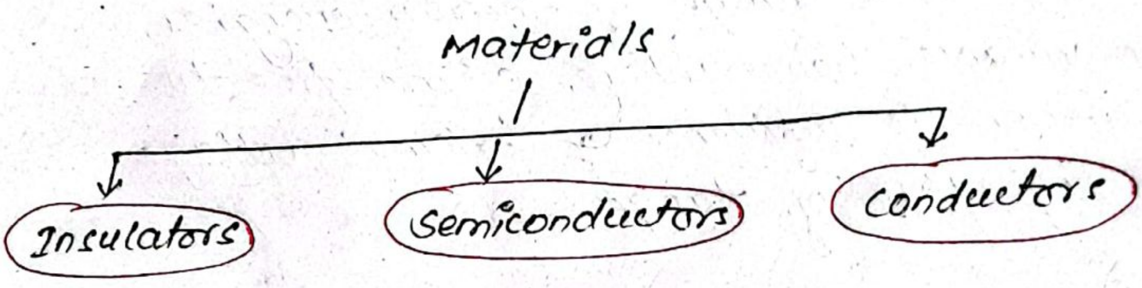
Semiconductor and semiconductor materials

Based on the electrical conductivity, all the materials in nature are classified as ;

- insulator
- semiconductor and
- conductors.



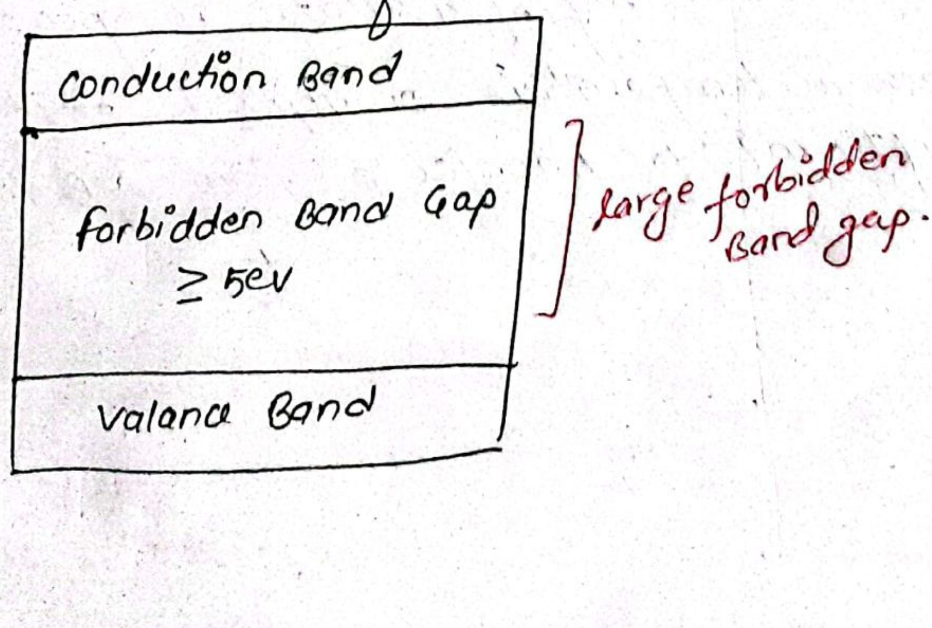
a Insulators:

An insulator is a material that are characterized by poor electrical conductivity. for eg: glass, quartz, rubber, bakellite, mica etc.

The resistivity level of an insulator is of the order of 10^{10} to 10^{12} $\Omega \cdot m$ (ohm-meter)

$$\left[\because \text{Resistance } (R) = \frac{\rho l}{A} \quad \therefore \rho = \frac{RA}{l}\right]$$

The energy band structure of an insulator is as shown below.



Band structure of a material defines the band of energy level that an electron can occupy. valance band is the range of electron energy where the electron remain bonded to the atom and do not contribute to the electric current.

Conduction band is the range of electron energies higher than valance band where e⁻s are free to accelerate under the influence of external voltage source resulting flow of charge.

The energy band between the valance band and conduction band is called forbidden band gap or forbidden Energy gap. It is the energy required by an e^- to move from valance band to conduction band.

$$\boxed{1eV = 1.6 \times 10^{-19} J}$$

There is a large forbidden band gap $\geq 5ev$. Because of this large gap, there are very few e^-s in the conduction Band and hence conductivity of insulator is poor.

Even on increase in temperature or applied electric field is insufficient to transfer e^-s from VB to CB.

6. Conductors:

conductor or conducting materials are good conductors of electricity and characterised by a large conductivity & small resistivity. for eg. copper, Aluminium, silver etc. The resistivity of conductors is in the range of $10^{-8}\ \Omega m$.

In a conductor, there is no forbidden energy gap between valance band and conduction band i.e. they overlap each other. Electrons randomly move through the solid. so electrons in the conductors are called free electrons.

Therefore at a room temperature (25°C) when electric field is applied, an electric current flows through a conductor. The resistance of the conductor increases with the increase in temperature. (Temp ↑, collision ↑, resistance ↓ & flow of current ↓)

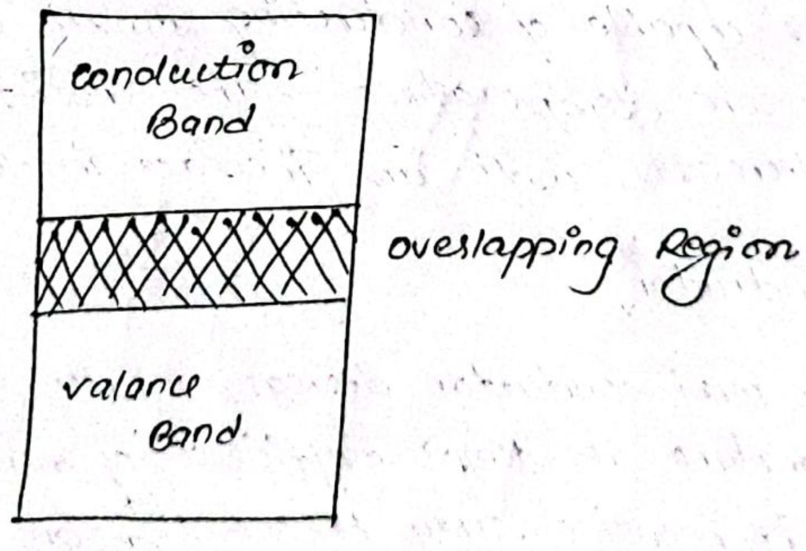


fig: Energy level diagram of conductor.

c. Semiconductor

A semiconductor is a material that has the conductivity somewhere between the insulator and conductor. The resistivity of semiconductor material lies in the range of 10^{-5} to 10^{5} Ωm.

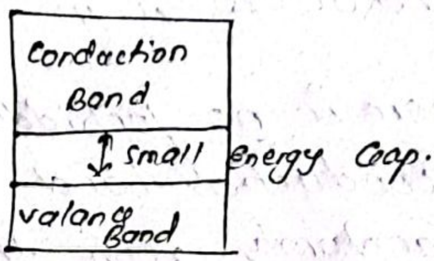


fig: semiconductor's energy band diagram.

(0K) (-273°c)

Thus semiconductor acts as a insulator at absolute zero. However at normal room temperature (25°c) some e⁻s can easily jump to conduction band due to low energy gap between valance band and conduction band. Thus semiconductors are capable of conducting small current even at normal room temperature. The resistance of semiconductor decreases with an increase in temperature.

Types of semiconductor

x——x—f—x

The resistance of semiconductor decreases with an increase in temperature. ie. tempr coefficient of resistance of semiconductor is negative. They behave like an insulator at very low temperature but act as conductor at high temperatures.

→ The mostely used semiconductors are Germanium (Ge), and silicon (Si).

. properties of semiconductor (S/C)

1. The resistivity of s/c depends on illumination and decreases in brighter surroundings. (negative temp, light coefficient)

2. The resistivity of s/c depends on the magnitude of electric field.

3. s/c are non-linear elements. [do not follow ohm's law]

4. The conductivity of s/c changes considerably when small amount of impurities added to it. so that its conductivity can be controlled.

There are 2 types of s/c:

1. Intrensic (pure) s/c
2. Extrinsic (impure) s/c

Semiconductor
- Intrinsic
- Extrinsic
  - P-Type
  - N Type.

1. **Intrinsic semiconductors**

The extremely pure form of semiconductors in which there are almost equal no of holes and electrons. In V.B and C.B respectively are called intrensic semiconductors.
Pure germanium and silicon are widely used intrinsic semiconductors.

Production of Holes and free electrons

Let us consider a structure of silicon atom. Silicon atomic no. is 14 and has 4 valance electrons. These 4 electrons are shared by 4 neighbouring atoms in the crystal structure by means of covalent bond.

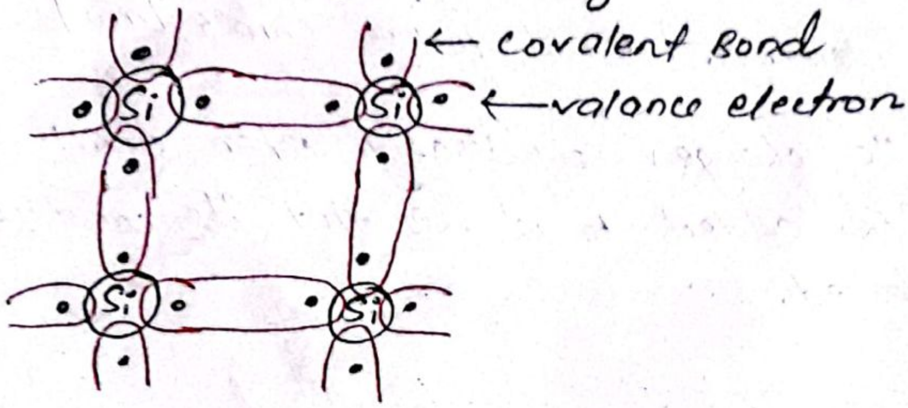
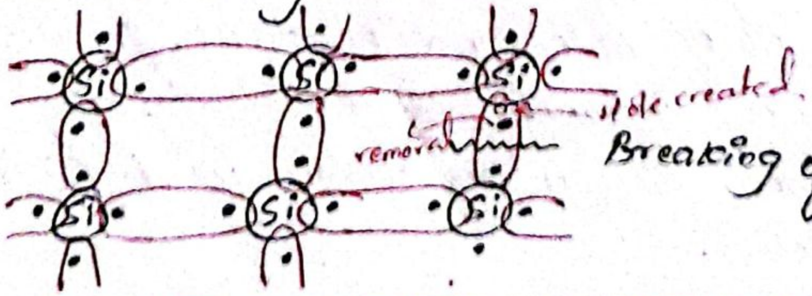


fig: Crystal structure of Si at absolute zero (-273°C)

Thus, pure s/c acts as poor conductor (due to lack of free electrons) at a low temperature or at absolute zero temperature.

At room tempr some of the covalent bonds break up. As a result, e-s are released and move to the conduction band, are called free electrons. The vacancy created in broken bond is called a hole. Since hole is created after a removal of e- from the covalent bond, it is considered as positive charge.



Breaking of covalent Bond.

fig: production of hole and free e-

Electrons and holes are created in pairs. where a free electron approaches the hole, it gets attracted and falls into the holes. This process of merging of free e- and a hole is called **recombination**.

During this process, both the free e-s and hole disappear. However, an energy is released and causes another covalent bond to break down and generate a new electron hole pair.

Conduction in Intrensic semiconductors

When an e-s are released during the breakdown of covalent bonds, they move randomly through a crystal lattice. When an external electric field is applied to the pure intrensic s/c, the free e-s in the conduction band move towards the +ve terminal while holes move towards the -ve terminal of power supply (battery). As a result, an electric current flow. This current is very small.

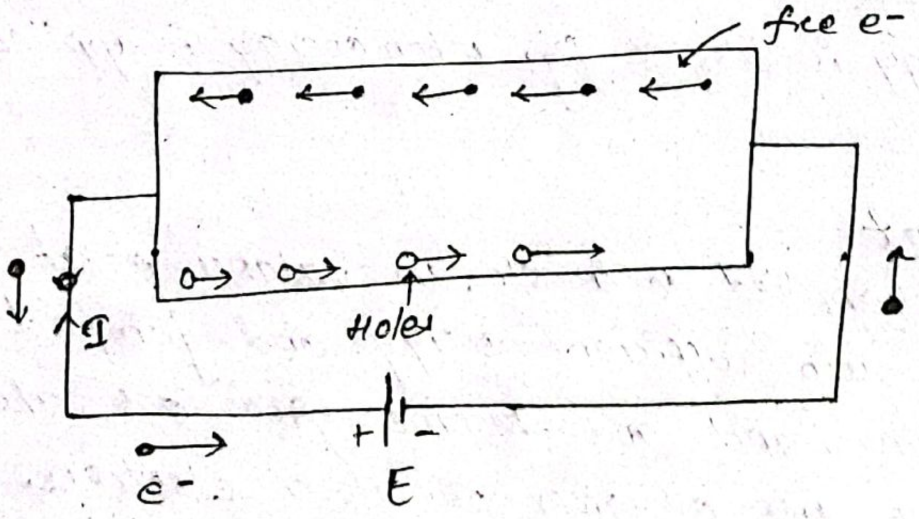


fig: conduction of current in Intrensic s/c.

