04 Semiconductor Electronics

Introduction

The word "electronics' is derived from electron+dynamics which means the study of the behaviour of an electron under different conditions of externally applied fields.

This field of science deals with electronic devices and their utilization. An electronic device is a device in which conduction takes place by the movement of electron - through a vacuum, a gas or a semiconductor.

Some familiar devices are : (i) Rectifier (ii) Amplifier (iii) Oscillator etc.

Application of Electronics

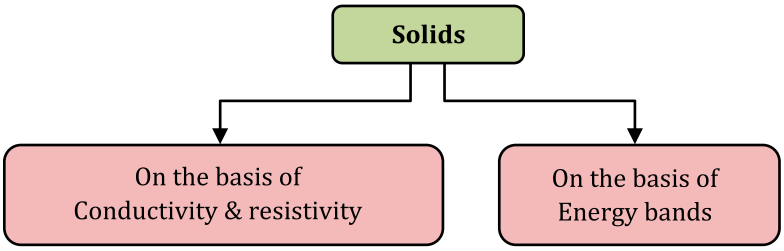
Communication	**Entertainment**	**Defence**	**Medical**
Telephone	TV Broadcast	Radar	X-rays
Telegraph	Radio Broadcast	Guided missiles	Electro cardio graph (E.C.G.)
Mobile phone	VCR, VCD		CRO display
FAX, FM mic			Electro Engio Graph (E.E.G.)

Main application of electronics is computer which is used in every field.

All electronics equipment's required D.C. supply for operation (not A.C. supply).

Classification of Materials and Energy Band Theory

Classification of Solids



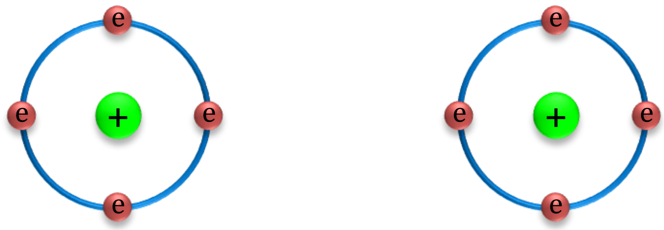
On the basis of conductivity & resistivity: It have three types;

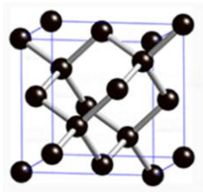
1. Conductors 2. Insulators 3. Semiconductors

Conductors	Insulators	Semiconductors
Abundance of free e^-	Very few free e^-	Few free e^-
High conductivity ($\sigma \sim 10^2 - 10^8$ S m^{-1})	Low conductivity ($\sigma \sim 10^{-11} - 10^{-19}$ S m^{-1})	Intermediate conductivity ($\sigma \sim 10^5 - 10^{-6}$ S m^{-1})
Low resistivity ($\rho \sim 10^{-2} - 10^{-8}\,\Omega$m)	High resistivity ($\rho \sim 10^{11} - 10^{19}\,\Omega$m)	Intermediate resistivity ($\rho \sim 10^{-5} - 10^{6}\,\Omega$m)
Effect of temperature: $T \uparrow R \uparrow \rho \uparrow \sigma \downarrow$	(At very high temperature) $T \uparrow R \downarrow \rho \downarrow \sigma \uparrow$	(At room temperature) $T \uparrow R \downarrow \rho \downarrow \sigma \uparrow$
α = +ve	α =– ve	α =–ve (α = temp. coefficient)
E.g. : Metals	E.g.: Rubber, Wood, Plastic, Diamond etc.	E.g. : Si, Ge, GaAs, CdS, anthracene, Polypyrole, Polyaniline etc

Energy Bands in Solids

- In isolated atoms the energy levels of electrons are discrete.
- When we draw the energy level diagram of isolated Si atom then we obtain different energy levels corresponding to the energy of different electrons in different orbits.





- However, if an atom belongs to a crystal, then the energy levels are modified.
- Consider a single crystal of silicon having N atoms. Each atom can be associated with a lattice site.
- Electronic configuration of $_{14}Si$ is $1s^2, 2s^2, 2p^6, 3s^2, 3p^2$.
- Therefore interaction of a silicon atom with the neighbouring atom causes change in energy levels of electron.
- This modification is not appreciable in the case of energy levels of electrons in the inner shells (completely filled).
- But in the outermost shells, modification is appreciable because the electrons are shared by many neighbouring atoms.
- So, what used to be the discrete energy levels, now split-up or spread out to form energy bands.

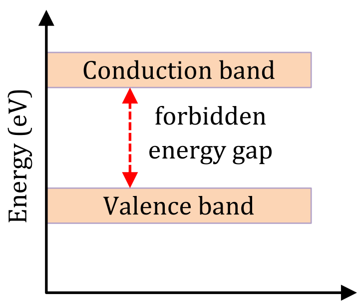
  Valence Band: This is lower energy band, which contains valence electrons.
  This band is either partially or completely filled with electrons but never be empty.
  The electrons in this band are not capable of taking part in conduction of current.
  Conduction Band: This is the higher band containing conduction electrons.
  This band is either empty or partially filled with electrons.
  Electrons present in this band take part in the conduction of current.
  This band is completely empty. Electron is forbid to be in this energy gap.
  The minimum energy required to shift an electron from valence band to conduction band is called band gap (ΔE_g).

$$\Delta E_g = (CB)_{min} - (VB)_{max}$$

  It depends on nature of solid and on the interatomic separation.
  It also depends on temperature, but this dependence is very weak.

Band gap or Forbidden Energy gap (FEG) (ΔE_g)

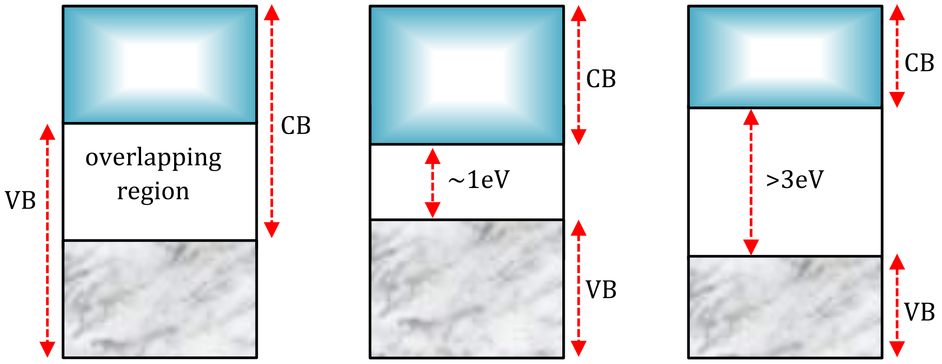
$$\Delta E_g = (CB)_{min} - (VB)_{max}$$



(i) It is the energy gap between CB and VB.
(ii) It is also called forbidden energy gap because free electrons cannot exist in this gap.
(iii) Width of forbidden energy gap depends upon the nature of substance.
(iv) Width is more, then valence electrons are strongly attached with nucleus.
(v) Width of forbidden energy gap is represented in eV.
(vi) As temperature increases forbidden energy gap decreases (very slightly).

Classification of solids According to Energy Band Theory

According to energy band theory solids are conductor, semiconductor and insulator :



conductor (Cu, Fe, Al, Na etc.) | semiconductor (Si, Ge, GaAs etc.) | insulator (Diamond, wood etc.)

Conductor: In some solids conduction band and valence band are overlapped so there is no band gap between them, it means $\Delta E_g = 0$. Due to this a large number of electrons are available for electrical conduction and therefore its resistivity is low ($\rho = 10^{-2} – 10^{-8}$ Ω-m) and conductivity is high [$\sigma = 10^{2} – 10^{8}$ $(\Omega\text{-m})^{-1}$]

Such materials are called conductors. For example, gold, silver, copper etc.

Insulator: In some solids energy gap is large ($E_g > 3$ eV). So, in conduction band there are no electrons and no electrical conduction is possible. Here energy gap is so large that electrons cannot be easily excited from the valence band to conduction band by any external energy (electrical, thermal or optical).

Such materials are called as "insulator". Their r > 10^{11} W-m and s < 10^{-11} $(\text{W-m})^{-1}$

Semiconductor: In some solids a finite but small band gap exists ($E_g < 3$eV). Due to this small band gap some electrons can be thermally excited to "conduction band". These thermally excited electrons can move in conduction band and can conduct current. Their resistivity and conductivity both are in medium range, ρ ; $10^{-5} – 10^{6}$ Ω-m and σ ; $10^{-6} – 10^{5}$ $\Omega\text{-m}^{-1}$.

Example of semiconducting materials

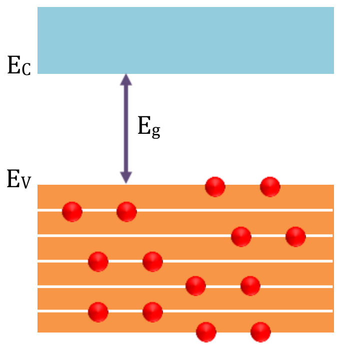
Elemental semiconductor : Si and Ge

Compound semiconductor
- Inorganic : CdS, GaAs, CdSe, InP etc.
- Organic : Anthracene, Doped pthalocyanines etc.
- Organic polymers : Poly pyrrole, Poly aniline, polythiophene

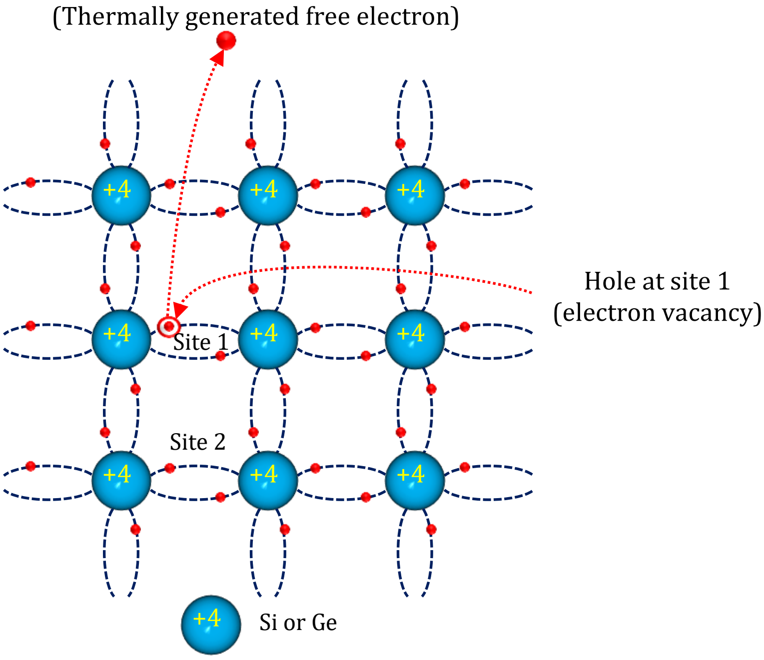
Intrinsic Semiconductors or Pure Semiconductor

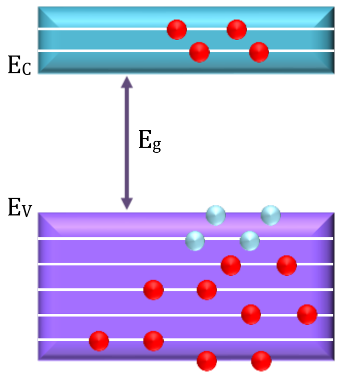
Semiconductors in their purest form. Free from any type of impurity All the covalent bonds are complete, No free electrons. Valence bands are completely filled. Conduction bands are complete empty. It behaves as perfect insulator.

