Question Bank: Semiconductors and Superconductors

1. Define the terms ‘Fermi factor’ and ‘Fermi energy’.
2. Explain the Fermi Dirac distribution of electrons with respect to different temperature conditions.
3. What is a Fermi factor? Explain the Fermi factor for different temperature conditions.
4. What is a semiconductor? Distinguish intrinsic and extrinsic semiconductor.
5. Explain direct and indirect band-gap semiconductors? Explain.
6. What is an intrinsic semiconductor? Explain the mechanism of carrier generation in intrinsic semiconductors
7. What are intrinsic semiconductors? Obtain an expression for the conductivity of an intrinsic semiconductor.
8. Explain the effect of temperature on the conductivity of an intrinsic semiconductor.
9. What are extrinsic semiconductors? Describe the mechanisms of carrier generation in extrinsic semiconductors.

10. Obtain an expression for the conductivity of an extrinsic semiconductor.

11. Explain the effect of temperature on the conductivity of an extrinsic semiconductor.

12. Explain the effect of temperature on the Fermi level in an intrinsic and extrinsic semiconductor.

13. Write any four differences between conductors and semiconductors. Increase in temperature decreases the resistivity of a semiconductor, why?

14. State Hall Effect? Obtain an expression for the Hall voltage and Hall coefficient of an n-type semiconductor.

15. Describe the experimental method of determining the carrier concentration in an extrinsic semiconductor using Hall effect.

19. What are superconductors? Explain its characteristic properties.
20. Explain Critical field and Meissner effect in superconductors.
21. Explain the classifications of superconductors.
22. Distinguish between Type-I and Type- II superconductors.
23. Explain Type-I and Type-II superconductors with suitable diagrams.
24. Write a note on BCS theory.
25. Write a note on various applications of superconductors.

1)**Fermi energy:** The energy of the highest occupied level at absolute zero temperature (0 K) is called the Fermi energy denoted by E_f and the corresponding energy level is called Fermi level.

Fermi factor: It is defined as the probability of occupation of a given energy state for a material in thermal equilibrium and is denoted by $f(E)$.

$$f(E) = \frac{1}{e^{(E-E_f)/k_B T} + 1}$$

where E_f is the fermi level, k_B is the Boltzmann constant, T is temperature in K.

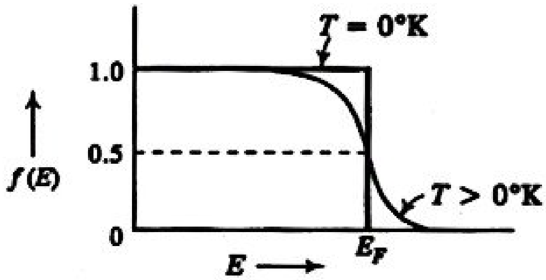
3) **Fermi factor f(E):** It is defined as the probability of occupation of a given energy state for a material in thermal equilibrium and is denoted by $f(E)$.

$$f(E) = \frac{1}{1+e^{\left[\frac{E-E_F}{k_B T}\right]}}$$

where Ef is the fermi level, k_B is the Boltzmann constant, T is the steady temperature

Dependence of Fermi factor on temperature:

The dependence of Fermi factor on temperature and energy is as shown in the figure.



VARIATION OF $f(E)$ WITH E

Following are the different cases.

1. Probability of occupation for $E < Ef$ at T=0K:

When T = 0K and $E < Ef$

$$f(E) = \frac{1}{1+e^{-\infty}} = \frac{1}{1+0} = 1$$

Thus, $f(E) = 1$ for $E < Ef$

This indicates at T= 0 K all the energy levels below the Fermi level are occupied.

2. Probability of occupation for E > Ef at T = 0 K:

When T=0 K and $E > Ef$

$$f(E) = \frac{1}{1+e^{\infty}} = \frac{1}{\infty} = 0$$

Thus, $f(E) = 0$ for $E > Ef$

This indicates at T = 0 K, all the energy levels above Fermi levels are unoccupied.

3. Probability of occupation for E = Ef at T = 0 K:

When T = 0K and $E = Ef$

$$f(E) = \frac{1}{1+e^{0/0}} = \text{Indeterminate}$$

Hence the occupation of Fermi level at T = 0K has an indeterminate value ranging between zero and one.

4. The probability of occupation at ordinary temperature (T>0K): At ordinary temperatures, though the value of probability $f(E)$ remains 1 for E<< E_F, it starts decreasing from 1 as the value of E become closer to E_F. ie. for the energylevels which are below the Fermi level, and the value of $f(E)$ is more than 0 for the energy levels which are above the Fermi level as shown in the figure.

At $E=Ef$ for T≠ 0 K

$$f(E) = \frac{1}{1+e^{0}} = \frac{1}{1+1} = \frac{1}{2}$$

Thus, at ordinary temperature, for E=E_F, the probability of occupation $f(E)$ is 0.5 or 50%

4) Semiconductors are materials whose conductivity lies in between that of conductors and insulators

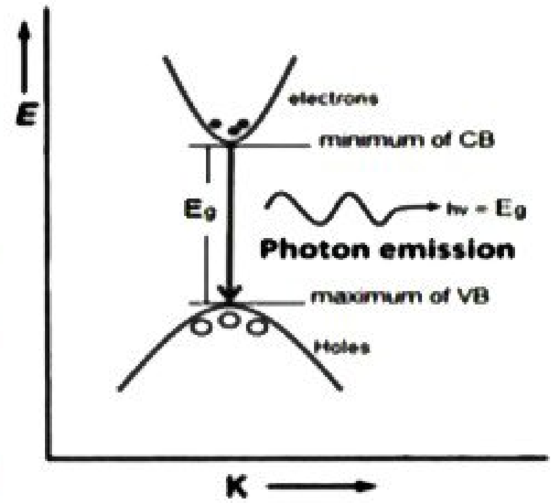
Intrinsic semiconductors	Extrinsic semiconductor
1. It is a chemically pure, structurally perfect and if compound, stoichiometric material	1. It is a doped semiconductor, obtained by adding a group III or group V element as dopant into an intrinsic semiconductor or nonstoichiometric, if compound.
2. At normal temperature, conductivity is low.	3. At normal temperature, the conductivity is high.
4. Carrier generation is due to breaking of covalent bonds.	5. Carrier generation is due ionisation of impurity atoms (forming majority carriers) and breaking of covalent bonds (forming minority carriers).
6. Current carriers, viz., electrons and holes are equal in number	7. Current carriers are essentially majority carriers at normal temperature
8. Fermi level lies at the centre of the forbidden energy gap at all temperatures	9. At 0 K, the Fermi level lies close to the conduction band in n-type semiconductor and close to the valence band in p-type semiconductor. Fermi level moves towards centre of the band gap as temperature increases.
10. Hall coefficient is negative due to higher mobility of electrons.	11. Hall coefficient is negative for n-type semiconductor and positive for p-type semi-conductor.

