09 – Semiconductor Devices

Syllabus: **Semiconductor Devices:** Review of Intrinsic and Extrinsic semiconductors, p-n junction and its Characteristics and Parameters, Diode approximations, Half-wave rectifier, Full-wave rectifier, Zener diode voltage regulators: Regulator circuit with no load, Loaded Regulator. [05 hour]

Introduction:

Classification of Solids: From electrical point of view, solids are broadly classified into three categories;

1) Conductors
2) Insulators and
3) Semiconductors

Conductors: Those substances whose atoms have their outermost orbits incomplete initially are conductors. In them, the valence electrons (number of electrons in outermost orbit of the atom) are very loosely bound to the nucleus and hence they can be easily set free from the atom. Electrons thus freely move inside the conductor and act as charge carriers.

Metals such as gold, silver, copper, aluminum etc. are good examples of conductors. They have a very high electrical conductivity or a very low resistivity (the resistance offered to the flow of current between opposite faces of a unit cube of the material).

The main properties of conductors are summarized as below:

1. Conductors have high electrical and thermal conductivity.
2. In the steady state, conductors obey Ohm's law according to which the current density $\vec{J}$ is proportional to the electrical field strength $\vec{E}$. Thus for metals $\vec{J} \propto \vec{E}$ or $\vec{J} = \sigma \vec{E}$
   where σ is the electrical conductivity.
3. Conductors have a positive temperature coefficient i.e., their resistance increases (or conductivity decreases) with rise of temperature.
4. Conductors obey Wiedmann-Franz law according to which the ratio of thermal and electrical conductivity at a given temperature is the same for all metals and is proportional to the absolute temperature T.
   Thus $\frac{k}{\sigma} \propto T$ or $\frac{k}{\sigma T} = constant$

Insulators: Those substances whose atoms have their outermost orbits saturated are called insulators. In them, the valence electrons are tightly bound to the nucleus. They thus have practically no free electrons to act as charge carriers and hence have a high electrical resistivity. Their examples are glass, mica, quartz, ebonite etc.

Semiconductors: Those substances which have their conductivity intermediate between conductors and insulators are called semiconductors. Their resistivity is higher than that of conductors but lower than that of an insulator. Typical values of resistivity of semiconductor (germanium) is $0.6\ ohm\ metre$ at room temperature while for conductor (silver) it is $1.6 \times 10^{-6}\ ohm\ metre$ and for insulator (quartz) it is $10^{12}\ ohm\ metre$.

A semiconductor has the following essential characteristics;

1) Semiconductors have negative temperature coefficient of resistance i.e., the electrical resistance of a semiconductor decreases with increase in temperature. The relation between temperature and resistance is of the form $R = A\, e^{-B/T}$ where R is the resistance of the semiconductor at temperature $T\ K$ and A and B are constants for the semiconductors.
2) Electrical conductivity of a semiconductor can be increased enormously by adding a small amount of suitable impurity.

Germanium (Ge) and silicon (Si) are the most common semiconductors. Germanium has been extremely used in early days as solid state devices, such as transistors, but is now being replaced by silicon due to its availability in abundance. In addition to these elementary semiconductors there are compound semiconductors like cadmium sulphide (CdS), lead sulphide (PbS) and gallium arsenide (GaAs) etc. which are being applied in the manufacture of solid state devices.

Energy Bands in Solids:

Valence Band:

The *Valence electrons have least binding energy and more orbital energy*. These electrons are therefore affected when number of atoms are brought very close to each other during formation of a solid.

*"The range of energies possessed by valence electrons is called the **valance band**"*.

It is the highest occupied band. This band may be either completely filled or partially filled with electrons but can never be empty.

Conduction Band:

The valence electrons are loosely bound to the nucleus. Even at ordinary temperatures, some of the valence electrons acquire sufficient energy and get easily detached. These detached electrons are called **free electrons** or **conduction electrons**.

*"The range of energies possessed by free electrons is called the **conduction band**"*.

The conduction band is the upper most energy band in a crystal and lies next to the valence band. This band may either be empty or partially filled with free electrons.

Forbidden Energy Gap:

"The separation between conduction and valence bands on the energy band diagram is called the ***forbidden energy gap****"*.

Since there is no allowed energy levels for an electron in this region, electrons are never found in this gap. The energy which is required to lift an electron from the valence band to the conduction band must be greater than the energy gap (E_g). The width of the forbidden gas is measure of the bondage of valence electrons to the atom. The greater the energy gap, more tightly the valence electrons are bound to the nucleus. For silicon $E_g = 1.12\ eV$ and for germanium it is $E_g = 0.72\ eV$ at $25^0\ C$.

Classification of Materials Based on Energy Band Theory:

Solids may be classified according to their electrical resistivity. A very poor conductor of electricity is called **insulator**; an excellent conductor is called a **metal**; and a substance whose conductivity or resistivity lies between these extremes is a **semiconductor**.

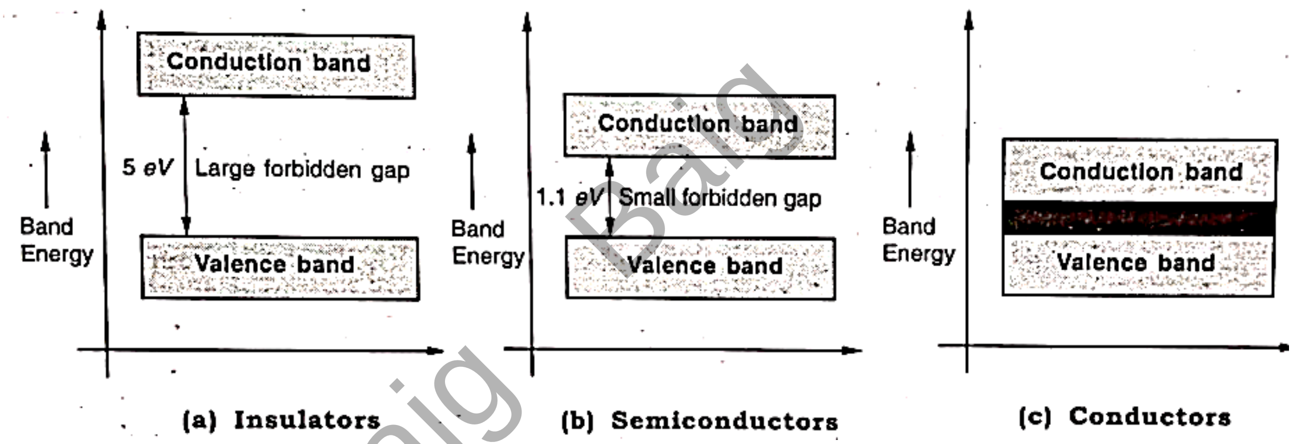


Fig (01)

Insulators:

"In terms of energy bands, insulators are those substances in which valence and conduction bands are widely separated". [see fig (01a)]

The forbidden gap is very large and is greater than $6\ eV$. In insulators;

1. The valence band is completely filled.
2. The conduction band is completely empty.
3. The energy gap between conduction and valence bands is large.

Insulators do not therefore conduct electricity, even with the application of a large electric field or heating to a very large temperature. The number of electrons that can be thermally excited across the gap at room temperature is very small for insulator, for example diamond. This accounts for the insulating properties of diamond and its high electrical resistivity at room temperature. The resistivity of diamond is of the order of $10^{10}\ to\ 10^{16}\ \Omega m$.

Semiconductors:

"***Semiconductors*** *are those substances which allow electric charges partially to flow through them*". Examples: Germanium, Silicon, Tellurium, Selenium, graphite, etc.

"*In terms of energy bands,* ***semiconductors*** *are those substances in which valence and conduction bands are moderately separated*". [see fig (01b)]

The forbidden gap is small and is of the order of $1\ eV$ at room temperature. In semiconductors;

1. The valence band is partially filled.
2. The conduction band is also partially filled.
3. The energy gap between valence and conduction bands is narrow.

At room temperature some electrons in valence band have enough energy to surmount the energy gap and get into conduction band. At low temperatures, the valence band is completely filled and conduction band is completely empty. Therefore, ***a semiconductor virtually behaves as an insulator at very low temperatures***. Conductivity of semiconductor increases with temperature. They have negative temperature coefficient of resistance. At room temperature, the resistivity of pure semiconductor is of the order of $10^3\ \Omega m$. The energy gap of silicon is $1.12\ eV$ and germanium is $0.72\ eV$.

Conductors:

"***Conductor*** *are substances which allow the easy flow of electric charges*". Examples: Almost all metals, salt substances, human body.

"*In terms of energy bands, conductors are those substances in which the valence and conduction bands overlap*". [see fig (01c)]

In fact, there is no physical distinction between these two bands. For that matter small amount of energy is required for excitation from the filled states to the Fermi level. Thus, conduction is possible by very weak electric field. The valence band is not filled, so electrons can move to higher states in the valence band and become free. The resistivity of conductors is of the order of $10^{-7}\ \Omega m$.

Semiconductors:

"***Semiconductors*** *are those substances whose electrical properties lie between those of conductors and insulators*".

Examples: Silicon, Germanium, selenium, gallium arsenide, lead sulphide, etc. Germanium and Silicon are the most commonly used semiconductors.

Properties of Semiconductors:

1. Semiconductors are crystalline in nature.
2. The resistivity of a semiconductor is less and insulator and more than the conductor.

3. The resistivity of a semiconductor decreases with increase in temperature.
4. Semiconductors are good conductors at high temperatures and they are insulators at low temperatures.
5. The distinctive feature of a semiconductor is the type and the degree of binding between atoms.
6. The conductivity of a semiconductor is generally sensitive to temperature, illumination, magnetic field and the impurity added.

Classification of Semiconductors:

Semiconductors may be classified into two types:

1. Intrinsic semiconductors and
2. Extrinsic semiconductors

Intrinsic Semiconductors:

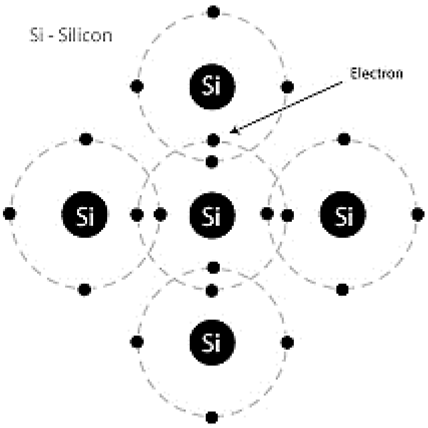


Fig (01a)

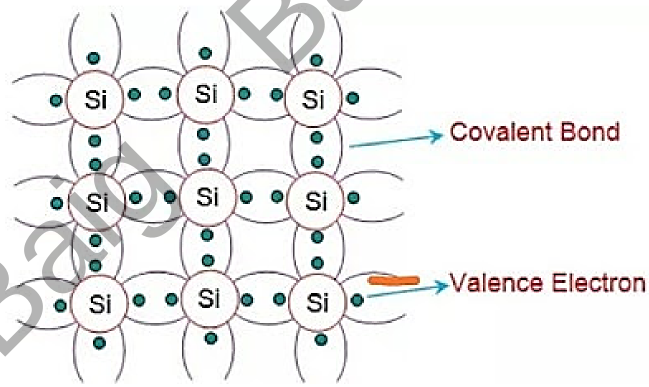


Fig (01b)

"A semiconductor in an extremely pure form is known as an intrinsic semiconductor".

When silicon atoms combine to form a solid, the arrange themselves into an orderly pattern called **crystal**. Each silicon atom shares its four valence electrons with its neighbouring silicon atoms. This effectively creates eight valence electrons for each atom [see fig (01)] and produce a state of chemical stability. The shaded circles represent silicon cores. Although the silicon atom originally has four electrons in its valence orbit, it now has eight electrons in this orbit.

In fig (01), each core has a charge of $+4$. Consider the central core and any one of the neighbouring cores. These two cores attract the pair of electrons between them with equal and opposite forces. This pulling in opposite directions is what holds the silicon atoms together. The idea is similar to tug-of-war teams pulling on a rope.

Since, each shared electron is being pulled in opposite directions, the electron is a bond between the opposite cores. Hence, the sharing of valence electrons produce the **covalent bonds**. Covalent bonding in an intrinsic silicon crystal is shown in fig (01b).

In a silicon crystal, there are billions of silicon atoms, each with eight valence electrons. These valence electrons are the covalent bonds that hold the crystal together that give it solidity.

We know that each atom in a silicon crystal has eight electrons in its valence orbit. These eight electrons produce chemical stability to the silicon material.

P N Junction: P-type and N-type semiconductors, taken separately are of very limited use. If we join a piece of P-type material to a piece of N-type material such that the crystal structure remains continuous at the boundary, a PN junction is formed. Such PN junctions are fundamental to the performance of functions such as rectification, amplification, switching and other operations in electronic circuits.

A useful PN junction cannot be produced by simply pushing two pieces together or by welding etc. because it gives rise to discontinuities across the crystal structure. Special fabrication techniques are adopted to form a PN junction. Among those, three popular techniques are;

1) Grown Junction
2) Fused or Alloyed Junction and
3) Diffused Junction method.

Rectifiers:

Introduction:

A d.c. source is essential for the operation of most of the electronic devices and circuits. Dry cells and batteries serve the purpose and are portable giving pure ripple free d.c. They are drained off their energy faster needing frequent replacement and as such highly expensive compared to d.c. power supplies.

Most economical and convenient source of power is the domestic a.c. supply (230 V AC 50 Hz), and it is easy and convenient to convert this a.c. voltage into d.c. voltage to required low values.

"The process of converting a.c. voltage into d.c. voltage is called ***rectification****"*.

A complete power supply consists of the following:

a) Rectifier Circuit
b) Filter Circuit and
c) Voltage Regulator Circuit

If a d.c. supply from the terminals of a source, is affected by the load and the voltage drops if more current is drawn by the load, then it is said to be **unregulated power supply**.

If a d.c. power supply whose terminal voltage remains constant irrespective of the load and the current drawn by the load, then it is said to be **regulated power supply**.

A d.c. power supply is shown in the following block diagram.

1) **Transformer:** Step down used to bring down the level of a.c. voltage to the desired value.
2) **Rectifier:** It is a circuit which uses one or more diodes to converts a.c. voltages into pulsating d.c. voltage.
3) **Filter:** This is a circuit which uses a combination of an inductor and a capacitor to remove the fluctuations i.e., ripples or a.c. component present in the d.c. output voltage. This d.c. output may not be exactly as that from a battery, but it is a closest approach to that from the battery.
4) **Voltage Regulator:** The purpose of this circuit is to keep the terminal voltage of the d.c. supply constant even when a) the a.c. input voltage changes, b) when the load changes or c) when the load current changes.
5) **Voltage Divider:** This is a circuit arrangement consisting of several resistors connected in series to provide different values of required d.c. voltages.

Fig (01) Fig (02)

The d.c. shown in fig (02) has high frequency pulsations or ripples in it. It can be viewed as a d.c. voltage having some a.c. voltage ridding on it.

"The amount of ***ripple*** *or* ***a.c. voltage variations*** *is a measure of the purity of d.c. of the power supply"*. Its numerical measure is given by a quantity known as ripple factor denoted by γ.

$$\gamma = \frac{r.m.s.\ \ value\ of\ ripple\ voltage}{d.c.\ \ output\ voltage\ of}$$

$$\gamma = \frac{r.m.s.\ \ value\ of\ a.c.\ \ component}{d.c.\ \ component}$$

$$\boxed{\gamma = \frac{V_{r\,(r.m.s.)}}{V_{dc}}}$$

The different types of rectifiers are:
1) Half Wave Rectifier
2) Full Wave Rectifier and
3) Full Wave Bridge Rectifier

Half Wave Rectifier:
Fig (01) depicts the rectification action of a semiconductor diode. The a.c. voltage to be rectified is connected to the primary coil P of the power transformer T. One end of the secondary S of the transformer is connected to P-region of the diode D while its another end is connected to N-region through a load resistance R.

Working: During the first half cycle of a.c., one end of the secondary, say A, becomes positive. Then the diode D is forward biased and hence current flows through the load R in the direction of arrows as shown in fig (01). During negative half cycle, the end A becomes negative and consequently, the diode D is reverse biased. Therefore, no (negligible) current flows through the load R_L. Thus we get a unidirectional current across R which flows in the form of half sine wave separated by a period of π radians, as shown in fig (01).

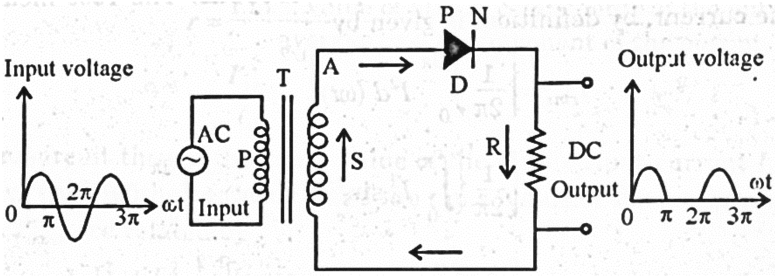


Fig (01)

Circuit Analysis: Let the input voltage applied to the P-N junction diode in series with load R_L is given by

$$e = E_0 \sin \omega t$$

Then, the instantaneous output current through the load resistance R_L is given by

$$i = \frac{E_0 \sin \omega t}{R_f + R_L} = I_0 \sin \omega t \qquad when\ 0 \le \omega t \le \pi$$

$$I = 0 \qquad when\ \pi \le \omega t \le 2\pi$$

where R_f is the dynamic resistance of the semiconductor diode and $I_0 = \frac{E_0}{R_f + R_L}$ is the peak value of the current.

D.C. (or Average) value of output current: The average d.c. current over one complete cycle is given by

$$I_{dc} = \frac{1}{2\pi} \int_0^{2\pi} i \cdot d(\omega t)$$

$$I_{dc} = \frac{1}{2\pi} \left[\int_0^{\pi} I_0 \sin \omega t \cdot d(\omega t) + \int_{\pi}^{2\pi} 0 \cdot d(\omega t) \right]$$

$$I_{dc} = \frac{1}{2\pi} [-\cos \omega t]_0^{\pi} = \frac{I_0}{\pi}$$

∴ $$I_{dc} = \frac{I_0}{\pi} = \frac{E_0}{\pi (R_f + R_L)} \qquad (01)$$

The d.c. (or average) output voltage across the load is given by

$$E_{dc} = I_{dc} \times R_L = \frac{I_0 R_L}{\pi} = \frac{E_0 R_L}{\pi (R_f + R_L)}$$

R.M.S. (effective) value of output current: The root means square value of the current, by definition, is given by

$$I_{rms} = \left[\frac{1}{2\pi} \int_0^{2\pi} i^2 \cdot d(\omega t) \right]^{1/2}$$

$$I_{rms} = \left[\frac{1}{2\pi} \left\{ \int_0^{\pi} I_0^2 \sin^2 \omega t \cdot d(\omega t) + \int_{\pi}^{2\pi} 0 \cdot d(\omega t) \right\} \right]^{1/2}$$

$$I_{rms} = \left[\frac{1}{2\pi} \int_0^{\pi} I_0^2 \sin^2 \omega t \cdot d(\omega t) \right]^{1/2}$$

$$I_{rms} = \frac{I_0}{2} \qquad (02)$$

It should be noted that this value differs from the r.m.s. value of a sinusoidal current which is $I_0/\sqrt{2}$.

