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UNIT - 3

SEMICONDUCTORS

Introduction to Semiconductors - Basic Properties of Semiconductors

- The substance whose current conducting properties lies between good conductors and insulators are called "semiconductors". In the case of semiconductors there exist covalent bond.
- At 0 K semiconductors acts as insulators due to strong covalent bond and at high temperatures they act as conductors due to breaking of covalent bond.
- In the case of semiconductors they have completely filled valence band (CFVB) and completely empty conduction band (CECB).
- They have negative temperature coefficient of resistance because their resistivity decreases with increase in temperature.
- They have two types of charge carriers namely Electrons and Holes.
- Semiconductors are available both in elemental and compound form. Compound semiconductors are formed by adding 3^{rd} and 5^{th} group elements (or) 2^{nd} and 4^{th} group elements.
- Semiconductors are tetravalent in nature i.e., atoms of semiconductors contains 4 valence electrons in their outermost orbital.

- Charge carriers in semiconductors can be moved under the process called drift and diffusion.
- Semiconductors are bipolar in nature, because they contains two types of charge carriers.
- Semiconductors are extensively used in solid state electronic devices.
- Conductivity of semiconductors can be enhanced by adding impurities.

Semiconductors are basically divided into two types

1. Intrinsic Semiconductors
2. Extrinsic Semiconductors

In

Intrinsic Semiconductors

- The semiconductors in pure form are called Intrinsic semiconductors.

(or)

- The semiconductors in which charge carriers are produced by thermal agitation are called Intrinsic semiconductors.

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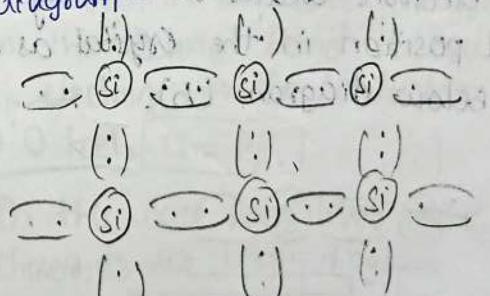
- Frequently available elemental semiconductors are silicon and germanium, they belongs to IV th group of periodic table, they are tetravalent. To get stability each of these atoms makes four covalent bonds with surrounding of four neighbouring atoms.
- The two-dimensional representation of silicon intrinsic semiconductor at 0 K along with energy band structure as shown in the below diagram



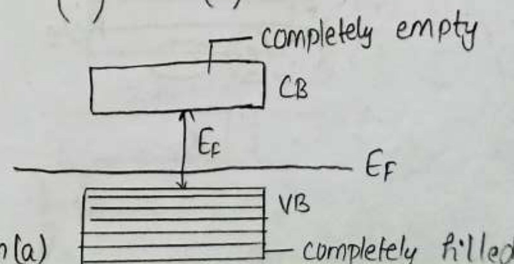
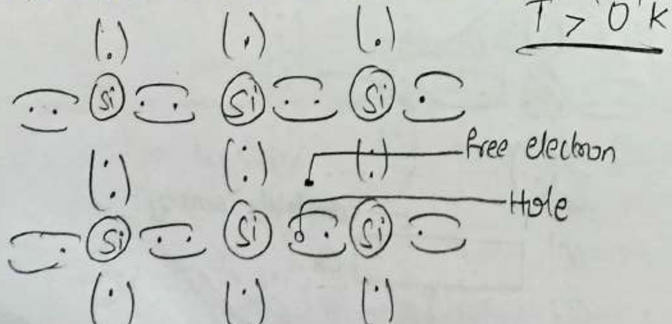


Diagram (a)

- At 'O'K all valence electrons are strongly bound to their atoms and actively participate in the covalent bond formation.
- As a result, there is no free electrons are available for conduction and it acts as insulator.
- Under this situation energy band diagram contains completely filled valence band and completely empty conduction band with fermi level exactly in between them as shown in the above diagram (a).
- At T > 'O'K, the valence electrons acquires sufficient amount of thermal energy. As a result of that breaking of covalent bond takes place releasing free electrons.
- These free electrons creates a vacancy in its initial position in the crystal as shown in the below diagram (b).