5) Direct and Indirect Band Gap Semicondcutors:

Based on the structure of energy bands and type of energy emission, semiconductors are classified into two types.

1. Direct band gap semiconductor
2. Indirect band gap semiconductor

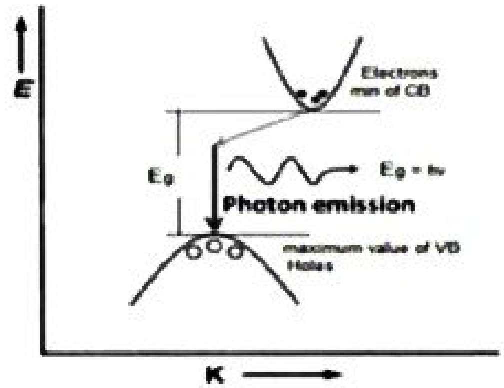
Direct Band Gap Semiconductor:



In direct band gap semiconductors, the maximum of VB and the minimum of CB exists at the same value of wave number (k). Where wave number (k) represents the propagation vector and is related to the momentum of the carrier. In this, electron can directly excite or de-excite by the absorption or emission of photon and there is no phonon involvement in the process of excitation and de-excitation. In this type during the recombination of electrons and holes, the energy difference Eg is released as a photon. This process is known as radiative recombination. These semiconductors are used to fabricate LEDs and laser diodes. These are mostly from the compound semiconductors. Ex: InP, GaAs, GaAsP etc.

Indirect Band Gap Semiconductor:

In Indirect Band Gap Semiconductors the maximum value of VB and the minimum value of CB exists at the different values of wave number (k). If an electron goes from the top of the valence band to the bottom of the conduction band, it has to change its energy as well as wave-vector K (momentum). For conservation of momentum and energy, there is the involvement of phonon in the process. If there is de-excitation of the electron, then not all the energy will be emitted in the form of the photon but some energy is emitted in the form of phonons i.e. some part is transferred to the lattice, and the lattice will vibrate and generate heat. This process is known as non-radiative recombination. So indirect bandgap semiconductor is not suitable for light emission. These are mostly from the elemental semiconductors. ***Ex: Si, Ge.***



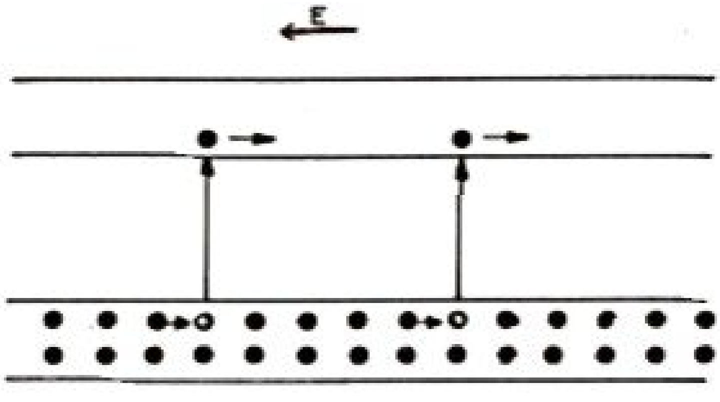
6) A semiconductor in its pure form, which does not have any external impurity is known as intrinsic semiconductor

Carrier generation in intrinsic semiconductors:

The number electrons in the conduction band per unit volume of the materials is called the electron concentration, similarly, the number of holes in the valence band per unit volume of the materials is called hole concentration. In general, **the number of charge carriers per unit volume of the materials is called carrier concentration.**

Carrier generation in an **intrinsic semiconductor is due to the breaking of covalent bonds.** Number of covalent bonds breaking is strong function of temperature. Breaking of covalent bond results in the release of an electron into the conduction band. Consequently, an electron energy state becomes vacant in the valence band. This vacant site provides an opportunity for the valence electrons to move under the influence of an electric field. The movement of electron in the valence band will thus equivalent to the movement of vacant site in the opposite direction (Fig.). the vacant site thus created by the transfer of an electron to the conduction band are called 'holes.

The movement of electrons in the valence band is conveniently explained as equivalent to the movement of holes. Since the direction of movement of these holes is opposite to that of electrons, holes behave as if they are positively charged. Thus, breaking of each covalent band results in the formation of an electron – hole pair, and they contribute to the electrical conductivity of the material. Since the electron and the hole are created together in pair, the number of electrons in the conduction band will be equal to the number of holes in the valence band at any given temperature.



Breaking of covalent bond and generation of electron – hole pairs

7) Conductivity of an intrinsic semiconductor:

When an electric field is applied to an intrinsic semiconductor, there will be movement of electrons in the conduction band and of holes in the valence band. Hence, there will be two currents, an electron current in the conduction band and a hole current in the valence band. As these currents are constituted by oppositely charged carriers and are in opposite directions, the net current will be sum of the two currents.

If v_e represents the drift velocity of electrons due to the applied field E, the current density due to electrons is given by

$$J_e = nev_e \quad \text{--- (1)}$$

where n is the number of conduction electrons available per unit volume and e is the charge of the electron.

Similarly, the current density due to holes is given by

$$J_h = pev_h \quad \text{---(2)}$$

The total current density is given by

$$J = (J_e + J_h) = nev_e + pev_h \qquad \text{---(3)}$$

The drift velocity is directly proportional to the applied field E.

$$\text{i.e.} \quad v \propto E \text{ or } v = \mu E \quad \text{--- (4)}$$

where μ is called the **mobility of charge carriers**. Hence the above equation becomes

$$J = ne\mu_e E + pe\mu_h E \qquad \text{------ (5)}$$

where μ_e and μ_h are the electron and hole mobilities respectively.

