18ECC102J
ELECTRONIC DEVICES
Semiconductor Devices

Syllabus Overview

- Learning Unit / Module 1: Semiconductor Diodes
- Learning Unit / Module 2: Diode Circuits
- Learning Unit / Module 3: Special Diodes
- Learning Unit / Module 4: Bipolar Junction Transistors
- Learning Unit / Module 5: MOS Field-Effect Transistors

Learning Unit / Module 1: Signals and Waveforms

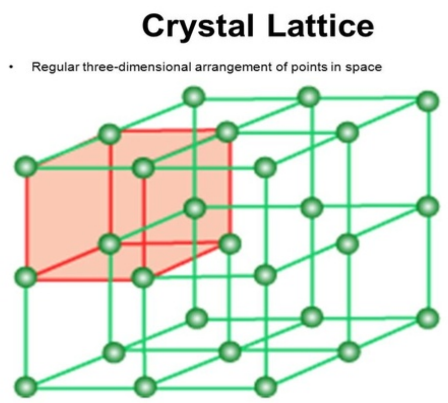
Duration (hour)		Semiconductor Diodes
		15
S-1	SLO-1	*Basic semiconductor theory: Intrinsic & extrinsic semiconductors*
	SLO-2	*Current flow in semiconductors*
S-2	SLO-1	*PN junction theory: Equilibrium PN junction*
	SLO-2	*Forward biased PN junction*
S-3	SLO-1	*Reverse biased PN junction*
	SLO-2	*Relation between Current and Voltage*
S 4-5	SLO-1	*Lab 1: PN Junction Diode Characteristics*
	SLO-2	
S-6	SLO-1	*Calculate depletion width*
	SLO-2	*Calculate barrier potential*
S-7	SLO-1	*Derive diode current equation*
	SLO-2	*Derive diode current equation*
S-8	SLO-1	*Effect of Capacitance in PN junction: Transition Capacitance*
	SLO-2	*Diffusion Capacitance*
S 9-10	SLO-1	*Lab 2: Zener diode characteristics*
	SLO-2	
S-11	SLO-1	*Energy band structure of PN Junction Diode*
	SLO-2	*Ideal diode and its current-voltage characteristics*
S-12	SLO-1	*Terminal characteristics & parameters*
	SLO-2	*Diode modeling*
S-13	SLO-1	*DC load line and analysis*
	SLO-2	*Problem solving*
S 14-15	SLO-1	*Lab 3: Diode rectifier circuits*
	SLO-2	

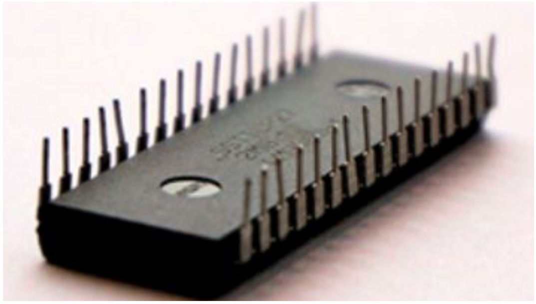
Electronics

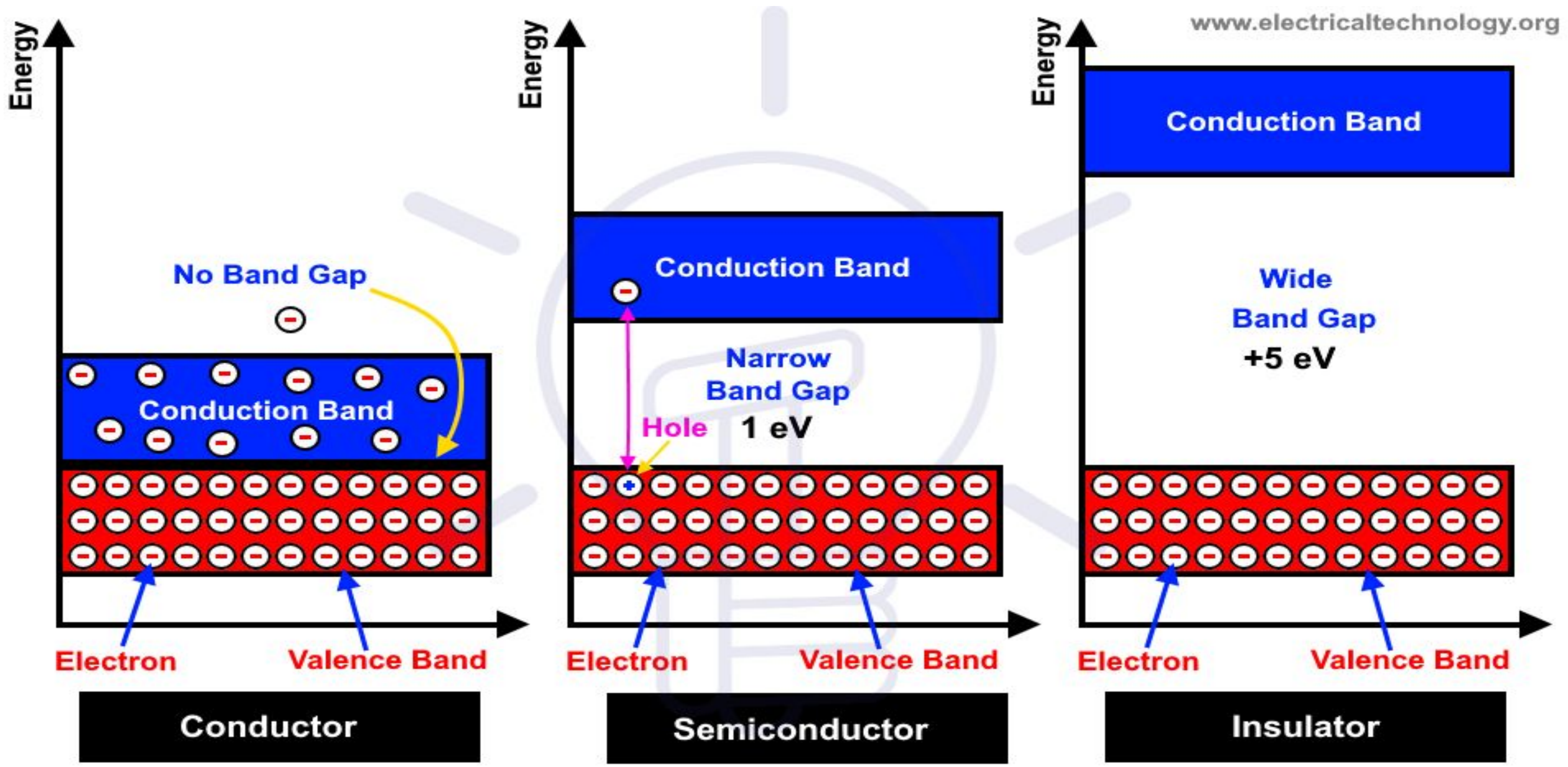
- Data – information formatted in human/machine readable form
  - • examples: voice, music, image, file
- Signal – electric or electromagnetic representation of data
  - • transmission media work by conducting energy along a physical path; thus, to be transmitted, data must be turned into energy in the form of electro-magnetic signals
- Transmission – communication of **data** through propagation and processing of **signals**

What is Semiconductor Devices?

- Electronic components that exploit the electronic properties of semiconductor materials, like as silicon, germanium, and gallium arsenide, as well as organic semiconductors.
- Semiconductor devices have replaced vacuum tubes in many applications.
- They use electronic conduction in the solid state as opposed to the thermionic emission in a high vacuum.
- Semiconductor devices are manufactured for both discrete devices and integrated circuits, which consist of from a few to billions of devices manufactured and interconnected on a single semiconductor substrate or wafer.







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Energy
No Band Gap
Conduction Band
Electron
Valence Band
Conductor
Energy
Conduction Band
Narrow
Band Gap
Hole
1 eV
Electron
Valence Band
Semiconductor
Energy
Conduction Band
Wide
Band Gap
+5 eV
Electron
Valence Band
Insulator

Semiconductor Materials

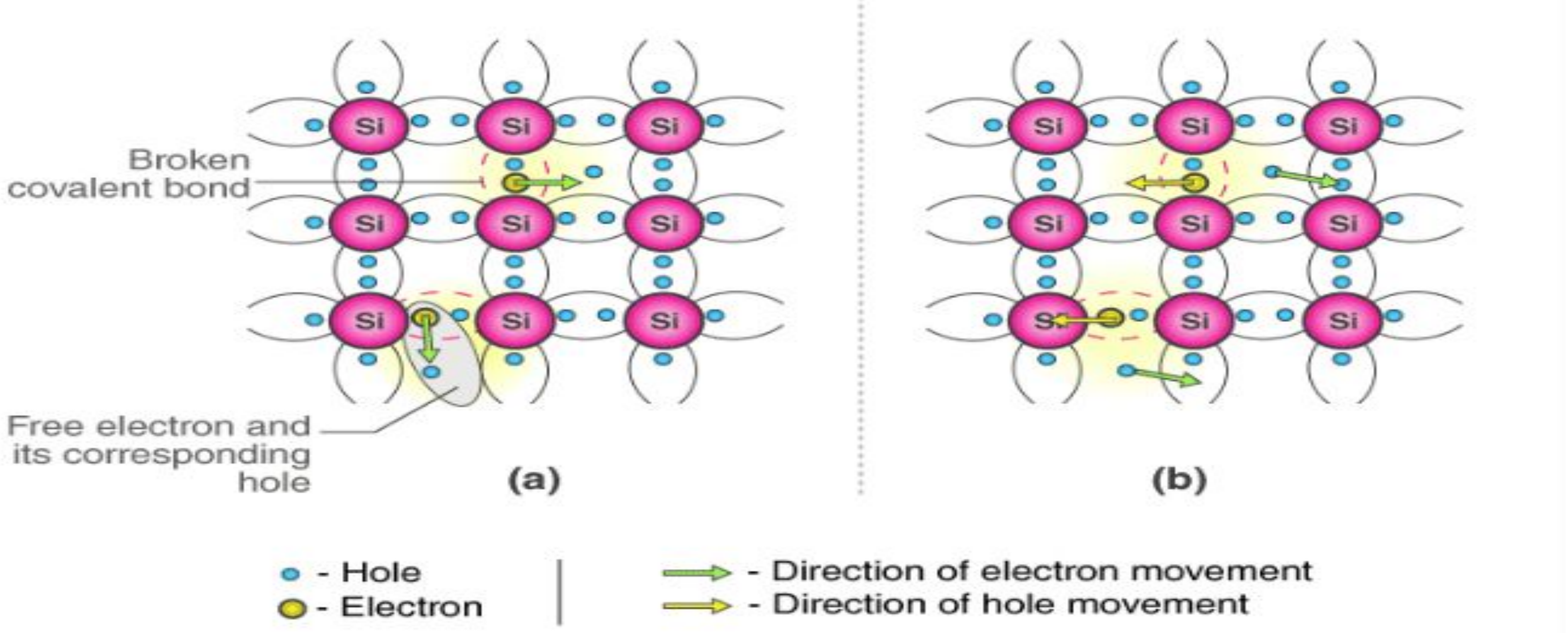
- The wide variety of electronic and optical properties of these semiconductors provides the device engineer with great flexibility in the design of electronic and opto-electronic functions.
- **Ge** was widely used in the early days of semiconductor development for transistors and diodes.
- **Si** is now used for the majority of rectifiers, transistors and integrated circuits.
- The electronic and optical properties of semiconductors are strongly affected by impurities, which may be added in precisely controlled amounts
- (e.g. an impurity concentration of one part per million can change a sample of Si from a poor conductor to a good conductor of electric current). This process called **doping**.

