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Electronic Devices and Circuits. {EDC}

Unit-1 PN Junction Diode.

Syllabus: PN Junction diode equation - Volt-Ampere Characteristics - Energy band diagram of PN diode - Temperature dependance of VI Characteristics - Ideal Versus Practical - resistance levels (Static and dynamic) - Diode equivalent ckts, load line analysis - Breakdown mechanisms in Semiconductor diodes. Zener diode characteristics.

Introduction:

The electrical and electronic components are broadly classified into two types.
1. Active elements or Components.
2. Passive Components.

* Active components do not have loss & it requires less power to operate. Ex: Generators, Battery, Transistors, Diodes etc.
* Passive components have whole loss.
  Ex: Resistors, Capacitors & Inductors. It plays an vital role in determining the characteristics of ckts.

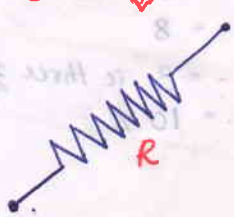
Resistors:

The physical material which oppose the flow of charge carriers & current are called as Resistors.

The unit of measurement of resistance is Ohm (Ω).

Types of Resistors:

Symbol?

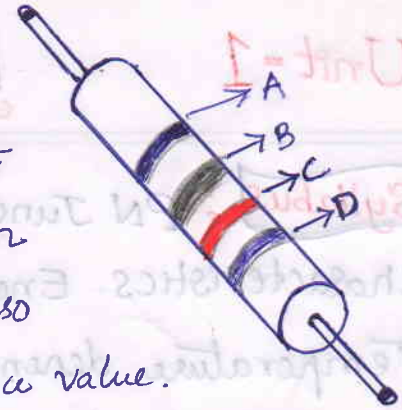


Resistors

Fixed resistors	Variable resistors
a) Carbon Composition	a) Potentiometer.
b) Carbon film	b) Rheostat
c) Metal film.	c) Trimmer.
d) Wire wound	

Applications: Resistors are used in
1. Electrical heaters.
2. Current limiting devices. &

Color Coding of Resistors :



To be able to visually identify the resistance and tolerance of carbon resistor without actually having to measure them a color code is utilized. and also Ohmmeter is used to verify the resistance value.

BBROYGBVGW → BB ROY Great Britan Very Good Wife.

	A&B	C
Black	0	×0
Brown	1	×10
Red	2	×100
Orange	3	×1000
Yellow	4	×10000
Green	5	$\times 10^5$
Blue	6	$\times 10^6$
Violet	7	$\times 10^7$
Gray	8	$\times 10^8$
White	9	$\times 10^9$

Tolerance:

Tolerance digit - D.

Gold → ± 5 %.

Silver → ± 10 %

No band → ± 20 %.

The term tolerance denotes the acceptable deviation in the resistance value of a resistor.

The usual tolerances are 5 %, 10 % & 20 %.

Ex : $R = 5K\Omega \pm 10\%$ → tolerance ie R have any value b/w $4.5K\Omega$ to $5.5K\Omega$.

In four color band resistor (A, B, C & D) one by the side of the other starting from the left end. The first two bands (A & B) denotes the first & second digits of the resistance value and the third band (c) indicates how many zeros follows the first two digits & Tolerance is given by the fourth band (D).

Example : Given a resistor with bands.

A → Blue = 6
B → Gray - = 8
C → Orange - = 3 ie three zeros needs to attach.
D → Silver . = 10 %

Resistance $R = 68000 \pm 10\%$

$= 68 \times 10^3 \pm 10\%$

Capacitors:

A capacitor is a ckt element capable of storing Energy in an electric field.

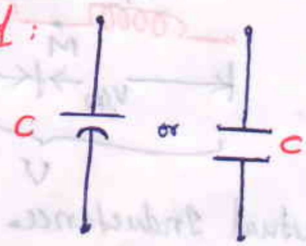
& Two parallel plates seperated by a small distance forms a Capacitor

(or) Mathematically as $Q/V = C$ ie The capacitance (C) refers to the amount of charge that the configuration can store for each volt of potential difference that exists b/w two bodies.

* The unit of capacitance is Farad (F).

ie 1 farad (C) = 1 Coulomb of charge stored (Q) / 1 volt (V).

Symbol:



Voltage across the capacitor

$$V_c = \frac{1}{C}\int i \, dt$$

where 'i' Current flowing through Capacitor.

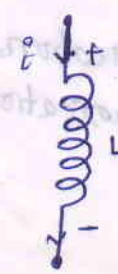
Types of Capacitors:

	C range
1. Mica	→ 1 PF − 0.1 μF.
2. Ceramic	→ 1 PF − 0.001 μF.
3. Tubular	→ 5 PF − 100 PF.
4. Paper	→ 500 PF − 50 μF.
5. Monolithic	→ 500 PF − 10 μF.
6. Electrolytic	→ 0.47 μF − 0.7 F
7. Air-Variable (Trimmer)	→ 10 PF − 500 PF.

Inductors:

An Inductor is a ckt element capable of storing energy in magnetic field.

Symbol:



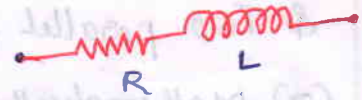
The counter emf is directly proportional to the rate of change of current through coil.

ie $V_L = L\frac{di}{dt}$.

* The unit of Inductance is Henrys (H)

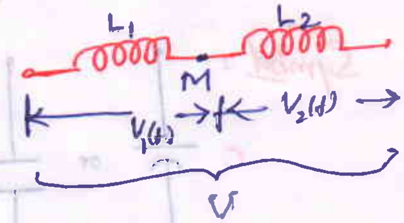
The Inductive reactance is given by

Q-factor: The quality factor or magnification factor of figure of merit of an inductor can be defined as ratio of reactance to resistance.



$$Q = \omega L / R$$

Mutual Inductance: When two or more inductance in series, the same current flows through each one of them, but voltage will differ depends the inductance. As current passing through one coil, will induce on flux in neighbouring coil ie mutual Inductance.



$$V = V_1(t) + V_2(t)$$
$$= L_1 \pm M + L_2 \pm M$$
$$V = L_1 + L_2 \pm 2M$$

where 'M' - mutual Inductance.

*** Electronic:** The term electronic means that electron mechanics. ie The electronics deals with the study of movement of electrons under the influence of an external field.

*** Electronic Devices:** A device in which conduction takes place by movement of electronse through a semiconductor devices such as diode, BJT, FET and IC's.

Applications of Electronics:

1. In communication field → Wire communication, Wireless communication.
2. For Entertainment → Radio and Video, Audio.
3. In defence → Radar, Guided missiles, Wire & Radio communication.
4. In medical → X-rays, ECG, EEG, SCAN ....
5. In instrumentation → CRO, DMM, Voltmeter, powermeter.

Introduction to Semiconductors :

The most fundamental unit of all matter is an atom. An atom is the smallest particle of an element. An element or the matter consists of 3 particles, which is named as Electron, Proton and Neutron.

SL NO	Name of the Particle.	Nature of Charge	Magnitude of Charge in columbs	Mass of charge in kg.
1.	Neutron	No Charge	-	1.675×10^{-27}.
2.	Proton	Positive	1.6×10^{-19}	1.672×10^{-27}.
3.	Electron.	Negative	-1.6×10^{-19}	9.107×10^{-31}.

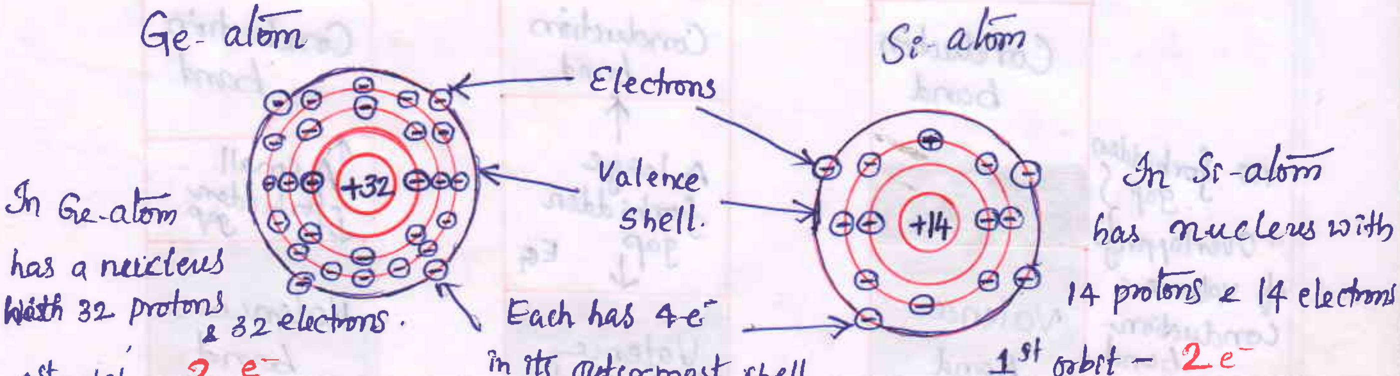
* The materials such as copper, aluminium etc. are good Conductors of electricity.

* The materials such as wood, glass, mica etc. are very bad conductors of electricity are called Insulators.

→ Ability to carry electricity, lies b/w that of conductors and insulators. Such materials are called Semiconductors.

Ex : Germanium (Ge) and Silicon (Si).

Atomic Structure of Ge & Si :



* When there are 4 electrons in the outer most orbit, then the semiconductor material is referred as pure or Intrinsic semiconductor.

The Energy-Band-Diagram:

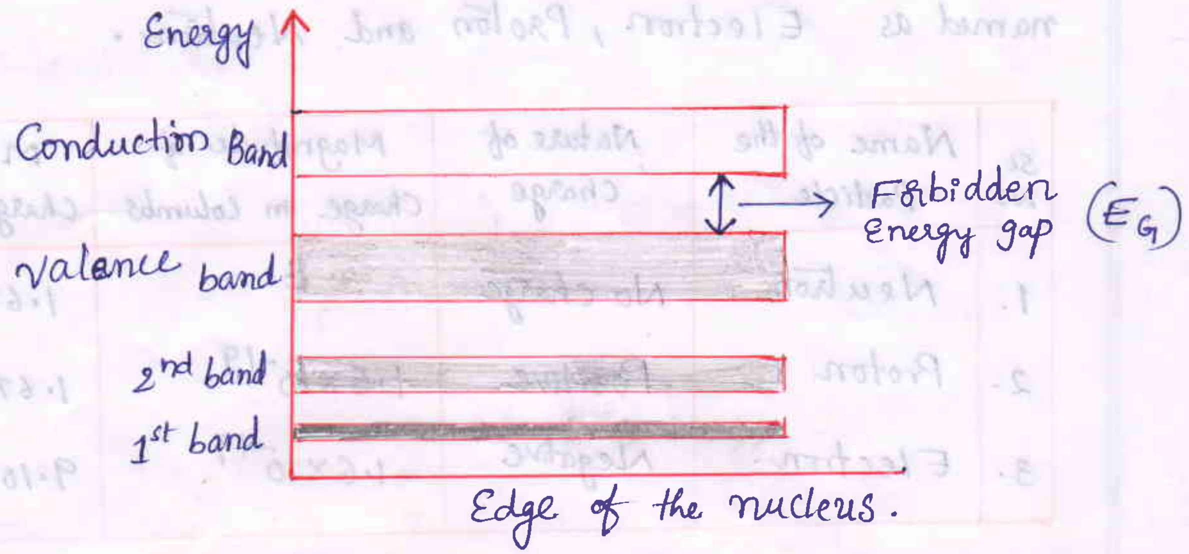


Fig: Energy band diagram for Silicon.

The graphical representation of the energy bands in a solid is called Energy band diagram.

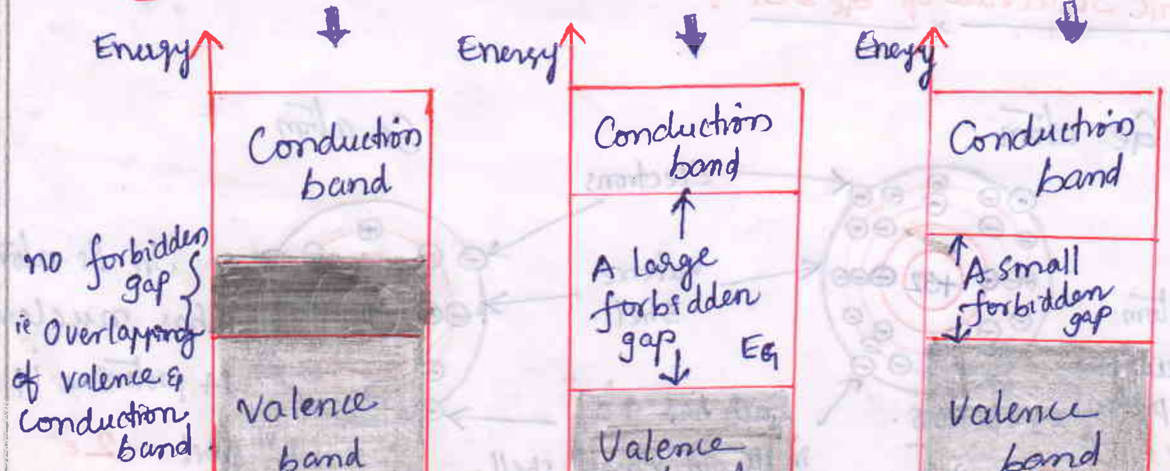
ie The Energy associated with forbidden band is called Energy gap (E_G) and measured in the unit electron-volt (eV)

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

Classification:

* Based on the energy gap E_G, the materials are classified as

① Conductors. ② Insulators. ③ Semiconductors.



Conductors : A material which conducts electric current when a potential difference is applied across them are called conductors.

In conductors valence band & Conduction band overlap with each other.

Ex : Metals, copper, lithium, Alluminium, silver etc.

Insulators : Solid materials which do not conduct electric current under normal conditions are known as Insulator.

In insulator, the energy gap E_G is large of the order of 6 eV or 7 eV.

In insulator the valence band is completely filled and it has no electrons in the conduction band, the forbidden energy gap will be very high.

