Insulators:→ Insulators are the solids which have very low conductivity and wide energy gap Eg($\simeq$10eV) between the filled valence band and empty conduction band. The electrons in valance band can not acquire so much energy from an applied electric field so that they could cross the gap to reach in conduction band. So the conduction is not possible in insulators.

Example:- Plastic, mica etc.

Conductors:→ Conductors are the solids which have partially filled ~~valence band~~ conduction band or overlapping valence and conduction bands. The electrons in this band can easily acquire energy from applied electric field and move to higher energy level in the same band.

Example:- Cu, Al etc.

2.2 Intrinsic and Extrinsic Semiconductors:→ There are two types of semiconductors:- Intrinsic semiconductors and extrinsic semiconductors.

Intrinsic Semiconductors:- Semiconductors in their pure form (or natural form) (Free from any impurity) are called an intrinsic semiconductors. The electrical conductivity of Intrinsic semiconductor is intrinsic conductivity which arise due to the thermal excitation, but the conductivity of Intrinsic semiconductor is zero at absolute zero temperature. The conductivity of intrinsic semiconductor (at room temp) is very small, It has no practical use.

Extrinsic Semiconductors:→ Semiconductors in their impure form are called extrinsic (or impurity) semiconductors. When small amount of pentavalent or trivalent impurity is added in pure semi-conductor, the conductivity of this mixture increases. Such impure

Semiconductor ~~are~~ called extrinsic semiconductors and the conductivity is called extrinsic conductivity. The process of adding the impurity is called doping and ~~the~~ So the extrinsic semiconductor is also known as doped semiconductors.

The extrinsic semiconductors are of two types that is n-type semiconductors and p-type semiconductors.

2.3 n-type Semiconductors:→ When a pentavalent impurity (antimony, phosphorus or arsenic) is added in pure semiconductor (Ge or Si), the pentavalent atom replaces the Ge or Si atom in the crystal lattice. Four of its five electrons form covalent bonds with neighbouring Si or Ge atoms. (Fig 2.2) The remaining fifth electron acts as a charge carrier. The crystal is now called n-type semiconductor. The remaining fifth electron requires lattice energy to be detached from the impurity atom (only 0.01 eV for Ge and 0.05 for Si), ~~After~~ It becomes ~~getting~~ free at room temperature ($kT \simeq 0.025$ eV) to move in the crystal. The impurity is called 'donor' because it donates the conducting electrons.

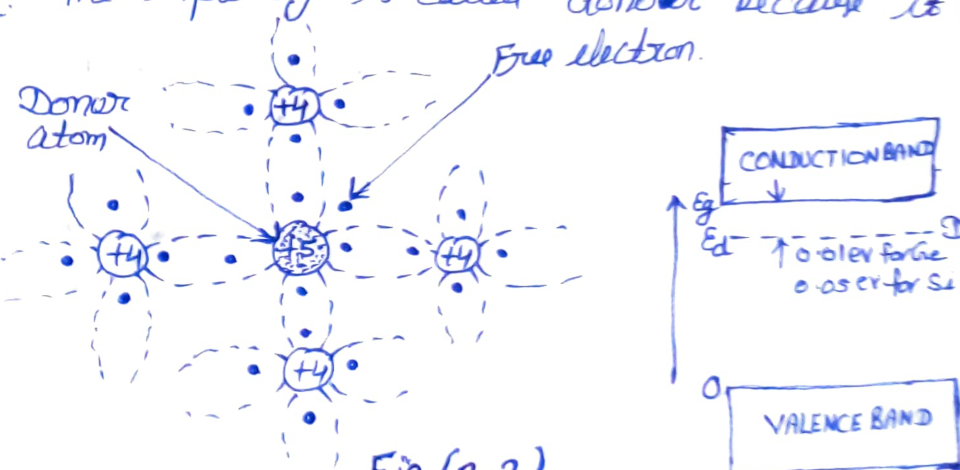


Fig (2.2)

When impurity (Pentavalent) is added in pure semiconductors (Ge or Si), the impurity atoms introduce the '¹discrete energy levels for the electrons just below the conduction band. These energy levels are called "donor impurity level". These energy levels are 0.05 eV below the conduction band ~~energy~~ in case of Si and 0.01 eV below the conduction band in case of Ge.