Power supplied to the circuit: The power supplied to the circuit from the a.c. source is given by

$$P_{ac} = I_{rms}^2 (R_f + R_L) = \frac{I_0^2}{4} (R_f + R_L) \qquad (03)$$

Average power supplied to the load: The d.c. power output across the load R_L is given by

$$P_{dc} = I_{dc}^2 R_L = \frac{I_0^2 R_L}{\pi^2} \qquad (04)$$

Efficiency: *"The efficiency of rectification η with which the half wave rectifier converts a.c. power into d.c. is defined as the ratio of d.c. output power to the total a.c. power supplied to the rectifier"*.

Thus, $$\eta = \frac{d.c.\, power\ supplied\ to\ the\ load}{total\ input\ a.c.\, power} \times 100\%$$

or $$\eta = \frac{P_{dc}}{P_{ac}} \times 100\%$$

$$\eta = \frac{I_0^2 R_L/\pi^2}{I_0^2 (R_f + R_L)/4} \times 100\% = \frac{4 R_L}{\pi^2 (R_f + R_L)} \times 100\%$$

$$\eta = \frac{400}{\pi^2} \times \frac{1}{\left(1 + \frac{R_f}{R_L}\right)} \% = \frac{40.6}{1 + \frac{R_f}{R_L}} \%$$

If $R_f \ll R_L$, the efficiency is maximum. Thus the theoretical maximum efficiency is

$$\eta_{max} = 40.6\%$$

Ripple factor: The output of a rectifier contains unidirectional (d.c.) current as well as a part of a.c. *"A measure of a.c. component in the output of rectifier is called ripple factor"*. It denoted by γ.

Ripple factor is also defined as

$$\gamma = \frac{r.m.s.\, value\ of\ the\ a.c.\, component\ of\ the\ output}{average\ or\ d.c.\, component\ of\ the\ output}$$

$$\gamma = \frac{I'_{rms}}{I_{dc}}$$

From a.c. circuit theory, the r.m.s. value of the total output current I_{rms}, the average or d.c. value of the current I_{dc} and the r.m.s. value of a.c. components of the output I'_{rms} are related by

$$I_{dc}^2 + I'^2_{rms} = I_{rms}^2$$

$$1 + \frac{I'^2_{rms}}{I_{dc}^2} = \frac{I_{rms}^2}{I_{dc}^2}$$

Therefore, ripple factor is given by

$$\gamma = \frac{I'_{rms}}{I_{dc}} = \sqrt{\left(\frac{I_{rms}^2}{I_{dc}^2} - 1\right)}$$

From equations (01) and (02)

$$\frac{I_{rms}}{I_{dc}} = \frac{I_0/2}{I_0/\pi} = \frac{\pi}{2}$$

$$\gamma = \sqrt{\left(\frac{\pi}{2}\right)^2 - 1} = 1.21$$

Thus for a half wave rectifier $\gamma > 1$ or $I_{rms} > I_{dc}$
i.e., the a.c. component of the output exceeds the d.c. value. It indicates that half wave rectifier is poor device for converting a.c. into d.c.

Full Wave Rectifier:

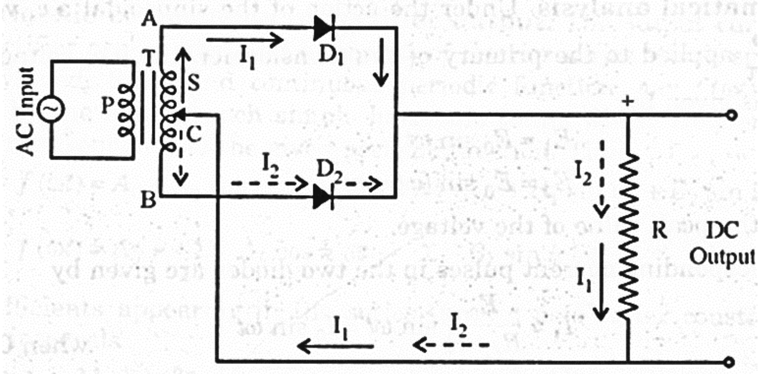


Fig (01)

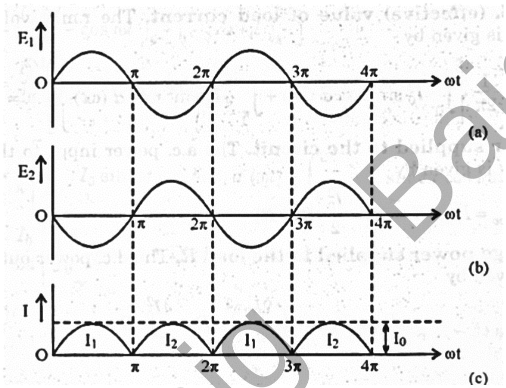


Fig (02)

Fig (01) shows the circuit of the centre tap full wave rectifier employing two P-N junction diodes D_1 and D_2. The P-regions of the diodes are connected to the ends A and B of the secondary of the power transformer, the middle point of which is tapped at and connected to the junction of N-regions through the load resistance R_L.

Working: During positive half-cycle of secondary voltage, one end of the secondary say, A, becomes positive and end B becomes negative. Consequently, the diode D_1 is forward biased and a current I_1 flows in the circuit in the direction AD_1RCA shown by solid arrows. During this time diode D_2 is reverse biased and hence no current flows through it. During the negative half cycle of AC input, end A becomes negative and end B positive. Consequently diode D_2 is forward biased and a current I_2 flows in the circuit through the diode D_2 along BD_2RCB as shown by the dotted arrows. During this period, D_1 is reverse biased and hence does not conduct.

Thus the diodes D_1 and D_2 conduct alternatively but each time the current through the load R_L flows in the same direction. Consequently, the resulting output current is unidirectional and flows in the form of half sine waves without separation as shown in fig (02c). Fig (02 a and b) give the input wave forms of two diodes D_1 and D_2.

Circuit Analysis: Under the section of the sinusoidal a.c. voltage of frequency $\frac{\omega}{2\pi}$ applied to the primary of the transformer, the a.c. voltage across AC and BC is given by

$$E_1 = E_0 \sin \omega t$$

$$E_2 = E_0 \sin (\omega t - \pi)$$

where E_0 is the peak value of the voltage.

The corresponding current pulses in the two diodes are given by

$$I_1 = \frac{E_0}{R_f + R_L} \sin \omega t = I_0 \sin \omega t \quad \text{and} \quad I_2 = 0 \qquad when\ 0 \le \omega t \le \pi$$

$$I_1 = 0 \quad \text{and} \quad I_2 = -\frac{E_0}{R_f + R_L} \sin \omega t = -I_0 \sin \omega t \qquad when\ \pi \le \omega t \le 2\pi$$

where R_f is the dynamic resistance of semiconductor diode.

D.C. (average) value of output current: Since the currents I_1 and I_2 are of the same form $\left(I = I_0 \sin \omega t\right)$, the average or d.c. value of current can be obtained by integrating the current expression between 0 and π and dividing by the period π, i.e.,

$$I_{dc} = \frac{1}{\pi}\int_0^{\pi} i \cdot d\,(\omega t)$$

$$I_{dc} = \frac{1}{\pi}\int_0^{\pi} I_0 \sin \omega t \cdot d\,(\omega t)$$

$$\therefore \quad I_{dc} = \frac{2\,I_0}{\pi} \qquad (01)$$

The d.c. (or average) output voltage across the load R_L is, therefore,

$$E_{dc} = I_{dc} \times R_L = \frac{2\,I_0\,R_L}{\pi} = \frac{2\,E_0\,R_L}{\pi\left(R_f + R_L\right)} \qquad (02)$$

R.M.S. (effective) value of load current: The r.m.s. value of total output current is given by

$$I_{rms} = \left[\frac{1}{2\pi}\int_0^{2\pi} i^2 \cdot d\,(\omega t)\right]^{1/2}$$

$$I_{rms} = \left[\frac{1}{2\pi}\left\{\int_0^{\pi} I_0^2 \sin^2 \omega t \cdot d\,(\omega t) + \int_{\pi}^{2\pi} I_0^2 \sin^2 \omega t \cdot d\,(\omega t)\right\}\right]^{1/2}$$

$$I_{rms} = \frac{I_0}{\sqrt{2}} \qquad (03)$$

Power supplied to the circuit: The a.c. power input to the rectifier from the supply is given by

$$P_{ac} = I_{rms}^2\left(R_f + R_L\right) = \frac{I_0^2}{2}\left(R_f + R_L\right) \qquad (04)$$

Average power supplied to the load: The d.c. power output across the load R_L is given by

$$P_{dc} = I_{dc}^2 R_L = \frac{4\,I_0^2\,R_L}{\pi^2} \qquad (05)$$

Efficiency: In a rectifier, the useful power output is the d.c. power which is developed across the load R_L *"The efficiency of rectification η with which the full wave rectifier converts a.c. power into d.c. is defined as the ratio of d.c. output power to the total a.c. power supplied to the rectifier"*.

Thus, $$\eta = \frac{d.c.\,power\ supplied\ to\ the\ load}{total\ input\ a.c.\,power} \times 100\%$$

or $$\eta = \frac{P_{dc}}{P_{ac}} \times 100\%$$

$$\eta = \frac{4\,I_0^2\,R_L/\pi^2}{I_0^2\left(R_f + R_L\right)/2} \times 100\% = \frac{8\,R_L}{\pi^2\left(R_f + R_L\right)} \times 100\%$$

$$\eta = \frac{800}{\pi^2} \times \frac{1}{\left(1 + \frac{R_f}{R_L}\right)}\,\% = \frac{81.2}{1 + \frac{R_f}{R_L}}\,\% \qquad (06)$$

If $R_f \ll R_L$, the efficiency is maximum. Thus the theoretical maximum efficiency is

$$\eta_{max} = 81.2\%$$

It is double that of a half wave rectifier.

Ripple factor: The output of a rectifier contains unidirectional (d.c.) current as well as a part of a.c. *"A measure of a.c. component in the output of rectifier is called ripple factor"*. It denoted by γ.

Ripple factor is also defined as

$$\gamma = \frac{r.m.s.\ value\ of\ the\ a.c.\ component\ of\ the\ output}{average\ or\ d.c.\ component\ of\ the\ output}$$

$$\gamma = \frac{I'_{rms}}{I_{dc}}$$

From a.c. circuit theory, the r.m.s. value of the total output current I_{rms}, the average or d.c. value of the current I_{dc} and the r.m.s. value of a.c. components of the output I'_{rms} are related by

$$I_{dc}^2 + I'^2_{rms} = I_{rms}^2$$

$$1 + \frac{I'^2_{rms}}{I_{dc}^2} = \frac{I_{rms}^2}{I_{dc}^2}$$

Therefore, ripple factor is given by

$$\gamma = \frac{I'_{rms}}{I_{dc}} = \sqrt{\left(\frac{I_{rms}^2}{I_{dc}^2} - 1\right)}$$

From equations (01) and (03)

$$\frac{I_{rms}}{I_{dc}} = \frac{I_0/\sqrt{2}}{2\,I_0/\pi} = \frac{\pi}{2\sqrt{2}}$$

$$\gamma = \sqrt{\left(\frac{\pi}{2\sqrt{2}}\right)^2 - 1} = 0.48$$

Thus for a full wave rectifier $\gamma < 1$ or $I_{dc} > I_{rms}$

i.e., the d.c. component of the output exceeds the a.c. value. It indicates that full wave rectifier is a better device for converting a.c. into d.c.

Comparison of Half Wave and Full Wave Rectifier:

1) Compared to half wave circuit, the full wave circuit has less ripple and is more easily filtered owing to the higher ripple frequency.
2) Rectification efficiency of a full wave rectifier is twice that of half wave rectifier.
3) Full wave rectifiers can supply a large load current as compared to half wave rectifiers.
4) For the same d.c. output voltage, the transformer secondary voltage required in full wave rectifier is twice that of required for half wave rectifier.
5) The half wave rectifier, however, has the advantages of simplicity and is less costly.

Bridge Rectifier

An important rectifier circuit arrangement is the bridge rectifier or double way rectifier shown in fig (01). It is known so because in this circuit the four PN junction diodes D_1, D_2, D_3 and D_4 are arranged in the form of four resistances of Wheatstone Bridge network. The two opposite ends A and C of the network are B and D are connected to the load resistance R.

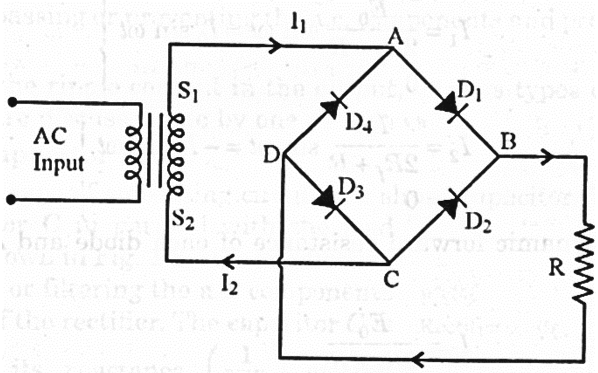


Fig (01)

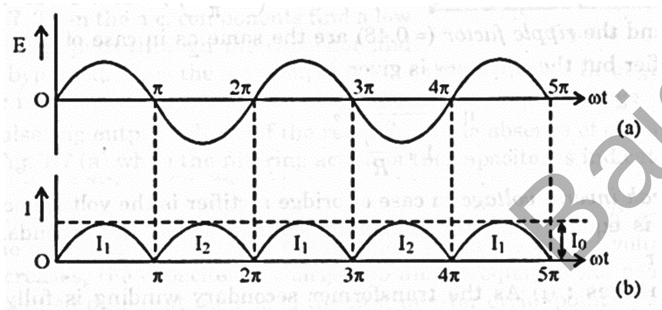


Fig (02)

Working: Under the action of an a.c. voltage applied to the primary of the transformer, the voltage across the secondary is given by

$$E_1 = E_0 \sin \omega t$$

which varies with ωt as shown in fig (02a).

In the half cycle in which the potential of the transformer has a polarity such that A is positive and C is negative, diodes D_1 and D_3 are forward biased and conduction takes place via diodes D_1, load resistance R_L and diode D_3. Consequently, a current I_1 flows in the direction $ABRDCS_2S_1A$ as shown in fig (01). On the other half cycle when the terminal C is positive with respect to A, diodes D_2 and D_4 are forward biased whereas diodes D_1 and D_3 are reverse biased. Therefore, conduction takes place via the diodes D_2 and D_4 and a current I_2 flows in the direction $CBRDAS_1S_2C$. Same process is repeated in the subsequent half cycles of the a.c. input. However, the current through the load R_L flows in the same direction in both halves of the applied a.c. voltage. Thus the current is unidirectional, and the wave shape of the current in the load is similar to that of full wave rectifier, as shown in fig (02b).

It is evident that two diodes conduct simultaneously in series. Therefore, the current pulses are represented by

$$I_1 = \frac{E_0}{2R_f + R_L} \sin \omega t = I_0 \sin \omega t \text{ and } I_2 = 0 \qquad when\ 0 \le \omega t \le \pi$$

$$I_1 = 0 \quad \text{and} \quad I_2 = -\frac{E_0}{2R_f + R_L} \sin \omega t = -I_0 \sin \omega t \qquad when\ \pi \le \omega t \le 2\pi$$

where R_f is the dynamic forward resistance of each diode and I_0 the maximum current is given by

$$I_0 = \frac{E_0}{2R_f + R_L}$$

The expression for average d.c. current $\left(= \frac{2I_0}{\pi}\right)$, r.m.s. value of current $\left(= I_0/\sqrt{2}\right)$ and the ripple factor $(= 0.48)$ are the same as in case of centre tap full wave rectifier but the efficiency is given by

$$\boldsymbol{\eta} = \frac{81.2}{1 + \frac{R_f}{R_L}} \%$$

The peak inverse voltage in case of bridge rectifier is the voltage across each diode and is equal to E_0, the maximum voltage across the secondary of the transformer.

Advantages:

1) As the transformer secondary winding is fully utilized, centre tap of the secondary is not required. It reduces the transformer cost in bridge rectifier.
2) The peak inverse voltage across each diode in a bridge rectifier is one half as that of centre tap full wave rectifier for the same d.c. output.
3) Since the current in both the primary and secondary of the transformer flow for the entire cycle, a smaller transformer can be used.

Disadvantages:

1) Two extra diodes are required in the circuit.

As the diodes are used in series, there is a larger voltage drop across the diodes. It results in poor rectification efficiency and poor voltage regulation.

Breakdown Mechanism:

With reverse bias voltage, the following two mechanisms are responsible for breakdown in P N junction diode:

1) Avalanche Breakdown: In this mechanism, the minority carriers (electrons in P-region and holes in N-region) gain large kinetic energy from the applied reverse voltage to collide with valence electrons of the atom fixed with the crystal and liberate them. Thus, in this process, covalent bonds are broken and the pair of electrons and holes are generated. The new carriers so produced, in turn, generate additional carriers and thus the number of free electrons and holes goes on increasing. This cumulative phenomenon is called ***avalanche multiplication*** and produces a sharp increase in the reverse current. The diode is then said to be in avalanche breakdown region.

The magnitude of the avalanche breakdown voltage increases with increase in temperature. As the temperature increases, the amplitude of vibration of crystal atoms increases. Consequently, there will be loss of energy of the carriers and therefore, the applied reverse voltage should be increased to make up the loss of energy and to start avalanche process.

2) Zener Breakdown: The second effect known as Zener breakdown, occurs in junctions which are heavily doped and have a very narrow depletion region, of the orderofonly$150\ to\ 200$ .Thus,thereexistsahighelectricfield,oftheorderof$10^8\ V\,m^{-1}$, across the junction. This field is strong enough to break or rupture the covalent bonds thereby generating electron-hole pairs. Even a small further increase in reverse voltage is capable of producing large number of current carriers. Zener breakdown is, thus, a field emission phenomenon, the strong electric field in the junction region pulling carriers from their atoms.