Ex : Wood, mica paper, glass etc.

Semiconductors : Materials which conducts electricity partially is known as semi conductor.

In semiconductor the valence band & conduction band are seperated forbidden gap as 1 eV.

Ex : Silicon (Si), Germanium (Ge).

Forbidden gap energy depends on the temperature ⟶ Temperature in °K.

For Silicon $E_G = 1.21 - 3.6 \times 10^{-4} \times T$ eV

For Geremanium $E_G = 0.785 - 2.23 \times 10^{-4} \times T$ eV.

At room temperature ie 27°c or 300°K.

$$\boxed{E_G = 1.12\ eV \text{ for } Si}, \quad \boxed{E_G = 0.72\ eV \text{ for } Ge}.$$

Si is most widely used Since, the valence shell of Si is 3rd shell while valence shell of Ge is 4th shell. Hence valence e^- of Ge are at larger distance from nucleus than Si & valance e^- of Ge can easily

Intrinsic Semiconductors :

Pure semiconductors are known as intrinsic semiconductors. Frequently available semiconductors are generally Ge & Si belongs to IV group in the periodic table. Each semiconductor has 4 valence electrons in their outermost orbit. Each of these 4 electrons form a bond with another valence e^- of the neighbouring atoms.

* The atoms align themselves to form a three dimentional uniform pattern called a Crystal.

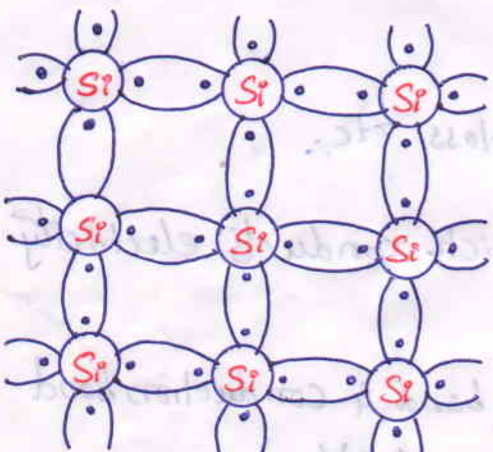


Fig. Intrinsic Si Crystal at OK.

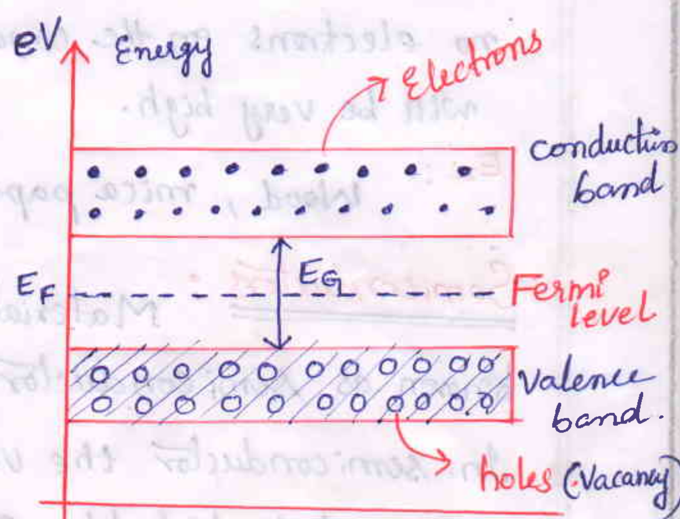


Fig: Energy band diagram.

At OK. valence electrons move from valence bond to conduction band. a vacancy is created known as holes.

At room temperature the max. energy level occupied by an electron is at the middle of the forbidden gap called as Fermi level.

At $t > 0K$, results, breakage of covalent bonds takes place. releasing free electrons. These free electrons create a vacancy in its initial position in the crystal.

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Extrinsic Semiconductors :

When impurities are added to an intrinsic semiconductor then it becomes an extrinsic semiconductor.

* An extrinsic semiconductor shows remarkable variations in conductivity due to the presence of impurities.

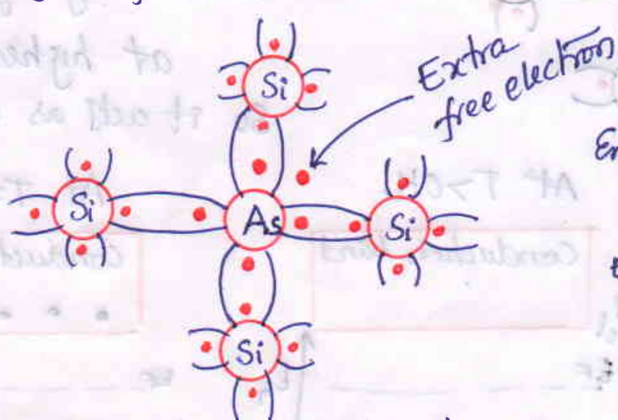
Depending upon the type of impurities added to the intrinsic semiconds, an extrinsic semiconductors are of two types.

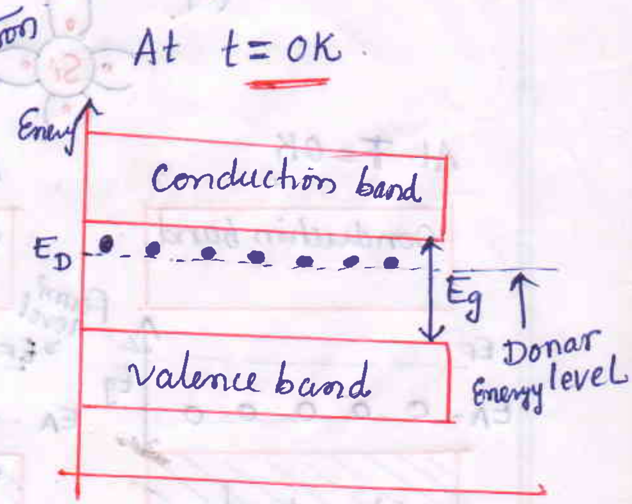
1. n-type extrinsic semiconductor.
2. p-type extrinsic semiconductor.

n-type extrinsic Semiconductor :

When a small amount of pentavalent impurity is added to a pure semiconductor, it is called n-type semiconductor.

* The pentavalent impurity has five valence electrons. These elements are Arsenic, Bismuth, Phosphorous & Antimony. Such an impurity is called Donor impurity. (an impurity donates a free electron hence called donor impurity).



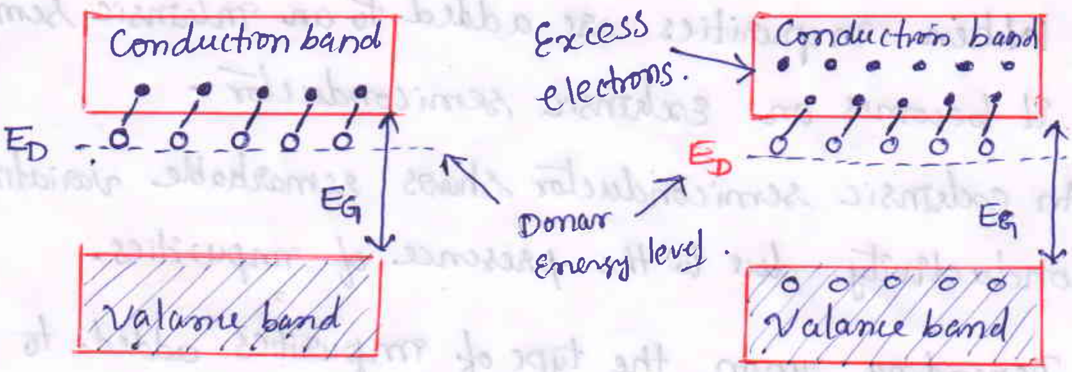


Each arsenic atom added into Si atom gives one free electron.

Near to the conduction band we have donar energy level (E_D)

Which is going to be donate an electron at ...

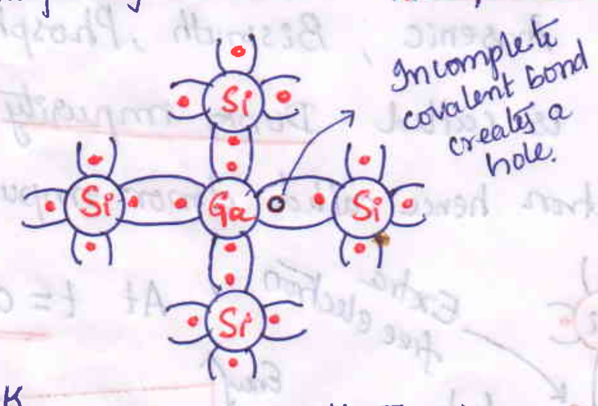
At $T > 0K$ At $T = 300^\circ K$



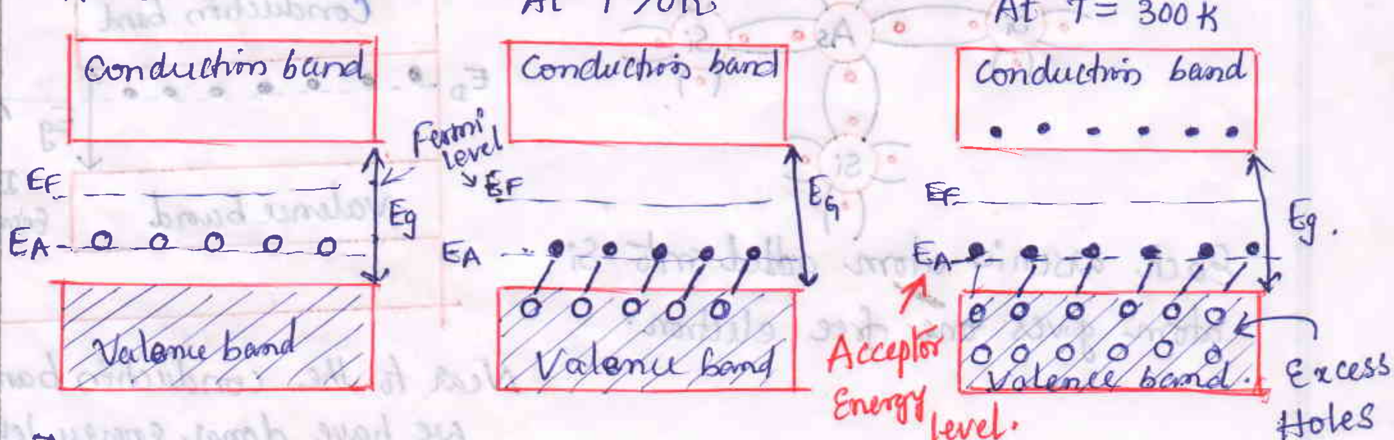
Hence in n-type semiconductors free electrons are called majority carriers while the holes which are small in number are called minority carriers.

P-type Extrinsic Semiconductor:

When a small amount of trivalent impurity is added to a pure semiconductor it is called P-type semiconductor. The trivalent impurity has 3 valence electrons, these elements such as Gallium, Boron, Indium. Such an impurity is called Acceptor impurity.



→ Near to the valance band we have Acceptor Energy level. which is going to be accept at higher temperature So it acts as an acceptor.



Hence. Holes are majority carriers and Electrons are

Conductivity of Intrinsic semiconductor :

The property called conductivity indicates with which a material can carry the current.

In intrinsic semiconductor, very few electron-hole pair get generated. So, conductivity is low, Hence not used in practice.

Intrinsic Semiconductor Concentration $n_i = n = p$.

It is measured in Units - number / m^3 or number / cm^3.

In semiconductor. Negatively charge particle free electrons.
Positively charge particle holes.

n = Concentration of free e^-/m^3. μ_n = Mobility of electrons in $m^2/V\text{-}s$

p = Concentration of holes / m^3. μ_p = Mobility of holes in $m^2/V\text{-}s$.

then the current density is given by

$$J = (n\mu_n + p\mu_p) q E \quad A/m^2$$

where q = charge on one e^- $= 1.6 \times 10^{-19}$ C.

E - Electric field in V/m.

Accordings to ohm's law. $J = \sigma E$

where σ = Conductivity in $(\Omega\text{-}m)^{-1}$.

$$\therefore \quad \sigma = (n\mu_n + p\mu_p) q \quad (\Omega\text{-}m)^{-1}$$

For intrinsic semiconductor $\sigma_i = n_i(\mu_n + \mu_p) q \quad (\Omega\text{-}m)^{-1}$.

Conductivity of Extrinsic Semiconductors :

n-type

Majority carriers - Free electrons
Minority carriers - holes

let n_n = concentration of free electrons in n-type

P_n = Concentration of holes in n-type

N_D = concentration of donor atoms.

$\therefore$ Conductivity $\sigma_n = (n_n \mu_n + P_n \mu_p) q$

If $P_n << n_n$ then $\sigma_n = n_n \mu_n q$.

P-type

Majority carriers - holes
Minority carriers - free electrons.

let n_p = Concentration of e^- in p-type

P_p = concentration of holes in p-type.

N_A = concentration of acceptor atoms.

$\sigma_p = (n_p \mu_n + P_p \mu_p) q$.

If $n_p << P_p$, $\sigma_p = P_p \mu_p q$.

SL NO	Conductors	Semiconductor	Insulator.
1	A conductor easily conducts the electrical current.	A Semiconductor conducts the electric current less than conductor and greater than insulator.	An insulator doesnot conduct any current.
2	A conductor has only one valence electron in its outer most orbit.	A semiconductor has 4 valance electrons in its outer most orbit.	An insulator has 8 Valance electrons in its outermost orbit.
3	Conductors formed using metallic bond.	Semiconductors are formed due to covalent bonding	Insulators are formed due to ionic bonding.
4	Valance & Conduction bands are overlapped	Valance & Conduction bands are seperated by forbidden energy gap of 1.1 eV.	Valance & Conductions bands are seperated by an forbidden gap of 6 to 10 eV.
5	Resistance is very small.	Resistance is high	Resistance is very high.
6	It has positive temp. coefficient.	It has negative temp. coeffieient.	It has negative temp. coefficient.
7	Ex: Copper, Alluminum Silver etc.	Ex. Silicon, Germanium etc.	Ex. Mica, paper, glass etc.