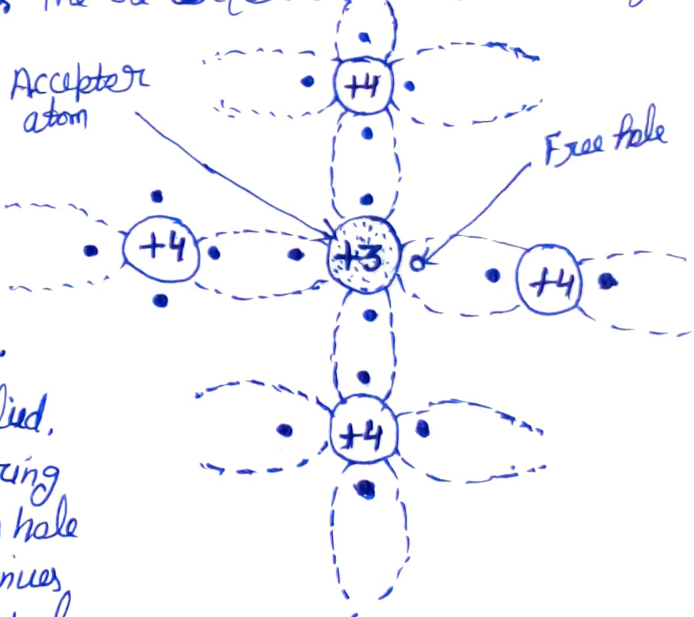
¹ These energy levels are discrete because the added impurity ~~levels~~ ~~atoms are far~~ are

-apart in the crystal lattice, so their interaction is small.

At room temperature, the fifth electrons of the donor atoms are excited and reaches to conduction band. ~~A~~ In conduction band these electrons can move by applying electric field.

At room temperature, ~~the~~ almost all the electrons in conduction band are from donor level but some of these are from valence band because some electrons ~~from the~~ reache in conduction band from valence band and creat hole in valence band. So the majority charge carriers in n-type semiconductor ~~is~~ are electrons and the minority charge carriers in p-type semiconductor are holes.

P-type Semiconductor:→ When a trivalent impurity (boron, Indium, aluminium or Gallium) is added in pure semiconductor (Germanium or Silicon). The trivalent atom replaces the Ge ~~or~~ (or Si) atom in the crystal lattice (Fig 2.4). Three valence electrons of the impure atom form covalent bond with neighbouring Ge atoms. There is an empty space or a positive hole around the impure atom. When an external field is applied, The electron bound to neighbouring Ge (or Si) atom drops into this hole creating a new hole. This continues and the hole moves in the crystal lattice acting as a positive charge carrier. So the semiconductor is called ~~to~~ P-type semiconductor.



(Fig 2.4)

The impurity is called "acceptor" because it creates hole which accepts the electrons.

When impurity (trivalent) is added in pure semiconductor (Si or Ge), The impure atoms introduce "the vaccant discrete energy levels" just above the top of the valence band. These energy levels are called acceptor impurity levels. At room temperature the electrons from valence band are excited from valence band to the acceptor level. The corresponding holes are created in valence band. These holes acts as main charge carrier in the crystal when an electric field is applied.

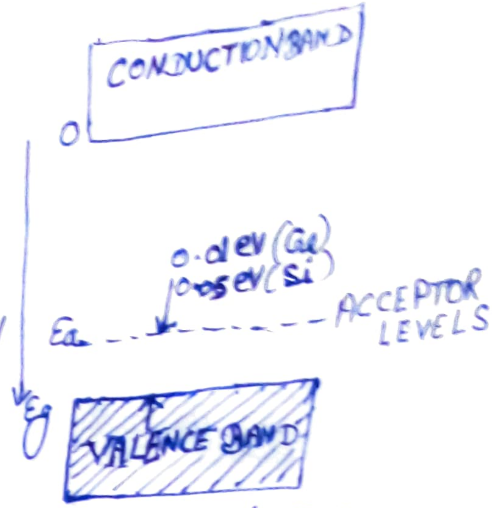


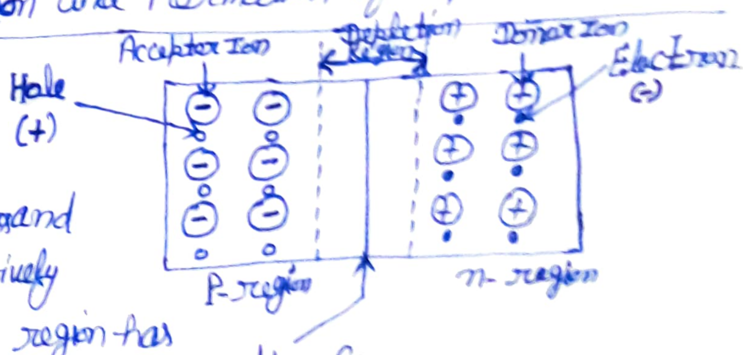
Fig 2.5

So The holes are the majority-charge carriers in P-type semiconductor and the electrons are the minority-charge carriers in P-type sem-conductor because at room temperature the few electrons are thermally excited from valence band to the conduction band.

P-n Junction diode:→ It is a single piece of semiconductor crystal having acceptor impurities in one region (P-type) and donor impurities in other region (n-type crystal). The boundary between the two regions is called P-n junction. It is not the interface between P-type and n-type semiconductor crystals pressed together.

The important property of P-n junction diode is that the electric current can pass through it much more easily in one direction than in the other.

