

QUESTIONS BANK
BBS01T1002 SEMICONDUCTOR PHYSICS
CAT-1 (Syllabus)

Unit -1 : Quantum and Band Theory of electron

**Quantum free electron theory, Fermi Dirac distribution function and Fermi level, density of states
Energy band in solids, E-K diagram and Brillouin zone.**

Unit -2 : Semiconductor

**Types of semiconductor, Fermi level in semiconductor, effect of carrier concentration and
temperature on Fermi- level, direct-indirect band gap semiconductors, compound semiconductors**

Unit-1_ (CO1): Identify the energy band in solids and electron occupation probability

S. N o.	SOLUTION
1	<p>Q-1. Find the least energy of an electron moving in one dimensional infinitely high potential box of width 0.05 nm. [Given Planck's Constant (h) =6.625×10^{-34} J.s. and mass of electron (m)= 9.1×10^{-31} kg.]</p> <p>Solution: We know that energy of electron is Given by [Particle in Box]</p> $E_n = n^2 h^2 / 8mL^2, \text{ where } n=1,2,3,\dots\text{etc.}$ <p>Given $L = 0.05 \text{ nm}$ but $1\text{nm} = 10^{-9} \text{ m}$</p> <p>For least energy $n=1$</p> <p>Therefore, $E_1 = h^2 / 8mL^2$ now put $h = 6.625 \times 10^{-34}$ and $m = 9.1 \times 10^{-31}$ kg. and $L = 0.05 \times 10^{-9} \text{ m}$</p> $E_1 = \{6.625 \times 10^{-34}\}^2 / 8 \times 9.1 \times 10^{-31} \times [5 \times 10^{-11}]^2$ $E_1 = 0.0241157 \times 10^{-15} \text{ jule}$ $E_1 = 0.0241157 \times 10^{-15} / 1-6 \times 10^{-19}$ $E_1 = 0.015072 \times 10^4$ <p>E1= 150.7 eV</p>
2	<p>Q-2. An electron is bound in a one dimensional potential box which has a width $2.5 \times 10^{-10} \text{ m}$. Assuming the height of the box to be infinite, calculate the lowest two permitted energy values of the electron.[Given Planck's Constant (h) =6.625×10^{-34} J.s. and mass of electron (m) = 9.1×10^{-31} kg.]</p> <p>Solution: We know that energy of electron is Given by [Particle in Box]</p> $E_n = n^2 h^2 / 8mL^2, \text{ where } n=1,2,3,\dots\text{etc.}$ <p>Given $L = 2.5 \times 10^{-10} \text{ m}$.</p> <p>For lowest two energy $n=1$ & $n=2$ for $n=1$ Energy E_1 and for $n=2$ energy $E_2=4E_1$</p> <p>Therefore, $E_1 = h^2 / 8mL^2$ now put $h = 6.625 \times 10^{-34}$ and $m = 9.1 \times 10^{-31}$ kg. and $L = 2.5 \times 10^{-10} \text{ m}$.</p> $E_1 = \{6.625 \times 10^{-34}\}^2 / 8 \times 9.1 \times 10^{-31} \times [2.5 \times 10^{-10}]^2$ $E_1 = 0.0964629 \times 10^{-17} \text{ jule}$ $E_1 = 0.0602893 \times 100$ $E_1 = 6.02893 \text{ eV}$ <p>& $E_2 = 4 \times 6.02893$</p> $E_2 = 24.11 \text{ eV}$ <p>Lowest two permitted energy are=6.02 eV and 24.11 eV</p>
3	<p>Q-3. Find the minimum energy of an electron moving in one dimension in an infinitely high potential box of width 1\AA. [Given Planck's Constant (h) =6.625×10^{-34} J.s. and mass of electron (m) = 9.1×10^{-31} kg.]</p> <p>Solution: We know that energy of electron is Given by [Particle in Box]</p> $E_n = n^2 h^2 / 8mL^2, \text{ where } n=1,2,3,\dots\text{etc.}$ <p>Given 1\AA. But $1\text{\AA}=1 \times 10^{-10} \text{ m}$</p> <p>For minimum energy $n=1$ we have to find E_1</p>

