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SSP-II

Assignment no 2

"Exam Preparation Questions"

Q1) What is a complex dielectric constant? How does it vary with frequency of applied field?

ANS **Complex Dielectric Constant** is a physical quantity that express the capability of a material to withstand external fields that have a strong dependence from the frequency.

→ It is denoted by 'ε_r^*'

→ It has two parts $\varepsilon_r^* = \underbrace{\varepsilon_r'}_{\text{Real Part}} - i\underbrace{\varepsilon_r''}_{\text{Imaginary Part}}$

(i) **Real Part** (ε_r') represents the material's ability to store electrical energy.

(ii) **Imaginary Part** (ε_r'') represents the material's ability to dissipate energy as heat.

⇒ **Variation with frequency:-**

The complex dielectric constant varies with the frequency of the applied electric field.

At low frequencies, ε' dominates, indicating material's ability to store energy.

Note:- When we apply DC, we get only real part of dielectric constant. But when we apply AC signal, we get both real and imaginary parts.

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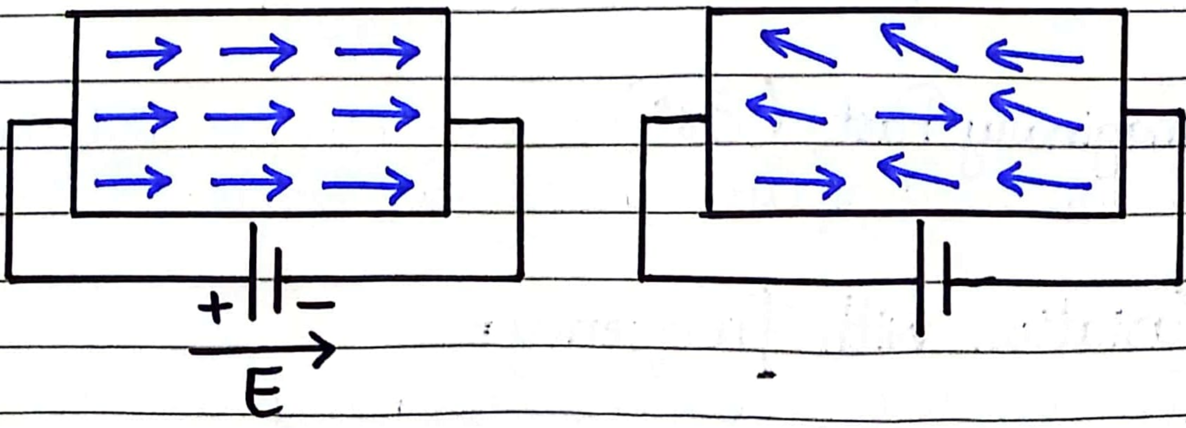
As frequency increases ε'' become more significant, indicating increased energy dissipation within the material due to processes like molecular rotation or polarization relaxation.

Q2) Explain the term dipolar relaxation and loss angle.

(i) **Dipolar Relaxation** refers to the reallignment of polar molecules within a material in response to an applied electric field.

$\Rightarrow$ When electric field is applied, polar molecules in the material tend to allign with the field direction. However, due to thermal motion they relax back to their random orientation when the field is removed.



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(ii) **Loss Angle** :- denoted by 'δ', is a measure of the phase shift between the electric field and polarization response of a material.

$$\tan \delta = \frac{\varepsilon''}{\varepsilon'}$$

Q3) Show that the imaginary part of the dielectric constant is a measure of dielectric loss.

ANS The imaginary part of dielectric constant (ε_r'') is related to dielectric loss in a material.

⇒ Dielectric loss / Loss Tangent ($\tan \delta$) is the ratio of imaginary part to real part of the dielectric constant.

$$\tan \delta = \frac{\varepsilon''}{\varepsilon'}$$

(i) ε' = real part of dielectric constant, representing the material's ability to store energy in an electric field.

(ii) ε'' = imaginary part of dielectric constant, representing the material's ability to dissipate energy as heat due to dielectric loss

$$\tan \delta \propto \varepsilon''$$

A higher ε'' value indicates higher loss tangent and hence more heat loss. So the imaginary part ε'' is a measure of dielectric loss.

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Q4) Explain with suitable diagrams.

(i) **Conduction Band** :- is the band in which electrons are free to move under the influence of electric field.

- It is at a higher energy level and thus lies above the valance band.
- It is partially filled by the electrons.
- Electrons in conduction band move freely and contribute to electrical conduction.

(ii) **Valance Band** :- have electrons tightly bound to the atoms. Their bond with neighbouring atom is so strong that they cannot move freely.

- It is at a lower energy level and thus lies below conduction band.
- It is completely filled with electrons.
- Electrons in valance band cannot move freely and thus do not contribute in conduction.

(iii) **Forbidden Band** :- is a band between valance and conduction band in which no free electron is present.

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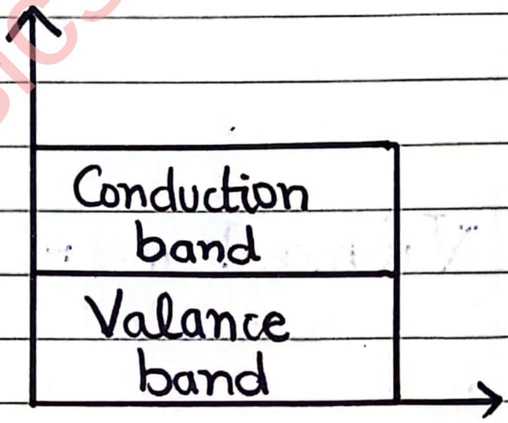
- The width of the forbidden gap depends upon the nature of the substance.
- As the temperature increases, the width of forbidden energy gap decreases.

(iv) **Conductors:-** have their valance and conduction band overlapped and hence electrons can easily move from valance to conduction band, resulting in high conductivity.