Potential Barrier at the junction and Formation of Depletion Region:→



(Fig 2.6)

The P-n junction is shown in fig 2.6. The P-type region has hole as majority charge carrier and an equal number of fixed negatively charged acceptor ions. The n-type region has electron as majority charge carriers and an equal number of fixed positively charged donor ions. The material (P type or n-type) as a whole is neutral. With these majority charge carriers, P-type region has few electrons as minority charge carriers and n-type region has few holes as minority charge carriers.

When the P-n junction is formed there is immediate diffusion of majority charge carriers across the junction due to thermal agitation. Some of the electrons from n-side diffuse to P-side and some of the holes from P-side diffuse to n-side.

The diffused holes and electrons are combined in vicinity of the junction. So in the vicinity of junction the positive charge in the form of fixed donor ions is built in n-side and the negative charge in the form of fixed acceptor ions is built in p-side. So potential difference is set up across the junction and hence an internal electric field E_i directed from the Positive (n-side) to the negative (p-side). Equilibrium is set up when the field E_i becomes strong enough to stop further diffusion of the majority charge carriers. It happens because the positive charge on n-side repels the holes from p-region and negative charge on p-side repels repels the electrons from n-region.

The internal field E_i, however helps to diffuse the minority charge carriers across the junction.

The region on both sides of junction which becomes depleted (free) of the mobile charge carriers is called depleted region. The width of the depletion region is of the order of 10^{-6} m. The potential across the depletion region is called potential barrier. It depends upon the dopant concentration in semiconductor.

Potential barrier for Si P-n junction = 0.7 volt

" " " Ge " " = 0.3 volt

So The magnitude of the barrier electric field for Silicon junction

$$= \frac{0.7V}{10^{-6}m} = 7\times10^{5}\ Vm^{-1}$$

Circuit Symbol for P-n junction diode:→ Every semiconductor device in electronic circuit, is represented by circuit symbol. The circuit symbol for P-n junction diode is shown in fig 2.7. The P-region of diode is represented by arrow-head and the n-region is represented by bar. The P-side is called anode and the n-side is called cathode. The direction of arrow is from P to n region and shows the direction of conventional current under forward bias.

Fig 2.7

Energy Level Diagram for P-n Junction:→ When we consider that P-type and n-type semiconductors are seperated, (Fig 2.8) we can visualise easily the energy level diagram of P-n junction diode.

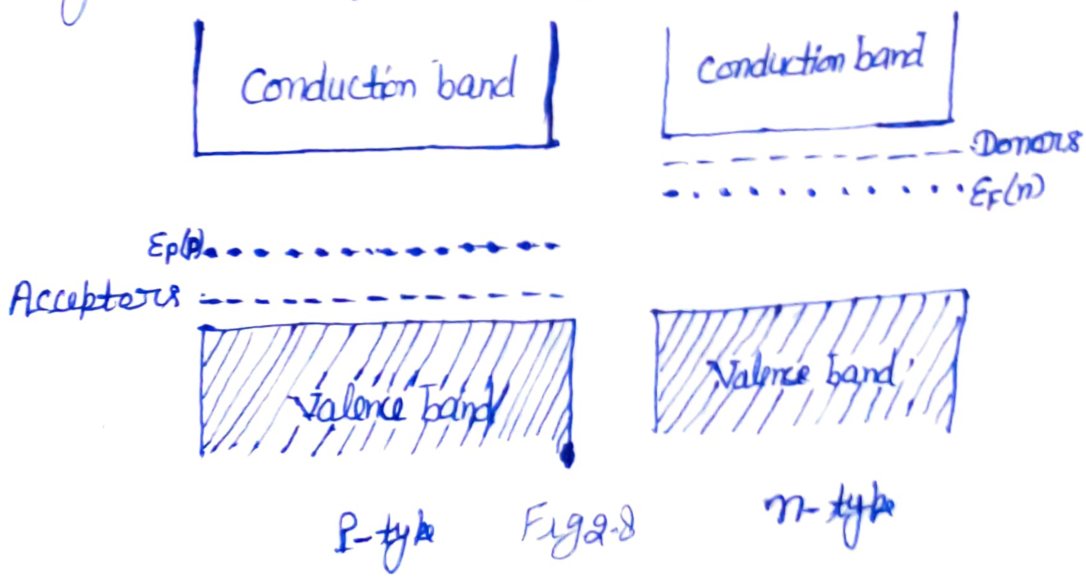
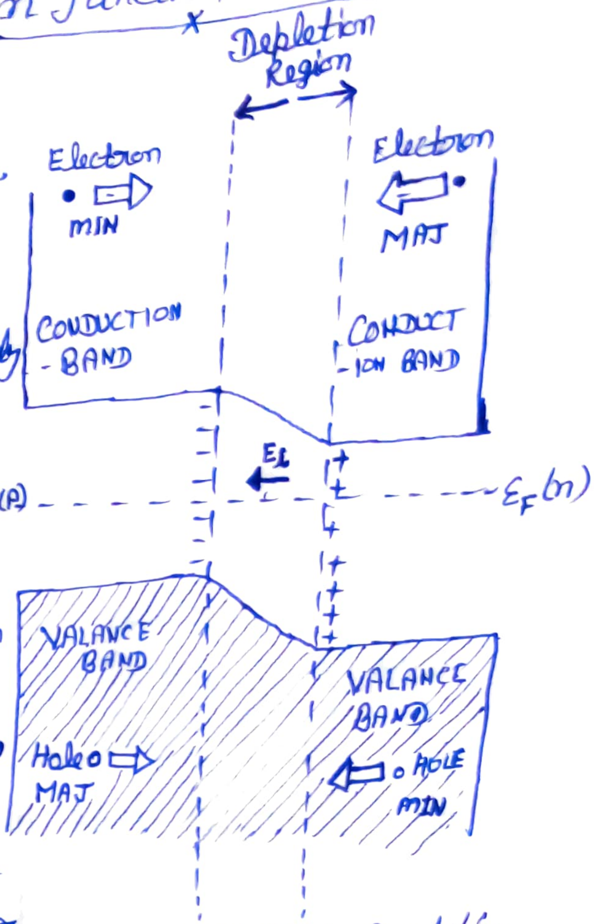


