 Colpitts Oscillator

- A Colpitts oscillator looks just like the Hartley oscillator but the inductors and capacitors are replaced with each other in the tank circuit.
- The resistors R1, R2 and Re provide necessary bias condition for the circuit. The capacitor Ce provides a.c. ground thereby providing any signal degeneration. This also provides temperature stabilization.
- The capacitors Cc and Cb are employed to block d.c. and to provide an a.c. path. The radio frequency choke offers very high impedance to high

frequency currents which means it shorts for d.c. and opens for a.c. Hence it provides d.c. load for collector and keeps a.c. currents out of d.c. supply

source.

Tank Circuit

- The frequency determining network is a parallel resonant circuit which consists of variable capacitors C1 and C2 along with an inductor L.
- The junction of C1 and C2 are earthed. The capacitor C1 has its one end connected to base via Cc and the other to emitter via Ce.
- The voltage developed across C1 provides the regenerative feedback required for the sustained oscillations.

Operation

- When the collector supply is given, a transient current is produced in the oscillatory or tank circuit.

- The oscillatory current in the tank circuit produces a.c. voltage across C1 which are applied to the base emitter junction and appear in the amplified form in the collector circuit and supply losses to the tank circuit.
- If terminal 1 is at positive potential with respect to terminal 3 at any instant, then terminal 2 will be at negative potential with respect to 3 at that instant

  because terminal 3 is grounded. Therefore, points 1 and 2 are out of phase by 180 deg.
- As the CE configured transistor provides 180deg phase shift, it makes 360o phase shift between the input and output voltages. Hence, feedback is properly phased to produce continuous Undamped oscillations. When the loop gain |βA| of the amplifier is greater than one, oscillations are sustained in the circuit.
- Frequency
- The equation for frequency of Colpitts oscillator is given as
- CT is the total capacitance of C1 and C2 connected in series.

Feedback Fraction $\frac{C_1}{C_2}$ %

A **Colpitts Oscillator** circuit having two capacitors of 24nF and 240nF respectively are connected in parallel with an inductor of 10mH. Determine the frequency of oscillations of the circuit, the feedback fraction and draw the circuit.

The oscillation frequency for a Colpitts Oscillator is given as:

$$f_r = \frac{1}{2\pi\sqrt{LC_T}}$$

The frequency of oscillations for the Colpitts Oscillator is therefore 10.8kHz with the feedback fraction given as:

$$F_F = \frac{C_1}{C_2} = \frac{24\text{nF}}{240\text{nF}} = 10\%$$

$$C_T = \frac{24\text{nF} \times 240\text{nF}}{24\text{nF} + 240\text{nF}} = 21.82\text{nF}$$

The inductance of the inductor is given as 10mH, then the frequency of oscillation is:

$$f_r = \frac{1}{2\pi\sqrt{LC_T}} = \frac{1}{6.283\sqrt{0.01 \times 21.82 \times 10^{-9}}} = 10.8\text{kHz}$$

Advantages

- Colpitts oscillator can generate sinusoidal signals of very high frequencies.
- It can withstand high and low temperatures.
- The frequency stability is high.
- Frequency can be varied by using both the variable capacitors.
- Less number of components are sufficient.
- The amplitude of the output remains constant over a fixed frequency range.
- The Colpitts oscillator is designed to eliminate the disadvantages of Hartley oscillator and is known to have no specific disadvantages. Hence there are many applications of a colpitts oscillator.

Applications

- Colpitts oscillator can be used as High frequency sinewave generator.
- This can be used as a temperature sensor with some associated circuitry.
- Mostly used as a local oscillator in radio receivers.
- It is also used as R.F. Oscillator.
- It is also used in Mobile applications.

- It has got many other commercial applications.

- Whenever an oscillator is under continuous operation, its frequency stability gets affected. There occur changes in its frequency. The main factors that affect the frequency of an oscillator are Power supply variations
- Changes in temperature
- Changes in load or output resistance
- In RC and LC oscillators the values of resistance, capacitance and inductance vary with temperature and hence the frequency gets affected.
- In order to avoid this problem, the piezo electric crystals are being used in oscillators.
- The use of piezo electric crystals in parallel resonant circuits provide high frequency stability in oscillators. Such oscillators are called as Crystal

5.4.3 Crystal Oscillators

- The principle of crystal oscillators depends upon the Piezo electric effect. The natural shape of a crystal is hexagonal. When a crystal wafer is cut perpendicular to X-axis, it is called as X-cut and when it is cut along Y-axis, it is called as Y-cut.
- The crystal used in crystal oscillator exhibits a property called as Piezo electric property.

