Introduction

We know that earlier electronic devices were made up of vacuum tubes or valves

Vacuum tubes or Valves:

- The evolution of vacuum tubes started with diode and proceeded to triode, tetrode and pentode
- Valves control the flow of electrons; In diodes, there were two electrodes – cathode and anode
- Similarly, triode had three electrodes – cathode, grid and anode; tetrode had four electrodes – anode, two grids and cathode; pentode had five electrodes –anode, three grids and cathode
- Generally in vacuum tubes, the electrons are produced by heating the cathode using low tension battery; The vacuum helps in electron not losing its energy by collision with air molecules in the way
- However, the vacuum tube devices had some disadvantages and they are
  - Bulky
  - Operate at high voltages
  - Consume more power
  - Have limited life
  - Low reliability

Diodes and transistors

- Next came the discovery of semiconductor junction, namely, junction diode and transistors
- These replaced the vacuum tubes or valves

- The advantages of semiconductor devices are
  - Small in size
  - Operate at low voltages
  - Consume small power
  - Long life
  - High reliability
- Though the above advantages are present, the circuits consisting of transistors were still bulky, less shock proof
- Hence, it led to the discovery of integrated circuits which is a major revolution in the electronic industry

Example – The earlier generation television and computer monitors were very bulky as they were based on the principle of vacuum tubes; now days, we have LCD (Liquid Crystal Display) monitors which support solid state electronics

Classification of metals, semiconductors and insulators

On the basis of conductivity

The conductivity of a material indicates whether they can be classified as metals, semiconductors or insulators

The electrical conductivity is expressed as σ whereas the reciprocal of conductivity is resistivity $\rho = 1/\sigma$

- Metals – Metals have high conductivity and low resistivity ; ρ is of order10^{-2} to 10^{-8} Ω m ; σ is of order 10^{2} to 10^{8} S/m

Aluminium (Metals)

- Semiconductors – They have conductivity and resistivity in between metals and insulators ; ρ is of order 10^{-5} to 10^{-6} Ω m ; σ is of order 10^{5} to 10^{6} S/m

Silicon (Semiconductors)

- Insulators – They have high resistivity and hence low conductivity ; ρ is of order 10^{-11} to 10^{-19} Ω m ; σ is of order 10^{2} to 10^{19} S/m

Wood (Insulator)

Classification of semiconductors

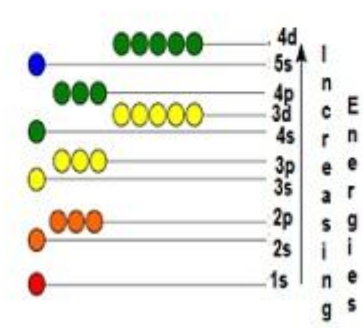
The semiconductors can be classified into Elementary type semiconductor and compound type semiconductor

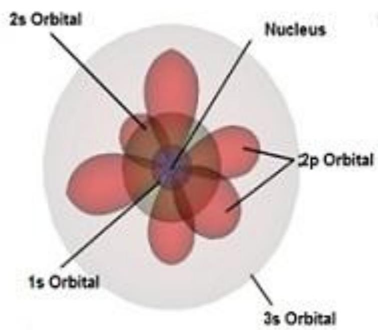
- Elementary type semiconductor – These type of semiconductors are available in natural form like Silicon (Si) and germanium (Ge)
- Compound type semiconductor – When semiconductors are made by compounding the metals, we get compound type semiconductor. They can be further classified into

- Inorganic semiconductors like CdS, GaAs etc
- Organic semiconductors like Antracene, doped pthalocyanines
- Organic polymers – Polypyrole, polyaniline, polythiophene

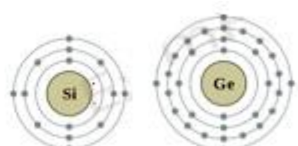
Band theory of solids

In a substance, as many atoms are close to each other, the energy levels of the atom form a continuous band, where in the electrons move. This is called band theory of solids.

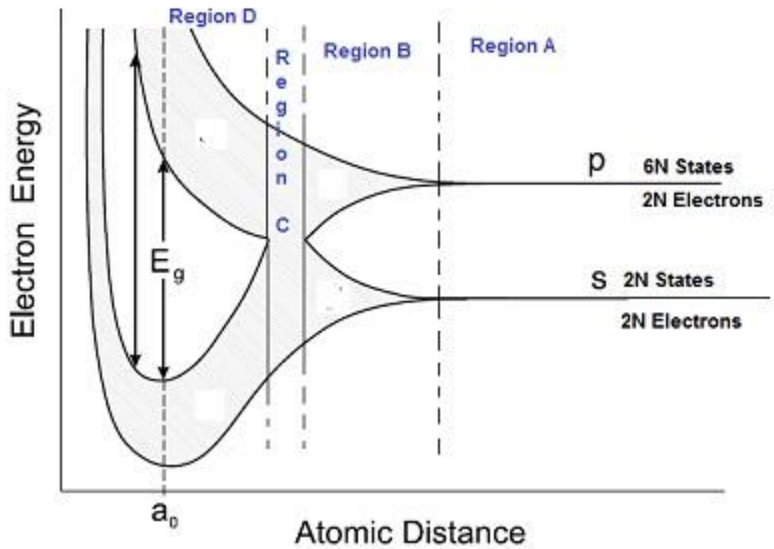




- We know that in an atom, the protons and the neutrons constitute the central part called the nucleus
- The electrons revolve around the nucleus in defined orbits
- The orbits are named as 1s, 2s, 2p, 3s, 3p, 3d etc. each of which has a discrete energy level
- All electrons in the same orbit have the same energy
- The electrons in the innermost orbits which are completely filled constitute the valence electrons whereas the electrons in the outermost orbit which do not completely fill that shell are called conduction electrons
- As seen in the diagram below, both Si and Ge have 4 electrons in the outermost shell



- When in the crystal, the atoms are close to each other and hence they may be flow of electrons from one atom to another in the conduction band
- Let us discuss in detail by considering interatomic distance in the X-axis and energy in the Y-axis:
- As seen in the diagram below, the graph is divided into 4 regions – Region A, B, C and D
- In the region A, the interatomic distance is large between atoms and in region D, the interatomic distance is small



- Region A
- Consider that the Si or Ge crystal contains N atoms. Electrons of each atom will have discrete energies in different orbits
- If the atoms are isolated, that is, separated from each other by a large distance, the electron energy will be the same
- However, in a crystal, the atoms are close to each other separated by a distance of 2-3 A^o. Hence, electrons interact with each other and also with the neighbouring atoms
- The overlap or the interaction will be felt more by the electrons in the outermost orbit while the inner electron energies will remain unaffected
- Hence, in the case of Si and Ge crystals, we need to consider the changes in energies of electron in the outer most orbit only
- For Si, the outermost orbit is the third orbit (n = 3) while for Ge, the outermost orbit is fourth orbit (n = 4)
- The number of electrons in both cases is 4 – namely 2s and 2p. Hence, the outer electrons in the crystal is 4
- The maximum possible number of outer electrons in the orbit is 8 (2s + 6p electrons)
- This is the case of well separated or isolated atoms as shown in region A
- Region B
- Suppose the atoms start coming nearer to each other to form a solid.
- The energies of the electrons in the outermost orbit may increase or decrease, due to the interaction between electrons of different atoms
- The 6N states for l=1, which originally had identical energies in the isolated atoms, spread out and form an energy band as shown in the region B
- Similarly, the 2N states for l = 0 split into a second band separated from the first one
- Region C
- At still smaller spacing, however, there comes a region in which the bands merge with each other
- The lowest energy state that is a split from the upper atomic level appears to drop below the upper state that has come from the lower atomic level
- In this region, no energy gap exists where the upper and the lower energy states gets mixed
- Region D
- If the distance between the atom further decreases, the energy bands again split apart and are separated by an energy gap E_g

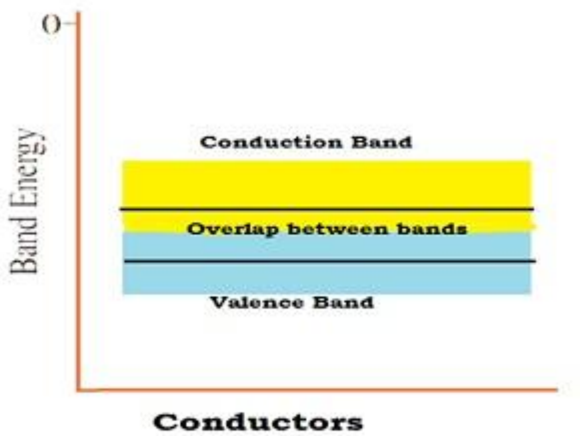
- The total number of available energy states 8N has been re-apportioned between the two bands (4N states each in the lower and upper energy bands)
- Here there are exactly as many states in the lower band (4N) as there are available valence electrons from the atoms (4N)
- This lower band called the valence band is completely filled while the upper band is completely empty. The upper band is called the conduction band

Classification on the basis of energy bands

- Depending upon the relative position of the valence band and the conduction band, the solids can be classified into conductors, insulators and semiconductors