Fig 2.8

The fermi energy $E_F(P)$ level is closer to the top of valence band in P-type semiconductor and the fermi energy $E_F(n)$ level is closer to bottom of conduction band in n type semicon. When P-n junction is formed between P-type and n-type materials, the holes flow from P-type to n-type via valence band and electrons flow from n-type to P-type material. Due to this flow, the equilibrium is reached when the Fermi levels in both materials are along the same line.

Energy Level Diagram for P-n Junction under-unbiased Condition:→

When P-n junction is formed, The conduction bands for P and n-regions and valence bands for P and n regions shift relatively (E_{F_P} E_{F_n}) to get the fermi levels along of ~~the same line~~ P and n regions (Fig 2.9) along the same line. The region in the vicinity of P-n junction and either side of junction is free from mobile charge carriers, this region is called depletion region. It has uncovered acceptor ions on P-side and uncovered donor ions on n-side. So an internal electric field E_i is produced in the depletion region from n-region to P-region.

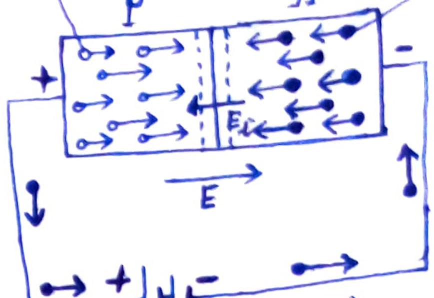


UNBIASED Condition.

Fig 2.9

When equilibrium is reached, there is still a flow of majority charge carriers across the junction because they overcome the internal electric field. At the same time there is flow of minority charge carriers across the junction, which are aided by the internal electric field. So the current produced by these majority charge carriers e is neutralised by the current produced due to minority charge carriers and equilibrium remains established.

Flow of Current in a P-n Junction diode:— If there is no external battery, no current flow through P-n junction diode. The P-n junction is connected to external battery in two ways, called Forward biasing and Reverse biasing.



Fig(2.10)

When the Positive terminal of external battery is connected to the P-region and negative terminal to the n-region, then the P-n junction is said to be under Forward bias(Fig2.10).

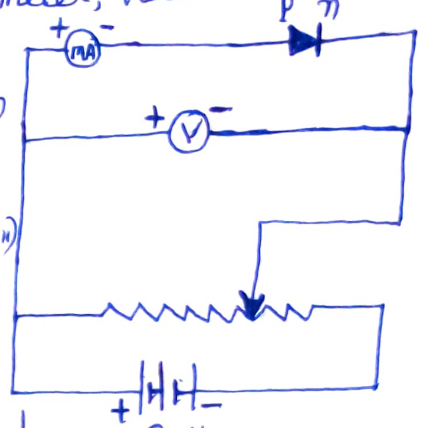
At this stage the external electric field E directed toward n-region from P-region. The external electric field is much greater than the internal electric field. The holes of P region moves toward n-region and The electrons of n region move tow
P-region. The holes and electrons are recombined near the junction and cease to exist. At the same time the covalent bond breaks
inthe P-region near the positive terminal of battery and elect
hole are produced. The hole moves toward the n-region and the
electron enters the positive terminal of the battery. At the same
time the electron is released from the negative terminal of the
battery and enters the n-region to replace the electron lost
by combining with a hole at the junction. So the motion of
majority charge carriers constitutes a current across the jun
This is called Forward current. There is also a small re
current due to minority charge carriers but it is almost
negligible. The current in external circuit is carried by e

In forward biased junction, the majority charge carriers are pulled toward the junction so the width of depletion region decreases. So the junction diode offers a low resistance to ~~flo~~ the current in forward bias Condition

Voltage - Current characteristics (V-I) of P-n junction diode under Forward-bias Condition:

Forward-bias Condition:→ The graph which shows the current variation through the junction with change in applied voltage is called voltage - current characteristics (V-I) of P-n junction diode. There are two cases i.e Forward biased characteristics and Reverse biased characteristics.