In order to study the effect of temperature on breakdown phenomenon, we see that an increase in temperature increases the energy of the valence electrons and hence makes it easier for these electrons to escape from the covalent bonds. Less applied voltage is, therefore, required to pull these electrons from their positions in the crystal lattice and convert them into conduction electrons. Then Zener breakdown voltage, therefore, decreases with an increase in temperature.

Zener Diode:

Zener diode is an ordinary PN Junction diode except that it is properly doped to have a very sharp and almost vertical breakdown. They are exclusively operated under reverse bias conditions and designed to operate in breakdown region without damage.

Zener diode primarily depend for their working on **Zener effect**. For a heavily doped diode, the depletion layer is very narrow. When the reverse bias across the diode is increased, *breaking of covalent bonds take place by the intense electric field* $\left(\approx 3 \times 10^{7}\ V\,m^{-1}\right)$ set up across the depletion layer. It produces a large number of electron-hole pairs resulting in a sharp increase in reverse current.

Circuit Symbol:

The circuit symbol for a Zener diode is shown in fig (01). It is similar to that of an ordinary diode except that the bar is turned into Z – shape.

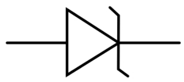


Fig (01)

I – V Characteristics of Zener Diode:

Typical current-voltage characteristics of Zener diode is shown in fig (02). It may be seen from the characteristics that, when forward biased, its characteristics are just those of an ordinary semi-conductor diode. When reverse biased, a small reverse saturation current flows through it which remains approximately constant until a certain critical voltage, called breakdown voltage, is reached. Beyond this voltage, the reverse current I_R increases sharply to a high value.

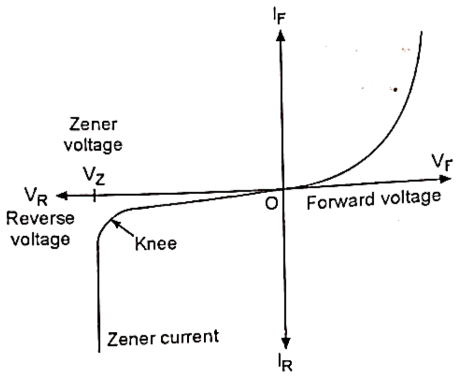


Fig (02)

This break down voltage V_Z is called **Zener voltage** and the reverse current is Zener current. The Zener voltage depends upon the amount of doping. A heavily doped diode has a narrow depletion layer and consequently a lower breakdown or Zener voltage. On the other hand, if the diode is lightly doped, the breakdown of the junction will occur at higher voltage. For breakdown voltages below 6 volt, the Zener effect is predominant. For higher voltages, the avalanche multiplication is effective. Between $5\ and\ 8\ volt$ both effects are present. But, ordinarily, all diodes which are operated in the breakdown region their reverse characteristics are called **Zener Diodes**.

Applications: When a Zener diode is operated in the breakdown region, the voltage across the diode remains almost constant (equal to V_Z) for large change of reverse current. The voltage across a Zener diode thus serves as reference and the diode is used as a voltage reference device for stabilizing a voltage at a predetermined value.

Due to this property, Zener diodes find numerous applications in transistor circuitry. Most important of them are:

1. as voltage regulators
2. as a fixed reference voltage in a network for biasing and comparison
3. for calibrating voltmeters
4. for avoiding meter damage by accidental application of excessive voltage.

Zener Diode as Voltage Regulator:

When a Zener diode is operated in the breakdown region, the voltage across the diode remains almost constant (equal to V_Z) for the large change of the reverse current. The voltage across a Zener diode thus serves as a reference and the diode is used as a voltage reference device for stabilizing a voltage at a predetermined value.

Circuit Diagram:

A simple Zener diode stabilizer circuit is shown in figure. This circuit is used to maintain constant voltage across a load resistor R_L inspite of variations in either the supply voltage or the load current (due to a change in the load resistance) or both.

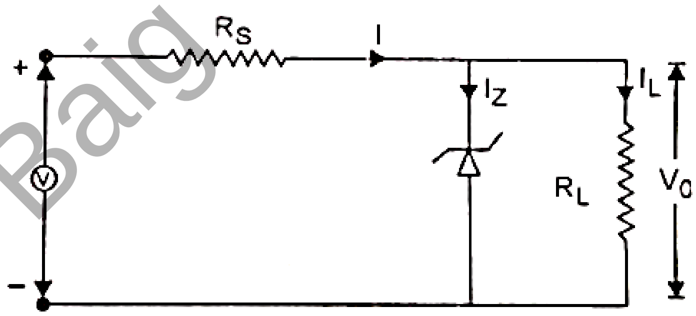


Fig (02)

In this circuit, the input is a d.c. voltage whose voltage variations are to be regulated. The P region of the Zener diode is connected to the negative of the input voltage and N region to the positive. Thus, the Zener diode is reverse biased. The value of the series resistor R_S is so chosen that initially the diode operates in the breakdown region.

Operation:

Let I be the current drawn from the supply source, I_Z the current through the Zener diode and I_L through the load resistance R_L. Then from Kirchhoff's laws, we get

$$I = I_Z + I_L \quad (01)$$

and $$V_0 = V - IR_S \quad (02)$$

where $$V_0 = I_L R_L \quad (03)$$

Case (01): When supply voltage V remains constant and load resistance R_L varies:

Since, the output voltage V_0 tends to remain constant, then equation (02) gives

$\delta I = 0$ (because V and R_S are constant)

And equation (01) gives

$$\delta I = \delta I_Z + \delta I_L = 0$$

or $\delta I_Z = -\delta I_L$

Thus, *if load resistance increases, when the supply voltage is fixed, the load current decreases and the Zener diode current I_Z increases by an equal amount.* Thus, *the voltage V_0 across the load will tend to remain constant*.

Case (02): When load resistance R_L remains constant and supply voltage V varies:

Since V_0 tends to remains constant, we get from equation (02),

$$\delta V = R_S \cdot \delta I$$

Also equation (03) gives

$\delta I_L = 0$ (because R_L is constant)

Therefore, equation (01) gives

$$\delta I = \delta I_Z$$

Thus, when the supply voltage varies but the load resistance remains constant, *the total current I and the Zener current I_Z change equally to keep the load current constant*. Thus, if total current I decreases by δI, the diode current I_z also decreases by the same amount, so the load current I_L remains constant and the voltage V_0 across the load will tend to remain constant.

10 – Junction Transistor

Syllabus: <u>Junction Transistor</u>: Basics of Bipolar Junction Transistors (BJT), BJT operation, Common Base, Common Emitter and Common Collector Characteristics. Field Effect Transistor (FET) and its characteristics. Transistor as an Amplifier and Oscillator. [06 hour]

Introduction:

Transistor one of the most important semiconductor devices, that can amplify radio and TV signals, was invented by William Shockley in 1951. The term transistor is derived by contracting the words "transfer resistor". The transfer of current here takes place from a low resistance to a high resistance circuit. The transistor created a revolution in the field of electronics leading to other inventions like integrated circuits (ICs), Opto-electronic devices and microprocessors. The transistor is available in several basic forms for a wide variety of applications ranging from implantable heart pacers to digital computers. The basic function of a transistor is to amplify a weak signal used in analogue circuits. It is also used as a switch or a gate in digital circuits. Transistor has replaced vacuum tubes in almost all applications.
Because; transistor has no internal filament, therefore, it requires much less power. Since transistor is a semiconductor device, it can last indefinitely. It is small in size and very light in weight and therefore occupies much less space. It can be operated at comparatively low voltages. Since it produces much less heat, electronic equipment can run of lower internal temperatures. It is mechanically strong and shock proof.

There are two types of transistors:
Unipolar Junction Transistor – the current conduction is only due to one type of charge carriers, majority charge carriers.
Bipolar Junction Transistor – the current conduction is because of both types of charge carriers, holes and electrons. Hence this is called Bipolar Junction Transistor or BJT or very popularly simply called transistor.

"**An electronic device that consists of two pn junctions, formed by sandwiching either p-type or n-type semiconductor between a pair of opposite layers is known as transistor**".

The junction transistor is a three layer (terminal) device, consisting of either two p- and one n-type regions or two n- and one p-type regions. The former is called a p-n-p transistor, while the latter is called the n-p-n transistor. Thus, there are two types of transistors.

Transistor Construction:

Fig (01): n-p-n Transistor

Fig (02): p-n-p Transistor

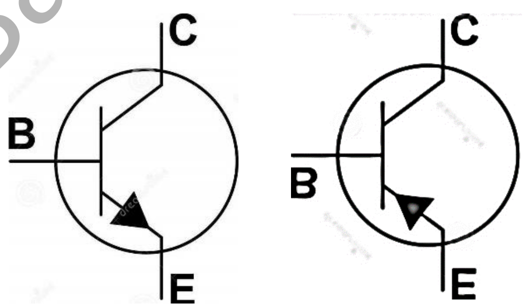
A transistor has, essentially, three regions known as emitter, base and collector. All these three regions are provided with terminals, which are labeled as E (for emitter), B (for base) and C (for collector) respectively are briefly described as follows:

Emitter: It is a region situated on one side of transistor, which supplies charge carriers (i.e., electrons or holes) to other two regions. The emitter is heavily doped region.

Base: It is the middle region that forms two p-n junctions in the transistor. The base of the transistor is thin, as compared to the emitter and is lightly doped region.

Collector: It is a region situated on the other side of transistor (i.e., the region opposite to the emitter), which collects charge carriers (i.e., electrons or holes). The collector of a transistor is always larger than the emitter and base of the transistor. The doping level of the collector is intermediate between the heavy doping of emitter and the light doping of the base.

As a matter of fact, the transistor has two pn junctions J_E and J_C as shown in fig (01) and fig (02). The junction J_E is a junction between emitter and base regions. Thus it is known as emitter-base junction. Similarly, the junction J_C is a junction between collector and base regions. Thus it is called collector-base junction. The circuit symbols of n-p-n transistor and p-n-p transistor are shown in the following figure.



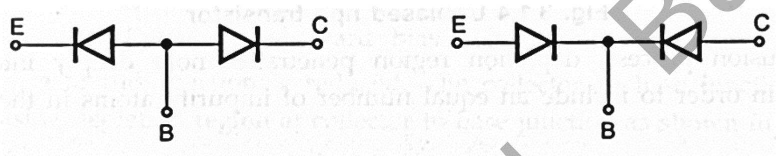
n-p-n Transistor p-n-p Transistor

The transistor symbol carries an arrow head in the emitter pointing from n-region towards the p-region. The arrowhead indicates the direction of a conventional current flow in a transistor.

Transistor Biasing: "The application of suitable dc voltages, across the transistor terminals, is called biasing".

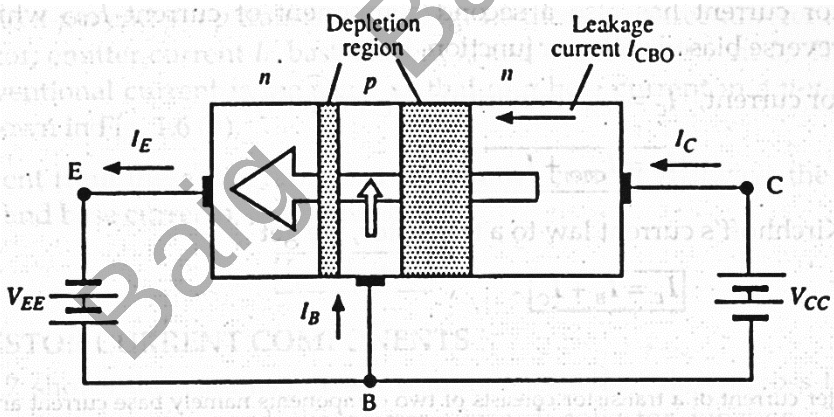
For normal operation of a transistor the following two rules are to be followed:
The emitter-base junction is forward biased so that the junction offers a low resistance to the flow of current.
The collector-base junction is reverse biased so that the junction offers a high resistance to the flow of current.

Note: The transistor has two pn junctions i.e., it is like two diodes. The junction between emitter and base may be called emitter-base diode or simply emitter diode. The junction between the base and the collector may be called collector-base diode or simply collector diode. Therefore the transistor is also treated as two diodes connected back to back as shown in the following figure.



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

Operation of NPN transistor:



The basic connection of an n-p-n transistor is shown in above figure. The emitter-base junction is forward biased by the voltage V_{EE} and the collector-base junction is reverse biased by the source V_{CC}.

The dc voltage source V_{EE} is switched on and the collector is unbiased. The voltage source V_{EE} forward biases the emitter-base junction and thereby the depletion region width gets reduced. The majority charge carriers (electrons) from the emitter diffuse into the base and the majority charge carriers (holes) from the base diffuse into the emitter. This constitutes the emitter current (I_E).

When the voltage source V_{CC} is switched on and the emitter region is unbiased, the width of the depletion region at the base-collector junction increases. Hence, there is no flow of majority carriers. But there is a leakage current (I_{CBO}) due to thermally generated minority charge carriers. This current is called the **reverse saturation current** or **collector leakage current** and is temperature dependent.

When both the voltage sources are switched on, the voltage source V_{EE} is greater than the barrier potential (V_B=0.7 V for Si and V_B=0.3V for Ge), a large number of electrons, say x in the emitter and the holes, y in the base will diffuse across the forward biased emitter-base junction. Hence the total current flowing across the junction is the sum of electron diffusion current and hole diffusion current. This total current is called the emitter current $\left(I_E\right)$.

$$Emitter current\ I_E = I_n\left(x\right) + I_p\left(y\right)$$

These majority electrons after reaching the base region, tend to combine with the holes. First the base is lightly doped and therefore free electrons have a long lifetime in the base region. Second, the base is very thin. This also gives the electrons a better chance of reaching the collector. In practice, about 2% $\left(x - y\right)$ of free electrons recombine with the holes in the base region and then as valence electrons they will flow towards the source V_{EE}. This constitutes the base current $\left(I_B\right)$. Hence, the magnitude of the base current is very small and is of the order of microampere.

$$Base current\ I_B = I_P\left(x+y\right)$$

Almost all the free electrons 98% go into the collector. Once they are in the collector, they are attracted by V_{CC} source voltage. This current is called collector current $\left(I_C\right)$ which is almost equal to the emitter current I_E

The collector current has also a second component of current I_{CBO} which flows through a reverse biased collector junction. Hence,

$$Collector current\ I_C = I_{CBO}\left(minority\right) + I_C\left(majority\right)$$

$$I_C = I_{CBO} + I\left(x\text{-}y\right)$$

Applying Kirchhoff's current law to a transistor, we get

$$\boxed{I_E = I_B + I_C}$$

Note:

The emitter current of a transistor consists of two components namely base current and collector current.

The base current is very small fraction of emitter current i.e., about 2% of the emitter current and collector current is about 98% of the emitter current.

The collector current is mainly due to injected electrons (majority charge carriers) from the emitter. The collector current also has a second component due to thermally generated minority charge carriers, called reverse saturation current.

Emitter-base junction is always forward biased and collector-base junction is always reverse biased.

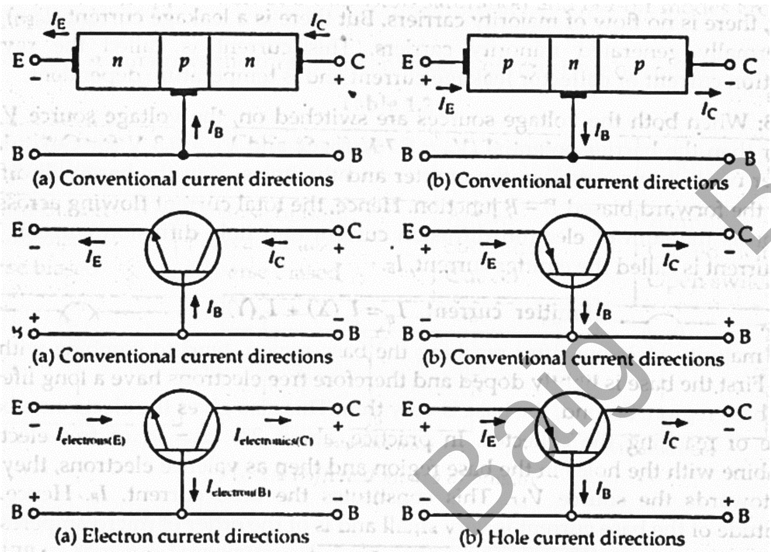
There are three configurations in which a transistor is connected in a circuit. They are:

1) Common Base Configuration: This is also called grounded base configuration because in this configuration the emitter is the input terminal, the collector is the output terminal and the base is the common terminal.

2) Common Emitter Configuration: This is also called grounded emitter configuration because in this configuration the base is the input terminal, the collector is the output terminal and the emitter is the common terminal.

3) Common Collector Configuration: This is also called grounded collector configuration because in this configuration the base is the input terminal, the emitter is the output terminal and the collector is the common terminal.

Transistor Currents:



We know that the direction of a conventional current is always opposite to the electron current. The above figure shows the direction of conventional and electron currents in n-p-n and p-n-p transistors. In above figure there are three different currents in a transistor, emitter current I_E, base current I_B and collector current I_C. The direction of a conventional current is the same as that of a hole current in a p-n-p transistor and is shown the above figure.