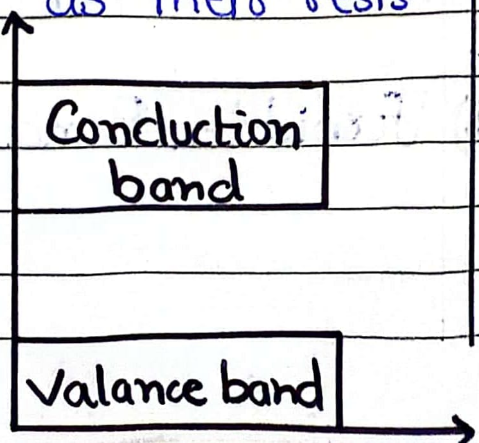
⇒ **Examples**

Metals are conductors

(i) Copper (Cu)
(ii) Mercury (Hg)
(iii) Aluminium (Al)
(iv) Silver (Ag)



(v) **Insulators:-** are the materials with large band gap. The electrons in the valance shell are tightly bound to atoms and they cannot jump from valance to conduction band without the aid of external force. Hence they are not good at conducting, as their resistivity is very high.



⇒ **Examples:-**

(i) Wood
(ii) Rubber

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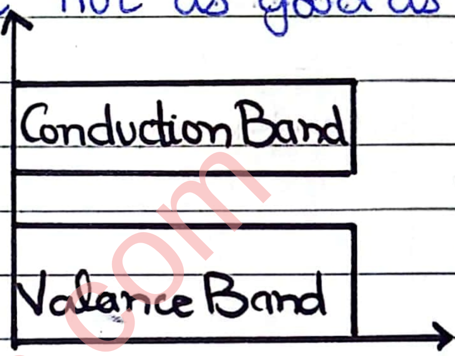
(vi) **Semi-conductors:-** are the materials with moderate band gap. Electrons can move from valance to conduction band with the aid of external energy like heat or light. They conduct but not as good as metals.



⇨ **Example:-**
(i) Silicon (Si)
(ii) Germanium (Ge)

(vii) Explain the contribution of electrons and holes to electrical conduction.

In semiconductors when an electron gains enough energy to move from valance band to the conduction band, it leaves behind a hole in the valance band. This hole serves as a positive charge carrier.

Both electrons and holes contribute to the electrical conduction in semiconductor.

Q5) What are semiconductors? How do they differ from conductors? Why an increase in temp decreases the résistivity of semiconductors?

ANS **SemiConductors:-** are materials whose conductivities range between that of conductors and insulators.

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⇒ They are classified into two types:-

Semiconductors

- **Intrinsic**
  - Pure semiconductors
  - example:-
    - Silicon
    - Germanium
- **Extrinsic**
  - Impure semiconductors
    - **N-type**
      - Pentavalent impurity added
      - example
        - Phosphorus
        - Antimony
    - **P-type**
      - Trivalent impurity added
      - example
        - Gallium
        - Boron

	Semiconductors	Conductors
1)	They have moderate conductivities. 10^{-10}	Their conductivities are high. 10^{-7} mho/m
2)	They have moderate resistivity values. $1 \Omega m$	They have low resistivity $10^{-5}\ \Omega m$
3)	They have small band gap. 1.1eV	They do not have any forbidden gap.
4)	They are formed by covalent bond.	They are formed by metallic bond.
5)	At 0K, they act as insulator.	At 0K, they acts as superconductors.

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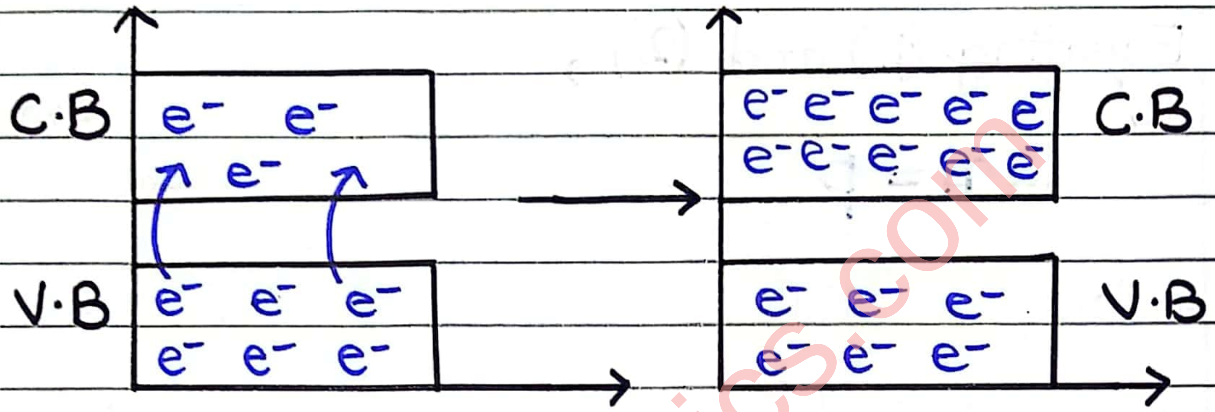
⇒ Effect of Temperature :-

As temperature increases, the electrons in the valance band gain enough thermal energy to jump into the conduction band.



⇒ As the number of electrons in conduction band increase, conductivity increases. The electrons move with a greater velocity and thus the resistivity decreases.

Q6) Write down the expression for density of electrons and holes in an intrinsic semiconductor. Equate these two equations and arrive at an expression for the fermi level. Discuss the significance of this equation.

ANS **Intrinsic Semiconductors** :- are pure crystals with no impurities and defects, with a band gap of 1eV.