Properties of Semiconductor

- This unique property makes it an excellent material to conduct electricity in a controlled manner as required.
- Unlike conductors, the charge carriers in semiconductors arise only because of external energy (thermal agitation).
- It causes a certain number of valence electrons to cross the energy gap and jump into the conduction band, leaving an equal amount of unoccupied energy states, i.e. holes. Conduction due to electrons and holes are equally important.

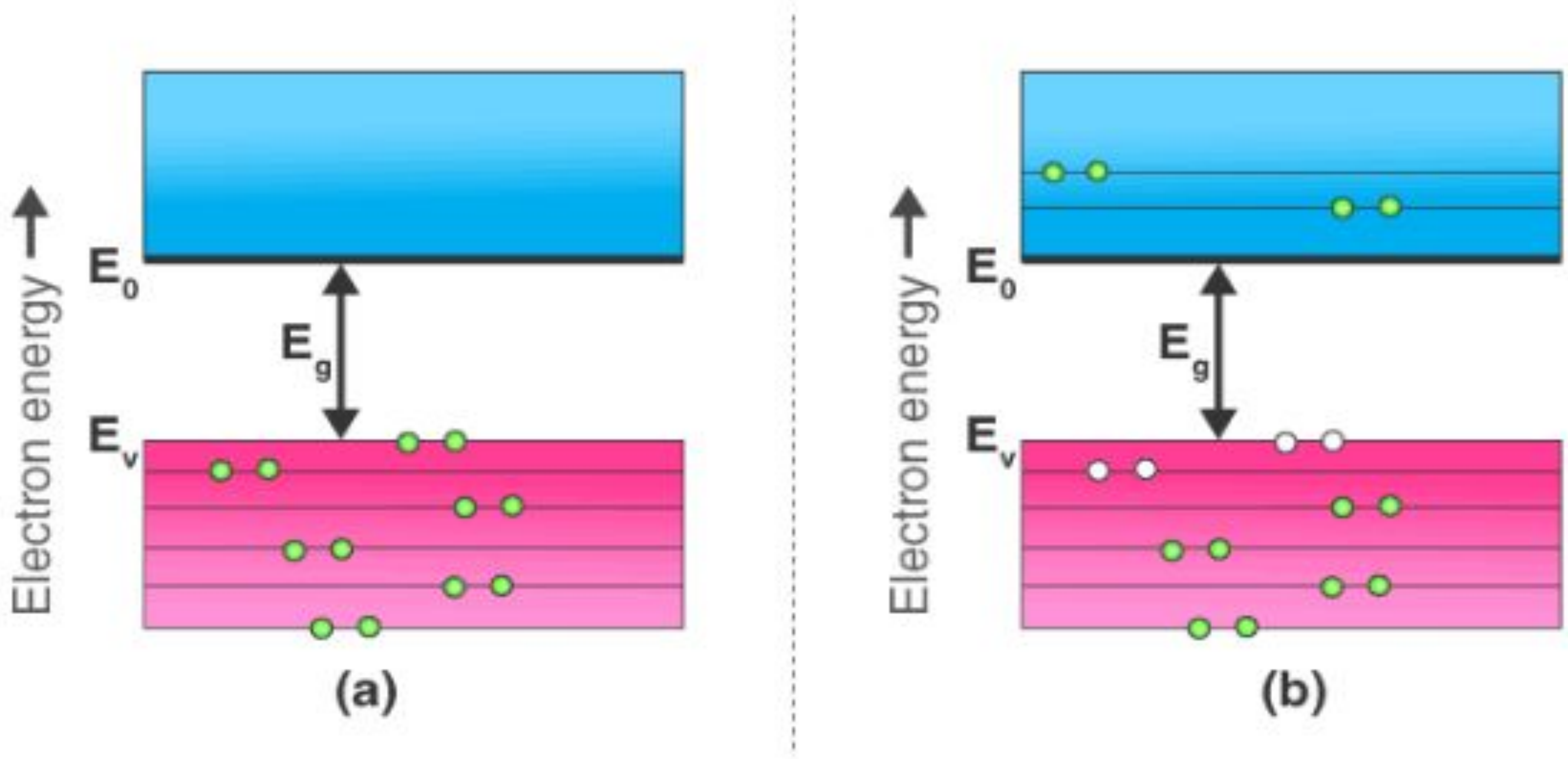
Resistivity: 10^{-5} to 10^{6} Ωm
Conductivity: 10^{5} to 10^{-6} mho/m
Temperature coefficient of resistance: Negative
Current Flow: Due to electrons and holes

Intrinsic Semiconductor



- Semiconductor in pure form is known as Intrinsic Semiconductor.
  - Ex. Pure Germanium, Pure Silicon.
  - At room temp. no of electrons equal to no. of holes.

Intrinsic Semiconductor- Energy Band Diagram



(a) Intrinsic Semiconductor at T = 0 Kelvin, behaves like an insulator (b) At t>0, four thermally generated electron pairs

Intrinsic Semiconductor- Energy Band Diagram_Explanation

- In intrinsic semiconductors, current flows due to the motion of free electrons as well as holes.
- The total current is the sum of the electron current I_e due to thermally generated electrons and the hole current I_h

Total Current (I) = $I_e + I_h$

For an intrinsic semiconductor, at finite temperature, the probability of electrons to exist in conduction band decreases exponentially with increasing bandgap (E_g)

$n = n_0 e^{-Eg/2.Kb.T}$

Where,

Eg = Energy bandgap

K_b = Boltzmann's constants

Extrinsic Semiconductor

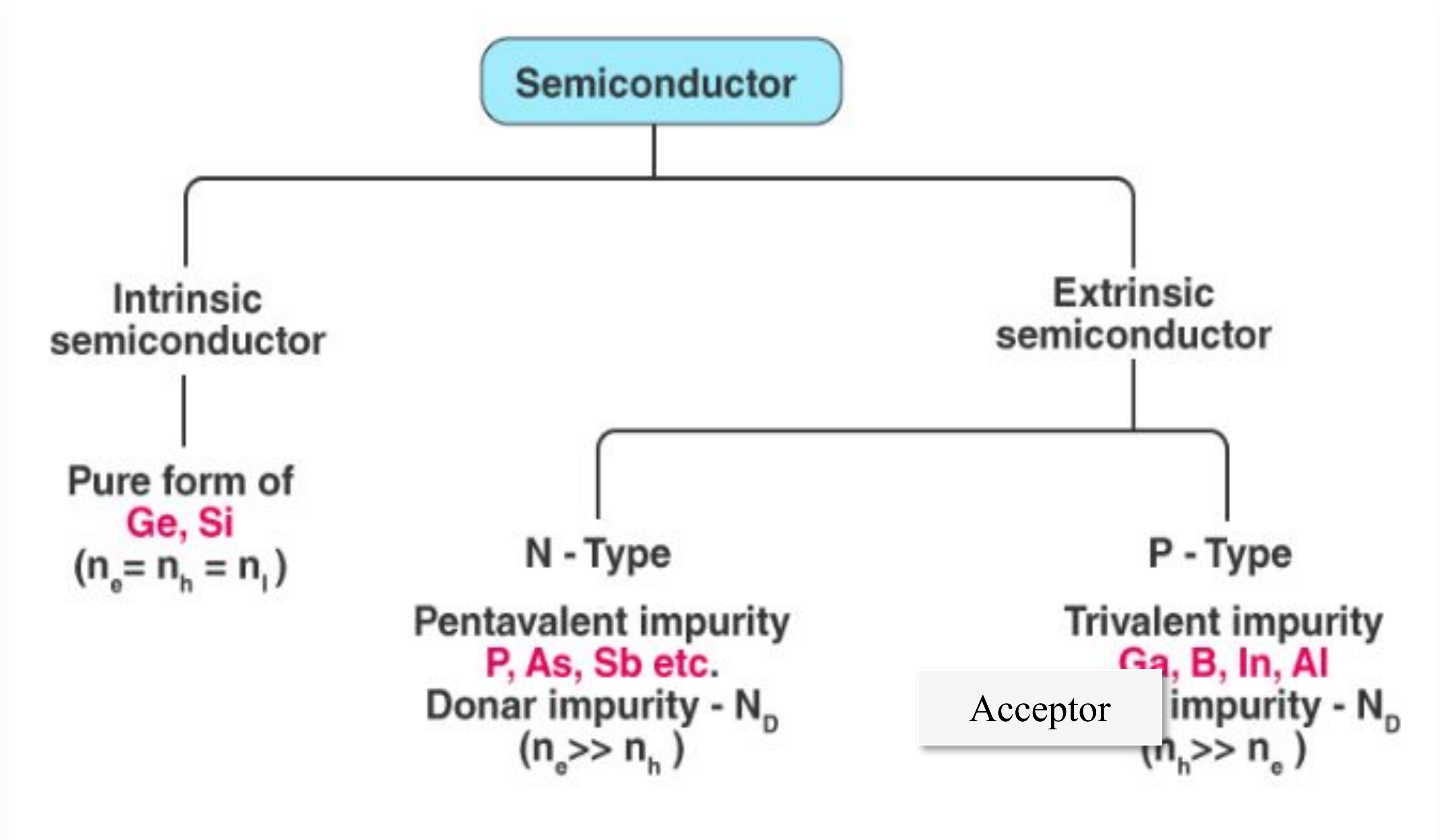
- The conductivity of semiconductors can be greatly improved by introducing a small number of suitable replacement atoms called IMPURITIES.
- Usually, only 1 atom in 10^8 is replaced by a dopant atom in the doped semiconductor.