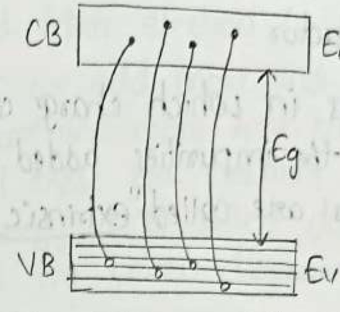
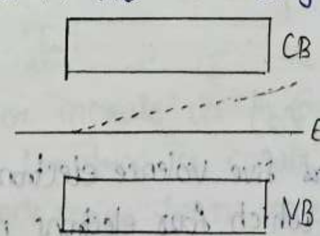


Diagram (b)

- This vacancy is called a hole and is assumed to carry a positive charge equivalent to charge of electron.
- This free electrons due to acquiring sufficient ~~energy~~ thermal energy cross the energy gap enter into the conduction band from valence band.
- Thus valence band has holes and conduction band has electrons.
- Therefore, in this case the number of holes in the valence band is equal to number of electrons in the conduction band.

  i.e., $\boxed{n = p}$

- In this case fermi levels slightly shifts as shown in the below diagram



Extrinsic Semiconductor

- The semiconductors in which charge carriers are produced by the impurities added to pure semiconductors are called "extrinsic semiconductors".
- Based on the type of impurities added to extrinsic semiconductors are divided into two types they are:
  1. N-type extrinsic semiconductors
  2. P-type extrinsic semiconductors

N-type Extrinsic Semiconductor

- When small amount of pentavalent impurity (V group elements) such as aresenic is added to the intrinsic semiconductor. Then impurity atoms occupy one of the position of the silicon atom as shown in the below diagram (a)

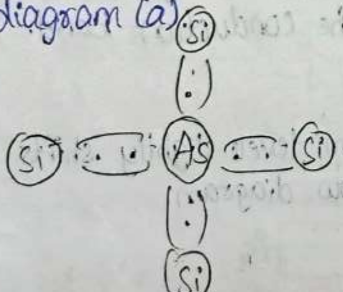
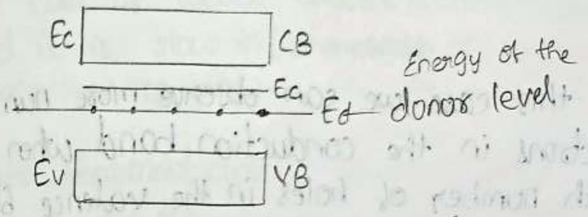


Diagram (a)

- Aresenic atom has five valence electrons in its outermost orbital which four electrons makes a covalent bond with adjacent silicon atoms and fifth electron is becomes free electron.
- If we add more and more arsenic atoms, more and more free electrons are produced. All these free electrons occupies a special energy level called donor level as shown in the below diagram (b).



$T = '0'K$

- This is the case when $T = '0'K$ in this case Fermi level E_F lies exactly in between donor level and conduction band.

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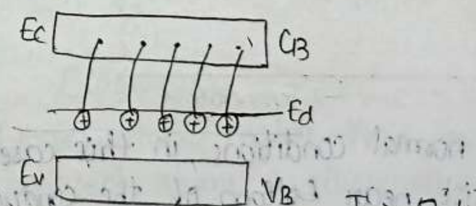
- If temperature is increased above '0'k, by receiving that thermal energy in the donor level makes a transition from donar level (E_d) to conduction band as shown in the below diagram (c)



$T > '0'K$

- Further increase in temperature $T = 300K$, makes breaking of covalent bonds due to this electrons moves from valence band to conduction band as shown in the diagram. (d) energy level is called acceptor level. as shown in the below diagram (b).

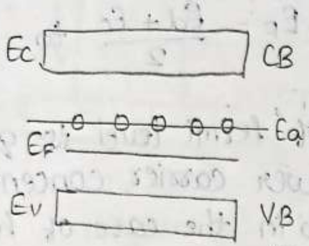
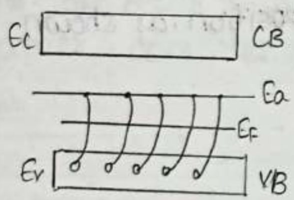


Diagram (b) T = 0 K

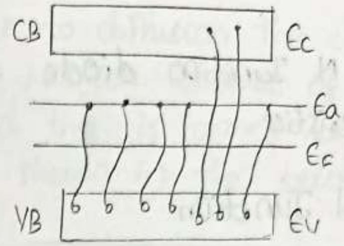
- As a temperature of P-type semiconductor the electrons move from valence band to Ea (acceptor level) as shown in the below diagram (c)



T > 0 K

diagram (c)

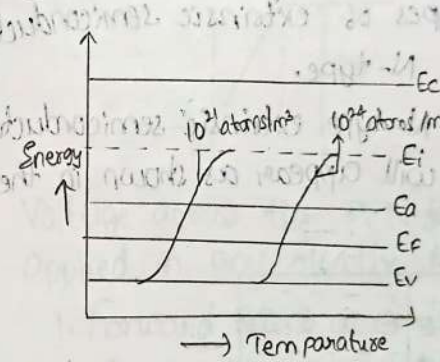
- At high temperature T = 300k due to breaking of covalent bonds more and more electrons move from valence band to conduction band. As a result of that there exist more holes in the valence band than number of electrons in the conduction band i.e., $\boxed{p > n}$ as shown in the diagram (d)



T = 300K

diagram (d)

Variation of fermi level with temperature and carrier conductors in P-type semiconductor



- In this case initially fermi level lies between acceptor level and valence band. When temperature increases above 0 K some of the electrons in the valence band moves to acceptor level.
- At high temperature (T = 300k) due to breaking of covalent bond more and more valence electrons moves from valence band to conduction band.
- Due to this fermi level shifts from $E_F = \frac{E_v + E_a}{2}$ to intrinsic level Ei.
- But for same temperatures shifting of fermi level is quick for low carrier concentration when compared with higher carrier concentration.

