Content:

Diodes: *Direct and indirect band gap, Band gap engineering, P-N junction diode-forward and reverse bias, diode equation, V-I characteristic, Application: bridge rectifier, breakdown mechanism in diodes: Avalanche & Zener breakdown, Zener diode as voltage regulator.*
Transistors: *Bi-junction polar transistor, V-I characteristics in Common Emitter, Common Base and Common Collector configuration, CE configuration as an amplifier. Numerical problems.*

Introduction

A semiconductor device is a electronic equipment that is made from a material that is a semiconductor, such as silicon or germanium. These materials are used to create devices such as transistors, diodes, and solar cells, which are used in a wide range of electronic devices, including computers, smartphones, and televisions. Semiconductor devices are important because they are smaller, faster, and more energy-efficient than traditional electronic devices, and they are also more reliable. They are used in many different fields such as microprocessors, memory devices and power electronic devices among many others.

Band theory of solids

The band theory of solids is a model that describes the electronic structure of solid materials, such as metals, semiconductors, and insulators. The theory explains how the electrons in a solid interact with each other and with the atoms that make up the solid, giving rise to unique electronic properties.

In a solid, the electrons are not bound to individual atoms, but are free to move throughout the material. According to the band theory, the electrons in a solid occupy energy levels that are grouped together in bands. The lowest energy band, called the valence band, is fully occupied by electrons that are tightly bound to the atoms. The next energy band, called the conduction band, is partially or completely empty and is separated from the valence band by an energy gap known as the band gap.

The energy gap between the valence and conduction bands determines whether a material is a conductor, semiconductor, or insulator is as shown in figure 1. The band theory predicts that metals have a partially filled conduction band, which allows the electrons to move freely through the material, resulting in high electrical conductivity. In contrast, insulators have a large band gap between the valence and conduction bands, which means that electrons cannot easily move through the material, resulting in low conductivity. Semiconductors have a small band gap, which allows electrons to move through the material under certain conditions, making them useful for electronic devices.

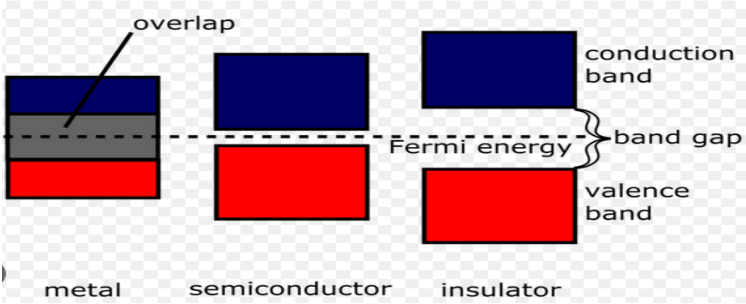


Figure 1: Band diagram for conductor, semiconductor and insulator

In summary, the band theory of solids provides a fundamental understanding of the electronic structure of solids and has important implications for the design and development of electronic devices and materials.

E-k diagram and effective mass:

The E-k diagram is a useful tool for understanding the relationship between energy and momentum in quantum mechanics, and can be applied in a variety of fields including materials science, solid-state physics, and particle physics.

In condensed matter physics, an E-k diagram as shown in figure 2 represents the energy of electrons (E) as a function of their momentum (k) in a crystalline material. The band structure of a material, which describes the allowed energy levels for electrons in the material, can be depicted using an E-k diagram.

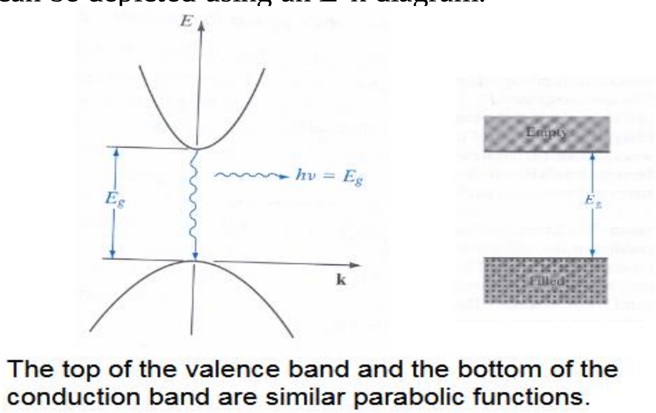


Figure 2: E-k diagram

In the E-k diagram, the energy of a particle is determined by its momentum, as well as other physical properties such as mass and potential energy. The electrons in a crystal are not completely free, but instead interact with the periodic potential of the crystal lattice. The slope of the energy curve on the diagram represents the particle's velocity, with steeper slopes indicating higher velocities.

The effective mass can be calculated from the curvature of the E-k diagram near the band edges using the following expression:

$$m* = \frac{\hbar^2}{\frac{d^2E}{dk^2}}$$

Where m* is the effective mass, h is Planck's constant, E is the energy, and k is the momentum. The effective mass is usually expressed in terms of the free electron mass (m_e), which is the mass of an electron in vacuum. For example, if the effective mass of an electron is $0.5m_e$, it means that the electron behaves as if it has half the mass of a free electron.

In summary, the E-k diagram and effective mass expression are important tools for understanding the electronic properties of semiconductors. The E-k diagram provides a graphical representation of the electronic band structure, while the effective mass expression relates the momentum and velocity of the charge carriers.

Direct and Indirect band gap semiconductors

Semiconductors are materials that have an energy gap between their valence band and conduction band, which can be manipulated by introducing impurities or changing the material's composition. These energy gaps are responsible for the unique electrical and optical properties of semiconductors, making them essential for modern electronics and optoelectronics.

There are two types of band gaps in semiconductors: direct and indirect. The energy-momentum relationship for electrons in the valence band and conduction band is given by the energy-momentum dispersion relation or the E-k diagram. In this diagram, the horizontal axis represents the momentum (k), while the vertical axis represents the energy (E).

Direct band gap semiconductor:

A direct bandgap semiconductor is a material where the transition of electrons from the valence band to the conduction band can take place without any change in momentum as shown in figure 3. This results in a high probability for direct transitions between the two bands, leading to efficient light emission and absorption. These properties make direct bandgap materials ideal for various optoelectronic applications such as LED lights and solar cells. Examples of direct bandgap semiconductors include GaAs, InP, ZnS, CdSe, CdTe and SiC.

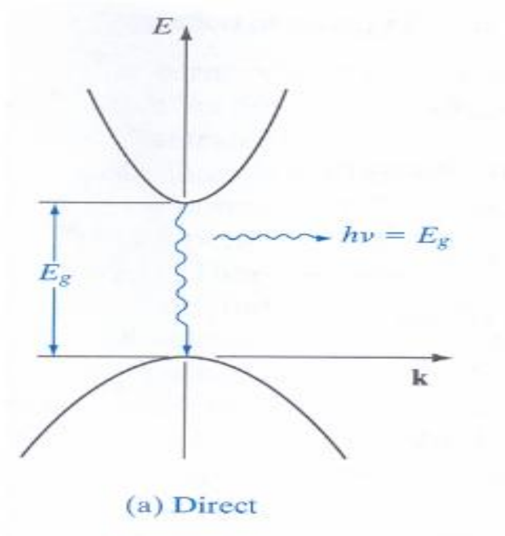


Figure 3: E-k diagram for Direct band gap semiconductor

Indirect band gap semiconductor:

An indirect bandgap semiconductor is a material where the transition of electrons from the valence band to the conduction band requires a change in momentum as shown in figure 4. This means that an electron in the conduction band minimum cannot fall directly to the valence band maximum. It must undergo a momentum as well as energy change as the transition is not occurring at the same value of k.

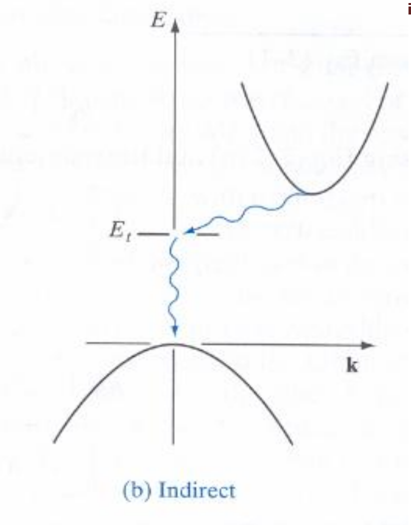


Figure 4: E-k diagram for Indirect band gap semiconductor

A photon by itself cannot excite an electron from the top of valence band to the bottom of conduction band. This is because the photons has sufficient energy to cause the transition but does not possess the necessary momentum. As the photons have zero momentum, the difference in momentum appears in the form of **phonons** (quantum of crystal lattice vibration). Indirect bandgap semiconductors include Si and Ge, and due to the lower probability of light emission, they are less suitable for optoelectronic applications.