	Intrinsic Semiconductors	Extrinsic Semiconductors
1.	It is a pure ofrom of Semiconductor	An impurity or doping agent is added in the pure form becoms extrinsic semiconductor.
2.	No. of electrons & holes are equal	No. of e^- & holes are not equal because of doping.
3.	Conductivity is poor.	Conductivity is improved.

	N-type - Semiconductors	P-type semiconductors.
1.	Pentavalent impurity is added in a pure Si & Ge to form n-type.	Trivalent impurity is added in a Si & Ge to form p-type Semiconductor
2.	Doping agent : Arsenic, Antimony etc.	Doping agent : Gallium, Indium etc.
3.	[illegible] are majority carriers &	[illegible] are majority carriers &

Introduction to PN Junction diode:

Drift Current:

When an electric potential (voltage) is applied across a semiconductor, the free electrons to drift in one direction and holes to drift in the opposite directions, the current is produced. This current is called drift current.

* Drift current depends on the ability of the charge carriers to move through semiconductor it depends on the type of material.
* The measure of this ability is called 'Mobility' denoted as μ

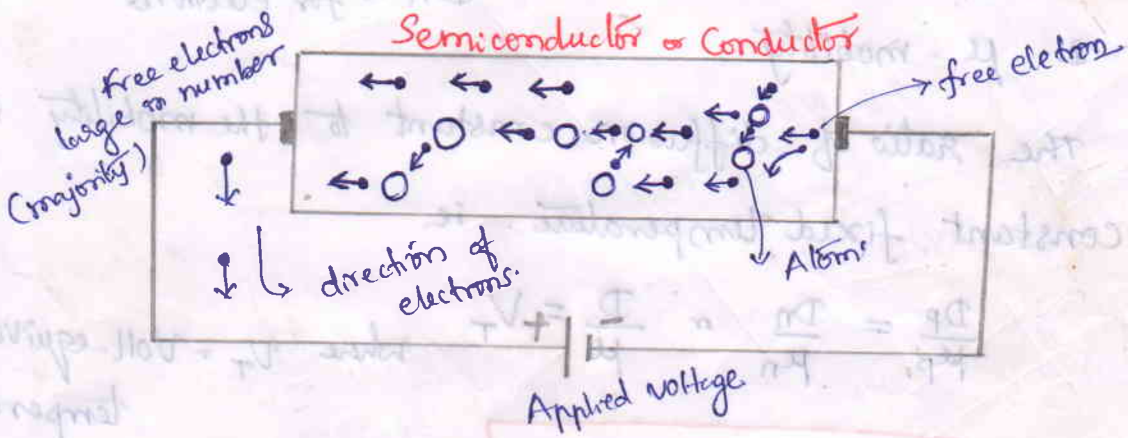


Fig: Drift mechanism ie drift current.

Diffusion Current:

The motion of charge carriers from region of higher concentration to lower concentration leads to a current is called "diffusion current".

Non uniform doping ie the holes are large in number on one side while less in number on other side. Due to this there is high concentration area on one side while low carrier concentration area on other side. This creates concentration gradient in P type.

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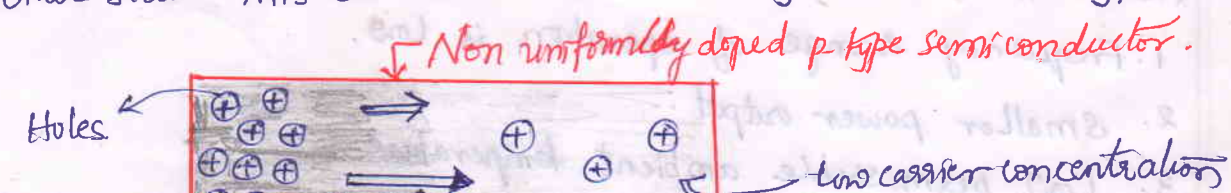
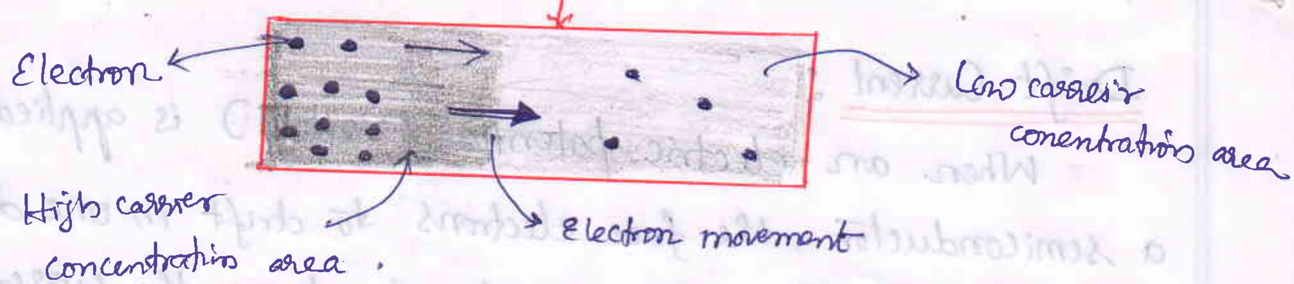


Nonuniformity doped in N-type semiconductor:



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Both drift current as well as diffusion current occur in the semiconductor devices like p-n junction diode.

Relation b/w D & μ:

where D - Diffusion constant D_p → for holes
D_n → for electrons

& μ - mobility.

* The ratio of diffusion constant to the mobility is constant fixed temperature. ie.

$$\frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} \text{ or } \frac{D}{\mu} = V_T$$

where V_T - Volt-equivalent temperature.

& $$V_T = \frac{KT}{q} = \frac{T}{11600}$$

where T - temperature in K.
K - Boltzmann constant
$K = 1.38 \times 10^{-23}$.
q - Charge in coulombs.
$q = 1.6 \times 10^{-19}$ C.

Advantages of Semiconductors:

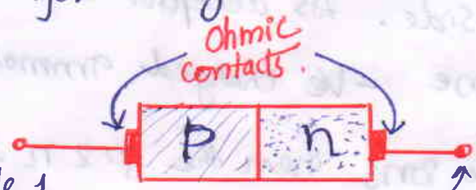
1. Smaller in size.
2. Requires no cathode heating power.
3. They operate on low DC power.
4. They have long life.

Disadvantages of Semiconductors:

1. Frequency range of operation is low.
2. Smaller power output.
3. Low permissible ambient temperature.

PN Junction Diode :

* A junction is formed between a sample of P-type semiconductor and sample of n-type semiconductor joined together then this device is called the P-N junction.
* The formation of PN junction is also called as 'Diode', because it has two electrodes one for p-region named as Anode and the other for N-region named as Cathode.



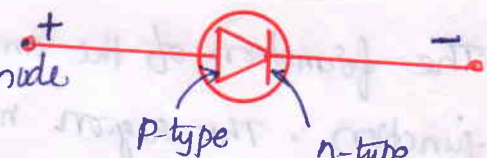


Fig: Symbol of a diode.

Here a contact between a metal and a heavilily doped semiconductor (P or n-type) is called 'Ohmic Contact'.

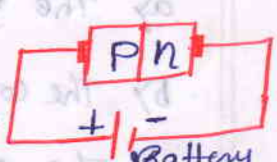
→ It conducts current equally in both the directions.
→ The drop across the contact is very small.
→ It donot affect the performance of the device.
→ It is used to connect n & p-type regions to the electrodes.

Biasing of p-n junction diode :

Applying external D.C voltage to any electronic device is called 'biasing'. Depending upon the polarity of the dc voltage externally applied to the device, the biasing is classified into two types.

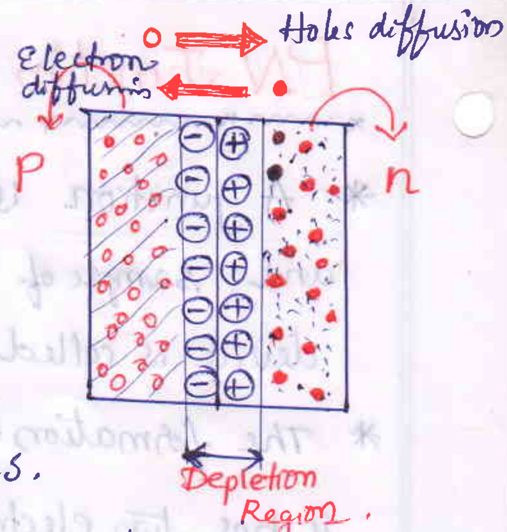
1. Forward biasing &
2. Reverse biasing.

Forward Biasing: '+' & '−' terminal of the battery is connected to p-type & n-type respectively.



Reverse Biasing: '−' & '+' terminal of the battery is

Formation of Depletion Region:



→ As holes enter the n-region, Atoms on n-side are donar atoms.

* The holes recombine with donar atoms. As donar atoms accept additional holes they become +ve charged immobile ions.

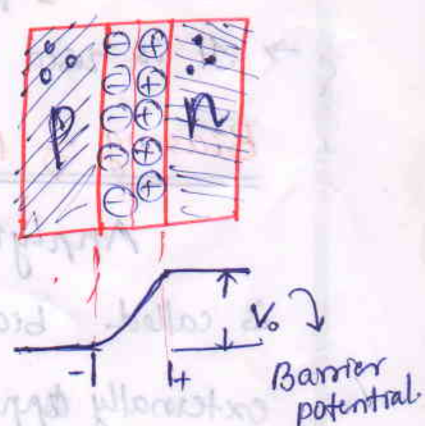
→ Atoms on p-side are acceptor atoms. The e^- diffusing from n-side to p-side recombine with the acceptor atoms on p-side. As acceptor atoms accept additional electrons they become -ve charged immobile ions.

* The formation of the immobile ions near the p & n region called junction. The region near the junction is called depletion region or depletion layer or space charge region.

Barrier Potential:

Barrier potential is the amount of potential & voltage required to cross the charge carriers from p type to n-type and n-type to p-type.

It is also known as Junction potential, built in potential of a p-n junction.



The barrier potential is 0.7 V for Si
at 25°C. 0.3 V for Ge.

The barrier potential of p-n junction depends on

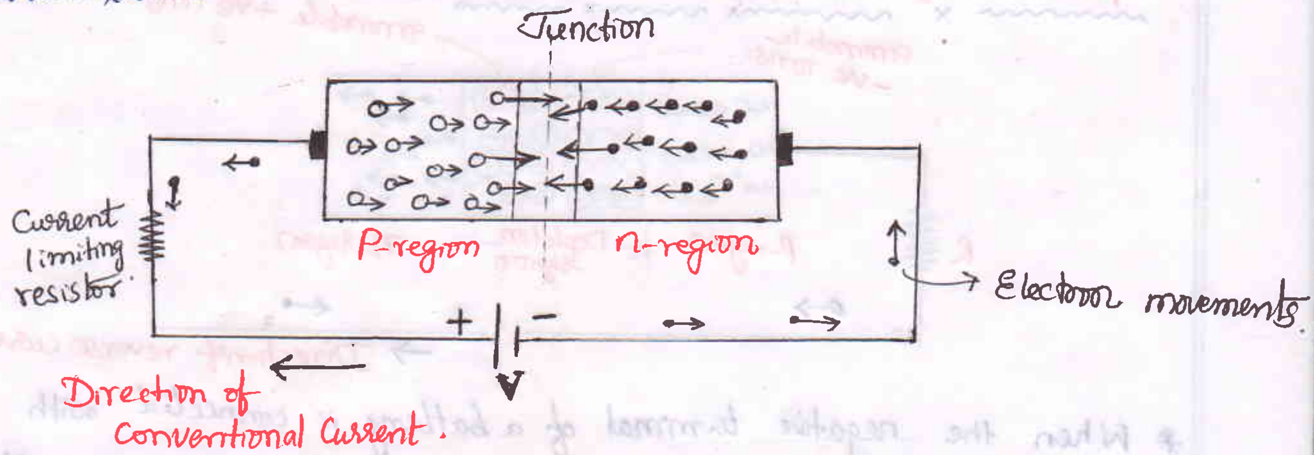
a) The type of semiconductor used.

b) The concentration of donar impurity on n-side.

c) The concentration of acceptor impurity on p-side.

d) The intrinsic concentration of basic semiconductor.

Operation of Forward biased Diode :



* When the positive terminal of a battery is connected with p-type and negative terminal of the battery is connected with n-type semiconductor then it provides the forward bias to PN junction.
* The applied forward potential establishes an electric field opposite to the potential barrier. (0.3V for Ge, 0.7V for Si).
* The applied positive potential repels the holes in the p-region so that the holes move towards the junction and applied negative voltage repels the electrons in the n-region towards the junction. ie
* Due to the forward bias voltage more electrons flow into depletion region which reduces the no. of positive ions, lly flow of holes reduces the no. of negative ions. This reduces the width of the depletion region in forward biased PN junction. Thus the junction resistance becomes zero.

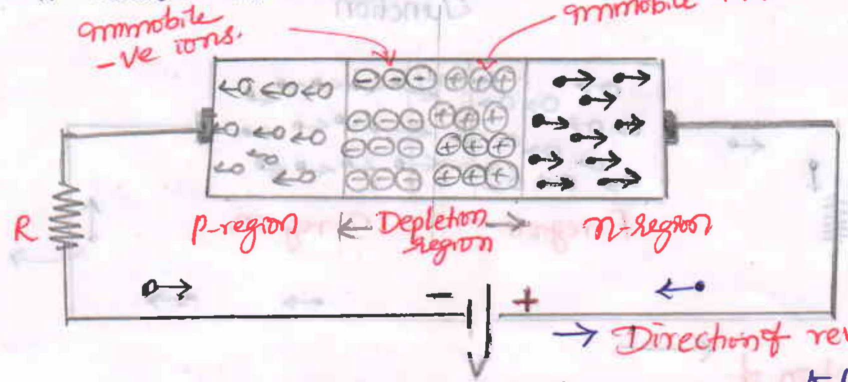
ie Due to forward voltage, junction establishes the low resistance path for the entire ckt, thus a current flow in ckt called as 'forward current'.

ie In forward biasing – Barrier potential $V_0 = 0$.