Some of the covalent bonds are broken due to thermal energy.



At T = 0 K





At Room temperature

On receiving an additional energy, one of the electrons from a covalent bond breaks and is free to move in the crystal lattice.

While coming out of the covalent bond, it leaves behind a vacancy named 'hole'. This process is called Electron-hole pair generation.

In intrinsic semiconductor, the number of thermally generated electrons always equals the number of holes.

n_e = free electron concentration, n_h = hole concentration

$n_e = n_h = n_i$

Total Current = $I_h + I_e$

Valence Band Current I_h , Conduction Band Current I_e

Conductivity (σ)

$\sigma = e\,(n_e\,\mu_e + n_h\,\mu_h) = \sigma_e + \sigma_h$

Where, $\sigma_e = \mu_e\, n_e\, e$ & $\sigma_h = \mu_h\, n_h\, e$

Properties of Semiconductor

Negative temperature coefficient (α), with increase in temperature resistance decreases.

Crystalline structure with covalent bonding [Face centred cubic (FCC)].

Conduction properties may change by adding small impurities.

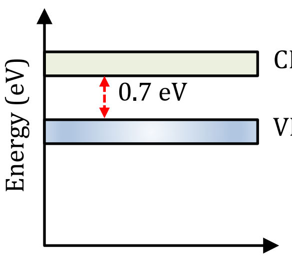
Position in periodic table $\rightarrow$ IV group (Generally)

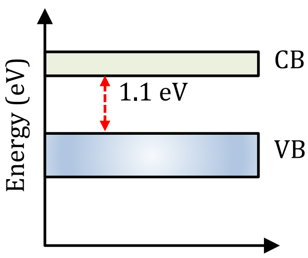
Forbidden energy gap (0.1 ev to 3 ev)

Charge carriers : electron and hole.

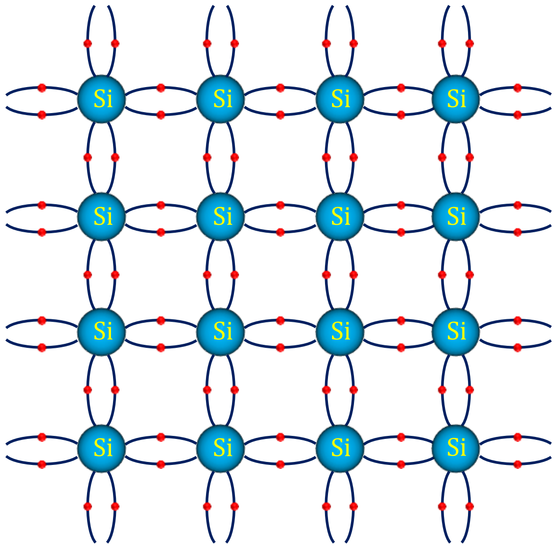
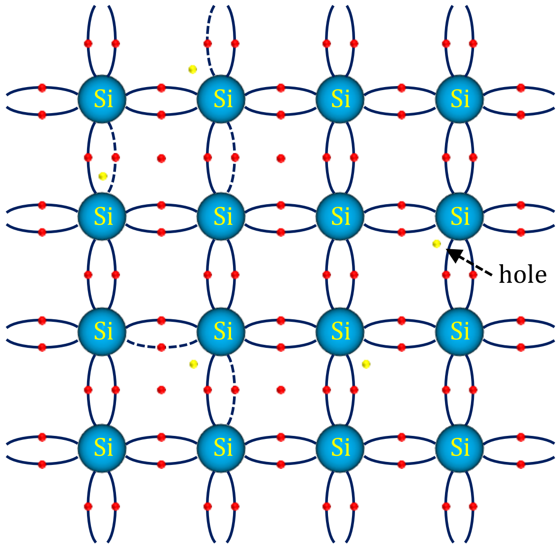
There are many semiconductors but few of them have practical application in electronics like

Ge^{32} : 2, 8, 18, 4 $\qquad$ Si^{14} : 2, 8, 4





Effect of temperature

At absolute zero kelvin temperature at this temperature covalent bonds are very strong and there are no free electrons and semiconductor behaves as perfect insulator.	Above absolute temperature with increase in temperature some covalent bonds are broken and few valence electrons jump to conduction band and hence it behaves as poor conductor.
 at 0 K Valence band fully filled conduction band fully empty	 at higher temperature Valence band partially empty conduction band partially filled

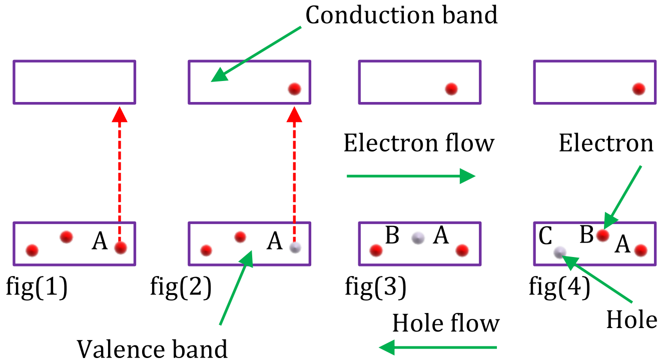
Concept of electron current and hole current

In conductors current is caused by only motion of electrons but in semiconductors current is caused by both electrons in conduction band and holes in valence band.

Current that is caused by electron motion is called electron current and current that is caused by hole motion is called hole current. Electron is a negative charge carrier whereas hole is a positive charge carrier.

At absolute zero temperature intrinsic semiconductor behaves as insulator. However, at room temperature the electrons present in the outermost orbit absorb thermal energy. When the outermost orbit electrons get enough energy then they will break bonding with the nucleus of atom and jumps in to conduction band. The electrons present in conduction band are not attached to the nucleus of an atom so they are free to move.

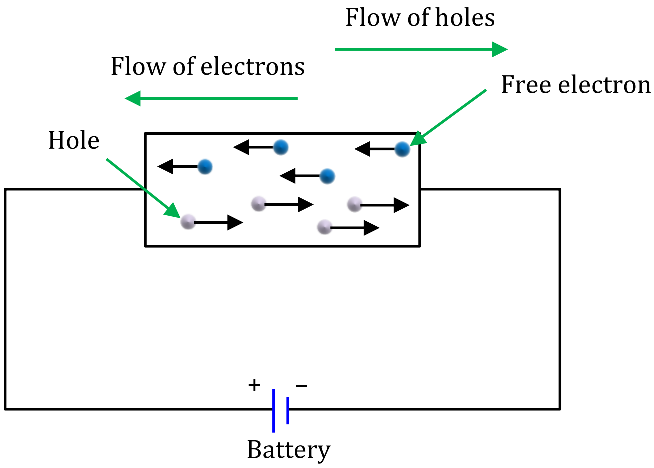
When the valence electron moves from valence band to the conduction band a vacancy is created in the valence band where electron left. Such vacancy is called hole.



Conduction in Intrinsic Semiconductor

The process of conduction in intrinsic semiconductor is shown in below fig. In the below fig, an intrinsic semiconductor is connected to a battery.

Here, positive terminal of battery is connected to one side and negative terminal of the battery is connected to other side. As we know like charges repel each other and opposite charges attract each other. In the similar way negative charge carriers (electrons) are attracted towards the positive terminal of battery and positive charge carriers (holes) attracted towards the negative terminal of battery.



Electrons will experience a attractive force from the positive terminal, so they move towards the positive terminal of the battery by carrying the electric current. Similarly, holes will experience a attractive force from the negative terminal, so they moves towards the negative terminal of the battery by carrying the electric current. Thus, in a semiconductor electric current is carried by both electrons and holes.

In intrinsic semiconductor the number of free electrons in conduction band is equal to the number of holes in valence band. The current caused by electrons and holes is equal in magnitude.

The total current in intrinsic semiconductor is the sum of hole and electron current.

$$I = I_{hole} + I_{electron}$$

Extrinsic Semiconductors

N-type and P-type Semiconductor

The conductivity of an intrinsic semiconductor depends on its temperature, but at room temperature its conductivity is very low. As such, no important electronic devices can be developed using these semiconductors.

Hence there is a necessity of improving their conductivity. This can be done by making use of impurities.

When a small amount, say, a few parts per million (ppm), of a suitable impurity is added to the pure semiconductor, the conductivity of the semiconductor is increased manifold. Such materials are known as extrinsic semiconductors or impurity semiconductors.

Extrinsic semiconductors are semiconductors that are doped with specific impurities. The impurity modifies the electrical properties of the semiconductor and makes it more suitable for electronic devices such as diodes and transistors.

The deliberate addition of a desirable impurity is called doping and the impurity atoms are called dopants. Such a material is also called a doped semiconductor.

Intrinsic Semiconductor + Dopants = Extrinsic Semiconductor

Doping

Doping is the mixing of impure atoms in a pure semiconductor material. Here the impure atoms refer to the atoms that are different from the pure semiconductor. The most commonly used impure atoms are Boron (B), Aluminum (Al), Arsenic (As), Phosphorus (P) etc.