Therefore, $E_1 = h^2/8mL^2$ now put $h = 6.625 \times 10^{-34}$ and $m = 9.1 \times 10^{-31} \text{ kg}$ and $L = 1 \times 10^{-10} \text{ m}$.

$$E_1 = \{6.625 \times 10^{-34}\}^2 / 8 \times 9.1 \times 10^{-31} \times [1 \times 10^{-10}]^2$$

$$E_1 = 0.602893 \times 10^{-17} \text{ jule}$$

$$E_1 = 0.602893 \times 10^{-17} / 1.6 \times 10^{-19}$$

$$\mathbf{E1=37.68 \text{ eV}}$$

$$\mathbf{\text{Minimum energy of electron = 37.68 eV}}$$

Q-4. The Fermi Energy for a given solid is 5.0 eV at T=0K. What is the average energy of the electron in the metal at 0 K?

Solution: We know that average energy of electron at T=0K is Given by

$$E_{av} = 3E_F / 5, \text{ where } E_F \text{ is Fermi energy of electron}$$

$$\text{Therefore, } E_{av} = 3 \times 5 / 5 = 3 \text{ eV}$$

$$\mathbf{\text{Average energy of electron= 3.0 eV}}$$

Q-5. The Fermi level for potassium is 2.0 eV. Calculate the velocity of the electrons at the Fermi level.

Solution: We know that

$$k_B T_F = E_F \text{ i.e. } T_F = E_F / k_B$$

$$\frac{1}{2} m v_F^2 = k_B T_F \text{ i.e. } v_F = (k_B T_F / m)^{1/2}$$

$$v_F = (E_F / m)^{1/2}$$

$$v_F = (2 \times 1.6 \times 10^{-19} / 9.1 \times 10^{-31})^{1/2}$$

$$V_F = 0.351648 \times 10^6$$

$$V_F = 3.516 \times 10^5 \text{ m/s}$$

$$\mathbf{\text{Velocity of electron =3.516x10}^5 \text{ m/s}}$$

Q-6. What is the value of Fermi-Dirac distribution function for T=0, when (i) energy is greater than Fermi Energy and (ii) when energy is less than Fermi Energy.

Solution: Fermi function describe the probable distribution of electron in the energy states, mathematically the Fermi-function is given by

$$f(E) = \frac{1}{1 + \exp[(E - E_F) / k_B T]}$$

when (i) energy is greater than Fermi Energy

$$\text{i.e. } E > E_F, f(E) = 0$$

and (ii) when energy is less than Fermi Energy

$$\text{i.e. } E < E_F, f(E) = 1$$

Q-7. Define the Fermi Energy. If the Fermi energy is 10eV, calculate the mean energy of electron at 0 Kelvin.

Solution: The Fermi energy is a concept in quantum mechanics usually refers to the energy difference between the highest and lowest occupied single-particle states in a quantum system of non-interacting fermions at absolute zero temperature.

Average energy of electron at T=0K is given by

$$E_0 = 3E_F / 5$$

$$E_0 = 3 \times 10 / 5 = 4 \text{ eV}$$

$$\mathbf{\text{Fermi energy of electron= 4.0 eV}}$$

Q-8. Write Schrodinger's time-independent equation for matter waves. Explain the physical significance of the wave function?

Solution: Schrodinger wave equation (time-independent form) for matter waves

In one dimension is written as

$$\frac{d^2\psi_n}{dx^2} + \frac{2m(E_n - V)}{\hbar^2} \psi_n = 0$$

Physical Significance of Wave-function: By analogy with waves such as those of sound, a wave function, designated by the Greek letter psi, Ψ , may be thought of as an expression for the amplitude of the particle wave (or de Broglie wave), although for such waves amplitude has no physical significance. The square of the wave function, Ψ^2 , however, does have physical significance: the probability of finding the particle described by a specific wave function Ψ at a given point and time is proportional to the value of Ψ^2 .