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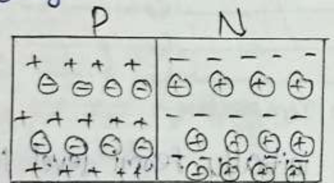
Formation of P-N Junction diode and its V-I Characteristics

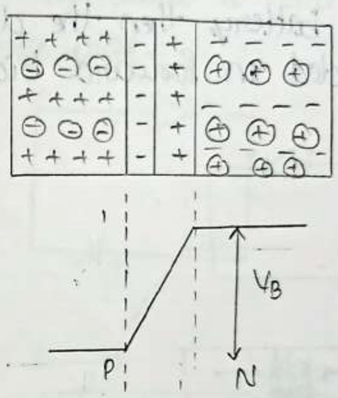
Formation of P-N Junction

- When P-type & N-type crystals are used separately conducts just like any poor conductors. Almost all semiconductor devices which are in use today are combination of the two types of extrinsic semiconductors. i.e., P-type and N-type.
- When P-type & N-type extrinsic semiconductors are joined it will appear as shown in the below diagram



- Here, uncircled charge i.e., positive charges on P-side and negative charges on N-side are charge carriers, whereas circled charges i.e., negative charges on P-type and positive charges on N-type are called immobility donors and acceptors.
- On P-side of the junction large number of free holes exist and on N-side of the junction large number of free electron exist.

- Due to diffusion this charge carriers cross the junction because of this potential barrier and this is formed between this region as shown in the below diagram.



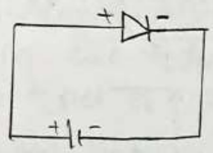
- Voltage across the P-N junction may be applied in any of the following two ways:
  1. Forward Bias
  2. Reverse Bias

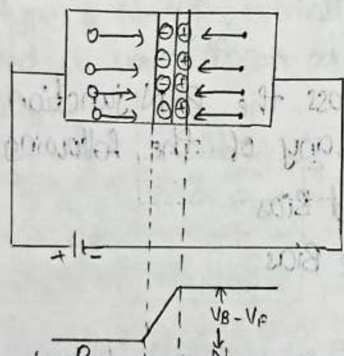
Note:

Biasing - Applying external voltage to the junction diodes is called biasing.

1. Forward Bias

- When P-region of the diode is connected to positive terminal of the battery and N-region of diode is connected to negative terminal of the battery then the diode is said to be connected in forward bias.

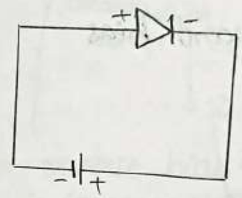


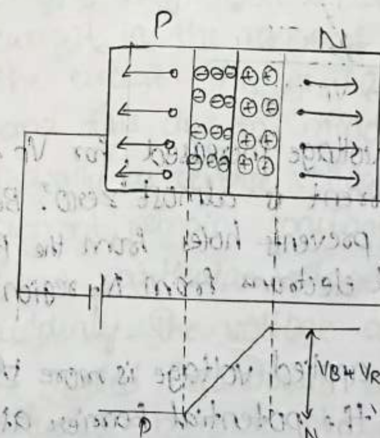


- Under forward bias majority charge carriers from respective regions moves towards the junction and hence 'junction thickness decreases.'
- As a result of that barrier height decreases, due to decrease in junction resistance p-n junction diode allows current to flow in the external circuit.

2. Reverse Bias

- When P-region of a diode, is connected to negative terminal of the battery and N-region is connected to positive terminal of the battery then the diode is said to be connected in reverse bias.





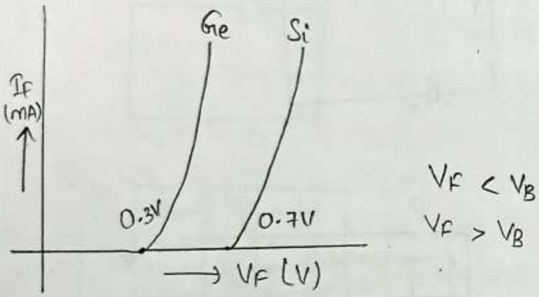
- Under reverse bias majority charge carriers moves away from the junction, and hence 'junction thickness increases.'
- As a result of that barrier height $(V_B + V_R)$ increases. Due to increase in junction resistance p-n junction diode does not allows current to flow in the external circuit.