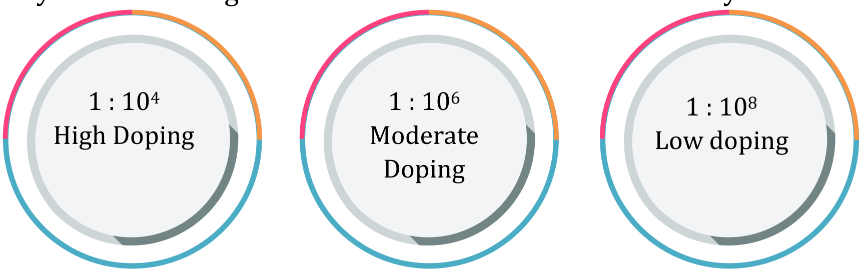
Necessity of Doping: The Conductivity of semiconductors is very poor at room temperature. To get a significant amount of conductivity we need to increase the temperature of the semiconductor to a high value. But it is practically impossible to use the semiconductor devices at a very high temperatures above 50°C.

Now, doping can increase the conductivity of semiconductors by a significant amount even at room temperature. At this one can use semiconductor devices comfortably at room temperature.

So, we need the doping in semiconductor materials to increase their conductivity without increasing the temperature which enables us to use semiconductor devices at room temperature.

Properties of Dopants

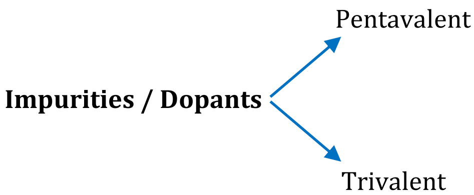
It occupies only a very few of the original semiconductor atom sites in the crystal.



It should not distort the original pure semiconductor lattice.

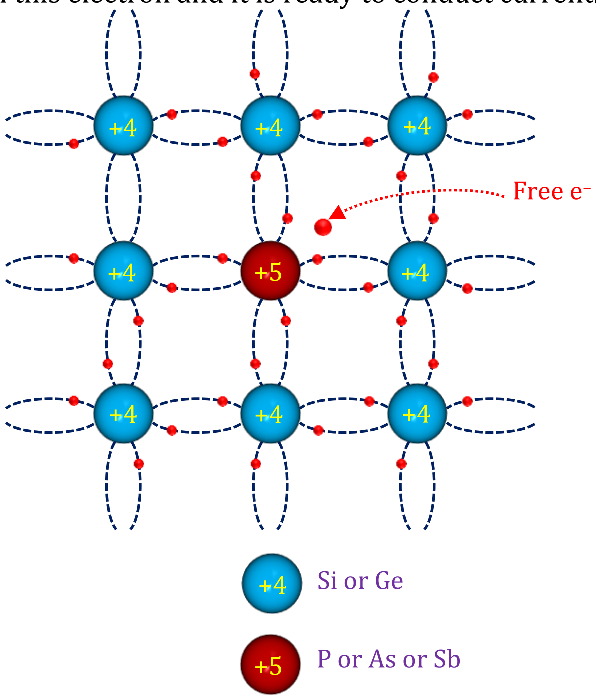
Sizes of the dopant and the semiconductor atoms should be nearly the same.

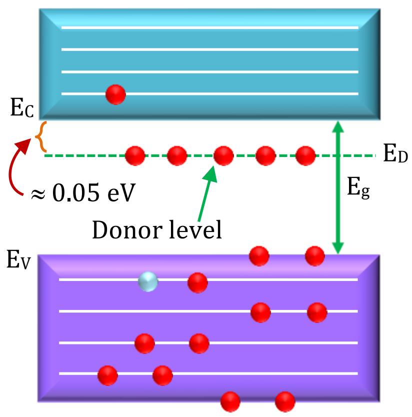
It should give away holes or electron for conduction very easily.



1. N-type semiconductor

When Si or Ge is doped with a pentavalent impurity, N-type semiconductor is formed. The force of attraction between this mobile electron and the positively charged (+5) impurity ion is weakened. So, such electrons from impurity atoms will have energies slightly less than the energies of the electrons in the conduction band. The energy required to detach the fifth loosely bound electron is only of the order of 0.05 eV for Si and 0.01 eV for Ge. A small amount of energy provided due to thermal agitation is sufficient to detach this electron and it is ready to conduct current.





Free electron concentration is mainly decided by the donor impurity concentration. ($n_e = N_D$)

The number of holes decreases because of increase in rate of recombination.

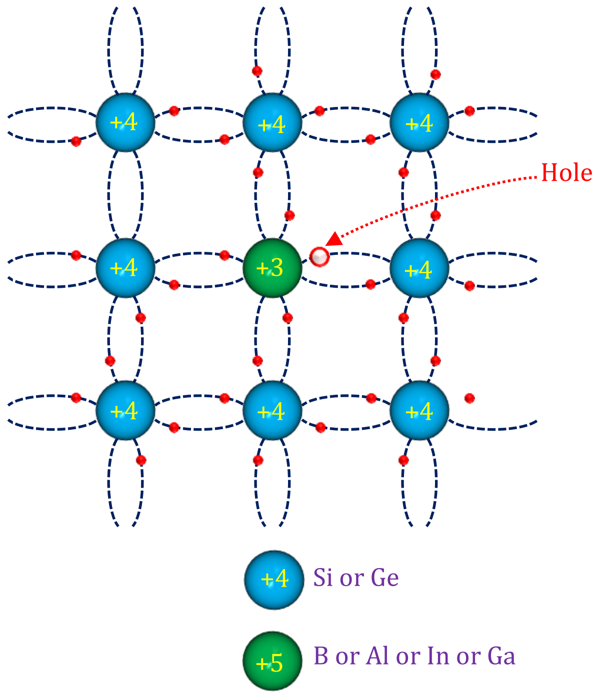
Free electrons are the majority carriers and holes are the minority carriers. ($n_e >> n_h$)

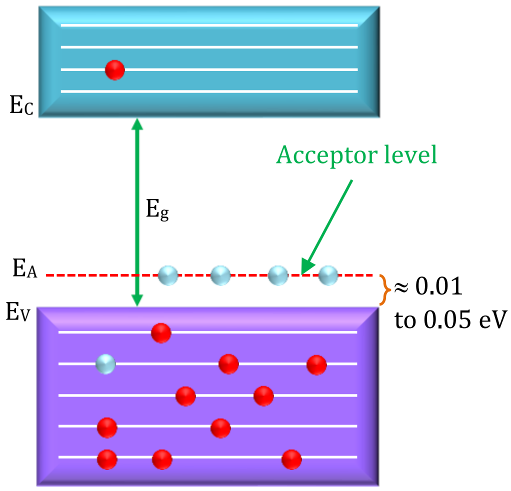
Total current in semiconductor is mainly due to electron current, $I = I_e + I_h \approx I_e$

Overall semiconductor is still neutral.

2. P-type semiconductor

When Si or Ge is doped with a trivalent impurity, P-type semiconductor is formed. The vacancy of trivalent impurity may be filled with an electron from neighbouring atom, creating a hole in that position from where the electron jumped. The acceptor impurity produces an energy level just above the valence band. The energy difference between the acceptor energy level and the top of the valence band is much smaller (0.01 eV) than the band gap. Electrons from the valence band can, easily move into the acceptor level by being thermally agitated.





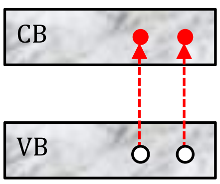
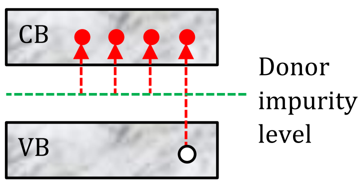
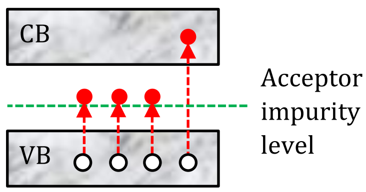
Hole concentration is mainly decided by the acceptor impurity concentration. ($n_h = N_A$)

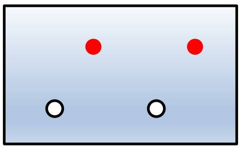
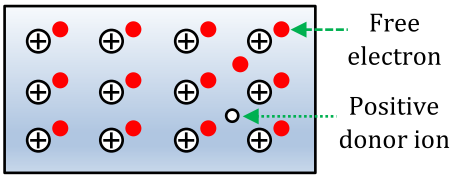
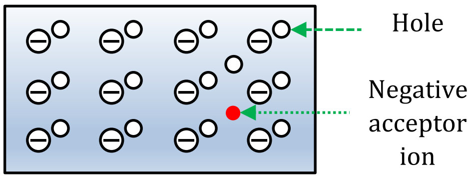
The number of electrons further decreases due to increase in rate of recombination.

Holes are the majority carriers and free electrons are the minority carriers. ($n_h \approx n_e$)

Total current in semiconductor is mainly due to hole current, $I = I_e + I_h \approx I_h$

Overall semiconductor is still neutral.

Intrinsic Semiconductor	N-type (Pentavalent impurity)	P-type(Trivalent impurity)
1. 		

2. 		
3. Current is due to both electrons and holes	Mainly due to electrons	Mainly due to holes
4. $n_e = n_h = n_i$	$n_e >> n_h$ ($N_D \simeq n_e$)	$n_h >> n_e$ ($N_A \simeq n_h$)
5. $I = I_e + I_h$	$I \simeq I_e$	$I \simeq I_h$
6. Entirely neutral	Entirely neutral	Entirely neutral
7. Quantity of electrons and holes are equal	Majority – Electrons Minority – Holes	Majority – Holes Minority - Electrons

Mass action law

At room temperature, most of the acceptor atoms get ionised leaving holes in the valence band. Thus at room temperature the density of holes in the valence band is predominantly due to impurity in the extrinsic semiconductor.

"Rate of generation of charge carriers is equal to rate of recombination of charge carriers."

$$n_e\, n_h = n_i^2$$

Note: n_i depends only on the nature of semiconductor material and temperature, it does not depend on the doping level.

Illustration 1

Pure Si at 300 K has equal electron (n_e) and hole (n_h) concentrations of 1.5×10^{16} m^{-3}. Doping by indium n_h increases to 3×10^{22} m^{-3}. Calculate n_e in the doped Si.