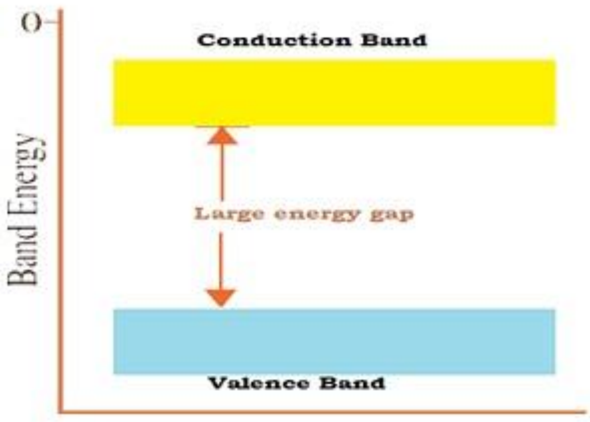
Conductors

- The conduction band and the valence band partly overlop each other and there is no forbidden energy band gap in between
- The electrons from the valence band can easily move into the conduction band
- Hence, large number of electrons are available for conduction
- The resistance of such materials is low and conductivity is high



Insulators

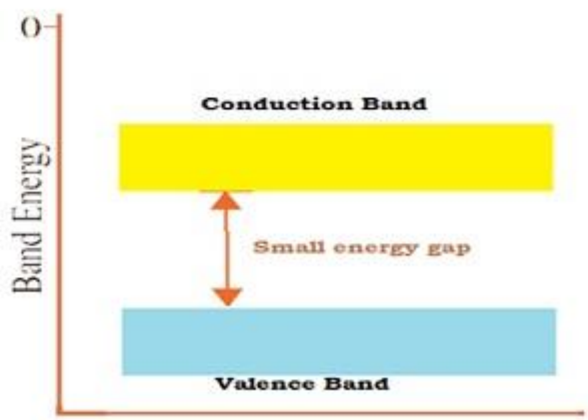
- In case of insulators, a large energy gap exists between the valence band and the conduction band
- The energy gap is so high that the electrons from the valence band cannot move to the conduction band by thermal excitation
- As there is no electrons in the conduction band, electrical conduction is not possible



Insulators

Semiconductors

- A finite but a small energy gap exists between the valence band and the conduction band
- At room temperature, some of the electrons from the valence band acquire energy and move into the conduction band
- Hence, at high temperature, semiconductors have conductivity and resistance is also not as high as insulators



Semiconductors

Types of semiconductors

- There are two types – Intrinsic semiconductor and Extrinsic semiconductor

Intrinsic semiconductor

- A pure semiconductor, free from impurities is called intrinsic semiconductor
    - The electrical conductivity of pure semiconductor is called intrinsic conductivity
    - Structure – Consider pure Germanium and Silicon. Both have 4 valence electrons

Crystalline structure

At temperature 0K –

- In the crystal structure, the four valence electron of the Ge atom forms four covalent bond by sharing of electron with the neighbouring atoms
- Each covalent bond is made of two atoms, each one from each atom
- By forming covalent bond, each Ge atom in the crystal behaves as if the outermost orbit of each atom is complete with 8 electrons, having no free electrons in the crystal

At room temperature

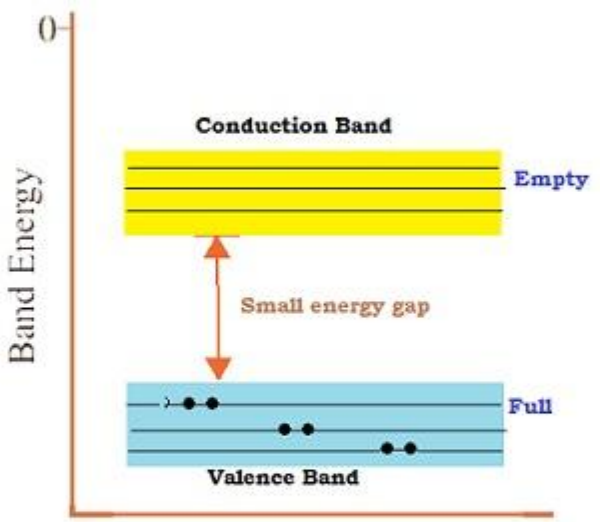
- The conduction is possible if the electrons break away from the covalent bonds and are free by the thermal energy
- When electron breaks away from the covalent bond, the empty space or vacancy left in the bond is called a hole
- An electron from the neighbouring atom can break away and can be attracted by the hole, creating hole in the other place
- In the crystal structure, thus, we can see, electrons break the covalent bond and keep moving. Similarly, due to attraction of hole and electron, hole also keeps moving in a crystal
- Thus, breakage of a covalent bond produces one free electron and one hole in the crystal
- In an intrinsic semiconductor, the number of holes = number of electrons. Thus $n_e = n_h = n_i$

Energy band theory

There is an energy gap of about 1 eV between the valence and the conduction band

At temperature 0K –

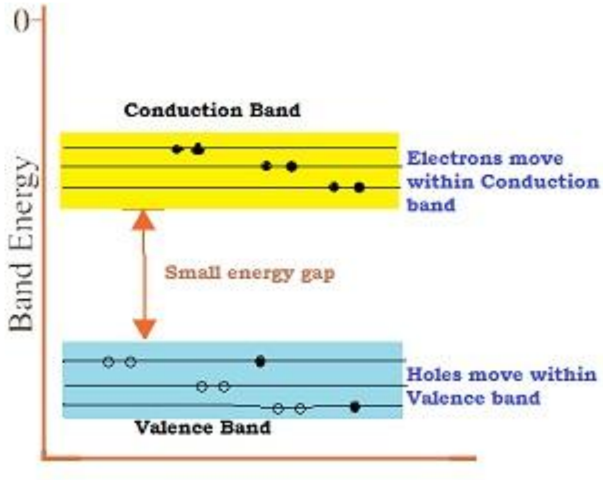
- In terms of energy band theory, the valence band is full and the conduction band is totally empty
- As no electrons are available for conduction, the Ge crystal behaves like a electrical insulator



Semiconductors

At room temperature -

- The thermal vibrations of the atoms provide energy to the electrons in the valence band to cross the energy gap and move into the conduction band as free electrons
- This results in electrical conductivity of the semiconductor
- As electrons move from the valence band to the conduction band, a vacancy is created in the valence band. This vacancy is called a hole
- As electrons move in the conduction band, the holes move in the valence band and electrical conduction in semiconductors is possible



Semiconductors

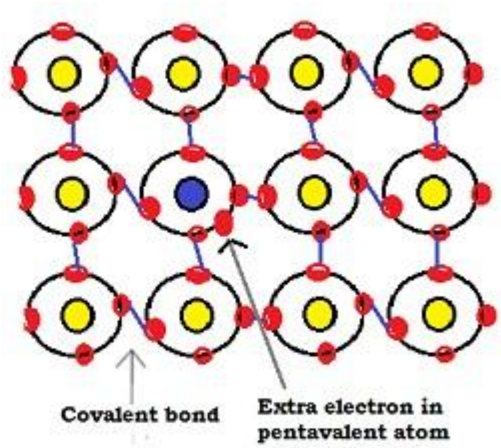
- At a higher temperature, when electric field is applied, the holes move towards the negative potential, giving rise to hole current and electrons move towards the positive potential giving rise to electron current. Thus $I = I_e + I_h$

Extrinsic semiconductor

- A doped semiconductor or a semiconductor with suitable impurity added to it is called extrinsic semiconductor
- There are two types – n-type and p-type
- In n-type semiconductor, the electrons are the majority carriers while the holes are the minority carriers
- In p-type semiconductor, the holes are the majority carriers while the electrons are the minority carriers
- A detailed study of n-type and p-type semiconductors, help us to understand better about the extrinsic semiconductor

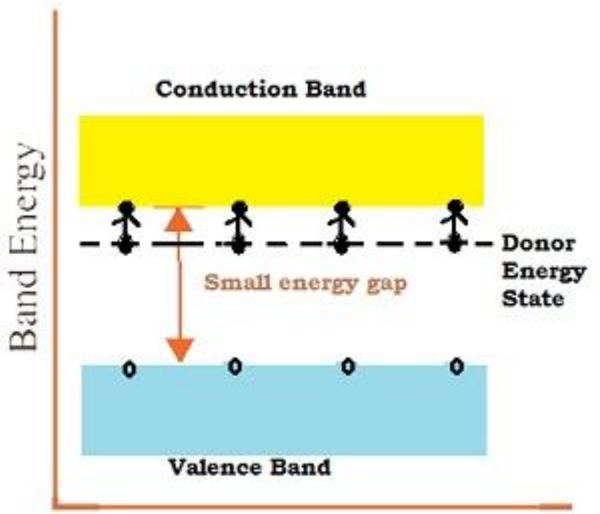
n-type semiconductor

- When pure Si or Ge which has four valency electrons is doped with controlled amount of pentavalent atoms, like Arsenic, Phosphorus, Antimony or Bismuth, we get a n-type semiconductor
- The four valence electron from the impure atom will combine with four electrons of the Si or Ge atom to form 4 covalent bonds
- The fifth electron of the impure atom is free to move. Thus, each atom of the impure substance, donates a free electron for conduction. Hence, it is called as donor atom
- Giving the free electron for conduction, the impure atom becomes positively charged, giving rise to a hole
- Thus in n-type semiconductors, electrons are the majority carriers and holes are minority carriers