Since the probability of a particle being somewhere in space is unity, the Integration of the wave-function over all space leads to a probability of 1. That is, the wave-function is normalized:

$$\int_{-\infty}^{\infty} \Psi^*(x, t)\Psi(x, t)dx = 1$$

Every acceptable wave function can be normalized by multiplying it by an appropriate constant

Q-9. Explain the idea of wave function for a quantum particle. Write the basic characteristics of well-behaved wave function 9

Solution: **wave function**, in [quantum mechanics](#), variable quantity that mathematically describes the [wave](#) characteristics of a [particle](#). The value of the wave [function](#) of a particle at a given point of space and time is related to the likelihood of the particle's being there at the time. By [analogy](#) with waves such as those of sound, a wave function, designated by the Greek letter psi, Ψ , may be thought of as an expression for the amplitude of the particle wave (or de Broglie wave), although for such waves amplitude has no physical significance. The square of the wave function, Ψ^2 , however, does have physical significance: the probability of finding the particle described by a specific wave function Ψ at a given point and time is proportional to the value of Ψ^2 .

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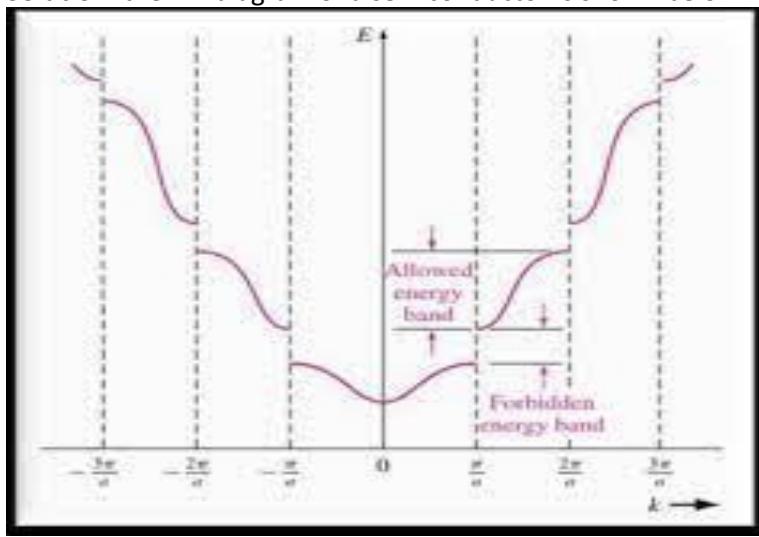
Characteristics for a suitable wave-function-(Well-Behaved Wave Functions)

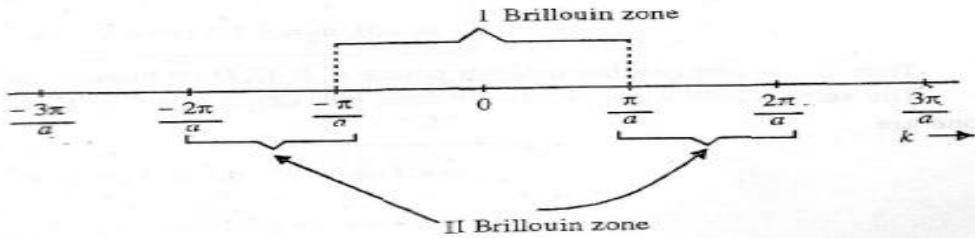
In order for $\Psi(x; t)$ to represent a viable physical state, certain conditions are required:

1. The wave-function must be a single-valued function of the spatial Coordinates. (single probability for being in a given spatial interval)
2. The first derivative of the wave-function must be continuous so that the second derivative exists in order to satisfy the Schrodinger equation.
3. The wave-function cannot have an infinite amplitude over a finite interval. This would preclude normalization over the interval.