For an intrinsic semiconductor, the number of conduction electrons will be equal to the number of holes. i.e. $n = p = n_i$

Hence $\quad J = n_i\, e\, E\, (\mu_e+\mu_h) \quad$ ------- (6)

The conductivity, which is defined as the current density per applied field, is given by

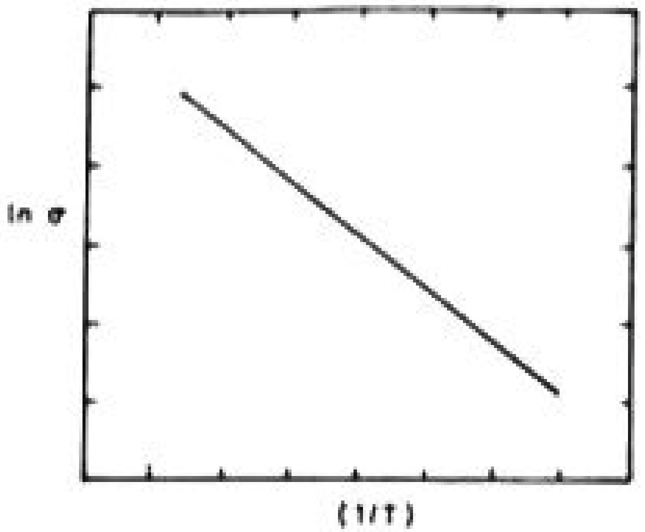
$$\boldsymbol{\sigma = J/E = n_i\, e\, (\mu_e + \mu_h)} \qquad \text{------ (7)}$$

This equation gives the conductivity of an intrinsic semiconductor.

8) **Effect of temperature on the resistivity of an intrinsic semiconductor:**

The conductivity of an intrinsic semiconductor depends strongly on temperature. The higher the temperature, more will be the number of electrons excited to the conduction band. The carrier concentration may be expressed as

$$n = k_1 T^{\frac{3}{2}} exp\left(\frac{-E_g}{2kT}\right) \text{--- (1)}$$



where E_g is the energy gap of the semiconductor and k_1 is a constant.
The mobility of electrons and holes generally depend on temperature as

$$\mu = k_2 T^{-3/2} \text{--- (2)}$$

where k_2 is a constant.
Hence the conductivity can be expressed as

$$\sigma = k_1 k_2 e \exp(-Eg/2kT)$$

$$\sigma = K \exp(-Eg/2kT) \quad \text{---} \quad (3)$$

where $K = k_1 k_2 e$

A plot of ln σ versus (1/T) will be a straight line with a slope equal to (Eg/2k). Hence, the band gap energy of the semiconductor can be calculated.

9) A semiconductor which is doped with some impurities are known as extrinsic semiconductor or doped semiconductor.

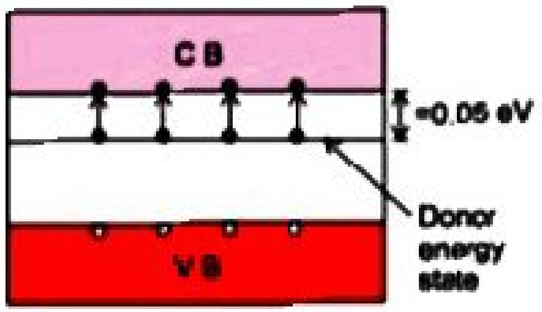
Carrier generation in extrinsic semiconductors:

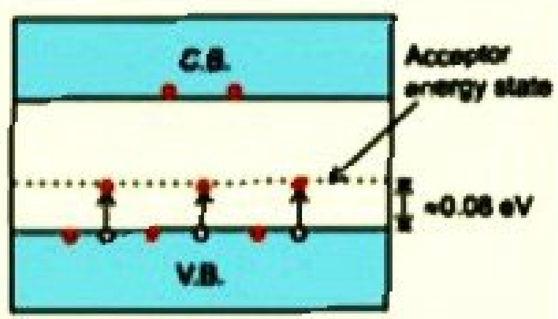
In case of extrinsic semiconductors, the carriers are generated due to two processes, namely

(i) ionization of impurity levels

(ii) breaking of covalent bonds

In an n-type semiconductor, for example, the donor levels are close to the bottom of conduction band and require only a small thermal energy to release an electron into the conduction band. This results in a mobile electron in the conduction band and an immobile positive ion of the donor impurity atom. Since the donor levels are very close to the conduction band, a large number of these levels will be ionised even at low temperature. At the same time, there are a few covalent bonds also being broken resulting in the generation of electron - hole pairs. Thus, there will be a large number of electrons (called majority carriers) and a few holes (called minority carriers) contributing to the conductivity of n-type semiconductor. Similarly, the conductivity of a p-type semiconductor will be dominated by majority carrier holes.





10) **Expression for the conductivity of an extrinsic semiconductor:**

The conductivity of an extrinsic semiconductor can be expressed as

$$\sigma = ne\mu_e + pe\mu_h \qquad \text{--- (1)}$$

where n represents the total number of electrons contributing to conductivity generated by both the mechanisms of carrier generation.

At normal temperature, most of the donor levels will be ionised and each donor atom contributes an electron to the conduction band. Further, the number of electrons generated due to breaking of covalent bonds is very small negligible compared to the number of electrons generated due to ionization of donor levels. Hence, the number of electrons contributing to conductivity may be taken as equal to the donor concentration and the conductivity will be given by

$$\sigma = N_d e\mu_e + pe\mu_h \qquad \text{--- (2)}$$

where N_d represents the donor concentration in the semiconductor. Since the donor concentration is quite high compared to the number of covalent bonds broken at room temperature, the second term in the conductivity equation may be neglected

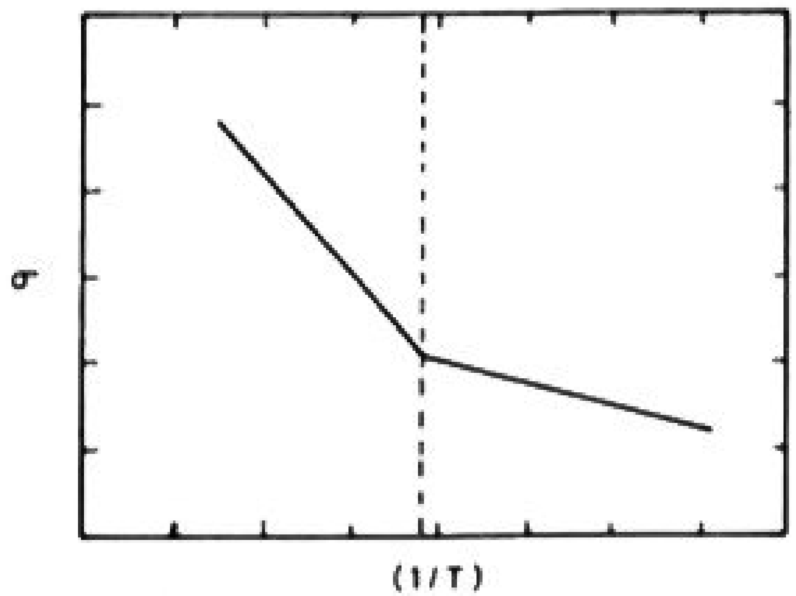
$$\sigma_e \approx N_d e\mu_e \qquad \text{--- (3)}$$

Similarly, the conductivity of a p-type semiconductor will be dominated by majority carrier holes and may be represented as $\sigma_h \approx N_a e\mu_h$ ---(4)

where N_a is the acceptor concentration in p-type semiconductor.