Energy band theory

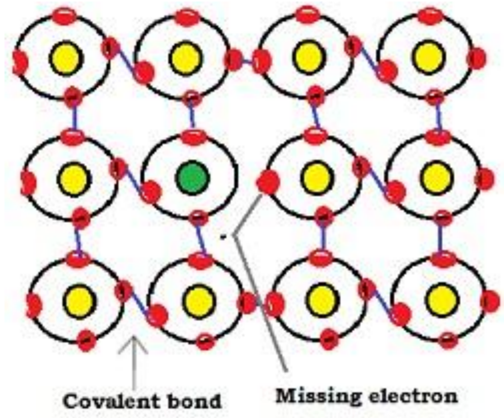
- Comparing Si or Ge doped with impurities like Arsenic with a pure Si or Ge, the lowest energy level of the conduction band is less
- The electrons occupy discrete energy levels called the donor energy level between the valence band and the conduction band
- This donor energy level is below the bottom of the conduction band
- Thus, very small energy supplied can excite the electron from the donor level to the conduction band, hence, conductivity of semiconductor becomes remarkably improved



p-type semiconductor

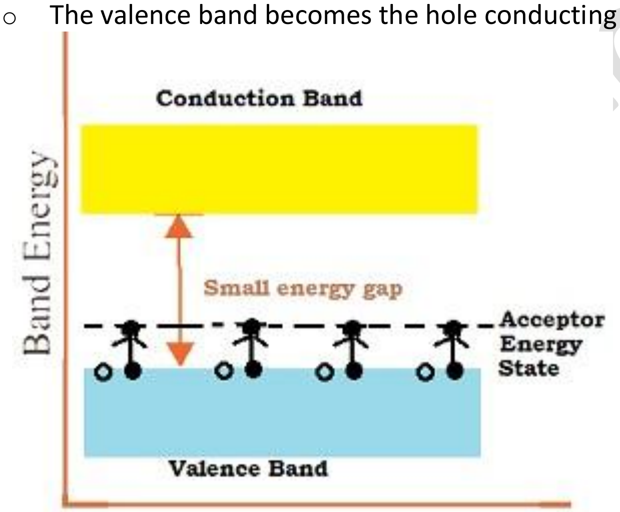
- When pure Si or Ge which has four valency electrons is doped with controlled amount of trivalent atoms, like Gallium, Indium, Boron or Aluminium, we get a p-type semiconductor
- The three valence electron from the impure atom will combine with three electrons of the Si or Ge atom to form 3 covalent bonds
- There will be one unbounded electron in the Ge atom which would try to form a covalent bond with the neighbouring Ge atom
- This Ge-Ge covalent bond creates a deficiency of electron in Ge atom. Thus, creating a hole

- This hole is compensated by the breakage of Ge-Ge covalent bond in the neighbourhood. Hence, electron moves towards the hole, resulting in hole formation at some other place
- The trivalent atoms are called acceptor atoms and conduction of electricity is due to the motion of holes
- Thus in p-type semiconductors, holes are the majority carriers and electrons are minority carriers



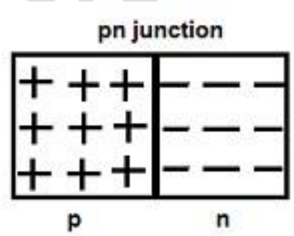
Energy band theory

- Si or Ge doped with impurities like Aluminium, produces energy level which is situated in the energy gap slightly above the valence band
- This is called as acceptor energy level
- At room temperature, the electrons in the valence band can easily be transferred to the acceptor level. This produces a large number of holes in the valence band.
- The valence band becomes the hole conducting band

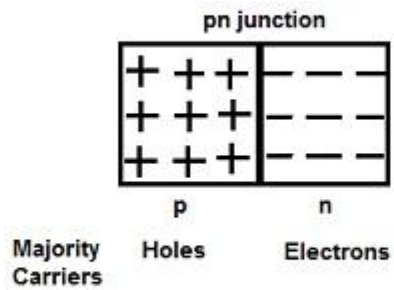


p-n junction formation

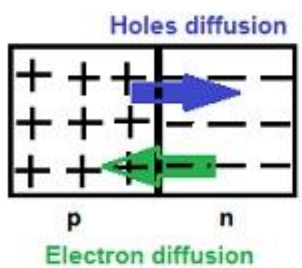
- A p-n junction is the basic building block of many semiconductor devices like diodes, transistor etc.



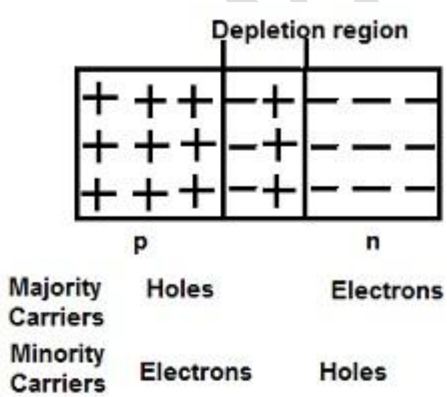
- Consider a thin p-type silicon semiconductor wafer. Convert a part of the p-type semiconductor into n-type silicon semiconductor by adding a small quantity of pentavalent impurity
- The holes are the majority carriers in the p-type semiconductor and electrons are the majority carriers in the n-type semiconductor



- In n-type semiconductor, the concentration of electrons is more compared to the concentration of holes. Similarly, in p-type semiconductor, the concentration of holes is more compared to the concentration of electrons
- The first process that occurs in the p-n semiconductor is diffusion
- In the formation of the p-n junction, due to the concentration gradient across the p and the n sides, the electrons diffuse from n region to p region and the holes diffuse from p region to n region

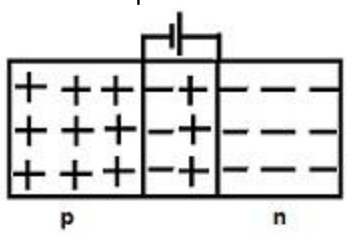


- Diffusion current –
  - The motion of charge carriers due to the difference in concentration in two regions of the p-n junction, across the junction gives rise to diffusion current
- As the diffusion continues, it leaves behind a positive charge on the n-side close to the junction. This positive charge, also called as ionised donor is immobile due to bonding with the surrounding atoms
- Similarly, in the p-region, close to the junction, there is a negative charge or acceptor ions which are immobile

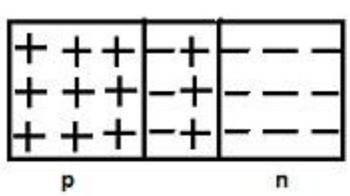


- Depletion region formation –

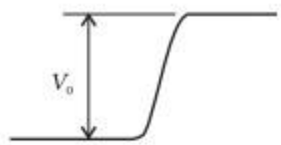
  - The space charge region on both sides of the p-n junction has immobile ions and is also devoid of any charge carriers
  - This results in the formation of depletion region near the junction
- Field setup –
  - The depletion region formation results in setting up a field at the junction
  - The field set up along the junction acts like a fictitious battery connected across the junction with positive terminal connected to the n-region



- Barrier creation –
  - The electric field at the junction sets a barrier which opposes further diffusion of majority charge carriers through the junction
  - Thus, the barrier gets created at the junction prevents further diffusion
  - Width of the barrier – The physical distance from one side of the barrier to the other is called the width of the barrier
  - Height of the barrier –The difference in potential from one side of the barrier to the other side is known as the height of the barrier
- Drift current
  - Due to the electric field developed at the junction, the electrons from the p-region move to the n-region. Similarly, the hole from the n-region move to the p-region. This results in drift current
  - The motion of charge carriers across the junction due to the electric field is called drift. This results in drift current
- Drift current Vs Diffusion current
  - The drift current is in a direction opposite to that of the diffusion current
  - At a particular stage, the drift current becomes equal to the diffusion current
  - This stage is set to be equilibrium state when no current flows across the p-n junction
  - Potential barrier becomes maximum and is equal to V_B
- Thus, a p-n junction is formed. Thus, in a p-n junction under equilibrium there is no net current
- The diagram below shows the p-n junction at equilibrium. . The n-material has lost some electrons and the p-material has acquired the electrons



- Thus the n material is positive with respect to p material. The potential also prevents the movement of electron from the n-region to the p-region. This potential is called the barrier potential and is indicated as



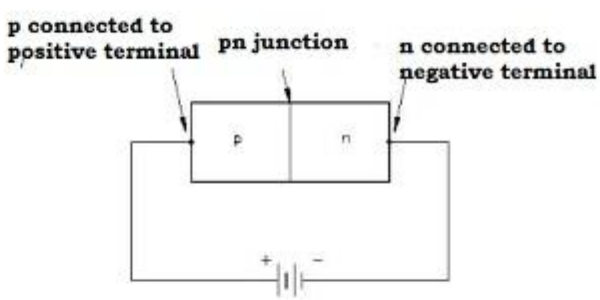
- When doping concentration is small, the electrons or holes move a large distance before collision with another electron or hole
- Hence, the width of the p-n junction becomes large
- As width of p-n junction increases, the electric field becomes small

p-n junction diode

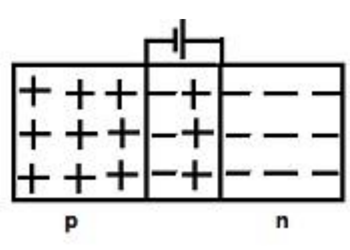
- A semiconductor diode is a p-n junction with metallic contacts provided at the ends for the application of an external voltage
- Thus p-n junction diode is a two terminal device represented as
- The equilibrium potential barrier can be altered by applying an external voltage V across the diode
- There are two methods of biasing a p-n unction – Forward bias and reverse bias