Difference between direct and indirect band gap semiconductors

Direct band-gap (DBG) semiconductor	Indirect band-gap (IBG) semiconductor
• A direct bandgap semiconductor is a material where the transition of electrons from the valence band to the conduction band can take place without any change in momentum. • A direct recombination takes place with the release of the energy equal to the energy difference between the	• An indirect bandgap semiconductor is a material where the transition of electrons from the valence band to the conduction band requires a change in momentum. • Due to a relative difference in the momentum, first, the momentum is conserved by release of energy and

recombining particles. • The probability of a radiative recombination is high. • The efficiency factor of a DBG semiconductor is higher. Example: Gallium Arsenide	only after the both the momenta align themselves, a recombination occurs accompanied with the release of energy. • The probability of a radiative recombination is comparatively low. • The efficiency factor of an IBG semiconductor is lower. Example: Silicon and Germanium

Band gap engineering:

Band gap engineering refers to the intentional modification of the electronic band structure of materials, particularly semiconductors, in order to control their electronic and optical properties.

The band gap is the energy difference between the highest energy level of the valence band and the lowest energy level of the conduction band in a material. Semiconductors have a relatively small band gap, which allows them to absorb and emit light at specific wavelengths. By engineering the band gap of a material, researchers can tune its optical and electronic properties to create new applications.

There are several techniques for band gap engineering, including alloying, doping, and quantum confinement. Alloying involves mixing different elements to create a new material with a modified band gap. Doping involves adding impurities to a semiconductor to change its electronic properties. Quantum confinement refers to the confinement of electrons and holes in a small space, such as a quantum dot, which can modify the band gap.

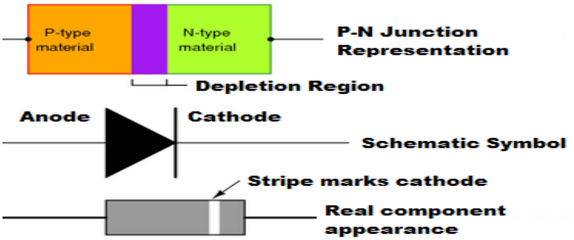
P-N junction: Background information

The construction of solid state electronic device begins with a semiconductor material of highest quality. The three semiconductors are most frequently used in the construction of electronic devices are Ge, Si and GaAs.

A semiconductor material that has been subjected to the doping process is called an extrinsic material. There are two extrinsic materials of immeasurable importance to semiconductor device fabrication are n-type and p-type materials. When a p-type semiconductor and n-type semiconductor are joined metallurgically, a p-n junction is formed. A p-n junction cannot be produced simply by joining two semiconductors. Actual process is a complex one. In practice, such a p-n junction may be prepared by employing two methods 1) Grown junction and 2) Fused junction.

P-N junction:

A diode is a semiconductor device that allows current to flow in only one direction. It consists of a p-n junction, which acts as a barrier that allows current to flow in one direction but not the other. Diodes are used in a variety of electronic circuits, such as rectifiers, voltage regulators, and signal processing circuits. They are also commonly used in power supplies and electronic devices such as televisions and radios.



A simple representation of a p-n junction is shown in the figure.

Diffusion of majority carriers and formation of depletion region:

When a p-type semiconductor and an n-type semiconductor are brought into contact with each other, a diffusion of electrons and holes occurs at the interface due to the concentration gradient of charge carriers. Electrons from the n-type region diffuse across the interface into the p-type region, and combine with holes to form neutral atoms. Similarly, holes from the p-type region diffuse across the interface into the n-type region and combine with electrons to form neutral atoms. This diffusion of charge carriers continues until a depletion region is formed at the interface where there are no free charge carriers.

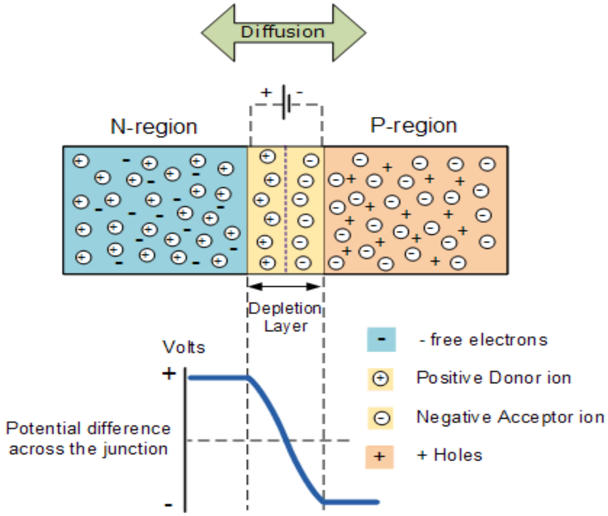


Figure 5: **Depletion region**

The depletion region is shown in figure 5 has a fixed electric field that prevents any further diffusion of charge carriers, and this creates a potential difference across the p-n junction. This potential difference is known as the built-in potential and it acts as a barrier for the flow of electric current in the reverse biased direction.

When a voltage is applied in the forward biased direction, the potential barrier is reduced, allowing electric current to flow through the p-n junction. This forms the basis of many electronic devices such as diodes, transistors, and solar cells.

The diffusion of majority carriers causes diffusion current to flow across the junction. It is easy to see that the current components due to holes and electrons add up although carriers are moving in opposite directions as shown in figure 6. The net diffusion current density flowing across the junction is given by J (diff) = J_{hp}+ J_{en}

Where J_{hp}: hole diffusion current
J_{en}: electron diffusion current

Drift current due to minority carriers:

The field due to space charge causes the flow of minority carriers across the junction. Electrons reaching the edge of the junction on p-region are accelerated by the electric field in to n-region and similarly, the holes reaching the edge of the junction on n-region are accelerated into p-region. As a consequence, an electric current flows across the junction. This current which is caused by electric field is called drift current. The current components due to drift motion of holes and electrons are in same direction and add up to each other as shown in figure 6. The net drift current through the junction is J (drift) = J_{hn} + J_{ep}

Where J_{hn}: hole drift current density
J_{ep} : electron drift current density

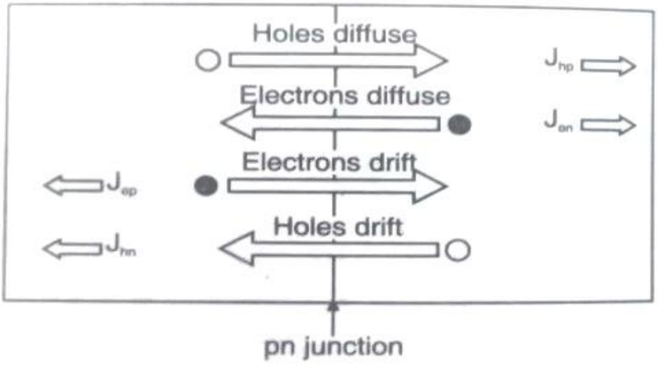
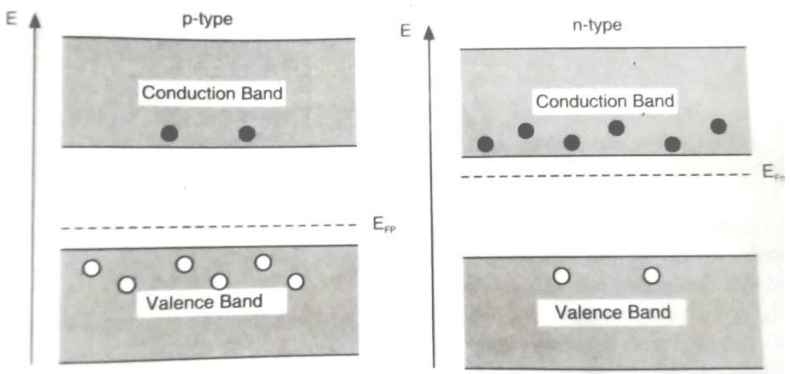


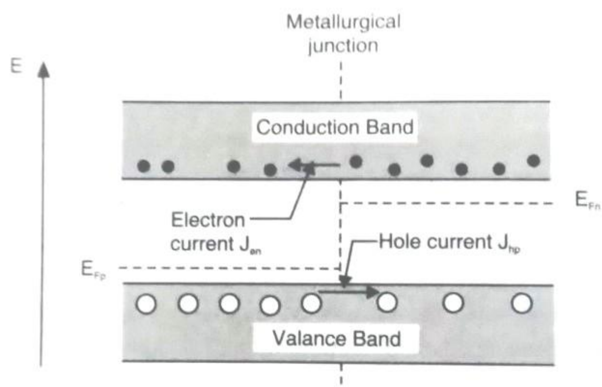
Figure 6: Diffusion and drift current across p-n junction

Energy band diagram of p-n junction at equilibrium:

Let us understand the formation of p-n junction from the point of view of energy band structure. When the two semiconductors are in contact, equilibrium is attained only when there is no net current flow across the junction region. The energy band diagrams of the p and n semiconductors are shown in the figure given below. Note that the Fermi levels E_{Fp} and E_{Fn} are at different levels.



At the instant of joining the levels in the two semiconductors are not aligned is shown in the figure given below.



The occupancy of energy levels by electrons in the conduction band on n-side is high while it is low on p-side. Therefore, the electrons occupying the energy levels in the conduction band on n-side move into the conduction band levels on p-side.

Similarly, the occupancy of energy levels by holes in the valence band on p-side is high while it is low on n-side. Hence, the holes occupying the energy levels in the valence band on p-side move into the valence band levels in n-side.