It is evident from these diagrams that the emitter current is always the sum of the collector and base currents. Mathematically,

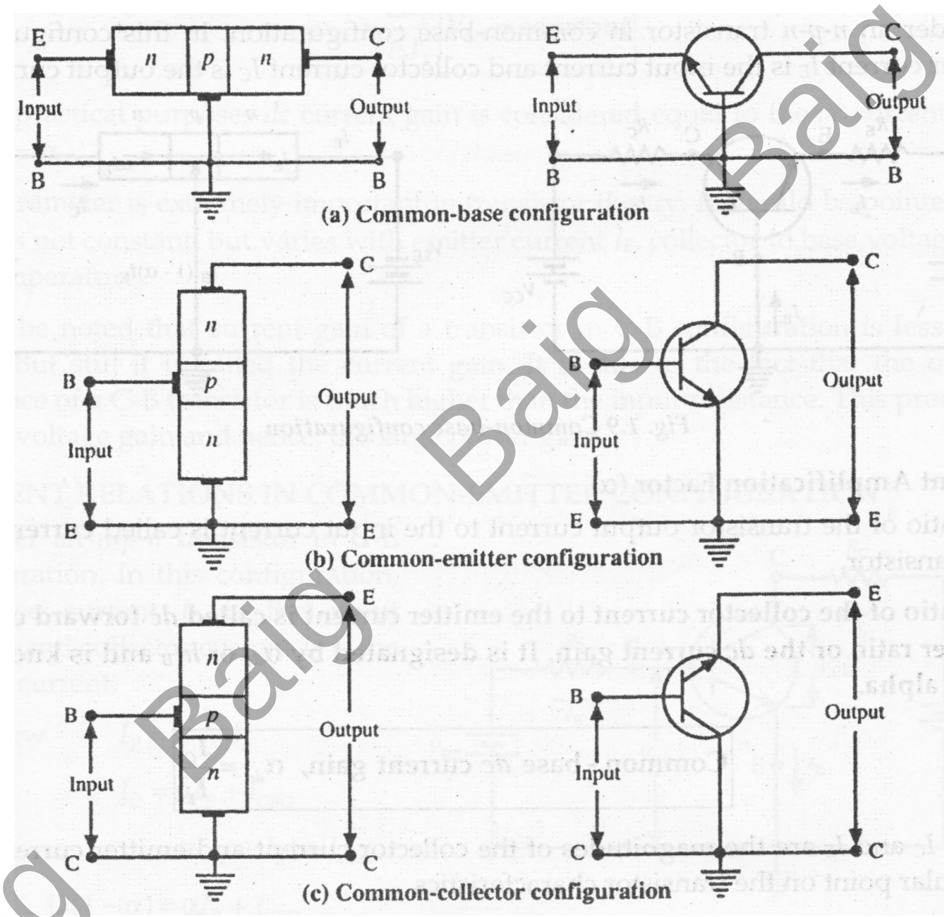
$$I_E = I_B + I_C$$

Transistor Circuit Configurations: When transistors are used in practical circuits such as amplifiers, oscillators etc., we require four terminals, two for the input port and two for the output port. Since the transistor has only three terminals, this difficulty is overcome by making one terminal common for the input and output ports. The input is applied between the common terminal and one of the other two terminals. The output is taken between the common terminal and remaining terminal.

The term “common” denote the region that is common to the input and output circuits. Accordingly, a transistor can be connected in the following three different configurations:

Common Base (CB) Configuration or Mode [see fig (a)]
Common Emitter (CE) Configuration or Mode [see fig (b)]
Common Collector (CC) Configuration or Mode [see fig (c)]

It may be noted that each circuit configuration has its own specific advantages and disadvantages. However, regardless of the type of connection, the emitter-base junction is always forward biased and collector-base junction is always reverse biased, when used as an amplifier. Three configurations with n-p-n transistors are shown in the following figure.



Current gain in CB mode: “It is the ratio of change in collector current (ΔI_C) to the change in emitter current (ΔI_E) when collector-base voltage (V_{CB}) is kept constant” i.e.

$$\alpha = \left.\frac{\Delta I_C}{\Delta I_E}\right|_{V_{CB} = constant}$$

Current gain in CE mode: "It is the ratio of change in collector current (ΔI_c) to the change in base current (ΔI_B) when collector-emitter voltage (V_{CE}) is kept constant" i.e.,

$$\beta = \left.\frac{\Delta I_C}{\Delta I_B}\right|_{V_{CE}=constant}$$

Current gain in CC mode: "It is the ratio of change in emitter current (ΔI_E) to the change in base current (ΔI_B) when emitter-collector voltage (V_{EC}) is kept constant" i.e.,

$$\gamma = \left.\frac{\Delta I_E}{\Delta I_B}\right|_{V_{EC}=constant}$$

Relation between α, β & γ:

We know that $\beta = \frac{\Delta I_C}{\Delta I_B} = \frac{\Delta I_C}{\Delta I_E - \Delta I_C}$ $\quad \because \Delta I_E = \Delta I_B + \Delta I_C$

or $\beta = \frac{\Delta I_C/\Delta I_E}{\Delta I_E/\Delta I_E - \Delta I_C/\Delta I_E}$ or $\boxed{\beta = \frac{\alpha}{1-\alpha}}$

Further $\gamma = \frac{\Delta I_E}{\Delta I_B} = \frac{\Delta I_E}{\Delta I_E - \Delta I_C} = \frac{\Delta I_E/\Delta I_E}{\Delta I_E/\Delta I_E - \Delta I_C/\Delta I_E}$

$\boxed{\gamma = \frac{1}{1-\alpha} = 1+\beta}$ or $\boxed{\beta = \alpha\gamma}$

Further collector current is given by

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

or $I_C = \alpha(I_B + I_C) + I_{CBO}$

or $(1-\alpha) I_C = \alpha I_B + I_{CBO}$

or $I_C = \frac{\alpha}{(1-\alpha)} I_B + \frac{I_{CBO}}{(1-\alpha)}$

$$\boxed{I_C = \beta I_B + (1+\beta) I_{CBO}}$$

A) Common Base Characteristics of a Transistor:

In this configuration input is applied between emitter and base, and output is taken from collector and base. Here, base of the transistor is common to both, input and output circuits, and hence the name common base configuration. Common base configurations for both n-p-n and p-n-p transistors are shown in figures (1A) and (1B) respectively.

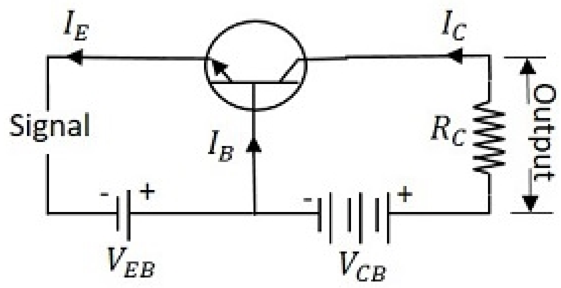


Fig (1A): n-p-n transistor

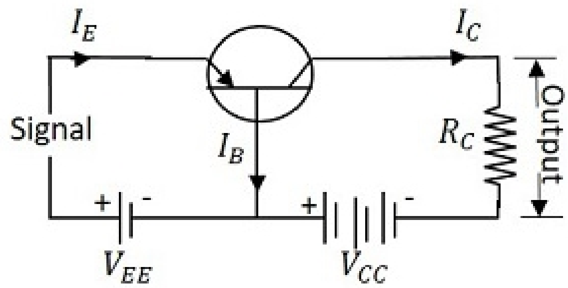


Fig (1B): p-n-p transistor

The input voltage in the CB configuration is the emitter-base voltage V_{EB} and the output voltage is the collector-base voltage V_{CB}. The input current is emitter current I_E and output current is the collector current I_C.

1) Input Characteristics:

"Input characteristics of a transistor in general is a graph or a curve which shows the relation between input current and input voltage when output voltage is kept constant".

"Input characteristics of a transistor in common base configuration is a graph or a curve which shows the relation between the emitter current I_E and the emitter-base voltage V_{EB} when the collector-base voltage V_{CB} is kept constant".

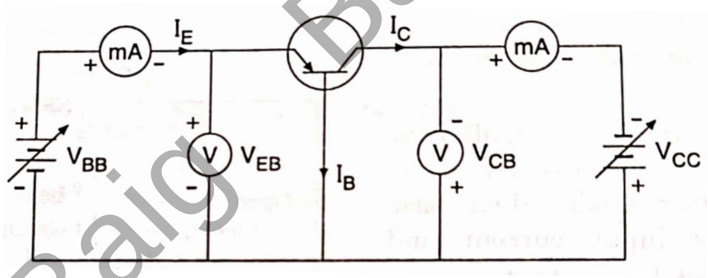


Fig (02)

Fig (02) shows the circuit arrangement of a CB circuit for obtaining the input, output and transfer characteristics of a PNP transistor. Emitter-base junction is forward biased by connecting the emitter to the positive terminal of a variable battery V_{BB} whose negative terminal is connected to base. The emitter base voltage V_{EB} is read by a voltmeter and the emitter current I_E by a milliammeter. The collector-base circuit is reverse biased by connecting the collector to the negative terminal of the battery V_{CC} whose positive terminal is connected to the base. The collector current I_C is read by another milliammeter.

To obtain the input characteristics, collector-base voltage V_{CB} is kept constant at a suitable value. The emitter-base voltage V_{EB} is now varied in small steps and the corresponding emitter current I_E is noted each time. A curve is then plotted between V_{EB} and I_E as shown in fig (03). A number of these characteristic curves are obtained for various collector-base voltages V_{CB}. It may be seen that these curves resemble very much with the forward biased characteristics of PN junction diode and is shown by the curve marked V_{CB} open.

A close look at these curves reveals the following facts:

1. The emitter current I_E increases rapidly with increasing values of emitter-base voltage V_{EB}. It means the input resistance $\left[r_i = \left(\frac{\Delta V_{EB}}{\Delta I_E}\right)_{V_{CB}}\right]$ is very small.
2. As the collect-base voltage ΔV_{CB} is made more negative, more holes are attracted by the collector and hence emitter current I_E rises more rapidly.
3. **2) Output Characteristics:**
4. "Output characteristics of a transistor in general is a graph or a curve which shows the relation between output current and output voltage when input current is kept constant".
5. "Output characteristics of a transistor in common base configuration is a graph or a curve which shows the relation between the collector current I_C and the collector-base voltage V_{CB} when the emitter current I_E is kept constant".
6. Again the circuit shown in fig (02) is used to obtain the output characteristics of the transistor in common base configuration. Here the emitter current I_E is adjusted to a suitable value and the collector current I_C is noted as a function of collector-base voltage V_{CB}. Similar observations are repeated for different settings of emitter current I_E. A graph is plotted between collector current I_C and collector-base voltage V_{CB} by fixing emitter current I_E at different values (say 1, 2, 3, 4, 5 mA) as shown in fig (04).

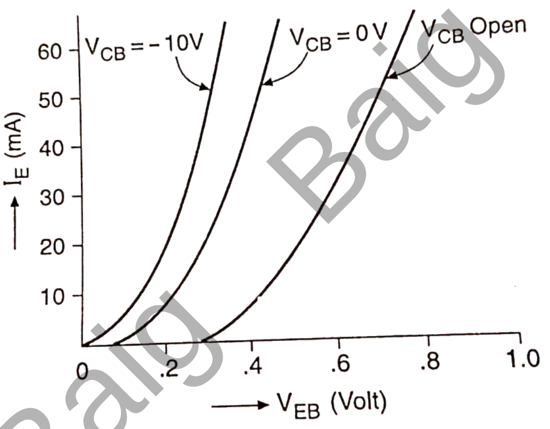


Fig (03)

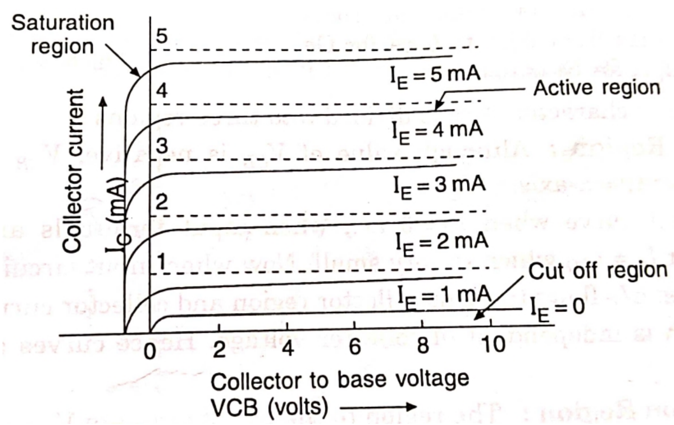


Fig (04)

A close look at these curves reveals the following facts:

1. As the collector-base voltage is made more negative (collector is reverse biased) starting from zero, there is a rapid and constant increase in the collector current I_C for low voltages. Thus entire variation in collector current takes place at very low values of collector voltage.

2. There exists a well defined knee above which the collector current I_C is almost independent of the collector-base voltage V_{CB} and depends only upon emitter current I_E.
3. A very large change in the collector-base voltage V_{CB} produces only a small change in the collector current I_C. It means that the output resistance is $\left[r_o = \left(\frac{\Delta V_{CB}}{\Delta I_C}\right)_{I_E}\right]$ is very large.
4. The collector current I_C is always a little less that the corresponding emitter current I_E due to a small percentage of the charge carries being lost in the base due to electron-hole recombination.
5. The collector current I_C does not become zero when the collector-base voltage V_{CB} becomes zero for any value of the emitter current, but is very small. It is called **leakage current** I_{CBO}. The subscript CBO stands of current from collector to base with emitter open. It is due to the thermally generated minority charge carriers for which collector base junction is forward biased (while it is reverse biased for majority charge carriers). This current flows even when emitter is disconnected from its DC supply as shown in fig (05). It flows in the same direction as the collector current of majority carriers. It is extremely temperature dependent and doubles for every $10^0\,C$ rise in temperature for Ge and $6^0\,C$ for Si. Its value at room temperature varies from $2\,\mu A\ to\ 5\mu A$ for Ge and $0.1\,\mu A\ to\ 1\mu A$ for Si transistor.

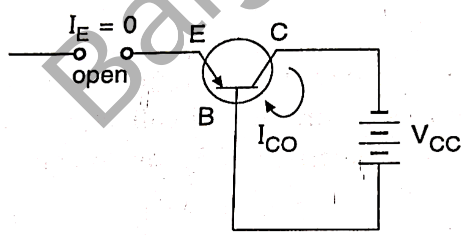


Fig (05)

The family of characteristics is divided into three regions;

1. **Active Region:** Although value of V_{CB} is negative, V_{CB} is generally plotted along positive x-axis.
   For the first curve when $I_E = 0$ i.e., when input terminals are open, the collector current $I_C = I_{CBO}$ which is very small. Now when input current is made on and I_E flows, the $\alpha\, I_E$ flows towards collector region and collector current becomes $\left(\alpha\, I_E + I_{CBO}\right)$ which is independent of collector voltage. Hence curves appear to be practically flat.
2. **Saturation Region:** The region to the left of the ordinate $V_{CB} = 0$ and above $I_E = 0$ characteristics is called saturation region. Here both emitter and collector junctions are forward biased. Thus, forward biasing of collector is responsible for large change in collector current I_C for a small change in V_{CB} and I_C increases exponentially with voltage.
3. **Cut-off Region:** The characteristic for $I_E = 0$ is similar to other characteristics but passes through origin. It does not coincide with X-axis (voltage axis) but there is a small gap between the characteristic and the voltage axis. The region

below $I_E = 0$ characteristic, for which both emitter and collector junctions are reverse biased, is called cut-off region.

3) Transfer Characteristics:

"Transfer characteristics of a transistor in general is a graph or a curve which shows the relation between input current and output current when output voltage is kept constant".

"Transfer characteristics of a transistor in common base configuration is a graph or a curve which shows the relation between collector current I_C and emitter current I_E when collector base voltage (V_{CB}) is kept constant".

In order to obtain the transfer characteristics of the transistor in common base configuration, adjust the collector supply voltage V_{CC} to set V_{CB} at a fixed value, say 4 V. Increase emitter current I_E in steps of 1 mA and record the corresponding collector current I_C. Make sure that collector-base current V_{CB} remains constant.
Continue increasing emitter current I_E till we get sufficient readings to plot a graph.
Plot the graph of collector current I_C versus emitter current I_E as shown in figure (06).

The transfer characteristics is nearly linear.

The forward current transfer ration or current gain in common emitter configuration is given by

$$\alpha = \left|\frac{\Delta I_C}{\Delta I_E}\right|_{V_{CB} = Constant}$$

The typical value of α is always close to but less than 1.

Fig (06)

Typical properties of CB Configuration:

1) Current gain of transistor in C-B mode is less than unity.
2) Voltage gain of transistor in C-B mode is large.
3) Power gain of transistor in C-B mode is moderate.
4) The input impedance of transistor in C-B mode is lowest.
5) The output impedance of transistor in C-B mode is highest.
6) Since the input and output voltages are in phase i.e., $\boldsymbol{E} = 0^0$.

B) Common Emitter Characteristics of a Transistor:

In this configuration input is applied between base and emitter, and output is taken from collector and emitter. Here, emitter of the transistor is common to both, input and output circuits, and hence the name common emitter configuration. Common emitter configurations for both n-p-n and p-n-p transistors are shown in figures (1A) and (1B) respectively.

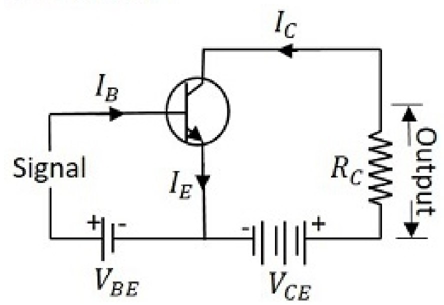


Fig (1A): n-p-n transistor

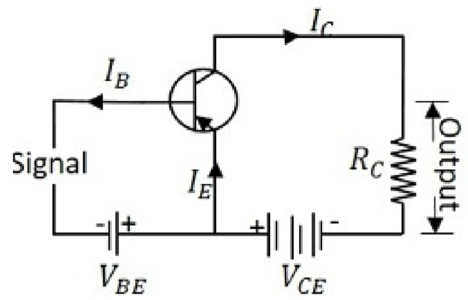


Fig (1B): p-n-p transistor

The input voltage in the CE configuration is the base-emitter voltage V_{BE} and the output voltage is the collector-emitter voltage V_{CE}. The input current is emitter current I_B and output current is the collector current I_C.

1) Input Characteristics:

"Input characteristics of a transistor in general is a graph or a curve which shows the relation between input current and input voltage when output voltage is kept constant".

"Input characteristics of a transistor in common emitter configuration is a graph or a curve which shows the relation between the base current I_B and the base-emitter voltage V_{BE} when the collector-emitter voltage V_{CE} is kept constant".

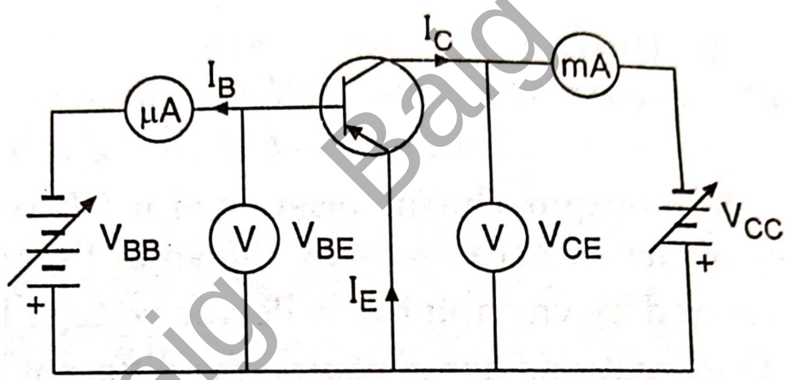


Fig (02)

Fig (02) shows the circuit arrangement of a CE circuit for obtaining the input, output and transfer characteristics of a PNP transistor. Emitter-base junction is forward biased by connecting the emitter to the positive terminal of a variable battery V_{BB} whose negative terminal is connected to base. The base-emitter voltage V_{BE} is read by a voltmeter and the base current I_B by a microammeter. The collector-emitter circuit is reverse biased by connecting the collector to the negative terminal of the battery V_{CC} whose positive terminal is connected to the emitter. The collector current I_C is read by another milliammeter.