Conclusion:

Hence P-N junction diode allows current under forward bias and it does not allows current in the reverse bias.

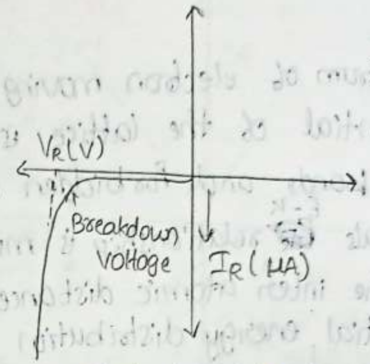
V-I characteristics of P-N junction diode -

1. Characteristics of forward bias



- As the forward voltage increased, for $V_F < V_B$, the forward current is almost 'zero'. Because potential barrier prevents holes from the P-region to N-region and electrons from N-region to P-region.
- for $V_F > V_B$ (if applied voltage is more than the barrier potential) the potential barrier at the junction completely disappears and hence charge carriers flows across the junction.
- As a result of that current flow is different for different materials as shown in the above diagram. The voltage at which current raises suddenly is called knee voltage (or) threeshold voltage.

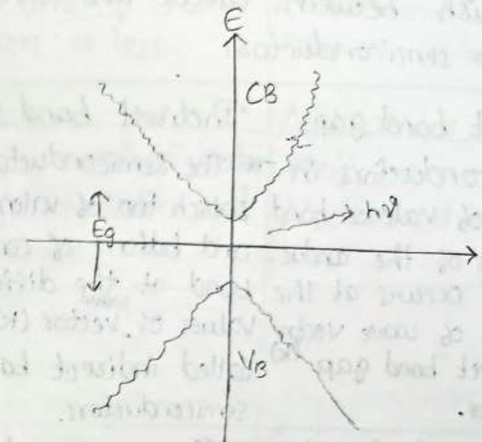
2. Characteristics of Reverse Bias



- Under reverse bias the barrier voltage of the diode is increased. Therefore the diode resistance becomes very high. In practise very small current in the range of micro amps flows in the circuit. This is called Reverse current and this due to minority charge carriers.
- Initially as reverse voltage increases, reverse current remains constant upto certain voltage.
- At a particular voltage reverse current raises suddenly. The voltage at which it happens is called Breakdown voltage. At this situation minority charge carriers gets enough energy to break to the junction. As a result the junction is destroyed.

Direct band gap and Indirect band gap Semiconductors

- Energy spectrum of electron moving in a periodic potential of the lattice is divided into allowed bands and forbidden bands.
- In real crystals E-K relationship is much more complicated. The inter atomic distance and the internal potential energy distribution vary with directions in the crystal.
- Hence the E-K relationship and energy band formation is depends on the orientation of the electron wave vector to the crystallographic axis.
- In few crystals (or) semiconductors like Silicon the maximum of valence band does not occur at the same value of wave vector 'k', as that of minimum of conduction band as shown in the below diagram (b).
- In few crystals like gallium, arsenaid (Ga,As) the maximum of valence band occurs at the same value of 'k' (wave vector) as that of minimum conduction band as shown in the below diagram (a).



Diagram(a)

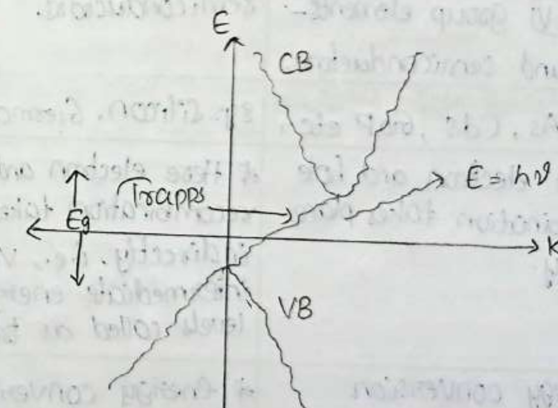


Diagram (b)

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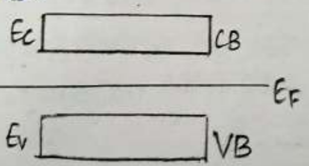
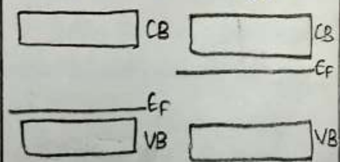
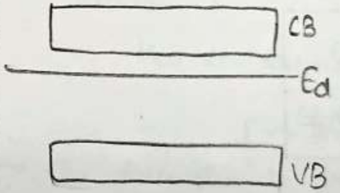
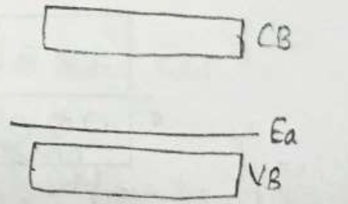
Distinguish between Direct and Indirect band gap semiconductors