Total current in the semiconductor is the sum of electron current and hole current.

ie. $\boxed{I = I_e + I_h}$

#1. Conduction in semiconductor

S/c consists of 2 types of charge carriers. positive charge carriers called holes and negative charge carriers called electrons.

The movement of these charge carriers give rise to the flow of current in s/c. Thus we can say that s/c possess two types of current.

i) Electron current
ii) Hole current

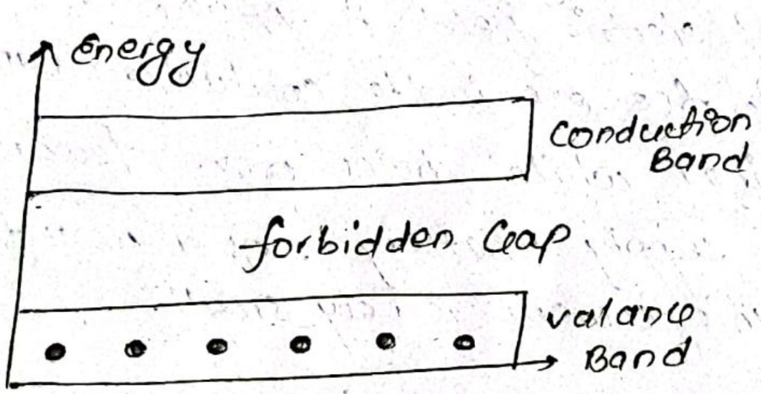


fig: when no energy is applied

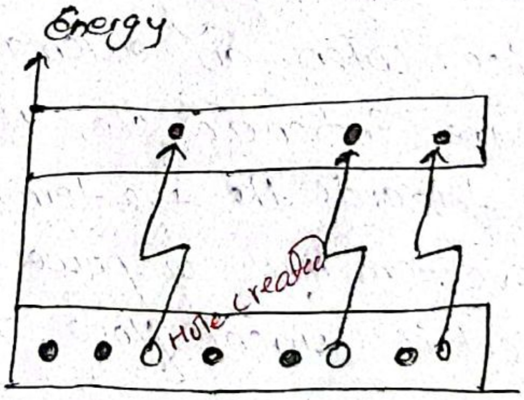


fig: when energy is applied

i) Electron current
When an energy is applied to a s/c, the valance e- at valance band can gain sufficient energy and jumped to the conduction band and become free e-s. The movement of these free e-s gives rise to a electron current (I_e).

(iii) Hole current

When a valance e^- gain sufficient energy and jumped to conduction band, they leave a hole at the valance band. Further valance electrons can move through this hole. Thus relative motion of valance e^-s at valance band through holes give rise to hole current (I_h).

Thus, total current in a s/c is the sum of e^- current and hole current.

i.e. $I = I_e + I_h$

2. Extrensic Semiconductor

An intrinsic s/c has very limited applications / significance as it conduct very small amount of current at room temperature. However, the electrical conductivity of intrensic s/c can be increased significantly by adding small amount of impurities to it during the crystallization process. (process of seperating solid compounds from the solution in the form of crystals.)

This process of adding an impurity to a pure s/c is called dopping and the resulted s/c formed is called extrensic s/c.

There are 2 types of semiconductor on the basis of type of impurities added.

(i) N-type semiconductors
(ii) P-type semiconductors.

is N-type semiconductor

when a small amount of pentavalent impurity is added, such as Arsenic (As), Antimony (Sb), Bismuth (Bi), phosphorous (P) to a pure s/c during crystallization process, the resulting crystal is called N-type s/c.

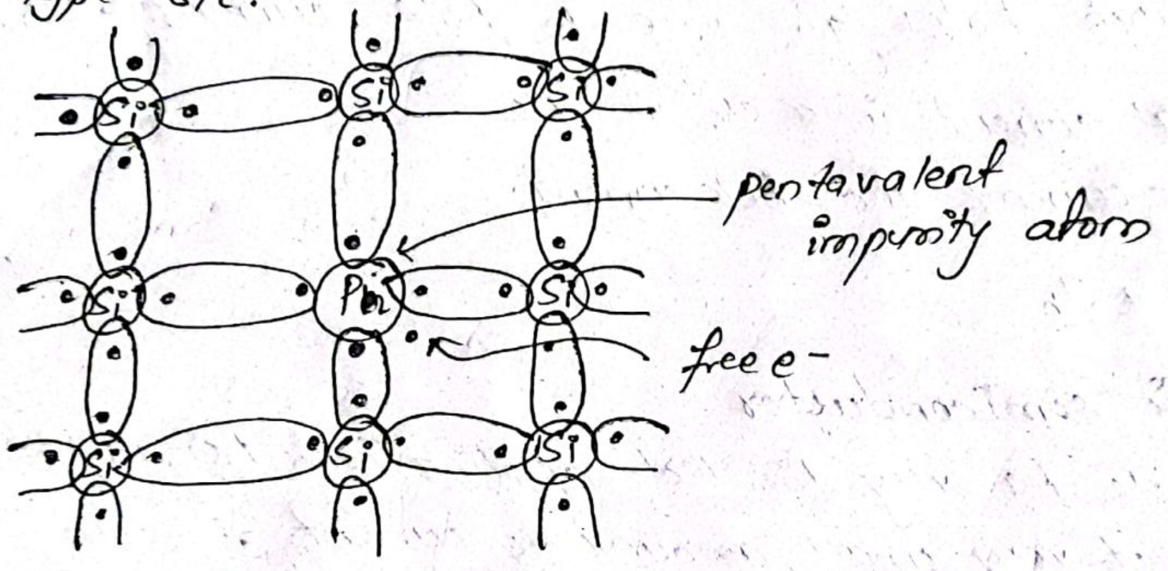
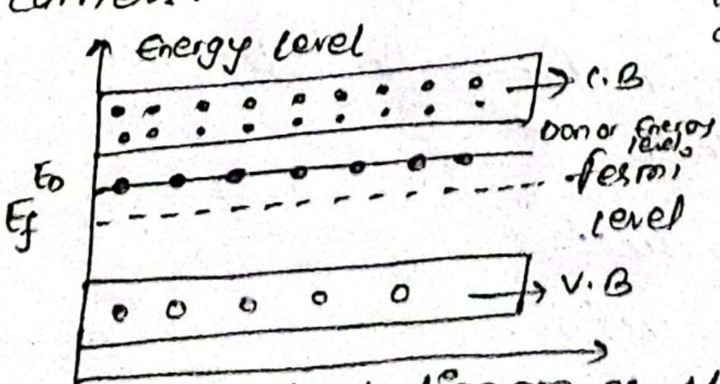


fig: crystal structure of N type s/c.

for each impurity added, one free e⁻ is generated, which then moves to conduction band. As the pentavalent impurity donates electron to crystal lattice, it is also called donor impurity or donor agent.

In N-type semiconductor, e⁻s are majority charge carriers.



* fermi level: The highest energy level that an electron can occupy at the absolute zero temperature. fermi level lies between valance band and conduction band because at absolute zero tempr the electrons are all in the lowest energy state.

fig: Energy level diagram of N-type semiconductor

(ii) P-type semiconductor

When a small amount of trivalent impurity such as aluminium, Gallium, Indium, Boron is added to a pure s/c, then P-type s/c is formed.

The crystal structure of P-type s/c is as shown below:

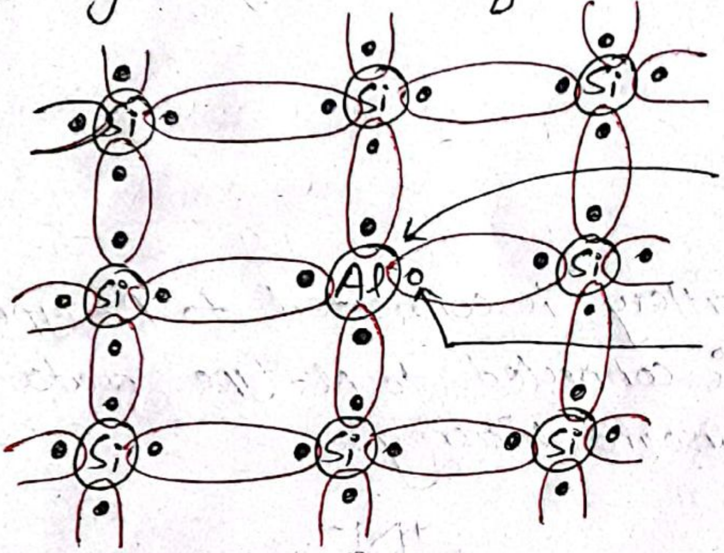
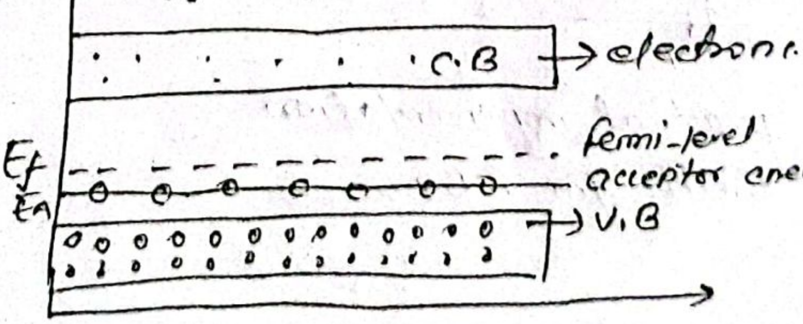


fig: crystal structure of P-type s/c.

The 3 valance e⁻s of the trivalent impurity forms 3 covalent bonds with the neighbouring atoms and a vacancy exists in the fourth bond giving rise to the holes, which can accept an electron. So, trivalent impurities are also called acceptor impurities or acceptor agents.

In P-type s/c, holes are majority carriers & e⁻s are minority carriers.



* P-type semiconductor मा fermi-level चाहिं सधैं V.B नजिक हुन्छ।

fig: Energy band diagram of P-type s/c.

#. Biasing of PN Junction ([illegible]) (operation of PN Junction Diode)

The process of connecting the diode terminals (ie. P and N) with the source terminal (voltage source) is known as biasing of diode.

A PN junction diode can be biased in two ways:

i) forward Biasing

ii) Reverse Biasing

i) forward Biasing:

If the +ve terminal of the battery is connected to P-type material and -ve terminal is connected to N-type material, the connection is called forward biasing.

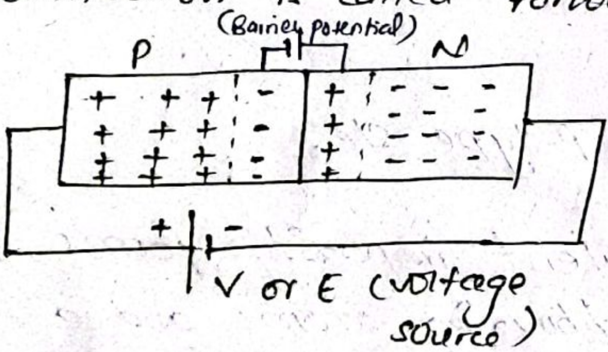


fig: forward Biasing of diode.

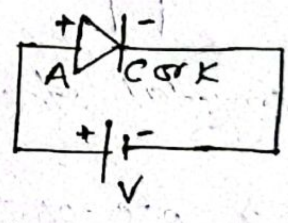


fig: symbolic circuit for forward Biasing.

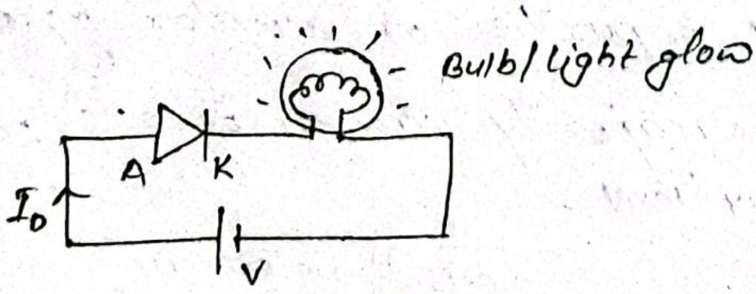


fig: practical implementation circuit for F.B.

The -ve terminal of battery flows electrons on N-region, these electrons repells the electrons on N-region towards depletion region. If the electrons have suffient energy to cross the barrier potential they will transfer to P-region. for this the battery should have potential difference more than barrier potential. In P-region these electrons recombines with holes but due to attraction of positive terminal of battery these electrons move towards +ve terminal through holes. finally electrons reached to the cell. The cell again pumps electrons to N-region and the process continuous. so we can ~~conducde~~ conclude that current flows through diode during forward biased condition.

(ii) Reverse Biasing

when a +ve terminal of a source is connected to -ve terminal of a diode (N-type s/c) and -ve terminal of a source is connected to +ve terminal of a diode (p-type s/c), then the diode is said to the Reverse Biased.