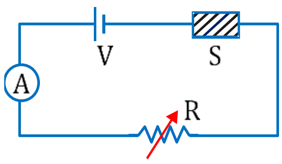
Solution:

For a doped semi-conductor in thermal equilibrium $n_e n_h = n_i^2$ (Law of mass action)

$$n_e = \frac{n_i^2}{n_h} = \frac{(1.5\times10^{16})^2}{3\times10^{22}} = 7.5 \times 10^{9}\ \text{m}^{-3}$$

BEGINNER'S BOX-1

1. The diagram shows a piece of pure semiconductor S, in series with a variable resistor R, and a source of constant voltage V. Would you increase or decrease the value of R to keep the reading of ammeter (A) constant, when semiconductor S is heated? Give reason.



PSE193

2.	Pure Si at 300 K has equal electron n_e and hole n_h concentration of $1.5 \times 10^{16}/m^3$. Doping by indium increases n_h to $4.5 \times 10^{22}/m^3$. Calculate n_e in doped silicon. **PSE194**	
3.	Suppose a pure Si crystal has 5×10^{28} atoms m^{-3}. It is doped by 1 ppm concentration of pentavalent As. Calculate the number of electrons and hole. (Given that $n_i = 1{\cdot}5 \times 10^{16}\ m^{-3}$.) **PSE195**	
4.	For given semiconductor contribution of current due to electron and hole is in ratio 3/1 and the ratio of drift velocity for electron and hole is 5/2, then calculate the ratio of electron to hole concentration. **PSE196**	

P-N Junction Diode & Diode Formation

When a P-type semiconductor is joined to a N-type semiconductor such that the crystal structure remains continuous at the boundary, the resulting arrangement is called a P-N junction diode.

There are two important processes in the p-n junction.

1. Diffusion 2. Drift

1. Diffusion

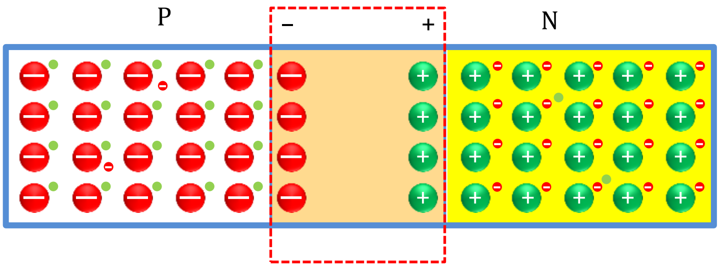
It occurs for majority charge carriers due to concentration gradient. Holes diffuses from p-side to n-side of the junction. Electrons diffuses from n-side to p-side of the junction. Direction of diffusion current is from p-side to n-side.

2. Drift

It occurs for minority charge carriers due to electric field in the depletion region. Electron drift from p-side to the n-side of the junction. Holes drift from n-side to the p-side of the junction.

Electrons and holes drift to their respective majority sides. Direction of drift current is from n to p, opposite to that of diffusion current. Initially, diffusion current is large and drift current is small. As the diffusion process continues, the electric field strength increases and hence drift current. This process continues until the diffusion current equals the drift current. Thus, a p-n junction is formed. In a p-n junction under equilibrium there is no net current. It means $|I_{Drift}| = |I_{Diffusion}|$

Depletion Width



Width of Depletion region $\approx 0.1\mu m$

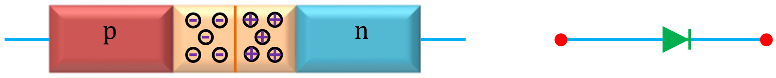
It depends on temperature, doping and type of material $\text{width} \propto \dfrac{1}{\sqrt{\text{Doping}}}$

Barrier Potential or Built–in Potential

An electric field is set up from n-side to p-side. Thus n-region have higher potential than p-region. The difference in potential between p and n regions across the junction makes it difficult for the holes and electrons to move across the junction. This acts as a barrier and hence called 'potential barrier'. Depends on temperature, doping and nature of semiconductor material. The potential barrier opposes the motion of the majority carriers and helps the movement of minority carriers.

Types of Biasing

A semiconductor diode is basically a P-N junction with metallic contacts provided at the ends for the application of an external voltage. It is a two terminal device.

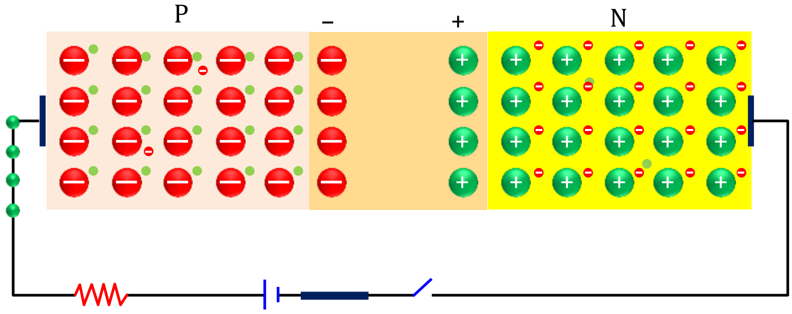


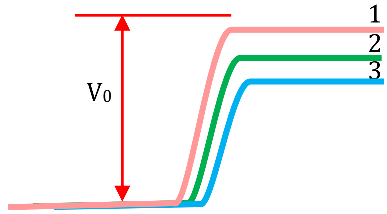
There are two ways of biasing (applying external voltage) a diode.

1. Forward Biasing 2. Reverse Biasing

1. Forward Biasing

p-side of semiconductor is connected to the positive terminal of the battery and n-side to the negative terminal. The direction of the applied voltage (V) is opposite to the barrier potential V_0. The depletion layer width decreases and the barrier height is reduced. The effective barrier height under forward bias is $(V_0 - V)$.





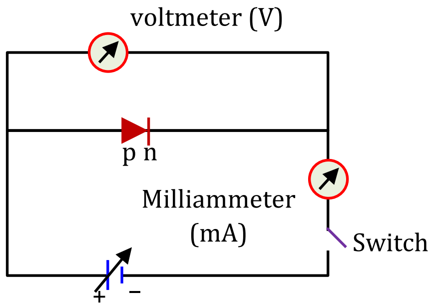
Current is mainly due to diffusion of charge carriers and it is of the order of mA.

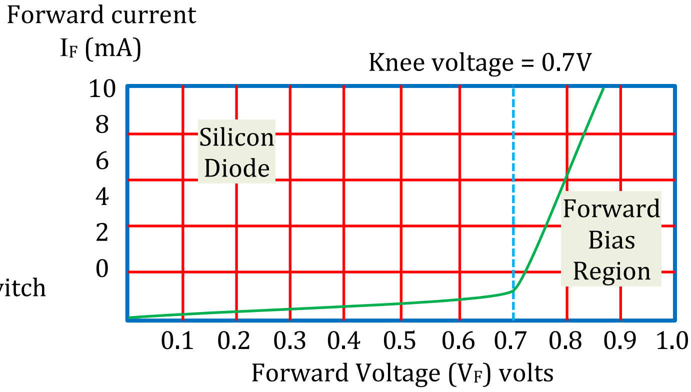
$$|I_{Diffusion}| > |I_{Drift}|$$

Forward bias resistance of diode is small and of the order of kΩ.

Current is almost zero up to certain value of applied voltage. This voltage is called as knee-Voltage or threshold voltage (V_{TH}).

Current increase exponentially after the knee-voltage.





2. Reverse Biasing

p-side of semiconductor is connected to the negative terminal of the battery and n-side to the positive terminal. The direction of the applied voltage (V) is in support to the barrier potential V_0. The depletion layer width increases and the barrier height also increases. The effective barrier height under reverse is $(V_0 + V)$.

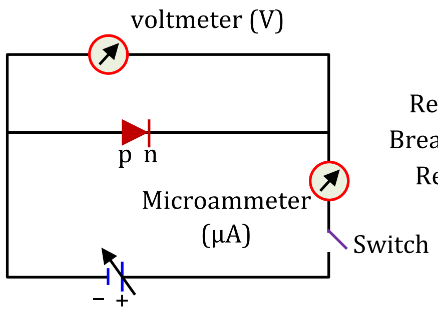
Diffusion of majority carrier stops and current is mainly due to minority carriers. It is of the order of μA.

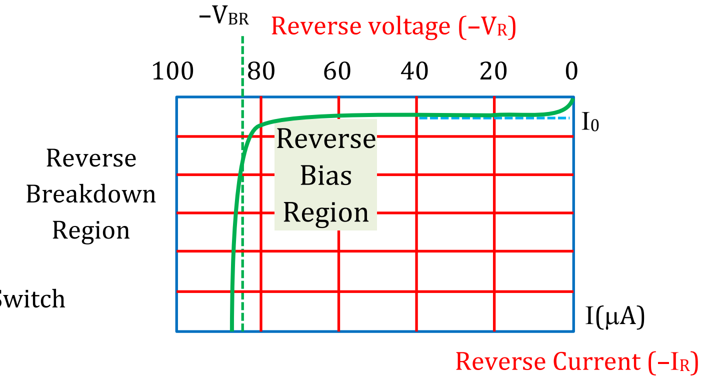
$$|I_{Diffusion}| < |I_{Drift}|$$

Reverse bias resistance of diode is large and of the order of MΩ.

Current is very small & almost constant for any value of applied voltage, as it is limited by the concentration of minority carriers. It is called reverse saturation current (I_0).

When $V = V_{BR}$, the diode reverse current increases sharply. Even a slight increase in the bias voltage causes large change in the current.





Conclusion:-

To check the biasing of diode or PN junction:

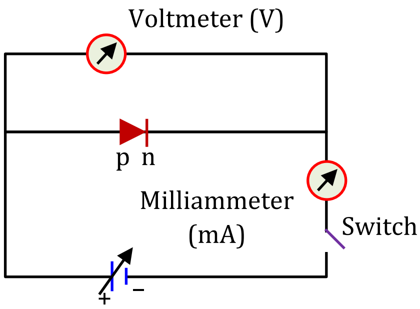
(1) If $V_P - V_N > 0$ then diode D is forward bias (F.B.)

(2) If $V_P - V_N < 0$ then diode D is reverse bias (R.B.)