Current I_f is increases (mA).

Resistance R_f is reduces. then

Operation of Reverse biased Diode :



* When the negative terminal of a battery is connected with p-type and positive terminal of the battery is connected with n-type then it provides the reverse biased to PN junction.

* When the p-n junction is reverse biased the -ve terminal attracts the holes in the p-region, away from the junction. The +ve terminal attracts the free electrons in the n-region away from the junction. No charge carrier is able to cross the junction. Both the electrons & holes move away from the junction the depletion region widens.

* The electrons on p-side and holes on n-side are minority charge carriers which constitute the current in reverse biased. Hence reverse current is always very small.

* For a constant temperature, the reverse current is almost constant though reverse voltage is increased upto a certain ~~time~~ limit. Hence it is called "Reverse saturation current" & denoted as I_0.

* I_0 is very small in order of few μA for Ge & nA for Si.

ie: In reverse biased → depletion region widens.

→ Barrier potential V_0 increases.

→ Reverse current I_R is very small (μA)

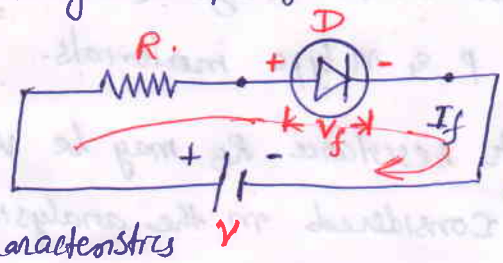
→ Reverse resistance is very high. then

V-I Characteristics of p-n junction Diode:

The response of p-n junction can be easily indicated with the help of characteristics called V-I characteristics of p-n junction.

It is the graph of voltage applied across the p-n junction and the current flowing through the p-n junction.

Forward Bias :



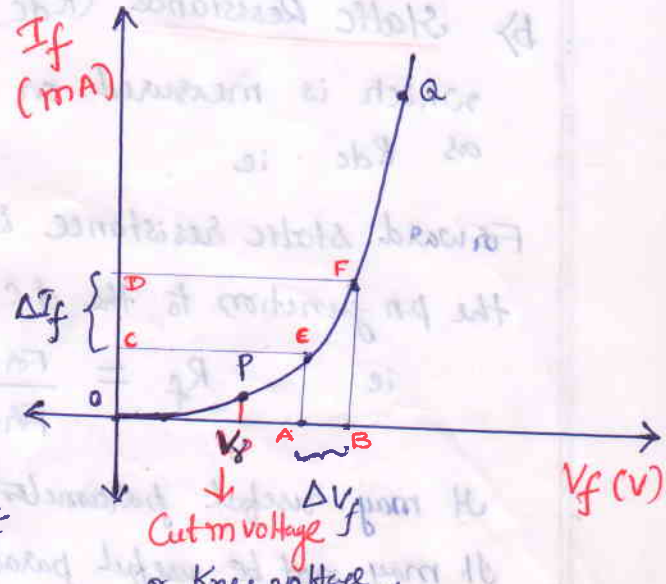
Forward Current I_f

voltage across the diode in forward biased. V_f.

Basically forward characteristics can be divided into two regions.

1. Region from O to P : As long as V_f is less than cut in voltage (V_γ). the current is very small ($\simeq$ zero)

2. Region from P to Q & onwards: As V_f increases the width of depletion region goes on reducing. ie When V_f exceeds V_γ, the depletion region becomes very thin & current I_f increases exponentially.



Knee voltage (or) Cut-in Voltage (or) threshold voltage (or) Firing Voltage (or) Offset voltage (or) Break point voltage :

It is the voltage at which the current through the junction starts to increase rapidly. (or)

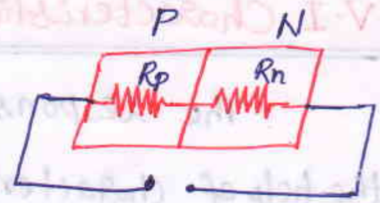
It is a forward bias voltage at which the current through PN junction diode starts increases exponentially. (or)

It is the forward bias voltage below which the current through diode is below of its maximum value.

Ex. Cut-in voltage of the diode for Si = 0.7 V or 0.6 V

Diode resistances :

a) **Bulk resistance (R_B) :**



$R_B = (R_p + R_N)\ \Omega$.

ie Sum of the resistance due to p-type and resistance due to n-type.

R_B value depends on the size (since $R = \rho \frac{l}{A}$) and doping concentration of P & n type materials.

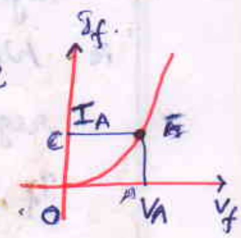
→ Generally the bulk resistance R_B may be very small & it is neglected or may not be considered in the analysis.

b) **Static Resistance (R_{dc}) :** It is the resistance of the device which is measured on V I characteristics as $R = \frac{V}{I}$ & It is denoted as R_{dc} . ie

Forward static resistance is the ratio of the d.c voltage applied across the p-n junction to the d.c current flowing through the p-n junction.

ie $$R_f = \frac{\text{Forward d.c voltage}}{\text{Forward d.c Current}} = \frac{OA}{OC} \text{ at point E.}$$

[PTO]



It may useful parameter in the linear devices Ex R, L, C

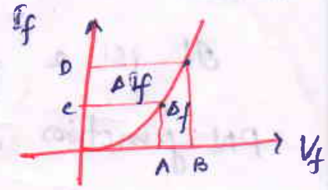
It may not be useful parameter for non linear devices

Ex : Diode , transistors all semiconductor materials.

c) **Dynamic Resistance (R_{ac}) :** The resistance measured under the V-I characteristics as ratio of change in voltage to change in current.

(or) It is reciprocal of the slope of the forward characteristics.

ie $$r_f = \frac{\Delta V_f}{\Delta I_f} = \frac{AB}{CD} \text{ at E\&F.}$$



(or) **Junction Resistance.**

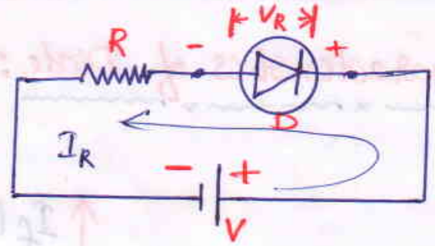
The slope of the characteristics $= \frac{1}{R} = \frac{\Delta I_f}{\Delta V_f}$. (∵ $R = V/I$).

$$r_f = \frac{1}{\text{Slope of forward characteristics.}}$$

It is a constant value.

... resistance is used to analyse.

Reverse Bias :

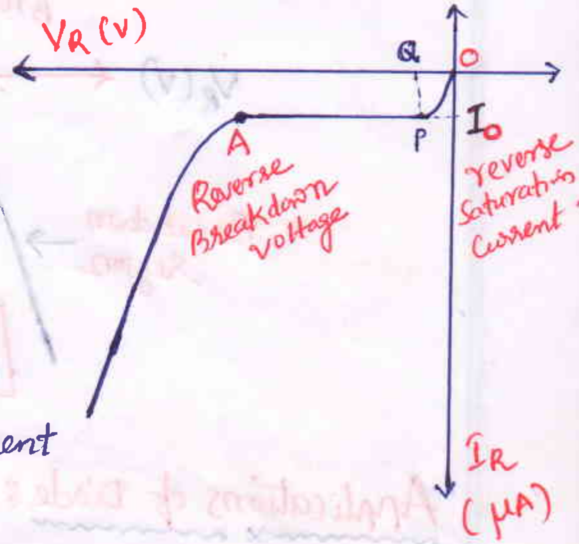


V_R - Voltage across the diode in reverse bias.

I_R - Current due to minority charge carriers.

* As reverse voltage is increased, reverse current increases initially but after a certain voltage, the current remains constant equal to reverse saturation current 'I_0' though reverse voltage is increased.

The point 'A' where breakdown occurs and reverse current increases rapidly is called knee of the reverse characteristics.



Break down voltage (V_{B0}) :

It is the reverse voltage at which p-n junction breaks down and reverse current increases suddenly.

Diode Resistances :

a) **Static Resistance** (R_r) : It is the resistance under the d.c. conditions. denoted as 'R_r'. It is the ratio of applied voltage to the reverse saturation current I_0.

$$\text{ie } R_r = \frac{OQ}{I_0} = \frac{\text{Applied reverse voltage}}{\text{Reverse saturation current}}$$

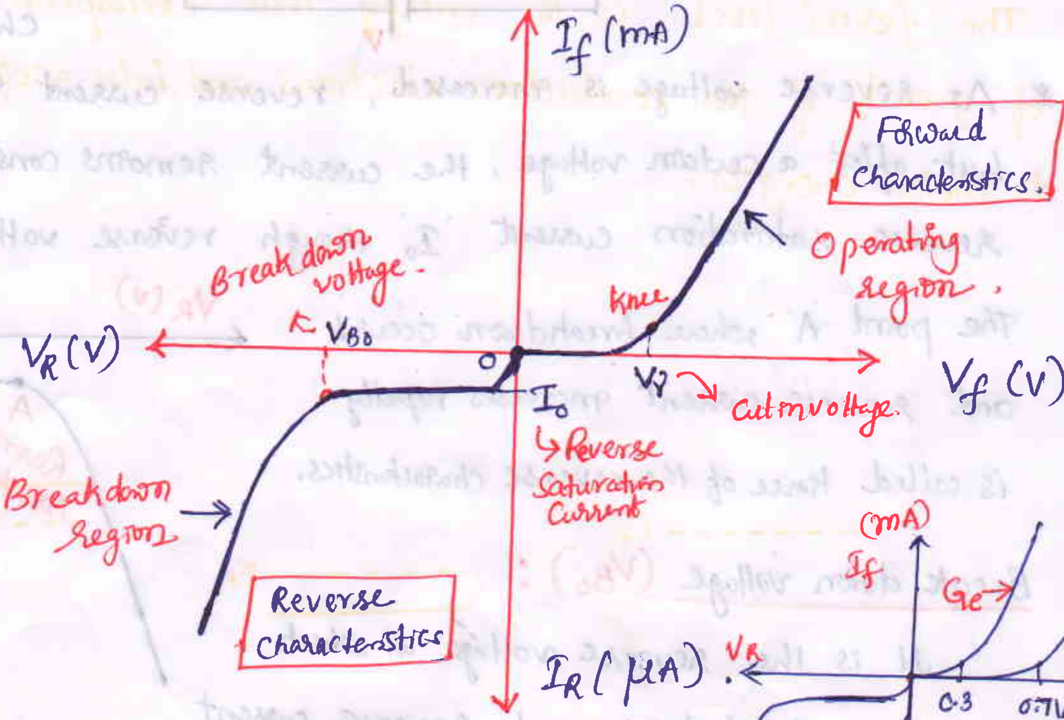
b) **Dynamic Resistance** (r_R) : It is the resistance under the a.c conditions, denoted as r_R. It is the ratio of incremental change in the reverse voltage applied to the corresponding change in the reverse current.

$$r_R = \frac{\Delta V_R}{\Delta I_R} = \frac{\text{Change in reverse voltage}}{\text{Change in reverse current}}$$

Peak inverse voltage : (PIV) = V_{B0} (max).

It is the max reverse bias voltage that can be applied to the

Complete V-I Characteristics of Diode :



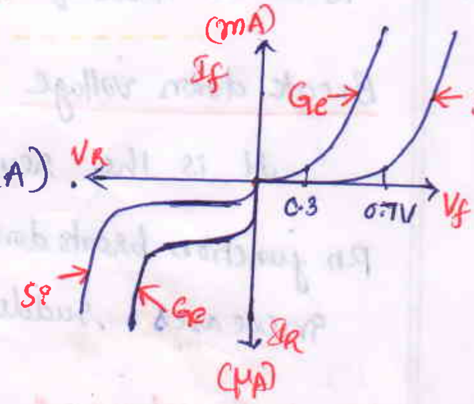


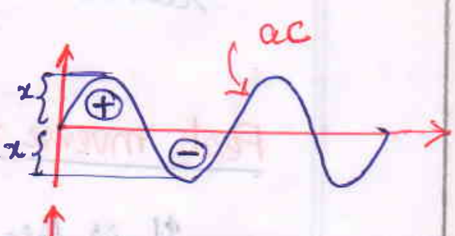
Fig: For Ge & Si V-I Characteristics

Applications of Diode :

* Diode is unidirectional conducting device.
  The direction is from P to N ie Anode to cathode.

1. Electronic switches (Diode) are used in digital circuits like calculator, computer, Integrated Circuits (IC) etc.
2. In wave shaping ckts ie Clippers & Clampers.
3. In communication systems - modulation & demodulation.
4. In Optical communication.
5. In voltage regulators.
6. As a tuning device in radio and T.V receivers.
7. The diode can convert a.c to d.c. The process is called Rectification & the device is called rectifier.

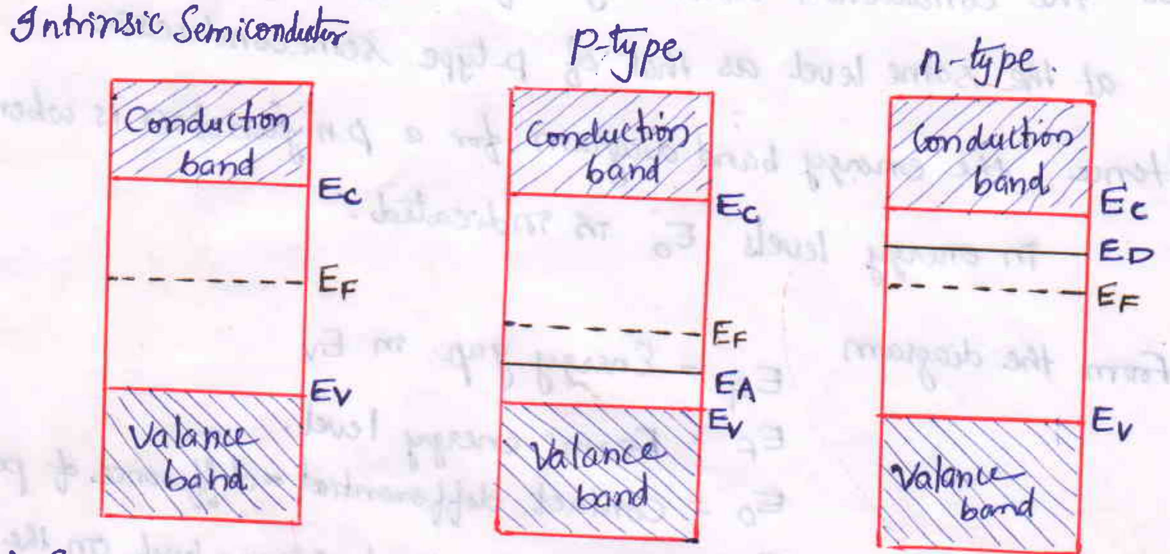
Alternating Current (ac) : Amplitudes do not change x
but polarity can change. x



Direct current (dc) : It never changes in

Energy Band Diagram of PN diode :

The fermi level is the energy that corresponds to the centre of gravity of the conduction electrons and holes weighted according to their energies.