To obtain the input characteristics, collector-emitter voltage V_{CE} is kept constant at a suitable value. The base-emitter voltage V_{BE} is now varied in small steps and the corresponding base current I_B is noted each time. A curve is then plotted between V_{BE} and I_B as shown in fig (03). A number of these characteristic curves are obtained for various collector-emitter voltages V_{CE}.

A study of these curves reveals the following facts:

1. The characteristics resemble with those of a forward biased junction diode because the base-emitter section of transistor is a junction diode and it is forward biased.
2. The base current increases non-linearly with increase in base voltage.
3. The base current I_B increases less rapidly with increasing values of base-emitter voltage V_{BE}. It means the input resistance $\left[r_i = \left(\frac{\Delta V_{BE}}{\Delta I_B}\right)_{V_{CE}}\right]$ of a CE circuit is higher as compared to that in CB configuration.
4. Input characteristics are only slightly dependent upon the collector to emitter voltage V_{CE}.

2) Output Characteristics:

"Output characteristics of a transistor in general is a graph or a curve which shows the relation between output current and output voltage when input current is kept constant".

"Output characteristics of a transistor in common emitter configuration is a graph or a curve which shows the relation between the collector current I_C and the collector-emitter voltage V_{CE} when the base current I_B is kept constant".

Again, the circuit shown in fig (02) is used to obtain the output characteristics of the transistor in common base configuration. Here the base current I_B is adjusted to a suitable value and the collector current I_C is noted as a function of collector-emitter voltage V_{CE}. Similar observations are repeated for different settings of base current I_B. A graph is plotted between collector current I_C and collector-emitter voltage V_{CE} by fixing base current I_B at different values (say 10, 20, 30, 40, 50 µA) as shown in fig (04).

A study of these curves reveals the following facts:

1. The collector current I_C varies rapidly with V_{CE} for very small voltage (say upto $V_{CE} = 2\ volt$). After this collector current becomes almost constant and is decided entirely by base current I_B. It then becomes independent of V_{CE}.
2. Collector voltage has only a minute effect on the collector current for low values of base current. But as the base current rises, the effect of collector voltage on collector current also increases.
3. The collector current I_C is not zero when base current is zero. This is due to the inherent intrinsic conduction in semiconductors, i.e., due to minority charge carries.
4. Since the input current I_B is measured in microampere and output current I_C is measured in milliampere, the common emitter configuration exhibits a current amplification $\beta = \left(\frac{\Delta I_C}{\Delta I_B}\right)_{V_{CE}}$

Thus, small input current I_B produces a large output current I_C or in other words, the collector current is β times greater than the base current.

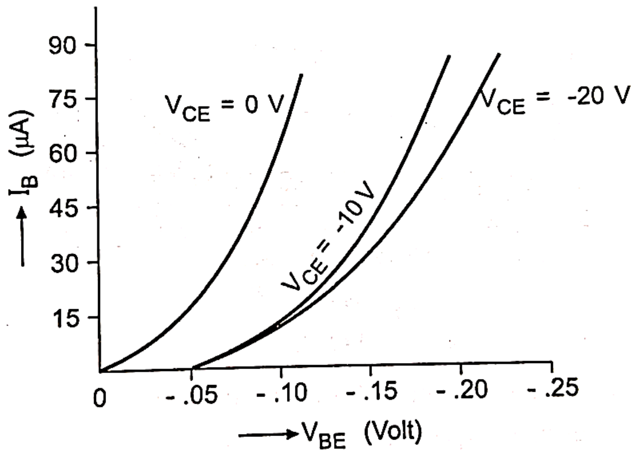


Fig (03)

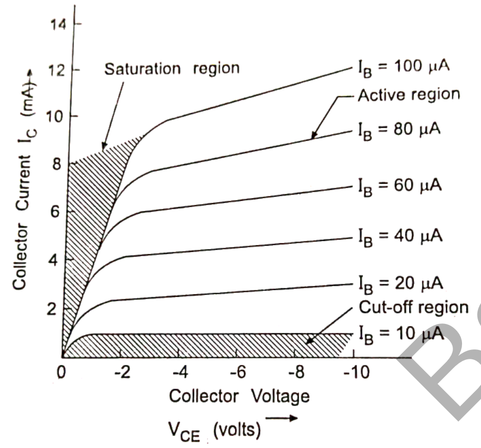


Fig (04)

Just like common base configuration, the family of curves is divided into three regions;

1. **Active Region:** When emitter junction is forward biased and collector junction is reverse biased, then in fig (04), the area above the $I_B = 0$ and the right of ordinate V_{CE} = a few tenth of volt, is known as active region. For a given value of I_B, emitter injects certain charge carriers into base region. When collector-emitter voltage V_{CE} is small, the collector is unable to collect all charge carriers. Therefore, when V_{CE} is increased, collect current I_C first increases rapidly and then rate of increase is quite small.
2. **Saturation Region:** Referring to fig (04), the region very close to the zero-voltage axis where all the curves, merge and fall rapidly towards origin, is known as saturation region. In this region, both the collector junction as well as the emitter junction are forward biased.
3. **Cut-off Region:** The characteristics for $I_B = 0$ passes through origin but there is appreciable gap between X-axis and the curve for $I_B = 0$. Thus, appreciable collector current exists under the conditions. This current I_{CEO} is known as reverse biased saturation current and the area under $I_B = 0$ and X-axis is known as cut-off region.

Since I_C is not zero when $I_B = 0$, there is a **leakage current** from collect to emitter with base open. It has been shown in fig (05) for a common emitter circuit of NPN transistor whose base lead is open.

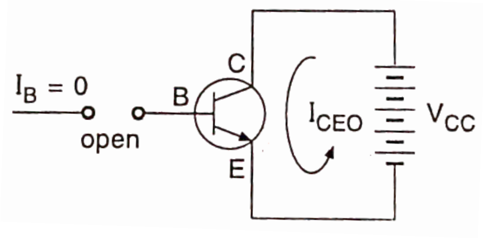


Fig (05)

Taking leakage current into account

$$I_C = \beta\, I_B + I_{CEO} = \beta\, I_B + (1 + \beta)\, I_{CBO}$$

$$I_C = \beta\, I_B + \left(\frac{1}{1-\alpha}\right) I_{CBO}$$

$$I_C = \left(\frac{\alpha}{1-\alpha}\right) I_B + \left(\frac{1}{1-\alpha}\right) I_{CBO}$$

But $\beta\, I_B = \alpha\, I_E$

∴ $I_C = \alpha\, I_E + I_{CEO}$

Also $I_B = I_E - I_C$

$I_B = I_E - \left(\alpha\, I_E + I_{CEO}\right)$

$$\boldsymbol{I_B = (1-\alpha)\, I_E - I_{CEO}}$$

3) Transfer Characteristics:

"Transfer characteristics of a transistor in general is a graph or a curve which shows the relation between input current and output current when output voltage is kept constant".

"Transfer characteristics of a transistor in common emitter configuration is a graph or a curve which shows the relation between collector current and base current when collector emitter voltage $\left(V_{CE}\right)$ is kept constant".

In order to obtain the transfer characteristics the collector supply voltage V_{CC} to set V_{CE} at a fixed value, say 4 V. Increase I_B in steps of 10 μA and measure I_C. Be sure that base current V_{CE} remains constant. Continue increasing I_B till we get sufficient readings to plot a graph. Plot the graph of I_C versus I_B as shown in figure (06).

The transfer characteristics is nearly linear. The forward current transfer ration or current gain in common emitter configuration is given by

$$\beta = \left|\frac{\Delta I_C}{\Delta I_B}\right|_{V_{CE}\ = Constant}$$

The typical value of β may range from 40 to 900. The value for the silicon transistor BC 108 or BC 148 is between 200 to 290.

Fig (06)

Typical properties of CE Configuration:

1) Voltage and current gain of transistor in C-E mode are greater than unity.
2) The input impedance of transistor in C-E mode is low.
3) The output impedance of transistor in C-E mode is high.
4) The transistor in C-E mode can be used as a voltage or power amplifier.
5) Since the input and output voltages are out of phase by 180^0, it can be used as an inverting amplifier with a voltage gain more than unity.

C) Common Collector Characteristics of a Transistor:

In this configuration input is applied between base and collector, and output is taken from emitter and collector. Here, collector of the transistor is common to both, input and output circuits, and hence the name common collector configuration. Common emitter configurations for both n-p-n and p-n-p transistors are shown in figures (1A) and (1B) respectively.

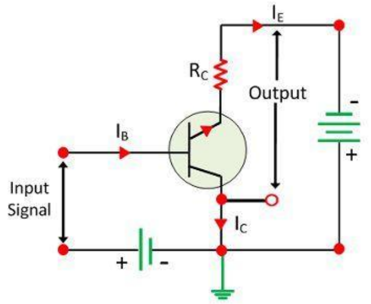


Fig (1A): n-p-n transistor

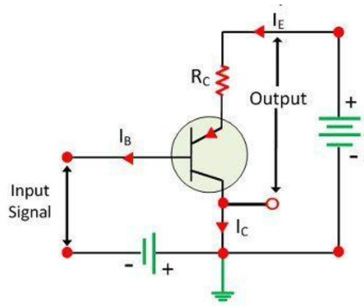


Fig (1B): p-n-p transistor

The input voltage in the CC configuration is the base-collector voltage V_{BC} and the output voltage is the emitter-collector voltage V_{EC}. The input current is base current I_B and output current is the emitter current I_E.

1) Input Characteristics:

"Input characteristics of a transistor in general is a graph or a curve which shows the relation between input current and input voltage when output voltage is kept constant".

"Input characteristics of a transistor in common collector configuration is a graph or a curve which shows the relation between the base current I_B and the base-collector voltage V_{BC} when the emitter-collector voltage V_{EC} is kept constant".

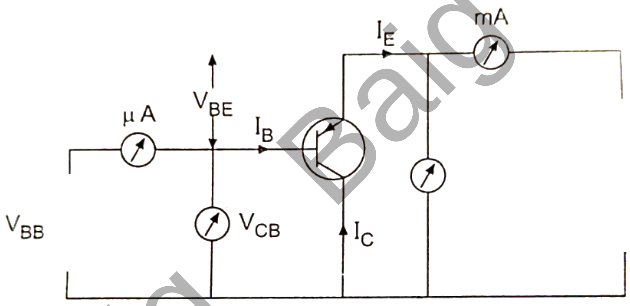


Fig (02)

Fig (02) shows the circuit arrangement of a CC circuit for obtaining the input, output and transfer characteristics of a PNP transistor.

To obtain the input characteristics, emitter-collector voltage V_{EC} is kept constant at a suitable value. The base-collector voltage V_{BC} is now varied in small steps and the corresponding base current I_B is noted each time. A curve is then plotted between V_{BC} and I_B as shown in fig (03). A number of these characteristic curves are obtained for various emitter-collector voltages V_{EC}.

Fig (03) gives a plot of I_B versus V_{BC} for different values of V_{CE}. These characteristics are quite different from those for CB or CE circuits because the input voltage V_{BC} is large determined by the value of V_{EC}, V_{BE} gets decreased, thereby decreasing I_B.

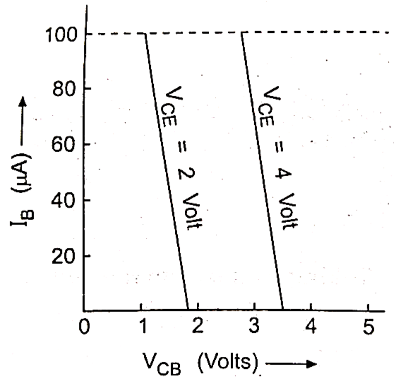


Fig (03)

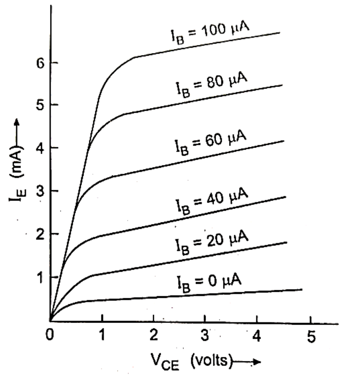


Fig (04)

2) Output Characteristics:

"Output characteristics of a transistor in general is a graph or a curve which shows the relation between output current and output voltage when input current is kept constant".

"Output characteristics of a transistor in common collector configuration is a graph or a curve which shows the relation between the emitter current I_E and the emitter-collector voltage V_{EC} when the base current I_B is kept constant".

Fig (05) gives the plot of I_E versus V_{EC} for several fixed values of I_B. It may be seen that these characteristics are practically identical to that of the CE circuit because $I_C \approx I_E$.

Comparison of CB, CE and CC Configurations:

The important characteristics of three configurations are summarized in the following table:

Sl. No.	Parameters	Type of Configuration		
		CB	CE	CC
1.	Current gain (A_i)	Less than 1	High	Highest
2.	Voltage gain (A_v)	High	Highest	Low (~ 1)
3.	Power gain (A_p)	Moderate	Highest	Low
4.	Phase shift	No (0^o)	180^o	No (0^o)
5.	Input impedance	Lowest	Moderate	Highest
6.	Output impedance	Highest	Moderate	Lowest

Junction Field Effect Transistor (JFET):

Like the bipolar junction transistor, the field effect transistor is also a semiconductor device. But the principle of operation is different. Whereas the bipolar transistor is controlled by current a field effect transistor is controlled by voltage. Further a bipolar transistor depends on both the majority and minority charge carriers for its behaviour. In an FET the current is controlled by the voltages on the terminal called the gate. The current through the gate is the leakage current which has no effect on the controlled output current. Thus current in FET is entirely due to the majority carriers. For this reason an FET is said to be unipolar device.

Types of FETs:

FETs are basically of two types. They are the junction field effect transistor (JFET) and the metal oxide semiconductor field effect transistor (MOSFET). The physical structure as well as the electrical performance of a JFET are different from those of a MOSFET. MOSFETs are of two types viz., enhancement type and depletion type. Doped semiconductors are, as we know, of two types, n-type and p-type. Accordingly each type of FET may be of the n-type or p-type. The following chart shows the classification of FETs.

Principle of operation of FET: The operating principle of a n-channel JFET can be studied with reference to figs (1), (2) and (3).

The n-channel JFET mainly consists of a bar of n-type semiconductor material (silicon), referred to as channel, with terminals at its two ends, marked as D and S. D is called drain and S is called source. Drain is the terminal through which the charge carriers (i.e. electrons in the n-channel FET) leave the channel and source is the terminal through which the charge carriers enter the channel. The channel has two small pieces of p-type material attached to its sides, forming pn junctions. The terminals fixed to these p-type blocks are marked as G, and they are internally connected. They together constitute the gate.

With zero gate voltage, if a voltage is applied across drain and source (D more positive than S), it is seen that electrons which are the majority charge carriers in the n-type channel are attracted towards the positive terminal, and hence they drift towards the drain. This causes a current I_D, called **drain current** to flow in the opposite direction, as shown in fig (1). It can be seen that the electrons leave the channel at D, and enter the channel at S. The magnitude of I_D depends upon the applied voltage V_{GS} and the resistance of the channel.

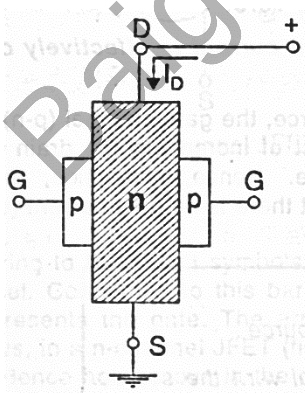


Fig (01)

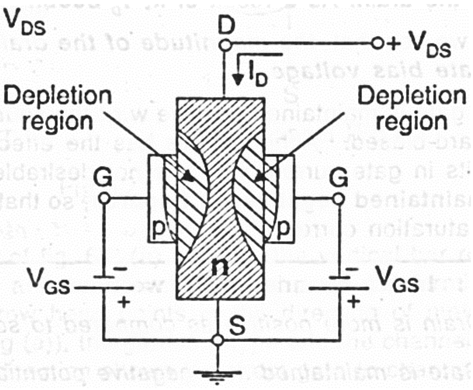


Fig (02)

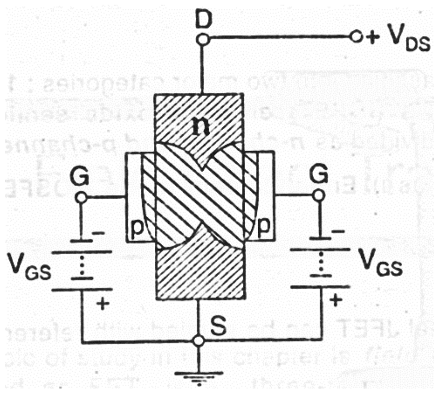


Fig (03)

If a negative voltage V_{GS} is now applied across the gate, and source terminals with polarity as shown in fig (02), it is seen that the gate channel (pn) junction becomes reverse biased. Depletion regions develop across the junctions. Since, in practice, the channel is more lightly doped than the gate, the depletion region regions penetrate deep into the channel. These depletion regions are totally devoid of charge carriers, and hence they act as insulator. The result is that the width of the conducting channel gets reduced. This increases the resistance of the channel, and hence the drain current I_D decreases.

If the gate is made more and more negative with respect to the source (i.e., if V_{GS} is progressively increased), the depletion regions would further extend, thereby reducing progressively the channel width and increasing the channel resistance. The result is that I_D progressively diminishes.

If the negative gate bias is further increased, as in fig (03), the depletion regions meet at the centre of the channel, thus totally blocking the motion of electrons from the source to the drain. As a result of it, I_D becomes zero.

Thus we see that the magnitude of the drain current is effectively controlled by the gate bias voltage.

If the gate is maintained positive with respect to the source, the gate channel (pn) junctions get forward biased. Although this has the effect of increasing the drain current, it also results in gate current which is not desirable. Hence, in practice, the gate is always maintained negative with respect to source, so that there is no gate current (except the reverse saturation current).