⇒ Density of electrons in intrinsic semiconductor is given by,

$$n = N_c \cdot e^{\frac{-(E_c - E_F)}{KT}} \rightarrow (1)$$

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⇨ Density of holes in intrinsic semiconductor:-

$$p = N_v . e^{\frac{-(E_F - E_V)}{KT}} \rightarrow (2)$$

⇨ Equating (1) and (2),

$$n = p$$

$$N_c . e^{\frac{-(E_C - E_F)}{KT}} = N_v . e^{\frac{-(E_F - E_V)}{KT}}$$

$$2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2} = N_c \quad , \quad N_v = 2\left(\frac{2\pi m_p^* KT}{h^2}\right)^{3/2}$$

⇨ Taking log on both sides,

$$\log N_c + \log e^{\frac{-(E_C - E_F)}{KT}} = \log N_v + \log e^{\frac{-(E_F - E_V)}{KT}}$$

$$\log N_c - \frac{(E_C - E_F)}{KT} = \log N_v - \frac{(E_F - E_V)}{KT}$$

$$-\frac{(E_C - E_F)}{KT} + \frac{(E_F - E_V)}{KT} = \log N_v - \log N_c$$

$$\frac{-E_C + E_F + E_F - E_V}{KT} = \log\left(\frac{N_v}{N_c}\right)$$

$$2E_F - E_C - E_V = KT \log\left(\frac{N_v}{N_c}\right)$$

$$2E_F = E_C + E_V + KT \log\left(\frac{m_p^*}{m_e^*}\right)$$

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$$E_F = \frac{E_c+E_v}{2} + \frac{3}{2}\cdot\frac{1}{2}(KT)\ln\left(\frac{m_p^*}{m_e^*}\right).$$

$$\boxed{E_F = \frac{E_c+E_v}{2} + \frac{3}{4}(KT)\ln\left(\frac{m_p^*}{m_e^*}\right)} \rightarrow (3)$$

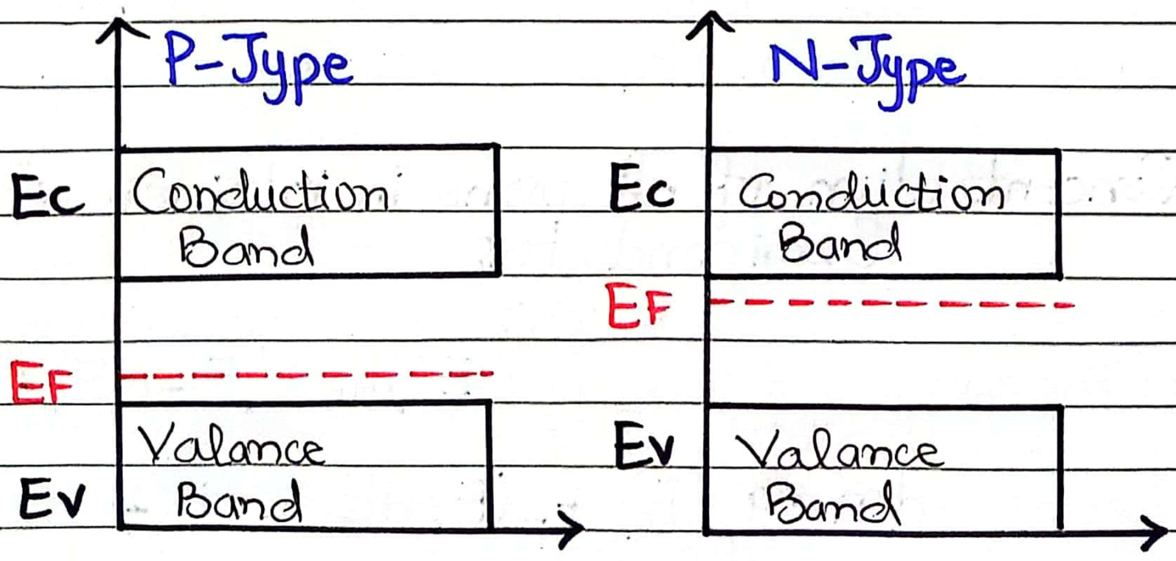
Expression for Fermi Level

⇨ **Significance:-**

- From equation (3), we can determine the position of fermi level, which helps us indicating the probability that electrons or holes would occupy certain states in a semiconductor.

- It helps us understand the behavior of charge carriers in the material and is crucial for analyzing it's electrical properties.

- Fermi level determines whether a semi-conductor behaves as an n-type or p-type semiconductor, depending upon it's relative position to conduction and valance band.



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Q7) Assuming the Boltzmann approximation applies write the equations for "n_o" and "p_o" in terms of the Fermi energy.

ANS) **Boltzmann Assumptions:-**

(i) At any finite temperature, some electrons will acquire sufficient thermal energy to raise from valance band to conduction band.

(ii) The actual number depends upon the number of permissible electrons in the energy level and probability of these levels occupied.

(iii) In order to calculate intrinsic carrier concentration, first we need to calculate the number of electrons excited to the conduction band at any given temperature which in turn are free to migrate in crystal.

(iv) It will be considered that conduction electrons behave as if they are free with the effective mass and energy will be measured from slope of valance band.

(1) Concentration of electrons in intrinsic Semiconductor

Number of electrons (dn) per unit volume in the range of energy (E) and ($E+dE$) is

$$dn = g_c(E)\, f_F(E)\, dE \quad \rightarrow (1)$$

where,

⇨ $g_c(E)$ = density of states.

$$g_c(E) = \frac{1}{2\pi^2} \cdot \left(\frac{2m_e^*}{\hbar^2}\right)^{3/2} \cdot E^{1/2} \rightarrow (2)$$

and,

⇨ $f(E)$ = Fermi-Dirac distribution function.

$$f(E) = \left[\exp\left(\frac{E-E_F}{KT}\right)+1\right]^{-1} \rightarrow (3)$$

⇨ '1' can be neglected for practical purposes,

$$f(E) = \left[\exp\left(\frac{E-E_F}{KT}\right)\right]^{-1} = \exp-\left(\frac{E-E_F}{KT}\right)$$

$$\frac{1}{e^{(E-E_F)/KT}} \rightarrow e^{\frac{-(E-E_F)}{KT}} \quad (4)$$

⇨ Put (2) and (4) in (1),

$$dn = \left[\frac{1}{2\pi^2}\left(\frac{2m_e^*}{\hbar^2}\right)^{3/2} E^{1/2}\right]\left[\exp-\left(\frac{E-E_F}{KT}\right)\right]dE$$