Direct band gap	Indirect band gap
* The semiconductors in which top of valence band and bottom of the conduction band occurs at the same value of wave vector (k) is called direct band gap semiconductor.	* The semiconductors in which top of valence band and bottom of conduction band at the different values of wave vector (k) is called indirect band gap semiconductors.
* They are made by combining III & V group elements or II & VI group elements - compound semiconductors.	* They are made of single elements - Elemental semiconductors.
Eg: GaAs (Gallium arsenide), CdS (Cadium sulphide), GaP (Gallium Phosphate) etc.,	Eg: Silicon, Germanium.
* Here electron and hole recombination takes place directly.	* Here electron and hole recombination takes place indirectly, i.e., via intermediate energy levels called as traps.
* Energy conversion efficiency is more.	* Energy conversion efficiency is less.
* Here due to direct recombination of electron & holes and releases only photons.	* Here due to indirect recombination phonons (thermal vibrations) are produced along photons.
* Life time of charge carriers is less.	* Life time of charge carriers is more.
Applications: They are used to make LEDs, Photo diodes and laser diodes.	Applications: They are used to make diodes and transistors.

Distinguish between Intrinsic and Extrinsic Semiconductor.

Intrinsic Semiconductor	Extrinsic Semiconductor
* Intrinsic semiconductors are in pure form	* Extrinsic semiconductors are impure form.
* Charge carriers are produced due to thermal agitations.	* charge carriers are produced by added impurities.
* Low electrical conductivity	* High electrical conductivity
* Low operating temperature.	* High operating temperature
* At '0'k, Fermi level exactly lies between valence band and conduction band. 	* At '0'k, Fermi level lies between Ev & Eg for P-type and between Ed & Ec for N-type.  P-type N-type
Eg: Silicon & Germanium	Eg: Silicon & Germanium doped III & V group elements.

Distinguish between N-type & P-type semiconductor

N-type Semiconductor	P-type Semiconductors.
* N-type semiconductors are obtained by doping intrinsic semiconductor with pentavalent impurities	* P-type semiconductors are obtained by intrinsic semiconductors with trivalent impurities.
* Here electrons are majority charge carriers and holes are minority charge carriers.	* Here electrons are minority charge carriers and holes are majority charge carriers.
* There exist donor level (Ed) nearer to conduction band. 	* There exist acceptor level (Ea) nearer to valence band. 
* At T > '0'k donor level readily donates electrons to conduction band.	* When T is increased acceptor level readily accepts electrons from valence band.

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HALL EFFECT AND ITS APPLICATIONS:

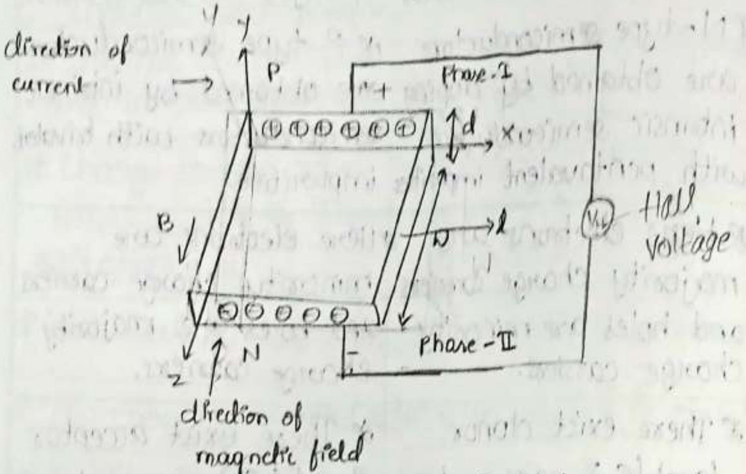
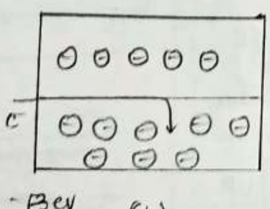


diagram (a)



(b)

When a piece of metal or semiconductor carrying a current is placed in a transverse magnetic field an electric field is produced inside the conductor in a direction normal to both the current and magnetic field. This phenomena is known as Hall effect and the voltage so developed is called "Hall voltage".

→ considering an e^- in n-type material to which current is applied allowed to pass along x-direction from left to right and magnetic field applied in z-direction as a result Hall effect voltage is produced as shown in the diagram (a).

→ Since the direction is from left to right, the electrons move from left to right to left in x-direction as shown in the diagram (b). Now due to the magnetic field applied the e^- moves downwards direction with velocity (v) and it cause the -ve charge to accumulate at phase-I of the material.