Q-10. Draw the E-K diagram of a semiconductor based on band theory of solids. Explain the Brillouin zones in a solid. 10

Solution: the E-K diagram of a semiconductor is shown below





In one dimensional periodic lattice, the energy discontinuities occur when the wave number k satisfies the condition $k = n\pi/a$ where n is a +ve or -ve integer. If we consider a line Fig 6, representing k values divided into energy discontinuities into segments of length $\pm\pi/a$, then these line segments are known as Brillouin zones

$$-\frac{\pi}{a} < k < +\frac{\pi}{a}$$

The first segment a a is called the First Brillouin zone.

$-\frac{2\pi}{a} < k < -\frac{\pi}{a}$ and $k = \frac{\pi}{a}$ to $\frac{2\pi}{a}$, This zone is called second Brillouin zone

Q-11. What would be the band structure if the barrier strength is extremely high or negligible? Justify your answer with a suitable diagram.

Solution: In the Kronig-Penney model/From Band Theory of Solids, We know that

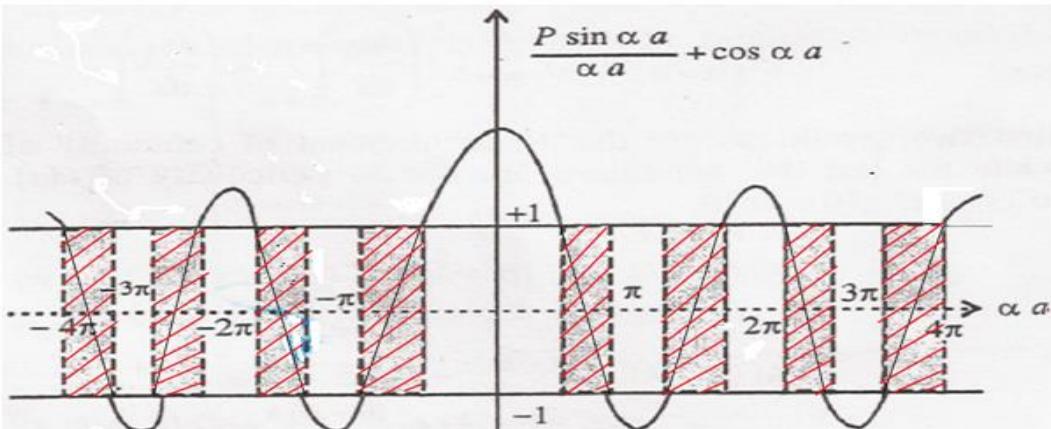


Fig.3: Plot the function $\left(\frac{P \sin \alpha}{\alpha} + \cos \alpha \right)$ for $P=3\pi/2$ where

allowed energy band is represented by the shaded region

where $P = \frac{m V_0}{\hbar^2} ab$

P is a measure of the quantity $V_0 b$, which is the area of potential

barrier, called barrier strength

- Equation (7) is satisfied only for those values of α for which left hand side lies between +1 and -1 this is because R.H.S must lie in the range +1 to -1. Such values of α will, therefore, represent the wave like solutions and are accessible. The other values of α will be inaccessible.
 - In Fig. 3, the part of the vertical axis lying between the horizontal lines represents the range acceptable. As α^2 is proportional to the energy E, the abscissa (α) will be a measure of the energy

- Clearly there are regions for αa where the value of αa does not lie between -1 and +1. For these values of αa and hence of energy E , no solutions exist. Such regions of energy are prohibited and are called forbidden bands.