⇨ If the energy of an electron is measured with respect to the bottom of conduction band (E_c), then

$$E - E_F + E_c - E_c$$

$$(E - E_c) - (E_F - E_c)$$

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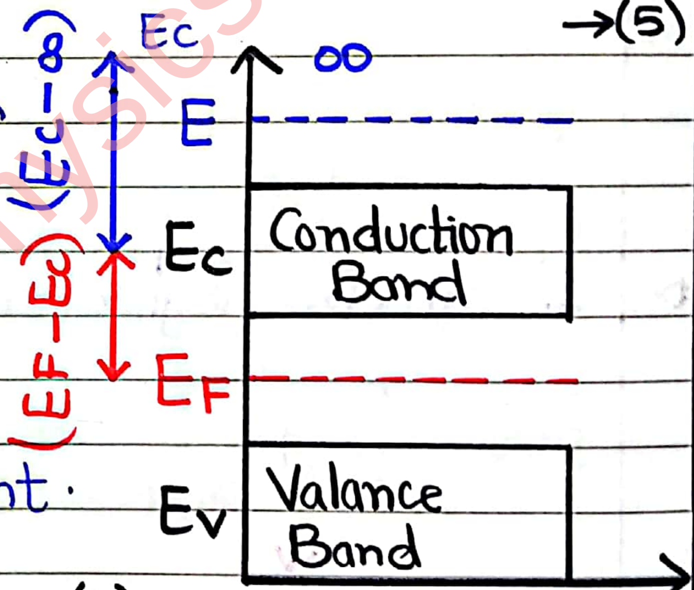
$$dn = \left[\frac{1}{2\pi^2}\left(\frac{2m_e^*}{\hbar^2}\right)^{3/2}(E-E_c)^{1/2}\right]\left[\exp-\left\{\frac{(E-E_c)-(E_f-E_c)}{KT}\right\}\right]$$

⇒ To find the total number of electrons in the conduction band, we need to integrate this equation from (E_c to ∞)

$$n_c = \frac{1}{2\pi^2}\cdot\left(\frac{2m_e^*}{\hbar^2}\right)^{3/2}\cdot\exp\left(\frac{E_F-E_c}{KT}\right)\int_{E_c}^{\infty}(E-E_c)^{1/2}e\left(-\frac{(E-E_c)}{KT}\right)dE \rightarrow (5)$$

⇒ The exponential term with ($E_F - E_c$) was taken out of the integral as it was not in the range of our limits. So it is considered constant.



⇒ Let, $\frac{(E-E_c)}{KT} = x \rightarrow (i)$

$$\frac{dE}{KT} - \frac{d\cancel{E_c}^{\,0}}{KT} = dx \longrightarrow dE = KT\,dx \rightarrow (ii)$$

⇒ Put (i) and (ii) in (5),

$$n_c = \frac{1}{2\pi^2}\left(\frac{2m_e^*}{\hbar^2}\right)^{3/2} e^{\frac{E_F-E_c}{KT}}\int_0^{\infty}(KTx)^{1/2}e^{-x}(KT\,dx)$$

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⇒ Changing Limits:-

(i) $E = E_c$ → $\frac{E-E_c}{KT} = x$ → $\frac{0}{KT} = x$ → $x = 0$

$x = ?$

(ii) $E = \infty$ → $\frac{\infty - E_c}{KT} = x$ → $\frac{\infty}{KT} = x$ → $x = \infty$

$x = ?$

$$n_c = \frac{1}{2\pi^2}\left(\frac{2m_e^*}{\hbar^2}\right)^{3/2} e\left(\frac{E_F-E_c}{KT}\right)(KT)^{3/2}\int_0^\infty x^{1/2} e^{-x}\, dx$$

⇒ Using Standard Integral,

$$\int_0^\infty x^{1/2} e^{-x}\, dx = \left(\frac{\pi}{4}\right)^{1/2}$$

$$n_c = \frac{1}{2\pi^2}\left(\frac{2m_e^*}{\hbar^2}\right)^{3/2} e\left(\frac{E_F-E_c}{KT}\right)(KT)^{3/2}\left(\frac{\pi}{4}\right)^{1/2}$$

$$n_c = \frac{1}{2\pi^2}\left(\frac{2m_e^* KT}{\hbar^2}\right)^{3/2}\left(\frac{\pi^{1/2}}{2}\right) e\left(\frac{E_F-E_c}{KT}\right)$$

$\therefore \pi^{2-1/2} \rightarrow \pi^{4-1/2} \rightarrow \pi^{3/2}$

$\therefore 2^{3/2-1-1} \rightarrow 2^{3/2-2} \rightarrow 2^{3-4/2} \rightarrow 2^{-1/2}$

$$n_c = \frac{1}{\sqrt{2}}\left(\frac{m_e^* KT}{\pi\hbar^2}\right)^{3/2} \exp\left(\frac{E_F-E_c}{KT}\right)$$

$\therefore 2^{-1/2} = 2^{-3/2+1}$

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$$n_c = 2\left(\frac{m_e^* KT}{2\pi\hbar^2}\right)^{3/2} \cdot \exp\left[-\frac{(E_c - E_F)}{KT}\right]$$

$\Rightarrow$ Let $(E = E_c)$

$$n_c = 2\left(\frac{m_e^* KT}{2\pi\hbar^2}\right)^{3/2} \exp\left[-\frac{(E - E_F)}{KT}\right].$$

$$\boxed{n_c = 2\left(\frac{m_e^* KT}{2\pi\hbar^2}\right)^{3/2} f(E)}$$

where,

N_c = effective density of states,

$$N_c = 2\left(\frac{m_e^* KT}{2\pi\hbar^2}\right)^{3/2} = \text{Pseudo constant}$$

$$\boxed{n_c = N_c \exp\left[-\frac{(E - E_F)}{KT}\right]}$$

Expression for density of electrons in the conduction band in intrinsic semiconductor

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(2) Concentration of holes in intrinsic Semiconductor :

Number of holes (dp) per unit volume in the range of energy (E) and $(E+dE)$,

$$dp = D(E)\left[1 - f(E)\right] dE \rightarrow (1)$$

or $g_v(E)$

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⇒ $g_v(E)$ = Density of states

$$(2) \rightarrow g_v(E) = \frac{1}{2\pi^2} \cdot \left(\frac{2m_p^*}{\hbar^2}\right)^{3/2} \cdot E^{1/2} \cdot (E_v - E)^{1/2}$$

and,

⇒ $f(E)$ = Fermi Dirac Distⁿ Function showing the probability of occupation of $\bar{e}$ in the conduction band.