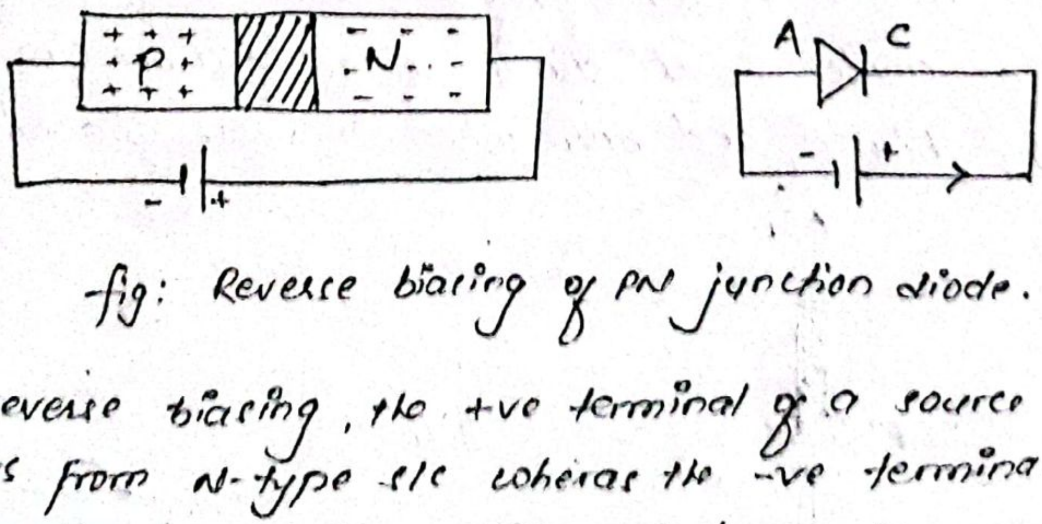


fig: Reverse biasing of PN junction diode.

In reverse biasing, the +ve terminal of a source attracts the e-s from N-type s/c whereas the -ve terminal of a source attracts the holes from P-type s/c, away from the junction. Due to the movement of e-s and holes the depletion region widens and diode doesn't conduct current.

When a diode is reverse biased, the majority charge carriers gives rise to small current, which is negligible.

When reverse bias voltage is greater than a breakdown voltage, the diode breakdown and acts as a short circuit, so it conducts high current.

Voltage Current (VI) characteristics of PN Junction Diode:

i. Ideal Diode:

- The diode that acts like perfect conductor when forward biased and perfect insulator when reverse biased is called an ideal diode.

- It produces zero current when reverse biased.
- It produces zero voltage when forward biased.
- It has zero resistance when forward ~~resistance~~ biased
- It has infinite resistance when reverse biased.

So, ideal acts as switch - The s/w is closed (short circuited) when forward biased and open when reverse biased.

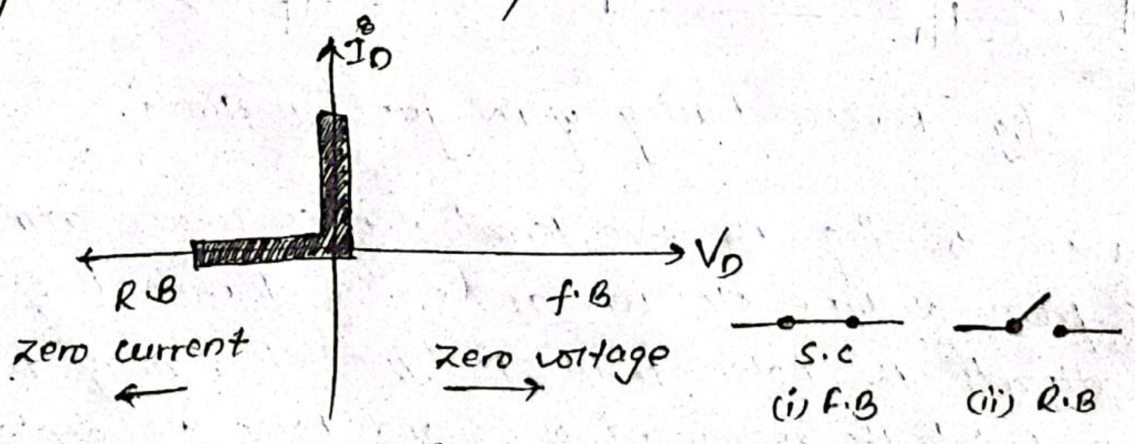


fig: V-I characteristic curve of ideal diode.

(ii) Real / practical diode VI characteristics.

If 'V_D' is the voltage (applied) across a diode and 'I_D' be the current flowing through it, then the relationship between V and I_D is given by,

$$I_D = I_S\left(e^{V_D/\eta V_T} - 1\right) \quad \text{---} (1)$$

* Reverse saturation current is the part of the reverse current in a s/c diode caused by diffusion of minority carriers from the neutral region to the depletion region.
→ Reverse saturation current is the term for negative current produced by a reverse bias.

where, I_S = reverse saturation current
V_T = Thermal voltage = 0.026V at room temp.
η = Emission coefficient ($1 \le \eta \le 2$)
(value 1 or 2 लिने, numerical गर्दा)
V_D = voltage drop across diode.

when eqn (1) is plotted in a graph, then VI characteristics of diode is obtained as shown below:

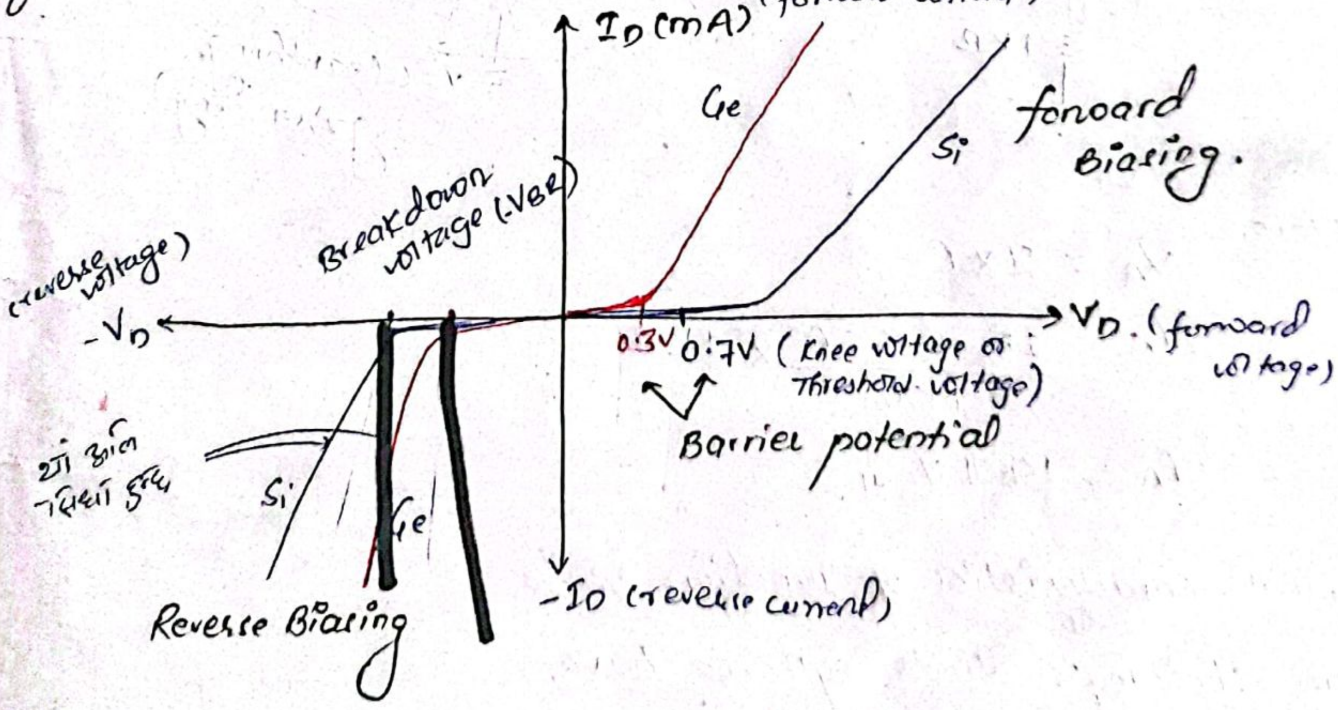


fig: V-I characteristics of a diode.

operation: when a diode is forward biased small amount of current flows through it until the supply voltage is greater than barrier potential.

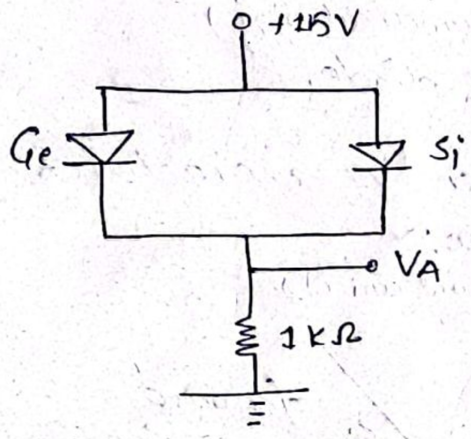
when the supply voltage exceeds the barrier potential, then the current rises sharply as shown in above figure.

Also when the diode is reversed biased, negligible amount of current flows through it, but if the supply voltage exceeds the breakdown voltage (V_{BR}), the diode is broken down (destroyed) and it acts as short circuit due to which the current increase sharply as shown in above figure.

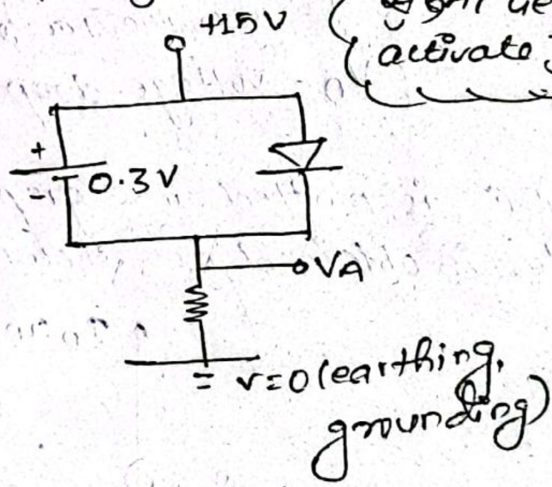
Q. Determine voltage V_A for the following.

Soln:

सुरुमा Ge activate हुन्छ।



⇒



Here,

$$V_A = I \times R$$

$$V_A = \frac{15-0.3-0}{1K\Omega} \times 1K\Omega$$

$$V_A = 14.7V \ \#.$$

#. Terminal characteristics of Junction Diode.

from shockley's diode eqn we have,

$$I_D = I_S\left(e^{\frac{V_D}{mV_T}} - 1\right) \quad \text{—— (1)}$$

where, I_D = diode current

I_S = leakage saturation current

V_D: voltage drop across diode

V_T: Thermal voltage

where, V_T is given by,

$$V_T = \frac{KT}{q}$$; K = Boltzmann's constant ($K = 1.38 \times 10^{-23}$ Joule/Kelvin)

T = absolute Room Tempr

q = electronic charge ($q = e = 1.67 \times 10^{-19}$ C)

Diode Resistance

Diode shows two types of resistive effects:

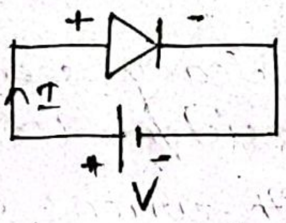
i) static resistance (DC Resistance)

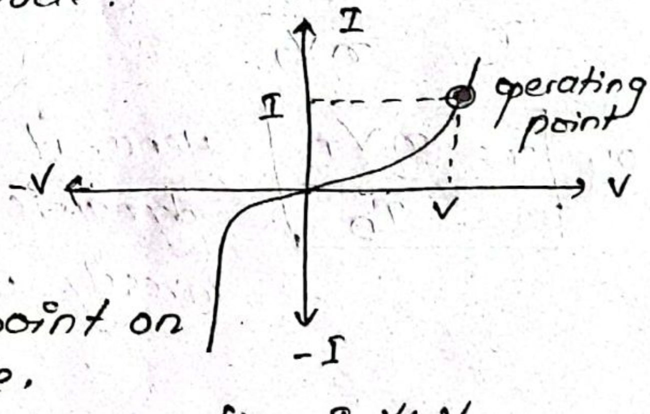
ii) Dynamic resistance (AC Resistance)

i) static Resistance or DC Resistance

If 'V' be the dc voltage applied to a diode and 'I' be the current flowing through it, then the ratio of V and I is called static resistance of a diode.

i.e. $R_{DC} = \frac{V}{I}$





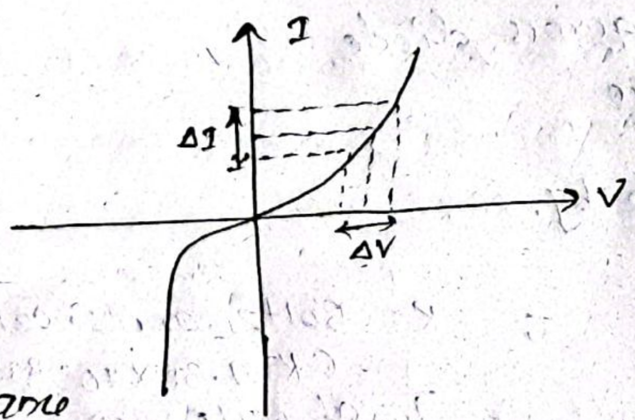
→ Its value depends on operating point on VI characteristics curve of diode.

fig: I Vs V

ii) Dynamic Resistance or AC Resistance

When the voltage applied across a diode is changed by ΔV, then the current flowing through it will also change by ΔI. The ratio of change in voltage to change in current is called dynamic or AC resistance of a diode.