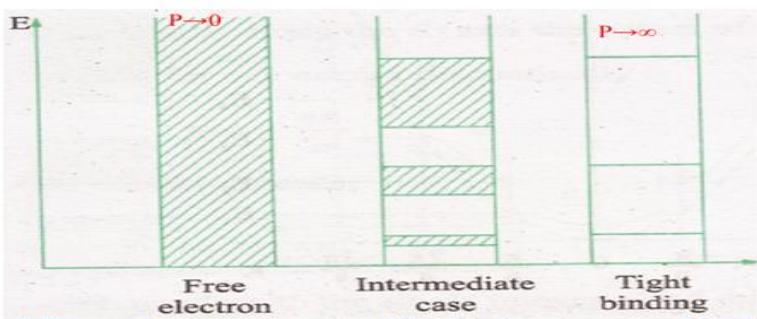


Fig. 4 Energy level structure for differentiating degrees of binding

The energy spectrum of the electron consists of alternate regions of allowed energy and forbidden energy

- i. The width of the allowed energy band increases as the value of αa (i.e., energy) increases.
- ii. It is to be noted that P is a measure of the potential barrier strength.

Case 1: When $P \rightarrow \infty$, corresponding to a infinitely deep potential well, the electron can be considered as confined into a single potential well. This case applies to crystals where the electrons are very tightly bound

Equation (7) has the solutions only if $\sin \alpha a = 0$ or, $\alpha a = n\pi$,

This is the equation of energy levels of particle in a constant potential box of atomic dimension

This is the equation of energy levels of particle in a constant potential box of atomic dimension. The allowed energy bands are compressed into energy levels and the energy spectrum is a line spectrum (As in Fig.4).

Case 2 : When $P \rightarrow 0$, corresponds to no barrier, the electron can be considered to be moving freely through the potential wells.

$$\cos \alpha a = \cos ka \text{ i.e., } \alpha = k \text{ or } \alpha^2 = k^2$$

$$\frac{2mE}{\hbar^2} = k^2$$

$$\frac{\hbar^2 k^2}{2m} = \frac{P^2}{2m}, \quad [\text{As } k = \frac{2\pi}{\lambda}, \lambda = \frac{\hbar}{P}]$$

$$E = \frac{\hbar^2 k^2}{2m} = \frac{P^2}{2m}, \quad [\text{As } k = \frac{2\pi}{\lambda}, \lambda = \frac{\hbar}{P}]$$

which is appropriate to the completely free particle.

Case 3 : Between these two extreme limits, intermediate case, the position and the width of the allowed and forbidden bands for any value of P are obtained by drawing vertical lines in Fig. 5, the shaded areas corresponds to the allowed bands (Fig. 4 and Fig.5). Thus by varying P from zero to infinity we cover the whole range, from the completely free electron to the completely bound electron.

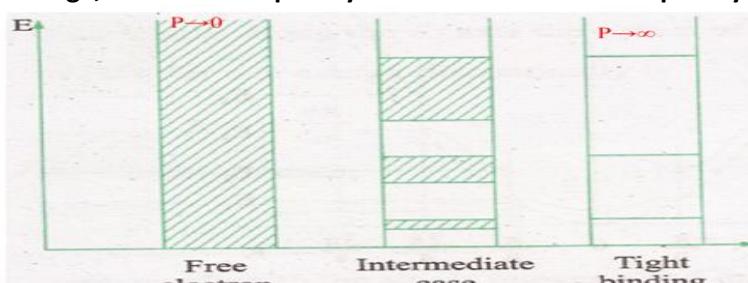


Fig. 4 Energy level structure for differentiating degrees of binding

Q-12. Define the density of energy state in a solid. Find the expression for density of states.
Solution:

$$1. \text{ The allowed energy for 1D potential box, } E_n = \frac{\hbar^2 n^2}{8mL^2}$$

where m is mass of particle, L is the length of potential box and n are positive integers like 1, 2, 3, 4, 5....