Forward biasing

- If the positive terminal of the external battery is connected to the p-side and the negative terminal of the external battery is connected to the n-side, then the p-n junction is said to be forward biased



- The direction of the applied voltage V is in a direction opposite to that of the potential barrier setup at the junction

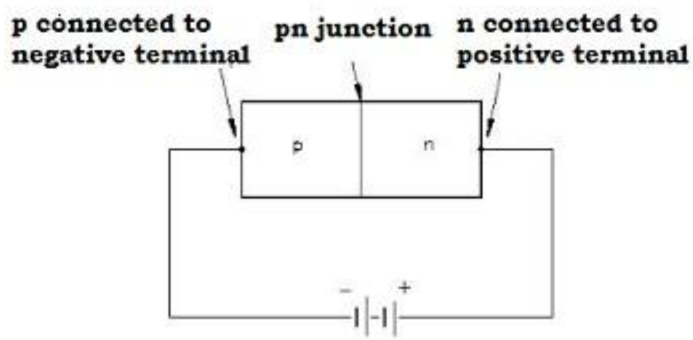


- As a result of this, the depletion layer width decreases and the barrier height is reduced. The effective barrier height under forward bias is $V_B - V$

- If the applied voltage V is small, the barrier potential will be reduced only slightly below the equilibrium value. Hence, only small number carriers will possess energy to cross the junction. Thus, the current is small
- If the applied voltage V is large, the barrier potential will be reduced significantly. Hence, the current is significant
- Due to the applied voltage, the electrons from the n-side cross the depletion region and reach the p-side. Similarly, the holes from the p-side reach the n-side
- As electrons reach the p-side and electrons are minority carriers in p-region, the forward bias is also known as minority carrier injection
- At the junction, the minority carrier concentration increases significantly
- Due to concentration gradient, the injected electrons on p-side diffuse from the junction edge of p-side to the other end of the p-side
- Similarly, the injected holes on the n-side diffuse from the junction edge of n-side to the other end of n-side
- The motion of charged carriers on either side gives rise to current and is usually measured in mA
- The total diode forward current is sum of hole diffusion current and conventional current due to electron diffusion

Reverse biasing

- If the positive terminal of the external battery is connected to the n-side and the negative terminal of the external battery is connected to the p-side, then the p-n junction is said to be reverse biased

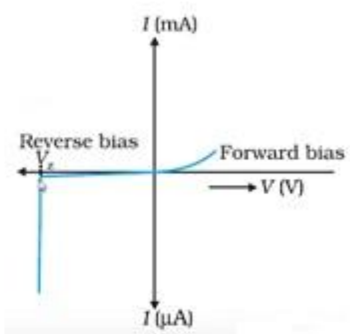


- The direction of the applied voltage is same as that of the barrier potential
- As a result, the barrier height increases and the depletion region widens due to change in electric field

- The effective barrier height is $V_B + V$
- This suppresses the flow of electrons from n region to p region and holes from the p region to n region. Hence, diffusion current decreases
- The electric field direction of the junction is such that if electrons on p-side or holes on n-side in their random motion come close to the junction, they will be swept to its majority zone. This gives rise to drift current of order of few µA
- The diode reverse current is not much dependent on the applied voltage. Even a small voltage is sufficient to sweep the minority carriers from one side of the junction to the other side of the junction
- The current under reverse bias is essentially voltage independent up to a critical reverse bias voltage, known as breakdown voltage V_{BE}
- When $V = V_{BE}$, the diode reverse current increases sharply. If the current is not limited, the p-n junction will get destroyed

Characteristics of a p-n junction diode

There are two types of characteristics – Forward characteristics and Reverse characteristics



Forward characteristics

The graphical relationship between the forward bias voltage applied and the forward current through the p-n junction is called forward characteristics

- We use a milliammeter in forward bias as the expected current is large
- The current increases very slowly, almost negligibly, till the voltage across the diode crosses certain value
- After this voltage, the current increases exponentially, even for a very small increase in the diode bias voltage. This voltage is called the threshold voltage or cut-in voltage which is 0.2V for germanium diode and 0.7 for silicon diode

Reverse characteristics

The graphical relationship between the reverse bias voltage applied and the reverse current through the p-n junction is called reverse characteristics

- In reverse bias, we use micro ammeter, as the current is very small
- The current almost remains constant even if voltage is increased and it is called reverse saturation current

Problem : The number of silicon atoms per m^3 is $5 * 10^{28}$. This is doped simultaneously with $5 * 10^{22}$ atoms per m^3 of Arsenic and $5 * 10^{20}$ per m^3 atoms of Indium. Calculate the number of electrons and holes. Given that $n_i = 1.5 * 10^{16}\ m^{-3}$. Is the material n-type or p-type ?

Solution : We know that $n_i^2 = n_e n_h$

Given $n_i = 1.5 * 10^{16}\ m^{-3}$

Then, $n_e = 5 * 10^{22} - 5 * 10^{20} = (5 – 0.05) * 10^{22} = 4.95 * 10^{22}\ m^{-3}$

Hence, $n_h = n_i^2 / n_e = (1.5 * 10^{16})^2 / 4.95 * 10^{22} = 4.54 * 10^9\ m^{-3}$

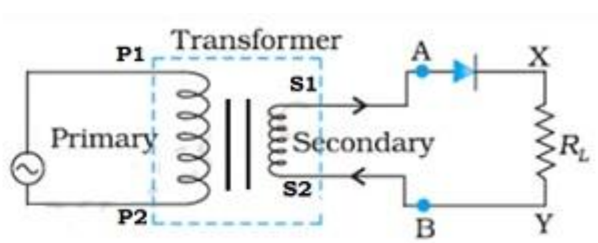
Comparing n_e and n_h , we find $n_e > n_h$ and so the material is n-type semiconductor

Application of junction diode as a Rectifier

- Rectifier is a device which is used for converting alternating current or voltage into direct current or voltage
- A p-n junction diode can be used as a half-wave and full-wave rectifier
- The resistance of a p-n junction diode becomes low when forward biased and becomes high when reverse biased. This is the principle of the working of rectifier

Half-wave Rectifier

Circuit Diagram:

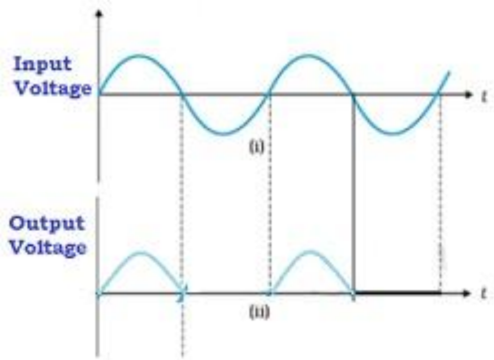


- Transformer with primary and secondary coils
- Diode

- Load resistance R_L

1. The AC voltage to be rectified is connected between the primary of the transformer
2. To one coil of the secondary , the p junction of the diode is connected
3. The output is measured across the load resistance R_L

Input and output:



Working:

Case 1

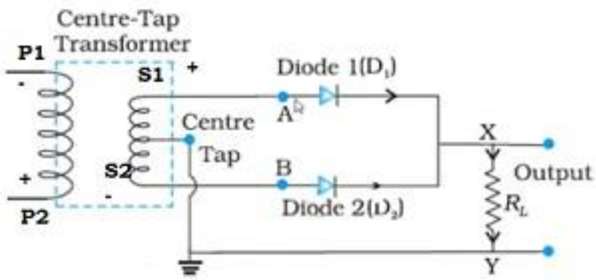
- During the positive half cycle of the input AC voltage, suppose P1 is negative and P2 is positive
- On account of inductance, S1 becomes positive and S2 becomes negative
- The p-n junction is forward biased and hence the resistance of the p-n junction diode becomes low
- Hence, current flows in the circuit and we get output across the load resistance R_L
- This is indicated in the graph above

Case 2

- During the negative half cycle of the input AC voltage, suppose P1 is positive and P2 is negative
- On account of inductance, S1 becomes negative and S2 becomes positive
- The p-n junction is reverse biased and hence the resistance of the p-n junction diode becomes high
- Hence, no current flows in the circuit and we do not get any output across the load resistance R_L
- This is indicated in the graph above
- The above process is repeated. Thus , we have current only in the positive half of the cycle. Hence, if is called as half-wave rectifier
- The output signal is not continuous and available as bursts. Hence, this is not of much use.