Effect of temperature on the conductivity of an extrinsic semiconductor -11)

The two mechanisms responsible for carrier generation in extrinsic semiconductors, the ionisation of impurity levels predominates at low temperatures as the probability of the covalent bonds being broken will be small. However, as the temperature is increased, more and more covalent bonds will be broken thereby increasing the minority carrier concentration. The temperature dependence of conductivity of an extrinsic semiconductor is shown in Figure. The graph shows a low temperature region, called the extrinsic region, where the conductivity is dominated by the ionisation of impurity levels and a high temperature region, called the intrinsic region, where the carrier generation is dominated by the breaking of covalent bonds. In the low temperature region is shown in Figure. The graph shows a low temperature region, called the extrinsic region, where the conductivity is dominated by the ionisation of impurity levels and a high temperature region, called the intrinsic region, where the carrier generation is dominated by the breaking of covalent bonds. In the low temperature region,



$$\sigma = K \exp(-E_a/kT)$$

where E_a is the activation energy for the extrinsic conduction and in the high temperature region,

$$\sigma = K \exp(-E_g/2kT)$$

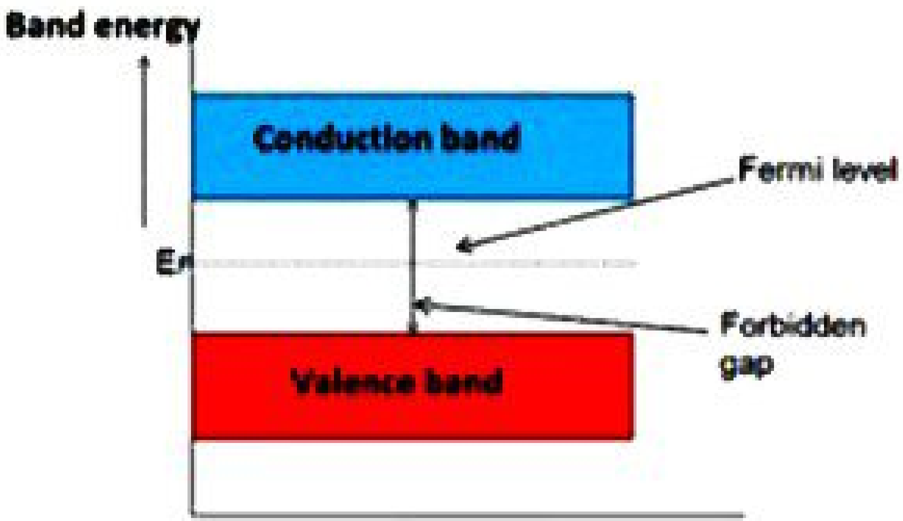
where E_g is the intrinsic band gap of the semiconductor.

The slope of the graph can be used to find the impurity ionization energy (low temp. region) and the intrinsic band gap (high temp. region) of the semiconductor.

Fermi level in an intrinsic semiconductor: 12)

At absolute zero temperature, a semiconductor behaves like an insulator since all the covalent bonds are intact. The valence band is full and the conduction band is empty. At higher temperature, the breaking of covalent bond generates the electron – hole pairs. The number of electrons in the conduction band will be equal to the number of holes in the valence band at any given temperature. It can be shown that for an intrinsic semiconductor, the Fermi level lies at the centre of the band gap and remains invariant with temperature.

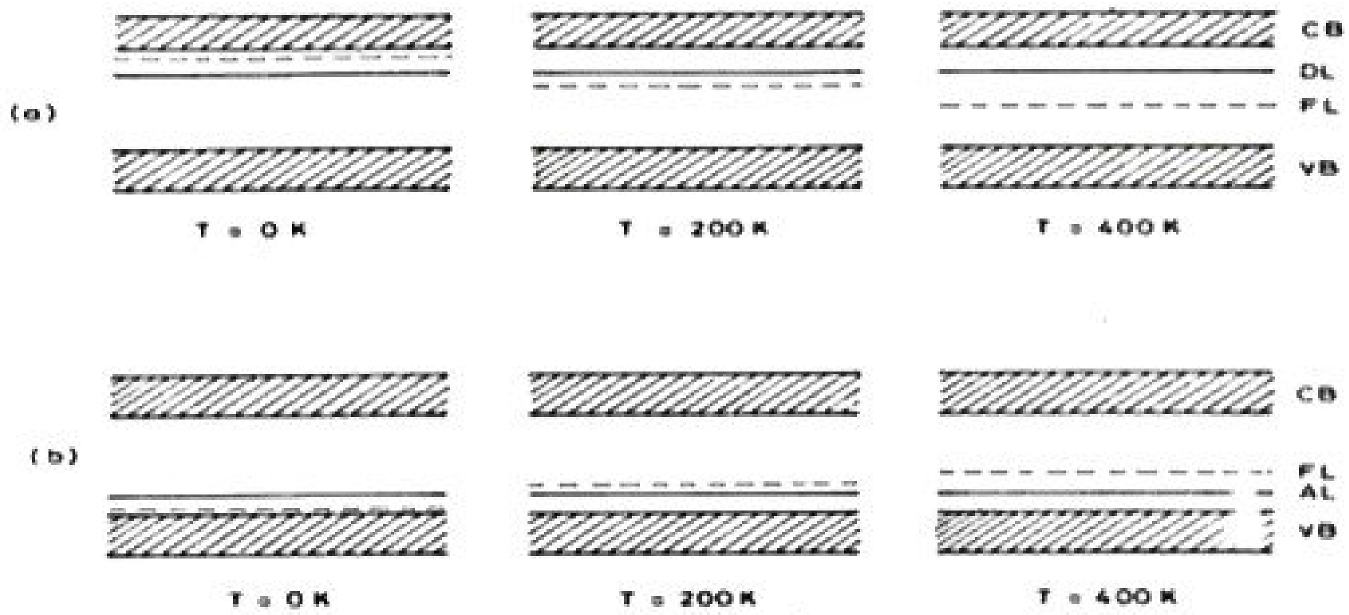
We notice that the Fermi factor has a non-vanishing value even for the energy values corresponding to the forbidden energy gap. However, no carriers are present in the forbidden gap since there are no sites available for occupation by the charge carriers.



Effect of temperature on the Fermi level in an extrinsic semiconductor: 12)

The effect of temperature is illustrated by the energy band diagrams shown in Figure.