→ Therefore the potential difference is established between phase I and phase II of this specimen which gives raise to electric field (E_H) in the negative direction

Here the force due to electric field

$$F = -eE_H \quad — ①$$

→ The force due to magnetic field

$$F = -Bev \quad — ②$$

* Therefore at equilibrium condition the force due to electric field is equal to the force due to magnetic field i.e ① = ②

$$-eE_H = -Bev \quad — ③$$

$$E_H = Bv \quad — ④$$

→ Now the current density J_x along the x-axis

$$J_x = -nev \quad — ⑤$$

$$\frac{-J_x}{ne} = V \quad \text{—⑥}$$

→ substitute eqn ⑥ in eqn ④

$$E_H = \frac{-BJ_x}{ne}$$

$$\boxed{E_H = BJ_x \cdot R_H} \quad \text{—⑦}$$

where $R_H = \frac{-1}{ne}$ —⑧

→ Here R_H is called "Hall coefficient"

→ In equation ⑧ -ve sign indicates that the field is developed along -ve Y-direction

Hall coefficient in terms of Hall voltage.

→ If the thickness of the sample is 't' and the voltage is "V_H"

$$\boxed{V_H = E_H t} \quad \text{—⑨}$$

Substitute eqn ⑦ in eqn ⑨

$$V_H = BJ_x R_H t \quad \text{— 10}$$

→ If 'b' is the width of the sample, then area of the sample is equal to 'bt'

$$\text{area} = bt$$

→ Therefore current density $J_x = \frac{I_x}{bt}$ —⑪

Substitute eqn ⑪ in eqn ⑩

$$\Rightarrow V_H = B \cdot \frac{I_x}{bt} \cdot R_H t$$

$$V_H = B \cdot \frac{I_x}{b} \cdot R_H$$

$$\boxed{R_H = \frac{V_H b}{BI_x}}$$

CONCLUSION :

In this equation b, B, I_x are constants, Therefore hall coefficient depends on Hall voltage.

APPLICATIONS

→ Using hall effect one can determine whether a given semiconductor is p-type or n-type.

→ Using Hall effect one can calculate carrier concentration

$$\boxed{n = \frac{-1}{eR_H}}$$

→ It is used to find mobility of the charge carriers

$$\boxed{\mu = \sigma R_H}$$

→ It is used to design magnetic flux meters.

→ It is used to determine sign of the charge carriers

If hall co-eint (R_H) is -ve the sample is n-type

If R_H is +ve the sample is p-type.

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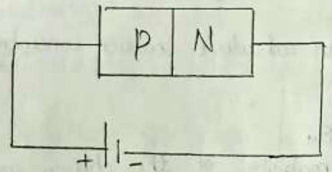
Semiconductor Devices

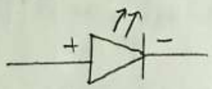
LED - Light Emitting Diode

Introduction

LED is a P-N junction device which emits light when forward bias by a phenomena called "Electro luminescence". LED under forward bias and its symbol is shown in below diagram



LED under forward bias



LED

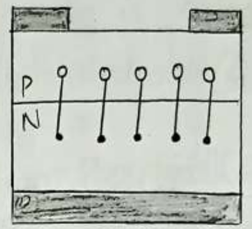
Principle:

When LED is forward biased the electrons and holes moves towards the junction and recombination takes place. As a result of recombination energy releases in the form of light.

$$e^- + e^+ \rightarrow h\nu$$

The brightness of emitted light is directly proportional to the forward biased current.

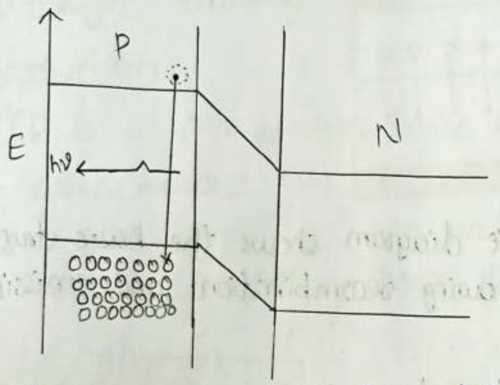
Construction:



The above diagram shows the basic structure of LED showing recombinations and emission of light.

- Here N-type layer is grown on a ~~substraight~~ substrate, a P-type layer is deposited on it by diffusion process. Since carrier recombination takes place in P-layer it is kept upper most, metal anode connections are made at the outer edge of the P-layer.
- So as to allow more central surface area for light to escape.
- A metal film (coated with gold or silver) is applied to the bottom of the substrate, for reflecting as much ~~as~~ light as possible to the surface of the device and also to provide cathode connections. LEDs are ~~allaco~~ always enclosed to protect their delicate wires.
- The efficiency of generation of light increases with the injection current and with a decrease in temperature.