Forward-Biased characteristics:→ The circuit connections consists of P-n junction diode, milliammeter, voltmeter, Potential dividers and Battery. The positive terminal of battery is connected to the P region and the negative terminal of battery is connected to n region of the junction through the potential divider arrangement. (Fig 2.11) Potential divider arrangement changes the applied voltage. Voltmeter V and milliammeter mA are used to read voltage and current respectively.



(Fig 2.11)

The Forward-bias voltage is increased step by step and the corresponding current is noted. A graph is plotted between the forward bias voltage and corresponding current. The curve OAB is the characteristic of P-n junction diode. (Fig 2.12)

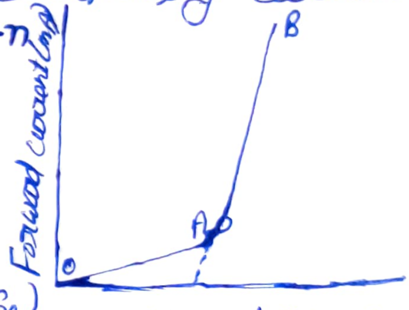


Fig 2.12

It is clear from the curve OAB, when the applied voltage is low. The current through the junction diode is almost zero because the Potential barrier (0.7 V for Si and 0.3 V for Ge) opposes the applied voltage. when the applied voltage is further increased, the current through junction increases slowly and non linearly Until the applied voltage is more than barrier potential. It is shown by the portion OA of the curve OAB. When the applied voltage is further increased, the current increases very rapidly and almost linearly (Infact, somewhat exponentially). It is shown by the portion AB of curve OAB. In this region P-n junction diode behaves as ordinary conductor. If straight line AB is projected back, this line intersects the voltage axis at barrier potential voltage.

The circuit connections consists of P-n junction diode, microammeter, voltmeter, Potential divider and Battery. The Positive terminal of battery is connected to n- region through the potential divider arrangement and Negative terminal of battery is connected to P- region of P-n junction diode. (Fig 2.14) Potential divider arrangement is used to change the applied voltage and voltmeter V, microammeter µA are used to read voltage and current respectively.

When reverse bias voltage is applied, a very small current (of the order of µA) flows across the junction. It is due to the motion of the few thermally generated minority charge carriers. This motion is aided by external applied electric field. This current is called reverse current. The characteristic curve is shown in fig 2.15.

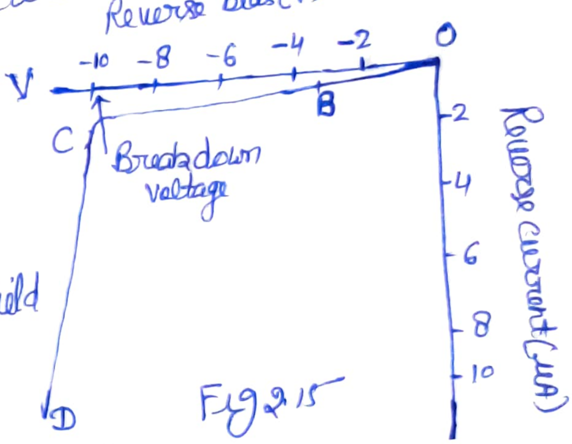


Fig 2.15

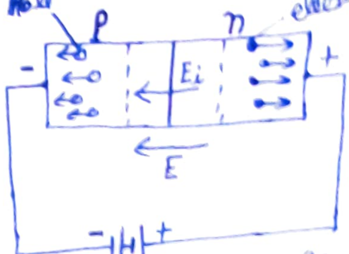
It is clear from the curve OC of characteristic curve that the reverse current is almost constant. It is because the minority charge carriers are aided by the barrier field E_i, So all of them cross over the junction. The reverse current is almost independent of applied reverse bias voltage.

Break Down of P-n Junction diode: When a reverse bias is applied across a P-n junction diode, a reverse current flows in P-n junction which is independent of applied voltage. This current is known as reverse current. If the reverse bias voltage is ~~further~~ increased, then at a particular voltage the reverse current increases abruptly. If the reverse bias voltage is further increased, then a relatively large current flows. The particular voltage/critical voltage at which current increases abruptly, is known as Zener voltage or breakdown voltage. In this situation, the diode is said to be in the breakdown state.

When reverse bias is increased, the breakdown takes place under two mechanisms which give rise to Zener Breakdown and avalanche Breakdown.

P-n Junction under Reverse Biasing:→

When the positive terminal of battery is connected to n region and negative terminal of battery is connected to P region of P-n junction diode, The junction is said to be under Reverse biasing. (Fig 2.13)



Battery

(Fig 2.13)

(Reverse Biased)

At this stage the external electric field directed from n-region to P-region, thus it supports the internal barrier field. So the electrons in region and holes in P-region are pushed away from the junction. The electrons and holes do not recombine at the junction. So the current due to majority charge carriers is almost zero through the junction.