As high energy electrons leave n-region, the Fermi level E_{Fn} which represents the average energy of electrons move downwards. Since the Fermi level is fixed relative to the band structure of the region, its movement causes downward shift of the entire band structure in the n-region.

On the p-side, holes having higher energy leave the valence band in that region. The direction of decrease in hole energy in upward and hence Fermi level moves E_{Fp} moves upward. Along with E_{Fp}, the entire band structure in the p-region shifts upward. The shifting of energy bands continues till the energy levels E_{Fp} and E_{Fn} attains the same level in both the regions as shown in the figure 7 given below.

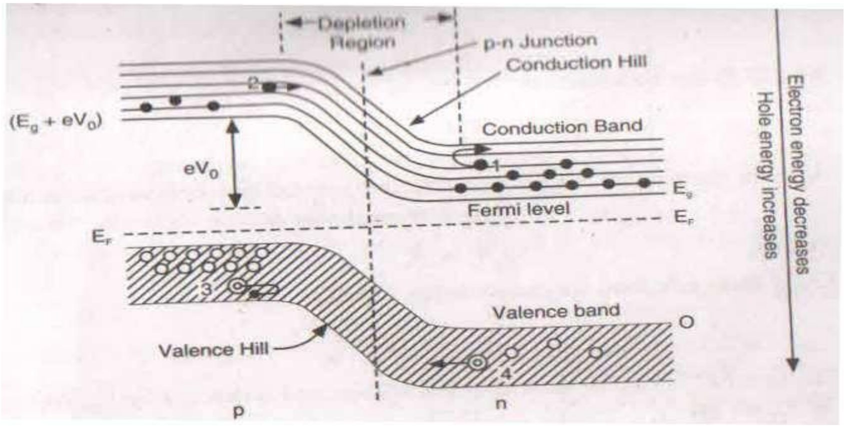


Figure 7: Energy band diagram of p-n junction at equilibrium

When the two levels are equalised, the carrier migration comes to a halt and equilibrium is established. The displacement of the energy bands in opposite directions on both the sides causes a bending of the energy bands in the junction region. Each side takes up a different electrostatic potential. It results in a potential barrier V_o or an energy hill of height eV_o. Electrons in the conduction band of n-region face an energy hill, namely conduction hill. Electrons approaching the junction cannot surmount the conduction hill unless they have minimum energy of eV_o. On the other hand, holes near the junction on the n-side can readily float up the hill irrespective of their energy. Thus the current due to diffusion of majority carriers is balanced by the drift of minority carriers and net current across the p-n junction is zero.

Internal Potential barrier (V_o):

The magnitude of the potential barrier V_o can be estimated from the knowledge of the electron concentrations in the p and n region of the diode. E_g is the edge of the conduction band on the n-side as shown in figure 7. The electron concentration in the conduction band on the n-side can be written as

$$n_n = N_C\ e^{\left[-\left(E_g - E_F\right)/KT\right]} \text{--------}(1)$$

The edge of the conduction band on the p-side is given by (E_g+eV_0). The electron concentration on p-side can be expressed as

$$n_p = N_C\ e^{\left[-\left\{(E_g + eV_o) - E_F/kT\right\}\right]} \text{--------}(2)$$

Dividing equation (1) by (2),we get

$$\frac{n_n}{n_p} = \exp\left[\frac{eV_o}{kT}\right] \text{---------}(3)$$

Equation (3) shows that at thermal equilibrium the concentrations of electrons on both sides of the junction are related through the Boltzmann factor $e^{eVo / kT}$. The concentrations of holes on both the sides are related by an equation similar to equation (3).

Taking logarithm on both sides of equation (3), we obtain

$$V_o = \frac{kT}{e} \ln \frac{n_n}{n_p} ---------(4)$$

Equation (4) can be written as

$$V_o = \frac{kT}{e} \ln \frac{n_n p_p}{n_p p_p}$$

At room temperature ,all the impurities are ionised and therefore,

we can write $n_n = N_D$ and $p_p = N_A$ Further $n_n p_p = n_i^2$

Using these relations we can write equation (4)as

$$V_o = \frac{kT}{e} \ln \frac{N_D N_A}{n_i^2} --------------(5)$$

The factor $\frac{kT}{e}$ has the dimensions of voltage and isdenoted by V_T,

we get $V_o = V_T \ln \frac{N_D N_A}{n_i^2} ---------------(6)$

Equation (6) indicates that the barrier potentia in a junction diode depends on the equilibrium concentrations of the impurities in p and n regions and does not depend on the charge density in the depletion region.

Effect of biasing on the band structure of the p-n junction:

A device is said to be biased when a dc voltage is applied to it. A p-n junction can be biased in two ways.

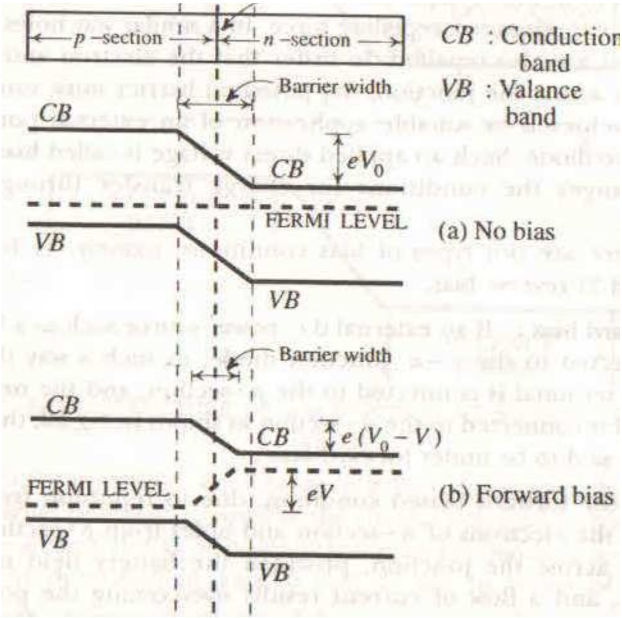
I. **Forward bias:** The positive terminal of the dc voltage source is connected to the p-region and the negative terminal to the n-region.

II. **Reverse bias:** The negative terminal of the dc voltage source is connected to the n-region and the negative terminal to the p-region.

When the diode is subjected to biasing, the equilibrium conditions that were established prior to the application of bias get disturbed, and the relative positions of the energy bands and the Fermi level get displaced in the following manner.

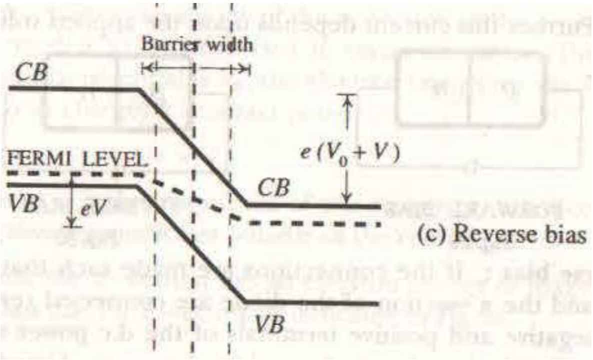
In case of forward bias, since the n-section is connected to the negative terminal of the dc source, the energy of the electron in the n-section increases by an amount of eV, where e is the charge on the electron and V is the applied voltage.

Consequently, the Fermi level rises by a value eV in the n-side with respect to that in p-side. Along with the Fermi level, the companion energy bands on the respective sides also get displaced by the same amount as shown in Figure.



As a result the energy associated with the potential barrier is reduced to $e(V_o\text{-}V)$, Where V_o is the contact potential. Thus for forward biasing the resultant potential across the junction will be the difference of the applied and contact potential. Thus the resultant field across the junction becomes weaker, which in turn renders the depletion region narrower.

In contrast to the above, changes occur in just the opposite way of reverse biasing the diode. In the reverse bias condition, since n-section is connected to the positive terminal of the battery, the electrons in the n-section need more energy to overcome the contact potential. This is equivalent to a reduction in its energy as compared to that in the unbiased state by an equal amount to eV, where V is the applied potential. As a result, the Fermi level on the n-section side gets lowered by eV. The energy bands of both n-section and p-sections also get displaced, in the same direction and by the same amount as that of Fermi level in order to suit the depression caused in the Fermi level position as shown in the figure given below.



Due to the shift in Fermi level, the potential barrier energy increases to

$e(V_o+V)$. The higher potential across the junction creates a stronger field in the vicinity of the junction which pushes electrons and holes away. This effect causes the depletion region to become wider.

Ideal diode characteristics:

1. It conducts current in one direction only, and it has zero resistance when forward biased.
2. It blocks current flow in the reverse direction, and it has infinite resistance when reverse biased. The reverse saturation current is zero.

Diode parameters:

1. *Static forward voltage drop (V_F)*: This is a maximum forward voltage for a given forward current, at a given device temperature.

2. *Forward Resistance (R_F)*: This is a static quantity, i.e., it is constant for specific current.

3. *Dynamic or a. c resistance (r_d)*: Suppose, in addition to a d.c current, a small a.c current is superimposed on it in a diode circuit. The resistance that the diode offers to this signal is called dynamic or a.c resistance. At any particular d.c voltage, the a.c resistance of a diode is the reciprocal of the slope of the characteristic at that point.