Circuit Symbol:

A JFET is symbolically represented as shown in fig (04)

(a) n – Channel FET (b) p – Channel FET

Fig (04)

Referring to the circuit symbol of Fig (4a) and (4b), the vertical bar represents the channel. Connected to this bar are the source (S) and drain (D) terminals. The arrow represents the gate. **The arrow head always points the n-type material.** Thus, in a n-channel FET [Fig(4a)], the gate is p-type and the channel is n-type material. Hence the arrow points the channel. Accordingly, the direction of the arrow is shown in fig (4a). In a p-type JFET, the channel is p-type, hence the arrow points away from channel towards n-type material. Accordingly, the direction of the arrow is shown in fig (4b).

Generally, in a FET, the source and drain terminals are interchangeable. Hence the arrow head is shown as being equidistant from the horizontal bars connecting D and S to the vertical bar. However, as is sometimes the case, the gate may be nearer to the source. In such an event, the FET would be symbolically represented as shown in fig (5).

(a) n – Channel FET (b) p – Channel FET
Fig (05)

Construction of JFET:

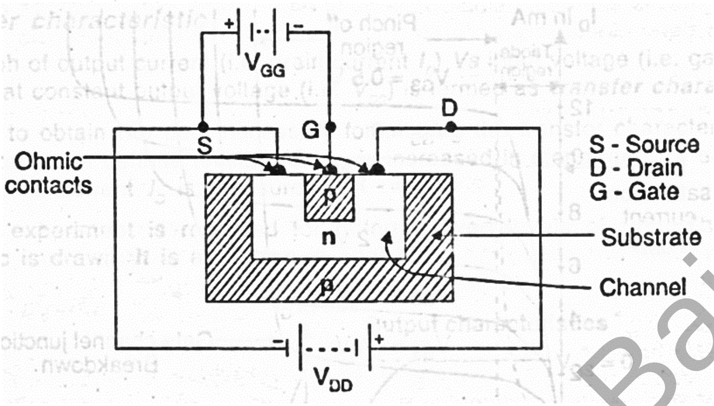


Fig (06)

Fig (06) shows an n-channel FET in section. The device is usually fabricated by the diffusion process. It essentially consists of a n-type epitaxial layer grown on a p-type substrate. The gate which is p-type material is diffused into the n-type channel at its centre in the form of a rectangle. Metal contacts are deposited on the surface as shown, and these are connected to the terminals of the device marked as S, D and G.

Source (S): It is the terminal through which the charge carriers enter the device.

Drain (D): It is the terminal through which the charge carriers leave the device.

Gate (G): It forms a pn junction with the channel. Normally, the gate channel (pn) junction is reverse biased. The drain (D) is maintained at positive potential with respective to the source (S).

As already studied, for a fixed drain to source voltage, the drain current depends upon the gate bias (which is negative). Larger the negative gate bias, smaller the drain current and vice versa. The drain current can be cut off completely by adequately increasing the negative gate bias.

FET Characteristics:

Output Characteristics:

"The graph of drain current $\left(I_D\right)$ versus drain-source voltage V_{DS}, at constant gate-source voltage V_{GS} is termed as ***drain characteristics or output characteristics****"*.

With zero gate voltage $\left(V_{GS} = 0\right)$, the drain-source voltage V_{DS} is gradually increased (drain is made positive with respect to source in the n-channel FET), and drain current I_D is noted for different increasing values of V_{DS}.

A definite negative gate bias is next applied, and the drain currents for different drain-source voltages are noted.

The experiment is repeated for different gate bias voltages like $V_{GS} = -1V, \ -2V, \ -3V, \ \cdots\cdots$

Next, a small positive gate bias, say $V_{GS} = 0.5V$ is applied, and the experiment is done as before.

From the data obtained, a family of drain (or output) characteristics is plotted as shown in fig (07).

A study of drain characteristics would reveal that:

a) **As the negative gate bias increases, drain current decreases for the same drain-source voltage**. This is due to the fact that the reverse bias of the gate channel junction increases, depletion region within the channel widens, thus reducing the channel width and increasing the channel resistance.

b) **The drain current rapidly increases up to the pinch-off point** and then the curve flattens. The drain current does not increase further, even if V_{DS} is increased until break-down of the gate channel junction occurs.

c) **The channel junction break-down voltage reduces with increase in negative gate bias**. This is so because the negative gate voltage $\left(-V_{GS}\right)$ adds to the reverse bias voltage of the junction.

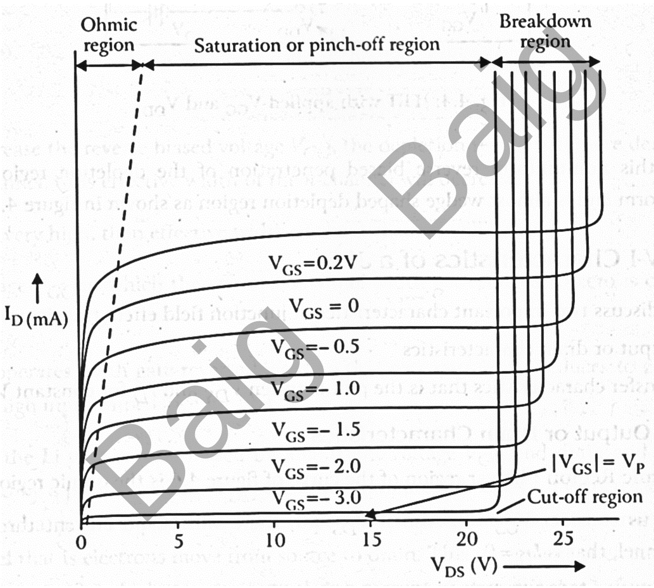


Fig (07)

"The drain-source voltage at which pinch off begins i.e., the curve flattens and there is no further increase of drain current is termed as ***pinch-off voltage****"*. It is seen that pinch off voltage decreases as the negative gate bias increases. This value of I_D in the pinch off region for $V_{GS} = 0$ is termed as **drain saturation current when gate is shorted**. It is denoted by I_{DSS} .

Transfer Characteristics:

"The graph or curve of output current (i.e., drain current) I_D versus input voltage (i.e., gate-source voltage) V_{GS} at constant output voltage (i.e., drain-source voltage) V_{DS} is termed as ***transfer characteristics****"*.

In order to obtain the data necessary for plotting the transfer characteristics, V_{DS} is kept constant at a definite level, and V_{GS} is increased in steps, and for each value of V_{GS}, the drain current I_D is measured.

The experiment is repeated for different fixed levels of V_{DS}. The transfer characteristics is drawn. It is shown in fig (08).

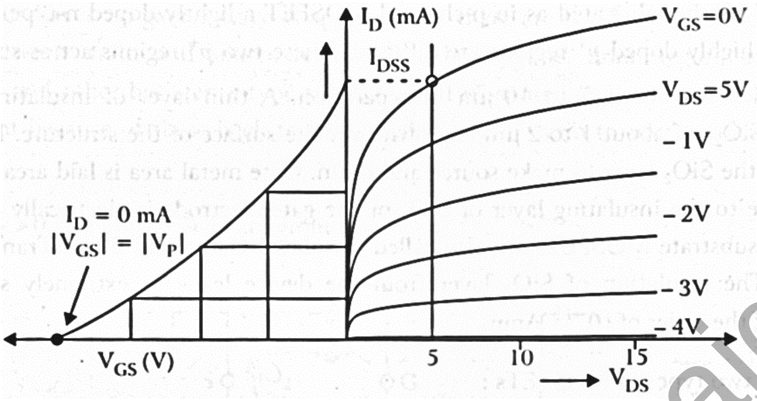


Fig (07)

The transfer characteristics may also be graphically obtained from the drain characteristics as shown in fig (07). The characteristics curves can be obtained for a definite level of V_{DS}.

Shockley's Equation:

The graph of I_D versus V_{GS} can be algebraically represented by the equation

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

where I_{DSS} is the drain-source saturation current at $V_{GS} = 0$ and V_P is the pinch-off voltage.

In the above equation, V_P and I_{DSS} are constant. V_{GS} is the controlling variable, and I_D is the controlled variable. It is easily seen that the relationship between I_D and V_{GS} is non-linear, and the transfer characteristics is as shown in fig (07).

Drain Resistance (r_d):

*"**Drain resistance** is defined as the a.c. resistance measured between the drain and source terminals, when the FET is operating in the pinch-off region".*

By definition, drain resistance is given by the ratio of a small change in V_{DS} to the corresponding change in I_D at constant V_{GS} i.e., the drain resistance r_d is given by

$$r_d = \left.\frac{\Delta V_{DS}}{\Delta I_D}\right|_{at\ constant\ V_{GS}}$$

Referring to the output characteristics of a JFET in fig (07), it is clear that above pinch off voltage, the change in I_D is small for a change in V_{DS} because the curve is almost flat. Therefore, drain resistance of JFET has a large value, ranging from $10\ k\Omega$

to 1 MΩ and cannot be determined very accurately from drain characteristics. r_d is also termed as **output resistance**.

Transconductance (g_m):

"***Transconductance (or mutual conductance)*** *is defined as the ratio of the change in drain current to the change in gate-source voltage which causes it, at constant drain- source voltage*". It is denoted by g_m or g_{fs}. Therefore by definition transconductance g_m is given by $g_m = \left.\frac{\Delta I_D}{\Delta V_{GS}}\right|_{at\ constant\ V_{DS}}$

g_m can be obtained from the transfer characteristics. Since the curve is not linear the value of V_{DS} at which g_m is determined must be specified.

"It is evident that transconductance is a measure of the control which the gate-source voltage has over the magnitude of the drain current".

Amplification Factor (μ):

"***Amplification factor*** *is defined as the ratio of the change in the drain-source voltage to the corresponding change in the gate-source voltage, at constant drain current*". It is denoted by μ. By definition amplification factor μ is given by

$$\mu = \left.\frac{\Delta V_{DS}}{\Delta V_{GS}}\right|_{at\ constant\ I_D}$$

We know that, with increase in V_{DS} at a given V_{GS}, the drain current I_D increases. This increase in I_D can be represented by adequately increasing V_{GS} (which is negative). The I_D can be maintained constant, by increasing both V_{DS} and V_{GS} (negative).

The value of μ range from about 50 to about 150. A large value of μ implies that the gate-source voltage is much effective in controlling the drain current, than the drain-source voltage.

Relation between μ, g_m & r_d:

The three major parameters of a JFET are the a.c. drain resistance r_d, the transconductance g_m and the amplification factor μ. It can be shown that they are inter-related. We know that

$$\mu = \left.\frac{\Delta V_{DS}}{\Delta V_{GS}}\right|_{at\ constant\ I_D} \quad \text{or} \quad \mu = \frac{\Delta V_{DS}}{\Delta I_D} \times \frac{\Delta I_D}{\Delta V_{GS}}$$

But $\frac{\Delta V_{DS}}{\Delta I_D} = r_d$ and $\frac{\Delta I_D}{\Delta V_{GS}} = g_m$ $\quad\therefore\quad$ $\boxed{\mu = r_d \times g_m}$

Applications of JFET:

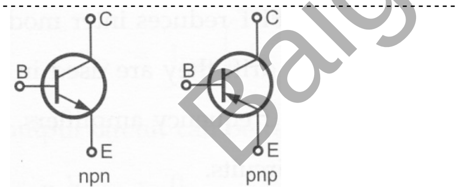
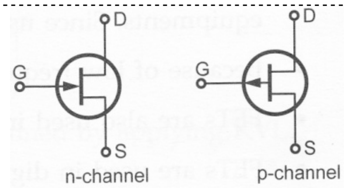
In general, like BJTs the FETs can be used in switch, digital and linear amplifier applications. But some of the specific applications of JFET are mentioned below:

1. Since JFET has high input impedance and low output impedance they are used as a buffer in measuring instruments.

2. Because of low noise, they are used in RF amplifiers in FM tuners and in communication equipments.
3. Since the input capacitance of FET is low, it is used in cascade amplifiers in measuring and testing equipments.
4. FETs are used in mixer circuits in FM and TV receivers, and communication equipments. Since FET reduces inter modulation distortion.
5. Because of low frequency drift they are used in oscillators.
6. FETs are used in low frequency amplifiers.
7. FETs are used in digital circuits.

Comparison between JFET and BJT:

The following table shows some of the important points of comparison between the Junction Field Effect Transistor and Bipolar Junction Transistor.

Sl. No.	Parameter	BJT	FET
1.	Control element	Current controlled device. Input current I_B controls output current I_C	Voltage controlled device. Input voltage V_{GS} controls drain current I_D.
2.	Device Type	Current flows due to both majority and minority carriers and hence **bipolar device**.	Current flows only due to majority carriers and hence **unipolar device**.
3.	Types	n-p-n and p-n-p	n-channel and p-channel
4.	Symbols		
5.	Configurations	CB, CE & CC	CS, CG & CD
6.	Input resistance	Less compared to JFET	High compared to BJT
7.	Size	Bigger than JFET	Smaller in construction than BJT, thus making them useful in integrated circuits (ICs).
8.	Sensitivity	Higher sensitivity to changes in the applied signals.	Less sensitivity to changes in the applied voltage.
9.	Thermal stability	Less	More
10.	Thermal runaway	Exists in BJT, because of cumulative effect of increase in I_C with temperature, resulting in the device.	Does not exist in JFET, because drain resistance r_d increases with temperature, which reduces I_D and hence the temperature of the devices.
11.	Relation between input and output	Linear	Non-linear

12.	Ratio of output to input	$\frac{\Delta I_C}{\Delta I_B} = \beta$	$\frac{\Delta V_{DS}}{\Delta V_{GS}} = \mu$
13.	Thermal noise	More in BJT as more charge carriers cross junctions.	Much lower in JFET as very few charge carriers cross the junction.
14.	Gain bandwidth product	High	Low

Transistor as an amplifier in CE Configuration:

Fig (01) shows the common emitter type n-p-n transistor amplifier circuit. Note that the battery V_{BB} is connected in the input circuit in addition to the signal voltage. This d.c. voltage is known as biasing voltage and its magnitude is such that it always keeps the emitter-base junction forward biased regardless of the polarity of the signal source.

Operation: During the positive half cycle of the signal, the forward bias across the emitter-base junction is increased. Therefore, more electrons flow from the emitter to the collector through the base. This causes an increase in collector current. The increased collector current produces a greater voltage drop across the collector load resistance R_C. However, during the negative half cycle of the signal, the forward bias across emitter-base junction is decreased. Therefore, the collector current decreases. This results in the decreased output voltage (in the opposite direction). Hence, an amplified output is obtained across the load.

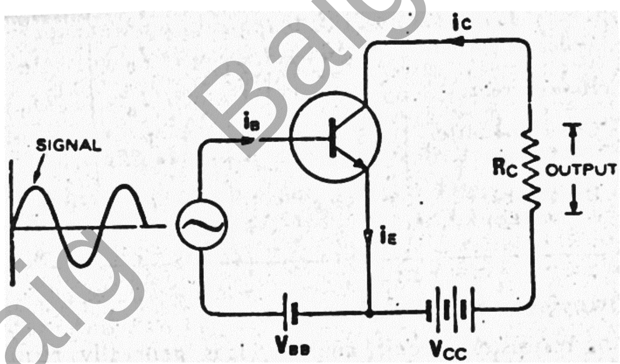


Fig (01)

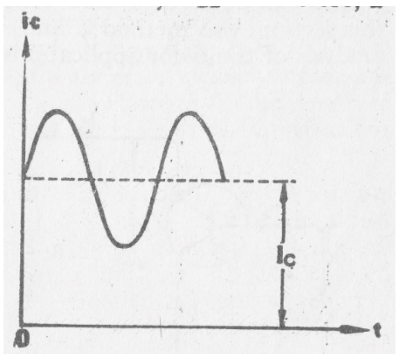


Fig (02)

Analysis of collector current: When no signal is applied, the input circuit is forward biased by the battery V_{BB}. Therefore, a d.c. collector current I_C flows in the collector circuit. This is called *zero signal current*. When the signal voltage is applied, the forward bias on the emitter-base junction increases or decreases depending upon whether the signal is positive or negative. During the positive half cycle of the signal, the forward bias on emitter-base junction is increased, causing total collector current i_C to increase. Reverse will happen for the negative half cycle of the signal.

Fig (02) shows the graph of total collector current i_C versus time. From the graph, it is clear that total collector current consists of two components, namely;
The d.c. collector current I_C (zero signal collector current) due to bias battery V_{BB}. This is the current that flows in the collector in the absence of signal.
The a.c. collector current i_C due to signal
Therefore, Total collector current $i_C = i_c + I_C$

The useful output is the voltage drop across the collector load R_C due to a.c. component i_c. The purpose of zero signal collector current is to ensure that the emitter-base junction is forward biased at all times.

One of the most important functions of electronic circuitry is amplification.

"***The process of increasing the amplitude of a desired ac signal voltage or current without altering its other properties is known as amplification***".

"***A device by means of which amplification is achieved is known as an amplifier***". Or

"***An amplifier is a device that increases the strength of voltage, current or power of an input signal with aid of vacuum tubes or transistors***".

Resistors, inductors and capacitors are also required to form complete amplifier circuits. They provide path for the input and output signals. A transistor used as an amplifier needs dc voltages applied to its electrodes in order to conduct any current. The amplification comes from having a small ac input signal control much larger dc values in the output circuit. Furthermore, load impedance is required in the output circuit to develop the output signal. The reason is that the current inside the transistor must be made to flow in an external component.

Classification of Amplifiers:

Amplifiers are classified in different ways depending on their mode of operation. Several factors are taken into account in making a classification. Some of the classifications are as follows:

1) **Based on the manner of coupling:**
    a) RC coupled amplifier
    b) Transformer coupled amplifier
    c) Direct coupled amplifier
2) **Based on the magnitude of the input signal:**
    a) Small signal amplifier
    b) Large signal amplifier
3) **Based on the magnitude of the output signal:**
    a) Voltage amplifier
    b) Power amplifier

4) **Based on the frequency:**
   a) Audio frequency (AF) amplifier
   b) Intermediate frequency (IF) amplifier
   c) Radio frequency (RF) amplifier
5) **Based on condition of biasing:**
   a) Class A amplifier
   b) Class B amplifier
   c) Class AB amplifier
   d) Class C amplifier
6) **Based on transistor configuration:**
   a) Common base amplifier
   b) Common emitter amplifier
   c) Common collector amplifier

Common Emitter Amplifier Circuit:

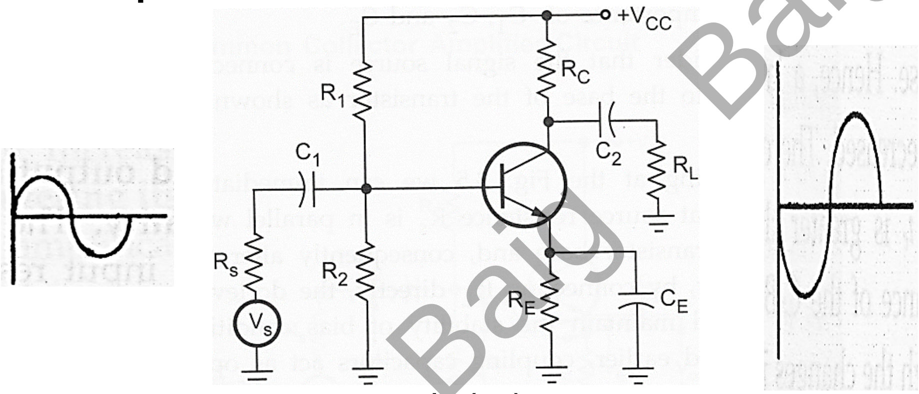


Fig (01)

Fig (01) shows the practical circuit of common emitter transistor amplifier. It consists of different circuit components. The functions of these components are as follows:

1. Biasing Circuit: The resistors R_1, R_2 and R_E forms the voltage divider biasing circuit for the CE amplifier. It sets the proper operating point for CE amplifier.

