Unit 3. SOLID STATE PHYSICS

INTRODUCTION

Solid-state physics is the study of rigid matter or solids, through methods such as quantum mechanics, crystallography, electromagnetism and metallurgy. It is the largest branch of condensed matter physics. Solid-state physics studies how the large-scale properties of solid materials result from their atomic-scale properties. Thus, solid-state physics forms a theoretical basis of materials science. It also has direct applications, for example in the technology of transistors and semiconductors.

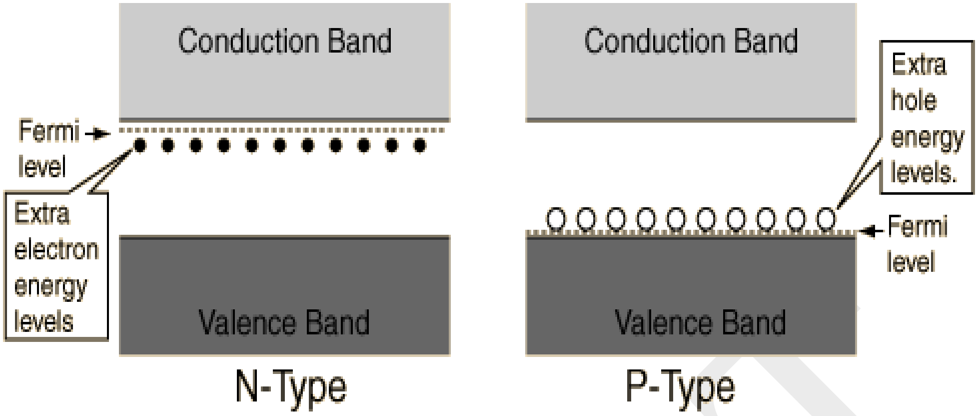
HISTORY

The physical properties of solids have been common subjects of scientific inquiry for centuries, but a separate field going by the name of solid-state physics did not emerge until the 1940s, in particular with the establishment of the Division of Solid State Physics (DSSP) within the American Physical Society. The DSSP catered to industrial physicists, and solid-state physics became associated with the technological applications made possible by research on solids. By the early 1960s, the DSSP was the largest division of the American Physical Society.

Large communities of solid state physicists also emerged in Europe after World War II, in particular in England, Germany, and the Soviet Union. In the United States and Europe, solid state became a prominent field through its investigations into semiconductors, superconductivity, nuclear magnetic resonance, and diverse other phenomena. During the early Cold War, research in solid state physics was often not restricted to solids, which led some physicists in the 1970s and 1980s to found the field of condensed matter physics, which organized around common techniques used to investigate solids, liquids, plasmas, and other complex matter. Today, solid-state physics is broadly considered to be the subfield of condensed matter physics, often referred to as hard condensed matter that focuses on the properties of solids with regular crystal lattices.

- **ENERGY LEVEL IN *n-type* AND *p- type* SEMICONDUCTOR**

The n type and p type semiconductors are produced by addition of impurity in pure semiconductor (Si, Ge). In n- type semiconductor materials, there are extra electron energy levels near the bottom of conduction band and can easily exited into the conduction band. In p-type semiconductor materials, extra holes energy level near to top of valence band allows excitation of valence electrons.



- **FERMI DIRAC DISTRIBUTION**

In conduction band, the distribution of an electron is OR its probability that electron occupies energy level at thermal equilibrium is

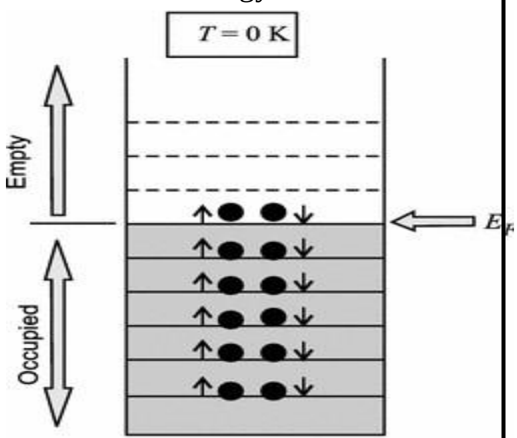
$$f(E) = \frac{1}{1+\exp(E-E_F)/kT} \text{..........(1)}$$

$where, E_F = Fermi\ energy\ level\ of\ eletrons\ or\ holes$

$f(E) =$ probability function

k=Boltzman constant

The above equation is also called as Fermi Dirac Distribution Function.The fermi energy of conductor can be calculated at zero and elevated temperatures.