An extrinsic semiconductor can be further classified into:

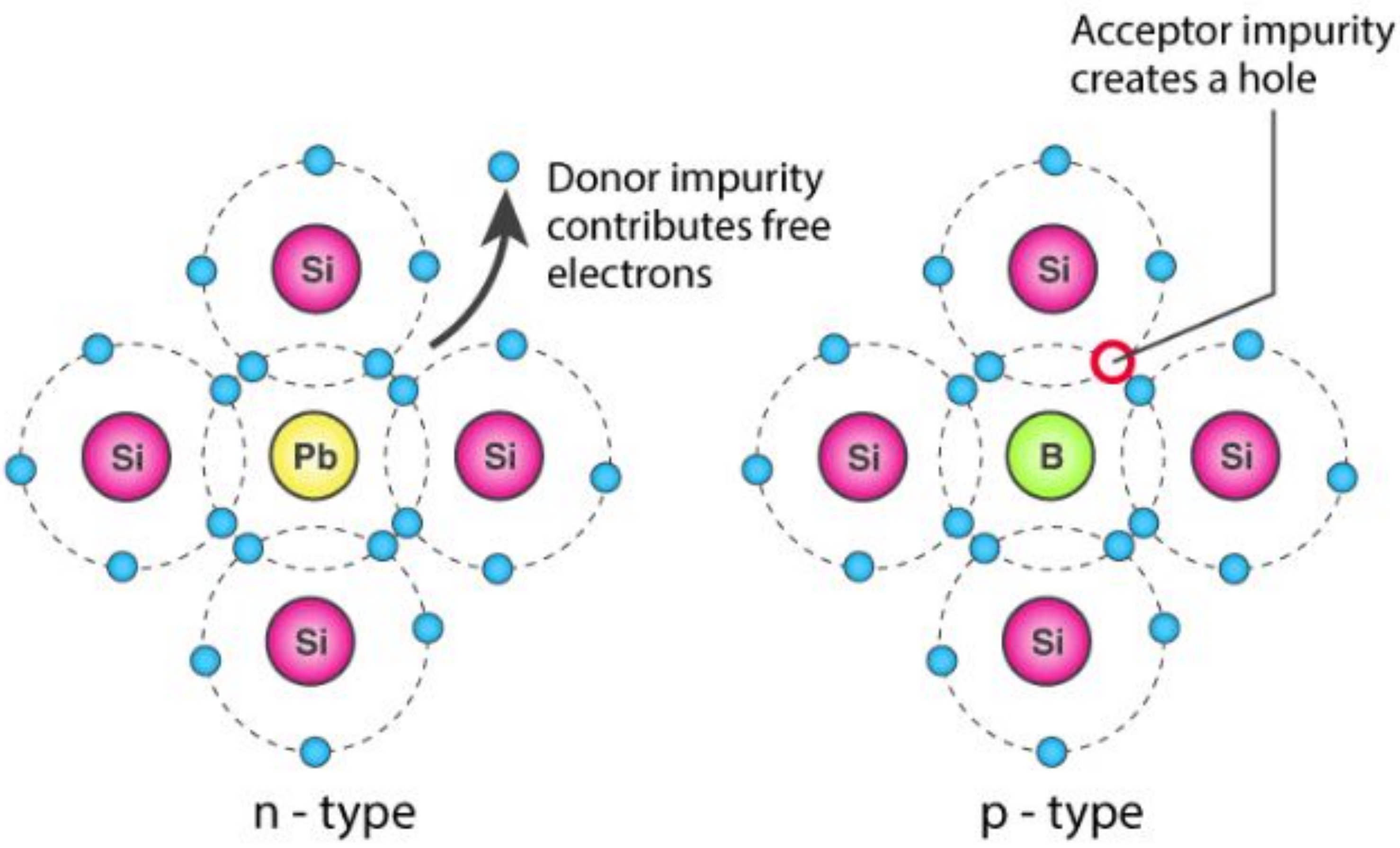
N-type Semiconductor

P-type Semiconductor

Types of Semiconductor



Extrinsic Semiconductor



Classification of Extrinsic Semiconductor

N-type Semiconductor

- Entirely neutral

  $n_h >> n_e$
- Majority – Electrons and Minority – Holes
- When a pure semiconductor (Silicon or Germanium) is doped by pentavalent impurity (P, As, Sb, Bi) then, four electrons out of five valence electrons bonds with the four electrons of Ge or Si.
- The fifth electron of the dopant is set free. Thus the impurity atom donates a free electron for conduction in the lattice and is called "**Donar**".
- Since the number of free electron increases by the addition of an impurity, the negative charge carriers increase. Hence it is called n-type semiconductor.
- Crystal as a whole is neutral, but the donor atom becomes an immobile positive ion. As conduction is due to a large number of free electrons, the electrons in the n-type semiconductor are the MAJORITY CARRIERS and holes are the MINORITY CARRIERS.

P-type Semiconductor

- Entirely neutral

  $n_h >> n_e$
- Majority – Holes and Minority – Electrons
- When a pure semiconductor is doped with a trivalent impurity (B, Al, In, Ga) then, the three valence electrons of the impurity bonds with three of the four valence electrons of the semiconductor.
- This leaves an absence of electron (hole) in the impurity. These impurity atoms which are ready to accept bonded electrons are called “**Acceptors**“.
- With the increase in the number of impurities, holes (the positive charge carriers) are increased. Hence, it is called p-type semiconductor.
- Crystal as a whole is neutral, but the acceptors become an immobile negative ion. As conduction is due to a large number of holes, the holes in the p-type semiconductor are MAJORITY CARRIERS and electrons are MINORITY CARRIERS.

Difference between Intrinsic and Extrinsic Semiconductor

Intrinsic Semiconductor	**Extrinsic Semiconductor**
Pure semiconductor	Impure semiconductor
Density of electrons is equal to the density of holes	Density of electrons is not equal to the density of holes
Electrical conductivity is low	Electrical conductivity is high
Dependence on temperature only	Dependence on temperature as well as on the amount of impurity
No impurities	Trivalent impurity, pentavalent impurity

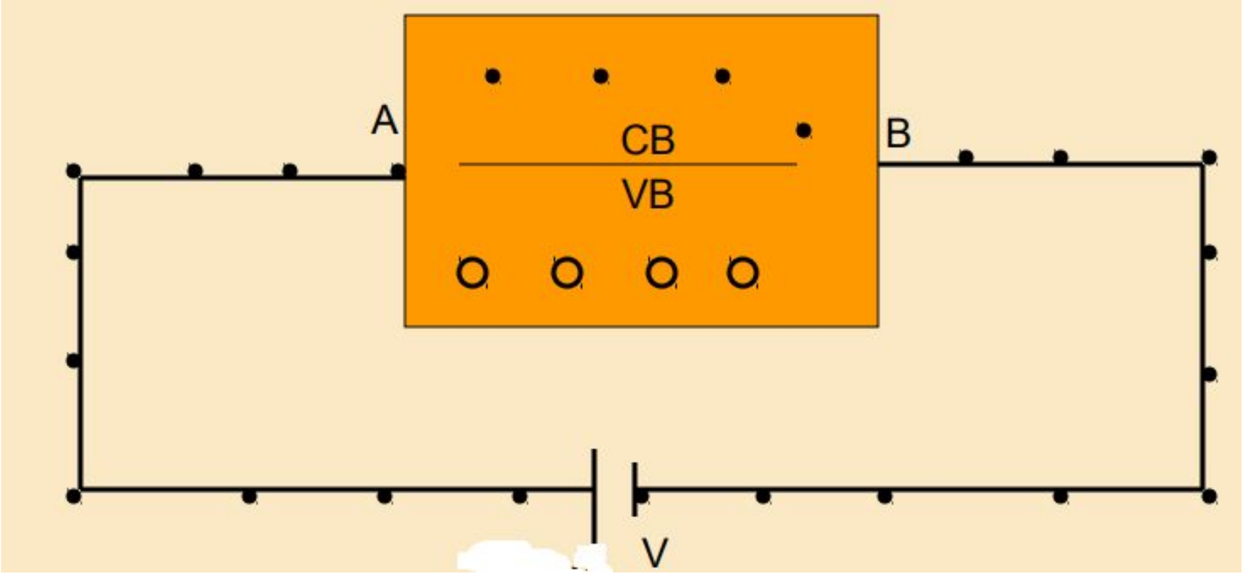
Conduction in Semiconductor

Conduction is carried out by means of

1. Drift Process.

2. Diffusion Process.

Drift Process



- Electrons move from external circuit and in conduction band of a semiconductor.
- Holes move in valence band of a semiconductor

Conductivity of metals

- The conductivity of a material is proportional to the of free electrons.
- A constant electric field E is applied to the metal , the free electron would be accelerated and the velocity would increase indefinitely with time.
- Electrons loss energy because collision of electrons.
- A steady-state conduction is reached where a finite value of drift velocity V_d is attained.
- The drift velocity V_d is opposite of the electric field and its magnitude is proportional to E.

$$v_{drift} = \mu E \qquad \text{..........} \quad (1)$$

μ = The mobility of electrons in m²/volt-second

conductivity of metal

Due to the applied electric field , a steady-state drift velocity has been superimposed upon the random thermal motion of the electrons. Such a directed flow of electrons constitutes current.