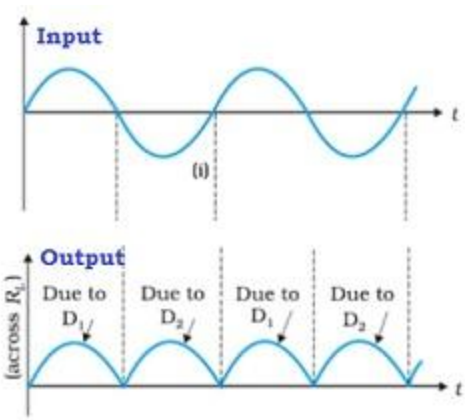
Fullwave Rectifier

Circuit Diagram:



- The main difference between half and full wave rectifier in circuit, is the usage of two diodes – D1 and D2

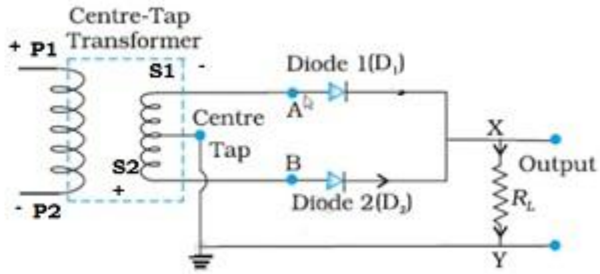
Input and Output:



Working:

Case 1

- During the positive half of the input cycle of AC voltage, the junction diode D1 is forward biased as shown in the diagram above
- Hence, current flows in the above circuit as indicated
- The diode D2 is reverse biased and hence no current due to D2
- We get output when the same is measured across the load resistance R_L due to the diode D1 alone
- ***Case 2***
- The circuit diagram for the negative half of the input cycle of AC voltage:



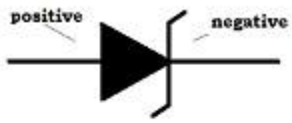
- During the positive half of the input cycle of AC voltage, the junction diode D2 is forward biased as shown in the diagram above
- Hence, current flows in the above circuit as indicated
- The diode D1 is reverse biased and hence no current due to D1
- We get output when the same is measured across the load resistance R_L due to the diode D2 alone
- We observe that one of the diode conducts and the flow of current across the load resistance is in the same direction
- Also, current flows during both cycles of the input AC voltage. However, the output though unidirectional has ripple contents. Ripple contents indicate both AC and DC components
- We can get only the DC component by passing it through a filter circuit
- The filter circuit consists of Resistance and Capacitance
- Circuit Diagram:
- C has a high capacitance value and serves as a filter circuit
- R_L is a load resistance
- Working:
- The capacitance offers low impedance to AC component and offers infinite impedance to DC component
- Due to this the AC component is bypassed or filtered out
- The DC component produces a voltage drop across the load resistance which is almost DC voltage

Problem : In half-wave rectification, what is the output frequency if the input frequency is 50 Hz. What is the output frequency of full wave rectifier for the same input frequency?
Solution : Half-wave rectifier –The output voltage is obtained is once in one cycle of input voltage, hence output ripple frequency after half-wave rectification = 50 Hz
Full-wave rectifier – For one cycle of input voltage, we get output twice in the same direction. Hence, the output after full wave rectification = 100 Hz

Special purpose p-n junction diode

<u>Zener diode</u>

- It is a special purpose diode, named after the inventor C. Zener
- It is designed to operate under reverse bias in the breakdown region
- The symbol for Zener diode is



- Fabrication – It has heavily doped p- side and n-side. Due to this, the depletion region formed is very thin about < $10^{-6.}$. Hence, the field at the junction is extremely high about -5 * 10^6 V/m for a small reverse bias voltage of 5 Volts

- The high electric field strength is high enough to pull the valence electrons from the host atoms on the p-side which is accelerated to the n-side. This is known as ionisation

- Characteristics – The Current – Voltage characteristics of Zener diode is shown below:

- As seen from the graph, when the applied reverse bias voltage in Zener diode reaches the breakdown voltage V_z of the zener diode, there is a large change in current

- The Zener voltage remains constant even though the current through the diode varies over wide range. This property of Zener diode is used for regulating the supply voltages so that they are constant

Zerner diode as a voltage regulator

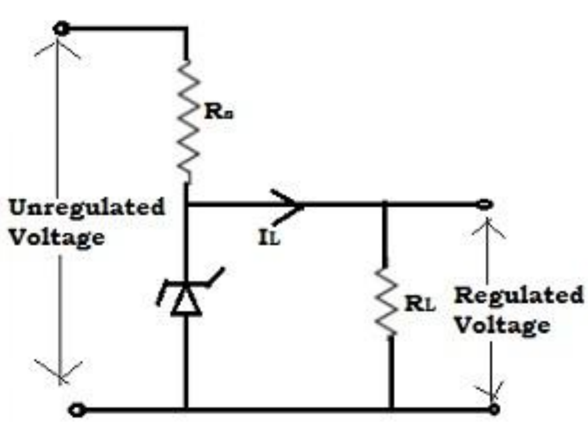
Why do we need to regulate voltage?

We know that the rectifier converts AC current into DC current. When the AC input voltage of a rectifier fluctuates, the rectified output also fluctuates. Hence, to get a constant DC voltage from the DC unregulated output of the rectifier, we use Zener diode.

Circuit Diagram:

- The unregulated DC voltage from the output of the rectifier is connected to the Zener diode through a series resistance R_s such that the Zener diode is reverse biased

- The output is measured across the load resistance R_L



Working:

Case 1

- When the input voltage increases, the current through R_s and Zener diode increases
- This increases the voltage drop across R_s without any change in voltage across the Zener diode
- This is because in the breakdown region, the Zener voltage remains constant even though the current in the Zener diode changes

Case 2

- Similarly, when the input voltage decreases, the current through R_s and hence Zener diode decreases
- The voltage drop across R_s decreases without any change in the voltage across the Zener diode

Thus, the increase or decrease in the input voltage results in increase or decrease of voltage drop across R_s without any change in voltage across the Zener diode

This way, Zener diode behaves as a voltage regulator

Precautions

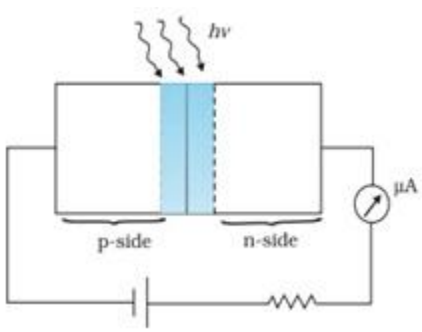
1. The zener diode must be reverse-biased
2. The zener diode must have voltage greater than zener break down voltage V_z
3. The zener diode is to be used in a circuit where the current is less than the maximum zener current I_z limited by power rating of the given zener diode

Opto electronic junction devices

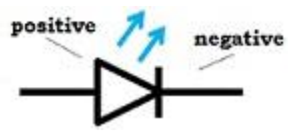
The semiconductor diodes in which the current carriers are generated by the photons(through photo excitation) is called optoelectronic devices

Some of the opto electronic junction devices are –Photodiode, Light emitting diode and solar cell.

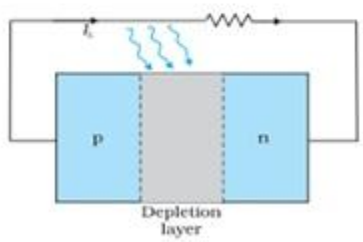
Photodiode – Electron-hole pair is generated due to the illumination of the junction with light



Light emitting diode – When forward biased properly, this special p-n junction emits light radiation continuously



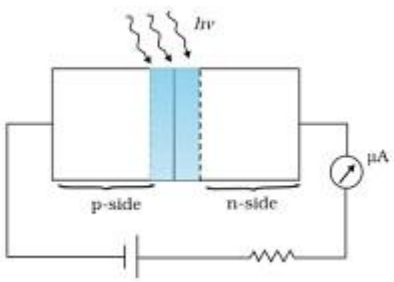
Solar cell–When solar light falls on p-n junction, it generates emf which can be used effectively



Photodiode

Application – Photodiodes are used for detecting optical signal or they act as photo detectors

Circuit Diagram:



- This is a special p-n junction diode made up of photosensitive semiconducting material
- The diode has a transparent window to allow light to fall on the diode

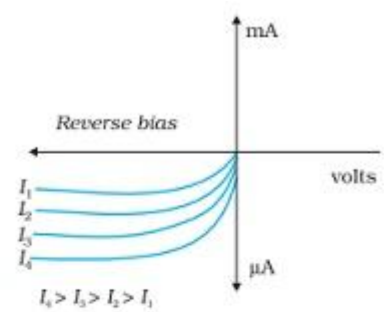
Working:

- It is operated under reverse bias below the breakdown voltage
- When photodiode is illuminated with light (photons) , with energy hυ greater than the energy gap of the semiconductor, the electron-hole pairs are generated due to the absorption of photons, in or near the depletion region of the diode

- Due to electric field at the junction, electrons and holes are separated before they combine
- The direction of electric field is such that the electrons reach n-side and the holes reach the p-side
- The movement of electrons and holes gives rise to emf
- When external load is connected, current flows. The magnitude of the photocurrent depends on the intensity of incident light
- In reverse bias, we can observe that as intensity increases, the current also increases

Characteristics:

The characteristic of a photodiode is shown below:



Problem : A p-n photodiode is fabricated from a semiconductor with band gap of 2.8 eV. Can it detect a wavelength of 6000 nm?