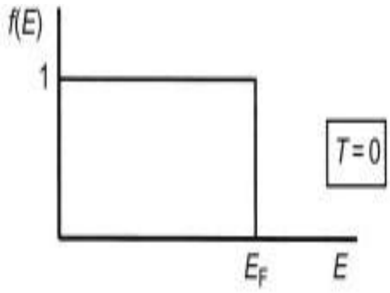


A) At 0 K, Figure shows the conduction band of conductor. The electron distribution is from the bottom of conduction band to upper level E_F. Thus, fermi level is defined as " **The maximum uppermost filled level in conductor at 0K".** Or the maximum energy that free electrons can have in conductor at 0K.

(i) If energy level (E) lying below the E_F then

$E<E_F= -Ve$

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



i.e. All the energy levels are lying below E_F are occupied by electron

(ii) If energy level (E) lying above the E_F then $E>E_F= +Ve$

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

i.e. all the levels above E_F are vacant.

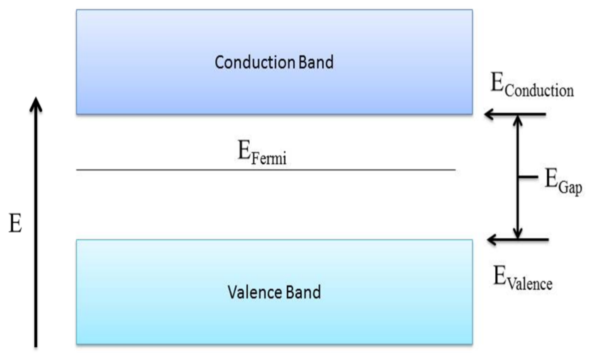
B) At T > 0K (increase in temperature), due to the result of thermal excitation, the probability of finding electrons is increases because the jumping of electrons increases above E_F increases. If we consider electron is present at fermi energy level then $E=E_F$

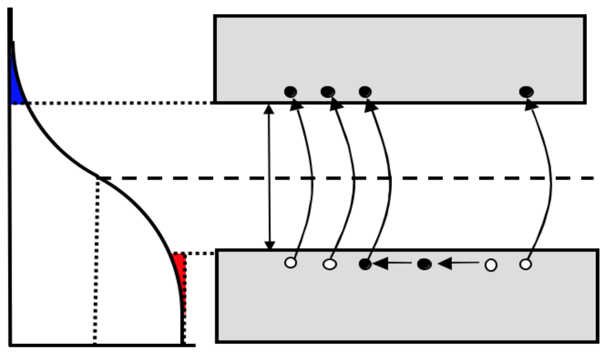
$$\therefore f(E)=\frac{1}{1+e^{(E-E_F)/kT}}=\frac{1}{1+e^{0/kT}}=\frac{1}{1+1}=\frac{1}{2}=0.5$$

This implies that probability of occupancy at increasing temperature is 0.5 i.e. 50%. Hence fermi energy can also defined as, "**Average energy of an electrons in conduction band at temperature above 0K**".

- **ENERGY BAND DIAGRAM FOR SEMICONDUCTORS AND ITS FERMI ENERGY**

1) INTRINSIC SEMICONDUCTOR





Band Diagram

F-D Distribution

At normal temperature, a significant number of electrons are exited from V.B. to C. B. An equal number of vacancies produced in V.B. called as holes.

Thus $n_e=n_h=n_i^2$

The electron concentration in conduction band in intrinsic Semiconductor is given by,

$$n = Nc\, e^{-(E_C-E_F)/kT} \text{.........(1)}$$

where Nc=density of electron in $C.B. = 2.8x10^{28}/m^3$

and the hole concentration in valance band in intrinsic Semiconductor is given by,

$$p = N_v\, e^{-(E_F - E_V)/kT} ....(2)$$

where N_v =density of holes(h^+) in $V.B. = 2.8x10^{28} / m^3$

- **FERMI ENERGY LEVEL IN INTRINSIC SEMICONDUCTOR**

In pure semiconductor, the electrons in conduction band are always equal to holes in valence band. The electron and holes concentration is given by equation,