Piezo Electric Effect

- The crystal exhibits the property that when a mechanical stress is applied across one of the faces of the crystal, a potential difference is developed across the opposite faces of the crystal.
- Conversely, when a potential difference is applied across one of the faces, a mechanical stress is produced along the other faces. This is known as Piezo electric effect.
- Certain crystalline materials like Rochelle salt, quartz and tourmaline exhibit piezo electric effect and such materials are called as Piezo electric crystals.
- Quartz is the most commonly used piezo electric crystal because it is inexpensive and readily available in nature.

- When a piezo electric crystal is subjected to a proper alternating potential, it vibrates mechanically. The amplitude of mechanical vibrations becomes maximum when the frequency of alternating voltage is equal to the natural frequency of the crystal.
- In order to make a crystal work in an electronic circuit, the crystal is placed between two metal plates in the form of a capacitor. Quartz is the mostly used type of crystal because of its availability and strong nature while being inexpensive. The ac voltage is applied in parallel to the crystal.

The circuit arrangement of a Quartz Crystal

- If an AC voltage is applied, the crystal starts vibrating at the frequency of the applied voltage.
- However, if the frequency of the applied voltage is made equal to the natural frequency of the crystal, resonance takes place and crystal vibrations reach a maximum value. This natural frequency is almost constant.
- Equivalent circuit of a Crystal
- If we try to represent the crystal with an equivalent electric circuit, we have to consider two cases, i.e., when it vibrates and when it doesn't.
- The figures below represent the symbol and electrical equivalent circuit of a crystal respectively.

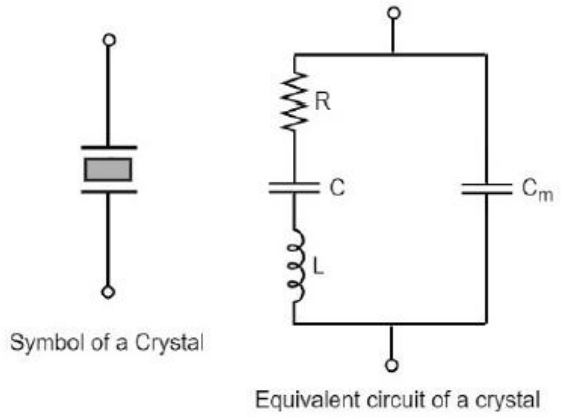

Figure 9 Crystal Oscillator

- The above equivalent circuit consists of a series R-L-C circuit in parallel with a capacitance Cm. When the crystal mounted across the AC source is not vibrating, it is equivalent to the capacitance Cm. When the crystal vibrates, it acts like a tuned R-L-C circuit.

Frequency response

- The frequency response of a crystal is as shown below. The graph shows the reactance (XL or XC) versus frequency . It is evident that the crystal has two closely spaced resonant frequencies.