Working principle :



When LED is under forward bias majority charge carriers from both N & P regions moves towards the junction and they will recombine at the junction region as a result of that emission of photons (radiations) takes place as shown in the above energy band diagram.

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Output Wavelength

LEDs radiates different colours such as red, green, yellow, organge and white. Some of the LEDs emit infrared light (invisible).

- The wavelength of the emitted light depends upon the type of material used (i.e., on energy gap) as given by $E_g = h\nu$

$$= \frac{hc}{\lambda}$$

$$\boxed{\lambda = \frac{hc}{E_g}}$$

where h is planck's constant
c is velocity of light
E_g is energy band gap.

- Gallium Aresnoid (GaAs) - IR radiation (invisible)
- Gallium Phosphite (GaP) - Red (or) Green
- Gallium Aresnoid phosphide (GaAsP) - Red (or) Yellow
- In order to protect LEDs the resistance 1kΩ (or) 1.5kΩ must be connected in series with LED.
- They operate voltage levels from 1.5 to 3.3volts with the current of milli amps.
- Power requirements is typically from 10 to 150 milli watts. LEDs can be switched ON and OFF at the faster rate of the order of 1ms (milli second).

Advantages

1. Life of the LED is more.
2. No heat or ultra voilet emissions are released from LEDs.
3. Instant lightning and ability to withstand for frequent switchings.

Disadvantages

1. High upfront cost.
2. Over heating causes reduced lamp light.
3. Potential colours shifts over lamp lights.

Applications

1. LEDs are used in instrument displays.
2. It is used in calculators.
3. It is used in digital clocks.
4. It is used for indicating power ON and OFF.
5. It is used for optical switching applications.
6. It is used in optical communications.
7. It is used for solid state video display.

03/07/2023

PIN - Photo Diode

For processing the light signals at the receiving end of the communication system we require a device to convert light signals ~~or~~ into electrical signals

The device used for this purpose is called a photo diode.

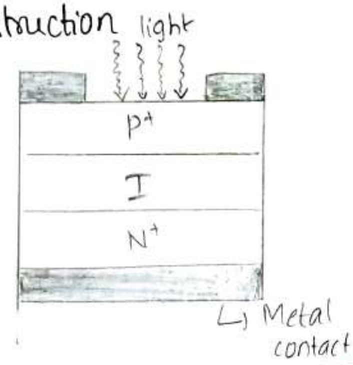
- Photo diode is a reverse biased P-N junction diode which converts light energy into equivalent ~~exer~~ electrical energy.

Principle

This diode works under reverse bias. Under reverse bias, when the light is made to fall on the neutral or intrinsic region (I) electron-hole pairs are generated.

- These electron-hole pairs are accelerated by an external electric field which results in "photo current". Thus the light is converted into electrical signals.

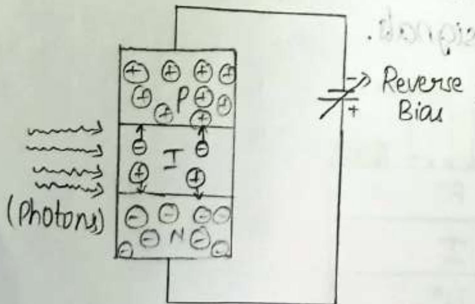
Construction



04/7/23

- The structure of a PIN-photo diode is shown in the above diagram.
- Planar structure of PIN diode consist of a substrate on which N-material is grown above intrinsic layer. Again p-material is grown on intrinsic layer either by diffusion or by an ion implantation.
- In this case both P & N-materials are heavily doped; whereas intrinsic layer is lightly doped.
- Here, P & N-materials made of silicon, the intrinsic layer is made as large as possible in order to absorb more of the incident radiation.
- Since P & N-regions are separated by intrinsic regions, it is also called as "PIN Photo diode"

Working principle



- The PIN Photo diode is connected with reverse bias as shown in the above diagram.
- Now, when a photon of energy having greater than band gap energy of a photo diode ($h\nu > E_g$) electron-hole pairs are created in the intrinsic layer.
- Due to addition of intrinsic layer between P-type & N-type, width of the depletion layer increases as a result of that more photo current will be produced which flows in the external circuit.
- Photo diode acts as a "linear device", because the photo current is directly proportional to the optical power incident on the PIN photo diode.

Applications:

1. They are used in microwave attenuators.
2. Radio frequency attenuators.
3. They are used in photo detector devices.
4. They are used in microwave switching.
5. They are used in radio frequency switching.