Solution : E_g = 2.8 eV; λ = 600 nm = 600 * 10^{-9}

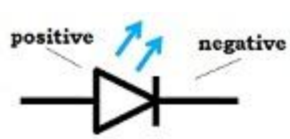
We know, Energy E = hc / λ

= 6.6 * 10^{-34} * 3 * 10^{8} / 600 * 10^{-9} * 1.6 * 10^{-19} eV

= 2.06 eV

As E < E_g, 2.06 < 2.8 eV so p-n junction cannot detect the radiation of given wavelength

Light emitting diode

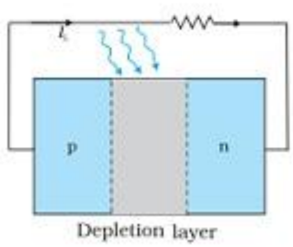


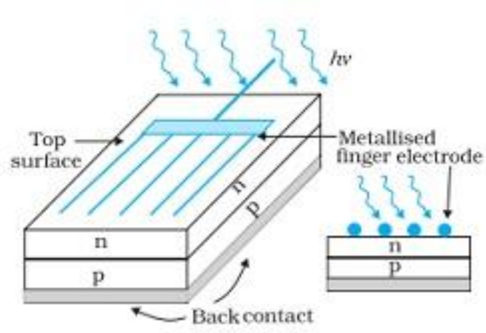
Application – They convert electrical energy into light

- It is a heavily doped p-n junction which under forward bias emits spontaneous radiation
- The diode is encapsulated with a transparent cover so that the emitted light can come out
- When the diode is forward biased, the electrons are sent from n layer to p layer and the holes are sent from p to n
- Thus, at the boundary due to forward bias, the concentration of the minority carriers increases
- The excess minority carriers recombine with the majority carriers, near the junction
- On recombination, energy is released in the form of photons
- Photons with energy equal to or slightly less than the band gap is emitted
- When the forward current of the diode is small, the intensity of the light emitted is small
- As the forward current increases, the intensity of light increases and reaches maximum.
- Further increase in forward current, results in the decrease of light intensity
- LEDs are thus biased in such a way such that the efficiency is maximum
- The reverse breakdown voltage of LED is very small (say) 5V. Proper precaution should be taken such that high reverse voltage do not appear across them
- LEDs have the following advantages over the conventional lamps:
    - Low operational voltage and less power
    - Fast action and no warm-up time required
    - Long life
    - Fast on-off switching capacity

Solar cell

Principle–These photo voltaic devices convert the optical radiation into electricity





Circuit

- When solar light falls on a p-n junction, it generates emf
- As the solar radiation is incident at the junction, the junction area is kept much larger for more power generation
- A p Si layer of about $300 * 10^{-6}$m is taken. About this a still thin layer of about $0.3 * 10^{-6}$ m n Si layer is grown on one side by the process of diffusion
- The other side of the p-layer is coated with a metal. This servers as a back contact
- On the top of n Si layer, metallic grid is deposited. This is called front contact
- The light is incident on the grid from the top

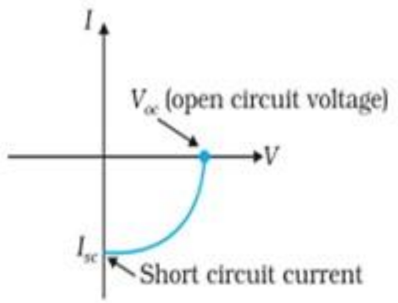
Working

- The generation of emf by the solar cell, when light falls on, is due to the following three basic processes – (a) generation (b) separation and (c) collection
- Generation
  - The generation of electron-hole paid due to light with energy hυ> E_g close to the junction
- Separation
  - The separation of electrons and holes due to the electric field of the depletion region
  - The electrons are swept to the n-side and the holes to the p-side
- Collection

- The electrons reaching the n-side are collected by the front contact and holes reaching the p-side are collected by the back contact
- Thus, the p-side becomes positive and the n-side becomes negative giving rise to photo voltage

- When external load is connected, a photo current I_L flows through the load

Graph



- The graph showing the VI characteristics, with V along the X-axis and I along the Y-axis is as given above
- The graph is indicated in the fourth quadrant as solar cell does not draw current but supplies the same to the load

Application

- Solar cells are used in power electronic devices in satellites and space vehicles
- They are also used as power supply in calculators

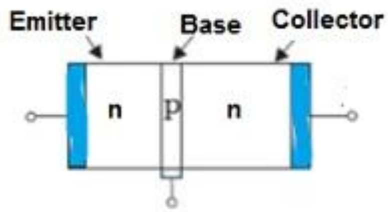
Criteria for material selection of material for solar cell

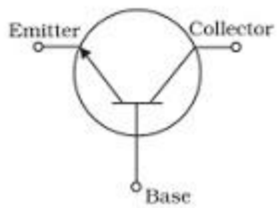
- Band gap between 1.0 and 1.8 eV
- High optical absorption
- Electrical conductivity
- Availability of raw material
- Cost effective

Junction Transistor

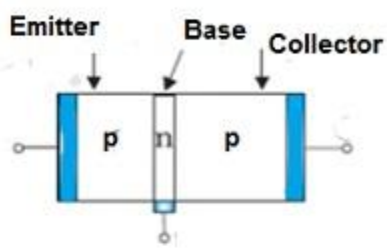
A junction transistor is a semiconductor device having two junctions and three terminals. The transistor has three doped regions forming two p-n junctions.

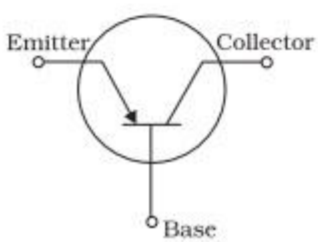
There are two types of transistors, namely, (a) n-p-n transistor (b) p-n-p transistor. The schematic representation and symbols of the two transistors are given below:





- Emitter and collector can be differentiated depending upon whether the arrow is present or not.
- Emitter has an arrow either pointing inwards or outwards
- The arrow direction for npn transistor is indicated outwards in the emitter





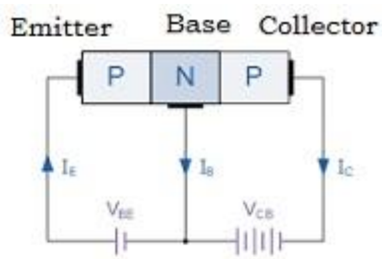
- The arrow head indicates the direction of the conventional current in the transistor
- The arrow direction for pnp transistor is indicated inwards in the emitter
- The p-n-p transistor is obtained by growing a thin layer of n-type semiconductor in between two relatively thick layers of p type semiconductor
- The n-p-n transistor is obtained by growing a thin layer of p-type semiconductor in between two relatively thick layers of n type semiconductor
- The 3 layers are – Emitter, Base and Collector

- Emitter – It is the left hand side thick layer of transistor which is heavily doped. This supplies a large number of majority carriers for the current flow through the transistor
- Base – It is the thin, central segment which is lightly doped
- Collector –It is the right hand side thick layer of transistor which is moderately doped. This segment collects a major portion of the majority carriers supplied by the emitter

- Depletion region –The depletion regions are formed at the emitter-base junction and the base-collector junction

p-n-p transistor

Circuit Diagram



- Biasing –
  - Forward bias- The emitter base junction is forward biased which means the p type emitter is connected to the positive pole of the battery and the n type base is connected to the negative pole of the same battery V_{EE}
  - Reverse bias – The collector base junction is reverse biased which means the n type base is connected to the positive pole of the battery and the p type emitter is connected to the negative pole of the same batter V_{cc}
- Current –
  - The emitter current I_E, base current I_B and the collector current is as indicated in the circuit diagram
- Resistance –
  - The emitter-base junction has low resistance while the base-collector junction has a high resistance

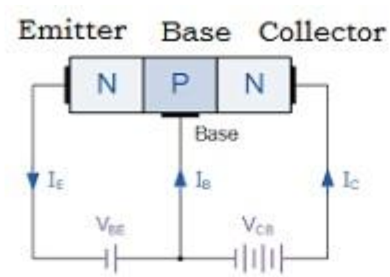
Working

- The holes are the majority carriers in the emitter p type semiconductor. This is repelled by the positive terminal of the battery V_{EE} resulting in emitter current I_E

- The base being lightly doped and thin, the electron density is less. Hence, only 5% of the holes entering the base combine with the electrons resulting in base current I_B. The base current is 5% of I_E
- The remaining 95% of the holes pass over to the collector on account of the high negative potential of the battery V_{cc}. This results in collector current I_c which is 95% of I_E
- When the hole coming from the emitter combines with the electron in the base, the deficiency of electron in the base is compensated by the flow of electrons from the negative terminal of the battery V_{EE} to the base through the connecting wire
- The current in the p-n-p transistor is due to holes however the concentration is maintained at any time; In the external circuit, the current is due to flow of electrons
- From the circuit, we fine $I_E = I_B + I_c$

n-p-n transistor

Circuit Diagram



- Biasing –
  - Forward bias- The emitter base junction is forward biased which means the n type emitter is connected to the negative pole of the battery and the p type base is connected to the positive pole of the same battery V_{EE}
  - Reverse bias – The collector base junction is reverse biased which means the ptype base is connected to the negative pole of the battery and the n type emitter is connected to the positive pole of the same batter V_{cc}
- Current –
  - The emitter current I_E, base current I_B and the collector current is as indicated in the circuit diagram
- Resistance –
  - The emitter-base junction has low resistance while the base-collector junction has a high resistance