⇒ $[1-f(E)]$ = Probability of occupation of holes in valance band.

⇒ Let's calaulate $[1-f(E)]dE$

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

$$= \left[\frac{e^{\left(\frac{E-E_F}{KT}\right)} \cancel{+1} \cancel{-1}}{e^{\left(\frac{E-E_F}{KT}\right)} + 1}\right] dE \quad \because KT \ll E - E_F$$

⇒ Neglecting exponential term in the denominator, but not in the numerator.

$$[1-f(E)]dE = e^{\left(\frac{E-E_F}{KT}\right)} dE \quad \rightarrow (3)$$

⇒ Put (2) and (3) in (1),

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$$dp_v = \left[\frac{1}{2\pi^2}\left(\frac{2m_p^*}{\hbar^2}\right)^{3/2}(E_v - E)^{1/2}\right]\left[\exp\left(\frac{E-E_F}{KT}\right)dE\right]$$

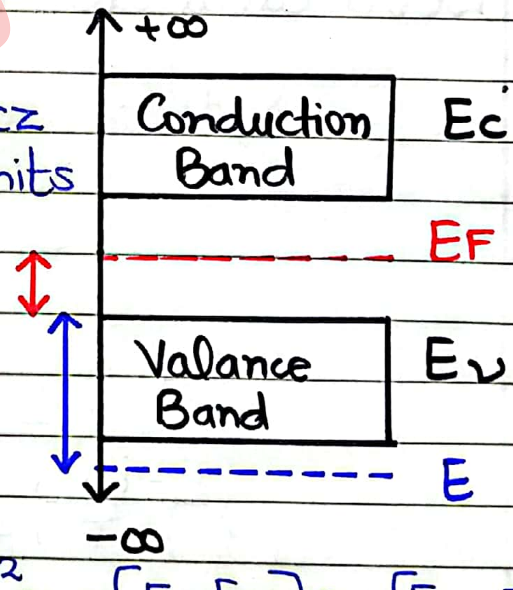
⇒ If the energy of holes is measured with respect to the bottom of valance band (E_v)

$$dp_v = \frac{1}{2\pi^2}\left(\frac{2m_p^*}{\hbar^2}\right)^{3/2}(E_v - E)^{1/2}\exp\left[\frac{(E-E_v)+(E_v-E_F)}{KT}\right]dE$$

⇒ To find the total number of holes in the valance band, we need to integrate this equation from $(-\infty$ to $E_v)$

⇒ $(E_v - E)^{1/2}$ would come inside the integral bcz it is between the limits

$\exp\left(\frac{E_v - E_F}{KT}\right)$ would be outside of integral.



$$\int dp_v = \frac{1}{2\pi^2}\left(\frac{2m_p^*}{\hbar^2}\right)^{3/2}\int_{-\infty}^{E_v}(E_v-E)^{1/2}\exp\left[\frac{E-E_v}{KT}\right]\exp\left[\frac{E_v-E_F}{KT}\right]dE$$

$$P_v = \frac{1}{2\pi^2}\left(\frac{2m_p^*}{\hbar^2}\right)^{3/2}\exp\left(\frac{E_v-E_F}{KT}\right)\int_{-\infty}^{E_v}(E_v-E)^{1/2}\exp\left(\frac{E-E_v}{KT}\right)dE$$

Let, $\frac{E_v - E}{KT} = x \longrightarrow -dE = KTx$

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$$P_\nu = \frac{1}{2\pi^2}\left(\frac{2m_p^*}{\hbar^2}\right)^{3/2} \exp\left(\frac{E_\nu - E_F}{KT}\right)\int_{-\infty}^{E_\nu} (KTx)^{1/2} \cdot e^{-x}(-KT\,dx)$$

⇒ Changing Limits :-

(i) $E \rightarrow E_\nu$, $x = ?$ $\longrightarrow \dfrac{E - E_\nu}{KT} = x \longrightarrow \dfrac{0}{KT} = x \longrightarrow x = 0$

(ii) $E \rightarrow -\infty$, $x = ?$ $\longrightarrow \dfrac{-\infty - E_\nu}{KT} = x \longrightarrow x = \infty$

$$P_\nu = \frac{1}{2\pi^2}\left(\frac{2m_p^*}{\hbar^2}\right)^{3/2} \exp\left(\frac{E_\nu - E_F}{KT}\right)\int_{\infty}^{0} (KT)^{1/2} x^{1/2} e^{-x}(-KT)\,dx$$

$$P_\nu = \frac{1}{2\pi^2}\left(\frac{2m_p^*}{\hbar^2}\right)^{3/2} \exp\left(\frac{E_\nu - E_F}{KT}\right)\int_{0}^{\infty} (KT)^{1/2} x^{1/2} e^{-x} KT\,dx$$

⇒ Using Standard Integral,

$$\int_0^\infty x^{1/2} e^{-x}\,dx = \left(\frac{\pi}{4}\right)^{1/2}$$

$$P_\nu = \frac{1}{2\pi^2}\left(\frac{2m_p^*}{\hbar^2}\right)^{3/2} \exp\left(\frac{E_\nu - E_F}{KT}\right)(KT)^{3/2}\left(\frac{\pi}{4}\right)^{1/2}$$

$\therefore \pi^{2-1/2} \rightarrow \pi^{4-1/2} \longrightarrow \pi^{3/2}$

$$P_\nu = 2\left(\frac{m_p^* KT}{2\pi\hbar^2}\right)^{3/2} \exp\left(\frac{E_\nu - E_F}{KT}\right)$$

$$\boxed{P_\nu = 2\left(\frac{m_p^* KT}{2\pi\hbar^2}\right)^{3/2} f(E_\nu)}$$

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N_v = effective density of states of holes at V.B

$$p_v = N_v \exp\left(\frac{E_v - E_F}{KT}\right)$$

$$\boxed{p_v = N_v \exp\left[-\left(\frac{E_F - E_v}{KT}\right)\right]}$$

Expression for density of holes in valance band in intrinsic semiconductor.