Here.



Dynamic resistance

$$r = \frac{\Delta V}{\Delta I} = \frac{dV}{dI_D} \quad \text{—— (i)}$$

we know that,

$$I_D = I_s \left(e^{\frac{V_D}{\eta V_T}} - 1 \right) \approx I_s \left(e^{\frac{V}{\eta V_T}} \right) \quad \text{—— (ii)}$$

Now,

$$\frac{dI_D}{dV} = \frac{d}{dV}\left[I_s e^{\frac{V}{\eta V_T}} \right]$$

or, $$\frac{1}{r} = \frac{I_s}{\eta V_T} e^{\frac{V}{\eta V_T}} \quad \left[\because r = \frac{dV}{dI_D} \right]$$

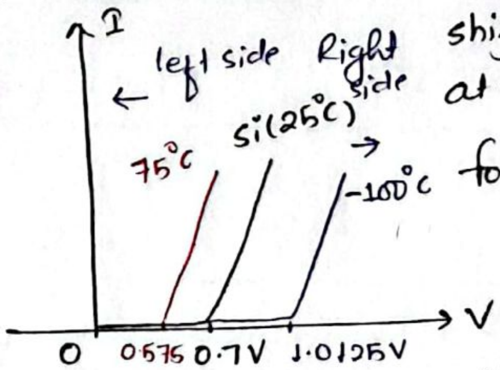
or, $$\frac{1}{r} = \frac{I_D}{\eta V_T} \quad (\because \text{from eq}^n \text{ (ii)})$$

or, $$\boxed{r = \frac{\eta V_T}{I_D}}$$

Hence, it is clearly seen that the dynamic resistance (r) varies inversely with current across diode.

Temperature Dependence of V-I characteristics

forward bias



for Si diode, characteristic in forward biased shifted towards left side by increasing temp^r at the rate of 2.5 mV/°C.

for eg: find thresold voltage at 75°C and at -100°C for Si PN Junction diode.

Soln. (i) for 75°C

New threshold voltage $(V_{Th}) = V_{Tho} - 2.5\times10^{-3}\times 50°C$

[→ यदि temp^r increase हो भने left side सर्छ। यहाँ Si को 25°C already छ, so 75°C पुग्याउन 50°C भए पुग्छ, जुन temp^r 2.5 mV को rate ले change हुन्छ।]

$$\therefore V_{Th} = 0.7 - 2.5\times10^{-3}\times 50$$
$$= 0.7 - 0.125$$
$$= 0.575V$$

[increase छ भने -ve
decrease छ भने +ve
reference चैं Si(25°C) लाई लिने]

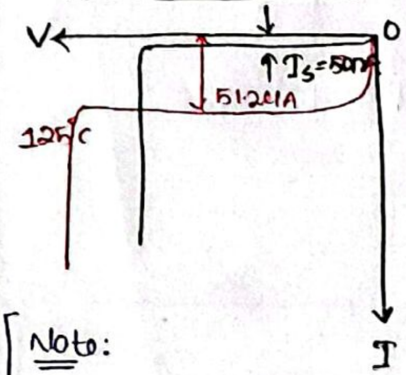
(ii) for -100°C

-100°C पुग्नको लागी 25°C to 0°C and 0°C to -100°C

$\therefore$ Total temperature 125°C.

Now, $V_{Th} = V_{Tho} + 2.5\times10^{-3}\times125$
$$= 0.7 + 2.5\times10^{-3}\times125$$
$$= 0.7 + 0.3125$$
$$= 1.0125V$$

Reverse Bias



while we increase temp^r in reverse bias, the reverse saturation current also increases. The reverse saturation current will double in every 10° rise in temperature.

It is given by,

$$I_{(new)} = I_{(old)}\, 2^{\left(\frac{\Delta T}{10}\right)} \quad \text{---(1)}$$

where, ΔT = change in Temp^r

[Note: Reverse Bias मा temp^r increase गर्दा Breakdown voltage पनि increase हुन्छ।]

eg: find the reverse current at 125°C temp where room temp^r is 25°C. The reverse saturation current is 50nA at room temp^r.

Soln we know,

$$I_{(new)} = I_{(old)} \times 2^{\frac{\Delta T}{10}}$$
$$= 50nA \times 2^{\left(\frac{125-25}{10}\right)}$$
$$= 50nA \times 2^{10}$$
$$= 50\times10^{-9}\times1024 = 51.2\mu A \text{ (micro ampere)}$$

depletion capacitance = Transition capacitance

Junction capacitance.

The depletion layer across the junction diode behaves as an insulating material or dielectric constant of the capacitor, similarly the P and N side acts as parallel plate of the capacitor. So junction exhibits the properties of capacitor which is called junction capacitance.

Types.

1. Diffusion capacitance (C_D)
2. Transition capacitance (C_T)

C_D Diffusion Capacitance	C_T Transition capacitance.
1. It occurs when diode is forward biased.	1. It occurs when diode is reversed biased.
2. with forward biasing the depletion width decreases so C_D increases with increasing forward biasing.	2. with reverse biasing the depletion width increases so, C_T decreases with increasing reverse biasing.
3. C_D is directly proportional to forward diode current I_D ie. $C_D \propto I_D$	3. C_T is inversly proportional to ~~xxx~~ square root of reverse voltage. ie. $C_T \propto \frac{1}{\sqrt{V_B}}$

4. C_D v/s forward voltage curve is:

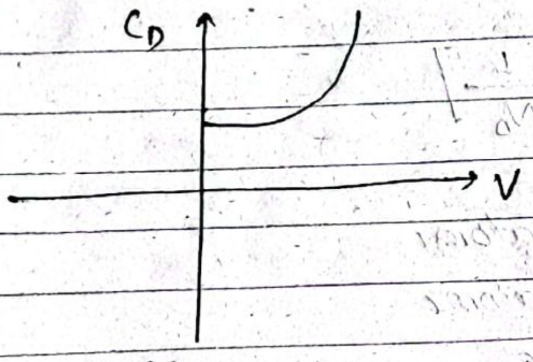


fig (i).

4. C_T v/s Reverse voltage curve is.

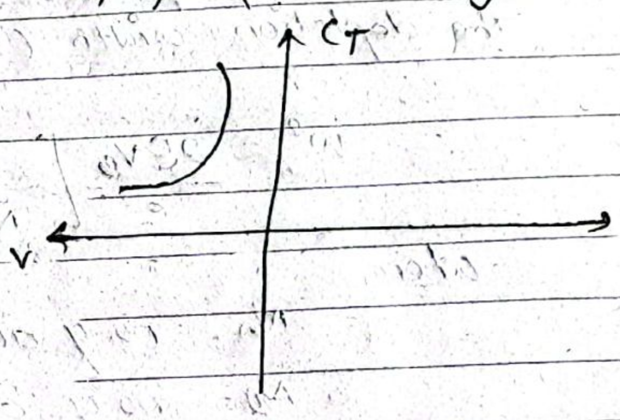


fig (ii).

short note

1: **Diffusion capacitance (C_D):**

we have,

$$\text{Capacitance } (C_D) = \frac{dQ}{dV}$$

$$\text{or, } C_D = \frac{d}{dV}(i \times t) \quad [\because Q = i \times t]$$

$$\text{or, } C_D = \tau \frac{dI_D}{dV_D}$$ where, τ is mean life time of charge carriers.

$$\text{or, } C_D = \tau \frac{\partial}{\partial V_D} I_s e^{V_D/\eta V_T}$$

$$\text{or, } C_D = \frac{\tau}{\eta V_T} I_s e^{V_D/\eta V_T}$$

$$\text{or, } C_D = \frac{\tau}{\eta V_T} I_D$$

$$\boxed{\therefore C_D \propto I_D}$$

proved.

20/2/2018

2. Transition capacitance (C_T):

The depletion width (W) can be written as,

$$W^2 = \frac{2\epsilon V_B}{e}\left[\frac{1}{N_A} + \frac{1}{N_D}\right]$$

where,

N_A = no. of acceptor atoms

N_D = no of donor atoms

e = electronic charge.

ϵ = permitivity.

we ~~Have~~, know,

$$C_T = \frac{\epsilon A}{W}$$, where A = area of plates.

$$\therefore C_T = \frac{\epsilon A}{\sqrt{\frac{2\epsilon V_B}{e}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)}}$$

$$= \frac{\epsilon A}{\sqrt{\frac{2\epsilon V_B}{e}\left(\frac{N_A + N_D}{N_A N_D}\right)}}$$

$$= \epsilon A \times \sqrt{\frac{e N_A N_D}{2\epsilon V_B (N_A + N_D)}}$$

$$\boxed{\therefore C_T \propto \frac{1}{\sqrt{V_B}}}$$ proved

8 transition capacitance is inversely proportional to the sq. root of the applied voltage.

2018: What do you mean by junction breakdown of a diode ? Distinguish betn a zener ~~diode~~ breakdown and avalanche breakdown.

Reverse biase.

Junction Breakdown

In reverse biasing a very small current flows due to minority charge carriers. This current is called leakage saturation current (I_s). If reverse voltage is further increased a large current flows suddenly at a certain reverse biase voltage. This mechanism of producing large reverse current is called junction breakdown.

Types:

i) Zener Breakdown

ii) Avalanche Breakdown.

Zener Breakdown	Avalanche Breakdown.
1. It occurs due to high electric field intensity across the junction.	1. It occurs due to collision of charge carriers with other atoms.
2. It occurs normally at low reverse voltage. (<4V)	2. It occurs normally at high reverse voltage. (>6V)
3. It occurs in heavily dopped diode.	3. It occurs in lightly dopped diode.
4. Zener Breakdown voltage decreases with rise of temperature. (negative tempr coeff)	4. Avalanche breakdown voltage increases with rise of temperature. (positive tempr coeff)
5. The width of depletion layer is thin.	6. The width of depletion layer is large in order.

#.2. Zener Diode

Zener diode is a special type of diode which works in breakdown region. It acts as simple diode when forward biased (current flows from anode to cathode). But when operated in reverse breakdown they have extremly stable breakdown voltage over wide range of current labels so they are considered as the back bone of voltage regulator.

- dopping level high हुन्छ PN junction diode भन्दा

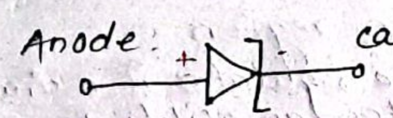


fig: circuit symbol of zener diode.

The VI characteristics of zener diode is;

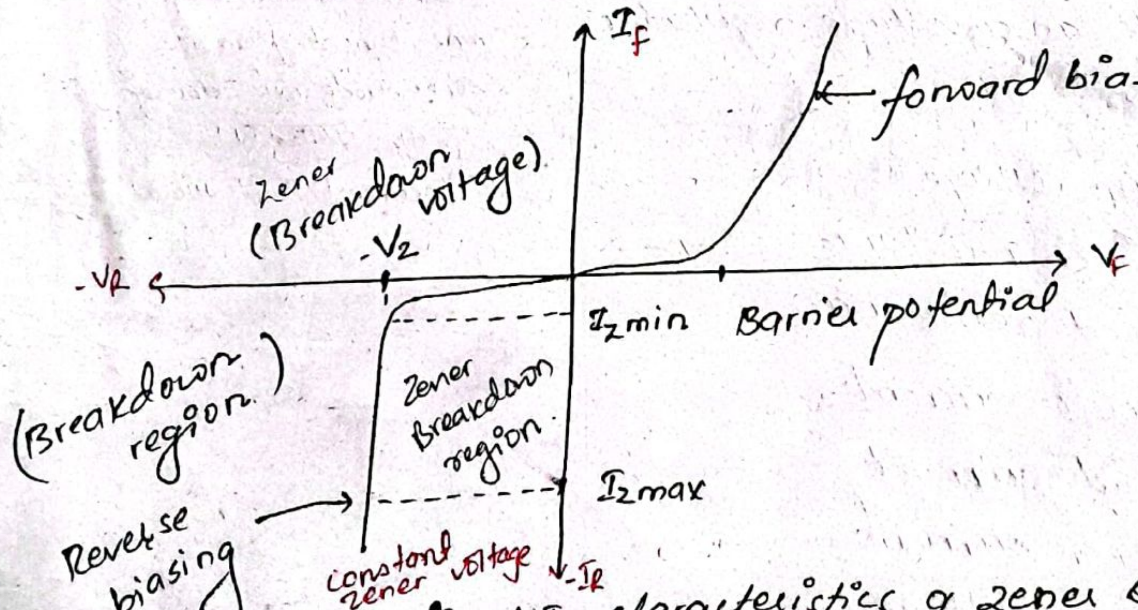


fig: VI characteristics of zener Diode.