Working

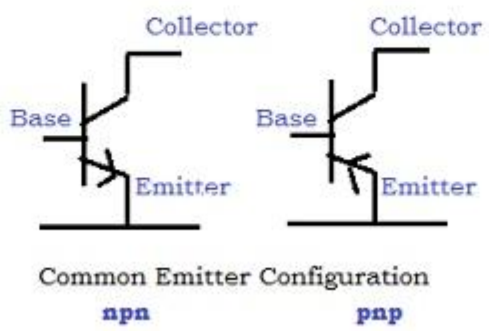
- The electrons are the majority carriers in the emitter n type semiconductor. This is repelled by the negative terminal of the battery V_{EE} resulting in emitter current I_E
- The base being lightly doped and thin, the electron density is less. Hence, only 5% of the electrons entering the base combine with the holes resulting in base current I_B. The base current is 5% of I_E
- The remaining 95% of the electrons pass over to the collector on account of the high positive potential of the battery V_{cc}. This results in collector current I_c which is 95% of I_E
- When the electron coming from the emitter combines with the hole in the base, the deficiency of hole in the base is compensated by the flow of holes from the positive terminal of the battery V_{EE} to the base through the connecting wire
- The current in the n-p-n transistor and the external circuit is due to the flow of electrons
- From the circuit, we fine $I_E = I_B + I_c$

Transistor configuration

The possible configurations of transistor are (a) Common Base (b) Common Emitter (c) Common Collector. The same can be represented as given below:

Common Emitter configuration

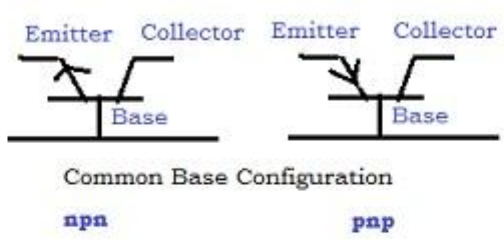
- The emitter of the transistor is common to both the input and the output



Common Emitter Configuration

Common Base configuration

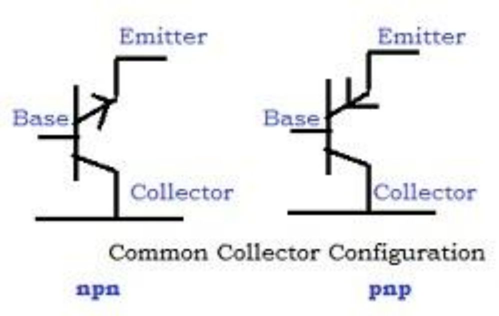
- The base of the transistor is common to both the input and the output



Common Base Configuration

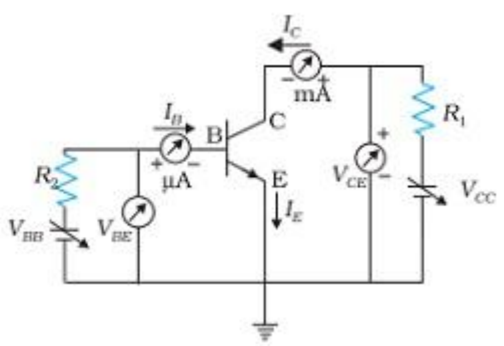
Common Collector configuration

- The collector of the transistor is common to both the input and the output



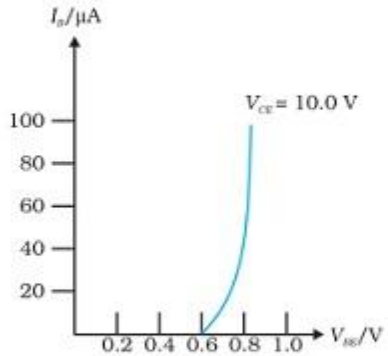
Common Emitter characteristics

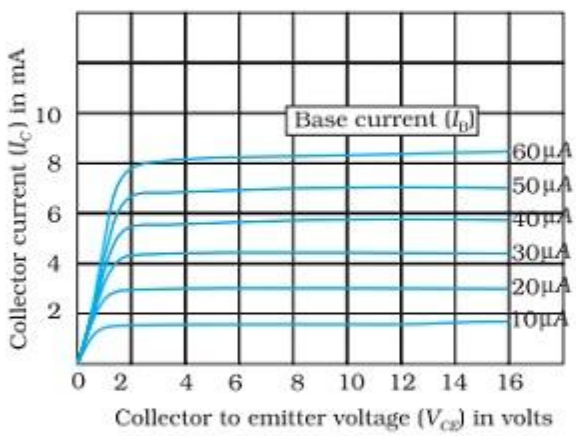
When the transistor is used in Common Emitter configuration, the input is measured between the base and the emitter; the output is measured between the collector and the emitter



Input characteristics

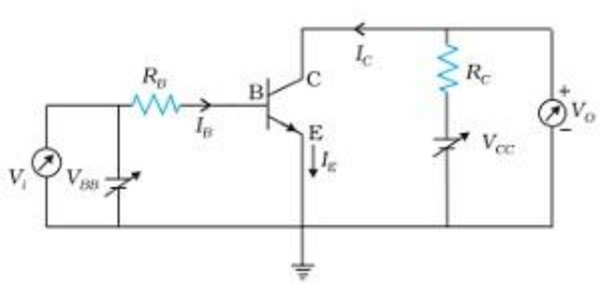
- The variation of base current I_B with base-emitter voltage V_{BE} is called input characteristics
- While studying the dependence of I_B on V_{BE} , the collector-emitter voltage V_{CE} is kept fixed
- The current is small as long as V_{BE} is less that the barrier voltage
- When V_{BE} is greater than the barrier voltage, the curves look similar to that of a forward biased diode
- Input dynamic resistance of transistor –Input dynamic resistance of transistor (R_i) is defined as the ratio of change in base-emitter voltage δV_{BE} to the resulting change in the base current δI_B at constant collector-emitter voltage V_{CE}
- $R_i = (\delta V_{BE} / \delta I_B)$ when V_{CE} is constant

- 

- Output characteristics
- The variation of collector current I_C with collector-emitter voltage V_{CE} is called output characteristics
- While studying the dependence of I_C on V_{CE} , the base current I_B is kept constant
- From the graph, we see that as long as the collector-emitter junction is reverse biased, we get I_C almost independent of V_{CE}
- We also find that for the given value of V_{CE}, I_C is large for large value of I_B
- Output dynamic resistance of transistor – Output dynamic resistance of transistor (R_o) is defined as the ratio of change in collector-emitter voltage δV_{CE} to the resulting change in the collector current δI_Cat constant base current I_B
- $R_i = (\delta V_{CE} / \delta I_C)$ when $I_B$is constant
- 

Circuit Diagram

- Let us consider n-p-n transistor which is of common emitter configuration



Working

Using Kirchhoff's law for the above circuit,

For the input side,

$-V_{BB} + I_B R_B + V_{BE} = 0$

In other words, $V_{BB} = I_B R_B + V_{BE}$ --(1)

Similarly, in the case of output side,

$-V_{CC} + I_c R_c + V_{CE} = 0$

In other words, $V_{CE} = V_{CC} - I_c R_c$ --(2)

Assume V_{BB} as the DC input voltage V_i and V_{CE} as output voltage V_o

Hence (1) and (2) becomes,

$V_i = I_B R_B + V_{BE}$--(3)

$V_o = V_{CC} - I_c R_c$--(4)

Let us consider the change of V_o as V_i changes from 0 to higher value

Case 1 – When $V_i < 0.6$ V, there is no collector current. Hence, from (4), we get

$V_o = V_{CC}$

The transistor is said to be in cut off state

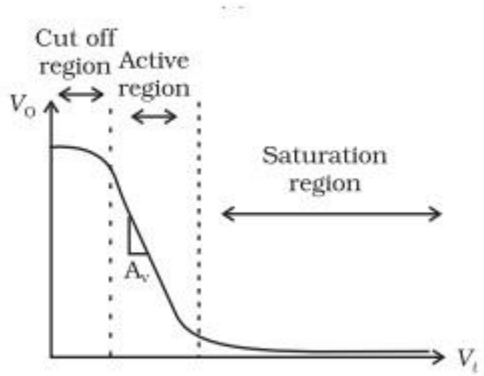
Case 2 – When $0.6V < V_i <= 1.0$ V, there will be some collector current.

Hence, from (4), we get I_c increases. Hence, as I_c term is subtracted in (4) the value of V_o output voltage decreases.

In this range, as I_c increases almost linearly, so V_o decreases linearly. The transistor is said to be in active state at this stage

Case 3 –When $V_i > 1.0$ V, V_o is found to decrease towards zero but not zero. The collector current I_c becomes maximum and the transistor is in saturation state.