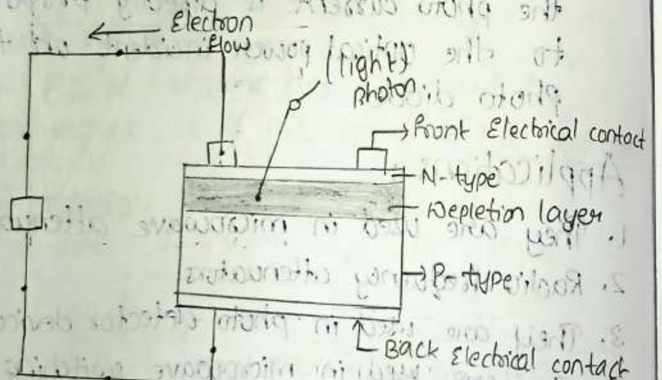
SOLAR CELL

Introduction

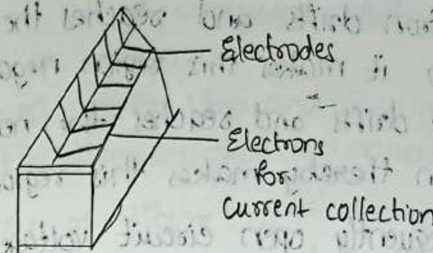
A Solar cell is an electronic device that converts the energy of light directly into electricity by the phenomena called <u>Photovoltaic effect</u>. It is also called Photovoltaic cell.

- Using this effect the generation of voltage and electric current in a material upon explosure to light.

Construction:

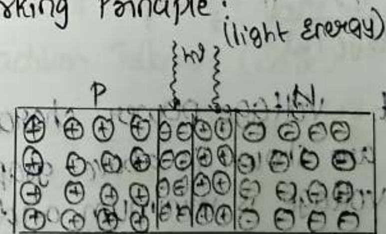


- Very thin layer of N-type semiconductor is grown on a relative thicker P-type semiconducting material, front electrical contacts (electrodes) are made on N-type layer which will not obstruct incident light to reach thin N-layer.



- Below N-type layer there is a P-N junction consist of depletion layer. Also there is a provision of electrodes at the bottom of the P-type layer.
- This entire assembly is encapsulated by thin glass to protect the solar cell from any mechanical shocks.
- Within anti reflecting coating on the surface reduces the reflections and allows more light to enter the device.

Working Principle:

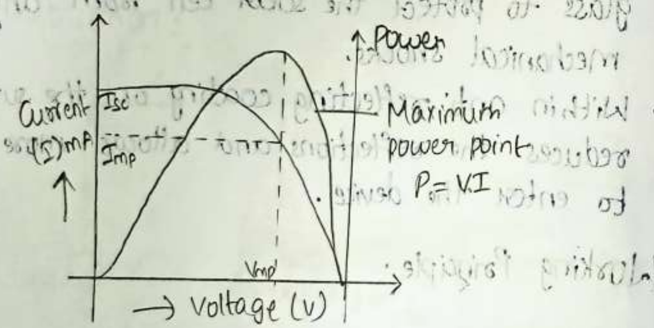


- When exposed to sunlight, the absorption of incident radiation creates electron-hole pairs in the depletion layer.
- Electron-hole pairs are immediately separated by build in field in the depletion layer

which drifts them apart.

- The electron drifts and reaches the neutral, N-region it makes this region negative. Similarly the hole drifts and reaches the neutral, P-region thereby makes this region positive.
- And consequently open circuit voltage is developed. If an external voltage is applied then the excess electrons on N-side can travel around the external circuit, do work and reach P-side to combine with excess holes over there.

Solar cell characterstics:



- Voltage current - Voltage power characteristics of solar cell are shown in above graph. Initially the voltage is minimum and the current is maximum, as voltage increases current remains constant upto certain voltage after that it reaches minimum and decreases. Similarily at low voltage power is minimum as voltage increases, the power also increases and it becomes maximum at a particular voltage, after that it decreases.
- The area under Vmp and Imp gives the amount of power that is generated.

Efficiency of solar cell

$$\text{Fill Factor} = \frac{V_{mp} \times I_{mp}}{V_{oc} \times I_{sc}}$$

$$\text{Efficiency} = \frac{P_{out}}{P_{in}} \times 100$$

fill factor

$$= \frac{V_{oc} \times I_{sc} \times FF}{P_{in}} \times 100$$

where, Pin is the power of incident sunlight.

Materials used

1. Silicon
2. Gallium Aresnoid (GaAs)
3. Cadium Telluride (CdTe)

Advantages of Solar cell

1. No pollution
2. Long life
3. Low maintaineance

Disadvantages of solar cell

1. High Installation cost
2. Low efficiency

3. During night time and cloudy days it will not give much output.

Applications

1. It is used to charge batteries.
2. It is used in light meters.
3. It is used in power calculators and smart watches.
4. It is used mainly in space crafts.