Note:
$I_{Z(min)}$: I_o or I_s हुन्छ।
$I_Z min$ देखि $I_Z max$ सम्मको region लाई zener Breakdown regi[on] भनिन्छ जहाँ V_Z, cons[tant] हुन्छ।

Applications of zener diode:

1. As a voltage regulator (stabilizer).
2. A clipper in wave shaping circuit
3. (voltage regulation*, input मा voltage vary गरेतापनी load मा constant voltage provide गर्छ।)

[eg: shunt Regulator stablizer #

Zener Diode as a voltage Regulator

To use zener diode as a voltage regulator, following condition must be satisfied,

i) Zener diode must be operated in reverse biase and connected in parallel with load.

ii) Input voltage must be greater than zener voltage ($V_{in} > V_Z$)

ie. it must be operated in a breakdown region

<u>Defn</u>: voltage regulator is a circuit that has an ability to maintain constant output voltage either input voltage is varying or load current is varying.

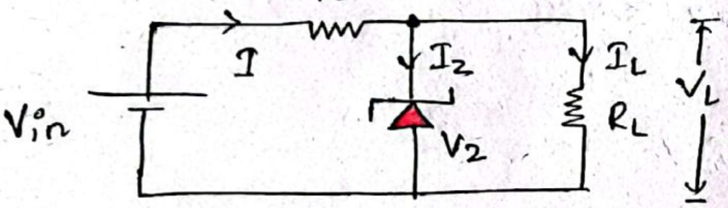


fig: zener diode as a voltage regulator.

R_s = series resistance हो, यसको काम अतेको max current flow भएर zener diode लाई damage हुनबाट बचाउनु हो। 'current limit गर्छ'

Here,

V_{in} = i/p voltage

R_S = source resistance

R_L = load resistance

I = source current

I_L = load current

I_Z = zener current

V_Z = zener voltage

V_L = load voltage

When zener diode regulate voltage across load, the load voltage will be equal to zener voltage.

ie. $V_L = V_Z$

from above figure,

$$I = I_z + I_L$$

and $V_L = I_L \cdot R_L$

case 1: when Vin changes

let Vin is increased. As Vin increased, the current I also increases. If I increased, both I_L and I_Z must be increased, but the zener diode conducts the increased current (ie. only I_Z increases) and maintain I_L constant.

Thus, $V_L = I_L R_L$ becomes constant even if Vin increases.

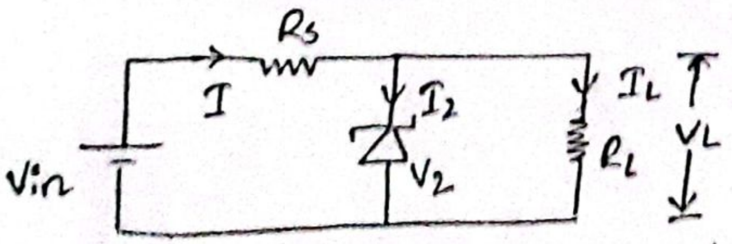
case 2: when R_L changes

Suppose R_L increases. When R_L increases, the zener diode conducts more (ie. I_Z increases) and minimizes the value of I_L. so that even increase of R_L, as I_L decreases,

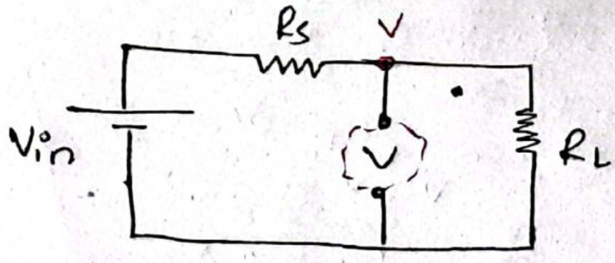
$V_L = R_L I_L$ remains constant.

Zener Diode Numerical : Different cases

case I: Vin = constant and R_L = constant



Here we have to find whether the zener diode is 'ON' or 'off'. for that, remove zener diode from circuit and find open ckt voltage 'V':



Here,

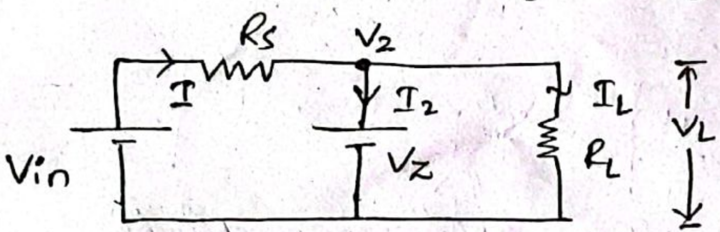
$$V = \frac{R_L}{R_L + R_S} * V_{in}$$

a> If $V < V_Z$, zener diode is OFF

b> If $V > V_Z$, zener diode is ON

a> If **zener diode is ON:**

Replace zener diode by voltage source with value V_Z.



Here, $V_L = V_Z$

$$I = \frac{V_{in} - V_Z}{R_S}$$

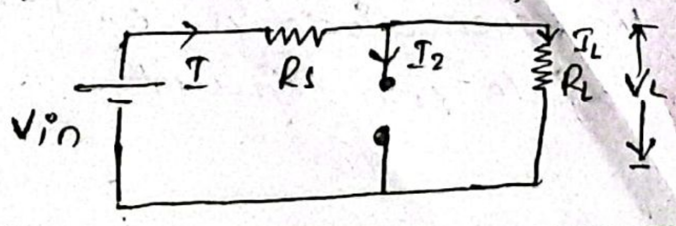
$I_L = \frac{V_L}{R_L}$ and, $V_R = I.R_S$ (ie. voltage across series resistance)

$I_Z = I - I_L$

power across zener diode $(P_Z) = V_Z I_Z$

b> If **zener diode is OFF:**

Replace zener diode by open circuit.



Here, $I_z = 0$

$$V_L = \frac{R_L}{R_L + R_s} \times V_{in}$$

$$I = I_L = \frac{V_{in}}{R_L + R_s} \quad \text{or,} \quad I_L = \frac{V_L}{R_L}$$

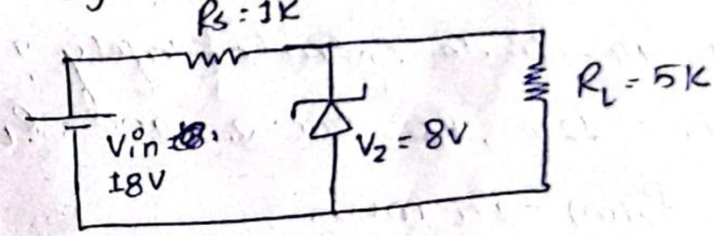
$\boxed{P_Z = V_Z \cdot I_Z = 0}$ and, voltage across series resistance $(V_R) = I \cdot R_s$

Q.N.1. for the circuit shown below; find

i) load voltage (V_L)

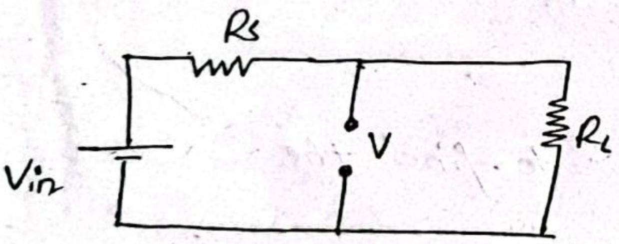
ii) zener current (I_Z)

iii) Power across zener diode.



soln Here,

Removing zener diode and have to find open ckt voltage 'V'



Here,

$$V = \frac{R_L}{R_s + R_L} * V_{in}$$

$$V = \frac{5}{5+1} \times 18$$

$V = 15\,V$

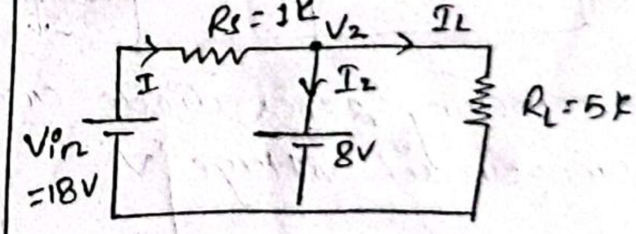
Here, it is clearly seen that

~~Vin (18V)~~ $> V_Z$

~~V(15V)~~ V

($15V > 8V$). So zener diode is ON.

now replace zener diode by its (breakdown) voltage source with value V_Z.



Now,

(i) Load voltage $(V_L) = V_Z = 8V$

(ii) current flowing through zener diode $(I_Z) = ?$

we know, $I_Z = I - I_L$

where, $I = \dfrac{V_{in} - V_Z}{R_s} = \dfrac{18-8}{1} = 10\,mA$

$$I_L = \frac{V_L}{R_L} = \frac{8}{5} = 1.6\,mA$$

$\therefore I_Z = 10\,mA - 1.6\,mA = 8.4\,mA$

(iii) Power across zener diode,

$$P_z = I_z \cdot V_z$$
$$= 8.4 mA * 8V$$
$$= 67.2 mW$$ //

Q.2. for the circuit shown below find,

① Load voltage (V_L)

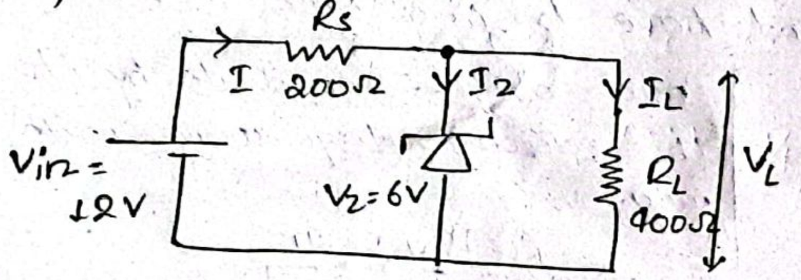
(ii) zener diode current (I_z)

(iii) P_z

Is the diode operate safely? Assume $V_{in} = 12V$, $R_s = 200\,\Omega$, and $R_L = 400\Omega$, $V_z = 6V$

$P_{z(m)} = 100$ mW.

solution, Here,



step 1: removing zener diode and have to find the open circuit voltage 'V'

we know,

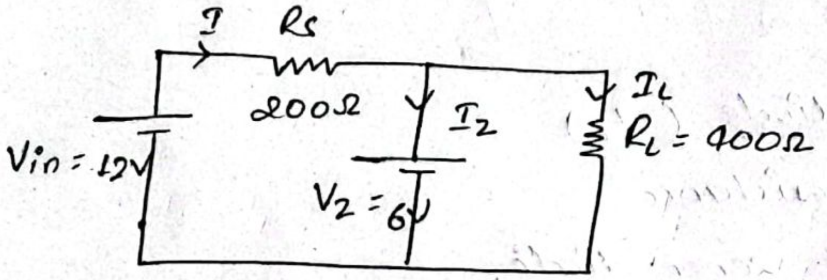
$$V = V_{in} * \frac{R_L}{R_L + R_s}$$

$$= 12 * \frac{400}{400+200} = 8V$$

Here, we get,

$V > V_z$, so zener diode operates (ie. ON state).

Now replace zener diode with voltage source.



(i) we know, $V_L = V_Z$ (when zener diode operates)

∴ load voltage $(V_L) = V_Z = 6V$

(ii) we know,

$$I = I_Z + I_L \quad \text{—— (1)}$$

where,

$$I_Z = I - I_L$$

$$I_Z = \frac{V_{in} - V_Z}{R_S} - \frac{V_L}{R_L}$$

$$I_Z = \frac{12-6}{200} - \frac{6}{400} = 0.015A$$

(iii) $P_Z = V_Z I_Z$

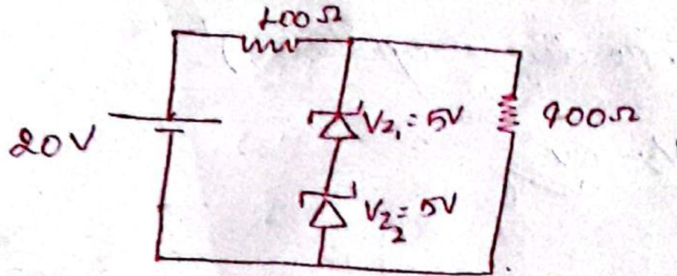
$= 6 \times 0.015$

$= 0.09W$

$= 90mW$

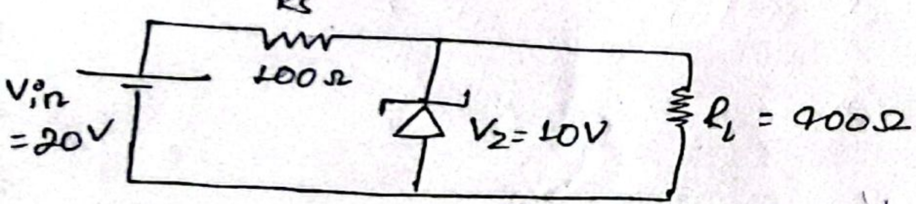
Here, P_Z (90mW) < $P_{Z(M)}$, so the diode operate safely.