$$n = Nc\, e^{-(E_C - E_F)/kT} ....(1)$$

$$\text{and } \; p = Nv\, e^{-(E_F - E_V)/kT} ....(2)$$

For Intrinsic S.C.,

The number of electrons in C.B (e^-) =number of holes in V.B.(h^+) then

i.e. n=p

$$Nc\, e^{-(E_C - E_F)/kT} = Nv\, e^{-(E_F - E_V)/kT} ....(3)$$

taking logarithm on both sides,we get

$$-\frac{(E_C - E_F)}{kT} = \ln \frac{N_V}{N_C} - \frac{(E_F - E_V)}{kT}$$

$$\therefore -E_C + E_F = kT \ln \frac{N_V}{N_C} - E_F + E_V$$

$$\therefore 2E_F = E_C + E_V + \ln \frac{N_V}{N_C}$$

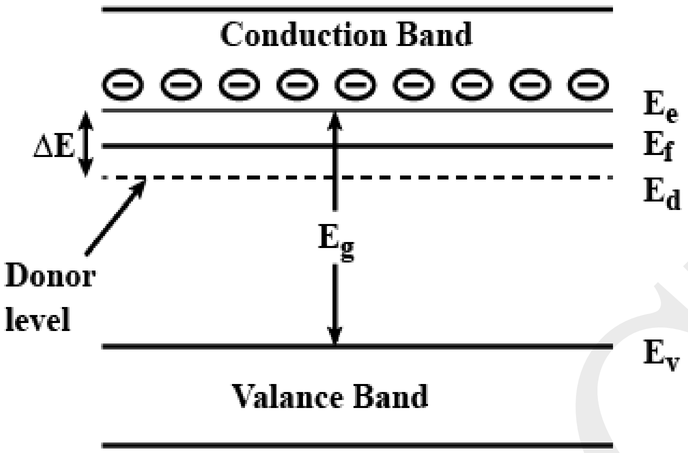
$$but\ N_V = N_C\ then\ \ln \frac{N_V}{N_C} = \ln(1) = 0$$

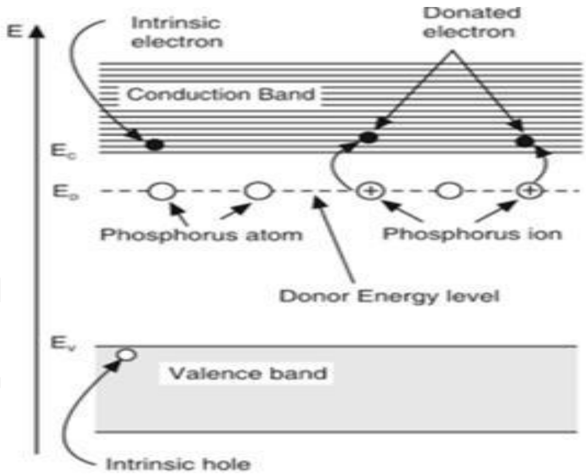
$$\therefore 2E_F = E_C + E_V \quad \therefore E_F = \frac{E_C + E_V}{2} ....(4)$$

Thus for intrinsic semiconductor, fermi energy level lies in the middle of forbidden energy gap (Band Gap energy) Eg.

• FERMI ENERGY LEVEL IN *n-type* SEMICONDUCTORS

The n-type semiconductor is shown in figure. The dopant atoms have their own energy level just below the conduction band called as "Doner energy level(E_D)". With increase in temperature, doner atoms gets ionized and electrons goes from E_D to E_C level first and then remaining from E_V to E_C. Hence fermi energy lies in between E_C and E_D.





: Energy band diagram of n-type semiconductor

Let n_D= number of doner electrons in doner energy level E_D and its concentration in E_D level is

$$n_D = N_D e^{(E_D - E_F)/kT} \text{..............(1)}$$

$$where, N_D = \text{density of doner electrons in doner level}$$

Also, electron concentration in conduction band is

$$n = Nc\, e^{-(E_C - E_F)/kT} \text{.........(2)}$$

$\therefore$ equating eqation (1) and(2)we get

$$N_D e^{(E_D - E_F)/kT} = Nc\, e^{-(E_C - E_F)/kT}$$

taking logarithm on both sides,we get,

$$\frac{(E_D - E_F)}{kT} = \ln \frac{Nc}{N_D} - \frac{(E_C - E_F)}{kT}$$

$$\therefore \frac{E_D - E_F + E_C - E_F}{kT} = \ln \frac{Nc}{N_D} \quad i.e. \quad E_D + E_C - 2E_F = kT \ln \frac{Nc}{N_D}$$