4. *Reverse Breakdown Voltage (V_{BR}):* If the reverse bias applied to a p-n junction is increased, a point is reached when the junction breaks down and reverse current shoots up to a value limited only by the external resistance connected in series with the junction. This critical value of the voltage is known as the reverse breakdown voltage.

5. *Reverse Saturation Current (I_S)*: The voltage at which the electric current reaches its maximum level and further increase in voltage does not increase the electric current is called **reverse saturation current**.

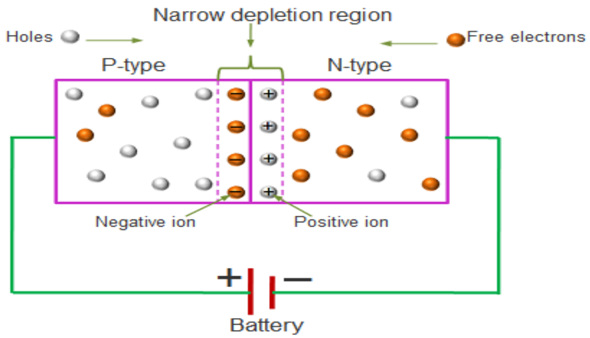
Forward bias I-V characteristics:

A P-N junction is said to be forward-biased, when the p-type is connected to the positive terminal and the n-type region is connected to the negative terminal of a voltage source resulting in a flow of current in the forward direction.This results in the following characteristics:

1. Low resistance: The forward-biased diode offers a low resistance to the flow of current, allowing current to flow easily.

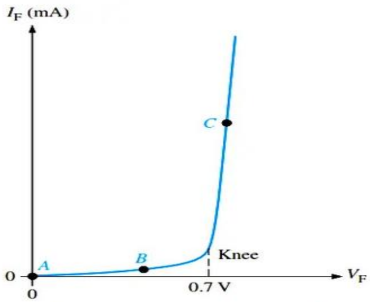
2. Voltage drop: A small voltage drop occurs across a forward-biased diode, which is due to the energy required to move electrons from the n-type material to the p-type material.
3. Increased current: As the voltage across the diode increases, the current through the diode also increases.
4. Continuous conduction: The forward-biased diode allows current to flow continuously as long as the forward voltage is maintained.

These characteristics make the forward-biased diode useful in various applications such as rectifiers, voltage regulators, and power supplies.

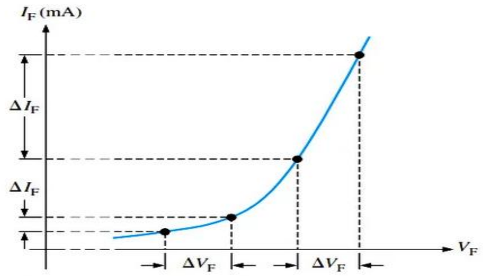


Forward bias

A positive bias voltage is applied to p-type and a negative voltage to the n-type as shown in the figure. As the holes on the p-type are positively charged particles they are repelled from the positive bias terminal and are forced to move towards the junction. Similarly, the electrons on the n-type are repelled by the negative bias terminal are driven towards the junction. Consequently the depletion region is narrowed down and along with it the barrier potential is also reduced. If the applied voltage is gradually increased from zero, the barrier potential too gets gradually smaller and charge carriers readily flow across the junction. Electrons from n-type are attracted across to the positive bias terminal and the holes from the p-type to the negative terminal. Thus, a majority carrier current flows and the junction is forward biased.



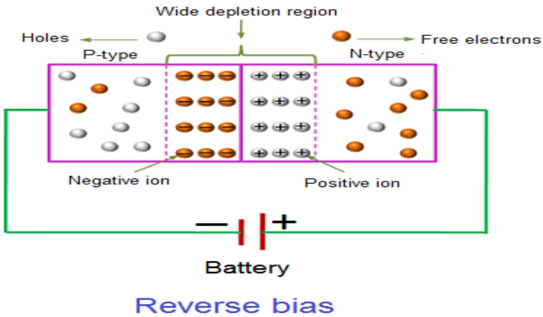
(a) *V-I* characteristic curve for forward bias.



(b) Expanded view of a portion of the curve in part (a). The dynamic resistance r'_d decreases as you move up the curve, as indicated by the decrease in the value of $\Delta V_F / \Delta I_F$.

The graph shows the forward characteristics, i.e., the forward current I_F is plotted against the forward voltage V_F

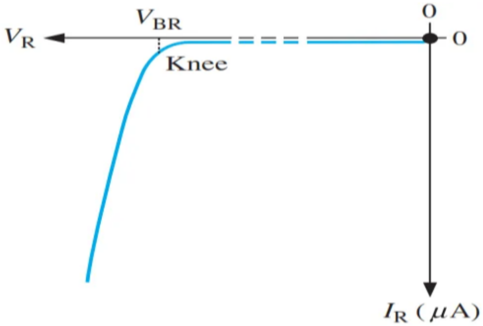
Reverse bias characteristics:



The process by which, a p-n junction diode blocks the electric current in the presence of applied voltage is called reverse biased p-n junction diode. In reverse biased p-n junction diode, the positive terminal of the battery is connected to the n-type semiconductor material and the negative terminal of the battery is connected to the p-type semiconductor material.

On application of an external bias - positive to n-type and negative to p-type, electrons from the n-type are attracted to the positive bias terminal and holes from the p-type are attracted to the negative terminal. As a result, the depletion region is widened and the barrier potential is increased by the magnitude of the applied voltage. Due to the increase in barrier potential and the resultant electric field, it is not possible for the majority carrier current to flow across the junction and the junction is reverse biased. However, minority carriers generated on either side can still cross the junction.

The phenomenon is shown by the junction reverse characteristics.



A small reverse bias voltage is enough to pull across all available minority carriers across the junction. When all the minority carriers have crossed over, any further increase in bias voltage will not increase in current. This is called reverse saturation current.

For a diode, the reverse saturation current is very much smaller than the forward current (I_F). Hence a reverse biased diode considered to be an open switch. At a particular value of high reverse voltage, the reverse current suddenly shoots up, resulting in overheating and diode is said to be in the breakdown region.

Diode equation:

The diode equation relates the current flowing through a diode to the voltage across it. It is given by:

$$I = I_s \left(e^{\left(\frac{V_D}{\eta * V_T}\right)} - 1 \right) ---------- (1)$$

Where I is the diode current, I_s is the reverse saturation current (a small current that flows when the diode is reverse biased), V_D is the voltage across the diode, η is the ideality factor (a dimensionless parameter that accounts for non-ideal behavior), and V_T is the thermal voltage (kT/e, where k is Boltzmann's constant, T is the temperature in Kelvin, and e is the charge of an electron).

The diode equation can be used to describe the forward and reverse characteristics of a diode.

For the **forward characteristics**, when the diode is forward-biased, its voltage is positive and the current flowing (I_F) through the diode is given by:

$$I_F = I_s\left(e^{\left(\frac{V_D}{\eta * V_T}\right)} - 1\right) ----------(2)$$

$$When\ V_D >>> V_T,\ e^{\left(\frac{V_D}{\eta * V_T}\right)} >>>> 1$$

Equation (2) reduces to $I_F = I_s e^{\left(\frac{V_D}{\eta * V_T}\right)}$

Which shows that that the diode current increases exponentially as the forward voltage increases, and the diode is said to be in the forward-active region.

The forward-bias diode equation is useful for analyzing and designing circuits that use diodes, as it allows us to calculate the expected current flowing through the diode as a function of the applied forward voltage

The diode equation for **reverse bias characteristics** describes the reverse leakage current (I_R) that flows through a diode when it is reverse biased. It is given by:

$$I_R = I_s\left(e^{\left(\frac{V_D}{\eta * V_T}\right)} - 1\right) ----------(3)$$

When reverse or negative voltage is applied across the diode, V_D is negative.

$$When\ V_D >>> V_T,\ \ e^{\left(\frac{-V_D}{\eta^* V_T}\right)} = \frac{1}{e^{\left(\frac{V_D}{\eta^* V_T}\right)}} <<< 1$$

Equation (3) reduces to $I_R = I_S$

In the reverse bias region, the diode current increases exponentially with increasing reverse voltage, and the diode behaves like a nearly constant-voltage source.

Note: the diode equation is an approximation and does not account for all possible diode behaviors, such as temperature effects or reverse breakdown.

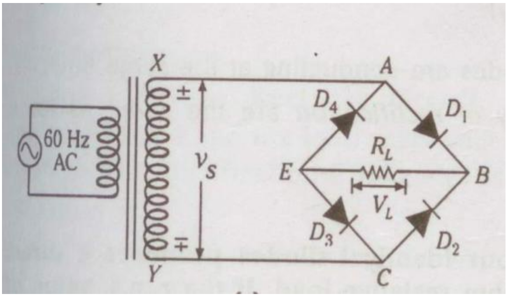
Application: **Bridge Rectifier**

A bridge rectifier is an electronic circuit that converts an alternating current (AC) voltage into a direct current (DC) voltage. It consists of four diodes connected in a bridge configuration that allows the current to flow in one direction, regardless of the polarity of the AC input voltage.