2. Input Capacitor C_1: This capacitor couples the signal to the base of the transistor. It blocks any dc component present in the signal and passes only ac signal for amplification. Because of this biasing conditions are maintained constant.

3. Emitter Bypass Capacitor C_E: An emitter bypass capacitor C_E is connected in parallel with the emitter resistance, RE to provide a low reactance path to the amplified ac signal. If it is not inserted, the amplified ac signal passing through R_E will cause a voltage drop across it. This will reduce the output voltage, reducing the gain of the amplifier.

4. Output Coupling Capacitor C_2: The coupling capacitor C_2 couples the output of the amplifier to the load or to the next stage of the amplifier. It blocks dc and passes only ac part of the amplifier signal.

Need for C_1, C_2 and C_E: We know that, the reactance of the capacitor is given by

$$X_C = \frac{1}{2\pi f C}$$

Thus, at signal frequencies all the capacitors have extremely small reactance and it can treated as an ac short circuit. For bias/dc conditions of the transistor all the capacitors act as a dc open circuit.

Now consider that the signal source is connected directly to the base of the transistor as shown in fig (02).

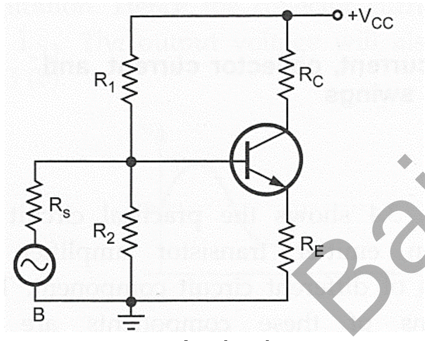


Fig (02)

Looking at the fig (02) we can immediately notice that source resistance R_S is in parallel with R_2. This will reduce the bias voltage at the transistor base and, consequently alter the collector current, which is not desired. Similarly, by connecting R_L directly, the dc levels of V_C and V_{CE} will change. To avoid this and maintain the stability of bias condition coupling capacitors are connected. As mentioned earlier, coupling capacitors act as open circuit to dc, maintain stable biasing conditions even after connection of R_S and R_L. Another advantage of connecting C_1 is that any dc component in the signal is opposed and only ac signal is routed to the transistor amplifier.

The emitter resistance R_E is one of the components which provides bias stabilization. But it also reduces the voltage swing at the output. The emitter bypass capacitor C_E provides a low reactance path to the applied amplifier ac signal increasing the output voltage swing.

For the proper operation of the circuit, polarities of the capacitors must be connected correctly. The curve bar which indicates the negative terminal must always be connected at a dc voltage lower level. For example, C_1 in fig (01) has its negative at dc ground level, because it is grounded through the signal resistance R_S. The positive terminal of C_1 is at $+V_B$ with respect to ground.

Phase Reversal:

The phase relationship between the input and output voltages can be determined by considering the effect of a positive half cycle and negative half cycle separately. Consider the positive half cycle of input signal in which terminal A is positive with respect to B. Due to this, two voltages, ac and dc will be adding each other, increasing forward bias on base emitter junction. This increases base current. The collector current is β times the base current, hence the collector current will also increase. This increase the voltage drop across R_C. Since $V_C = V_{CC} - I_C\,R_C$, the increase in I_C results in a drop in collector voltage V_C, as V_{CC} is constant. Thus, as v_{in} increases in a positive direction, v_o goes in a negative direction and we get negative half cycle of output voltage for positive half cycle at the output.

In the negative half cycle of input, in which terminal A becomes negative w.r.t. terminal B, the ac and dc voltages will oppose each other, reducing forward bias on base-emitter pn junction. This reduces base current. Accordingly collector current and drop across R_C both reduce, increasing the output voltage. Thus, we get positive half cycle at the output for negative half cycle at the input. Therefore, we can say that there is a phase shift of 180^o between input and output voltages for a common emitter amplifier.

Characteristics and Applications of CE Amplifier:

1. It has low input impedance $(1k\Omega \text{ to } 2k\Omega)$.
2. It has high output impedance $(50k\Omega)$.
3. Its current gain is very high $(50\ to\ 300)$.
4. Its voltage gain is also high (≈ 1500).
5. There is a phase reversal of $\pi\ or\ \ 180^o$ between input and output signals.

The CE amplifier is generally used for almost all applications because of its large voltage and power gains. In addition to this, its input and resistance are suitable for most of the applications.

Since the effective capacitance is large, the frequency response of CE amplifier is not good as in CB and CC amplifiers.

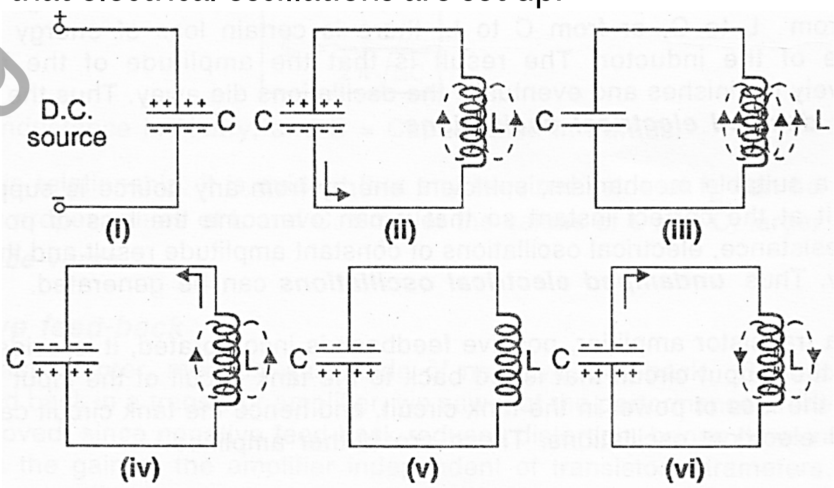
Oscillators:

*"An electronic circuit that generates an alternating voltage using energy from a dc source is called an **oscillator**"*. or

*"An **oscillator** is an electronic circuit that converts direct voltage into alternating voltage of a desired frequency and magnitude"*.

The waveform of the alternating voltage may be sinusoidal, square, sawtooth etc. In addition to the frequency and waveform of the oscillations, the conversion efficiency is important in the design of the oscillator circuits.

Tank Circuit: The simplest form of oscillatory circuit is a **tank circuit**. A tank circuit essentially consists of an inductor L and a capacitor C connected in parallel. Let the capacitor C be charged from a dc voltage source. It can be shown that, in such a tank circuit continuous interchange of energy occurs between the inductor and capacitor, with the result that electrical oscillations are set up.



In the above figures;

(i) Charging of capacitor C from dc source.
(ii) Capacitor discharging. The arrow indicates the direction of flow of electrons.
(iii) Capacitor fully discharged.
(iv) Capacitor being charged with opposite polarity.
(v) Capacitor fully charged.
(vi) Capacitor discharging in the opposite direction.

When the capacitor is charged, energy gets stored in the dielectric (i.e., in the electrostatic field). If the dc source is removed, and an inductor is connected across the capacitor, the capacitor discharges and a current flows through the inductor, thus creating a magnetic field. All the energy stored in the capacitor gets transferred to the magnetic field of the inductor, by the time the capacitor fully discharges.

When no more current flows, the magnetic field of the inductor collapses, and all the energy of the inductor gets transferred to the capacitor, thus charging it again, but in the opposite direction as shown.

After getting fully charged, the capacitor beings to discharge, since it is now short circuited by the inductor. The energy of the capacitor flows into the inductor and a current results in the opposite direction. When the capacitor fully discharges, the magnetic field of the inductor again collapses, and the energy of the inductor flows into the capacitor, thus charging it again in the opposite direction.

Thus we see that the capacitor alternately gets charged and discharges and an alternating current results. In other words, **an oscillatory current is produced**. However, these electrical oscillations cannot persists forever, since during each energy transfer from L to C or from C to L, there is certain loss of energy due to the resistance of the inductor. The result is that the amplitude of the oscillations progressively diminishes and eventually the oscillations die away. Thus the tank circuit generates **damped electrical oscillations**.

If, by a suitable mechanism, sufficient energy from any source is supplied to the tank circuit at the correct instant so that it can overcome the loss of power due to inductor resistance, electrical oscillations of constant amplitude result and these persists indefinitely. Thus **undamped electrical oscillations** can be generated.

If, in a transistor amplifier, positive feedback is incorporated, it is evident that the energy of the output circuit that is fed back to the tank circuit of the input circuit, can supply for the loss of power in the tank circuit, and hence the tank circuit can generate undamped electrical oscillations. These are further amplified.

Thus in a transistor amplifier provided with positive feedback, all the three conditions are satisfied – **The LC tank circuit is the oscillatory circuit which generates oscillations, the amplifier supplies for the loss of power in the tank circuit, and there is a feedback circuit which supplies energy to the tank circuit in correct phase and magnitude**.

Hence the transistor amplifier functions as an oscillator.

The block diagram of transistor oscillator is shown in fig (01). The feedback circuit employs different circuit elements like resistors, inductors and capacitors.

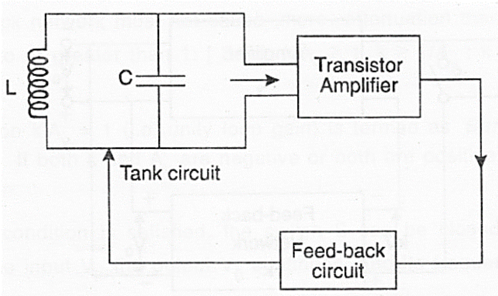


Fig (01)

Frequency of oscillations: The frequency of oscillations generated by the tank circuit is given by the expression $f = \frac{1}{2\pi\sqrt{LC}}$

where L is the inductance in henry and C is the capacitance in farad.
From this relation it is evident that any required value of frequency can be obtained by choosing proper values of L and C. Smaller the values of L and C, larger the value of f and vice-versa.

Conditions for sustained oscillations:

The **Barkhausen Criterion** state that:

1. The total phase shift around a loop, as the signal proceeds from input through amplifier, feedback network back to input again, completing a loop, is precisely 0^o or 360^o or in other words the feedback should be positive.
2. The magnitude of the product of the open loop gain of the amplifier (A_v) and the magnitude of the feedback factor β is unity i.e., the loop gain $|\beta A_v| = 1$.

Satisfying these conditions, the circuit works as an oscillator producing sustained oscillations of constant frequency and amplitude.

In reality, no input signal is needed to start the oscillations. In practice, βA_v is made slightly greater than 1 to start the oscillations and then the circuit adjusts itself to get $\beta A_v = 1$, finally resulting into self sustained oscillations. Let us see the effect of the magnitude of the product βA_v on the nature of oscillations.

Case (01): When the total phase shift around a loop is 0^o and $|\beta A_v| > 1$, then the output oscillates but the oscillations are of growing type. The amplitude of oscillations goes on increasing as shown in fig (01)

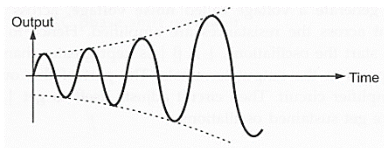


Fig (01)

Case (02): As stated by Barkhausen criterion, when total phase shift around a loop is 0^o or 360^o ensuring positive feedback and $|\beta A_v| = 1$ then the oscillations are with constant frequency and constant amplitude

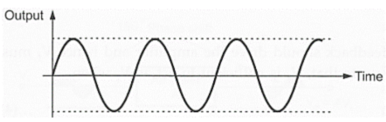


Fig (02)

called sustained oscillations as shown in fig (02)

Case (03): When total phase shift is around a loop is 0^o o but $|\beta A_v| < 1$ then the oscillations are of decaying type i.e., such oscillation amplitude decreases exponentially and the oscillations finally cease. Thus the circuit works as an amplifier without oscillations. The decaying oscillations as shown in fig (03).

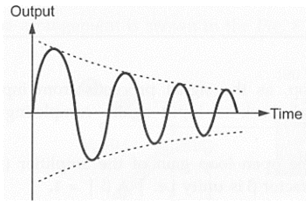


Fig (03)

Thus to start the oscillations without input, $|\beta A_v|$ is kept slightly more than unity and then the circuit adjusts itself to get $|\beta A_v| = 1$ to result sustained oscillations.

Classification of Oscillators:

A) Based on the type of waveform generated, oscillators are classified as;
1) Sinusoidal oscillators and
2) Non-sinusoidal (Relaxation) oscillators.

B) Based on the frequency of oscillations generated, oscillators may be classified as;
1) Audio frequency oscillators
2) Radio frequency oscillators
3) Ultra high frequency oscillators
4) Microwave oscillators

C) Yet another classifications is
1) Feedback oscillators and
2) Negative resistance oscillators

D) Sinusoidal oscillators are further classified as
1) LC oscillators and
2) RC oscillators

Some of the LC oscillators are;
1) Tuned collector oscillator
2) Hartley oscillator
3) Colpitts oscillator and

Some of the RC oscillators are
1) Phase shift oscillator and
2) Wien bridge oscillator

In addition to these, we have crystal oscillator whose operation is based on piezo electric effect.

Tuned Collector Oscillator:

Fig (01) shows the circuit of a tuned collector oscillator. It contains L_1 and C_1 in the collector circuit and hence the name. The frequency of oscillations depends upon the values of L_1 and C_1 and is given by

$$f = \frac{1}{2\pi\sqrt{L_1 C_1}} \quad (01)$$

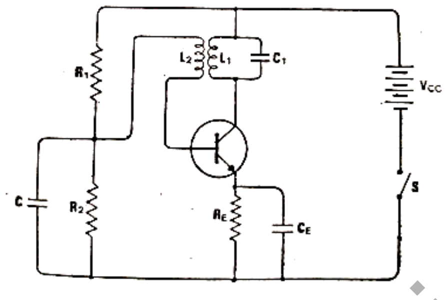


Fig (01)

The feedback coil L_2 in the base circuit is magnetically coupled to the tank circuit coil L_1. In practice, L_1 and L_2 form the primary and secondary of the transformer. The biasing is provided by potential divider arrangement. The capacitor C connected in the base circuit provides low reactance path to the oscillations.

Circuit Operations: When switch S is closed, collector current starts increasing and charges the capacitor C_1. When this capacitor is fully charged, it discharges through coil L_1, setting up oscillations of frequency determined by equation (01). These oscillations induce some voltage in the coil L_2 by mutual induction. The frequency of voltage in coil L_2 is the same as that of tank circuit but its magnitude depends upon the number of turns of L_2 and coupling between L_1 and L_2. The voltage across L_2 is applied between base and emitter and appears in the amplified form in the collector circuit, thus overcoming the losses occurring in the tank circuit. The number of turns of L_2 and the coupling between L_1 and L_2 are so adjusted that oscillations across L_2 are amplified to a level just sufficient to supply losses to the tank circuit.

It may be noted that the phase of feedback is correct i.e., energy supplied to the tank circuit is in phase with the generated oscillations. A phase shift of 180^0 takes place between base emitter and collect circuit due to transistor properties. As a result, the energy feedback to the tank circuit is in phase with the generated oscillations.

Phase Shift Oscillator:

This is basically a ladder type RC phase shift oscillator. The feedback network consists of three resistors and three capacitors arranged in the form of a ladder, as shown in fig (01).

The oscillator basically consists of a transistor amplifier which operates in the CE mode, and a three stage (or three leg) RC ladder feedback network. As already studied, the transistor amplifier brings about 180^o phase shift between output voltage V_o and the input voltage V_s. The feedback network causes a further phase shift of 180^o, so that the net phase difference between the input voltage and the fraction of output voltage fed back into the circuit is $180^o + 180^o = 360^o$ (or 0^o). This is what is required for positive feedback.

Each leg of the ladder causes a phase shift of 60^o. This can be shown as follows:

Consider fig (02), we have voltage drop across R = V_R = IR, and voltage drop across C = V_C = IX_C

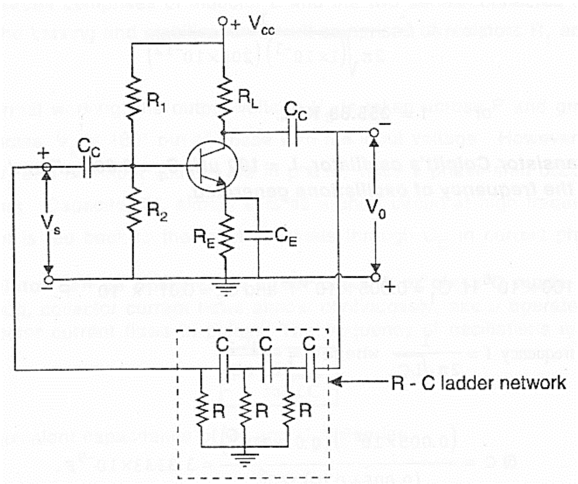


Fig (01)

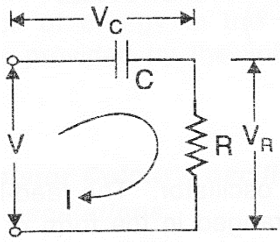


Fig (02)

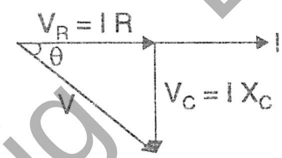


Fig (03)

Total voltage V = V_R + V_C (phasor sum). It is seen from the phasor that V_R leads V by an angle θ where

$$\tan\theta = \frac{X_C}{R} = \frac{1}{2\pi fRC} \qquad \text{since } X_C = \frac{1}{2\pi fC}$$

$$\theta = \tan^{-1}\left(\frac{1}{2\pi fRC}\right)$$

by choosing proper values of R and C, θ can be made equal to 60°.