In an **n-type semiconductor**, at 0 K, all the donor levels will be neutral, i.e., no electrons are contributed to the conduction band by the impurity atoms. The Fermi level, which represents the energy level for which the probability of occupation is half, lies mid-way between the donor level and the bottom of the conduction band. As the temperature is increased, the donor levels will be ionised to a greater extent as compared to breaking of covalent bonds. At elevated temperatures, when most of the donor levels are ionised, the carrier generation due to breaking of covalent bonds will dominate the variation of conductivity with temperature. The Fermi level gradually shifts closer to the centre of the forbidden energy gap and the semiconductor behaves more like an intrinsic semiconductor.



The resistivity of a semicondutor decreases with temperature. This is because of increasing temperature, the electrons in the valence band gain sufficient thermal energies to jump to the conduction band.

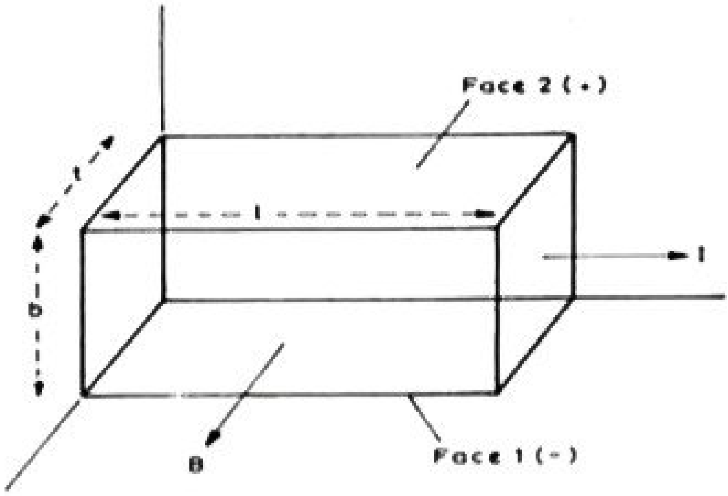
13)

S.No	Conductors	Semiconductors
1	Easily conducts the electrical current.	Conducts the electric current less than conductor and greater than insulator.
2	Has only one valence electron in its outermost orbit.	Has four valence electron in its outermost orbit.
3	Conductor formed using metallic bonding.	Semiconductors are formed due to covalent bonding.
4	Valence and conduction bands are overlapped.	Valence and conduction bands are separated by forbidden energy gap of 1.1eV.
5	Resistance is very small	Resistance is high
6	It has positive temperature coefficient	It has negative temperature coefficient
7	Ex: copper,aluminium,etc	Ex: silicon, germanium, etc

14) HALL EFFECT:

If a conductor carrying a current is placed in a transverse magnetic field, an electric field is produced in the conductor in a direction perpendicular to both the current and the magnetic field. This phenomenon is called Hall effect. The electric field generated is called Hall field and the corresponding voltage is called Hall voltage.

Consider a rectangular slab of an n-type semiconductor sample of length l, breadth b and thickness t. Let I be the current flowing through the sample along positive x-direction. A magnetic field B is applied perpendicular to the direction of current flow, say along positive z-direction. The effect of the magnetic field is to exert a force on the current carriers, namely electrons, flowing in the negative x-direction.



As a result of this force, the electrons will be forced downwards in the negative y-direction. This results in the lower face (Face 1 in the figure) becoming negatively charged with respect to the top face (Face 2). This constitutes the Hall field E_H. The electrons entering later will experience two forces –

(i) force Bev due to magnetic field, acting downwards and

(ii) force eE_H due to Hall field, acting upwards. In equilibrium, these two forces will be equal and opposite.

Hence $e E_H = Bev$---(1) where v is the drift velocity of the electrons.

Or $E_H = Bv$----(2)

The current density J can be expressed in terms of concentration of carriers n and their drift velocity as

$J = nev$ or $v = J/ne$

Therefore, we can write the equation (2) as

$$\mathbf{E_H = BJ/ne} \quad \text{---(3)}$$

Or $$\mathbf{E_H = R_H BJ} \quad \text{------ (4)}$$

Where $\mathbf{R_H = \frac{1}{ne}}$ is called **Hall coefficient**, which is a measure of strength of the Hall field induced.

For a given semiconductor, the **Hall coefficient R_H** is defined as the **Hall field generated in the material per unit magnetic field applied when the current density is unity.**

i.e, $$R_H = \frac{E_H}{BJ} \quad \text{---- (5)}$$

14) In case of n-type semiconductor,

$$R_H = -\frac{1}{ne} \qquad \text{---- (6)}$$

since the Hall field developed is in negative Y- direction.

For a p-type semiconductor, R_H will be positive and is given by

$$R_H = \frac{1}{Pe} \qquad \text{---- (7)}$$

Expression for Hall voltage and carrier concentration: Let the rectangular slab has length l, breadth b and thickness t and a current I flowing through it results in a current density J across the cross-section A= bt. Let B be the magnetic field acting along the thickness t.

Then, $E_H = V_H / b$ and Cross sectional area, A=b x t,

Therefore, current density

$$J = \frac{I}{A} = \frac{I}{b \times t}$$

Therefore equation (3) can be written as

$$\frac{V_H}{b} = \frac{B}{ne}\frac{I}{bt}$$

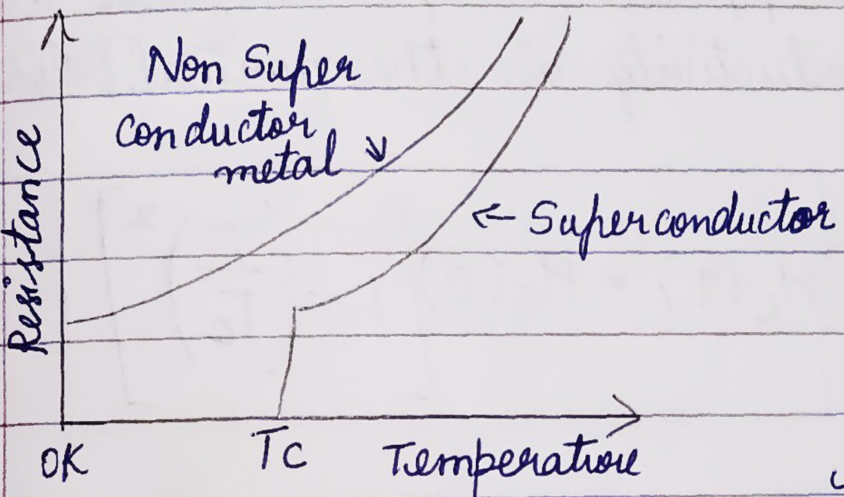
where V_H is the Hall voltage generated across the breadth and I is the current flowing along the length.