If the concentration of free electrons is n (electrons/m³) ,the current density J (ampere/m²) is...

$$J = nqV_d \quad \text{................(2)}$$

From eq. (1)

$$J = nq\mu E$$

$$J = \sigma E$$

where,

$$\sigma = nq\mu$$

σ = The conductivity of metal in (ohm-metre)$^{-1}$

Conductivity of intrinsic semiconductor

Intrinsic semiconductors behave as perfect insulator at 0K. Because at 0K, the valence band remains full, the conduction band empty and no free charge carriers for conduction. But at room temperature (300K) , the thermal energy is sufficient to create a large number of electron-hole pairs. Now if an electric field is applied, the current flows through the semiconductor. The current flows in the semiconductor due to the movement of electrons in one direction and holes in opposite direction.

so, the current density of a metal is..

$$J = nq\mu E \qquad \text{..................(1)}$$

The current density in a pure semiconductor , due to the movement of electrons and holes is given by....

$$J_n = qn\mu_n E \qquad \text{..................(2)}$$

$$J_p = qp \cdot \mu_p E \qquad \text{..................(3)}$$

where-

q= the charge on electron or hole

n= electrons concentration

p= holes concentration

E= applied electric field

μ_n = mobility of electrons

μ_p = mobility of holes

The total current density will be,

$$J = J_n + J_p \qquad \text{.................(4)}$$

From eq^n.(2) & (3), we get

$$J = qn\mu_n E + qp\mu_p E \qquad \text{.............(5)}$$

$$J = qE(n_i\mu_n + n_i\mu_p) \qquad \text{.............(6)}$$

Where- $J = \sigma E$ ....(7)

$$\sigma = (n\mu_n + p\mu_p)q$$

σ = the conductivity of semiconductor

For pure semiconductor, the number of electrons is equal to the number of holes. i.e, $n=p=n_i$

n_i= intrinsic carrier concentration

So eq^n. (6) will be,

$$J = qE(n_i\mu_n + n_i\mu_p) \qquad \text{..........(8)}$$

The conductivity of pure semiconductor will be

$$\sigma = q(n_i\mu_n + n_i\mu_p)$$

$$\sigma = qn_i(\mu_n + \mu_p)$$

The conductivity of pure semiconductor depends upon its *intrinsic semiconductor , mobility of electrons and holes.*

Conductivity of N-type and P-type Semiconductor

The conductivity of an intrinsic semiconductor is given by

$$\sigma = q(n_i\mu_n + n_i\mu_p)$$

Putting $n=p=n_i$

$$J_n = qn\mu_n E$$

$$J_p = qn\mu_p E$$

For N-type semiconductor

$$n>>>p$$

So , the conductivity of n-type semiconductor

$$\sigma = qn\mu_n$$

For P-type semiconductor

$$p>>>n$$

So, the conductivity of P-type semiconductor

$$\sigma = qp\mu_p$$

Mass-Action law

When a pure semiconductor is doped with N-type impurities, the number of electrons in the conduction band increases above a level and the number of holes in the valence band decreases below a level which would have been available in the pure semiconductor. Similarly, if the P-type impurities are added to a pure semiconductor ,the number of holes increases in the valence band above a level and the number of electrons decreases below a level which would have been available in the pure semiconductor.

Under thermal equilibrium for any semiconductor , the product of the number of holes and the number of electrons is constant and is independent of the amount of donor and acceptor impurity doping.

Mathematically,

$$n.p=n_i^2$$

Where,

n= *the number of free electrons per unit volume,*

p= *the number of holes per unit volume, and*

n_i= *the intrinsic concentration.*

Diffusion & Diffusion current

The diffusion current density J_n for electrons is proportional to the concentration gradient.

$$j_n \propto \frac{dn}{dx}$$

Or $$J_n = qD_n \frac{dn}{dx}$$

The diffusion current density J_p for holes,

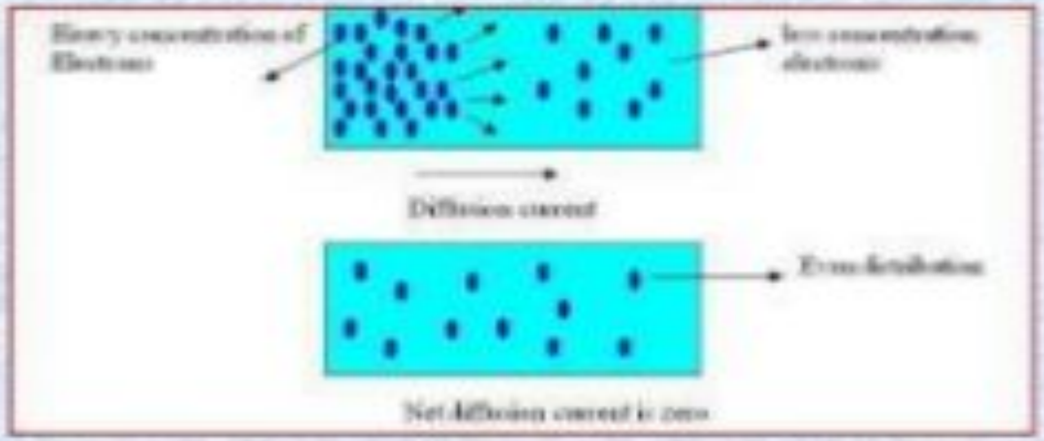
$$J_p = -qD_p \frac{dn}{dx}$$

where-

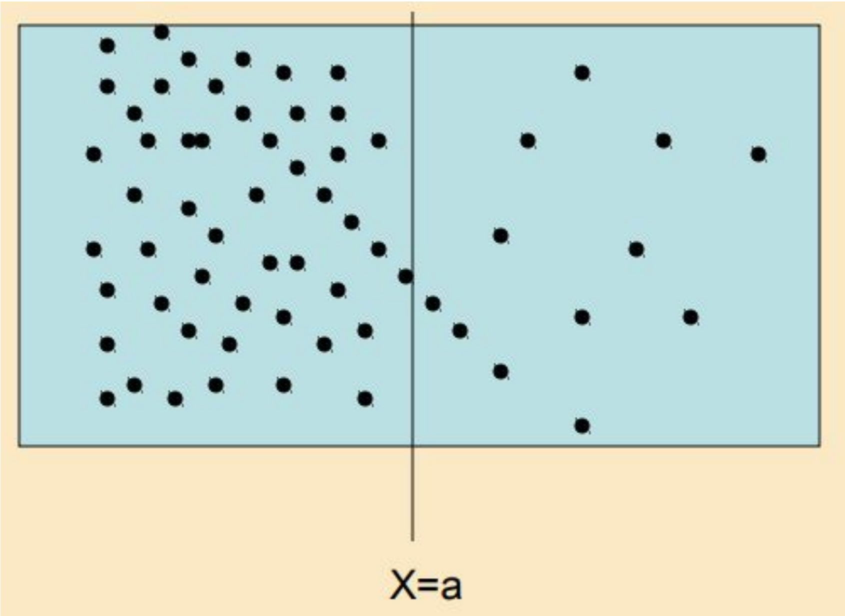
D_p & D_n = Diffusion constant for holes and electrons

q= charge of an electrons

The negative sign shows that $\frac{dn}{dx}$ is negative when the charge density falls with increase of x.



Diffusion Process



- Moving of electrons from higher concentration gradient to lower concentration gradient is known as diffusion process.

Diffusion & Diffusion current

The diffusion current density J_n for electrons is proportional to the concentration gradient.

$$j_n \propto \frac{dn}{dx}$$

Or $$J_n = qDn\frac{dn}{dx}$$

The diffusion current density J_p for holes,

$$J_p = -qDp\frac{dn}{dx}$$

where-

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q= charge of an electrons

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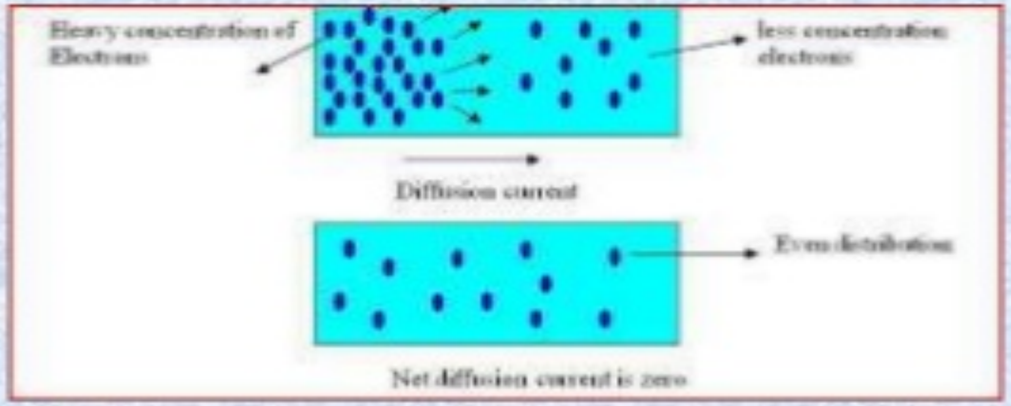

Charge Density in N & P type semiconductor

- Total no of positive charges = ND+p
- Total no of negative charges = NA+n
- N type: ND=n;   np=n_i^2;   p=$\frac{n_i^2}{n}$=$\frac{n_i^2}{N_D}$
- P type:
- **Carrier Life Time**: Time for which on average a charge carrier will exist before recombination with a carrier of opposite charge. Ns to 100s of μs
- Depend on impurity concentration and temperature

The depletion region formation

The p- region contains –

- Holes as majority carriers,
- Electrons as minority carriers ,
- Acceptor ions (i.e, negative charged immobile ions)

The n-region contains –

- Electrons as majority carriers,
- Holes as minority carriers,
- Donor ions (i.e, positive charged immobile ions)

Therefore , the hole sample is neutral.

No voltage is applied to the p-n junction, as soon as the p-n junction is formed. The following actions take place;

- Holes from the p-region diffuse into the n-region and they combine with the electrons in the n-region.
- Electrons from the n-region diffuse into the p-region and they combine with the holes in the p-region.

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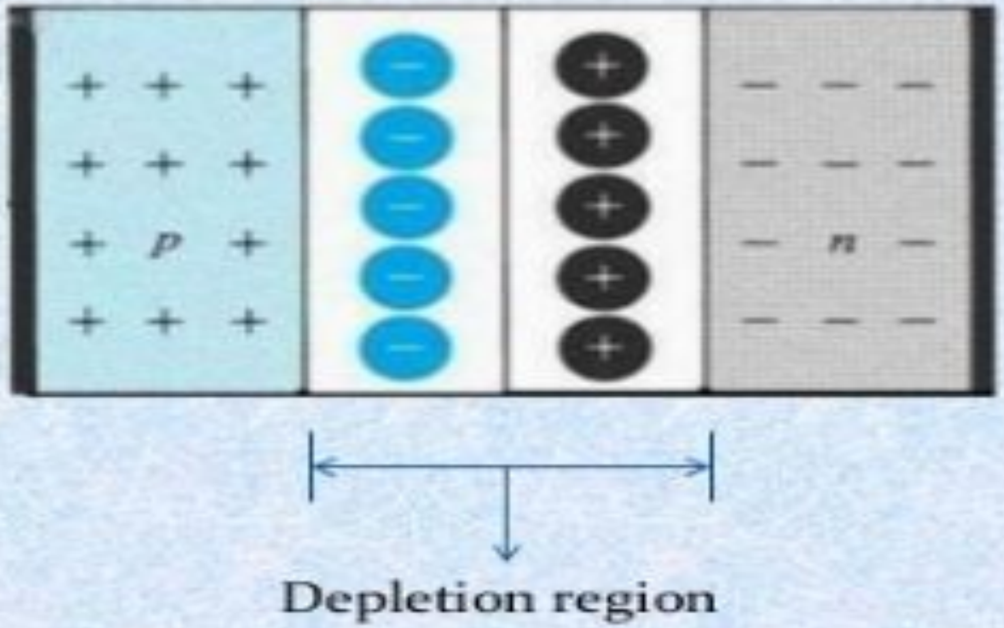
➢ The formation of this barrier may be given in following steps :-

- As the p-n junction is formed, some of holes in the p- region and some of the electrons in the n- region diffuse in each other and recombine.
- Each recombination eliminates a hole and a free electron.
- The negative acceptor ions in the p-region and positive donor ions in the n-region are left uncovered or uncompensated in the neighbourhood of the junction.