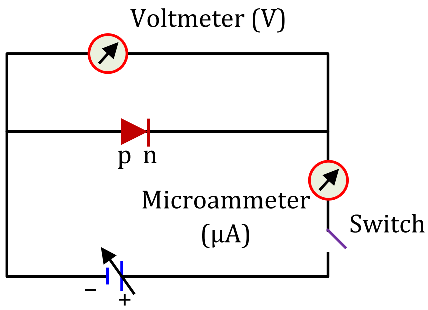
(3) If $V_P - V_N = 0$ then diode D is unbiased

Characteristic Curve of P-N Junction Diode

symbol



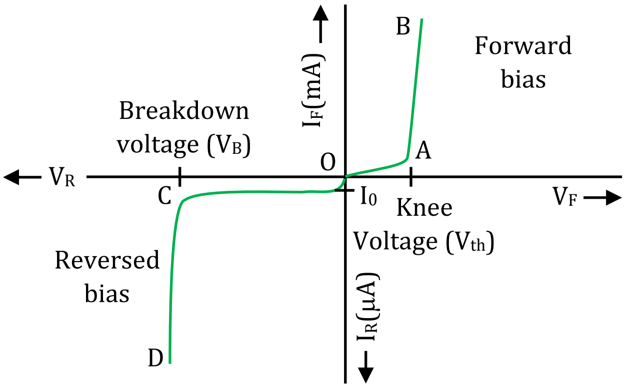
(a) forward bias



(b) reverse bias

In forward bias when voltage is increased from 0V in steps and corresponding value of current is measured, the curve comes as OB of figure. We may note that current increases very sharply after a certain voltage knee voltage. At this voltage, barrier potential is completely eliminated and diode offers a low resistance.

In reverse bias a microammeter has been used as current is very small. When reverse voltage is increased from 0V and corresponding values of current measured the plot comes as OCD. We may note that reverse current is almost constant hence called reverse saturation current. It implies that diode resistance is very high. As reverse voltage reaches value V_B, called breakdown voltage, current increases very sharply.



Ideal Diode

Forward Bias : R = 0 (short circuit)

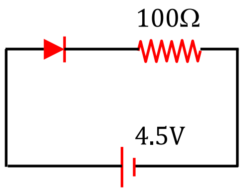
Reverse Bias : R = ∞ (open circuit)

Real Diode

- It allows the current only in forward direction.
- There will be finite potential difference, when current is passing through the diode.
- For all practical purpose current in Reverse bias is zero. It acts as very high resistance in reverse bias.

Illustration 2

Figure shows a diode connected to an external resistance and an e.m.f. Assuming that the barrier potential developed in diode is 0.5 V, obtain the value of current in the circuit in milliampere.



Solution:

E = 4.5 V, R = 100 Ω,

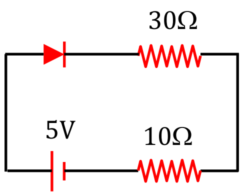
Voltage drop across p-n junction = 0.5 V

Effective voltage in the circuit V = 4.5 – 0.5 = 4.0 V

Current in the circuit $I = \frac{V}{R} = \frac{4.0}{100} = 0.04$ A = 0.04 × 1000 mA = 40 mA

Illustration 3

If current in given circuit is 0.1 A then calculate resistance of P–N junction.

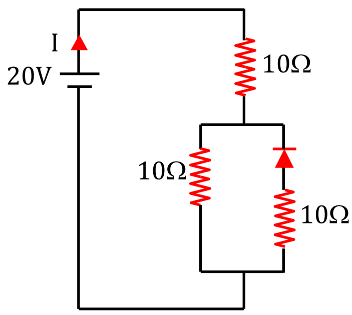


Solution:

Let resistance of PN junction be R then $I = \frac{5}{R+30+10} = 0.1 \Rightarrow R = 10\ \Omega$

Illustration 4

What is the value of current I in given circuits?



Solution:

$$I = \frac{20}{10+10} = 1\text{A}$$

BEGINNER'S BOX-2

1. The potential barrier existing across an unbiased p–n junction is 0.2 volt. What minimum kinetic energy a hole should have to diffuse from the p–side to the n–side if –

(a) The junction is unbiased (b) The junction is forward biased at 0.1 volt

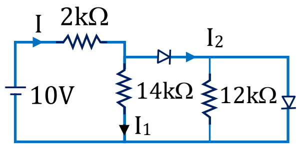
(c) The junction is reverse-biased at 0.1 volt.

PSE197

2. A silicon P–N junction is in forward biased condition with a resistance in series. It has knee voltage of 0.75 V and current flow in it is 10 mA. If the P–N junction is connected with 2.75 V battery then calculate the value of the resistance.

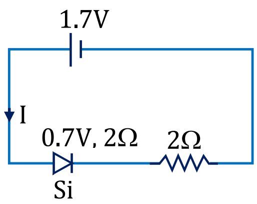
PSE198

3. In given circuit determine I, I_1 and I_2



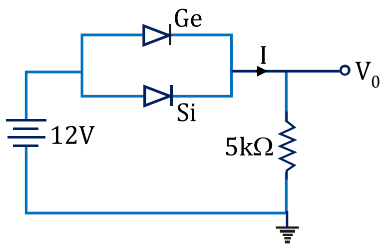
PSE199

4. Find the value of current I in given circuit.



PSE200

5. (a) Calculate the value of V_0 and I if the Si diode and the Ge diode start conducting at 0·7 V and 0·3 V respectively, in the given circuit. (b) If the Ge diode connection be reversed, What will be the new values of V_0 and I ?



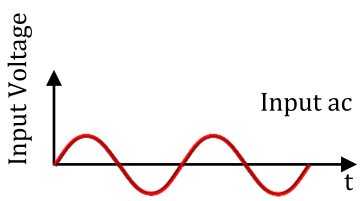
PSE201

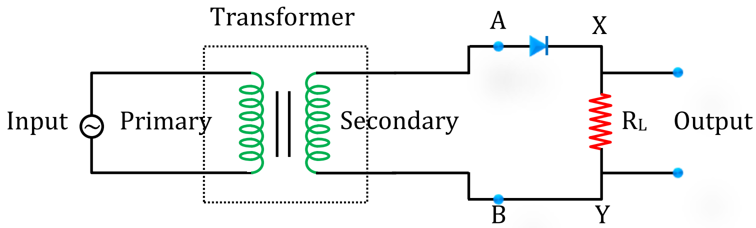
Application of P-N Junction Diode

1. Rectifier

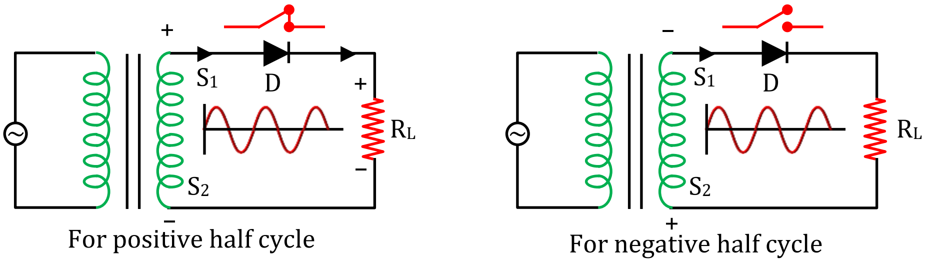
It is device which is used for converting alternating current into direct current. Diode can be used as rectifier as it is uni-directional device.

(i) Half Wave Rectifier





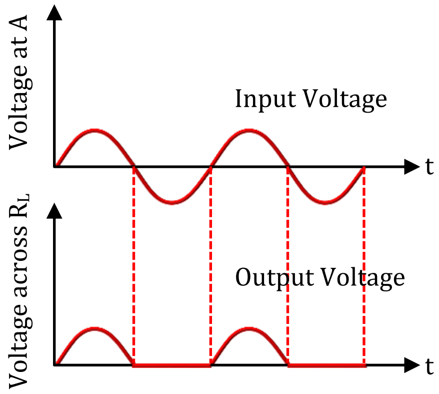
Working:



During the first half (positive) of the input signal, S_1 is at positive and S_2 is at negative potential. So, the PN junction diode D is forward biased. The current flows through the load resistance R_L and output voltage is obtained across the R_L.

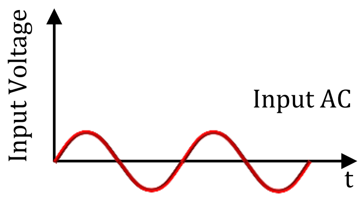
During the second half (negative) of the input signal, S_1 is at negative potential and S_2 is at positive potential. The PN junction diode will be reversed biased. In this case, practically no current would flow through the load resistance. So, there will be no output across the R_L.

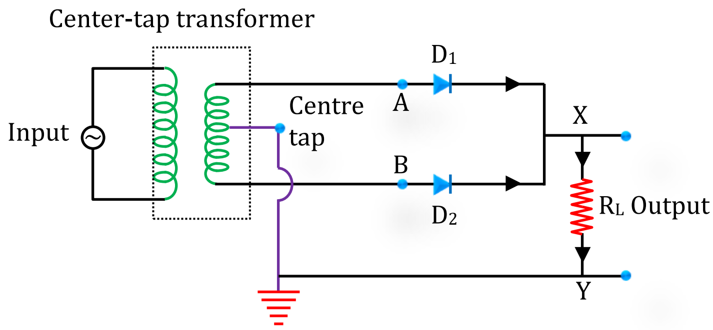
Thus, corresponding to an alternating input signal, we get a unidirectional pulsating output called rectified output.



(ii) Full-wave Rectifier (Centre Tap Full Wave Rectifier)

We need two diodes working for both the half cycles. Also, we need a centre-tap arrangement for transformer.