Fermi Energy Gap

$F_{EG} = E_C - E_V$

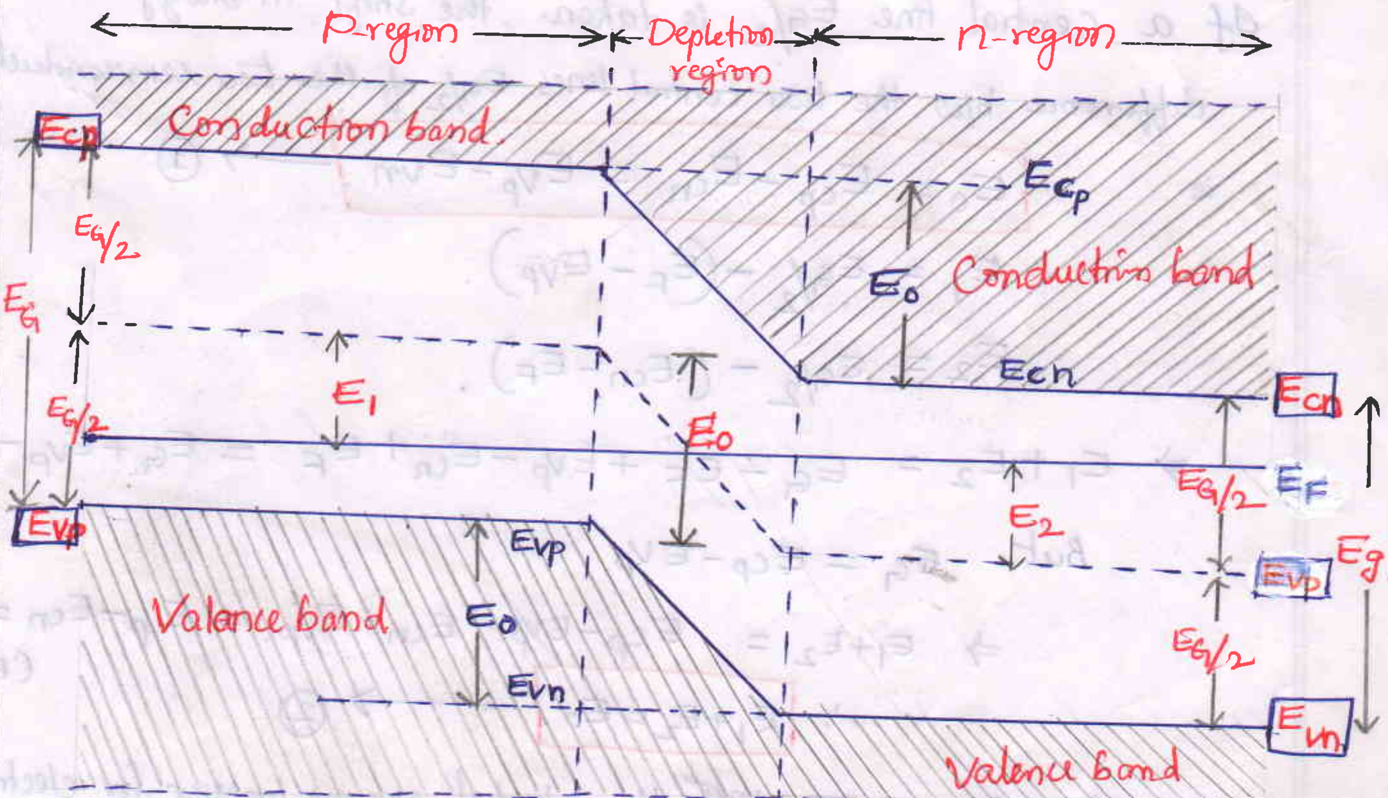
(Acceptor Type)

$F_{EG} = E_C - E_A$

(Donar Dype)

$F_{EG} = E_D - E_V$

Energy Band Structure of Open ckted Diode :



ie When p-type & n-type semiconductors are brought into intimate contact p-n junction is formed.

In n-type semiconductor E_F is close to conduction band E_{cn}

p-type semiconductor E_F is close to valance band edge E_{Vp}.

So the conduction band edge of n-type semiconductor cannot be at the same level as that of p-type semiconductor.

Hence the energy band diagram for a p-n junction is where a shift in energy levels E_0 is indicated.

From the diagram E_G = Energy gap in E_V

E_F = Fermi energy level.

E_0 = Contact ~~differentiat~~ or difference of potential.

E_{cn} = Conduction band Energy level on the n-side.

E_{cp} = Conduction band Energy level on the p-side.

E_{Vn} = Valence band energy level on the n-side.

E_{Vp} = Valence band energy level on the p-side.

If a central line '$E_G/2$' is taken, the shift in Energy level is the difference b/w the two central lines $E_G/2$ of the two semiconductors.

ie $$E_0 = E_{cp} - E_{cn} = E_{Vp} - E_{Vn} \longrightarrow (1)$$

$$E_1 = E_G/2 - (E_F - E_{Vp}).$$

$$E_2 = E_G/2 - (E_{cn} - E_F).$$

$$\Rightarrow E_1 + E_2 = E_G - \cancel{E_F} + E_{Vp} - E_{cn} + \cancel{E_F} = E_G + E_{Vp} - E_{cn}$$

But $E_G = E_{cp} - E_{Vp}$.

$$\Rightarrow E_1 + E_2 = E_{cp} - \cancel{E_{Vp}} - E_{cn} + \cancel{E_{Vp}} = E_{cp} - E_{cn} = E_0$$

(From (1))

$$\therefore E_1 + E_2 = E_0 \longrightarrow (2)$$

... represents the total energy barrier for electrons

The contact difference of potential

$$E_F - E_{Vp} = E_G/2 - E_1 \longrightarrow (3)$$

$$E_{Cn} - E_F = E_G/2 - E_2 \longrightarrow (4)$$

By adding (1) & (2)

$$E_F - E_{Vp} + E_{Cn} - E_F = E_G - (E_1 + E_2)$$

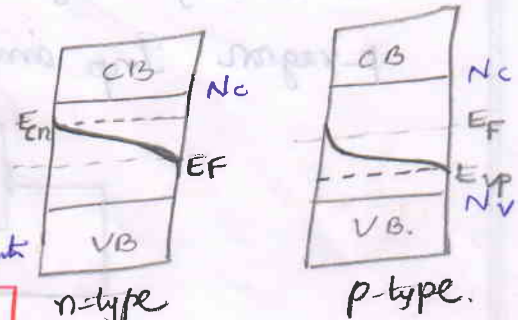
$$\Rightarrow \quad E_1 + E_2 = E_G - (E_{Cn} - E_F) - (E_F - E_{Vp}) \longrightarrow (5)$$

But

Fermi level in doped semiconductor

$$n = N_C \, e^{-(E_{Cn} - E_F)/KT}$$

$$P = N_V \, e^{-(E_F - E_{Vp})/KT}$$



In n-type $n \simeq N_D$ - donar atoms concent

$$\Rightarrow \boxed{E_{Cn} - E_F = KT \ln\left(\frac{N_C}{N_D}\right)}$$

In p-type $\Rightarrow$ $P = N_A$. Acceptor atoms concentration No/m^3.

$$\Rightarrow \boxed{E_F - E_{Vp} = KT \ln\left(\frac{N_V}{N_A}\right)}$$

From mass action law $n \times p = n_i^2$ $\Rightarrow \boxed{E_G = KT \ln\left(\frac{N_C N_V}{n_i^2}\right)}$

From eqn (5)

$$E_0 = KT\left\{\ln\left(\frac{N_C \cdot N_V}{n_i^2}\right) - \ln\left(\frac{N_C}{N_D}\right) - \ln\left(\frac{N_V}{N_A}\right)\right\}.$$

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

$$\boxed{E_0 = KT \ln\left(\frac{N_A N_D}{n_i^2}\right) \; eV.}$$

∴ Junction Voltage or Barrier potential

$$\boxed{V_0 = \frac{E_0}{q}}$$

where K = Boltzman's constant in eV/°K

$K = 8.62 \times 10^{-5}$ eV/°K.

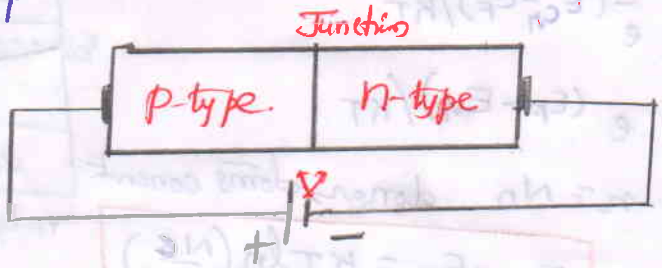
T - Temperature in °K

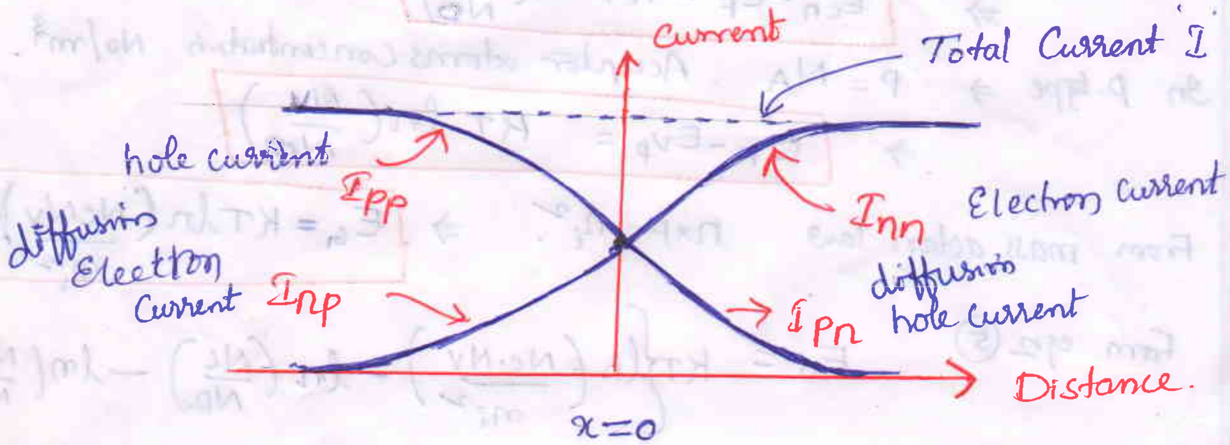
N_A = Acceptor atom concentration in No/m^3.

N_D = Donar atom concentration in No/m^3.

Current Components in PN Junction Diode :

* When a forward bias is applied to the diode, holes are injected into the n-side & electrons to the p-side.
* The no. of these injected carriers decreases exponentially with distance from the junction
* The minority charge carrier current one due to electrons in the p-region I_{np} and due to holes in the n-region I_{pn}.





* In forward biased p-n junction, the edge of the diode on p-side the current is hole current (majority carriers are holes), on the n-side hole current is zero. At the edge of the diode on n-side the current is electron current (majority carriers are electrons) on the p-side electron current is zero.

Total Current $I = I_{pn}(0) + I_{np}(0)$

(or) $I = I_{nn} + I_{pn}$ in n-side $\quad I = I_{pp} + I_{np}$ in p-side.

Law of the junction

P_{Po} = thermal equilibrium hole concentration on p-side where V_0 = Barrier potential, V_T = Volt equivalent at temp.

Thermal equilibrium, hole concentration on the p-side

$$P_{p0} = P_n(0)\, e^{(V_0 - V)/V_T} \longrightarrow (2)$$

where $P_n(0)$ - hole concentration on n-side near the junction

V - applied forward bias voltage.

From (1) & (2)

$$P_n(0)\, e^{(V_0 - V)/V_T} = P_{n0} \cdot e^{V_0/V_T}$$

$$P_n(0) = P_{n0} \cdot e^{V_0/V_T - \frac{V_0}{V_T} + \frac{V}{V_T}}$$

$$\therefore P_n(0) = P_{n0}\, e^{V/V_T} \longrightarrow (3)$$

$\therefore$ From Law of the junction $P_n(0) = P_n(0) - P_{n0}$

$$= P_{n0}\, e^{V/V_T} - P_{n0} \quad (\text{From } (3))$$

$$P_n(0) = P_{n0}\left(e^{V/V_T} - 1\right) \longrightarrow (4)$$

Forward Current :

The hole current in the n-side $I_{pn}(x)$ is given as

$$I_{pn}(x) = \frac{Ae \times D_p}{L_p} \cdot P_n(0) \cdot e^{-x/L_p}$$

At $x = 0$. $I_{pn}(0) = \frac{Ae\, D_p}{L_p} \times P_{n0}\left(e^{V/V_T} - 1\right) \cdot e^{0}$ ($\because$ From (4))

Hole current $I_{pn}(0) = \frac{Ae\, D_p}{L_p}\, P_{n0}\left(e^{V/V_T} - 1\right) \longrightarrow (5)$

Similarly the electron current in the p-side $I_{np}(0)$ is

Electron Current $I_{np}(0) = \frac{Ae \cdot D_n}{L_n} \cdot n_{p0}\left(e^{V/V_T} - 1\right) \longrightarrow (6)$

The total diode current is the sum of the $I_{pn}(0)$ & $I_{np}(0)$.

$$\therefore I = I_{pn}(0) + I_{np}(0).$$

$$I = \left[\frac{Ae\, D_p}{L_p} P_{n0} + \frac{Ae\, D_n}{L_n} n_{p0}\right]\left(e^{V/V_T} - 1\right).$$

where

∴ Current equation of the pn junction Diode:

$$I = I_0 \left(e^{V/\eta V_T} - 1\right)$$

where $I_0 = \dfrac{A e D_p P_{no}}{L_p} + \dfrac{A e D_n n_{po}}{L_n}$

where

I = The current that flows in the diode.