- Holes trying to diffuse into n- region are repelled by the uncovered positive charge of the donor ions. Similarly, electrons trying to diffuse into p- region are repelled by the uncovered negative charge of the acceptor ions.
- Due to this , further diffusion of holes and electrons across the junction is stopped.

➢ The region having uncompensated acceptor and donor ions is called *"depletion region"*.

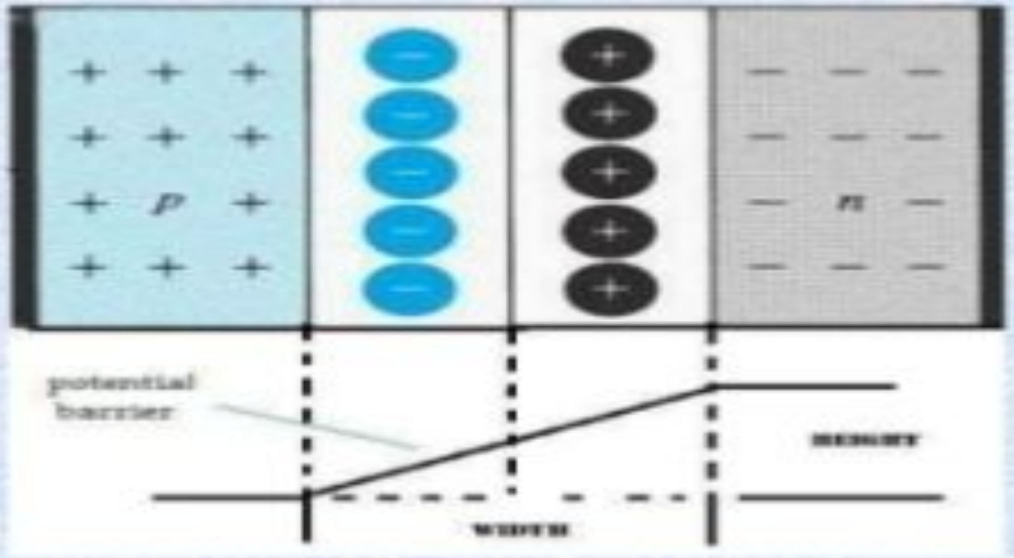
➢ This depletion region is also called "space-charge region"

➢ The width of depletion region depends upon the doping level of impurity in n-type and p-type semiconductor.

➢ The greater the doping level, the depletion region will be thinner.

Potential barrier for a pn-junction

- The electric field between the acceptor and the donor ions is called a barrier.
- The width of the barrier is the physical distance from one side of the barrier to the other side .
- The height of the barrier = The difference of potential from one side of the barrier to the other side.



pn Junction Under Open-Circuit Condition

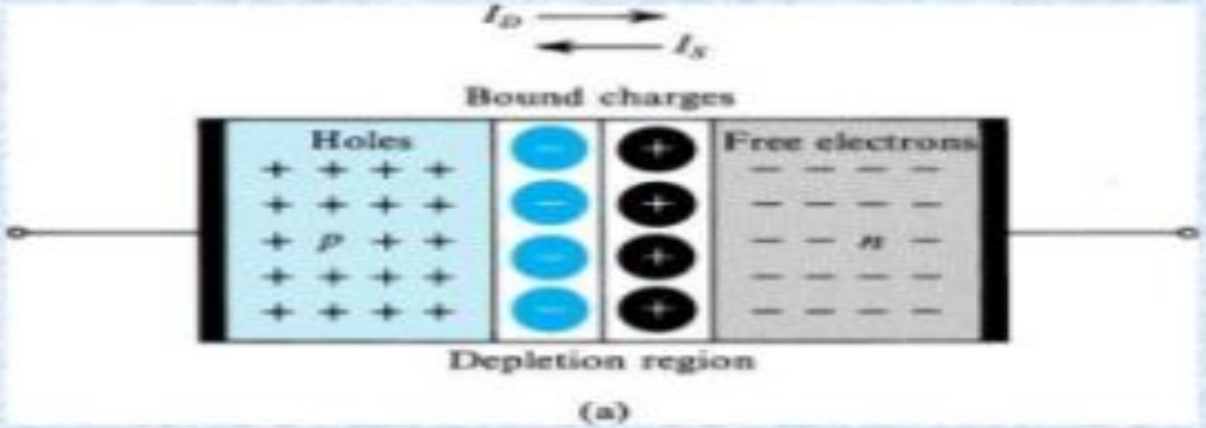


Fig **(a)** shows the *pn* junction with no applied voltage (open-circuited terminals).

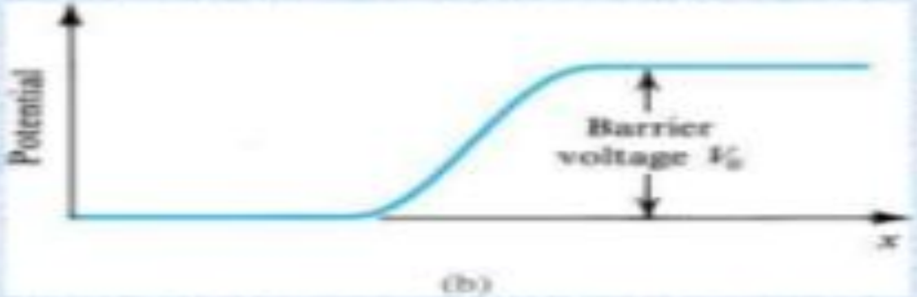


Fig.(**b**) shows the potential distribution along an axis perpendicular to the junction.

Biasing of a pn-junction

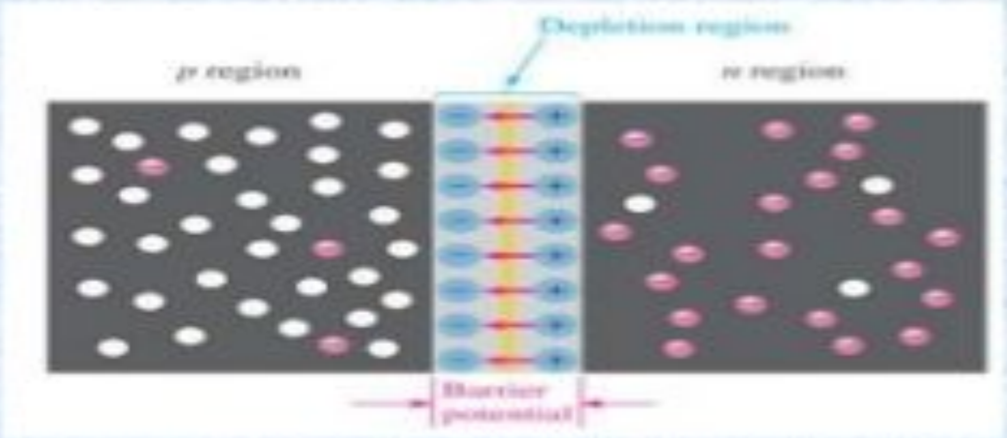
- When we apply a battery across the pn-junction, this process is called *"Biasing of a pn-junction"*.
- The width of the depletion region can be controlled by applying external voltage source across the pn-junction.
- The pn-junction can be biasing in two ways :

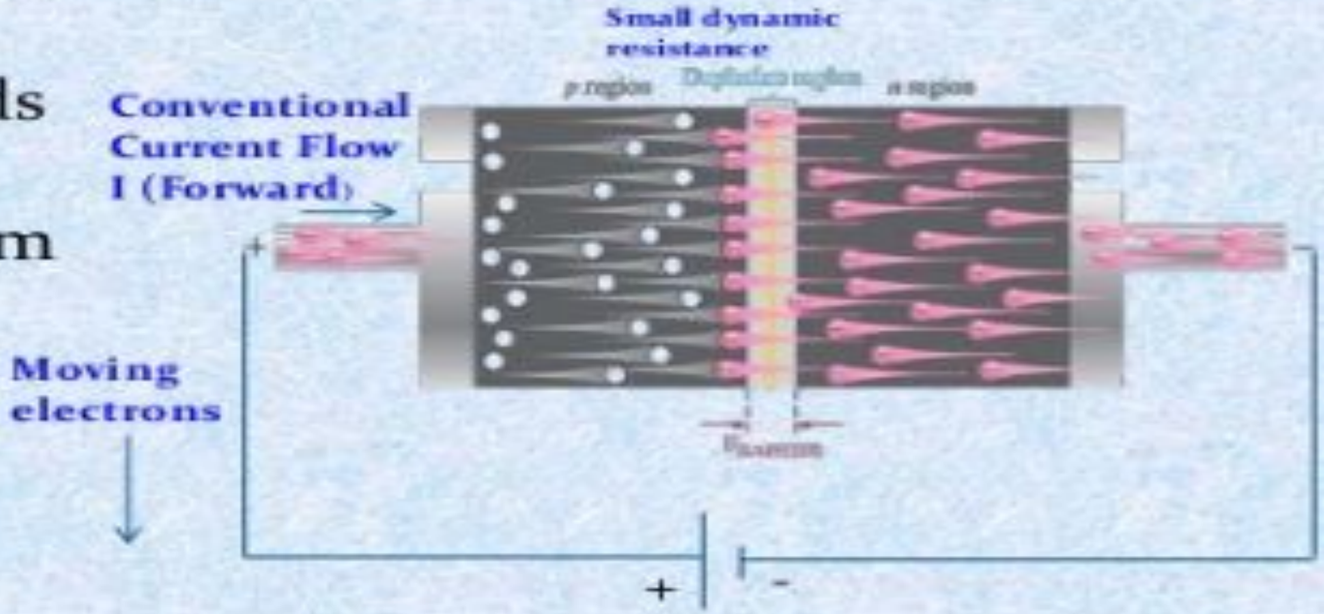
I. Forward-Bias

II. Reverse-Bias

The pn Junction Under Forward-Bias Conditions

- Positive terminal of the battery is connected to the p-side and the negative terminal to the n-side.
- Holes are repelled from the positive terminal of the battery and forced towards the junction.
- Electrons are repelled from the negative terminal of the battery and forced towards the junction.