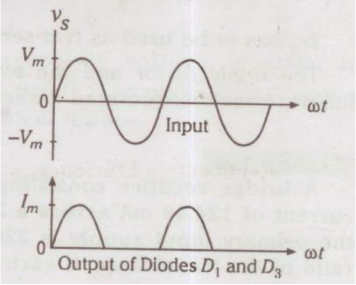
The AC voltage is applied across the two input terminals of the bridge rectifier. Each pair of diodes conducts in turn, allowing the current to flow in only one direction through the load. This process of converting AC to DC is called rectification.

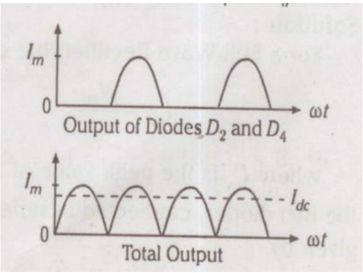
The advantage of using a bridge rectifier over a half-wave rectifier is that the former provides a higher output voltage and efficiency, as it uses the entire cycle of the AC input voltage. This makes it a commonly used component in power supplies for electronic devices and in many other applications where DC power is needed.

Bridge rectifiers are in the same class of electronics as half-wave rectifiers and full-wave rectifiers. Figure shows such a bridge rectifier composed of four diodes D_1, D_2, D_3, and D_4 in which the input is supplied across two terminals A and C in the figure while the output is collected across the load resistor R_L connected between the terminals E and B.



During the positive input half cycle, terminal X of the secondary is positive and terminal Y is negative. Diodes D_1 and D_3 become forward biased (ON), where as D_2 and D_4 are reverse-biased (OFF). Hence current flows along XABECY producing drop across R_L. During the negative input half cycle, secondary terminal Y becomes positive and X becomes negative. Now D_2 and D_4 are forward biased and current flows along YCBEAX. Thus, we see that current passes through the load resistance R_L in the same direction (BE) during both the half cycles of ac input supply. The output voltage across R_L is shown in figure.





Breakdown mechanism in diodes:

An ordinary p-n junction diode does not conduct when it is reverse biased, if the reverse bias is increased and exceeds a threshold value the junction breaks down and starts conducting heavily. This critical value of the voltage is called breakdown voltage of the junction.

The breakdown voltage depends on the width of the depletion region and doping levels of p and n regions. This can occur through mechanisms such as avalanche breakdown or Zener breakdown, depending on the specific characteristics of the device.

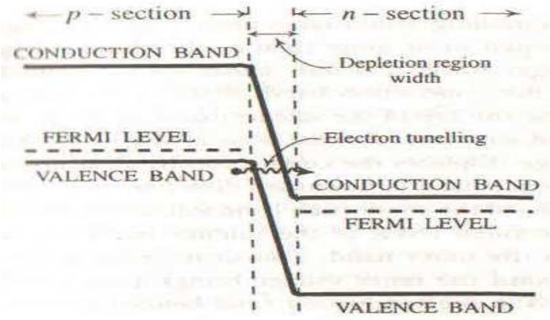
Avalanche breakdown:

Avalanche breakdown is a type of reverse breakdown mechanism that can occur in a p-n junction diode or other semiconductor device. When p and n regions are lightly doped, a breakdown due to avalanche effect occurs in a crystal. In a reverse bias condition, the current in the circuit is mainly due to minority carriers. These carriers fall down the potential barrier and acquire energy. The charge carriers collide with the crystal ions and impart their energy to it in the process. If the reverse voltage is increased further accelerates minority carriers across the junction. The velocity of the minority carriers is proportional to the bias voltage. The accelerated minority carriers acquire sufficient kinetic energy to knock off electrons by disrupting the covalent bonds during collision in the depletion under the influence of external electric field and causes further ionisation of more atoms resulting in a chain reaction. This cumulative effect is known as avalanche breakdown. This creates a self-sustaining avalanche effect that leads to a rapid increase in current flow through the device.

Zener breakdown

When the p and n regions are highly doped, breakdown in a junction occurs even by applying a small reverse voltage across the junction. This sets up a very high electric field across the narrow depletion region and ruptures the covalent bond of atoms and creates electron –

hole pairs leading to sharp increase in the reverse current such a breakdown is known Zener breakdown.



This breakdown does not involve collisions of carriers with the ions of the crystal, as in the case of avalanche effect. This results in a voltage drop across the diode that remains relatively constant, making Zener diodes useful for voltage regulation and other applications.

Zener diode as voltage regulator:

Zener diode is a semiconductor diode specially designed to operate in the breakdown region of reverse bias. By varying the impurity concentration and other parameters, it's possible to design the breakdown voltage to suit specific applications

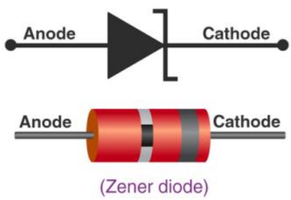
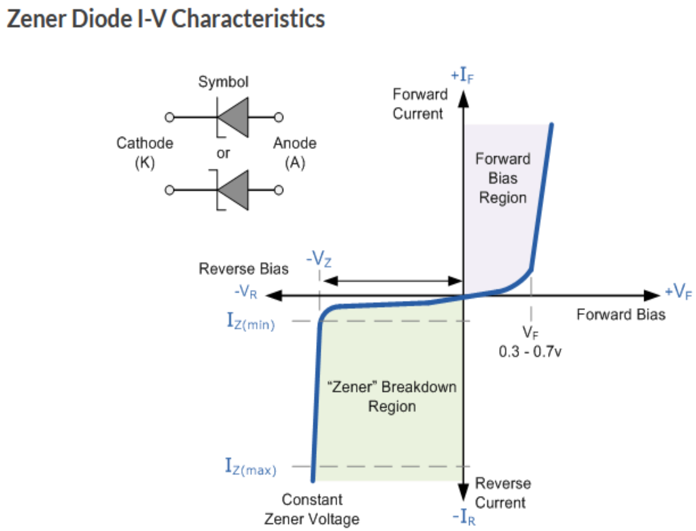


Figure: Schematic representation of zener diode

Zener diode works similar to ordinary diode under forward bias condition. However, the reverse bias characteristic is different from that of an ordinary diode.

A zener diode is a type of diode that is designed to operate in the reverse-bias breakdown region. When a zener diode is reverse-biased and the applied voltage reaches a certain value known as the breakdown voltage, the diode starts conducting current in the reverse direction. The voltage at which the sudden increase in reverse current occurs is called zener breakdown voltage or zener voltage (V_Z).



Zener diodes can be used as voltage regulators because they are able to maintain a nearly constant voltage level even when the input voltage varies over a wide range. Voltage regulation is a measure of a circuit's ability to maintain a constant output voltage when either input voltage or load current varies.

The circuit arrangement is as shown in the figure 8. The power supply provides the input voltage (V_i) and R is the current limiting resistor. The load resistor (R_L) is connected in parallel with the diode across which constant output is desired.

The total current I passing through R equals the sum of diode current and load current ($I = I_z + I_L$)

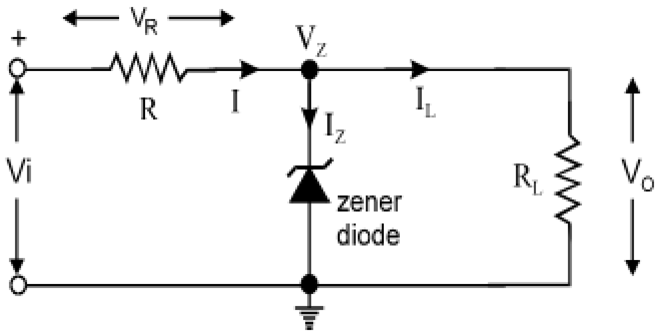


Figure 8 : Circuit diagram

This circuit makes use of the fact that under reverse bias breakdown voltage, the voltage across the zener diode remains constant even if larger current drawn. Since the resistance R_L is parallel to the zener diode, the voltage across the load resistance does not vary even though the current through the load changes. Hence, the voltage across the load is regulated against the variations in the load current.

Operation:

Case 1: We assume that the load resistance R_L is constant and V_i is varying.

As R_L is constant, I_L is also constant because $I_L = V_Z / R_L$. But supply current keeps changing due to change in V_i. The current through R is $I = \frac{V_i - V_z}{R}$ and is the sum of $I = I_z + I_L$.

If V_i increases, then the current I will increase. But as V_z and R_L are constant, the load I_L will remain constant. Naturally, the increase in current will increase zener current I_Z. Thus, the increase in I will be absorbed by the zener diode without affecting I_L. The increase in V_i results in a larger voltage drop across R by keeping V_o as constant.

If V_i decreases, I will decrease causing I_z to decrease. The diode takes a smaller current and voltage drop across R is reduced. As a result the output V_o remains constant. Thus, whenever V_i changes I and IR drop is such a way as to keep V_o constant.

Case 2: We assume that V_i is constant and the load resistance R_L is varying.