Graph



The relationship between V_i and V_o is called transfer characteristic curve of a base biased transistor in Common emitter configuration. The above mentioned regions – Cut off region, Active region and Saturation region are marked in the graph.

In cut-off state when V_i is low, the transistor is not working and hence said to be in switched off state. In saturation state when V_i is high, the transistor is fully conducting as I_c is nearly equal to maximum or saturated. As the transistor is fully conducting, it is said to be in switched on state.

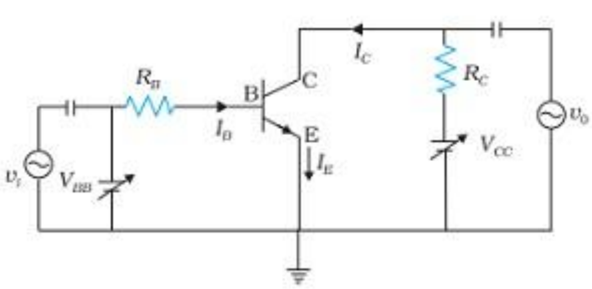
Thus the transistor acts as a switch.

Transistor as an amplifier

Amplifier – It is a device which is used for increasing the amplitude of the alternating voltage, current or power

Amplifier using n-p-n transistor in common emitter configuration is shown below:

Circuit Diagram:



- The emitter is common to both the input and output circuit
- The input circuit is forward biased with the battery V_{BB} and the output circuit is reverse biased with the battery V_{cc}

- R_L is the load resistor connected in the collector circuit

Input and output:

Working:

Case 1 – No AC signal voltage is applied to the input circuit

- When no AC signal voltage is applied to the input circuit, let the emitter current, base current and collector current be I_E, I_B and I_c
- By applying Kirchhoff's law, we know, $I_E = I_B + I_c$
- From the output circuit, we find, $V_{CC} = V_{CE} + I_c i_{ly}$ Hence, $V_{CE} = V_{CC} - I_c R_L$

Case 2 – When AC signal voltage is applied to the input circuit

- There will be a change in the emitter-base voltage and hence the emitter current
- As emitter current changes, collector current changes
- In equation, $V_{CE} = V_{CC} - I_c R_L$ as the collector current changes, the collector voltage V_{CE} changes accordingly as V_{CC} is fixed
- The change in the collector voltage appears to be amplified output of the input variation

Current and Voltage gain

- The change in the output current by the input current is called current gain indicated by β_{ac}

β_{ac} = Change in I_c / Change in I_B = i_c / i_b

- The change in the output voltage by the input voltage is called voltage gain indicated by A_v

$A_v = v_o / v_i = \delta V_{CE} / r \delta I_B$ where r is the input resistance

$= - \beta_{ac} R_L / r$

The negative sign indicates that the output voltage is opposite with the phase of input voltage

Power gain

- The power again is the product of the current gain and voltage gain.
- $A_p = \beta_{ac} * A_v$
- The power gain is also defined as the ratio of change in output power to the change in input power

<u>Problem</u>

For a CE-transistor amplifier, the audio signal voltage across the collector resistance of 2 KΩ is 2 V. Suppose the current amplification factor of the transistor is 100, find the input signal voltage and base current, if the base resistance is 1KΩ.

Solution

$R_o = 2$ KΩ = 2000 Ω ; $V_o = 2V$; $\beta_{ac} = 100$; $R_i = 1K\Omega = 1000\ \Omega$

(a) $A_v = V_o / V_i = \beta_{ac} R_0 / R_i$

which is $2 / V_i = 100 * (2000 / 1000)$; Hence, $V_i = 0.01$ V

(b) $I_b = V_i / R_i$

$= 0.01 / 1000 = 10 * 10^{-6}$ A

Problem

Two amplifiers are connected one after the other in series (cascaded). The first amplifier has a voltage gain of 10 and the second has a voltage gain of 20. If the input signal is 0.01 V, calculate the output of ac signal'

Solution

Total voltage gain is $A_V = A_{V1} * A_{V2} = \delta V_o / \delta V_i$

$\delta V_o = \delta V_i * A_{V1} * A_{V2}$

$= 0.01 * 10 * 20 = 2V$

Digital electronics – Introduction

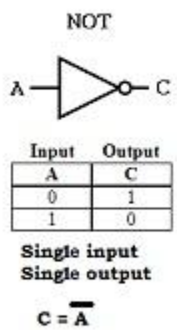
Logic gates

- In digital electronics, we consider only two values of voltage – high represented as 1 and low represented as 0
- Logical gates are electronic circuits
- Just as a gate controls the flow of vehicles, the logical gates controls the flow of information based on the logical relations. Only if the logical relations are satisfied, the digital circuit allows the signal to pass through
- The logic gates are the basic building blocks of digital electronics.
- We can say logic gate is a digital circuit which follows a logical relationship between the input and output

- Some of the basic types of logical gate are – NOT, OR, AND, NOR and NAND. Every gate has a single or multiple input and output
- Every gate is represented by a symbol
- The input and output of the logical gate is represented in the form of a truth table. The truth table considers all possible combinations of the input and shows the respective output in each case

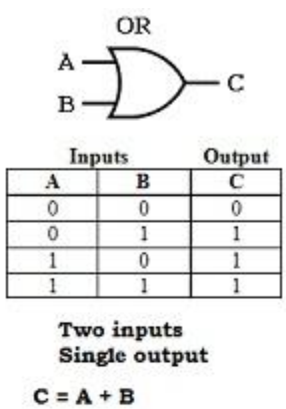
<u>NOT gate</u>

The symbol and truth table for NOT gate is as given below:



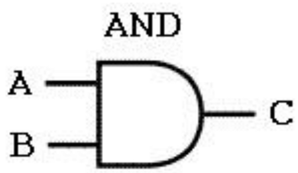
<u>OR gate</u>

The symbol and truth table for NOT gate is as given below:



<u>AND gate</u>

The symbol and truth table for NOT gate is as given below:



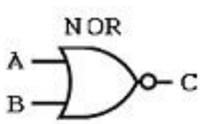
Inputs		Output
A	B	C
0	0	0
0	1	0
1	0	0
1	1	1

Two inputs
Single output

C = A.B

<u>NOR gate</u>

The symbol and truth table for NOT gate is as given below:



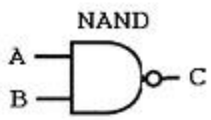
Inputs		Output
A	B	C
0	0	1
0	1	0
1	0	0
1	1	0

Two inputs
Single output

$C = \overline{A + B}$

<u>NAND gate</u>

The symbol and truth table for NOT gate is as given below:



Inputs		Output
A	B	C
0	0	1
0	1	1
1	0	1
1	1	0

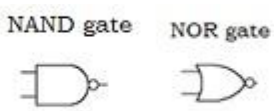
Two inputs
Single output

$C = \overline{A.B}$

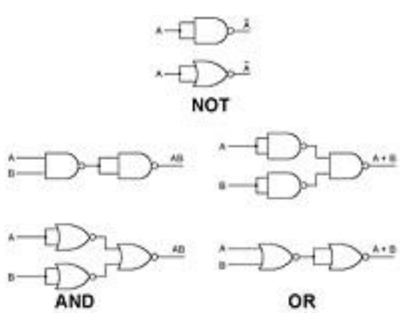
C = A.B

Universal gate

The NAND gate and the NOR gate are called as universal gates as any Boolean function can be implemented without the need to use any other gate.

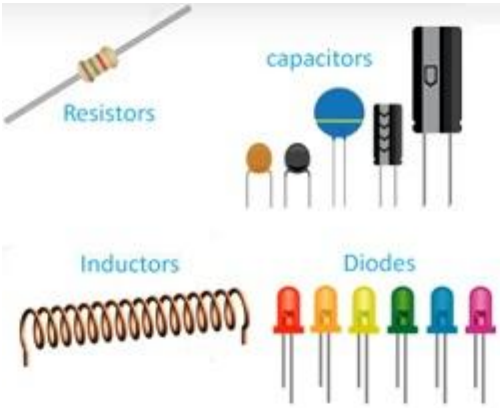


The following diagrams below show NAND gate and NOR gate combinations as NOT, AND and OR gates:



Integrated circuits

- The components like diode, transistor, resistor, inductor, and capacitor are connected by soldering wires in desired manner, to make conventional circuits



- But still such circuits are still bulky; They are also less reliable and less shock proof
- The concept of fabricating an entire circuit on a small single chip of semiconductor is called Integrated circuit; The chip dimensions are as small as 1mm * 1 mm or even less than that

- The integrated chip can be categorised into (a) linear or analog IC (b) digital IC
- Linear or Analog IC – The signals change continuously over a range of values between maximum and minimum; The output varies linearly as the input ; The most useful linear IC is an operational amplifier
- Digital IC – These have two values – high and low; These contain logical gates. – Depending upon the number of circuit components or logic gates used, they can be classified into SSI, MSI, LSI or VLSI
- If the number of gates is less than or equal to 10, we call it as SSI – small scale integration
- If the number of gates is less than or equal to 100, we call it as MSI – medium scale integration
- If the number of gates is less than or equal to 1000, we call it as LSI – large scale integration
- If the number of gates is greater than 1000, we call it as VLSI – very large scale integration