Or $$n = \frac{BI}{e\,t\,V_H} \quad \text{and} \quad V_H = \frac{BI}{net}$$

Super Conductors :

> Certain metals and alloys exhibit almost zero resistivity, when they are cooled to sufficiently low temperature. This effect is called 'superconductivity'

> This was first discovered in 1911 by H. K. Onnes



> Critical temperature (T_C)

The temperature at which the transition from normal state to superconducting state takes place on cooling in the absence of magnetic field is called critical temperature / transition temperature

> ## Properties of Superconductors :-

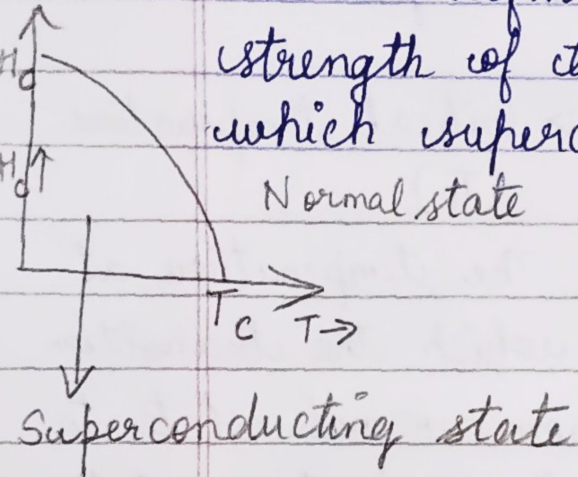
→ Critical Magnetic field (H_C)

- Superconductivity of a metal mainly depends on the temperature and strength of magnetic field in which the metal is placed.

- Superconductivity dissapears if the temperature of the specimen is raised by T_c or a strong enough magnetic field is applied.

- At temperatures below T_c, in the absence of M.F the material is in superconductivity state.

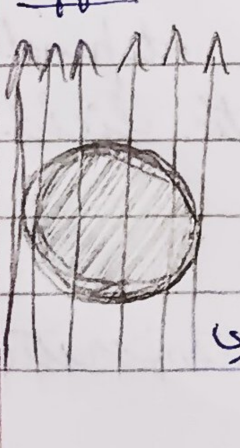
> We can define - <u>Critical magnetic field</u>, as the strength of the applied magnetic field above which superconductivity in the material disappears



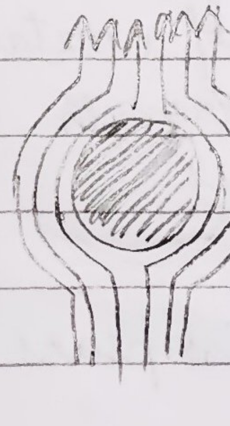
$$\boxed{H_c(T) = H_c(0)\left[1 - \left(\frac{T}{T_c}\right)^2\right]}$$

→ <u>The Meissner Effect</u> :

When a weak magnetic field is applied to a superconducting specimen at a temperature below transition temperature T_c, the magnetic flux lines are expelled. This phenomenon is called <u>Meissner effect</u>.



↳ $T > T_c$



↳ $T < T_c$

→ All superconductors are 'Diamagnetic'

- When a magnetic field is applied to the material the magnetic flux lines pass through the material

- Now, if the temperature is reduced below critical temperature the magnetic flux lines will be expell-ed from inside the superconductor. Hence we have, $B = \mu (H + M) = 0$
  where M is the magnetization of material due to an applied magnetic field H.

- The magnetic susceptibility is given by

$$\boxed{\chi = \frac{M}{H} = -1}$$

→ Critical Current :- I_c

Critical current is the maximum current that a superconductor can carry without becoming non-superconductive.

$$\boxed{I_c = 2\pi r H_c}$$ where r is radius

Silsbee's rule

This puts a limit on the electric current that can be passed through a superconductor.

Isotopic Effect

In superconducting material, the transition temperature varies with the average isotopic mass (M) of their constituents. The variation is found to be in general form.

$$\boxed{T_c M^{1/2} = \text{Constant}}$$

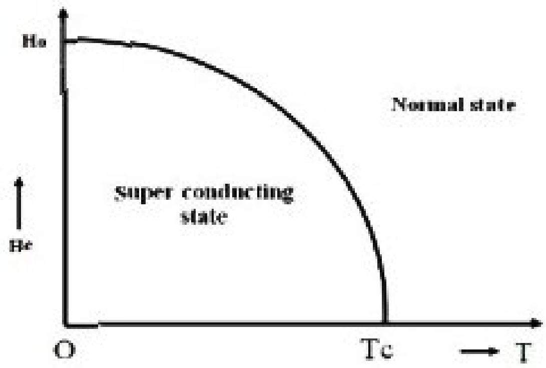
$$\boxed{T_c \propto \frac{1}{\sqrt{M}}}$$

1. Critical magnetic field (Hc)

Superconductivity of a metal mainly depends on the temperature and strength of the magnetic field in which the metal is placed. Superconductivity disappears if the temperature of the specimen is raised above Tc or a strong enough magnetic field is applied. At temperatures below Tc, in the absence of magnetic field, the material is in superconducting state. When the strength of the magnetic field is increased to a critical value Hc the material loses its superconducting property. **Thus, the critical magnetic field is defined as, the strength of the applied magnetic field above which superconductivity in the material disappears.** The dependence of critical magnetic field upon the temperature is given by

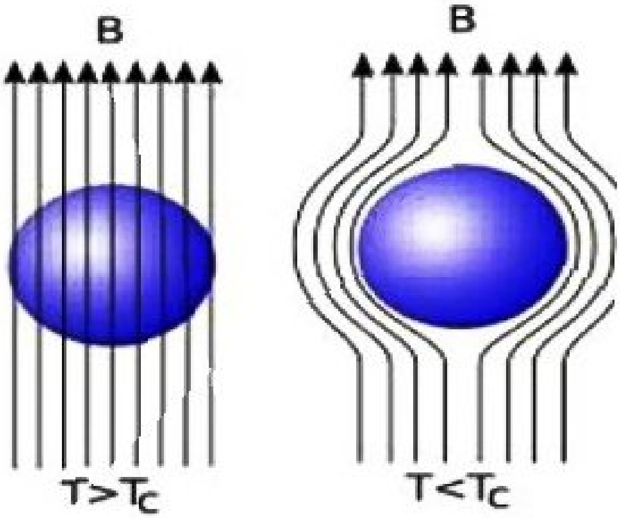
$$H_C(T) = H_C(0)\left[1 - \left(\frac{T}{T_C}\right)^2\right]$$

The variation of Hc with respect to T is shown in figure.