V = Applied external voltage

If V is +Ve ie forward bias then $I = I_f$.

If V is −Ve ie reverse bias then $I = I_R$.

I_0 = reverse saturation current.

ie It is the current due to the application of reverse bias due to the flow of minority charge carriers.

(or) $$I_0 = K_1 T^m e^{-V_{G0}/\eta V_T}$$

A = Area of cross section.

e = Charge of an electron. $e = 1.6 \times 10^{-19}$ C.

D_p = Diffusion constant (holes) cm^2/sec.

P_{no} = hole concentration in n-type.

L_p = Diffusion length in cm.

D_n = Diffusion constant (electrons) cm^2/sec.

n_{po} = electron concentration in p-type.

L_n = Diffusion length in cm.

K_1 = Constant depends on material and

V_{G0} = Volt equivallent energy at equillibrium.

T = Temperature in °K.

V_T = volt equivallent temperature $V_T = \dfrac{KT}{q}$ ($K = 1.38 \times 10^{-23}$ J/s, $q = 1.6 \times 10^{-19}$ C.)

η = 1 for Ge, 2 for Si. ∴ $V_T = \dfrac{T}{11600}$ V.

Temperature dependance of diode V-I Characteristics :

The rise in temperature increases the generation of electron-hole pairs in semiconductors and increases their conductivity.

The pn junction diode current equation is given by.

$$I = I_0 \left[e^{V/\eta V_T} - 1 \right] \longrightarrow (1)$$

where $\eta = 1$ for Ge
$= 2$ for Si , $V_T = \frac{KT}{q} = \frac{T}{11600}$ V.

&

$$I_0 = K_1 T^m e^{-V_{G0}/\eta V_T} \longrightarrow (2)$$

where $m = 2$ for Ge
$= 1.5$ for Si. & $V_{G0} = 0.785$ V for Ge
$= 1.21$ V for Si

Voltage that equals to forbidden Energy gap.

I_0 is reverse saturation current, it depends on the temperature not on the applied voltage. ie $I_0 \propto T^m \longrightarrow (3)$

As temperature increases reverse saturation current increases basically I_0 is due to minority charges present in both p-type & n-type.

Taking logarithm on both sides of eqn (2) $\cdot \frac{-V_{G0}}{\eta V_T}$, $\frac{KT}{q}$

$$\log I_0 = \log(K_1) + m \log(T) - \left[\frac{-V_{G0}}{(T)\eta V_T} \right] \frac{1}{T^2} \longrightarrow (4)$$

Differentiating eqn (4) w.r.t. T.

$$\frac{d}{dT}[\log I_0] = 0 + \frac{m}{T} + \frac{V_{G0}}{\eta V_T . T} = \frac{m}{T} + \frac{V_{G0}}{T \eta V_T}.$$

$$\frac{1}{I_0} \cdot \frac{dI_0}{dT} = \frac{m}{T} + \frac{V_{G0}}{T \eta V_T} \longrightarrow (4)A.$$

$$\frac{1}{I_0} \frac{dI_0}{dT} = \frac{V_{G0}}{T \eta V_T} \longrightarrow (5)$$

(∵ $\frac{m}{T}$ is very small & neglected)

$$\frac{dI_0}{...} = ...$$

above eqn can be written as

$$\frac{dI_0}{dT} = \frac{\Delta I_0}{\Delta T} = I_0 \cdot \left[\frac{V_{G0}}{\eta T V_T}\right]$$

$$\Rightarrow \Delta I_0 = \Delta T \cdot I_0 \left[\frac{V_{G0}}{\eta T \cdot V_T}\right]$$

$$\therefore \boxed{\Delta I_0 \propto \Delta T} \longrightarrow (6)$$

All other terms are constant & substituting the values of η, V_T, T & V_{G0} in eqn (5)

For Si → $V_{G0} = 1.21$
→ $\eta = 2$
→ $T = 300K$
$V_T = 26mV$

$$\frac{1}{I_0}\frac{dI_0}{dT} = \frac{1.21 \times 1000}{(2)(300)(26)} = 8\%$$

For Ge → $V_{G0} = 0.785$
$\eta = 1$
$T = 300K$
$V_T = 26mV$

$$\frac{1}{I_0}\frac{dI_0}{dT} = \frac{0.785 \times 1000}{(1)(300)(26)} = 11\%$$

Hence I_0 increases approximately by 7% /°c for both Si and Ge.

Thus 7% increase means the reverse saturation current for every °c

$$I_0 = I_0(1.07) \Rightarrow (1.07)^{10} = 2 \text{ (approximation)}$$

∴ * The reverse saturation current I_0 approximately doubles for every 10°c raise in temperature.

Ex: If 25°c, $I_0 = 10\mu A$ then for 45°c $I_0 = ?$

$T = 25°c \longrightarrow I_0 = 10\mu A$ ie $\boxed{I_{0_2}(T) = \left[I_{0_1} \cdot 2^{(T_2 - T_1)/10}\right]}$

$T = 35°c \longrightarrow I_0 = 20\mu A$

$T = 45°c \longrightarrow I_0 = 40\mu A$

Consider the current equation of the diode ie eqn (1).

$$I = I_0\left[e^{V/\eta V_T} - 1\right]$$

(−1 → neglected.)

$$\Rightarrow \frac{I}{I_0} = e^{V/\eta V_T}$$

Taking logorithm on Both sides

$$\log(I/I_0) = \log e^{V/\eta V_T} = \frac{V}{\eta V_T}$$

$$\Rightarrow V = \eta V_T \log(I/I_0) \longrightarrow (7)$$

$$\frac{dV}{dT} = \eta\left[\frac{dV_T}{dT}\log\left(\frac{I}{I_0}\right) - V_T \cdot \frac{1}{I_0}\cdot\frac{dI_0}{dT}\right] \longrightarrow (8)$$

but $V_T = \frac{T}{11600} \Rightarrow \frac{dV_T}{dT} = \frac{1}{11600}\cdot\frac{dT}{dT} = \frac{1}{11600} \longrightarrow (9)$

Substitute eqn (9) & eqn (4)A in eqn (8), we get

$$\frac{dV}{dT} = \left[\frac{\eta}{11600}\cdot\log\left(\frac{I}{I_0}\right) - \eta V_T\left\{\frac{m\eta V_T + V_{G0}}{T\eta V_T}\right\}\right]$$

$$= \left[\frac{\eta}{11600}\times\frac{V}{\eta V_T} - \frac{(m\eta V_T + V_{G0})}{T}\right]$$

($V_T \to \frac{T}{11600}$)

$$= \frac{V}{T} - \frac{(V_{G0} + m\eta V_T)}{T}$$

$\left[\because \; I/I_0 = e^{V/\eta V_T},\; \log I/I_0 = \frac{V}{\eta V_T}\right]$, $V_T = T/11600$.

$$\boxed{\frac{dV}{dT} = \frac{V - (V_{G0} + m\eta V_T)}{T}} \longrightarrow (10)$$

Substituting values of η, V_T for Si & Ge we get.

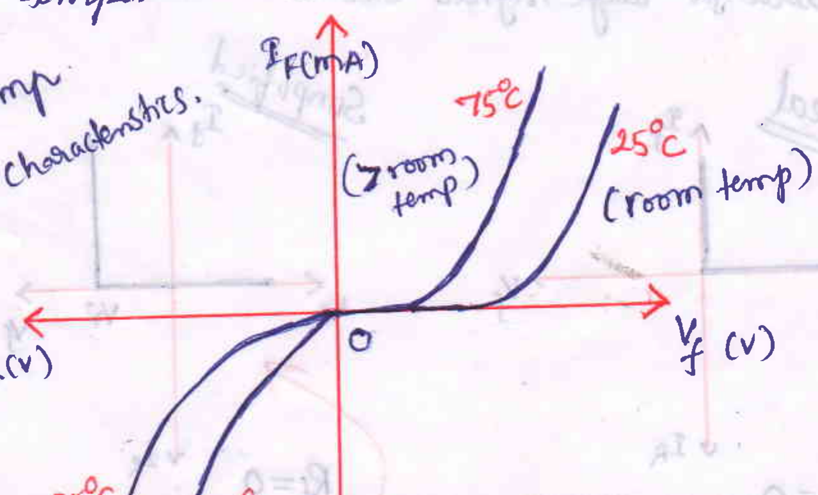
for Si $\frac{dV}{dT} = -2.3\ mV/^\circ C$ | $V = 0.6V$, $m = 1.5$, $\eta = 2$, $V_T = 26mV$, $T = 300$ | $\boxed{\frac{\Delta V}{\Delta T} = -2.5\ mV/^\circ c}$

for Ge $\frac{dV}{dT} = -2.1\ mV/^\circ c$. (or)

For all Si & Ge average value $\boxed{\frac{dv}{dT} = -2.5\ mV/^\circ c}$.

ie **Hence** As temperature increases reverse saturation current also increase by 7% double for 10°C. And As temperature increases voltage decreases by 2.5mV/°c.

Fig: Effect of temp on the diode characteristics.



Diode Equivalent Circuits: (or) Piecewise linear diode model :

An equivalent circuit is a combination of elements chosen to represent actual terminal characteristics of a device.

(Anode)  (Cathode)

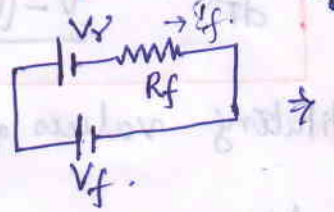
1. Practical diode
2. Ideal diode
3. Piecewise linear model,

If the voltage applied across the diode exceeds the cut-in voltage (V_γ) the diode is forward biased & it is ON state with diode forward resistance (R_f)

For a reverse biased, the diode is open switch & it is in OFF state with infinitely large reverse resistance (R_r). (Dynamic Resistances)

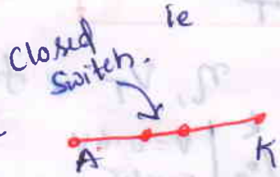
Under forward biased :

Practical :



ie $\Rightarrow$ $V_f = V_\gamma + I_f R_f$

Ideal



ie An ideal diode offers zero forward resistance, ie $R_f = 0$ & V_γ is neglected.

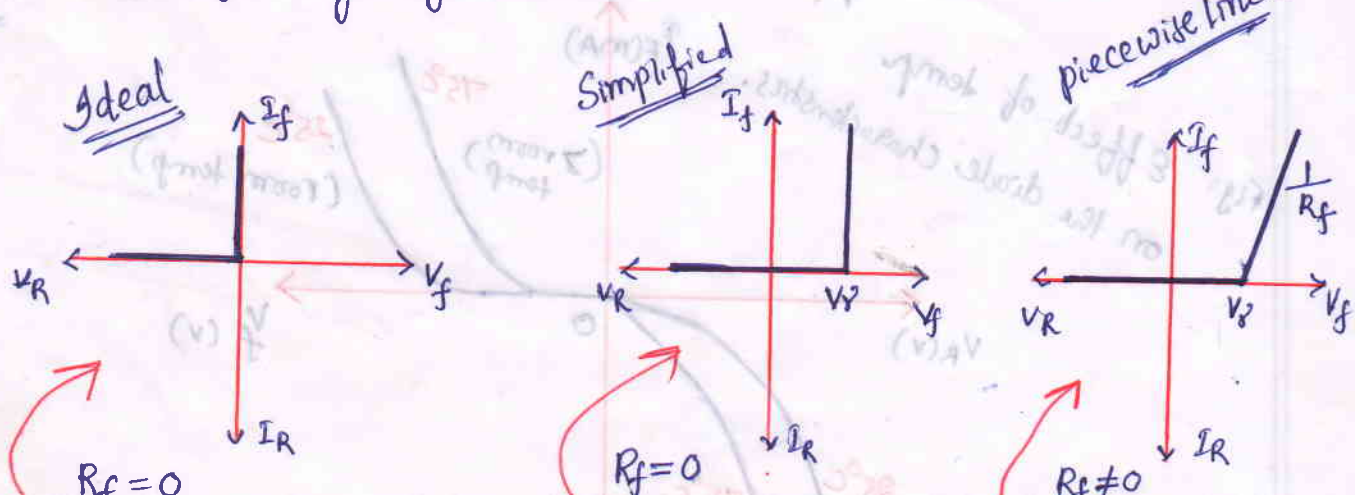
Under reverse biased:

Practical

Ideal :

$R_r = \infty$

Piecewise linear model is used when a more accurate model and used for large signal ckt.



Diffusion or Storage Capacitance : {C_D}

The capacitance that exists in a forward biased junction is called diffusion or storage capacitance, denoted as 'C_D'.

(or)

The rate of change of injected charge with applied voltage.

ie $$C_D = \frac{dQ}{dV}$$

where dQ - the change in the no. of minority carriers stored outside the depletion region.

dV - a change in voltage across the diode is applied.

Diffusion Capacitance $$C_D = \frac{\tau I}{\eta V_T}$$ ⇒ $C_D \propto I_f$

where τ - the mean life time for holes & electrons. (sec).

The value of C_D ranges from 10 pF to 1000 pF.

The value of C_D is inversely proportional to frequency, it is high at low frequency and it decreases with increased frequency.

Transition or Space Charge or Depletion region Capacitance : {C_T}

The capacitance that exists in a reverse biased junction is called transition capacitance, denoted as C_T.