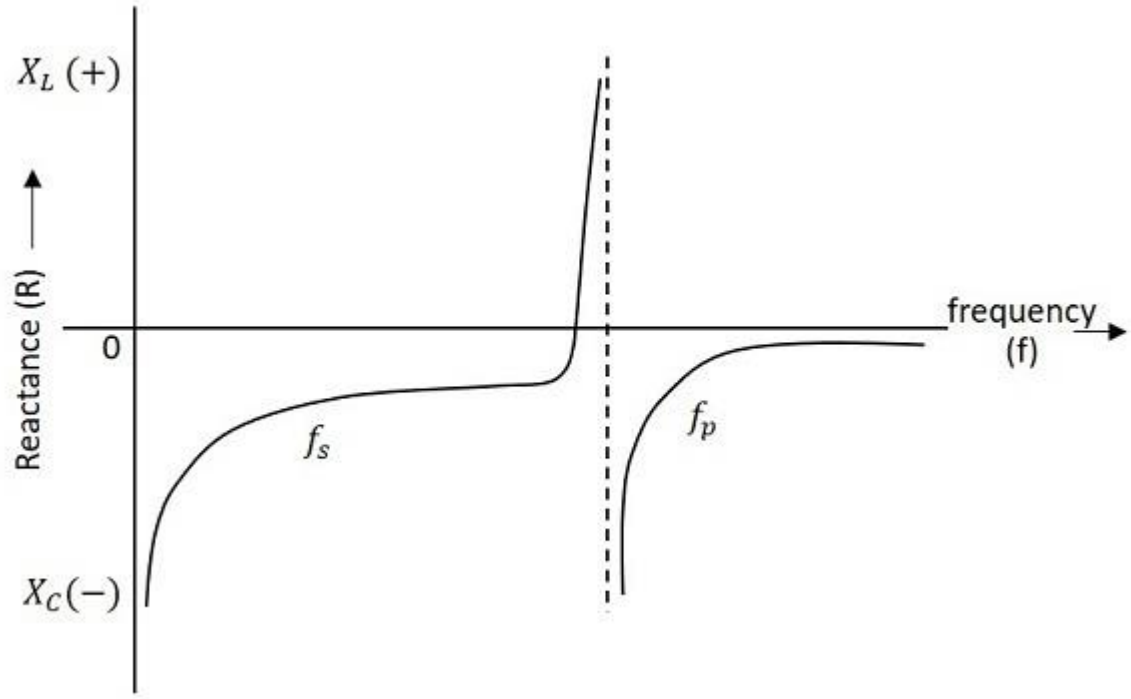

Figure 10 Frequency response

- The series resonant frequency (fs), which occurs when reactance of the inductance (L) is equal to the reactance of the capacitance C.
- The impedance of the equivalent circuit is equal to the resistance R and the frequency of oscillation is given by the relation,

$$f = \frac{1}{2\pi\sqrt{L.C}}$$

- the parallel resonant frequency (f_p), which occurs when the reactance of R-L-C branch is equal to the reactance of capacitor C_m. At this frequency, the crystal offers a very high impedance to the external circuit and the frequency of oscillation is given by the relation.

$$f_p = \frac{1}{2\pi\sqrt{L.C_T}}$$

- The value of Cm is usually very large as compared to C. Therefore, the value of CT is approximately equal to C and hence the series resonant frequency is approximately equal to the parallel resonant frequency (i.e., fs = fp)

$$C_T = \frac{CC_m}{(C + C_m)}$$

- The crystal is connected as a series element in the feedback path from collector to the base.
- The resistors R_1, R_2 and R_E provide a voltage-divider stabilized d.c. bias circuit.
- The capacitor C_E provides a.c. bypass of the emitter resistor
- RFC (radio frequency choke) coil provides for d.c. bias while decoupling any a.c. signal on the power lines from affecting the output signal.
- The coupling capacitor C has negligible impedance at the circuit operating frequency. But it blocks any d.c. between collector and base.

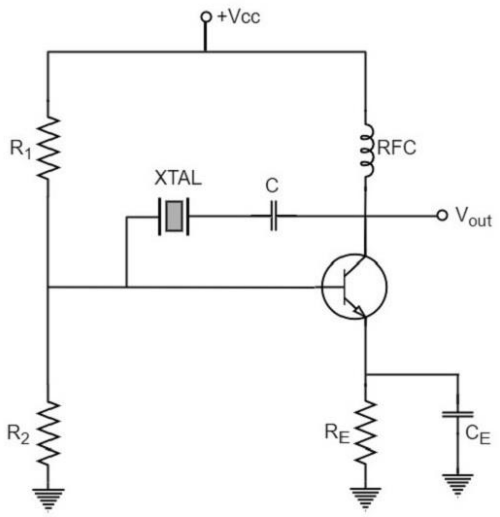

Figure 11. Crystal Oscillator

- The changes in supply voltage, transistor device parameters etc. have no effect on the circuit operating frequency, which is held stabilized by the crystal.

Advantages

- They have a high order of frequency stability.
- The quality factor (Q) of the crystal is very high.

Disadvantages

- They are fragile and can be used in low power circuits.
- The frequency of oscillations cannot be changed appreciably
- A quartz crystal has the following values: Rs = 6.4Ω, Cs = 0.09972pF and Ls = 2.546mH. Calculate the fundamental oscillating frequency of the crystal.

$$f_S = \frac{1}{2\pi\sqrt{L_S C_S}} = \frac{1}{2\pi\sqrt{2.546\text{mH} \times 0.09972\text{pF}}}$$

$$f_S = \frac{1}{2\pi\sqrt{0.002546 \times 99.72 \times 10^{-15}}} = 9.987\text{MHz}$$