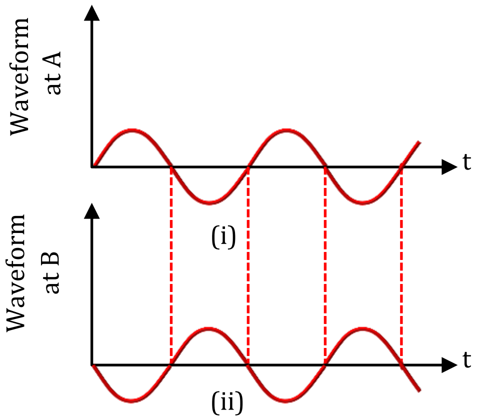


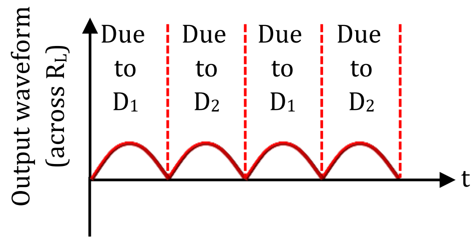


During the positive half of the input signal : S_1 positive and S_2 negative. In this case diode D_1 is forward biased and D_2 is reverse biased. So only D_1 conducts and hence the flow of current in the load resistance R_L is from A to B.

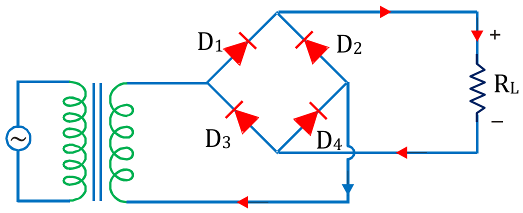
During the negative half of the input signal : S_1 is negative and S_2 is positive. So D_1 is reverse-biased and D_2 is forward biased. So only D_2 conducts and hence the current flows through the load resistance R_L again from A to B.

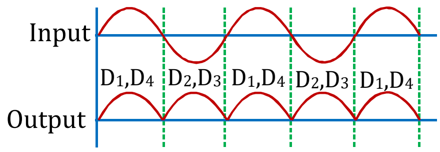
It is clear that whether the input signal is positive or negative, the current always flows through the load resistance in the same direction and thus output is called full wave rectified.





(iii) Bridge Rectifier





During positive half cycle

D_1 and D_4 are forward biased $\rightarrow$ 'On' switch

D_2 and D_3 are reverse biased $\rightarrow$ 'Off' switch

During negative half cycle

D_2 and D_3 are forward biased $\rightarrow$ 'On' switch

D_1 and D_4 are reverse biased $\rightarrow$ 'Off' switch

For half wave rectifier

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

For full wave rectifier or bridge wave rectifier

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

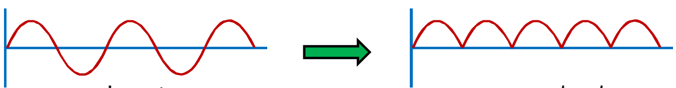
Ripple Frequency

(i) For half wave rectifier

input — Input frequency = 50 Hz

output — Ripple frequency = 50 Hz

(ii) for full wave rectifier



input — Input frequency = 50 Hz

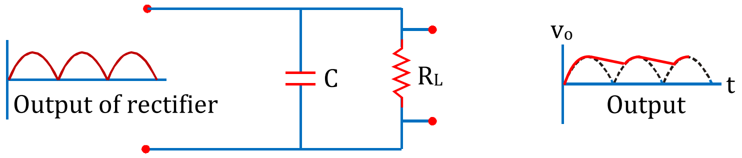
output — Ripple frequency = 100 Hz

Filter Circuit

The rectified output is in the form of pulses or in shape of half sinusoids. Though it is unidirectional, it does not have a steady value. To get steady dc output from the pulsating voltage, normally a capacitor is connected across the output terminals (parallel to the load R_L) called filter circuit.

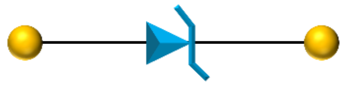
Capacitor Filter

When the voltage across the capacitor is rising, it gets charge. If there is no external load, it remains charged to the peak voltage of the rectified output. When there is a load, it gets discharged through the load and the voltage across it begins to fall. In the next half-cycle of rectified output it again gets charged to the peak value but due to large value of time constant of capacitor, voltage across the capacitor approximate remains constant.

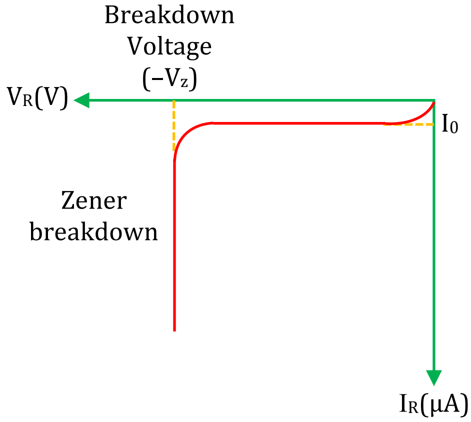


2. Zener Diode

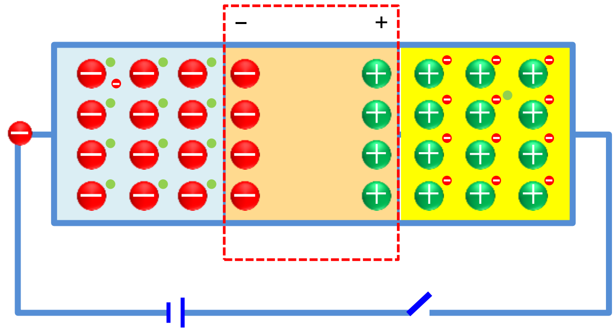
Special purpose diode invented by C. Zener. Heavily doped P-N junction. Works like a normal diode in forward bias. Mainly operated in reverse bias breakdown region.



I-V characteristic:



It can handle large variation in current without change in Zener voltage, and hence it will be used in regulation.



Increase in reverse bias voltage, increases the $\vec{E}$ in depletion region.

The electric field may become large enough causing electron-hole pairs to be created.

This creates a huge reverse bias current.

Voltage at which this phenomenon happens is called Breakdown voltage and breakdown voltage is a function of doping concentration in p-region and n-region.

In reverse biasing, breakdown can occur in two ways:

I. Avalanche Breakdown

II. Zener Breakdown

I. Avalanche Breakdown

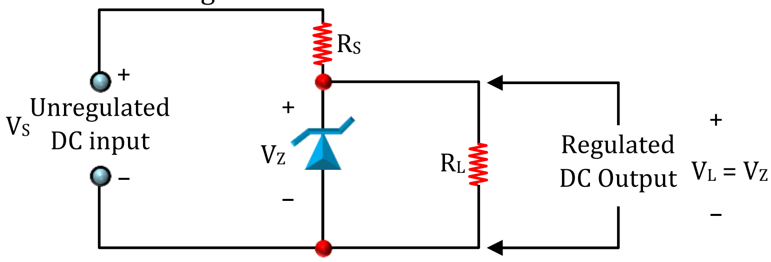
It occurs in p-n junction having low doping. Breakdown voltage is very high. Depletion layer width is also more. Charge carriers crossing the depletion region gain enough kinetic energy and make collision with other atoms, and hence it starts the avalanche effect. Damage to the diode is permanent.

II. Zener Breakdown

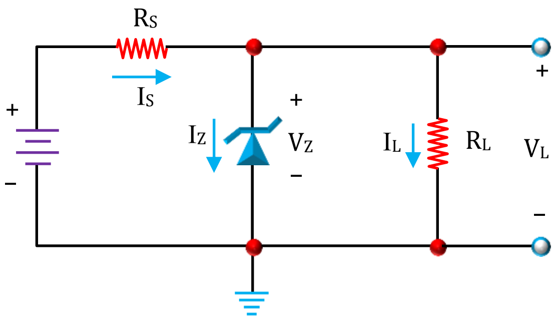
Occurs in heavily doped p-n junction. Breakdown voltage is very small. Depletion layer is very thin. Breaking of covalent bonds is mainly due to electric field. Hence damage is not permanent.

Zener diode as a voltage regulator

Regulation is possible because in the breakdown region, Zener voltage remains constant even though the current through the Zener diode changes.



If the input voltage increases, the current through R_S and Zener diode also increases. Similarly, if the input voltage decreases, the current through R_S and Zener diode also decreases. Thus any increase/decrease in the input voltage results in increase/decrease of the voltage drop across R_S without any change in voltage across the load. This is how Zener diode acts as a voltage regulator.

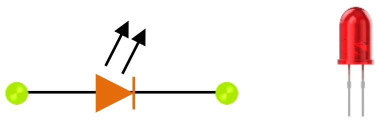


Load voltage is constant and load current is also constant $\frac{V_Z}{R_L}$.

Input current is, $I_S = \frac{V_S - V_Z}{R_S}$; Zener Current $I_Z = I_S - I_L$ and $P_Z = V_Z I_Z$

3. Light Emitting Diode (L.E.D)

A Light Emitting Diode converts electrical current into light. LEDs are heavily doped p-n junctions and operated under forward bias. Outer material must be transparent so that photons can escape.



Working : when LED is forward biased then electrons move from N $\rightarrow$ P and holes move from P $\rightarrow$ N. At the junction boundary these are recombined. On recombination, energy is released in the form of photons of energy equal to or slightly less than the band gap.

When the forward current of the diode is small, the intensity of light emitted is small. As the forward current increases, intensity of light increases and reaches a maximum. Further increase in the forward current results in decrease of light intensity. LEDs are biased in such a way that the light emitting efficiency should be maximum.

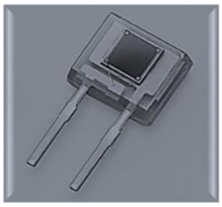
In case of Si or Ge diodes, the energy released in recombination lies in infra-red region. Therefore to form LED, such semiconductors are to be used which have band gap from 1.8 eV to 3 eV. Hence $GaAs_{1-x}P_x$ is used in forming LED.

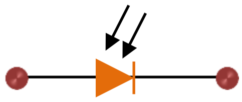
Advantages of LED:

1. Low operational voltage and less power
2. Fast action with no warm up time
3. Emitted light is nearly monochromatic
4. They have long life

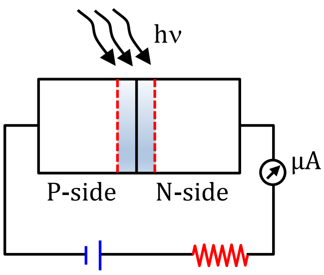
4. Photodiode

A photo-diode converts light into electrical current or voltage. Photo-diode are moderately doped p-n junctions and operated under reverse bias. Outer material must be transparent so that photons can enter.