Thus, since there are three legs of the ladder network, the total phase shift would be $60^o \times 3 = 180^o$. The frequency of oscillations generated by the phase shift oscillator is given by the expression

$$\boldsymbol{f} = \frac{1}{2\boldsymbol{\pi RC}\sqrt{6 + 4\,\boldsymbol{R_L/R}}} \quad \text{or} \quad \boldsymbol{f} = \frac{1}{2\boldsymbol{\pi RC}\sqrt{10}}$$

if $R_L = R$

Advantages:

1) It does not require transformers or inductors.
2) It can be used to produce very low frequencies.
3) The circuit provides good frequency stability.

Disadvantages:

1) Frequency of oscillation cannot be changed easily. For changes in frequency, the three capacitors or resistors should be changed simultaneously.
2) It not easy to control the amplitude of oscillation without affecting the frequency of operation.
3) These oscillators are not suitable for high frequency operation. At high frequencies, the internal phase shift of the transistor and reduction in h_{fe} cause difficulties in designing the circuit.

Wien Bridge Oscillator:

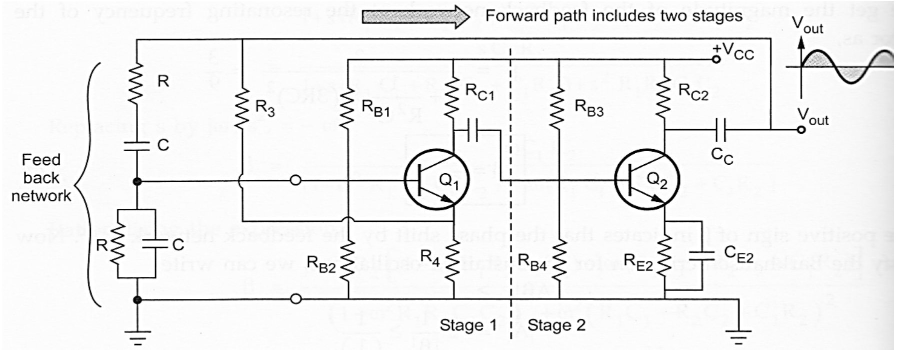


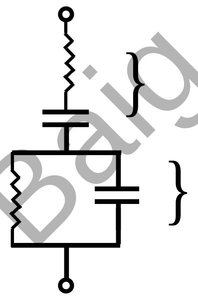
Fig (01)

In the above circuit two stage common emitter amplifier is used. Each stage contributes 180° phase shift hence the total phase shift due to the amplifier stage becomes 360° or 0° which is necessary as per the oscillator conditions.

The practical, transistorized Wien bridge oscillator circuit is shown in fig (01). The bridge in the circuit consists of R and C in series, R and C in parallel, R_3 and R_4. The feedback is applied from the collector of Q_2 through the coupling capacitor, to the bridge circuit. The resistance R_4 serves the dual purpose of emitter resistance of the transistor Q_1 and also the element of the Wien bridge.

The two stage amplifier provides a gain much more than 3 and it is necessary to reduce it. To reduce the gain, the negative feedback is used without by passing the resistance R_4. The negative feedback can accomplish the gain stability and can control the output magnitude. The negative feedback also reduces the distortion and therefore output obtained is a pure sinusoidal in nature. The amplitude stability can be improved using a nonlinear resistor for R_4. Due to this, the loop gain depends on the amplitude of the oscillations. Increase in the amplitude of the oscillations, increases the current through nonlinear resistance, which results into an increase in the value of nonlinear resistance R_4. When this value increases, a greater amount of negative feedback is applied. This reduces the loop gain. And hence signal amplitude gets reduced and controlled.

Theory:



Reactance of the capacitance $X_C = \frac{1}{j\omega C}$

Feedback voltage v_f is given by

$$v_f = \frac{v_0\, Z_P}{Z_S + Z_P}$$

or $$\frac{v_f}{v_0} = \frac{Z_P}{Z_S + Z_P}$$

or $$\beta = \frac{Z_P}{Z_S + Z_P}$$

where $\beta = \frac{v_f}{v_0}$ is the feed back fraction, where v_0 is the output voltage of the amplifier

and

$$Z_P = \frac{R \times X_C}{R + X_C} = \frac{R/j\omega C}{R + 1/j\omega C} = \frac{R/j\omega C}{(j\omega RC + 1)/j\omega C} = \frac{R}{j\omega RC + 1}$$

$$Z_S = R + X_C = R + 1/j\omega C = \frac{j\omega RC + 1}{j\omega C}$$

Therefore,

$$\beta = \frac{\frac{R}{j\omega RC + 1}}{\frac{j\omega RC + 1}{j\omega C} + \frac{R}{j\omega RC + 1}} = \frac{\frac{R}{j\omega Rc + 1}}{\frac{(j\omega RC + 1)^2 + j\omega Rc}{j\omega C\,(j\omega RC + 1)}} = \frac{j\omega RC}{(j\omega RC + 1)^2 + j\omega RC}$$

Multiply both sides by the gain (A) of the amplifier.

$$\beta A = \frac{jA\omega RC}{(j\omega RC + 1)^2 + j\omega RC}$$

Further from Barkhausen criterion, we known $\beta A = 1$. Therefore

$$1 = \frac{jA\omega RC}{(j\omega RC + 1)^2 + j\omega RC}$$

or $$(j\omega RC + 1)^2 + j\omega RC = jA\omega RC$$

or $$-\omega^2 R^2 C^2 + 2j\omega RC + 1 + j\omega RC = jA\omega RC$$

or $$-\omega^2 R^2 C^2 + 3j\omega RC + 1 = jA\omega RC$$

Comparing imaginary terms we get

$$3\omega RC = A\omega RC$$

∴ $\boxed{\boldsymbol{A} = 3}$ is the condition for sustained oscillations

Comparing real the terms we get

$$-\omega^2 R^2 C^2 + 1 = 0$$

or $$\omega^2 R^2 C^2 = 1$$

or $$\omega^2 = \frac{1}{R^2 C^2}$$

or $$\omega = \frac{1}{RC}$$

or $$f = \frac{1}{2\pi RC} \qquad \because \ \omega = 2\pi f$$

The frequency of oscillation of the signal generated is given by

$$\boxed{f = \frac{1}{2\pi RC}}$$

Advantages:

1) It gives constant output.
2) The circuit works quite easily.
3) The overall gain is high because of two transistors.
4) The frequency of oscillations can be easily changed by a potentiometer.

Disadvantages:

1) The circuit requires two transistors and a large number of components.
2) It cannot generate very high frequencies.

Question Bank

1. Why a semiconductor is called so?
2. Distinguish between intrinsic and extrinsic semiconductor.
3. What is doping? Why is it necessary in semiconductors?
4. What are donor and acceptor impurities?
5. What is a hole? How hole current is set up?
6. Distinguish between minority and majority charge carriers.
7. What is the effect of temperature on the conductivity of a semiconductor?
8. What do you mean by band gap or energy gap?
9. Explain valance band and conduction band.
10. What is potential barrier? Give its significance.
11. What is depletion region? Why is it named so?
12. What is the role of depletion region in PN junction diodes?
13. Why is biasing of semiconductor named so? What are the two types of biasing?
14. Why a Zener diode is different from semiconductor diode?
15. When and why Zener breakdown takes place in a semiconductor diode in reverse biasing?
16. Why a semiconductor diode conducts current in forward biasing but does not conduct in reverse biasing?
17. Do semiconductors obey Ohm's law as in conductors?
18. What is an ideal diode?
19. A semiconductor diode is damaged when large current is made to pass through it. Why?
20. Why germanium is preferred over silicon for making semiconductors?
21. Name two donor and acceptor impurities.

22. Discuss the relative magnitude of resistance of a PN junction diode in forward and reverse bias conditions?
23. Explain band theory of solids. Based on this theory distinguish between insulators, conductors and semiconductors.
24. What do you mean by intrinsic and extrinsic semiconductors?
25. What is Zener breakdown and avalanche breakdown in a junction diode?
26. Discuss the working of a PN junction diode in forward and reverse bias conditions.
27. What is doping? Explain the concept of doping with examples with its utility.
28. What do you mean by intrinsic and extrinsic semiconductors? Discuss in detail the formation of P type and N type semiconductors formed by doping process. Give the mechanism of hole current flow in a semiconductor.
29. Why P type and N type semiconductors are named so? Distinguish between them.
30. What is PN junction diode? How this junction is formed practically? Explain the formation of potential barrier in PN junction.
31. What is the meaning of biasing a junction diode? Explain various types of biasing with explanation of characteristics of PN junction diode.
32. What is Zener diode? Discuss its functioning.
33. What do you mean by ripple factor? What does it signify?
34. Why a Zener diode is suitable for voltage stabilization?
35. What are the uses of rectifiers in daily life?
36. What is a rectifier? Why a semiconductor diode acts as a rectifier? Discuss various types of rectifiers.
37. What is a half wave rectifier? Explain its working. Give its advantages and disadvantages.
38. Explain the working of half wave rectifier and derive an expression for its rectification efficiency and ripple factor. Compare its results with full wave rectifier.
39. What is a full wave rectifier? Explain its working. Give its advantages and disadvantages.
40. Explain the working of full wave rectifier and derive an expression for its rectification efficiency and ripple factor. Compare its results with half wave rectifier.
41. What is a bridge full wave rectifier? Explain its working. Give its advantages and disadvantages.
42. Explain the working of bridge full wave rectifier and derive an expression for its rectification efficiency and ripple factor. Compare its results with half wave rectifier and full wave rectifier.
43. What is a regulated power supply? Discuss its circuit diagram and working using Zener diode.
44. Explain Zener diode as line regulator and load regulator.

45. What is a transistor?
46. Draw the symbol of n-p-n transistor.
47. Draw the symbol of p-n-p transistor.
48. Is doping in all regions of transistor the same?
49. Why the name transistor explain.
50. How many pn junction a transistor has?
51. What is biasing of a transistor?
52. Mention heavily doped region of a transistor.
53. Mention the moderately doped region of a transistor.
54. Mention the lightly doped region of a transistor.
55. Which region of the transistor is physically large.
56. What does the arrow in the circuit symbols of a transistor indicates?
57. In what mode of operation the transistor can be used as an amplifier?
58. In what mode of operation the transistor can be used as a switch?
59. Write the relation between the current components of a transistor.
60. What is meant by amplification?
61. Define voltage gain.
62. Define current gain.
63. Define current gain of the transistor in common base configuration.
64. Define current gain of the transistor in common emitter configuration.
65. Define current gain of the transistor in common collector configuration.
66. Write the relation between α and β.
67. Write the relation between α and γ.
68. What is meant by dc load line?
69. What is meant by the linear region of the transistor's operation?
70. Define quiescent point.
71. What is meant by stabilization?
72. What is meant by thermal runaway?
73. Define stability factor.
74. Mention the transistor parameter which are temperature dependent.
75. What is the function of emitter in the transistor?
76. What is the function of base in the transistor?
77. What is the function of collector in the transistor?
78. Is transistor leakage current is independent of temperature?
79. Is transistor a current controlled device or voltage controlled device?
80. What is I_{CBO}?
81. Why does leakage current exist?
82. Define input resistance of an n-p-n transistor in CB mode.
83. Define output resistance of an n-p-n transistor in CB mode.
84. Define input resistance of an n-p-n transistor in CE mode.
85. Define output resistance of an n-p-n transistor in CE mode.
86. Define input resistance of an n-p-n transistor in CC mode.

87. Define output resistance of an n-p-n transistor in CC mode.
88. What is a transistor? Draw the schematic symbol of p-n-p transistor.
89. Write a brief note on (i) emitter (ii) base and (iii) collector of a transistor.
90. Distinguish between biased transistor and unbiased transistor.
91. Why is the base of a transistor made thin and lightly doped?
92. Why is the collector of a transistor made larger and moderately doped?
93. Distinguish between α and β.
94. Prove that $\alpha = \frac{\beta}{1+\beta}$ and $\beta = \frac{\alpha}{1-\alpha}$
95. Write a brief note on collector to base leakage current.
96. Define α of a transistor. Show that it is always less than unity.
97. Transistor means "Transfer of Resistance". Justify.
98. Explain why a transistor should be biased?
99. Mention the essentials of biasing.
100. What is a transistor? Explain the working of a p-n-p / an n-p-n transistor.
101. Distinguish between different types of transistor configurations with necessary diagrams.
102. Draw and explain the input and output characteristics of an n-p-n transistor in CB configuration.
103. Draw and explain the input and output characteristics of an n-p-n transistor in CE configuration.
104. Distinguish between the active, saturation and cut-off regions of a transistor.
105. Sketch and explain the current components crossing each junction of a transistor biased in the active region.
106. What are the biasing rules for a transistor, so that it can be used as an amplifier? Show the biasing arrangement for an n-p-n transistor with two power supplies.
107. What are the requisites of a good biasing circuit? Analyze the potential divider bias for a transistor. What are its advantages?
108. Draw a self bias circuit. Explain qualitatively why such a circuit is advantageous as far as stability is concerned.
109. What is faithful amplification? Explain the conditions to be fulfilled to achieve faithful amplification in a transistor amplifier.
110. Describe the construction and working of a junction field effect transistor.
111. Describe the output and transfer characteristics of JFET.
112. Describe how the output and transfer characteristics of JFET can be experimentally drawn.
113. Explain the four distinct regions of the output characteristics of a JFET.
114. State and explain Shockley's equation.
115. Define and explain the parameters transconductance, drain resistance and amplification factor of a JFET. Establish the relation between them.

116. Explain how the transconductance of a JFET varies with drain current and gate voltage.
117. Compare the JFET with BJT.
118. What is meant by amplification?
119. What is meant by amplifier?
120. Name the basic transistor amplifier circuits.
121. Why CB amplifier is seldom used in AF applications?
122. Which transistor amplifier has voltage gain less than unity?
123. Which transistor amplifier has more input impedance?
124. Which transistor amplifier has more collector gain?
125. Define voltage gain (A_v).
126. Define current gain (A_i).
127. Define power gain (A_p).
128. What is meant by feedback?
129. Name the types of feedback.
130. What is meant by feedback factor?
131. What is positive feedback?
132. What is Barkhausen Criterion?
133. What is an oscillator?
134. What are sinusoidal oscillators?
135. What are non-sinusoidal oscillators?
136. What are damped oscillations?
137. What are undamped oscillations?
138. What is an oscillatory circuit (or tank circuit)?
139. Define frequency stability.
140. How many RC sections are required in a phase shift oscillator?
141. What is the value of phase shift in each RC section of a phase shift oscillator?
142. Write the formula for the frequency of oscillations of a phase shift oscillator.
143. What is the value of open loop gain of a the amplifier stage of a phase shift oscillator to satisfy the Barkhausen criterion?
144. Write the formula for the frequency of oscillations of Wien Bridge oscillator?
145. Does the bridge circuit introduce any phase shift in the Wien bridge oscillator?
146. Draw a LC tank circuit.
147. Explain the generation of sinusoidal waves in a tuned LC circuit.
148. Draw the diagram of phase shift oscillator and explain its action. Also mention the expression for the frequency of oscillations.

149. Draw the diagram of Wien bridge oscillator and explain its action. Also mention the expression for the frequency of oscillations.
150. Draw the diagram of Wien bridge oscillator and explain its action. Also derive the expression for the frequency of oscillations and the condition for sustained oscillations.
151. What is an operational amplifier?
152. What is meant by differential amplifier?
153. Write an expression for the output voltage of differential amplifier.
154. Draw the schematic symbol of an op amp.
155. Define common mode rejection ratio.
156. What is the input impedance of an ideal op amp?
157. What is the output impedance of an ideal op amp?
158. What is the voltage gain of an ideal op amp?
159. What is a practical op amp?
160. What is the value of output voltage if both the input voltages are equal in differential amplifier.
161. Write the popular op amp IC number?
162. What is inverting operational amplifier?
163. What is non-inverting operational amplifier?
164. Draw the circuit of inverting amplifier using an op amp.
165. Draw the circuit of non-inverting amplifier using an op amp.
166. What is virtual ground?
167. Draw the output waveform of an inverting amplifier when a sinusoidal input is given.
168. What is the value of voltage gain of a practical operational amplifier?
169. What is the value of the input impedance of a practical operational amplifier?
170. What is the value of the output impedance of a practical operational amplifier?
171. Mention the bandwidth of an ideal operational amplifier?
172. Mention the expression for the voltage gain of an inverting op amp.
173. Mention the expression for the voltage gain of a non-inverting op amp.
174. Determine the value of voltage gain of an inverting op amp if $R_f = 2k\Omega$ & $R_1 = 1k\Omega$.
175. Determine the value of voltage gain of a non-inverting op amp if $R_f = 2k\Omega$ & $R_1 = 1k\Omega$.
176. Define open loop voltage gain.
177. Define input impedance of an op amp.
178. Define output impedance of an op amp.
179. Define input offset voltage of an op amp.
180. Define input offset current of an op amp.
181. Define input bias current of an op amp.
182. Define bandwidth.
183. Define common mode rejection ratio.

184. Define input offset current drift.
185. Define input offset voltage drift.
186. Define slew rate.
187. Classify the amplifiers and write their applications.
188. Explain with a circuit diagram the action of a CE amplifier.
189. Draw the dc and ac equivalent circuits of a single stage CE amplifier.
190. Derive the general formulae for input impedance, current gain, voltage gain, output impedance and power gain of a CE amplifier.
191. Write a note on frequency response curve of a single stage CE amplifier.
192. What do you understand by hybrid parameter? What are their dimensions?
193. How will you measure h parameters of a linear circuit?
194. Draw the h parameter equivalent circuit of a linear circuit.
195. What is the physical meaning of h parameters?
196. Derive the general formulae in terms of h parameters for input impedance, current gain, voltage gain, output impedance and power gain.
197. What are the notations of h parameters of a transistor when used in CB, CE and CC configurations?
198. Derive the formulae in terms of h parameters for input impedance, current gain, voltage gain, output impedance and power gain in case of CE amplifier circuit.
199. How h parameters of a transistor measured from the transistor characteristics study?
200. What are the advantages of h parameters approach?
201. Mention the limitations of h parameters approach.
202. What is an operational amplifier? Mention the characteristics of an ideal op amp.
203. List the characteristics of an ideal op amp.
204. What is an inverting amplifier? Derive an expression for the voltage gain in case of an inverting op amp.
205. What is a non-inverting amplifier? Derive an expression for the voltage gain in case of a non-inverting op amp.