The allowed energy for 3D cubical potential box

$$E = \frac{\hbar^2}{8mL^2} (n_x^2 + n_y^2 + n_z^2) \quad \dots \dots \dots (1)$$

where n_x , n_y and n_z are three quantum numbers which are only positive integer value.

$$\text{where } n^2 = n_x^2 + n_y^2 + n_z^2 \quad \dots \dots \dots (2)$$

$$E = \frac{\hbar^2}{8mL^2} n^2$$

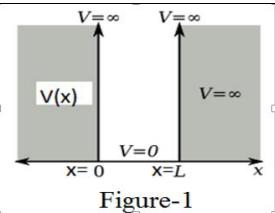


Figure-1

The potential energy within the 1D crystal or box is

$$V(x) = 0 \quad \text{for } 0 < x < L$$

$$V(x) = \infty \quad \text{for } x \leq 0 \text{ and } x \geq L$$

Density of energy states is defined by the number of allowed energy states present in unit volume at a given energy.

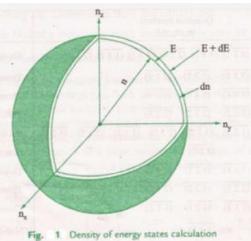
Since even at highest energy, the difference between neighbouring energy levels is as small as 10^{-6} eV, in a macroscopically small energy interval dE there are still many discrete energy levels. So the concept of density of energy states is introduced.

The Fermi energy, E_F is the energy of the highest filled level at absolute zero.

- Number of energy states with a particular value of E, depends on the how many combinations of the quantum number (n_x , n_y , n_z) result in the same value n. [From equation (1)]

$$E = \frac{\hbar^2}{8mL^2} (n_x^2 + n_y^2 + n_z^2)$$

- A space of points is constructed with the values of n_x , n_y , n_z
- Each point (n_x , n_y , n_z) with positive integer values of coordinates represents an energy state.
- A radius vector n from the origin is drawn to a point n_x , n_y , n_z in this space and according to equation (2) [$n^2 = n_x^2 + n_y^2 + n_z^2$] all points on the surface of a sphere of radius n will have the same energy.
- n represents a vector to a point n_x , n_y , n_z in three-dimensional space.
- In this space every integer specifies a state, that is a unit cube contains exactly one state.
- The number of states in any volume is just equal to the numerical value of the volume expressed in units of cubes of lattice parameters.



$$\text{Number of available states within a sphere of radius } n = \frac{1}{8} \left(\frac{4}{3} \pi n^3 \right)$$

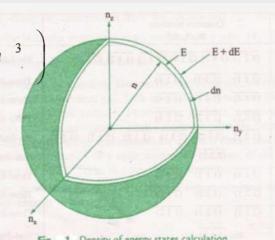
$$\text{Number of available states within a sphere of radius } (n+dn) =$$

$$\frac{1}{8} \left[\frac{4}{3} \pi (n + dn)^3 \right]$$

The factor 1/8 accounts for the fact that only positive integers are allowable and thus only one octant of the sphere alone be considered.

$$\begin{aligned} \text{Number of available states within } n \text{ to } (n+dn) &= \frac{1}{8} \frac{4}{3} \pi [(n+dn)^3 - n^3] \\ &\approx \frac{\pi}{6} (3n^2 dn) \end{aligned}$$

[Neglecting higher order terms of dn]



$$\text{Number of available states within } n \text{ to } (n+dn) = \frac{\pi}{2} n^2 dn = \frac{\pi}{4} n (2n dn)$$

$$\text{From Equation (1), } n^2 = \frac{8mL^2}{h^2} E \quad n = \left[\frac{8mL^2}{h^2} \right]^{1/2} E^{1/2}$$

$$2n dn = \left[\frac{8mL^2}{h^2} \right] dE$$

Number of available states within E to $(E+dE)$,

$$Z'(E) dE = \frac{\pi}{4} \left[\frac{8mL^2}{h^2} \right]^{1/2} E^{1/2} \left[\frac{8mL^2}{h^2} \right] dE$$