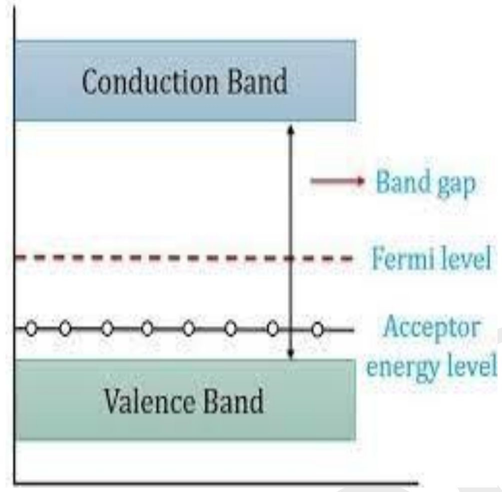
$$\therefore At\ T \neq 0 \text{ then } kT \ln \frac{Nc}{N_D} \ \&\ Nc = N_D \ \therefore kT \ln(1) = 0$$

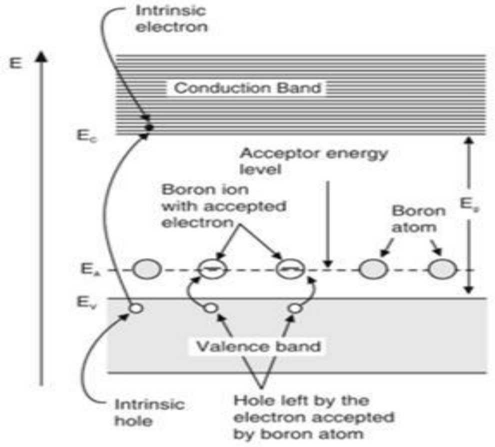
$$\therefore E_D + E_C - 2E_F \quad \therefore E_F = \frac{E_D + E_C}{2} \text{..........(3)}$$

Equation (3) gives the equation for fermi energy in n-type semiconductors.

• FERMI ENERGY LEVEL IN *p-type* SEMICONDUCTORS

The Energy band diagram for *p-type* semiconductor is shown in figure. The acceptor atoms have their own energy level just above the valence band. With increase in temperature, acceptor atoms gets ionized and holes concentration in V.B. increases. Here e^- goes from E_V to E_A and then E_A to E_C. Therefore, hole concentration between E_V and E_A is the fermi energy E_F for p-type semiconductor.





. Energy band diagram for a *p-type* semiconductor

The number of hole concentration in acceptor level is,

$$p+ = N_A e^{(E_F - E_A)/kT} \text{.............}(1)$$

$$where, N_A = \text{density of Acceptor holes in Acceptor level}$$

Also, holes concentration in Valance band is

$$p = N_V\ e^{-(E_F - E_V)/kT} \text{.........}(2)$$

equating (1) and (2), we get,

$$N_A e^{(E_F - E_A)/kT} = N_V\ e^{-(E_F - E_V)/kT}$$

taking logarithm on both sides, we get,

$$\frac{(E_F - E_A)}{kT} = \ln\frac{N_V}{N_A} - \frac{(E_F - E_V)}{kT}$$

$$\frac{E_F - E_A + E_F - E_V}{kT} = \ln\frac{N_V}{N_A}$$

$$\therefore -(E_A + E_V) + 2E_F = kT\ln\frac{N_V}{N_A}$$

$$but, \frac{N_V}{N_A} = 1 \therefore kT\ln(1) = 0$$

$$\therefore 2E_F = (E_A + E_V) \quad \therefore E_F = \frac{E_A + E_V}{2} \text{...........}(3)$$

Equation (3) is the equation for fermi energy in *p-type* semiconductor.

Unit 3. SOLID STATE PHYSICS

- **HALL EFFECT**

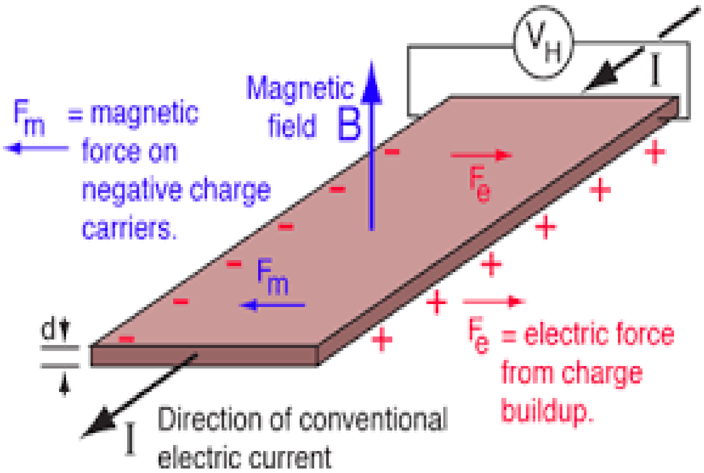
STATEMENT

When metal conductor (semiconductor) carrying current 'i' placed in transverse magnetic field 'B', potential difference 'V_H' is produced across conductor, is called **"Hall Effect".**

CONSTRUCTION

A thin rectangular semiconductor wafer mounted between magnetic field. One pair of the cubic sample connected to ammeter and other pair to the voltmeter.