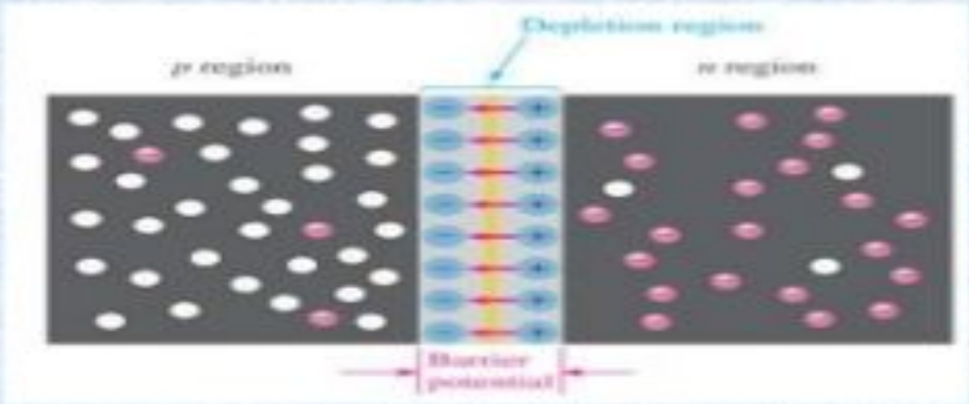




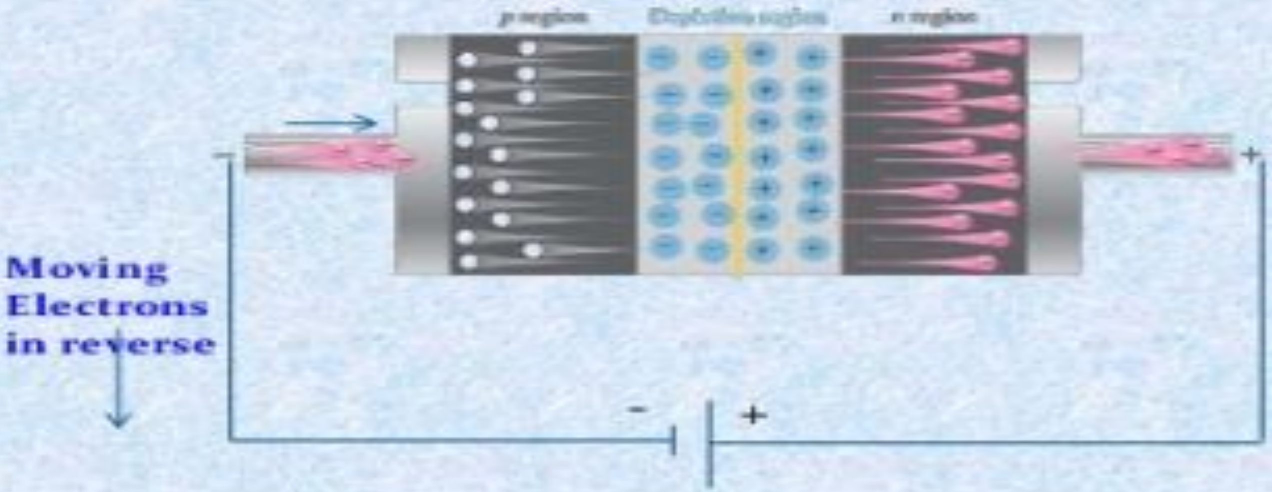
- Because of this increased energy , some holes and electrons enter the depletion region. This reduces the potential barrier.
- Resistance of device decreases.
- For each recombination of free electron and hole, an electron from the negative terminal of the battery enters the n-type region and then moves towards the junction.
- In the p-type region near the positive terminal of the battery, an electron breaks a bond in the crystal structure and enters the positive terminal of the battery.
- For each electron which breaks its bond, a hole is created.
- Hole move towards to the junction.
- The current through the external circuit is due to the movements of electrons only.
- The current in the p-type region is due to the movements of holes.
- The current in the n-type region is due to the movements of electrons.

The pn Junction Under Reverse-Bias Conditions

- Positive terminal of the battery is connected to the n-side and the negative terminal to the p-side.
- Holes in the p-region are attracted towards the negative terminal of the battery.
- Electrons in the n-region are attracted towards the positive terminal of the battery.



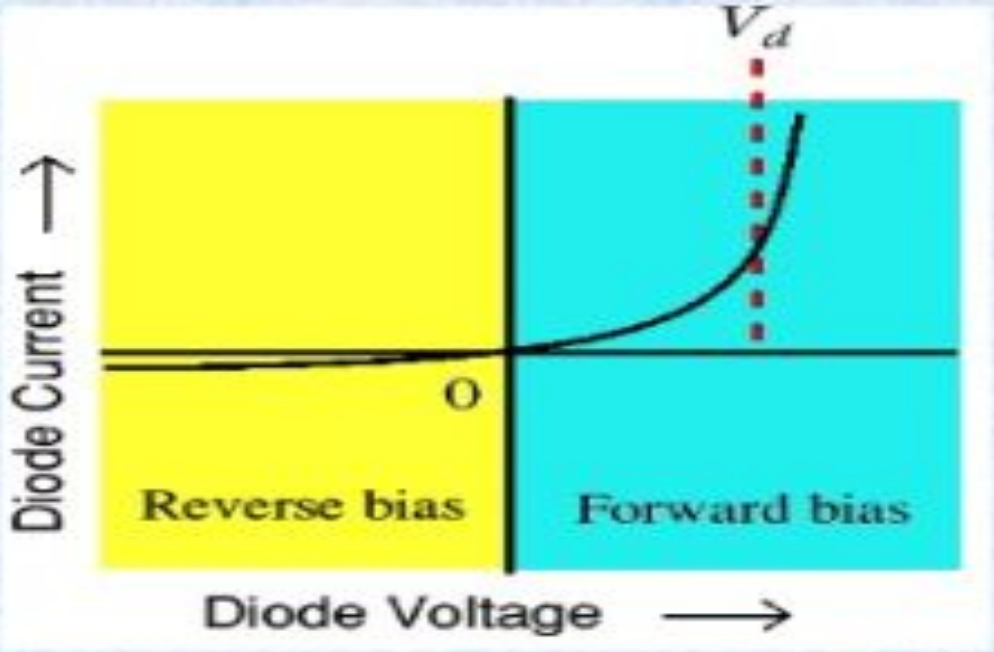
large dynamic resistance



- Majority charge carriers are drawn away from the pn-junction.
- The depletion region becomes wider and increases the barrier potential.
- Due to this, the majority charge carriers are not able to cross the junction.
- There is no current due to the majority charge carriers.
- There are few thermally generated minority carriers in both the regions.
- The increased barrier potential enhances the flow of the minority carriers across the junction.
- The generation of the minority carriers depends upon the temperature and independent of the reverse voltage applied.
- When the temperature is constant, the current due to the minority carriers also remains constant whether the reverse bias voltage is increased or decreased. Therefore , due to this region , the current is called "*reverse saturation current*".
- *The reverse saturation current is order of microamperes (μA) for Ge pn-junction and nanoamperes (nA) for Si pn-junction.*

P-N Junction - V-I characteristics

Voltage-Current relationship for a p-n junction (diode)



$$I = I_0\left(\mathrm{Exp}\left\{\frac{eV}{kT}\right\} - 1\right)$$

I = Current through diode in Amps

I_0 = The diode's 'Saturation Current' value

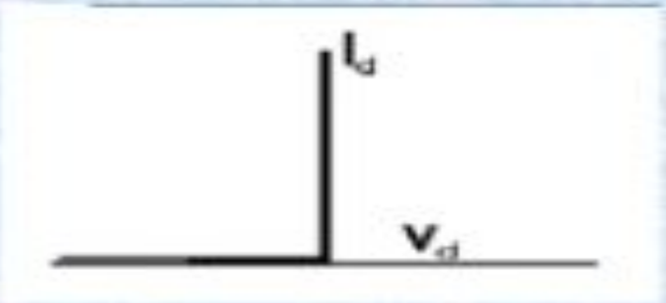
e = electron charge, $1{\cdot}602 \times 10^{-19}$ C

T = temperature in degrees Kelvin

V = Applied voltage in Volts

k = Boltzmann's constant, $1{\cdot}380 \times 10^{-23}$ J/K

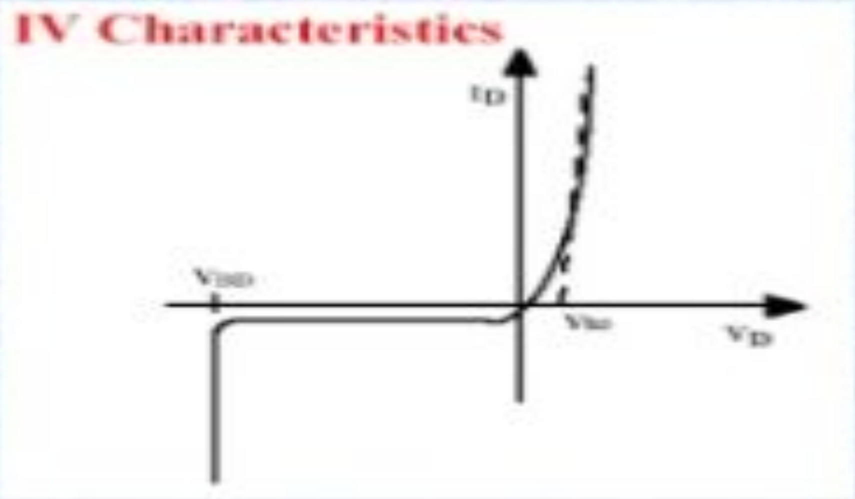
Current-Voltage Characteristics



THE IDEAL DIODE

Positive voltage yields finite current

Negative voltage yields zero current



REAL DIODE

Applications of semiconductor devices

Semiconductor devices are all around us. . They can be found in just about every commercial product we touch, from the family car to the pocket calculator.

- Rectifiers which are used in d. c. power supplies.
- Wave shaping circuits such as clippers and clampers.
- Voltage regulator circuits.
- Portable Radios and TV receivers.
- Science and industry,
- solid-state devices, space systems, computers, and data processing equipment,
- military equipment,
- Data display systems, data processing units, computers, and aircraft guidance-control assemblies etc...