There are ~~few~~ few minority charge carriers (electrons in P region and holes in n-region) in P-n junction diode. These minority charge carriers are supported to flow by applied external field, So very small reverse current (≈ a few microamperes) flows across the junction. The minority charge carriers are thermally-generated. So the reverse current is very much temperature dependent and increases with increasing temperature of the junction.

The External applied electric field E supports the barrier electric field E_i. Therefore, the majority charge carriers are pushed away from junction. So the width of the ~~junction~~ depletion region increases. Hence the junction diode offers a high resistance for the current to flow in reverse bias.

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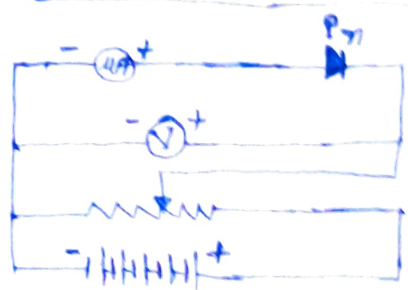
Voltage - Current characteristics of P-n junction diode under Reverse biasing :→



Battery

Zener Breakdown:→ In this mechanism, when reverse bias is applied, then the electric field across the p-n junction is strong enough to pull the electrons from covalent bonds. So the electron-hole pairs created and the reverse current increases abruptly. It occurs at low voltage (upto a few volts) in heavily doped junctions because the depletion layer is very narrow.

If the temperature of junction increases, The zener ~~volt~~. Breakdown voltage decreases because the valence electrons get the kinetic energy and It is easier to escape these valence electrons from covalent bonds. So smaller reverse voltage is sufficient to produce electric field to pull the electrons from the covalent bonds.

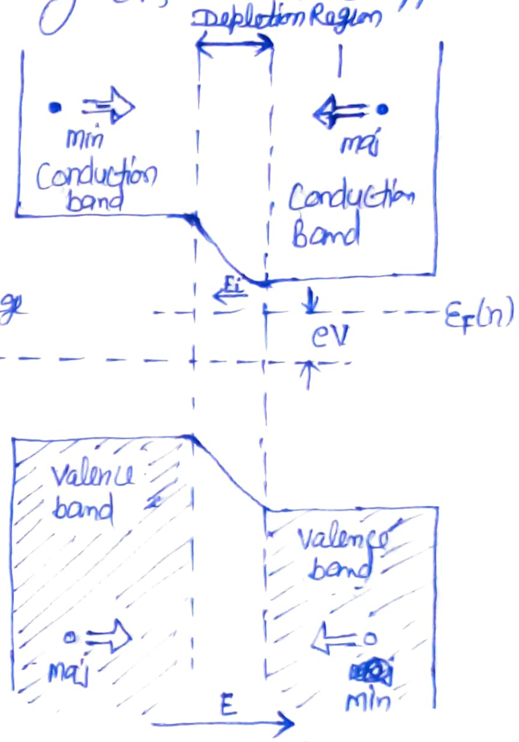
Avalanche Breakdown:→ This mechanism occurs at higher voltages than zener breakdown voltages (from a few voltages to thousands of volts). In this mechanism the thermally generated electrons and holes receive sufficient kinetic energy from the applied voltage to break covalent bonds. So new electrons and holes are produced. These new carriers produce additional carriers again by breaking bonds. The process is cumulative, producing avalanche of charge-carriers, which results in the flow of large reverse current. This is known as avalanche breakdown. It occurs in lightly doped junctions.

If the temperature of junction increases, The avalanche breakdown voltages increases. It is so because as the temperature of junction increases ~~the electrons and holes gains kinetic energy~~ the amplitude of vibration of the crystal atom increases. So The probability of collisions of electrons and holes with the crystal atom increases. So the electrons and holes loose their energy in collisions and demands higher applied reverse bias voltage to start the avalanche process.

Energy Level Diagram for P-n junction diode under Forward bias:→

When the positive terminal of the battery is connected to P-region and the negative terminal of the battery is connected to n-region of P-n junction diode, then the junction is said to be under Forward bias. This forward biasing creates external electric field E opposite to the internal electric field E_i and raises the electron energy levels of the n-type semiconductor relative to those of the P-type semiconductor. The Fermi level in n-region ~~raises~~ is raised relative to that in P-region by eV, where V is applied voltage (Fig 2.16)

The electrons in the n-region now easily cross over to the P-region ~~and the holes~~ via conduction band and The holes in the P-region now easily cross over to the n region via valence band. So these majority charge-carriers produce large forward current. The current due to minority carriers ~~are~~ remains unaffected by applied voltage. ~~The current due to minority charge carrier electrons are balanced by the current due to minority charge carriers holes.~~ So the current in forward bias is due to majority charge carriers and is known as forward current.