When magnetic field applied normal to the two faces of semiconductor then current is allowed to pass through it. Due to magnetic field, the electrons are moving towards left side of semiconductor and holes are towards the right side.



$\therefore$ F_E due to current and F_B due to magnetic field trying to pull electrons towards each other. At certain stage the number of electrons gets saturated to the left side and holes to the right side and then electron is moving undeviated because $F_E=F_B$

At equilibrium, $F_E=F_B \therefore$ e E=eV_dB i.e. E= V_d. B……(1)

If 'w' is the width of semiconductor then electric field across potential difference V_H is

$$E = \frac{V_H}{w}\text{.............}(2)$$

Put equation (2) in (1), we get

$$\frac{V_H}{w} = V_d B\text{............}(3)$$

For current carrying semiconductor, number of charge carrier in length 'L' is 'nAL', where, n= number of charge carriers. Therefore, Total charge carriers in length 'L' each of charge 'e' is given by, q= (nAL).e……… (4)

Now the drift velocity of an electron through length 'L' is

$$V_d = \frac{L}{t} \quad \therefore t = \frac{L}{V_d} ......(5)$$

& current flowing through Semiconductor is,

$$i = \frac{q}{t} = \frac{(nAL).e.V_d}{L} = (nAe).V_d \quad ....(6)$$

$$\therefore V_d = \frac{i}{nAe} \quad ....(7)$$

put equation in (3), *we get*

$$\frac{V_H}{w} = \left(\frac{i}{nAe}\right).B$$

$$\therefore V_H = \frac{Biw}{nAe} = \frac{Biw}{n(w.d)e} = \frac{Bi}{ned} .....(A = w\,x\,d)$$

$$\therefore V_H = \frac{Bi}{ned} ....(8) \quad OR \quad V_H = \frac{Bi}{d}\left(\frac{1}{ne}\right)$$

HALL COEFFICIENT (R_H)

The Hall field (E) per unit current density (J_x) per unit magnetic field (B) is called "Hall Coefficient".

$$i.e.\ R_H = \frac{E}{J_x.B} = \frac{V_H/w}{J_x.B} = \frac{V_H}{J_x.B.w} ......(1)$$

$$R_H = \frac{1}{J_x.B.}\left(\frac{V_H}{w}\right) = \frac{1}{J_x.B}\left(\frac{B.i}{n.A.e}\right) = \left(\frac{i}{J_x n.A.e}\right)$$

$$R_H = \frac{1}{ne}\left(\frac{i}{A}\right).\frac{1}{J_x} = \frac{J_x}{neJ_x} = \frac{1}{ne}$$

$$\therefore R_H = \frac{1}{ne} ....(2)$$

$$OR\ R_H = \frac{V_H.d}{Bi} ....(3)$$

- **DEPENDENCE OF FERMI ENERGY ON TEMPERATURE**

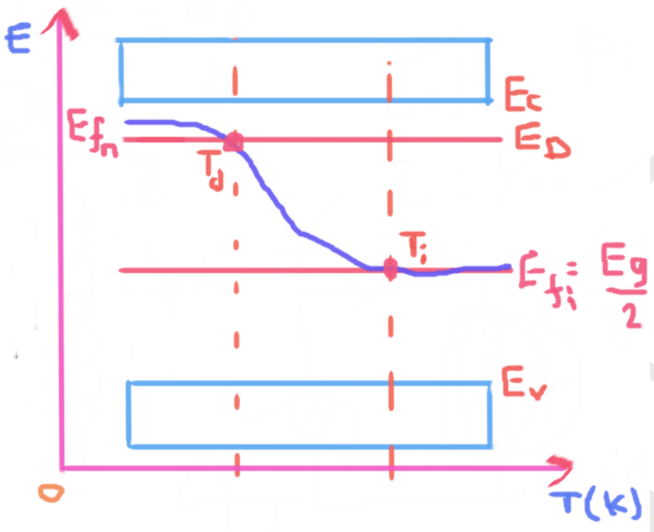
1. **Variation of Fermi Energy with temperature in *n- type* Semiconductor**

At lower temperature, some doner atoms are ionized and provide electrons to conduction band. As electron in C.B. is due to doner level & fermi energy lie between doner level and conduction band. i.e. $E_{f_n} = \frac{E_C + E_D}{2}\ at\ T = 0K ....(1)$

As the temperature across semiconductor increases, the doner level is depleted and fermi level moves downwards.