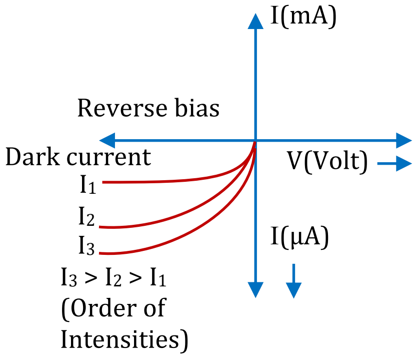




Working: When light of energy "hν'' falls on the photodiode (Here, hν > energy gap) more electrons move from valence band to conduction band, due to this current in circuit of photodiode in "Reverse bias", increases. As light intensity is increased, the photo current goes on increasing. So, photo diode is used "to detect light intensity". Example used in "Video camera".



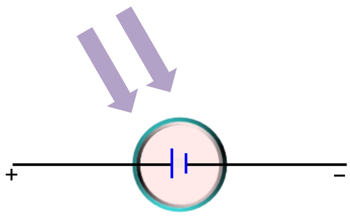
(a) An illuminated photodiode, under reverse bias



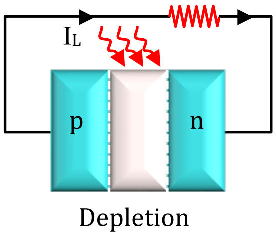
(b) I-V characteristics of a photodiode for different illumination intensity $I_3 > I_2 > I_1$

5. Solar Cell

It converts light energy into electrical energy. It has same working principle as that of photo-diode but working method is different. It is operated unbiased. The surface layer of p-region is made very thin so that the incident photons may easily penetrate to reach the junction which is the active region.

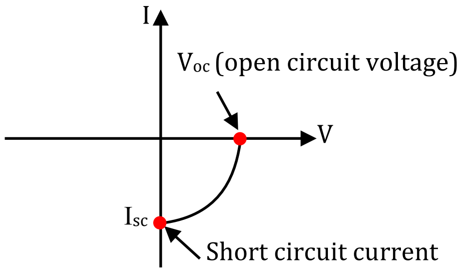


Working: When light falls on, emf generates due to the following three basic processes: generation, separation and collection- (i) generation of e-h pairs due to light (with, hν > Eg) in junction region; (ii) separation of electrons and holes due to electric field of the depletion region. Electrons are swept to n-side and holes to p-side by the junction field; (iii) On reaching electrons at n-side and holes on at p-side. Thus n-side becomes negative and p-side becomes positive potential and giving rise to photovoltage.



A typical illuminated p-n junction solar cell

(a)



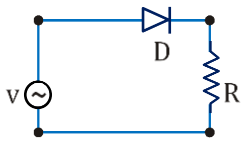
I-V characteristics of a solar cell

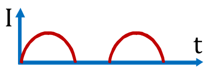
(b)

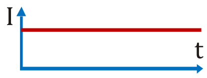
BEGINNER'S BOX-3

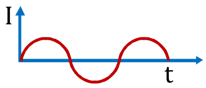
1. A p-n junction diode (D) shown in the figure can act as a rectifier. An alternating current source (V) is connected in the circuit. The current (I) in the resistor (R) can be shown by :-

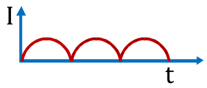
[AIEEE - 2009]



(1) 

(2) 

(3) 

(4) 

PSE202

2. A zener diode of voltage V_Z (=6 V) is used to maintain a constant voltage across a load resistance R_L(=1000 Ω) by using a series resistance R_S (=100 Ω). If the e.m.f. of source is E (= 9 V), calculate the value of current through series resistance, Zener diode and load resistance. What is the power being dissipated in Zener diode?

PSE203

3. A Zener diode is specified having a breakdown voltage of 9.1 V with a maximum power dissipation of 364 mW. What is the maximum current that the diode can handle?

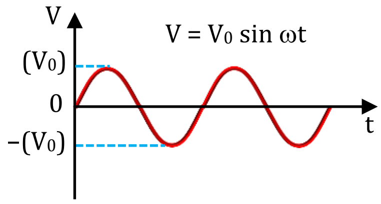
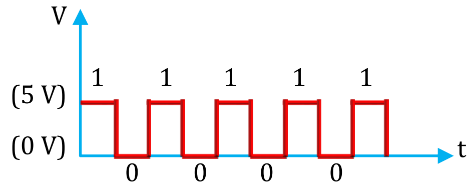
PSE204

4. A semiconductor (GaAs) has an energy gap of 1.43 eV. What is the maximum wavelength emitted when a hole and an electron recombine in such semiconductor?

PSE205

Boolean Algebra

Analog v/s Digital Electronics

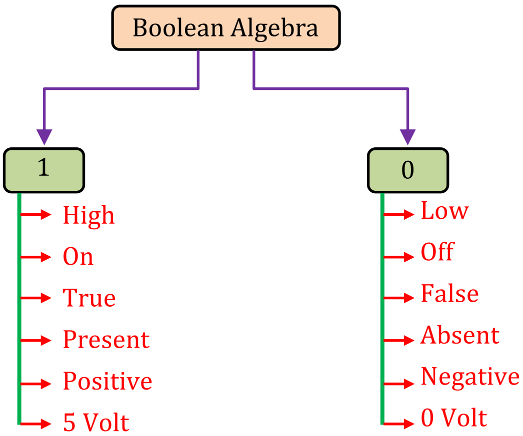
<table>
<tr><th>Analog Signal</th><th>Digital Signal</th></tr>
<tr><td>A continuous signal value which at any instant lies within the range of a maximum and a minimum value.

</td><td>A discontinuous(discrete) signal value which appears in steps in pre-determined levels rather than having the continuous change.

</td></tr>
</table>

Digital Circuit

An electrical or electronic circuit which operates only in two states (binary mode) namely ON/1 and OFF/0 is called a Digital Circuit. To understand the Digital circuits, we need to understand the Boolean algebra.

Boolean Algebra was invented by George Boole.

Boolean algebra have binary variables that take only 2 discrete values (0 and 1).



OR	AND	NOT
0+0=0	0.0=0	$0'=\overline{0}=1$
0+1=1	0.1=0	$1'=\overline{1}=0$
1+0=1	1.0=0	
1+1=1	1.1=1	
FORMULAE		
A+0=A	A.0=0	A+A′=1
A+1=1	A.1=A	A.A′=0
A+A=A	A.A=A	A″=A

Boolean Algebra Laws

Commutative law : $A + B = B + A$

$A . B = B.A$

Associative law : $A + (B + C) = (A + B) + C$

$A . (B . C) = (A . B) . C$

Distributive law : $A . (B + C) = A . B + A . C$

$A + (B . C) = (A + B) . (A + C)$

De-Morgan's Theorem: $\overline{A \cdot B} = \overline{A} + \overline{B}$

$\overline{A + B} = \overline{A} \cdot \overline{B}$

Illustration 5

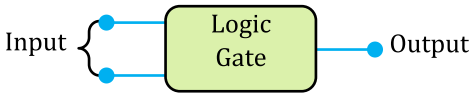
By using Boolean Algebra prove that, $\overline{A}B+A\overline{B}+AB=A+B$

Solution:

LHS = $\overline{A}B+A\overline{B}+AB=\overline{A}B+A\overline{B}+AB+AB=A(B+\overline{B})+B(\overline{A}+A)$ = A.1 + B.1 = A + B = RHS

Logic Gates

A logic gate is a digital circuit which is based on certain logical relationship between the input and the output voltages of the circuit. The logic gates are built using the Semiconductor diodes and transistors.

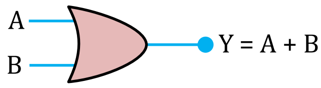


These are the basic building blocks of a digital circuit.

Basic logic gates

1. OR Gate

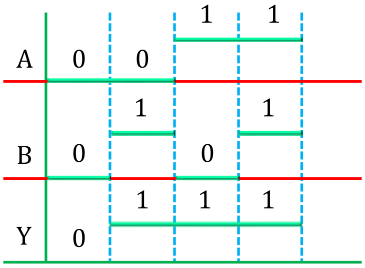
Representation :



Boolean expression : Y = A + B

Truth table :

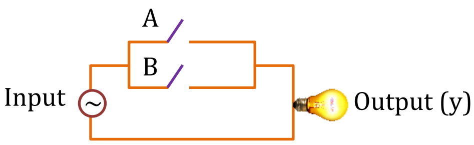
A	B	Y
0	0	0
0	1	1
1	0	1
1	1	1



Waveforms

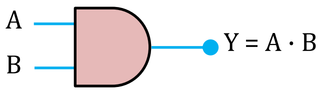
Note : Output is ON if any of the inputs are ON.

Electric analogous circuit :



2. AND Gate

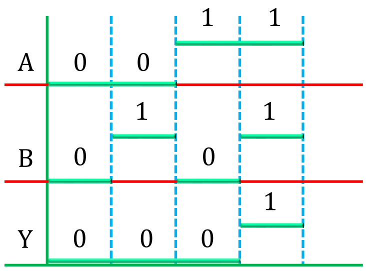
Representation :



Boolean expression : Y = A . B

Truth table :

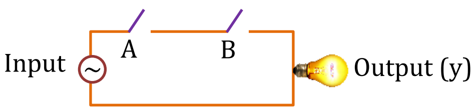
A	B	Y
0	0	0
0	1	0
1	0	0
1	1	1



Waveforms

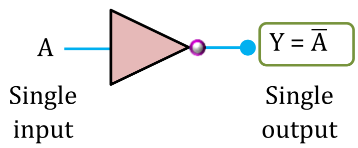
Note : Output is ON if and only if all the inputs are ON.

Electric analogous circuit :



3. NOT Gate (Inverter)

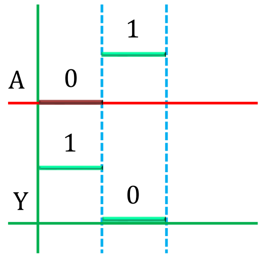
Representation :



Boolean expression : $Y = \overline{A}$

Truth table :

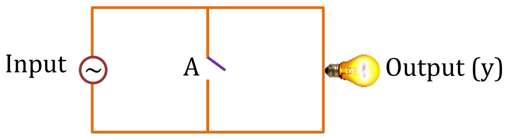
A	Y
0	1
1	0



Waveforms

Note : The output of a NOT gate attains the state ON if and only if the input does not attain the state ON.