The width of the space-charge region at the junction increases with reverse voltage due to majority carriers move away from the junction.

$$C_T = \left|\frac{dQ}{dV}\right|$$ where dQ - the change in charge

dV - the change in voltage.

(or)

$$C_T = \frac{\varepsilon A}{W}$$ where ε - Permittivity of the material.

A - Cross sectional area of the junction

W - Width of the depletion region.

$$C_T \propto \frac{1}{W}$$

* Both C_D & C_T are not fixed capacitors and they may have

Ideal Vs Practical Resistance levels :

An ideal diode should offer zero resistance in forward bias and infinite resistance in reverse bias.

But in practice no diode can act as an ideal diode.

1. DC (or) Static resistance (R) : It is the ratio of voltage to the current & it varies widely with V and I. $R = V/I$.

   It is not a useful parameter.

2. A.C (or) Dynamic resistance (r) : It is the reciprocal of the slope of the volt-ampere characteristics. (or) $\Rightarrow r = \frac{\Delta V}{\Delta I}$

$$r = \frac{\text{Change in voltage}}{\text{Change in current}} = \frac{dV}{dI} = \frac{\Delta V}{\Delta I}.$$

It can be estimated using the diode current equation

$$I = I_0 \left(e^{V/\eta V_T} - 1 \right)$$

where η = emission coefficient, $\eta = 1$ for Ge, $= 2$ for Si

$V_T = \frac{T}{11600} \approx 26\,mV$.

Differentiate above eqn w.r.t. voltage.

$$\Rightarrow \frac{dI}{dV} = \frac{d}{dV}\left[I_0 \left(e^{V/\eta V_T} - 1 \right) \right]$$

$$\Rightarrow \frac{dI}{dV} = I_0 \cdot e^{V/\eta V_T} \cdot \frac{1}{\eta V_T}$$

$$\Rightarrow \frac{dI}{dV} = \frac{I + I_0}{\eta V_T}$$

$\because I = I_0 e^{V/\eta V_T} - I_0$

$I + I_0 = I_0 e^{V/\eta V_T}$.

$\therefore$ Dynamic resistance $r = \frac{dV}{dI} = \frac{\eta V_T}{I + I_0}$

For forward bias greater than few 10's of volts, the current is more ie if $I >> I_0$ then $r = \frac{\eta V_T}{I}$

Dynamic conductance :

It is the reciprocal of the dynamic resistance (g)

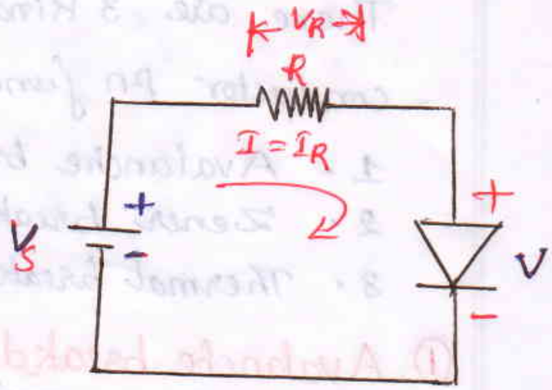
$$g = 1/r \Rightarrow g = I/\eta V_T$$

Reverse resistance : It is the resistance offered by pn junction under reverse bias condition. It is very large compared to forward ... (mega ohms)

Load Line Analysis:

Consider a simple p-n diode as a ckt. element.

The ckt consists of DC voltage V_s applied across resistor and a diode.



To find diode voltage V & Current I.

Apply KVL $V_S = V_R + V$

$$\boxed{V_S = IR + V} \rightarrow (1) \quad (\because V_R = I.R)$$

The diode current equation is given by.

$$I = I_0 \left(e^{V/\eta V_T} - 1\right) \longrightarrow (2)$$

from eqn (1) & (2)

$$V_S = I_0 . R \left(e^{V/\eta V_T} - 1\right) + V.$$

→ Load line construction allows graphical analysis.

* Graphical analysis that involves plotting simultaneous equations and locating point of intersection called operating or Quiescent point.

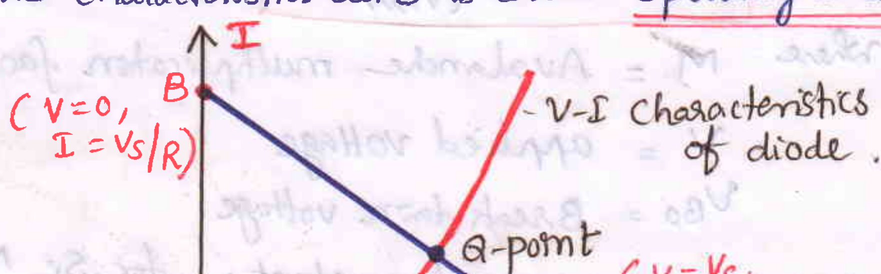
* To draw the load line I is determined when a device is short ckted and V is determined when a device is open ckted.

$$\Rightarrow V_S = IR + V \Rightarrow \boxed{I = \frac{V_S - V}{R}}$$

when $I = 0 \Rightarrow V = V_S$ ie $A(V = V_S, I = 0)$. &

when $V = 0 \Rightarrow I = V_S/R$ ie $B(V = 0, I = V_S/R)$.

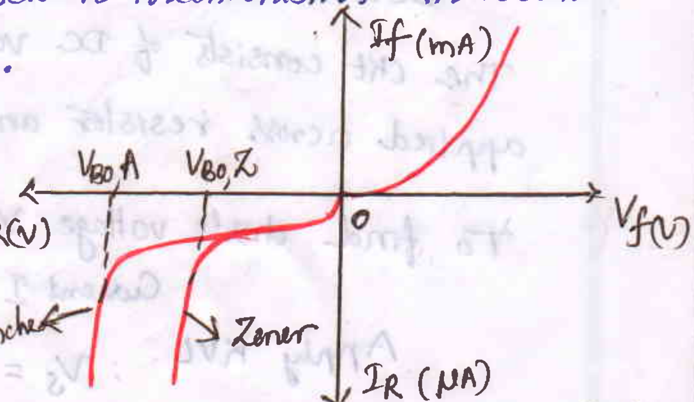
The straight line drawn connecting the point A and B called the load line. & The intersection point of the load line and the diode static characteristics curves is called Operating or Q-point of the device.



Break down Mechanisms in Semiconductor Diodes :

There are 3 kinds of breakdown mechanisms in semi-conductor pn junction diode.

1. Avalanche breakdown
2. Zener breakdown
3. Thermal break down.



①. Avalanche breakdown :

* Breakdown means breaking of covalent bonds in Semiconductor diode.
* When excess energy is liberalid breakdown takes place.
* Excess of charge carrier ie electrons will be liberated so, current increases rapidly.
* When certain amount of reverse bias voltage ie $V_R > V_{BO}$ then this additional voltage is sufficient to break some of the covalent bonds which gives more no. of charge carriers.
* When this additional charge carriers collides with the electron heat may be released, some of this additional charges may break some more bonds.
* It is a cumulative process in which charge is multiplied, this multiplication is known as 'avalanche multiplication factor' and this process is known as avalanche breakdown.

$$M = \frac{1}{1-\left(\frac{V}{V_{BO}}\right)^{n}}$$

where
M = Avalanche multiplication factor.
V = applied voltage
V_{BO} = Breakdown voltage

for Si N-type → $n = 4$

* Avalanche breakdown occurs in an ordinary PN-diode.
* Avalanche breakdown takes place in the diodes where depletion region (layer) is wider.
* The electric field at the junction is very low compared to zener breakdown.
* This type of breakdown occurs at high voltages (some tens of volts).
* In this type of breakdown, the breakdown voltage increases with temperature. It consists of +ve temp. coefficient of resistance ie 0.1%/°C. It is due to collision because of rise of reverse bias voltage.

Temperature Coefficient: It is the % change in the applied voltage per degree centigrade in the diode temperature.

(2). Zener breakdown:

* It takes place in diode which are heavily dopped ie. It takes place in zener diode which is heavily dopped.
* the field at the junction is very high compared to field of Pn diode. (about 10^6 V/m).
* The break down occurs at very low voltages ie even at less than 6V.
* In this case covalent bonds ruptured, with their lattice atoms.
* The lattice atoms may not come back to their original reference level, where as in PN junction diode when the voltage is removed then the atoms will come to their original position.
* As temperature increases the zener break down voltage may decrease. ie It has negative temperature coefficient of resistance ie -0.1%/°C

(3) Thermal breakdown:

Thermal breakdown means breakdown of the diode by keeping bias voltage constant and increasing the

Comparison of Avalanche & Zener breakdown:

SL NO.	Avalanche Breakdown	Zener breakdown.
1	It occurs in lightly doped junction	* It occurs in heavily doped junction
2.	It occurs in pn junction diode with reverse voltage greater than 6V.	* It occurs with reverse bias voltage is less than 6V.
3	Temperature coefficient is positive	* Temperature coefficient is negative
4	The VI characteristics in reverse bias is not sharp (ie soft).	* The reverse bias VI characteristic is very sharp in breakdown region.
5	It occurs by breaking covalent bonds due to collision of accelerated electrons as a chain reaction.	* It occurs by breaking covalent bonds due to very high electric field established by the reverse bias.
6	The break down voltage increases if junction temperature increases	* The break down voltage decreases if the junction temp. increases.

PN diode Applications:

PN diode is used in

1. Rectifiers in dc power supplies.
2. Switching in digital logic ckts used in computers.
3. DC restorer (clamper) in TV receivers & voltage multipliers.
4. Clipping ckts used in computers, radars, radio & TV receivers.
5. Demodulation (detector) circuits.
6. Detectors (APD, PIN diode (photo diode) in optical communication ckts.
7. Zener diodes in voltage regulators.
8. Varactor diodes in tuning section of radio & TV receivers.
9. Light emitting Diode (LED) in digital displays.
10. Tunnel diodes as a relaxation oscillator at microwave frequencies.

Zener diode Characteristics :

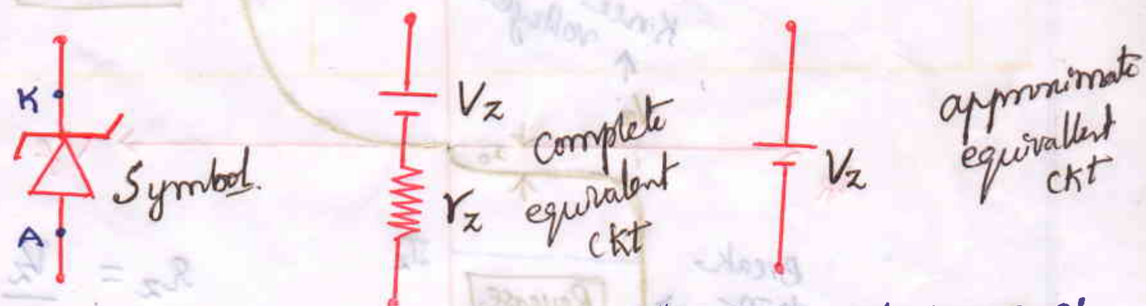
* A properly dopped (heavily doped) crystal diode , which has a sharp breakdown voltage is known as zenerdiode .

* It is a pn junction device in which zener breakdown mechanism dominates .

* zener diode is always used in reverse bias .

Features :

1. Doping concentration is heavily on p and n regions of the diode, compared to normal pn junction diode.
2. Due to heavy doping , depletion region width is narrow.
3. Due to narrow depletion region width , electric field intensity $E = \frac{V}{d} = \frac{V_z}{W}$ will be high , near the junction , of the order of 10^6 V/m . So zener breakdown mechanism occurs.



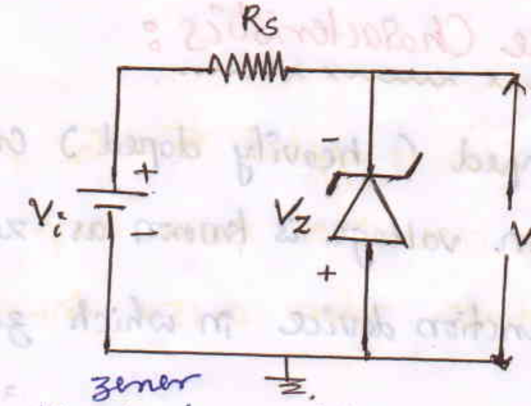
When connected in forward biased zener diodes behaves as an ~~diode~~ ordinary diode (pn diode) .

→ Zener diode breaks down even at very less voltages (less than 3V).

* In reverse biase as the reverse voltage is increased the reverse current $I_R \cong I_0$ is very small and almost constant upto knee of volt.

At $V_R = V_z$ due to high electric field zener breakdown occurs and reverse current increases rapidly as r_z (zener resistance) & ... almost constant.

Circuit :

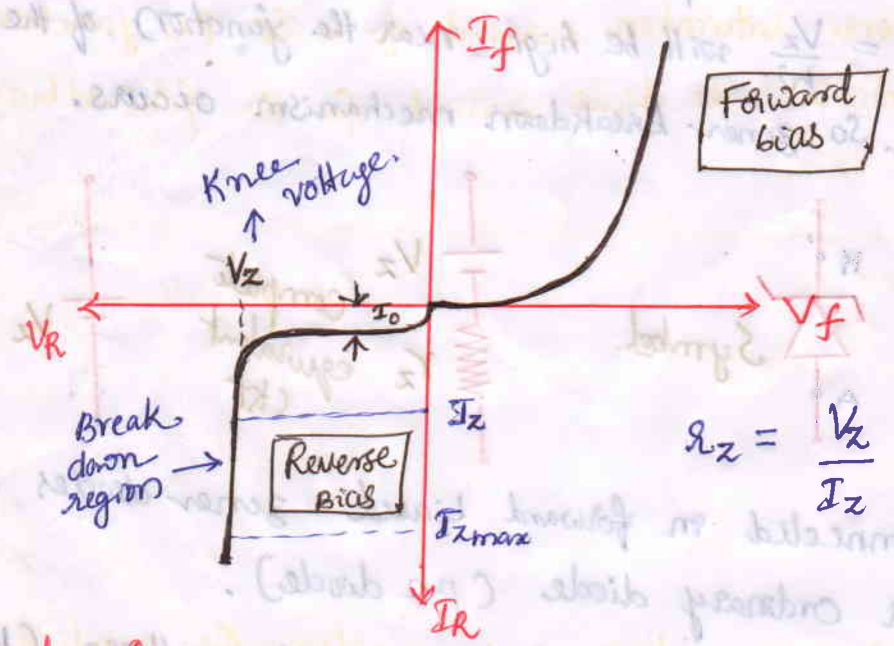


When $V_i \geq V_z$, the diode will be ON, $V_0 = V_z$

when $V_i < V_z$ the diode will be OFF, $V_0 = V_i$.