Q8) What is the source of electrons and holes in intrinsic semi-conductor?

ANS **Intrinsic Semiconductors** are pure crystals with no impurities and defects with a band gap of 1eV.

⇒ Silicon and Germanium are elemental intrinsic semiconductors.

⇒ At room temperature, thermal energy is sufficient that some 'electrons' move to conduction band and leave number of vacancies 'holes'.

⇒ Hence, thermal energy is the main source of electrons and holes in intrinsic semi-conductor whereas in extrinsic semiconductors doping generates electrons and holes.

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Q9) Under what condition would the intrinsic Fermi level be at the midgap energy?

ANS The intrinsic fermi level would be at the midgap energy in an intrinsic semiconductor when the concentration of electrons and holes are equal.

$$n_c = p_v$$

$$N_c \exp\left[\frac{-(E_c - E_F)}{KT}\right] = N_v \exp\left[\frac{-(E_F - E_v)}{KT}\right]$$

$$E_F = \frac{E_C + E_v}{2} + \frac{3}{4} KT \ln\left(\frac{m_p}{m_e}\right).$$

This condition occurs when the temperature is absolute zero (0K) or the rate of generation of electron-hole pair is equal to the rate of recombination.

Q10) Derive the equations for **n_o** and **p_o** in terms of impurity doping concentrations.

ANS Extrinsic Semiconductor :- are those with controlled amount of specific dopant or impurity added to it.

Thermal equation concentration of electrons and holes is different from intrinsic semi-conductor.

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⇒ Semiconductor in Equillibrium

(1) In order to find electrical properties of semiconductor. We need to find the electron and hole concentration.

(2) Current is the flow of charges and in case of semiconductors, both electrons and holes serves as charge carriers.

(3) To find the carrier concentration in semiconductor. First consider the semiconductor in equillibrium.

(4) Thermal equillibrium implies that no external force like voltage, electric field, magnetic field or temperature gradient is applied.

⇒ Concentration of electrons (n_o) in extrinsic Semiconductor.

For intrinsic semiconductor, the electron density was,

$$n_e = 2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2} e^{\left(\frac{E_F - E_c}{KT}\right)} \rightarrow (1)$$

where,

$$E_F = \frac{E_c + E_d}{2} + \left(\frac{KT}{2}\right) \ln \frac{N_d}{2}\left(\frac{2\pi m_e^* KT}{h^2}\right)^{-3/2} \rightarrow (2)$$

⇒ Put (2) in (1),

$\therefore 4 \times \frac{3}{2} - \frac{3}{4}^{\times 4}$

$\therefore \frac{6-3}{4} = \frac{3}{4}$

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$$\Rightarrow e^{\left(\frac{E_F - E_c}{KT}\right)} = e^{\frac{E_F}{KT}} \cdot e^{\frac{-E_c}{KT}}$$

$$= e^{\frac{\frac{E_c+E_d}{2} + \frac{\cancel{KT}}{2} \ln \frac{N_d}{2}\left(\frac{2\pi m_e^* KT}{h^2}\right)^{-3/2}}{\cancel{KT}}} \cdot e^{\frac{-E_c}{KT}}$$

$$= e^{\frac{E_c+E_d}{2KT}} \cdot e^{\frac{1}{2}\ln \frac{N_d}{2}\left(\frac{2\pi m_e^* KT}{h^2}\right)^{-3/2}} \cdot e^{\frac{-E_c}{KT}}$$

$$= e^{\frac{E_c+E_d-2E_c}{2KT}} \cdot \cancel{e}^{\cancel{\ln}\left(\frac{N_d}{2}\right)^{1/2}\left(\frac{2\pi m_e^* KT}{h^2}\right)^{-\frac{3}{4}}}$$

$$= e^{\frac{E_d-E_c}{2KT}} \cdot \left(\frac{N_d}{2}\right)^{1/2}\left(\frac{2\pi m_e^* KT}{h^2}\right)^{-3/4} \rightarrow (3)$$

$\Rightarrow$ Put (3) in (1),

$$n_e = 2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2}\left(\frac{N_d}{2}\right)^{1/2}\left(\frac{2\pi m_e^* KT}{h^2}\right)^{-3/4} e^{\left(\frac{E_d-E_c}{2KT}\right)}$$

$$n_e = 2\left(\frac{N_d}{2}\right)^{1/2}\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/4} \exp\left(\frac{E_d-E_c}{2KT}\right)$$

$$n_e = 2^{1-1/2}\left(N_d\right)^{1/2}\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/4} e^{\left(\frac{E_d-E_c}{2KT}\right)}$$

$$\boxed{n_e = \left(2N_d\right)^{1/2}\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/4} e^{\left(\frac{E_d-E_c}{2KT}\right)}}$$

Expression for number of electrons in conduction band for extrinsic S.C. $\rightarrow (4)$

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⇒ Concentration of holes in extrinsic Semi-conductor