Applications of Semiconductor

- Semiconductors are used in almost all electronic devices.
- Their reliability, compactness, low cost and controlled conduction of electricity make them ideal to be used for various purposes in a wide range of components and devices.
- Transistors, diodes, photosensors, microcontrollers, integrated chips and much more are made up of semiconductors.

Review questions

Section – A

1) In n- type semiconductors electrons are the ……………… carriers.
2) Silicon doped with Arsenic is an example of ……………………………
3) The addition of small amount of impurity to a semiconductor before it crystallises is called ……………
4) Free Electron theory of metals was proposed by ……………………
5) A ……………………… is that material whose electrical properties lie between those of insulator and ……………………
6) Impurity added to a semiconductor is known as …………… agent.

Section – B

1) Discuss p-n junctions.
2) Explain intrinsic and extrinsic semiconductors.
3) Explain Band theory in metals.

Junction Capacitance/ Transition capacitance

- Total no of positive charges = ND+p
- Total no of negative charges = NA+n
- N type: ND=n;   np=n_i^2;   p=$\frac{n_i^2}{n}$=$\frac{n_i^2}{N_D}$
- P type:
- **Carrier Life Time**: Time for which on average a charge carrier will exist before recombination with a carrier of opposite charge. Ns to 100s of μs
- Depend on impurity concentration and temperature

Diffusion/ storage capacitance C_D

- Forward bias

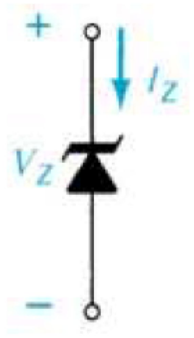
$$C_D = \frac{\mathrm{d}Q}{\mathrm{d}V}$$

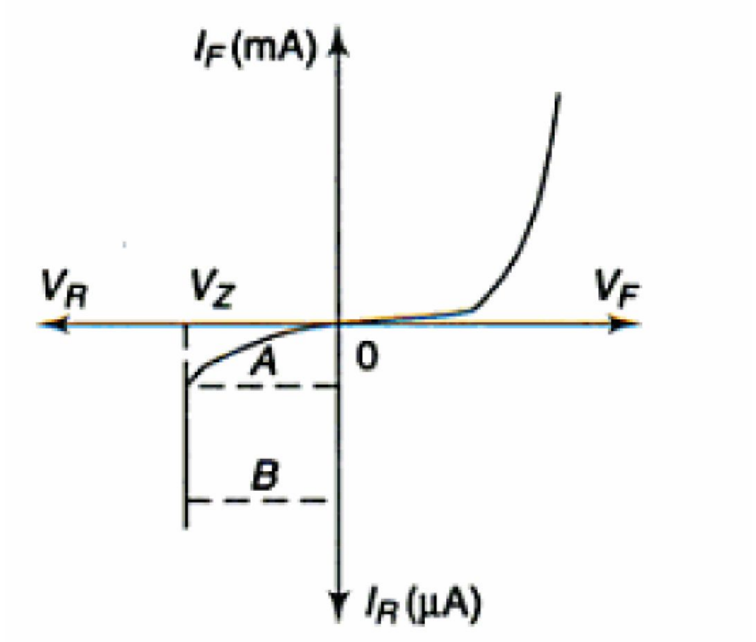
- CD prop to IF

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

Zener diode

- A Zener diode is operated in reverse bias at Zener voltage v_z
- Zener voltage are between 1.8V to 200V

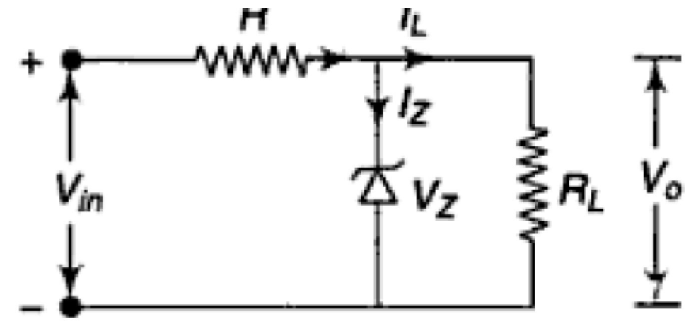




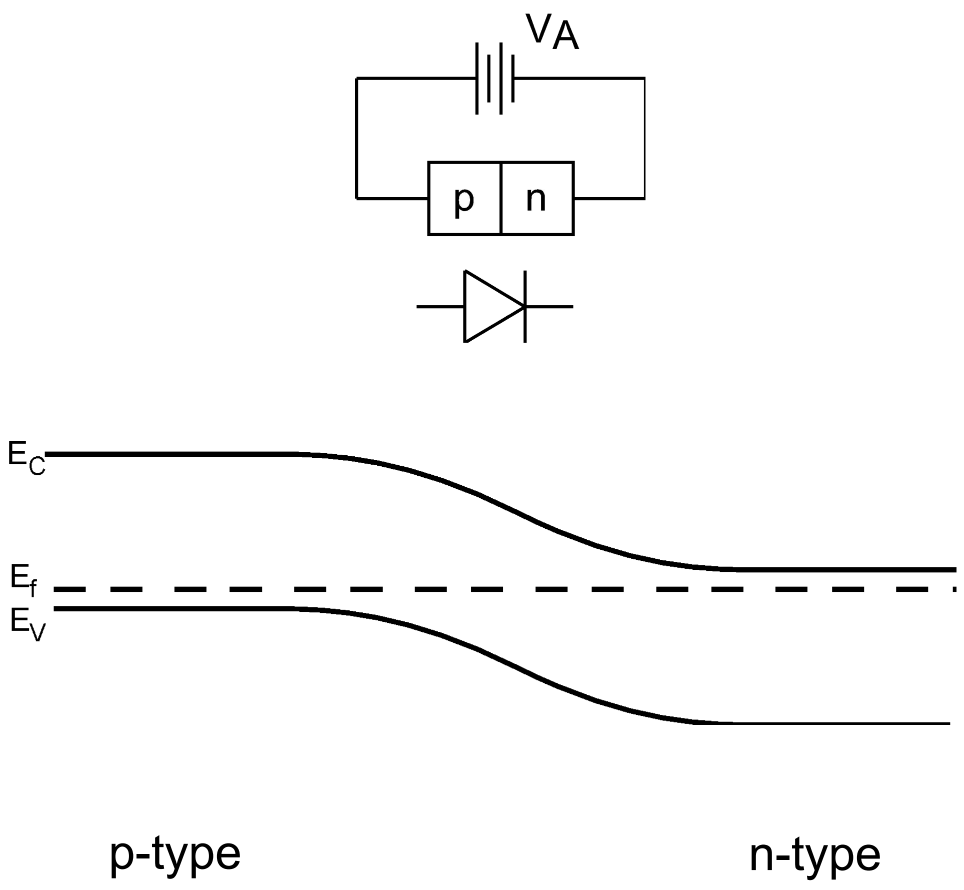
- The VI characteristics of Zener diode is same as that of PN diode under forward bias condition.
- Under reverse bias condition the breakdown of diode occurs. The breakdown depends on doping
- The sharp breakdown is due to Avalanche breakdown and Zener breakdown

Avalanche and Zener breakdown

- As the applied reverse voltage increases the field across the junction increases.
- Thermally generated carriers while traversing the junction acquire large amount of Kinetic energy.
- The electrons disrupt the covalent bond by colliding create electron hole pairs
- This is cumulative and leads to avalanche multiplica
- Zener breakdown happens when PN junction is hea
- Direct rupture of covalent bond occurs due to strong electric field.
- The increase in current takes place at a constant value of 6V.
- Zener diode as voltage regulator.