* Zener diode is also called as "stabilizer diode" or "Stabistor" (when connected in forward bias).

V-I characteristics:



$r_z = \frac{V_z}{I_z}$

Applications:

1. Zener diode may be used as voltage regulator for constant voltage.
2. It can be used in wave shaping circuits (clippers).
3. It is used for reshaping waveforms.
4. It is used for meter protection against damage from accidental application of excessive voltage.

Problems:

① When a reverse bias is applied to a Ge p-n junction diode, the reverse saturation current at room temp. is $0.3\,\mu A$. Determine the current in diode when $0.15V$ forward bias is applied at room temperature.

Sol Given data $I_0 = 0.3\mu A$

$V = 0.15V$

for Ge $\eta = 1$ (300K)

$V_T = \frac{T}{11600} = 25mV = 0.025$

$I = ?$

$$I = I_0 [e^{V/\eta V_T} - 1]$$

$$= 0.3\times10^{-6}\left[e^{\frac{0.15}{1\times0.025}} - 1\right]$$

$$= 0.3\times10^{-6}(402.4)$$

$$I = 120.7\,\mu A \;\&\; 0.12mA$$

② The reverse saturation current of a Si pn junction diode is $10\,\mu A$. Calculate the diode current for the forward bias voltage of $0.6V$ at $25°c$.

Sol Given data $V = 0.6V$

$I_0 = 10\,\mu A$

$T = 25+273 = 298K$

$\eta = 2$ for Si.

$V_T = \frac{T}{11600} = 25.7\times10^{-3}V.$

$I = ?$

$$I = I_0 [e^{V/\eta V_T} - 1]$$

$$= 10\times10^{-6}\left[e^{0.6/2\times25.7\times10^{-3}} - 1\right]$$

$$I = 1.174\,A$$

③ The diode current is $0.6mA$ when the applied voltage is $400mV$ and $20mA$ when the applied voltage is $500mV$. Determine 'η' assume $\frac{KT}{q} = 25mV \cong V_T$.

Sol The diode current $\left[I = I_0 (e^{V/\eta V_T} - 1)\right] \cong I_0 . e^{V/\eta V_T}$.

Given data. $I_1 = 0.6\,mA$, $V_1 = 400\,mA$ & $I_2 = 20mA$, $V_2 = 500\,mV$.

$$I_1 = I_0 e^{V_1/\eta V_T} \Rightarrow 0.6\times10^{-3} = I_0 \cdot e^{\frac{400\times10^{-3}}{\eta\cdot 25\times10^{-3}}}$$

$$0.6\times10^{-3} = I_0 \cdot e^{16/\eta} \longrightarrow (1)$$

$$I_2 = I_0 e^{V_2/\eta V_T} \Rightarrow 20\times10^{-3} = I_0 \cdot e^{\frac{500\times10^{-3}}{\eta\cdot 25\times10^{-3}}}$$

$$20\times10^{-3} = I_0 \cdot e^{20/\eta} \longrightarrow (2)$$

Dividing eqn (2) by eqn (1), we get

$$\frac{20\times10^{-3}}{0.6\times10^{-3}} = \frac{I_0\, e^{20/\eta}}{I_0\, e^{16/\eta}}$$

$$\frac{100}{3} = e^{4/\eta}$$

Apply natural logarithms.

$$\ln(100/3) = 4/\eta$$

$$3.507 = 4/\eta$$

$$\therefore \boxed{\eta = 1.14}$$

(4) Determine the value of the forward current in the case of a PN junction diode with $I_0 = 10\,\mu A$ and $V_f = 0.8V$ at $T = 300K$. Assume silicon diode.

Sol Given data $I_0 = 10\,\mu A$

V_f or $V = 0.8V$

$T = 300K$

$\eta = 2$ for Si

$V_T = 26\text{ mV} = 26\times10^{-3}$

$$\therefore I = I_0 \cdot [e^{V/\eta V_T} - 1]$$

$$= 10\times10^{-6}\left[e^{\frac{0.8}{2\times26\times10^{-3}}} - 1\right] = 48.02A$$

Forward $I = 48.02A$

(5) Derive an expression for the change in diode voltage forward drop for a given current ratio I_2/I_1 if $V_D >> \eta V_T$.

Sol.

$$I = I_0\left(e^{V/\eta V_T} - 1\right) \cong I_0 \cdot e^{V/\eta V_T}$$

$$\Rightarrow I_1 = I_0 e^{V_1/\eta V_T} \longrightarrow (1)$$

$$\Rightarrow I_2 = I_0 \cdot e^{V_2/\eta V_T} \longrightarrow (2)$$

eqn $\frac{(2)}{(1)} \Rightarrow$

$$\frac{I_2}{I_1} = \frac{e^{V_2/\eta V_T}}{e^{V_1/\eta V_T}} = e^{(V_2 - V_1)/\eta V_T}$$

apply logarithms.

$$\log(I_2/I_1) = \frac{V_2 - V_1}{\eta V_T}$$

$$\Rightarrow V_2 - V_1 = \eta V_T \cdot \log(I_2/I_1)$$

$$\therefore V_D = \eta V_T \log(I_2/I_1)$$

(6) Given for a Si diode $I_1 = 2mA$, when $V_f = 0.6V$ and $I_2 = 10mA$ when $V_f = 0.7V$. Find the temperature for which data were taken.

Sol. Given data

$I_1 = 2mA$, $V_f = 0.6V = V_1$

$I_2 = 10mA$, $V_f = 0.7V = V_2$

$$V_T = \frac{KT}{q} = \frac{T}{11600} = 26mV, \quad \eta = 2 \text{ for Si}$$

$$V_D = V_2 - V_1 = \eta V_T \cdot \log(I_2/I_1)$$

$$0.7 - 0.6 = 2 \cdot \frac{T}{11600} \cdot \log\left(\frac{10m}{2m}\right) \quad \text{5} \quad \text{* ln}$$

$$0.1 = \frac{2T}{11600} \ln(5)$$

$$T = \frac{0.1 \times 11600}{2 \times \ln(5)} = 360.4°K$$

(7) Find the value of dc resistance and AC resistance of a Ge. diode at 25°C with $I_0 = 25\,\mu A$ and at an applied voltage of 0.2 V across the diode.

Sol. Given data. $I_0 = 25\,\mu A$, $V = 0.2V$, $\eta = 1$ for Ge.

$T = 25°c$
$= 25 + 273$
$T = 298°K$.

Diode Current $I = I_0 \cdot (e^{V/\eta V_T} - 1)$

$V_T = \frac{T}{11600} = \frac{298}{11600}$

$\therefore V_T = 25.68\,mA$.

$$= 25 \times 10^{-6} \left[e^{\frac{0.2}{2 \times 25.68 \times 10^{-3}}} - 1 \right]$$

$$\boxed{I = 0.0603\ A}$$

DC resistance $R_f = \frac{V}{I} = \frac{0.2}{0.0603} = 3.32\,\Omega$

$\therefore \boxed{R_f = 3.32\,\Omega}$.

A.C resistance $r_f = \frac{\eta V_T}{I} = \frac{1 \times 25.68 \times 10^{-3}}{0.0603} = 0.426\,\Omega$

$\therefore \boxed{r_f = 0.426\,\Omega}$

(8) Calculate the dynamic forward and reverse resistance of pn junction Si diode when the applied voltage is 0.25V at $T = 300°K$ with given $I_0 = 2\,\mu A$.

Sol. Given data $V = 0.25V$, $\eta = 2$ for Si, $I_0 = 2\,\mu A$

$T = 300\,K$

$V_T = 26\,mV$ for 300 K.

For forward resistance use $V_f = 0.25V$.

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

$$I = I_0 \cdot [e^{V_f/\eta V_T} - 1]$$

$$I = 2 \times 10^{-6} \left[e^{\frac{0.25}{2 \times 26 \times 10^{-3}}} - 1 \right]$$

$$I = 2.43 \times 10^{-4}\ A$$

$$\therefore r_f = \frac{2 \times 26 \times 10^{-3}}{2.43 \times 10^{-4}} = 213.99\,\Omega$$

For reverse resistance use $V_r = -0.25$ V.

$$I = I_0 \left(e^{V_r/\eta V_T} - 1\right)$$

$$= 2\times10^{-6}\left[e^{\frac{-0.25}{2\times 26\times10^{-3}}} - 1\right]$$ → neglect 1

$$I = 1.63\times10^{-8}\ A$$

$$\therefore r_r = \frac{\eta V_T}{I} = \frac{2\times 26\times10^{-3}}{1.63\times10^{-8}} = 3.19\times10^{6}\ \Omega$$

$$\therefore \boxed{r_r = 3.2\,M\Omega}$$

(9) A p-n junction diode has a reverse saturation current of 30 μA at a temperature of 125°C. At the same temperature, find the dynamic resistance for 0.2 V bias in forward and reverse direction.

Sol Given data. $I_0 = 30\,\mu A$

$V = 0.2V$

$T = 125°c = 125 + 273K = 398\,°K$.

Assume $\eta = 1$ for Ge diode. $V_T = \frac{T}{11600} = \frac{398}{11600}$

$V_T = 0.0343$

For forward Resistance $r_f = \frac{\eta V_T}{I_0}$

$V = 0.2V$

where $I = I_0\left(e^{V/\eta V_T} - 1\right) \cong I_0\left(e^{V/\eta V_T}\right)$

$$= 30\times10^{-6}\left[e^{\frac{0.2}{1\times0.0343}}\right]$$

$$= 0.0102\,A$$

$$r_f = \frac{1\times0.0343}{0.0102}$$

$$\boxed{r_f = 3.363\,\Omega}.$$

for reverse resistance

$V = -0.2V$.

$$I = I_0\left(e^{-V/\eta V_T}\right) = 30\times10^{-6}\left[e^{\frac{-0.2}{1\times0.0343}}\right]$$

$$I = 8.81\times10^{-8}$$

$$r_r = \frac{\eta V_T}{I} = \frac{1\times0.0343}{\ldots}$$

(10) A Si diode operates at a forward voltage of 0.4V. Calculate the factor by which the current will be multiplied when temperature increases from 25°C to 150°C.

Sol

Given data $\eta = 2$ for Si $\quad V_T = \frac{T}{11600}$ V.

$V = 0.4V$.

$T_1 = 25°C = 25 + 273 = 298°K$.

$T_2 = 150°C = 150 + 273 = 423°K$.

I_0 at 25°C be I_{01}

& I_0 at 150°C be I_{02} $\Rightarrow$ $I_{02} = I_{01} \cdot 2^{(T_2 - T_1)/10}$.

ie. The reverse saturation current I_0 approximately doubles for every 10°C raise in temperature.

$\therefore \quad I_{02} = I_{01} \cdot 2^{(150-25)/10}$.

$\frac{I_{02}}{I_{01}} = 5792.6$. $\Rightarrow I_{02} = (5792.6) I_{01}$ → (1)

ie Initially reverse saturation current gets multiplied by a factor of 5792.6 when temp. increases from 25°C to 150°C.

$I_1 = I_{01} e^{V/\eta V_{T_1}}$ → (2) $\quad V/\eta V_{T_2} = \frac{0.4 \times 11600}{2 \times 423} = 5.48$

$I_2 = I_{02} e^{V/\eta V_{T_2}}$ → (3) $\quad V/\eta V_{T_1} = \frac{0.4 \times 11600}{2 \times 298} = 7.78$

Divide eqn. (3) by (2) ie

$\frac{(3)}{(2)} \Rightarrow \frac{I_2}{I_1} = \frac{I_{02} \cdot e^{V/\eta V_{T_2}}}{I_{01}\, e^{V/\eta V_{T_1}}} = \frac{5792.6\, I_{01}}{I_{01}} \times \frac{e^{5.48}}{e^{7.78}}$.

$= 5792.6 \times e^{(5.48 - 7.78)}$

$= 5792.6 \times 0.10025$

$\frac{I_2}{I_1} = 580.71$

(11) Determine the forward resistance of a PN junction diode when the forward current is 5 mA at T = 300K. Assume Si diode.

Sol. Given

$I = 5\,mA$

$T = 300K$

$V_T = \frac{T}{11600} = \frac{300}{11600} = 26\,mV.$

$\eta = 2$ for Si

∴ Forward resistance $r_f = \frac{\eta V_T}{I}.$

$= \frac{2 \times 26 \times 10^{-3}}{5 \times 10^{-3}}.$

$r_f = 10.34\,\Omega$

(12) The voltage across a Si diode at room temperature of 300°K is 0.7V when 2mA current flows through it. If the voltage increases to 0.75V Calculate the diode current assuming $V_T = 26\,mV$.

Sol. Given.

$V = 0.7V$

$T = 300K$

$V_T = 26\,mV.$

$I = 2\,mA$

$V' = 0.75\,V$ & $\eta = 2$ for Si.

$I' = ?$

Diode current equation $I = I_0 \left[e^{V/\eta V_T} - 1\right]$

$2 \times 10^{-3} = I_0 \left[e^{0.7/2 \times 26 \times 10^{-3}} - 1\right]$

Reverse Saturation current. $\Rightarrow I_0 = 2.8494 \times 10^{-9}\,A$

$\therefore I' = I_0 \left[e^{V'/\eta V_T} - 1\right]$

$= 2.8494 \times 10^{-9} \left[e^{0.75/2 \times 26 \times 10^{-3}}\right]$

$= 5.2313\,mA$

∴ Diode current $I' = 5.2313\,mA$