The hole density for intrinsic semiconductor was,

$$p = 2\left(\frac{2\pi m_p^* KT}{h^2}\right)^{3/2} \exp\left(\frac{E_V - E_F}{KT}\right) \rightarrow (1)$$

where,

$$E_F = \frac{E_V + E_a}{2} - \frac{KT}{2} \ln\left(\frac{N_a}{2}\right)\left(\frac{2\pi m_p^* KT}{h^2}\right)^{-3/2} \rightarrow (2)$$

$$\Rightarrow e^{\left(\frac{E_V - E_F}{KT}\right)} = e^{\frac{E_V}{KT}} \cdot e^{\frac{-E_F}{KT}}$$

$$= e^{\frac{E_V}{KT}} \cdot e^{\frac{-\left[\frac{E_V + E_a}{2} - \frac{\cancel{K}T}{2} \ln\left(\frac{N_a}{2}\right)\left(\frac{2\pi m_p^* KT}{h^2}\right)^{-3/2}\right]}{\cancel{K}T}}$$

$$= e^{\frac{E_V}{KT}} \cdot e^{\frac{-(E_V + E_a)}{2KT}} \cdot e^{\frac{1}{2} \ln\left(\frac{N_a}{2}\right)\left(\frac{2\pi m_p^* KT}{h^2}\right)^{-3/2}}$$

$$= e^{\frac{2E_V - E_V - E_a}{2KT}} \cdot \cancel{e}^{\cancel{\ln}\left(\frac{N_a}{2}\right)^{1/2}\left(\frac{2\pi m_p^* KT}{h^2}\right)^{-3/4}}$$

$$= e^{\frac{E_V - E_a}{2KT}} \cdot \left(\frac{N_a}{2}\right)^{1/2}\left(\frac{2\pi m_p^* KT}{h^2}\right)^{-3/4} \rightarrow (3)$$

⇒ Put (3) in (1),

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$$p = 2\left(\frac{2\pi m_p^* KT}{h^2}\right)^{3/2}\left(\frac{N_a}{2}\right)^{1/2}\left(\frac{2\pi m_p^* KT}{h^2}\right)^{-3/4}\exp\left(\frac{E_v - E_a}{2KT}\right)$$

$$p = 2\left(\frac{2\pi m_p^* KT}{h^2}\right)^{3/4}\cdot\left(\frac{N_a}{2}\right)^{1/2}\cdot\exp\left(\frac{E_v - E_a}{2KT}\right)$$

$$p = 2^{1-1/2}\,(N_a)^{1/2}\left(\frac{2\pi m_p^* KT}{h^2}\right)^{3/4} e^{\left(\frac{E_v - E_a}{2KT}\right)}$$

$$\boxed{p = (2N_a)^{1/2}\left(\frac{2\pi m_p^* KT}{h^2}\right)^{3/4}\exp\left(\frac{E_v - E_a}{2KT}\right)}$$

Expression for number of holes in valance band for extrinsic semiconductor.

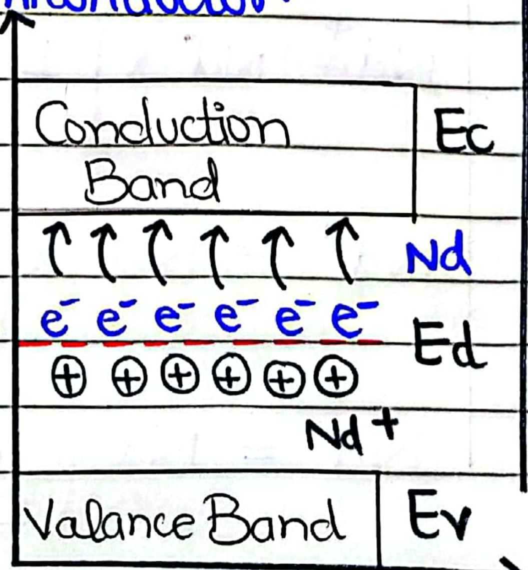
Q11) Derive the equations for the fermi energy in terms of impurity doping concentrations.

EXTRINSIC SEMICONDUCTOR

are those with controlled amount of specific dopant added to it.

(1) Fermi Level in N-type Semiconductor:-

In N-type semiconductor the charge carriers are free electrons which readily move to the conduction band leaving behind holes, vacancies in it's place.



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⇒ We know that concentration of electrons in conduction band is given as, in intrinsic semiconductor

$$n_e = 2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2} \exp\left(\frac{E_F - E_c}{KT}\right) \quad (1)$$

⇒ At 0K, all donor electrons move to the conduction band. So we can write.

$$N_d = n_e = 2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2} \exp\left(\frac{E_F - E_c}{KT}\right) \quad (2)$$

⇒ The free e^-s that went to the conduction band would generate same amount of holes.

$$N_d = N_d^+ \quad \rightarrow (3)$$

$$N_d^+ = N_d \times \text{Probability of +ive charge}$$

$$N_d^+ = N_d \times [1 - f(E)]$$

$$N_d^+ = N_d \times \left[1 - \frac{1}{1 + e^{(E-E_F)/KT}}\right]$$

$$N_d^+ = N_d \times \left[1 - \frac{1}{1+e^x}\right] \qquad \because E = E_d$$

donor energy level

$$N_d^+ = N_d \times \left(\frac{\cancel{1} + e^x - \cancel{1}}{1+e^x}\right)$$

$$N_d^+ = N_d \left(\frac{e^x}{1+e^x}\right).$$

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$$N_d^+ = N_d\left[\frac{1}{\frac{1+e^x}{e^x}}\right] = N_d\left[\frac{1}{\frac{1}{e^x}+1}\right]$$

$$N_d^+ = N_d\left[\frac{1}{e^{-x}+1}\right] \qquad \therefore x = \frac{E_d - E_F}{KT}$$

$$N_d^+ = N_d\left[\frac{1}{e^{-\left(\frac{E_d-E_F}{KT}\right)}+1}\right] \qquad E_F - E_d > KT$$

$$\frac{E_F - E_d}{KT} \gg 1$$

$$N_d^+ = N_d\left[\frac{1}{e^{\left(\frac{E_F-E_d}{KT}\right)}+1}\right] \qquad e^{\left(\frac{E_F-E_d}{KT}\right)} \gg 1$$

$$N_d^+ = N_d\left[\frac{1}{e^{\left(\frac{E_F-E_d}{KT}\right)}}\right]$$

$$\boxed{N_d^+ = N_d \cdot e^{\left(\frac{E_d-E_F}{KT}\right)}} \rightarrow (4)$$