If R_L decreases then I_L will increase. But as I is constant, the zener current will decrease thereby keeping I and IR drop constant. The output voltage remains constant.

If R_L increases then I_L will decrease. With decrease in I_L, the zener current I_Z will increase in order to keep I and IR drop constant. Again, the output voltage remains constant.

Bipolar Junction Transistor

Introduction:

A transistor is a semiconductor device that is used to amplify or switch electronic signals. It is a fundamental component of modern electronics and is used in a wide variety of applications, including computer processors, audio amplifiers, power regulators, and many more. The transistor was invented in 1947 by William Shockley, John Bardeen, and Walter Brattain at Bell Labs. The invention of the transistor marked a major milestone in the development of electronics and paved the way for the modern computer age.

Transistors are typically made from materials such as silicon or germanium, which have properties that make them suitable for use as semiconductors. They consist of three layers of material: a P-type layer, an N-type layer, and another P-type layer, or an N-type layer, a P-type layer, and another N-type layer. These layers are carefully designed and arranged to create a device that can control the flow of electrons through it.

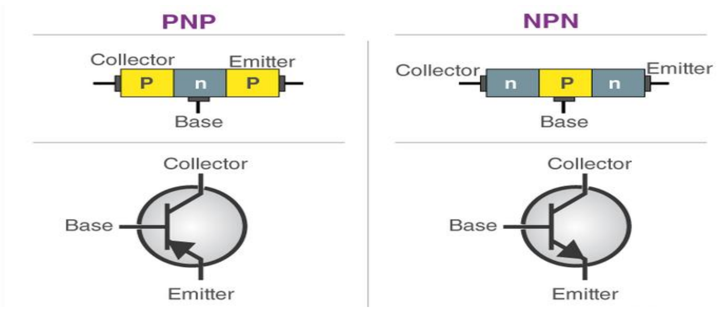
Transistors can be classified into two main types: bipolar junction transistors (BJTs) and field-effect transistors (FETs). BJTs have three layers and are controlled by the flow of current through the base terminal, while FETs have three terminals and are controlled by the electric field created by the voltage applied to the gate terminal.

Transistors have revolutionized the world of electronics and have made possible many of the technological advances that we enjoy today. Their ability to amplify and control electronic signals has led to the development of smaller, faster, and more powerful devices, and they continue to be an essential component of modern electronics. We study about BJT in this unit.

What is bipolar junction transistor?

A **transistor** is a semiconductor device consisting of three regions separated by two distinct junctions. The central region is called ***base***. It may be p-type or n-type semiconductor. The two outer regions are called ***emitter*** and ***collector***. They are of the same type extrinsic semiconductor but different from that of base. Thus, if the base is p-type the emitter and collector are n-type and if the base is n-type the emitter and collector are p-type.

Thus, two types of transistors are available as shown in figure. They are called npn and pnp transistors.



In a junction of the pnp type, a thin layer of n-type silicon is sandwiched between two layers of p-type silicon. Alternatively, a junction transistor of npn type consists of a semiconductor crystal in which a thin layer of p-type semiconductor is sandwiched between two layers of n-type semiconductor.

The n-region contains free electrons and p-region contains holes. Thus, two types of charge carriers namely holes and electrons are involved in current flow through npn or pnp transistor. Therefore, these transistors are known as bipolar junction transistors.

In pnp transistor, the arrow points toward the base. In this device holes flow from the emitter into the base and hence the current flows from the emitter into the base. In npn transistor, the arrow points away from the base. In this device electrons flow from the emitter into the base and hence the current flows from the base to the emitter.

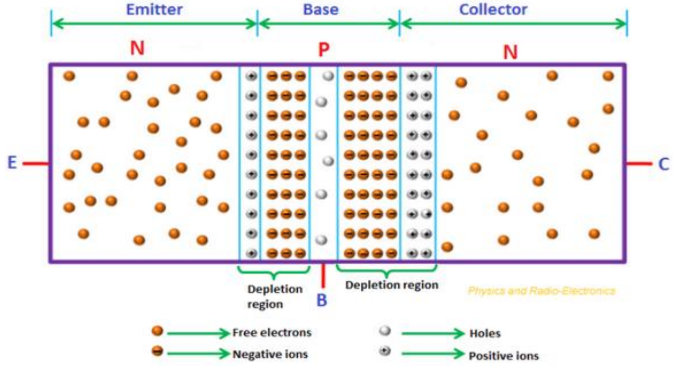
The function of each element is as follows:

1. The emitter provides the majority carriers necessary to support current flow
2. The base controls the flow of the majority carriers within all elements of the transistor.
3. The collector supports the majority of the current flow in the transistor.

Formation of depletion regions:

Transistor is a piece of crystalline material that has been doped to create the three elements. Each transistor has two p-n junctions. The junction that separates the base and the emitter is called the ***emitter-base (EB)*** junction and one separating the base and the collector is called the ***collector-base (CB)*** junction.

During the process of formation of junctions, diffusion of majority carriers takes place and depletion layers form. As the doping levels in the three regions are different, the two depletion layers form with different widths. Because emitter is heavily doped and the base is lightly doped the depletion layer at EB junction penetrates slightly into the emitter region and deeply into the base region. Similarly, at the CB junction, the depletion layer extends into the base region while it penetrates to a lesser extent into the collector region. This results in a narrow depletion layer at EB junction and a wide depletion layer at CB junction. The base region becomes thinner compared to its physical dimension, as two depletion layers encroach on it.



The two p-n junctions can be viewed as two diodes. Therefore, a transistor may be regarded as two p-n junctions arranged back to back with the base being common to both the diodes. As both the diodes have the base in common, they influence each other strongly

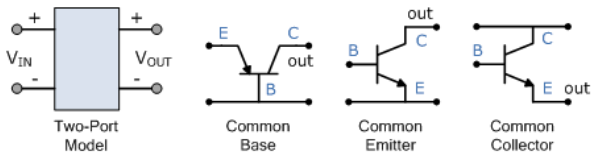
Transistor configurations

A transistor being a three terminal device, it can be connected in the three electrical modes, with one terminal common to both, the input and output. The basic three modes are

1. Common base(CB) mode
2. Common emitter (CE) mode
3. Common collector (CC) mode

Whenever, a transistor is connected in any mode, it should be remembered that the basic bias conditions are satisfied, i.e the emitter-base junction is forward biased and the collector-base junction is reverse-biased.

Bipolar Transistor Configurations



Any two-port network which is analogous to transistor configuration circuits can be analyzed using three types of characteristic curves.

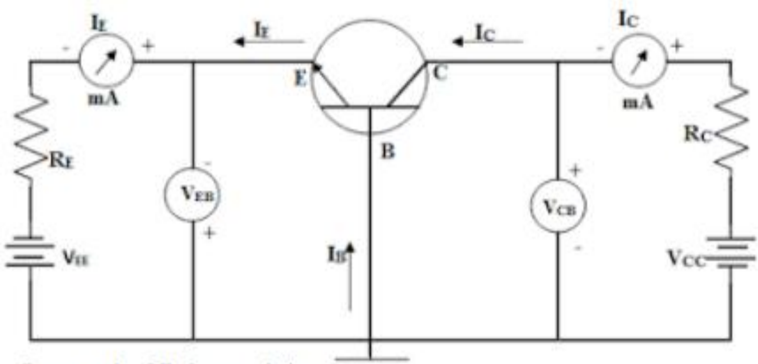
Input Characteristics: The curve describes the changes in the values of input current with respect to the values of input voltage, keeping the output voltage constant.

Output Characteristics: The curve is obtained by plotting the output current against output voltage, keeping the input current constant.

Current Transfer Characteristics: This characteristic curve describes the variation of output current in accordance with the input current, keeping the output voltage constant.

Common Base Configuration

Consider an n-p-n transistor in common base configuration. In this common base configuration, emitter current I_E is the input and collector current I_C is the output current.

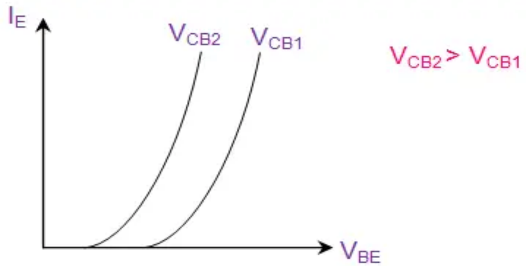


Setup to plot CB charscteristic

The above figure shows that the experimental arrangement for determining the static characteristic of an n-p-n transistor in common-base mode. In this mode emitter base junction is forward biased and collector base junction is reverse biased. Two variable dc regulated power supplies V_{EE} and V_{CC} are connected to emitter and collector terminals of a transistor in the circuit. Two milli-ammeters and voltmeters are required to note down the current and voltage to study the I-V characteristics.