Q.3. for the circuit shown below, find
1. load voltage (V_L)
2. current through zener diode (I_z)
3. voltage across series resistance
4. power dissipated across zener diode.



Note:
Remember:
In series
↳ voltage add हुन्छ
↳ current same हुन्छ
In parallel/shunt
↳ voltage same हुन्छ
↳ current add हुन्छ

soln. Here the equivalent circuit is.



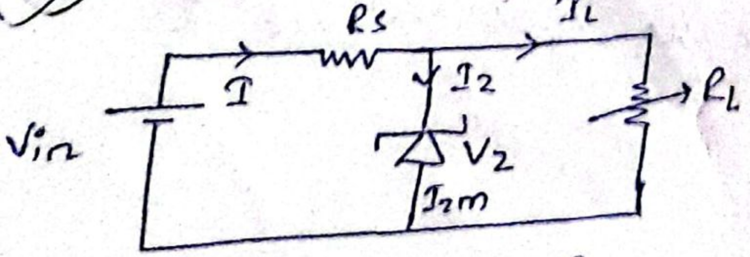
$[\because V_z = V_{z_1} + V_{z_2}]$

अब बाँकी अगाडिको जस्तै prosses गर्ने

Homework

ans: $\boxed{\begin{aligned} V_L &= 10V \\ I_z &= 0.075\ A \\ P_z &= 0.75\ watt \end{aligned}}$

case 2: R_L = variable and Vin = constant.



Here, I_{zm} = maximum zener current

Here we have to find range of R_L [$R_{L(min)}$ and $R_{L(max)}$] required for safe turn ON of zener diode.

Since, zener diode must be ON,

$$V_L = V_Z$$

for minimum value of R_L [$R_{L,min}$]

The open circuit voltage is given by,

$$V = \frac{R_L}{R_L + R_S} * V_{in} \quad \text{--- (1)}$$

for minimum condition, $V = V_Z$

Now, eqn (1) becomes,

$$V_Z = \frac{R_L}{R_L + R_S} * V_{in}$$

or, $V_Z (R_L + R_S) = R_L . V_{in}$

or, $V_Z . R_L + V_Z R_S = R_L . V_{in}$

or, $V_{in} R_L - V_Z R_L = V_Z R_S$

or, $R_L [V_{in} - V_Z] = V_Z . R_S$

or, $R_L = \dfrac{V_Z . R_S}{V_{in} - V_Z}$

$$\therefore \boxed{R_{L,min} = \frac{V_Z . R_S}{V_{in} - V_Z}}$$

(Concept:
for $R_{L,min}$, I_L should be max
for $I_{L(max)}$, I_Z should be zero)

and,

$$\boxed{I_{L,max} = \frac{V_L}{R_{L,min}}}$$

CamScanner

for maximum value of R_L [$R_{L,max}$]

As we know,

$$R_L = \frac{V_L}{I_L}$$

$$R_{L,max} = \frac{V_L}{I_{L,min}} \quad \text{--- (1)}$$

Again, $I = I_L + I_Z$

$\therefore I_L = I - I_Z$

Here, $I_L \longrightarrow I_{L,min}$, when $I_Z \rightarrow I_{Zm}(\text{max}^m)$

$$\therefore I_{L,min} = I - I_{Zm} \quad \text{--- (2)}$$

from eqn (1) and (2)

$$R_{L(max)} = \frac{V_L}{I - I_{Zm}}$$

where,

$$I = \frac{V_{in} - V_Z}{R_S}$$

Q. A zener diode voltage regulator has 12V zener voltage with variable load resistance. calculate. ($V_{in} = 20V$)

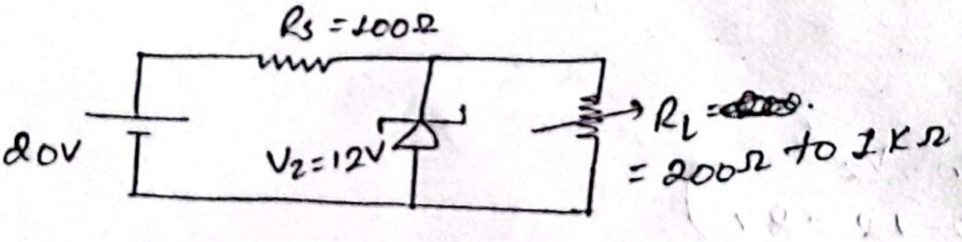
i) maximum and minimum load current

ii) maximum and minimum power dissipation across load.

iii) voltage drop across series resistance.

iv) minimum value of load resistance to ensure that zener diode is ON.

soln Here,



Given,

$V_{in} = 20V$

$R_S : 100\Omega$

$V_Z = 12V$

$R_L(min) : 200\Omega$

$R_L(max) = 1K = 1000\,\Omega$

(i) maximum load current, $I_L(max) = \frac{V_L}{R_L\,min} = \frac{V_Z}{R_L(min)} = \frac{12}{200}$

$= 60mA$

and, $I_L(min) = \frac{V_L}{R_{L,max}} = \frac{V_Z}{R_L(max)} = \frac{12}{1000} = 12mA$

(ii) maximum power dissipation $(P_Z(max)) = V_Z \cdot I_Z(max)$

minimum power dissipation $(P_Z(min)) = V_Z \cdot I_Z(min)$

Here, $I = \frac{V_{in} - V_Z}{R_S} = \frac{20-12}{100} = 80mA$

$\therefore I_Z(min) = I - I_L(max) = 80mA - 60mA = 20mA$

$I_Z(max) = I - I_L(min) = 80mA - 12mA = 68\,mA$

CamScanner

$\therefore P_{z(min)} = 12 * 20 = 240\,mW$

$P_{z(max)} = 12 * 68 = 816\,mW$

(iii) voltage drop across series resistance

$V_R = IR_S$

$V_R = 80mA * 100\Omega = 8V$

Or,

$$\left(\begin{array}{l} V_R = V_{in} - V_Z \\ V_R = 20 - 12 = 8V \end{array} \right)$$

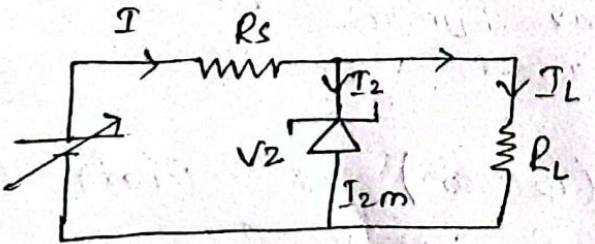
(iv) minimum load resistance

$$R_{L,min} = \frac{V_Z \cdot R_S}{V_{in} - V_Z} = \frac{12 * 0.1K}{20 - 12} = 0.15K\Omega$$

Thus,

0.15KΩ is the ideal load resistance, which ensure to operate zener diode in ON state.

Case 3: V_{in} = variable and R_L = constant.



I_{zm}: maximum zener current.

Here, we have to find range of V_{in} [ie. $V_{in,max}$ and $V_{in,min}$] required for safe turn 'ON' of zener diode.

Zener must be ON. Thus,

$\underline{V_L = V_2}$

for minimum value of Vin [$V_{in(min)}$]

The open circuit voltage is given by,

$$V = \frac{R_L}{R_L + R_S} * V_{in}$$

for minimum condition, $V = V_2$

so, $$V_2 = \frac{R_L}{R_S + R_L} * V_{in}$$

or. $V_Z (R_S + R_L) = R_L . V_{in}$

or, $$V_{in} = \frac{V_2 (R_S + R_L)}{R_L}$$

or, $$\boxed{V_{in(min)} = \frac{V_Z (R_S + R_L)}{R_L}}$$

Also,

$$\boxed{I_{min} = \frac{V_{in(min)} - V_Z}{R_S}}$$

for maximum value of Vin [$V_{in(max)}$]

we know that,

$$I = \frac{V_{in} - V_2}{R_S}$$

or, $I R_S = V_{in} - V_2$

$\Rightarrow V_{in} = V_Z + I . R_S$ —— (1)

Here, $V_{in} \longrightarrow V_{in(max)}$, when $I \longrightarrow I_{max}$

$V_{in(max)} = I_{max} \cdot R_s + V_z$ —— (II)

again,

$I = I_L + I_z$ —— (III)

Here,

$I \to I_{max}$ when, $I_z \to I_{zm}$

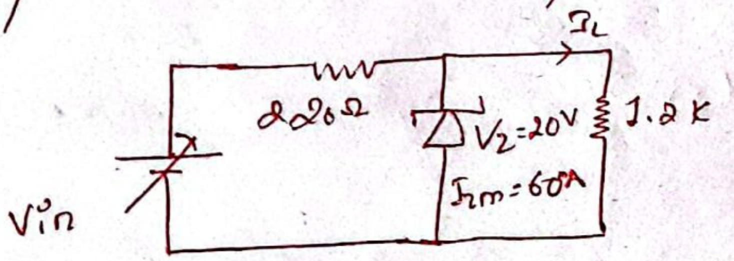
$\therefore$ Eqn (III) becomes,

$I_{max} = I_L + I_{zm}$ —— (IV)

Now, from eqn (II) and (IV)

$$\boxed{V_{in(max)} = (I_L + I_{zm}) \cdot R_s + V_z}$$

Q. Determine the range of values of vin that maintain zener diode in ON-state. Also find the maxm power that can be dissipated in diode.



Soln Here,

$V_{in(max)} = (I_L + I_{zm}) R_s + V_z$

where, $V_z = V_L = I_L R_L$

$\Rightarrow I_L = \frac{V_z}{R_L} = \frac{20}{1.2 \times 10^3} = 16.67 \text{ mA}$

$\therefore V_{in(max)} = (16.67mA + 60mA) \cdot 220 + 20V$

$= 36.867 V$

Also,

$$V_{in(min)} = \frac{R_s + R_L}{R_L} * V_2$$

$$= \frac{(1.2\times10^3 + 220)}{1.2\times10^3} * 20$$

$\therefore V_{in(min)} = 23.67\ V$

Thus, the range of values of V_{in} that maintain zener diode in ON state = 23.67 V to 36.86 V #.

Also,

Maximum power dissipation in zener diode is

$$P_{max} = I_{zm} * V_z$$

$$= 60 \times 20$$

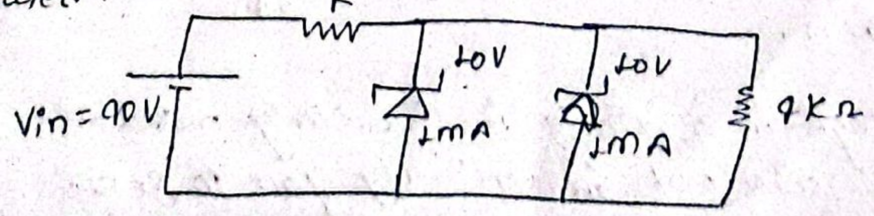
$$= 1200\ mW$$

$$= 1.2\ watt$$

<u>Homework</u>

① for the circuit shown below find V_o, R_s, I_{zm}, V_{in} varies from 20V to 40V. Given, $V_z = 10V$, $P_{zm} = 100\ mW$, $R_L = 10K\Omega$

② A zener diode rating connected in the circuit shown below is 10V, 1mA in each branch. find the value of series Resistance R_s, so that the output across the load is regulated.



Diode switching Time (अचानक polarity change गर्दा के हुन्छ?)

A P-N junction diode may be used as an electrical switch. The electrical circuit can be made 'ON' and 'OFF' by forward biasing or reverse biasing the diode. In both cases diode response is accomplained by transient and an interval of time ellapses before the diode recovers it's steady state.

The time interval for the recovery of steady state of the diode is called recovery time.

It is of two types:

i) Forward Recovery Time
ii) Reverse Recovery Time.

i) Forward Recovery Time

The time required to the diode recover from ~~forward~~ backward biased to forward biased condⁿ. The diode takes certain interval of time called forward recovery time (t_{fr}).

This is defined as time interval betⁿ instant of 10% diode voltage to 90% of its final value.

ii) Reverse Recovery Time

When PN junction is forward biased a large no of electrons cross over from N-region to P-region and a large no of holes cross over from P-region to N-region. They establish a large no of minority carriers in each region.

If the external voltage in a diode is suddenly reversed the diode current will not immediately fall to zero.

A large current flows due to large no of minority carriers for certain interval of time t_1 to t_2 as shown in fig below.