$$Z'(E) dE = \frac{\pi}{4} \left[\frac{8mL^2}{h^2} \right]^{3/2} E^{1/2} dE$$

It should be remembered that the Pauli's exclusion principle permits **two electrons in each state**, so that the number of energy levels actually available are

$$Z'(E) dE = 2 \frac{\pi}{4} \left[\frac{8mL^2}{h^2} \right]^{3/2} E^{1/2} dE$$

$$Z'(E) dE = \frac{\pi}{2} \left[\frac{8mL^2}{h^2} \right]^{3/2} E^{1/2} dE \quad \dots \dots \dots (4)$$

Density of energy states having energy values lying between E and $E+dE$,

$$Z(E) dE = Z'(E) dE / V = \frac{\pi}{2} \left[\frac{8m}{h^2} \right]^{3/2} E^{1/2} dE \quad [\text{As } L^3 = V]$$

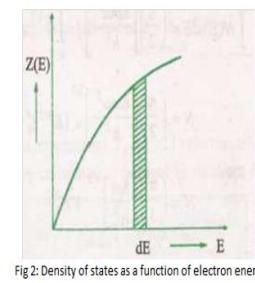


Fig 2: Density of states as a function of electron energy

The last expression is the formula of density of energy states.

Q-13. An electron is in motion along a line between $x=0$ and $x=L$ with zero potential energy. At points for which $x \leq 0$ and $x \geq L$, the potential energy is infinite. The wave function for the particle in the n^{th} state is given by $\psi_n = A \sin(n\pi x/L)$. Find the expression for the normalized wave function.

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Solution: The wave function for the particle in the n^{th} state is given by $\psi_n = A \sin(n\pi x/L)$.

It is certain that the particle is somewhere inside the box. The constant A in the given equation is determined by using this information that the probability of finding an electron somewhere on the line is unity, i.e.

$$\int_0^L \psi_n^* \psi_n dx = 1$$

This is called as normalization condition. We get

$$A^2 \int_0^L \sin^2\left(\frac{n\pi}{L}x\right) dx = 1, \text{ or}$$

$$A^2 \int_0^L 1 - \cos\left(\frac{2n\pi}{L}x\right) dx = 2, \text{ or } A^2 \int_0^L dx = 2, \text{ or}$$

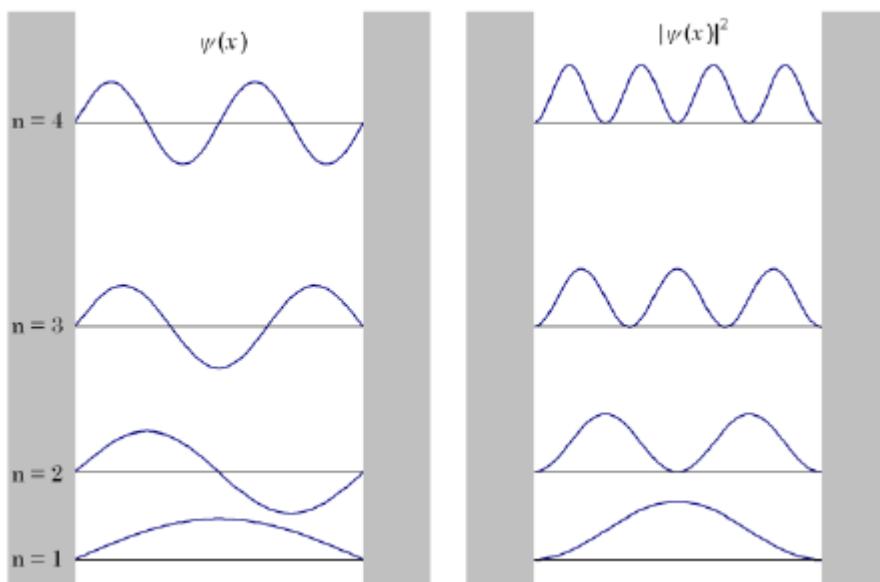
$$A = \sqrt{\frac{2}{L}}$$

The energy levels and the wave functions corresponding to $n=1, 2, 3$, and 4 are shown

So, we get the normalized wave function as

$$\psi_n = \left(\frac{2}{L}\right)^{1/2} \sin\left(\frac{n\pi}{L}x\right)$$

Where $n=1, 2, 3, 4, \dots$ etc.