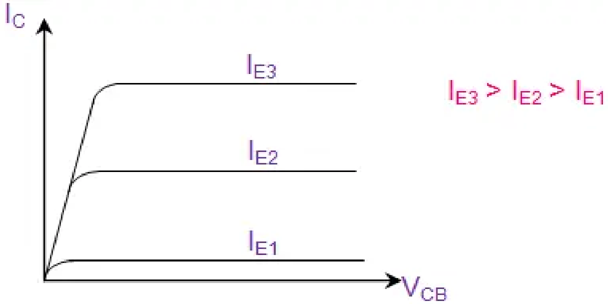
Input Characteristics

To plot the input characteristics, the collector to base voltage V_{CB} be kept constant. The emitter to base voltage V_{EB} is varied in small steps and the corresponding values of emitter current I_E are noted for each value of V_{EB}. Similar graphs for other values can be plotted by keeping V_{CB} constant as shown in figure.



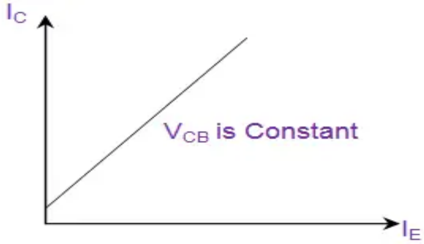
Output Characteristics

The emitter current, I_E is kept constant. The collector to base voltage (V_{CB}) is varied from zero in suitable steps and corresponding values of I_C are noted. The experiment is repeated for different values of I_E. The output characteristic curves obtained are shown in figure.



Current transfer characteristics

To plot current transfer characteristics, for a common base mode, keeping collector to base voltage constant V_{CB}, the emitter current (I_E) is slowly increased in steps corresponding collector current (I_C) is noted. A graph is plotted between I_C along y-axis and I_E along x-axis. The graph is a straight line as shown in figure. The transfer characteristic is ne



In a common base circuit, the current gain is defined as the ratio of the change in collector current and the emitter current at a constant collector-base voltage.

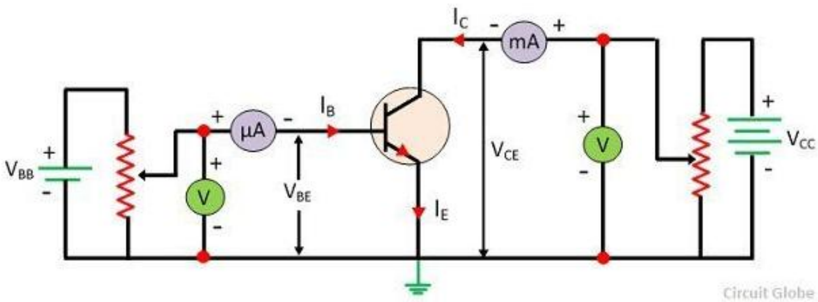
The current gain is denoted by **α** and is given by

$$\alpha = \left(\frac{\Delta I_C}{\Delta I_E}\right)_{V_{CB}}$$

Where ΔI_C and ΔI_E are the magnitude of the collector current and emitter currents.

Common Emitter Configuration

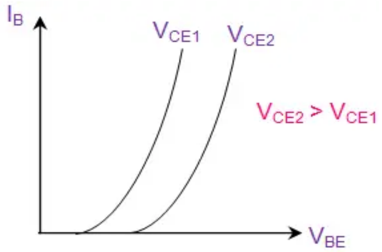
Consider an n-p-n transistor in *common emitter configuration.* In this configuration the base current I_B is the input current and collector current I_C is the output current.



The above figure shows that the experimental setup for determining the static characteristic of an n-p-n transistor used in a common emitter configuration circuit. Two variable dc regulated power supplies V_{BB} and V_{CC} are connected to base and collector terminals of a transistor. A micro ammeter and a voltmeter are connected to measure the base current I_B and V_{BE}, and a milli ammeter and a voltmeter are connected to measure I_C and V_{CE} in the circuit.

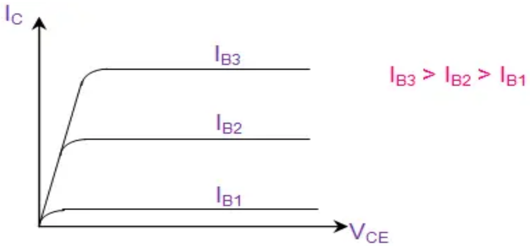
Input Characteristics:

The input characteristic curves are obtained by plotting base emitter voltage V_{BE} versus base current I_B keeping V_{CE} constant. The characteristic curves are plotted for various values of collector to emitter voltage V_{CE} as shown in figure.



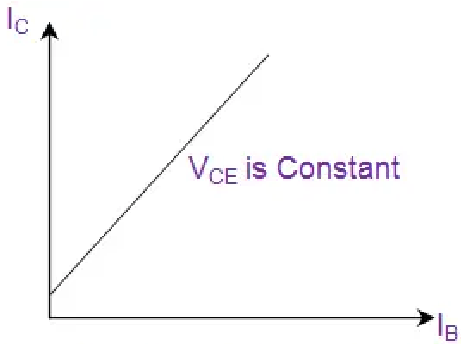
Output characteristics

To plot this characteristic curves, the base current I_B is maintained at a suitable constant value. The collector emitter voltage V_{CE} is varied in small steps from zero and the corresponding collector current I_C is noted. A graph is plotted between collector current I_C along y-axis and collector emitter voltage V_{CE} along x-axis. The procedure is repeated for other fixed values of I_B.



Current transfer characteristics

To plot current transfer characteristics for a common emitter mode, collector emitter voltage V_{CE} is maintained at a constant value, the base current I_B is varied in steps and the corresponding collector current I_C is noted. A graph is plotted between I_C taken along y-axis and I_B along x-axis. The characteristics obtained as shown in figure.



It is clear from the graph that a small change in base current produces a large change in collector current for a constant collector-emitter voltage.

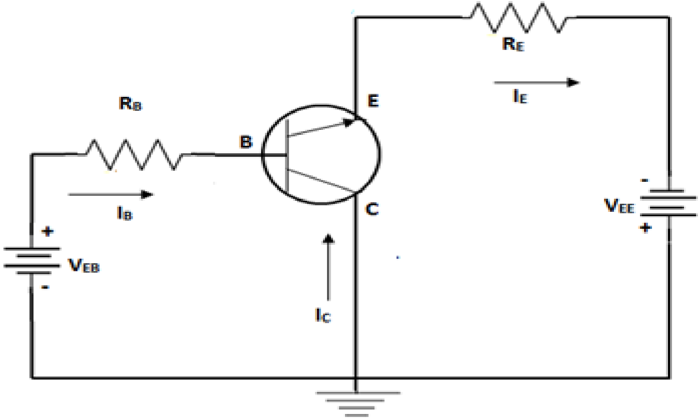
In a common emitter circuit, the current gain is defined as the ratio of the change in collector current and the base current at a constant collector-emitter voltage. The current gain is denoted by a letter β.

$$\beta = \left(\frac{\Delta I_C}{\Delta I_B}\right)_{V_{CE}}$$

Where ΔI_C and ΔI_B are the magnitude of the collector current and emitter currents.

Common Collector Configuration:

Consider n-p-n transistor in ***common collector configuration*** as shown in the figure. In this configuration, the base terminal of the transistor serves as the input, the emitter terminal is the output and the collector terminal is common for both input and output. Hence, it is named as common collector configuration. The input is applied between the base and collector while the output is taken from the emitter and collector.



The dc current gain is given by γ_{dc} as

$$\gamma_{dc} = \left(\frac{\Delta I_E}{\Delta I_B}\right)_{V_{CE}}$$

The common collector configuration is used for impedance matching purposes since it has high input impedance and low output impedance; opposite to that of the common-base and common-emitter configuration.

Relation between current gain of common base (α) and common emitter (β)

The d c current gain for a common emitter is given by $\beta = \frac{I_C}{I_B}$ and

For common base configuration is given by $\alpha = \frac{I_C}{I_E}$

The emitter current is given by $I_E = I_B + I_C$ or $I_B = I_E - I_C$

Hence α and β are dependent on each other

$$\beta = \frac{I_C}{I_E - I_C}$$

Dividing numerator and denominator by I_E we get

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

Similarly $\alpha = \frac{I_C}{I_B + I_C}$

Dividing numerator and denominator by I_B we get

$$\alpha = \frac{I_C / I_B}{1 + I_C / I_B}$$

$$\alpha = \frac{\beta}{1+\beta}$$

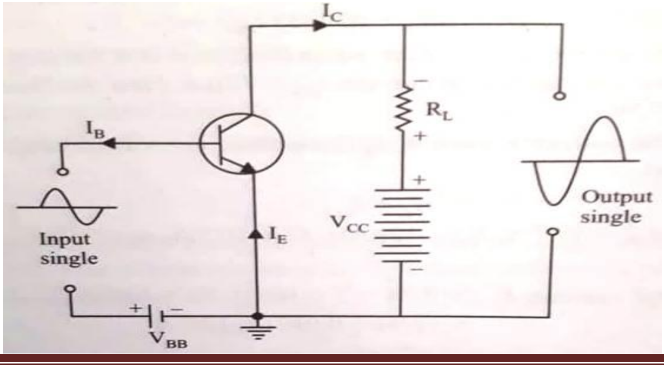
Transistor as an amplifier

An amplifier is an electronic circuit that causes an increase in the voltage or power level of a given signal. Accordingly amplifiers are classified as current amplifiers, voltage amplifiers and power amplifiers respectively. Transistor amplifiers are used in a wide range of electronic devices, including radios, televisions, and audio amplifiers. They offer high gain, low noise, and low distortion, making them ideal for amplifying small signals from microphones, sensors, and other sources.