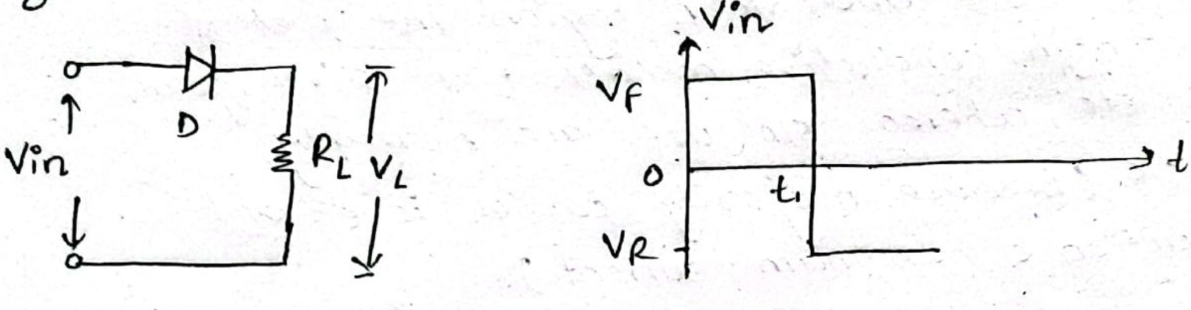
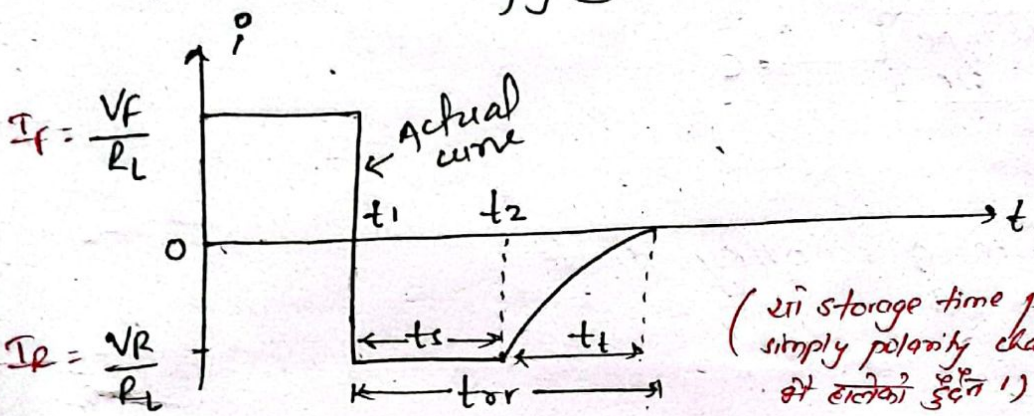


fig (a)



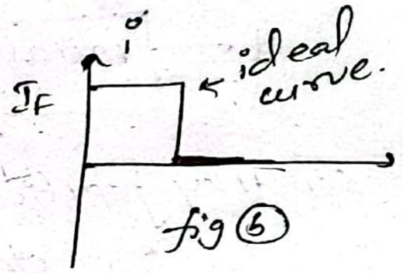


fig (b)

(यो storage time period मा current को simply polarity change भएको हुन्छ, zero मा भने झरेको हुँदैन।)

fig (c)

During time interval t_1 to t_2 the stored minority charge carriers causes large reverse current. This time interval is called storage time (t_s). After t_2 diode begins to reversed and diode current begins to fall exponentially to normal steady state reverse saturation current.

The time ellapse betn t_2 and time instant when diode is ~~normally~~ nominally recovered is called transition time (t_t).

The sum of storage time (t_s) and transition time (t_t) is called reverse recovery time (t_{rr}) of diode.

$$\boxed{\text{i.e. } t_{rr} = t_s + t_t}$$

#. 3. Schottky Diode.

→ It is a metal semiconductor diode designed to be used for fast switching applications.

→ It consists of metal and s/c n-region. The metals used are high conductive metals like silver, gold, platinium etc, whereas s/c used are normally n-type s/c (because majority carrier is e- and for conduction of maximum current).

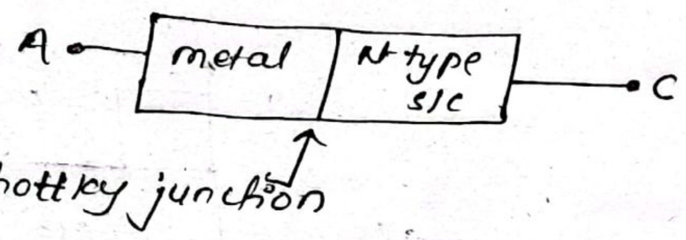


fig: structure of schottky diode

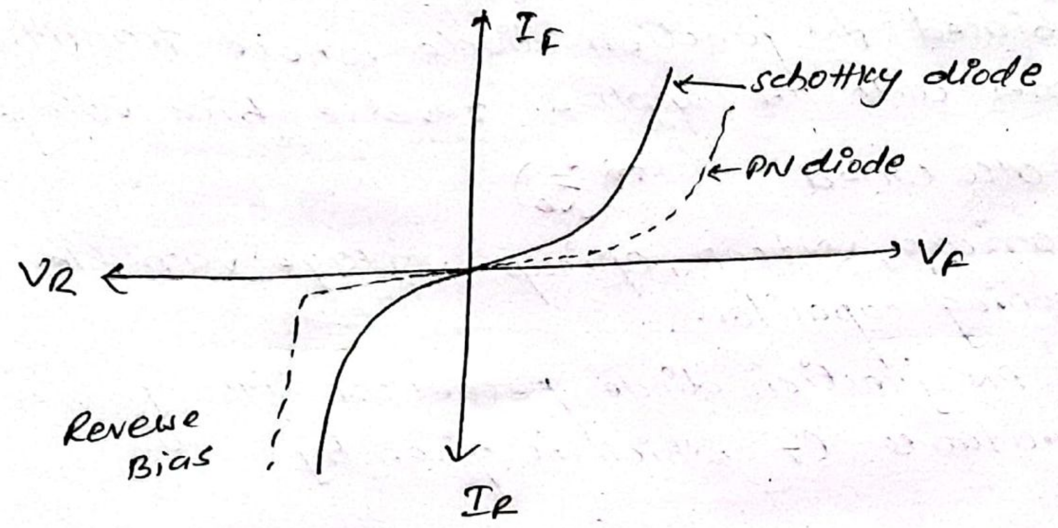
fig: circuit symbol of schottky diode.

→ It is unipolar diode (ie. only e's conduct current). It is also called hot carrier diode, because the e- must gain high energy to cross metal s/c junction to conduct current.

The metal-s/c junction is called schottky junction.

→ The metal region of schottky diode is called +ve terminal or anode, whereas the s/c region is called -ve terminal or cathode.

The VI characteristics of PN and schottky diode is,



Applications:

1. To rectify the very high frequency signal.
2. As a switching device in digital computer.
   (depletion region पातलो हुने भएकाले reverse recovery time थोरै लाग्छ त्यही भएर fast switching device को रूपमा काम गर्छ।)
3. In clipping and clamping circuits
4. In mixing and detecting circuits used in communication.

Non - Linear model

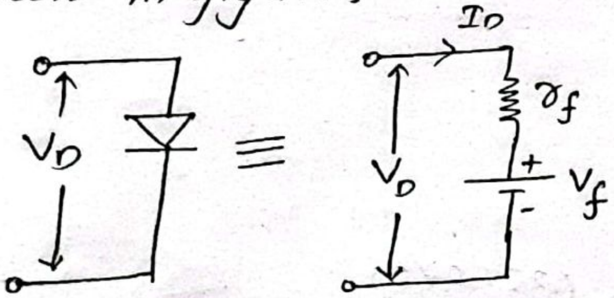
The electronic devices which do not follow ohm's law or whose V-I characteristics curve is not straight line are non-linear device.

Properties of Non-linear device:

1. They donot follow ohm's law.
2. Their V-I characteristics curve is not straight line
3. They do not follow network theories, like Thevinin's, Norton's, superposition theorem etc.
4. The circuit containing Non-linear device can be analyzed by using KCL or KVL.
5. The internal resistance of non-linear device depends on operating conditions like temperature, current, voltage etc.
6. Example, diodes, transistors, FET etc.
[field effect transistor]

Piecewise linear model of Diode

Although diode is non linear device, it can be considered as linear device when it's operated in small linear region. The piecewise linear model of diode is shown in figure.



a) diode b) piecewise linear model of diode

As derived in previous chapter,

$$r_f = \frac{\Delta V}{\Delta I_D}$$

$$r_f = \frac{\partial V}{\partial I_D} \quad \text{——} \quad (1)$$

we have, $I_D = I_s\left(e^{V_D/\eta V_T} - 1\right)$

$$\frac{dI_D}{dV_D} = I_s \frac{e^{V_D/\eta V_T}}{\eta V_T} = \frac{I_D}{\eta V_T}$$

$\therefore \boxed{r_f = \frac{\eta V_T}{I_D}}$ where r_f is diode forward resistance.

$$\boxed{V_T = \frac{KT}{q}}$$

from figure, we have

$$V_D = I_D r_f + V_f$$

$$\boxed{V_f = V_D - I_D r_f}$$

Numerical:

find piecewise linear model of S-I diode with $\eta = 1.6$ and $I_s = 10^{-11} A$ in the vicinity operating point. Assume $I_D = 1mA$.

soln Here,

$\eta = 1.6$

$I_s = 10^{-11} A$

$I_D = 1mA = 1 \times 10^{-3} A$

we know,

$$V_T = \frac{KT}{q} = \frac{1.38 \times 10^{-23} \times 298}{1.6 \times 10^{-19}} \quad (25+273)$$

$$= 0.025V$$

Now,

$$r_f = \frac{\eta V_T}{I_D}$$

$$= \frac{1.6 \times 0.025}{1 \times 10^{-3}} = 41.4\Omega$$

Again,

$$V_f = V_D - I_D r_f \quad \text{---} ①$$

where,

$$I_D = I_s \left(e^{V_D/\eta V_T}\right)$$

$$\Rightarrow e^{V_D/\eta V_T} = \frac{I_D}{I_s}$$

$$\Rightarrow \frac{V_D}{\eta V_T} = \ln\left(\frac{I_D}{I_s}\right)$$

$$\Rightarrow V_D = \eta V_T \ln\left(\frac{I_D}{I_s}\right)$$

$$\Rightarrow V_D = 1.6 \times 0.025 \ln\left(\frac{10^{-3}}{10^{-11}}\right)$$

$$\Rightarrow V_D = 0.76V$$

from eqⁿ ①

$$V_f = 0.76 - 10^{-3} \times 41.4$$

$$\boxed{V_f = 0.7186V} \text{ ans}$$

[**Note:** If I_s is not given take $V = 0.7V$ for Si and 0.3V for Ge.]

CamScanner

#. Taking an appropriate example of non-linear device show that non-linear device doesnot follow principle of superposition theorem.

Proof:

Consider a non-linear device (square law device). whose characteristics eqn is given by,

$$I_s = A(V_s - V_{TR})^2 \quad \text{—(I)}$$

where,

I_s = current through non-linear device

V_s = voltage across non-linear device

A = constant = 1 mA/V²

V_{TR} = Threshold voltage = 0

∴ Eqn (I) becomes,

$$I_s = V_s^2 \quad \text{—(II)}$$

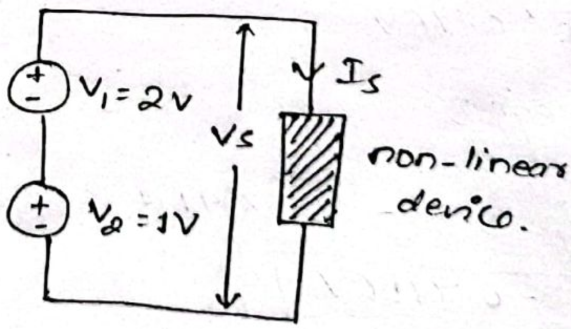
Now, let the non-linear device be connected to a source.