⇒ From eq (2), (3) and (4),

$$2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2} \cdot e^{\left(\frac{E_F-E_c}{KT}\right)} = N_d \cdot e^{\left(\frac{E_d-E_F}{KT}\right)}$$

$$\frac{e^{\left(\frac{E_F-E_c}{KT}\right)}}{e^{\left(\frac{E_d-E_F}{KT}\right)}} = \frac{N_d}{2}\left(\frac{2\pi m_e^* KT}{h^2}\right)^{-3/2}$$

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$$e^{\left(\frac{E_F - E_c - E_d + E_F}{KT}\right)} = \frac{N_d}{2}\left(\frac{2\pi m_e^* KT}{h^2}\right)^{-3/2}$$

⇒ Taking log on both sides,

$$\cancel{\ln}\, \cancel{e}^{\left[\frac{2E_F}{KT} - \frac{(E_c+E_d)}{KT}\right]} = \ln\left(\frac{N_d}{2}\right)\left(\frac{2\pi m_e^* KT}{h^2}\right)^{-3/2}$$

$$\frac{2E_F}{KT} - \left(\frac{E_c+E_d}{KT}\right) = \ln\left(\frac{N_d}{2}\right)\left(\frac{2\pi m_e^* KT}{h^2}\right)^{-3/2}$$

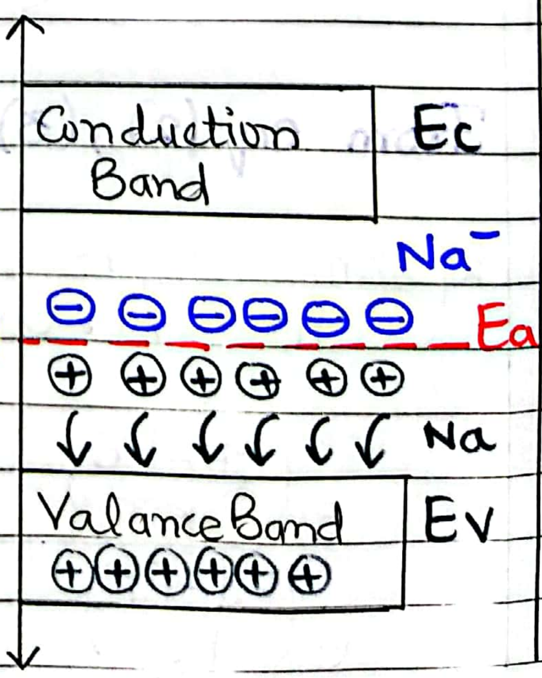
$$\frac{2E_F}{KT} = \frac{E_c+E_d}{KT} + \ln\left(\frac{N_d}{2}\right)\left(\frac{2\pi m_e^* KT}{h^2}\right)^{-3/2}$$

$$\boxed{E_F = \frac{E_c+E_d}{2} + \left(\frac{KT}{2}\right)\ln\left(\frac{N_d}{2}\right)\left(\frac{2\pi m_e^* KT}{h^2}\right)^{-\frac{3}{2}}}$$

Fermi Energy for N-type Semiconductor

(2) Fermi Level in P-type Semi-conductor:-

Consider an intrinsic semi-conductor having conc. of holes in valance band



(1) → $$p = 2\left(\frac{2\pi m_p^* KT}{h^2}\right)^{3/2} e^{\left(\frac{E_v - E_F}{KT}\right)}$$

By adding a trivalent impurity to it, we get a P-type semiconductor.

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The charge carriers for P-type S.C are holes which lie on acceptor level (Ea). Now all the holes would go to the valance band. So we can write

(2) $\rightarrow N_a = p = 2\left(\frac{2\pi m_p^* KT}{h^2}\right)^{3/2} \exp\left(\frac{E_V - E_F}{KT}\right)$

Leaving behind negative charges of number (N_a^-)

$$N_a = N_a^- \rightarrow (3)$$

To find the total number of negative charges

$N_a^- = N_a \times$ Probability of -ive charges

$= N_a \times F(E)$

$= N_a \times \left[\frac{1}{1 + e^{(E - E_F)/KT}}\right]$

$= N_a \times \left[\frac{1}{e^{\left(\frac{E - E_F}{KT}\right)}}\right]$ ∴ $E = E_a$ acceptor energy level

$$\boxed{N_a^- = N_a \cdot \exp\left(\frac{E_F - E_a}{KT}\right)} \rightarrow (4)$$

⇒ From (2), (3), (4), we have,

$$2\left(\frac{2\pi m_p^* KT}{h^2}\right)^{3/2} \exp\left(\frac{E_V - E_F}{KT}\right) = N_a \cdot \exp\left(\frac{E_F - E_a}{KT}\right)$$

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$$\frac{\exp\left(\frac{E_V-E_F}{KT}\right)}{\exp\left(\frac{E_F-E_a}{KT}\right)} = \frac{N_a}{2}\left(\frac{2\pi m_p^* KT}{h^2}\right)^{-3/2}$$

$$\exp\left(\frac{E_V-E_F-E_F+E_a}{kT}\right) = \quad ''$$

⇒ Taking log on both sides,

$$\left(\frac{E_V-2E_F+E_a}{kT}\right) = \ln\left(\frac{N_a}{2}\right)\left(\frac{2\pi m_p^* kT}{h^2}\right)^{\frac{-3}{2}}$$

$$-\frac{2E_F}{kT} + \frac{(E_V+E_a)}{kT} = \quad ''$$

$$-\frac{2E_F}{kT} = -\frac{(E_V+E_a)}{kT} + \ln\left(\frac{N_a}{2}\right)\left(\frac{2\pi m_p^* KT}{h^2}\right)^{-3/2}$$

$$\frac{2E_F}{kT} = \left(\frac{E_V+E_a}{KT}\right) - \ln\left(\frac{N_a}{2}\right)\left(\frac{2\pi m_p^* kT}{h^2}\right)^{\frac{-3}{2}}$$

$$E_F = \left(\frac{E_V+E_a}{2}\right) - \left(\frac{KT}{2}\right)\ln\left(\frac{N_a}{2}\right)\left(\frac{2\pi m_p^* kT}{h^2}\right)^{\frac{-3}{2}}$$

Fermi Energy for P-type Semiconductor.

THE END