A transistor can be employed as an amplifier in anyone of the three modes (1) Common base amplifier (2) Common collector amplifier and (3) Common emitter amplifier.

Common Emitter Amplifier:

Basic circuit of common emitter amplifier using npn transistor:



The battery V_{BB} provides the necessary forward bias between emitter base junction and another battery V_{CC} provides the reverse bias between collector base junction. A load resistance R_L is connected in the collector circuit as shown in figure. The signal to be amplified is applied at the input and an amplified output is obtained between collector and the ground.

Working: When no signal is applied, some d.c collector current flows through the load R_L. Hence voltage drop across R_L is $I_C R_L$ is in opposition to the collector supply voltage V_{CC} and hence the collector voltage is reduced to some value say V_C is given by $V_C = V_{CC} - I_C R_L$

Suppose now a signal from signal source say A.F.O (Audio Frequency Oscillator) is applied at the input. During the positive half cycle of the first cycle, the forward bias of the junction increases. This increases the emitter current. Since $I_E = I_B + I_C$, the increase in I_E will increase the collector current I_C and there by voltage drop across R_L increases. But the output is given by $V_C = V_{CC} - I_C R_L$

Thus, increase in $I_C R_L$ will result in decrease in V_C i.e., the collector becomes more negative. In other words, we get a negative half cycle at the output corresponding to the positive half cycle at the input.

During the negative half cycle, the forward bias of p-n junction (i.e. emitter-base) decreases, this decreases the emitter current. Correspondingly collector current decreases and hence voltage drop at the load resistance R_L decreases. This results in increase of collector voltage V_C and we get a positive half cycle at the output corresponding to the negative half cycle at the input. Thus we conclude that in a common emitter circuit, the input and output voltages are out of phase i.e. 180^o.

Voltage gain of CE Amplifier

$$\text{The a.c base current}, \quad i_b = \frac{v_i}{R_i}$$

Where v_i = a.c input voltage

R_i = input a.c. resistance in CE mode

The current gain in CE mode is given by $\beta = \frac{i_c}{i_b}$

$\therefore$ the collector a.c current, $i_c = \beta i_b = \beta \frac{v_i}{R_i}$

The magnitude of the output volatge = $|v_o| = i_c R_L = \frac{\beta v_i R_L}{R_i}$

Hence the magnitude of the voltage gain in CE mode is

$$|a_v| = \frac{|v_o|}{|v_i|} = \frac{\frac{\beta v_i R_L}{R_i}}{v_i} = \frac{\beta R_L}{R_i}$$

Since β is very large for most of the transistors, R_L is taken large and R_i is moderate, the voltage gain of CE amplifier is large, Hence CE mode is popular and it has large voltage and power gain.

Advantages of CE Amplifier

The common emitter amplifier is widely used as it has the following advantages:

1. The current gain (β) is very large.
2. The voltage gain is also very high.
3. The power gain is very large.
4. Since the input and output impedance do not differ much from each other, large number of stages can be cascaded to achieve the desired gain.
5. The input impedance of the CE amplifier is relatively high, making it easy to interface with different input sources without affecting the signal.

Disadvantages of CE Amplifier

1. The CE amplifier is temperature-dependent, which means that changes in temperature can affect its performance. The biasing circuit must be designed to compensate for these changes.
2. The frequency response of CE amplifier is fairly poor, particularly at high frequency as compared to CB and CC mode, because of its large effective input capacitance.

Comparison of CB, CE and CC configurations

No	Parameter	Common Base (CB)	Common Emitter (CE)	Common Collector (CC)
1.	Input Resistance (R_i)	Low	Low	Very High
2.	Output Resistance (R_o)	Very High	High	Low
3.	Current gain	α - Less than 1	β - 100 to 500 (High)	γ - about 35 (Moderate)
4.	Voltage gain	100-1000	250-300	Less than 1
5.	Power gain	20-30	40	15-30
6.	Applications	For high frequency (RF and VHF)	For audio frequency (20Hz to 20KHz)	For impedance matching

Q.No	Sample Questions	CO
1.	What is pn junction diode?	**1**
2.	Explain the term depletion region.	**1**
3.	Explain the equilibrium condition in unbiased p-n unction.	**2**
4.	Draw a neat energy band diagram of a p-n junction at equilibrium and explain the formation of a conduction hill and a valence hill.	**2**
5.	Explain the mechanism of current flow in forward and reverse biased p-n junction. Draw the I-V characteristics of a p-n junction diode under both modes.	**2**
6.	What is reverse breakdown? Explain the mechanism in details of (i) Avalanche breakdown (ii) Zener breakdown.	**1**
7	Explain how zener diode is different from an ordinary p-n	**1**

	junction diode.	
8	Explain function of zener diode with the help of I-V characteristics.	1
9.	Explain the effect of forward and reverse biasing on the width of the depletion region.	2
10.	Explain how zener diode can be used as a voltage regulator.	2
11.	Explain the three different configurations? Draw the circuit diagrams using p-n-p and n-p-n transistor.	1&2
12.	Explain the input and output characteristics of a common base transistor circuit.	1
13.	With the help of an experimental arrangement, explain how the input, output and transfer characteristics of common emitter mode are studied.	2
14.	Define α and β. Establish the relation between α and β.	2
15.	Why transistor is called an active device? Explain the mechanism of amplification in a transistor. Show that output of a common emitter amplifier is 180^o out of phase with the input signal. Calculate the voltage gain of CE amplifier.	2
16.	List the merits and demerits of CE amplifier.	1

PNo.	Problems	CO
1.	A silicon pn junction diode is formed from p-material doped with 10^{22} acceptors / m^3 and n-material doped with 1.2 x10^{21} donors / m^3. Find the thermal and barrier voltage at 25°C. **Solution:** T= 273+25= 298K, n_i=1.5 x $10^{16}/m^3$ Thermal voltage $V_T = \frac{kT}{e} = \frac{(1.38\times10^{-23})\times298}{1.6\times10^{-19}} = 25.7mV$ Using relation for barrier potential V_o, we get $V_o = V_T \ln\frac{N_D N_A}{n_i^2} = 25.7\times10^{-3}\ \ln\frac{10^{22}\times1.2\times10^{21}}{2.25\times10^{32}}$ $V_o = (0.0257)(24.699) = 0.635V$	3

<table>
<tr><td>2.</td><td>A transistor with an α =0.99 is operated in a common emitter configuration. What is the maximum alternating current gain?
Solution:
$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.99}{1-0.99} = 99$$</td><td>3</td></tr>
<tr><td>3.</td><td>The current gain of transistor in common emitter (CE) configuration is 49. What will be the current gain of the same transistor in common base (CB) configuration?

Solution:
$$\beta = \frac{\alpha}{1-\alpha} \qquad 49 = \frac{\alpha}{1-\alpha}$$
$$\alpha = 49(1-\alpha) \quad \alpha = \frac{49}{50} = 0.98$$</td><td>3</td></tr>
<tr><td>4.</td><td>Find I_C and I_E for a transistor. Given that α = 0.96 and I_B = 110μA. Also calculate the β of the transistor.
Solution:
$$\alpha = \frac{I_C}{I_E} \quad I_C = \alpha\ I_E = \alpha\ (I_C + I_B)$$
$$I_C = \frac{\alpha\ I_B}{(1-\alpha)} = \frac{0.96 \times 110\mu A}{(1-0.96)} = 2.64mA$$
$$I_E = \frac{I_C}{\alpha} = \frac{2.64mA}{0.96} = 2.75mA$$
$$\beta = \frac{\alpha}{(1-\alpha)} = \frac{0.96}{(1-0.96)} = 24$$</td><td></td></tr>
<tr><td>5.</td><td>Claculate α and I_B for a transistor which has I_C = 2.5mA and I_E = 2.6mA. Also determine β for the transistor.

Solution:
$$\alpha = \frac{I_C}{I_E} = \frac{2.5mA}{2.6mA} = 0.96$$
$$I_B = I_E - I_C = 2.6mA - 2.5mA = 0.1mA = 100\mu A$$
$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.96}{1-0.96} = 24$$</td><td></td></tr>
</table>

6.	An unregulated d.c supply of 40V is applied to a shunt zener regulator to give a regulated output of 10V. The series resistor is 3kΩ. Calculate the current through the zener diode and also current through load resistor of 2kΩ. **Solution:** Zener breakdown voltage V_z = 10V, unregulated input voltage V_i = 40V. Hence ($V_i - V_o$) = (40-10)=30V must drop across the series resistor R_S of 3kΩ The current I through the resistor R_S $I = \frac{30}{3\times10^3} = 10\times10^{-3} = 10mA$ The volatge across load $R_L = 2k\Omega$ is 10V. Hence current through R_L is $I_L = \frac{10}{2\times10^3} = 5\times10^{-3} = 5mA$ We know that $I=I_z + I_L$ The current through the zener is $I_z = I - I_L = 10mA - 5mA = 5mA$	**3**