Here,

$V_s = V_1 + V_2$

$= (2+1)V$

$= 3V$



from eqn (II),

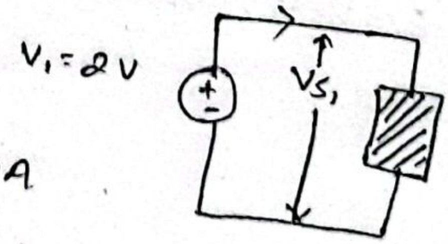
$I_s = V_s^2 = (3)^2 = 9\ mA.$

Now, To apply superposition theorem. firstly

$V_{s_1} = V_1 = 2V$

∴ from (II) $I_s = V_s^2$

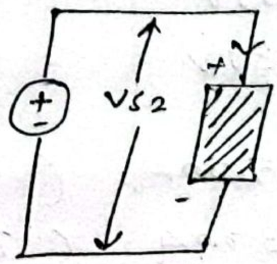
$I_{s_1} = V_{s_1}^2 = (2)^2 = 4 mA$



Now, consider source V_2 only

$V_{S2} = V_2 = 1V$

so, from eqn (II)



$I_{S2} = V_S^2 = 1^2 = 1mA$

$V_2 = 1V$

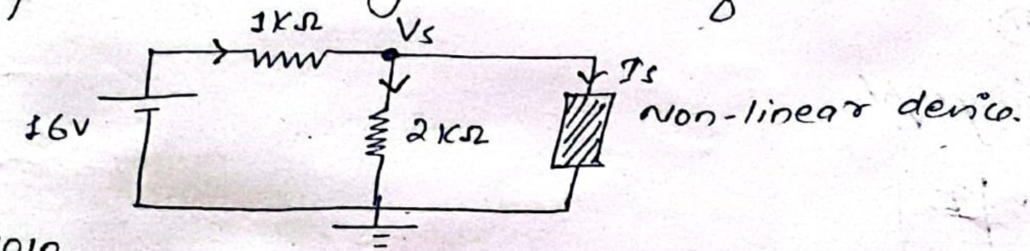
from superposition theorem,

$I_{S1} + I_{S2} = 4 + 1 = 5mA$

$I_S = 9mA$

Since, $I_S \neq I_{S1} + I_{S2}$, this proves that non-linear device doesnot follow principle of superposition.

from the circuit given below, find I_s and V_s.



soln. Given, $I_S = A(V_S - V_{TR})^2$ —(I)

where,

$A = 1mA/V^2$

$V_{TR} = 0$

from eqn (I),

$I_S = V_S^2$ —(II)

Now, using KCL,

$-\left(\frac{V_S - 16}{1}\right) - \left(\frac{V_S}{2}\right) - I_S = 0$ / $\frac{16 - V_S}{1} = \frac{V_S}{2} + I_S$

or, $16 - V_S = \frac{V_S}{2} + V_S^2$ $[\because I_S = V_S^2]$

or, $32 - 2V_S = V_S + 2V_S^2$

or, $2V_S^2 + 3V_S - 32 = 0$

$\therefore V_{s_1} = 3.31V$

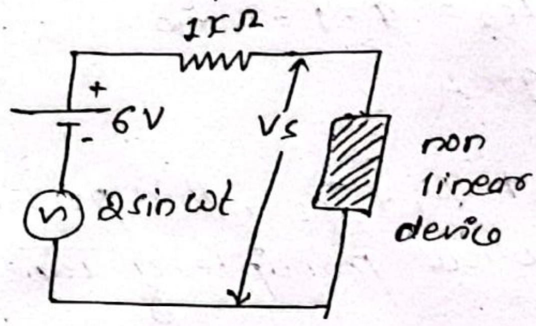
$V_{s_2} = -4.81V$

$\therefore I_s = 10.95\ mA \quad (I_{s_1} = V_{s_1}^2)$

$I_s = 23.13\ mA \quad (I_{s_2} = V_{s_2}^2)$

Graphical Analysis of ckts with non-linear devices.

eg: find the operating point (I_s and V_s) for the ckt given below.



Given, $I_s = A(V_s - V_{TR})^2$ — (I)

where,

$A = 1\ mA/V^2$ and

$V_{TR} = 0$

Eqn (I) becomes,

$I_s = V_s^2$ — (II)

To plot eqn (I) in graph,

V_s	0	1	2	3	4
I_s	0	1	4	9	16

Now, applying KVL in given ckt:

$2\sin\omega t + 6 - I_s \times 1 - V_s = 0$

or, $2\sin\omega t + 6 = I_s + V_s$ —— (II)

Take, $\omega t = 0$, then eqn (II) becomes,

$2\sin 0 + 6 = I_s + V_s$

$\therefore I_s = 6 - V_s$

To plot in graph,

V_s	0	6V
I_s	6mA	0

Now, take $\omega t = \pi/2$ then ⑪ becomes,

$2\sin \pi/2 + 6 = I_s + V_s$

$\therefore I_s = 8 - V_s \qquad (\because \sin \pi/2 = 1)$

To plot in graph,

V_s	0	8V
I_s	8mA	0

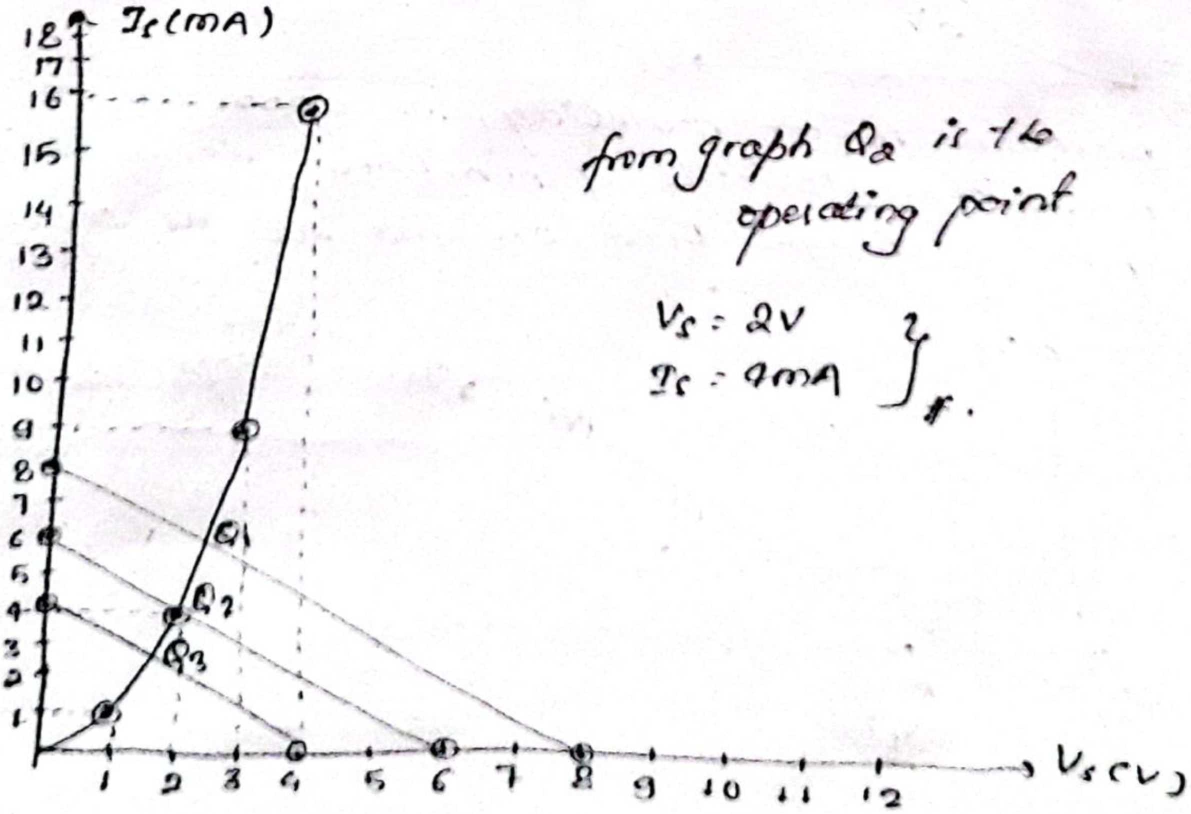
finally, take $\omega t = \frac{3\pi}{2}$ then eqn ⑪ becomes,

$2\sin \frac{3\pi}{2} + 6 = I_s + V_s$

$\therefore I_s = 4 - V_s \qquad (\because \sin \frac{3\pi}{2} = -1)$

To plot graph,

V_s	0	4V
I_s	4mA	0



from graph Q_2 is the operating point

$\left.\begin{array}{l} V_s = 2V \\ I_s = 4mA \end{array}\right\}_{\#}$

Piecewise linear modeling of non-linear device.

Consider a non-linear device with V-I characteristics as,

$$I_s = A(V_s - V_{TR})^2 \quad \text{—(I)}$$

where,

A = constant = 1 mA/V²

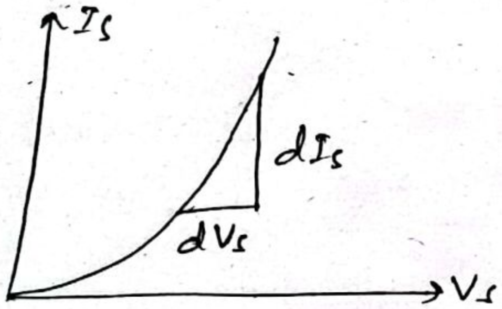
I_s = current in non-linear device

V_s = voltage across non-linear device

V_{TR} = Threshold voltage = 0

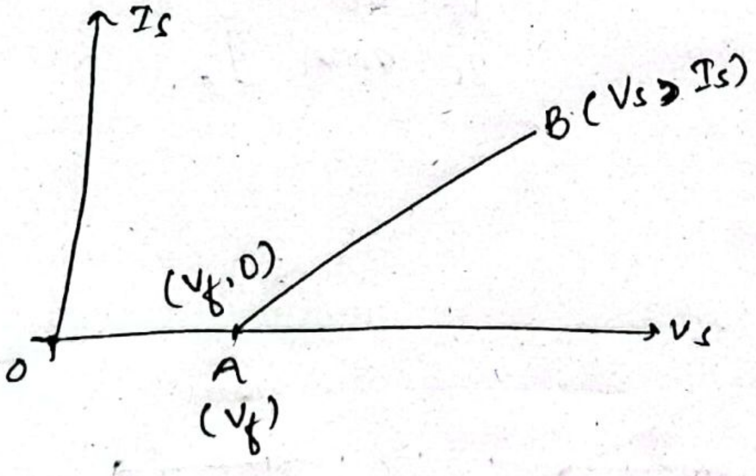
$$\therefore \; I_s = V_s^2 \quad \text{—(II)}$$

If we plot the graph of above eqn (I), we get a non-linear characteristics as shown in fig below:



$$\text{slope} = \frac{dI_s}{dV_s}$$

In piecewise linear modeling, we approximate the non-linear characteristics of non-linear device by using two piece of straight lines OA and AB as shown in fig.



$$\text{slope} = \frac{I_s}{V_s} = \frac{1}{r_f}$$

Here, eqⁿ of OA : $I_s = 0$ for $V_s < V_f$

eqⁿ of AB : $I_s - 0 = \frac{1}{r_f}(V_s - V_f)$ $[\because y - y_1 = m(x - x_1)]$
two point formula

where,

$I_s = \frac{1}{r_f}(V_s - V_f)$ — (II)

$r_f = \frac{1}{slope} = \frac{1}{\frac{dI_s}{dV_s}}$

$\therefore r_f = \frac{dV_s}{dI_s}$ — (III)

from eqⁿ (II), $I_s = \frac{V_s - V_f}{r_f}$

[r_f = barrier resistance
V_f = barrier voltage]

or, $I_s \cdot r_f = V_s - V_f$

$$\boxed{\therefore V_f = V_s - I_s \cdot r_f}$$

from eqⁿ (I), $I_s = V_s^2$

$\therefore \frac{dI_s}{dV_s} = 2V_s$

$\therefore \frac{dV_s}{dI_s} = \frac{1}{2V_s}$

$$\boxed{\therefore r_f = \frac{1}{2V_s}}$$ from eqⁿ (III).

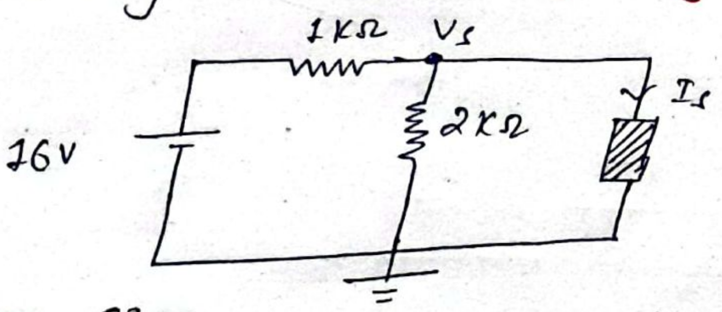
$I_s = V_s^2$

$\frac{dI_s}{dV_s} = \frac{d}{dV_s}(V_s^2)$

$\frac{dI_s}{dV_s} = 2V_s \Rightarrow \frac{dV_s}{dI_s} = \frac{1}{2V_s}$

$\Rightarrow \boxed{r_f = \frac{1}{2V_s}}$

Q.24. find the piecewise linear model of the diode in the following circuit. (r_f = ? V_f = ?)



soln Given,

$I_s = A(V_s - V_{TR})^2$

$\therefore I_s = V_s^2$ — (I)

using KCL,

$$\frac{16 - V_s}{1} = \frac{V_s}{2} + I_s$$

or, $16 - V_s = \frac{V_s}{2} + V_s^2$

or, $16 - V_s = \frac{V_s + 2V_s^2}{2}$

or, $32 - 2V_s = V_s + 2V_s^2$

or, $2V_s^2 + 3V_s - 32 = 0$

$$\left.\begin{aligned} V_{s1} &= 3.31V \\ V_{s2} &= -4.81V \end{aligned}\right\}$$

from eqn ①,

$I_{s1} = 10.95 mA$

$I_{s2} = 23.13 mA$

$r_{f_1} = \frac{1}{2V_{s1}} = \frac{1}{2\times(3.31)} = 0.15 k\Omega$

$\therefore V_f = V_{s1} - I_{s1} \cdot r_{f_1}$

$V_f = 3.31 - 10.95 * 0.15$ $(\because I_s = 10.95 mA)$

$\boxed{V_f = 1.66V}$

where, $V_s = -4.81$

$V_f = -4.81 - 23.13 * 0.15$

$\boxed{V_f = -8.28V}$