(+) P-type Fig 2.15 (−) n-type

Energy Level Diagram for P-n junction diode under Reverse Bias:→

When the positive terminal of the battery is connected to n-region and the negative terminal of the battery is connected to P-region of P-n junction diode, then the junction is said to be reverse biased. This Reverse biasing creates external electric field in the direction of internal electric field and the fermi-level in n-region moves down with respect to that in the P-region (Fig 2.17).

Zener Diode (or Breakdown Diode):→ The reverse current remains virtually (really) constant ~~in~~ even at high voltages in many semiconductor diodes (Fig 2.16). But in certain diodes the reverse current increases abruptly when a particular voltage is reached; like in zener diode.

Zener diode is a reverse-biased P-n junction diode properly doped for a specific, sharp breakdown voltage with adequate power dissipation capability. Zener diode is like an ordinary diode except that it is suitably doped to have a sharp breakdown voltage (or zener voltage).

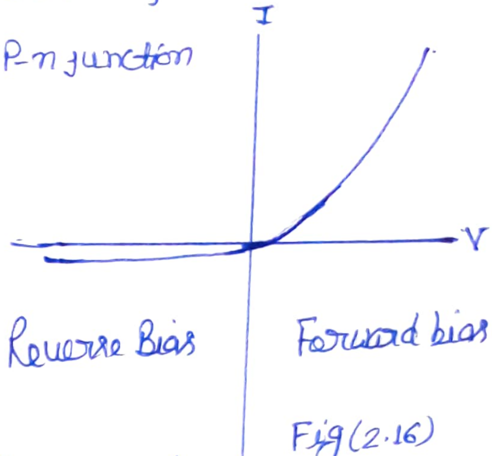


Fig (2.16)

The breakdown voltage depends upon the amount of doping. If the diode is heavily doped, the breakdown voltage is low. On the other hand, if the diode is lightly doped, the breakdown voltage is high. ~~Zener diode is represented~~ The circuit symbol of zener diode is shown in fig 2.17.

Fig 2.17

The current-voltage characteristics of zener diode is shown in fig 2.18. When reverse bias is applied to junction diode, then at a particular voltage the reverse current increases sharply. There are two mechanisms which contribute to sharp rise in current that is zener breakdown and avalanche breakdown.

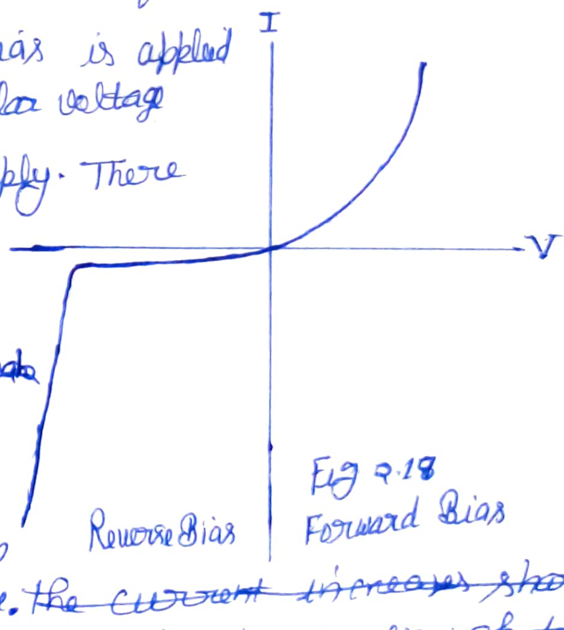


Fig 2.18

In zener break down, when reverse bias is applied to P-n junction diode then at a particular voltage. ~~the current increases sharply.~~ the electric field across the P n junction is strong enough to pull the electrons from covalent bonds. So the electron-hole pairs created and contribute in reverse current. In zener ~~breakdown~~ break down the electrons created in ~~ab~~ valence band of p side tunnel to conduction band of side n ~~of~~ even though these electrons do not have enough energy to first enter the conduction band on the P-side or and the reverse current increases abruptly.

The other mechanism is avalanche breakdown. When the reverse bias voltage is higher than zener breakdown voltage, the created electrons and holes in zener breakdown gets sufficient kinetic energy to produce new electrons and holes via collision. These new carriers create additional charge carriers. This process continues and a flood of charge carriers ~~occurs~~ is obtained, which is responsible for sharp increase in reverse current. It is known as avalanche Break down.

Manufacturers gives the following specifications regarding zener diode

Zener Voltage V_Z:→ It is the reverse voltage at some test value i_{zt} of zener current i_z on the linear portion of the reverse characteristics. The zener voltage V_Z is corresponding to approximately one-quarter of the maximum power dissipiation ($V_Z \times i_Z$) capability of the diode.