2. The Meissner Effect

When a magnetic field smaller than critical field is applied to a superconducting specimen at a temperature below transition temperature Tc, the magnetic flux lines are expelled out of the superconductor. This phenomenon is called **Meissner effect**.



Types of superconductors: Type I and type II superconductors:

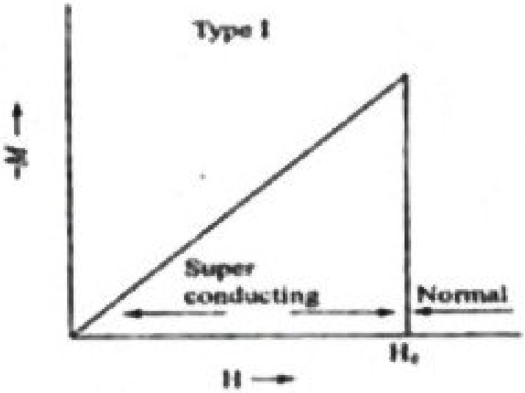
Based on the diamagnetic response superconductors can be classified into two types, they are

1. Type - I superconductors
2. Type - II superconductors

Type I superconductors:

Type-I superconductors also known as soft superconductors which follow a complete Meissner effect. Type I superconductors have a small critical magnetic field and the transition from the superconducting to the normal phase at the critical field is abrupt. When the applied magnetic field strength is gradually increased, at Hc the diamagnetism abruptly disappears and the transition from superconducting state to normal state takes place sharp at the critical field value as shown in figure. For all values of magnetic field above the critical field, the material shows finite resistivity, and the magnetic flux penetration is complete. In other words, Type I superconductors display Meissner effect completely. The low critical field value restricts these materials from its application in superconducting magnets.

Examples: Hg, Pb, Zn, and Sn.



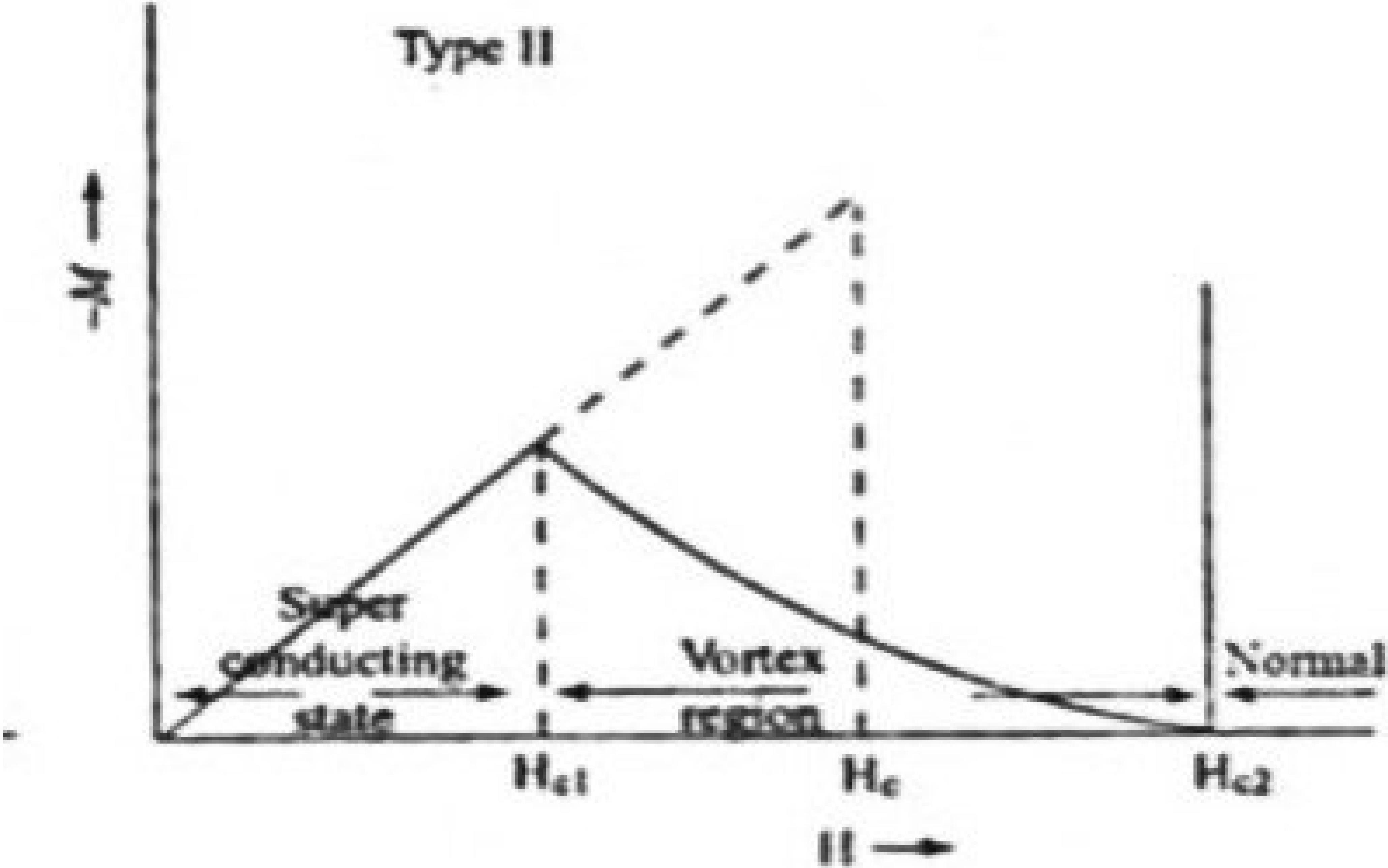
Effect of magnetic field on Type I superconductor

Type II Superconductors:

Type II superconductors also known as hard superconductors do not follow the complete Meissner effect. They have two critical fields lower critical field H_{C_1} and upper critical field H_{C_2}. The value of Hc_1 is small, Hc_2 is quite large. For the applied field less then H_{C_1}, it expels the magnetic flux completely and behave as a perfect diamagnetic. As applied field exceeds H_{C_1} the flux starts to penetrate through the superconductor. Between $H_{C_1}$and $H_{C_2}$the flux penetration increases with increase in field, but superconductor retains zero resistivity property. This state is called vortex state or mixed state. At H_{C_2} the flux penetrates completely, and the specimen comes to normal state. The flux penetration takes place through thin channelized regions called filaments, the width of which increases with increase in field strength and at H_{C_2} there will be a single filament.