The temperature at which Fermi level coincides with doner level called as "**Depleted Temperature (T_d)**"

$$\text{i.e. } E_{f_n} = E_D \text{ at } T = T_d \text{.......(2)}$$



Further temperature increases above T_d ($T>T_d$), then fermi level again shift downwards linearly. And reaches to temperature Ti then Ef_n equals to Eg/2

i.e. Fermi level of n-type semiconductor coincides with fermi level of intrinsic semiconductor.

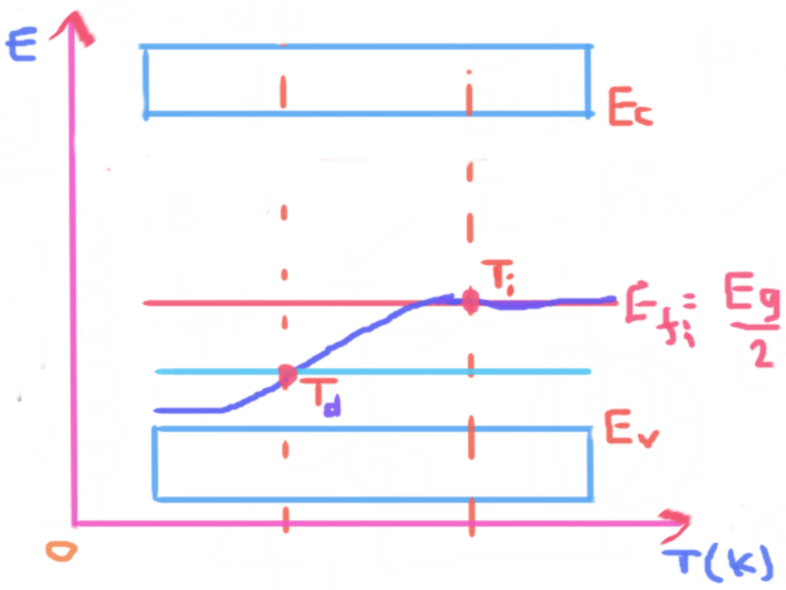
$$\text{i.e } E_{f_n} = E_{f_i} = \frac{Eg}{2} \quad T > T_i \text{.........(3)}$$

Where Ti = **inversion temperature at which n-type Semiconductor convert into intrinsic semiconductor.**

2. **Variation of Fermi Energy with temperature in *p- type* Semiconductor (4 Marks)**

At lower temperature, holes in Valence Band are only due to transition of electrons from V.B. to Acceptor level. As valance band is source of electrons and acceptor level is recipients for them. The fermi energy lies between top of E_V and Bottom of E_A as shown in figure i.e.

$$E_{f_p} = \frac{E_V + E_A}{2} \, at \; T = 0K \text{.......(1)}$$



As the temperature across semiconductor increases, the acceptor level filled & fermi level moves downwards. Later wards, the temperature at which Fermi level coincides with acceptor level called as "**Depleted Temperature (T_d)**"

$$\textbf{i.e. } E_{f_p} = E_A \; at \; T = T_d ....(2)$$

Again T >Td, the fermi level increases linearly and reaches to temperature 'Ti', at which Ef_p equals to Eg/2.

i.e. Fermi level of p-type semiconductor coincides with fermi level of intrinsic semiconductor.

$$E_{f_p} = E_{f_i} = \frac{Eg}{2} \quad T > T_i ....(3)$$

Where Ti **= inversion temperature at which p-type Semiconductor convert into intrinsic semiconductor.**

Numericals

1) A copper strip 2.0 cm wide and 1.0 mm thick is placed in a magnetic field with B= 1.5 wb/m^2. If a current of 200A is set up in the strip, calculate Hall voltage that appears across the strip (R_H=6 x 10^{-7} m^3/C.) (2M)

2) In a Hall coefficient experiment, a current of 0.25 A is sent through a metal strip having thickness of 0.2 mm and width of 5 mm. The Hall voltage is found to be 0.15mV when a magnetic field of 2000G is used.(4M)…..(2000G= 0.2T)
   (a) What is the carrier concentration (n) ?
   (b) What is the drift velocity of carriers?