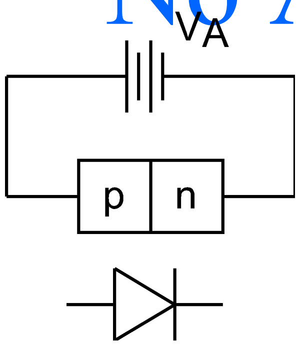


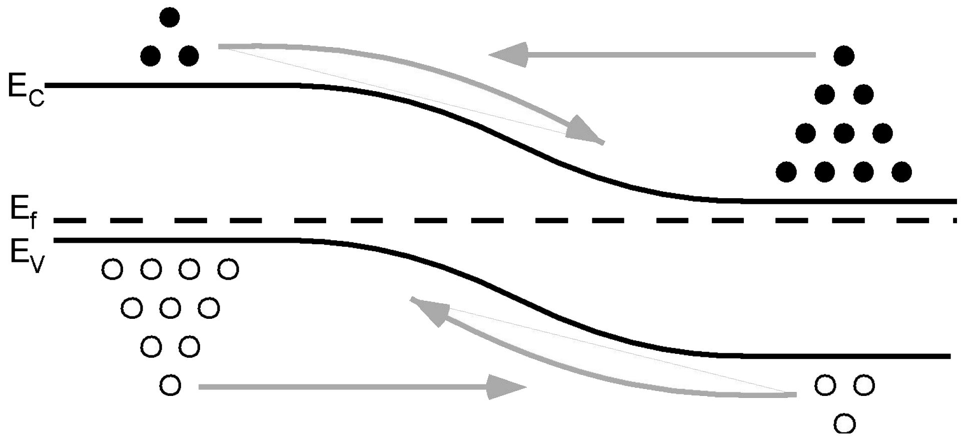
p-n Junction Band Diagram



p-n Junction – No Applied Bias

If $V_A = 0$





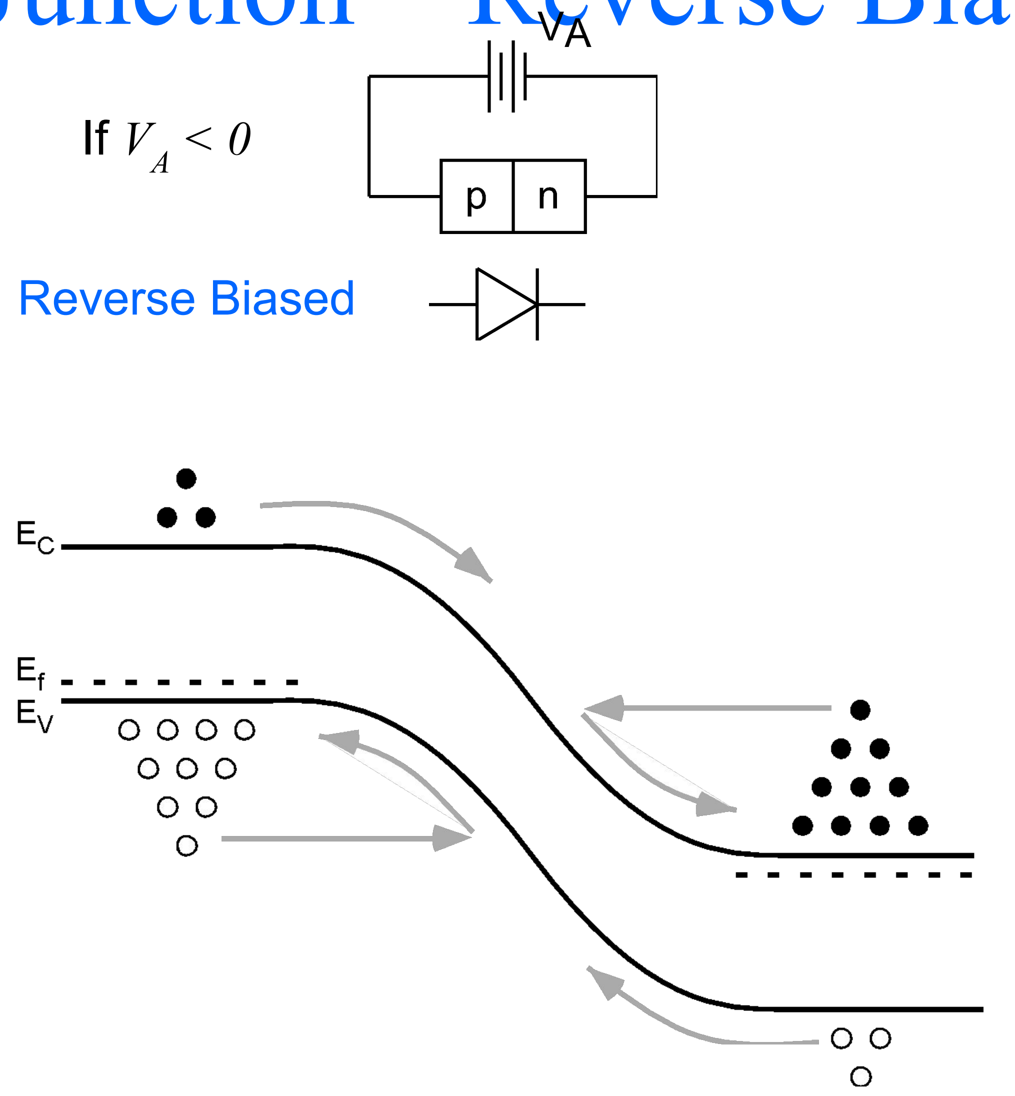
- Any e^- or h^+ that wanders into the depletion region will be swept to the other side via the E-field
- Some e^- and h^+ have sufficient energy to diffuse across the depletion region

- If no applied voltage

$$I_{drift} = I_{diff}$$

p-n Junction – Reverse Biased

If $V_A < 0$

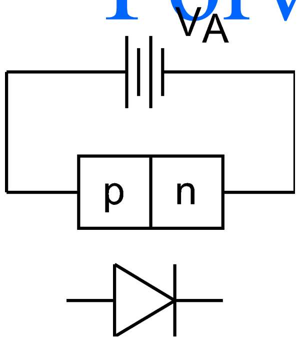


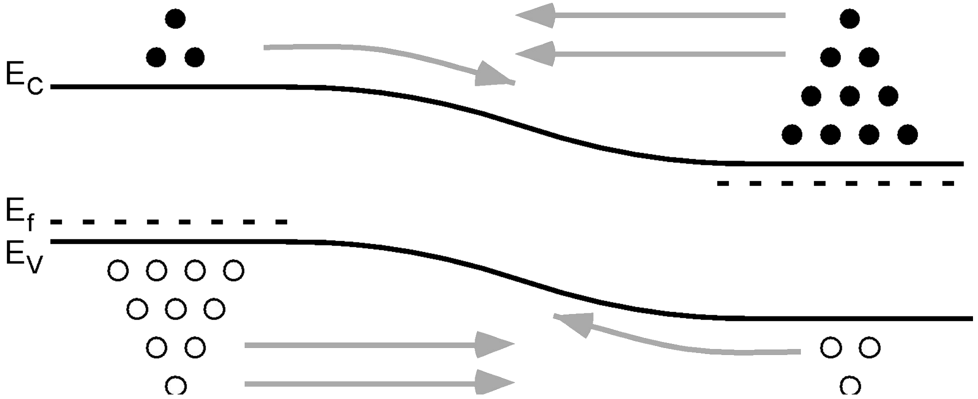
- Barrier is increased
- No diffusion current occurs (not sufficient energy to cross the barrier)
- Drift may still occur
- Any generation that occurs inside the depletion region adds to the drift current
- All current is drift current

p-n Junction – Forward Biased

If $V_A < 0$

Forward Biased



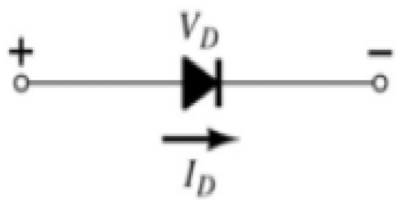


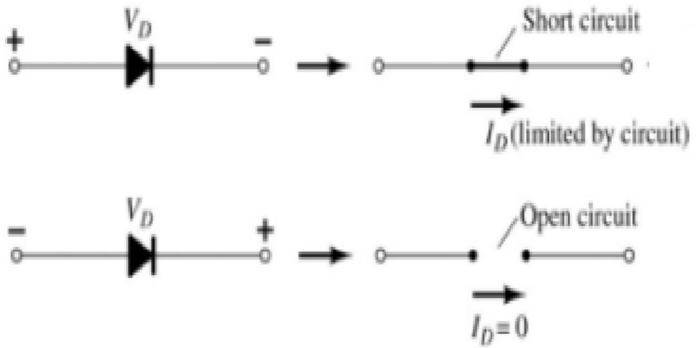
- Barrier is reduced, so more e^- and h^+ may diffuse across
- Increasing V_A increases the e^- and h^+ that have sufficient energy to cross the boundary in an <u>exponential</u> relationship (Boltzmann Distributions)

  →Exponential increase in diffusion current
- Drift current remains the same

Diodes

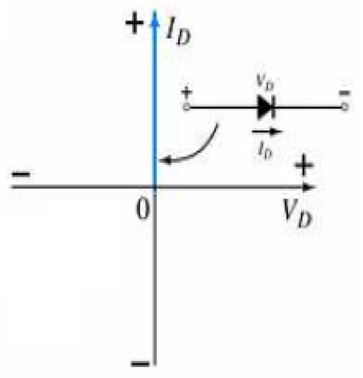
- The diode is a two terminal device
- It conducts only in one direction

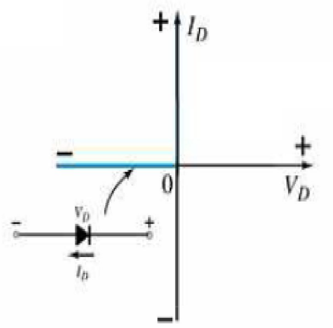




Diode characteristics

- Conduction region — Non conduction region
- Voltage across diode=0 — All voltage is across diode
- Current ∞ — Current 0
- Rf=Vf/If — RR=vR/IR





Energy band structure of open circuited PN junction

- A PN junction has P-type and N-type material in close physical contact at the junction
- The energy band diagram undergo a relative shift to equalize the fermi level.

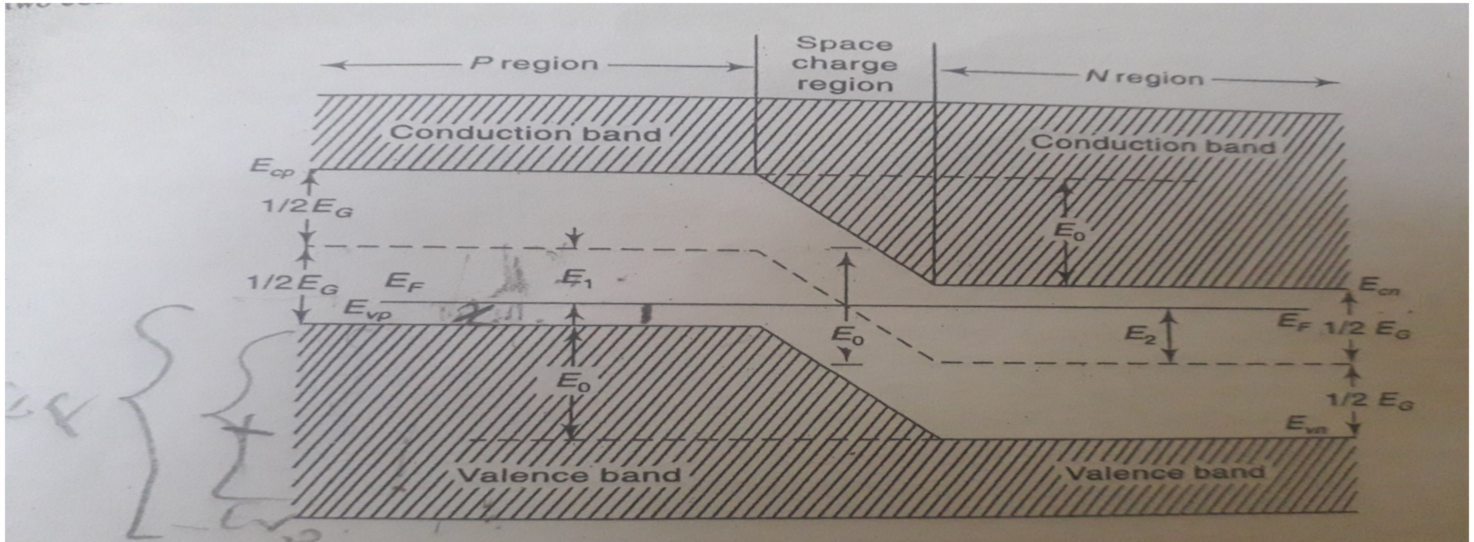


Fig. 4.16 *Energy band structure*

- Contact difference in potential

$$E_G = kT \ln \frac{N_C N_V}{n_i^2}$$

- For n type material

$$E_F = E_C - kT \ln \frac{N_C}{N_D}.$$

- For P type material

$$E_F = E_V + kT \ln \frac{N_V}{N_A}$$

$$E_0 = \left[\ln \frac{N_C N_V}{n_i^2} - \ln \frac{N_C}{N_D} - \ln \frac{N_V}{N_A} \right]$$