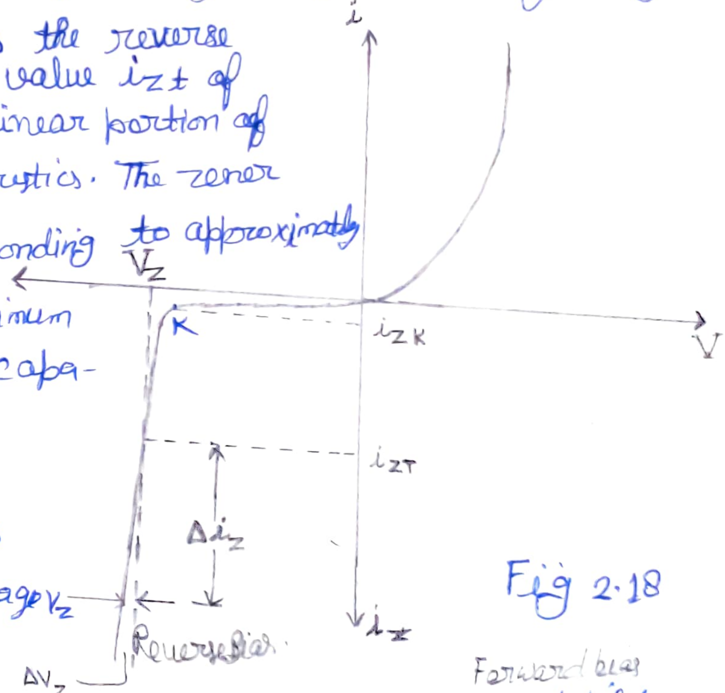


Fig 2.18

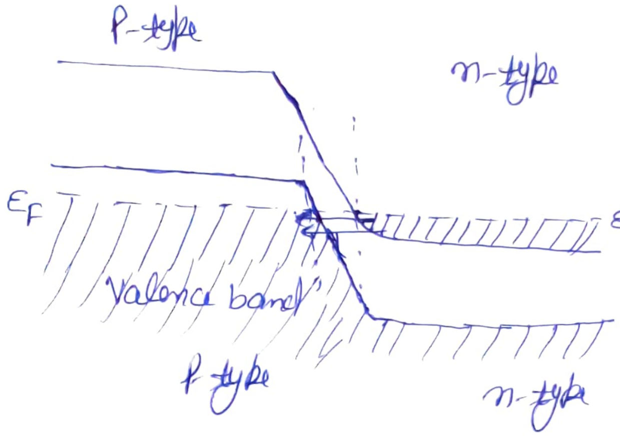
Power Dissipiation:→ It is the product of zener voltage V_Z and zener current i_Z.

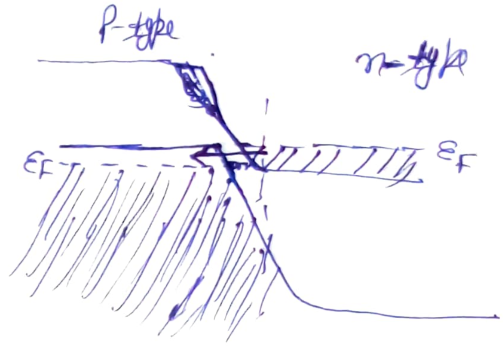
Manufacturers specifies the maximum power dissipiation capability value on the diode. The zener current should be limited to a value such that the power dissipiation does not exceed the maximum power dissipiation capability otherwise it would be damaged due to over-heating.

Breakdown Current (i_{ZK}):→ It is the minimum reverse current below which the diode should not be used. Graphically the reverse current through the zener diode is corresponding to knee-point K just beyond the curvature of the characteristic. So the curvature is avoided.

Tunnel diode:→ It is a P-n junction made from quite hi[ghly] doped semiconductors (that is why fermi level in P-type coincide with valence band and fermi level in n-type coincide with C[.B.]) The quantum mechanical phenomenon of potential barrier penetration is used here.

* The depletion region is narrower than that of P-n junction diode.

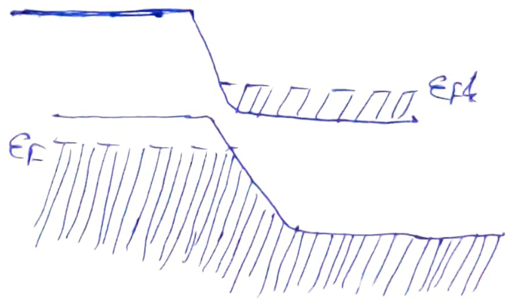




Unbiased condition – electrons from conduction band in n-type move to V.B in P-type bcoz depletion region is much narrower

ⓐ

Small forward voltage – when we apply small forward voltage then the energy levels in the n-type semiconductor move up relative to those in P-type semiconductor now the no. of ē tunneling from n to P side increases bcoz they find ~~vacant~~ vaccant energy levels in P-side, So current increases.



ⓒ

further increase voltage –

In this case we do not have ~~free~~ empty state to move ē from n side C.B to P-side V.B. So current decreases and at particular voltage ~~for~~ tunnel diode start to ~~be~~ behave as P-n junction (P-n junction characterist[ics]) this is known as negative resistance region and in this region tunnel diode is useful and work as switching circuits ~~in~~ of computers