Examples: - NbTi, Nb_3Sn

Type-II superconductors are used in the manufacturing of the superconducting magnets of high magnetic fields above 10 Tesla.



Effect of magnetic field on Type II super-conductor

→ <u>Type I</u> :

- Superconductors which follow complete Meissner effect.
- When the Magnetic field strength is gradually increased from its intial value $H < H_c$ at H_c, the diamagnetism is abruptly disapear and the transition from superconducting state to normal state.
- Soft Superconductors
- Eg: Al, Zn, Hg and Sn

→ <u>Type II</u> :

- Does not follow complete Meissner effect.
- Exists in 3 stages - i) Superconducting state
  ii) Mixed state
  iii) Normal state.
- For the field less than H_{C_1} it expels the magnetic field completely and becomes a perfect diamagnetic state or superconducting state.
- Between HC_1 and HC_2 the flux starts penetratin-g throughout the specimen. This state is called Vortex or mixed state.
- At HC_2 the flux penetrates completely and becom-es normal conductor : Also called hard super Conductors

Examples: NbTi, Nb, Sn

Type-I	Type-II
• These are usually elements in their pure form	• These are impure alloys or compounds.
• The transition to normal state occurs abruptly at a critical magnetic field (H_c)	• The transition to normal state begins at H_{c1} and is complete only at H_{c2}
• The value of critical magnetic field (H_c) is usually very small	• Though the value of HC1 is small, H_{c2} is quite large
• They exhibit complete Messiner effect	• They do not exhibit complete Messiner effect
• The superconductivity state is observed upto critical magnetic field (H_c)	• The material remains in this resistance less state even in the intermediate state between HC1 and HC2
• Small value of HC restricts their use	• Large value of HC_2 makes it suitable for application

24)

BCS Theory

- BCS theory of superconductor was put forward by Bardeen, Cooper and Schrieffer in 1957
- Hence named as BCS theory.
- This theory could explain the phenomena of superconductivity.
- This BCS theory is based upon the formation of Cooper pairs.

BCS Theory

- The main idea behind the BCS theory is the discovery of isotopic effect of superconductivity.
- The isotope effect suggests that the current carrying electron in a superconductor do not move independently but instead they move interacting with lattice. (Electron lattice interaction via lattice deformation.)
- The lattice is slightly deformed as an electron comes near the lattice and also lattice will displace from its position.
- This displacement of lattice is called **lattice distortion.**

BCS Theory

- The deformation produce increased positive charge at the lattice.
- Another electron moving through this positive region will be attracted by the greater concentration of the positive charge there.
- This attraction is stronger than the repulsion between the electrons
- Electrons are effectively coupled together into form a Cooper pair with the deformed lattice as the intermediary.

BCS Theory

- The electron – lattice – electron interaction does not keep the electrons a fixed distance.
- Electrons moving in opposite directions and their separation are as great as 10^{-6} m.
- The binding energy of a Cooper pair called Energy gap E_g is of the order of 0.001 eV.

$$E_g \text{ at } 0\text{ K} = E_g(0) = 3.53kT_C$$

(k – Boltzmann constant & T_C – Critical temperature.

BCS Theory

- At room temperature (300 K) energy is $kT = 0.026$ eV which is higher than the binding energy of cooper pairs
- This energy is sufficient to break the cooper pair.
- This is the reason why superconductor phenomena is observed only at low-temperature.
- The electrons in a cooper pair have opposite spins, so the pair has a total spin of zero.
- As a result, the electron pairs in a superconductor are **bosons**.

BCS Theory

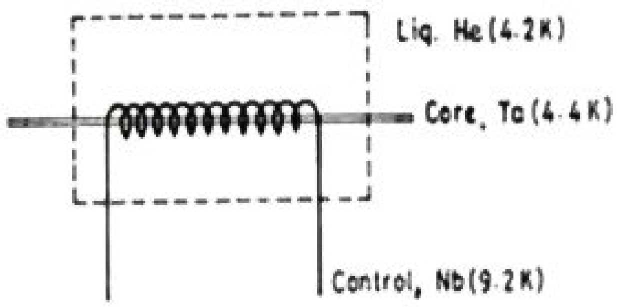
- Spin angular momentum of the electrons in a cooper pair is equal and opposite and total momentum is zero.
- Cooper pairs are bosons and exist in same energy state or quantum state.
- All these cooper pairs are involved in current in a superconductor.

25) **Applications of superconductors:**

The major applications that are based on the properties of the superconducting phase are

1. Superconducting memories and switches (Cryotron)
2. Magnetic levitation
3. Lossless power transmission
4. Superconducting magnets
5. Superconducting quantum interference devices (SQUIDS)

1. **Superconducting switch - Cryotron:** The disappearance ofsuperconductivity for magnetic fields higher than the critical field is the principle used in the construction of a **cryotron.**



It consists of a core wire A around which a control coil B is wound. The core A is made of tantalum (Tc=4.4 K) and control coil B is made of niobium (Tc=9.2 K) or lead (Tc=7.2 K). The whole assembly is maintained at liquid helium temperature (4.2 K). At this temperature, both the control coil and the core wire are in the superconducting phase. Hence, the resistance of the core wire will be zero. A current can be passed through the control coil to produce a magnetic field sufficient to make the core wire 'normal'. Thus, the core wire can be made to possess zero or finite resistance depending on the control current being 'off' or 'on' respectively. These two states of the core wire may be considered as the ON and OFF states. Thus, cryotrons can be used as switches.

2. **Magnetic levitation:** The principle of the repulsion ofmagnetic flux from a superconductor can be used in **magneticlevitation** applications. When a magnet is brought near asuperconductor, there will be a repulsion and the superconductor tries to move away from the magnet. Because of this superconducting wheel experience reduced friction on magnetic tracks.
3. **Lossless power transmission:** The transmission of electricalpower on a large scale is limited due to the restrictions on the current carrying capacity of transmission lines and their maintenance. Loss of power due to power dissipation in transmission lines due to the finite resistance offered by the cables is quite considerable. If the transmission lines are made of materials in their superconducting state, their current carrying capacity increases. Since these lines do not offer any resistance to the flow of electric current, there is no power dissipation due to joule heating. Thus, power losses are minimized and current carrying capacity is improved. This is the principle used in **lossless power transmission.**

4. **Superconducting magnets:** Use of superconducting coils in the electromagnets can enhance the magnetic field generated as they can carry large currents with practically no dissipation. This is the principle used in the construction of **superconductingmagnets**.

- 2), 15) Didn't find answers for these
- 16),17), 18) Not included for MSE-2

~ISE-'I'