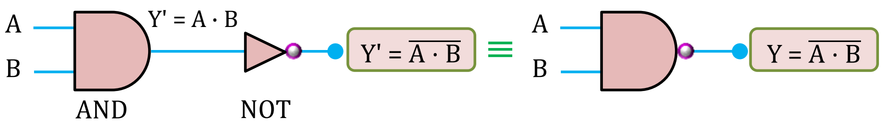
Electric analogous circuit :



Universal gates

1. NAND Gate

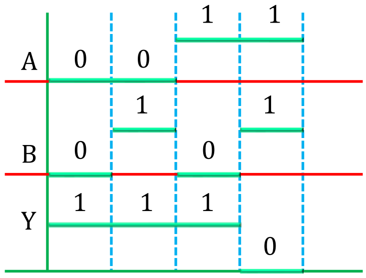
Representation :



Boolean expression : $Y = \overline{A \cdot B}$

Truth table :

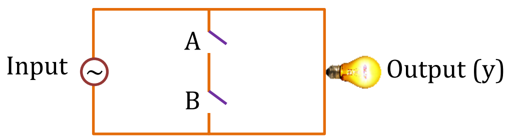
A	B	Y' = A · B	$Y = \overline{A \cdot B}$
0	0	0	1
0	1	0	1
1	0	0	1
1	1	1	0



Waveforms

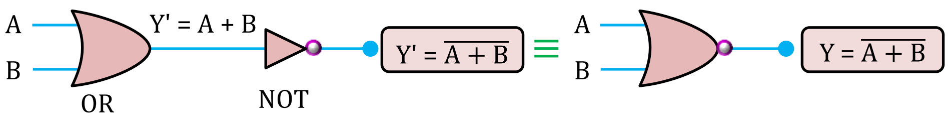
Note : The output is low only when both the input are high.

Electric analogous circuit :



2. NOR Gate

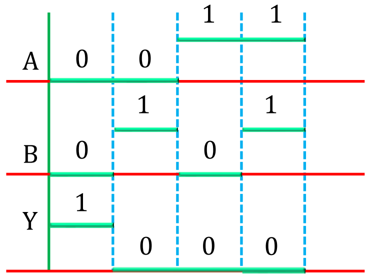
Representation :



Boolean expression : $Y = \overline{A+B}$

Truth table :

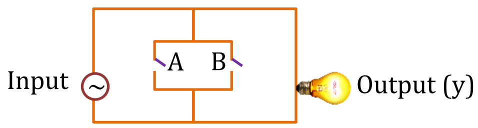
A	B	Y' = A + B	$Y = \overline{A+B}$
0	0	0	1
0	1	1	0
1	0	1	0
1	1	1	0



Waveforms

Note : The gate give high output only when both the inputs are low.

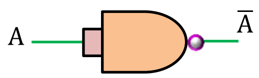
Electric analogous circuit :



Realization of gates by universal gates

The NAND or NOR gate is the universal building block of all digital circuits. Repeated use of NAND gates (or NOR gates) gives other gates. Therefore, any digital system can be achieved entirely from NAND or NOR gates. We shall show how the repeated use of NAND (and NOR) gates will gives us different gates.

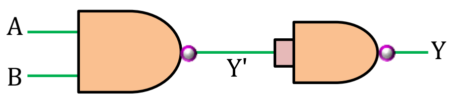
The NOT gate from a NAND gate :- When all the inputs of a NAND gate are connected together, as shown in the figure, we obtain a NOT gate.



Truth table of a single input NAND gate

A	B=(A)	Y
0	0	1
1	1	0

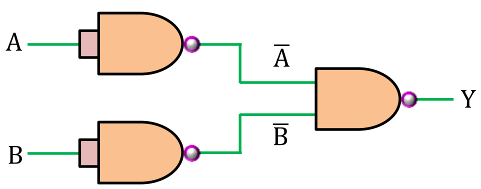
The AND gate from a NAND gates :- If a NAND gate is followed by a NOT gate (i.e., a single input NAND gate), the resulting circuit is an AND gate as shown in figure and truth table given show how an AND gate has been obtained from NAND gates.



Truth table

A	B	Y'	Y
0	0	1	0
0	1	1	0
1	0	1	0
1	1	0	1

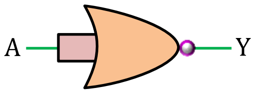
The OR gate from NAND gates :- If we invert the inputs A and B and then apply them to the NAND gate, the resulting circuit is an OR gate.



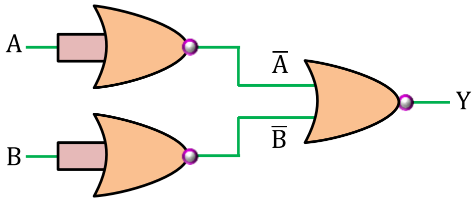
Truth table

A	B	Y'	Y
0	0	1	0
0	1	1	1
1	0	0	1
1	1	0	1

The NOT gate from NOR gates :- When all the inputs of a NOR gate are connected together as shown in the figure, we obtain a NOT gate



The AND gate from NOR gates :- If we invert the inputs A and B and then apply them to the NOR gate, the resulting circuit is an AND gate.



The OR gate from NOR gate :- If a NOR gate is followed by a single input NOR gate (NOT gate), the resulting circuit is an OR gate.

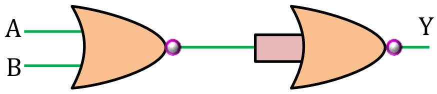
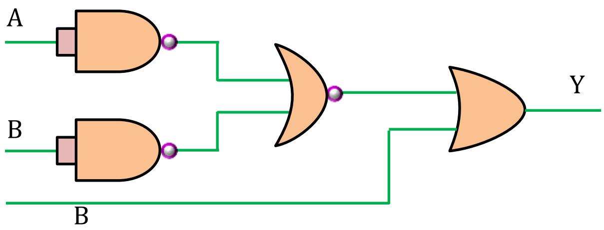


Illustration 6

Write down output Y in terms of inputs A and B.

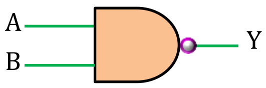


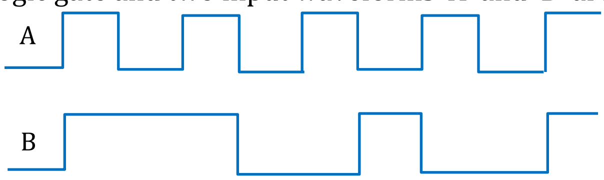
Solution:

$$Y=\overline{\overline{A}+\overline{B}}+B=\overline{\overline{A.B}}+B=A.B+B=(A+1)B=B$$

Illustration 7

In the figures below, Circuit symbol of a logic gate and two input waveforms 'A' and 'B' are shown.





(a) Name the logic gate & Write its Boolean expression

(b) Write its truth table

(c) Give the output wave form

Solution:

(a) NAND gate ;

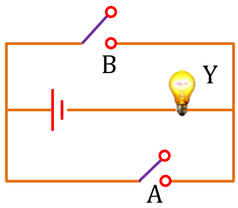
(b) Truth table

Input A	Input B	Output Y
0	0	1
0	1	1
1	0	1
1	0	1

(c) Output waveform

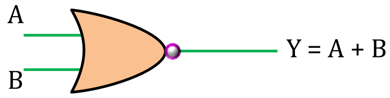
Illustration 8

Given electrical circuit is equivalent to which logic gate, also draw its symbol and truth table.



Solution:

OR gate



A	B	Y
0	0	0
0	1	1
1	0	1
1	1	1

Illustration 9

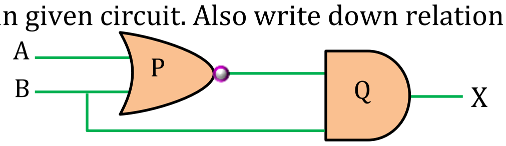
Write the truth table for the logical function D = (A AND B) OR B

Solution:

A	B	X = A AND B	D = X OR B
0	0	0	0
0	1	0	1
1	0	0	0
1	1	1	1

Illustration 10

Identify the logic gates P and Q in given circuit. Also write down relation in A, B and X.



Solution:

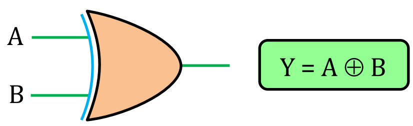
P is NOR gate & Q is AND gate, $X = \left(\overline{A+B}\right)\cdot B = \left(\overline{A}\cdot\overline{B}\right)\cdot B = \overline{A}\cdot(\overline{B}\cdot B) = \overline{A}\cdot 0 = 0$

Special purpose gates

1. XOR Gate

Representation :

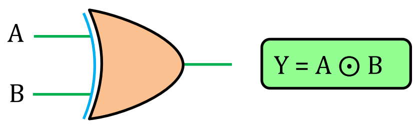
Boolean expression : $Y = \overline{A}\cdot B + A\cdot\overline{B}$ or $Y = A \oplus B$



2. XNOR Gate

Representation :

Boolean expression : $Y = A\cdot B + \overline{A}\cdot\overline{B}$ or $Y = A \odot B$



BEGINNER'S BOX ANSWER KEY

BEGINNER'S BOX-1

1. Value of R should be increased because with the increase in temperature of semiconductor as circuit resistance decreases and current tends to increase.

2. $n_e = 5 \times 10^9 m^{-3}$ **3.** $n_e = 5 \times 10^{22} m^{-3}$, $n_h = 4{\cdot}5 \times 10^9 m^{-3}$ **4.** $n_e/n_h = 6/5$

BEGINNER'S BOX-2

1. (a) 0.2 eV (b) 0.1 eV (c) 0.3 eV **2.** 200 Ω

3. $I_1 = 0$ and $I = I_2 = 5mA$ **4.** 0.25A

5. (a) $V_0 = 11.7$ V, I = 2.34 mA (b) $V_0 = 11.3$ V, I = 2.26 mA

BEGINNER'S BOX-3

1. (1) **2.** $I_S = 30$ mA, $I_L = 6$ mA, $I_Z = 24$ mA, $P_Z = 0.144$ W

3. 40 mA. **4.** 8671.33 Å