Q-14. An electron is in motion along a line between $x=0$ and $x=L$ with zero potential energy. At points for which $x \leq 0$ and $x \geq L$, the potential energy is infinite. Solving Schrodinger's equation, obtain energy Eigen values

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Consider an electron of mass 'm' which is bound to move in a one dimensional crystal of length 'L'. The electron is prevented from leaving the crystal by the presence of a large potential energy barrier at its surfaces.

Although the barriers extend over a few atomic layers near the surface, these are taken infinitely large for the sake of simplicity. The problem is identical to that of an electron moving in a one – dimensional potential box which is represented by a line and is bounded by infinite potential energy barriers as shown in figure

The potential energy within the crystal or box is assumed to be zero. Thus, we have

$$\begin{aligned} V_{(x)} &= 0 && \text{for } 0 < x < L \\ V_{(x)} &= \infty && \text{for } x \leq 0 \text{ and } x \geq L \end{aligned} \quad \dots \dots \dots (1)$$

The wave function ψ_n of the electron occupying the nth state is determined from the solution of the Schrodinger equation, i.e.

$$\frac{d^2\psi_n}{dx^2} + \frac{2m(E_n - V)}{\hbar^2} \psi_n = 0 \quad \dots \dots \dots (2)$$

Where E_n represents the kinetic energy of the electron in the nth state and V is its potential energy. Since $V=0$ inside the box Equation (2) becomes

$$\frac{d^2\psi_n}{dx^2} + \frac{2mE_n}{\hbar^2} \psi_n = 0 \quad \dots \dots \dots (3)$$

Solution:

The general solution of this equation is

$$\psi_n = A \sin(kx) + B \cos(kx) \quad \dots \dots \dots (4)$$

Where A and B are arbitrary constants to be determined from the boundary conditions and k is given by

$$k = \sqrt{\frac{2mE_n}{\hbar^2}} \quad \dots \dots \dots (5)$$

The boundary conditions are, $\psi_n = 0$ when $x = 0$ and $\psi_n = 0$ when $x = L$

For $x = 0$ equation (4) gives $B = 0$ and the solution (4) becomes

$$\psi_n = A \sin(kx) \quad \dots \dots \dots (6)$$

Also $\psi_n = 0$ when $x = L$, therefore, equation (6) yields

$$\sin(KL) = 0$$

Since A cannot be zero as this will make the wave function zero everywhere. Therefore

$$\sin(KL) = 0 \text{ hence } KL = n\pi$$

$$\text{Or } K = n\pi/L$$

Where $n = 1, 2, 3, 4, 5, \dots$. Thus the expression (6) for the allowed wave function becomes

$$\psi_n = A \sin\left(\frac{n\pi}{L}\right)x \quad \dots \dots \dots (8)$$

The allowed energy can be obtained from equations (5) and (7) as

$$E_n = \frac{\hbar^2}{2m} \left(\frac{n\pi}{L}\right)^2$$

$$E_n \propto n^2$$

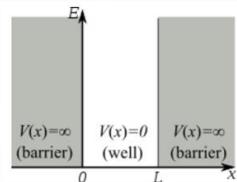
$$E_n = n^2 \hbar^2 / 8mL^2, \text{ where } n=1,2,3, \dots \dots \dots \text{etc.}$$

This is the expression of energy Eigen Values

Q-15. Explain the energy band in solids and classify the materials based on energy gap.

Solution: The band theory of solids is different from the others because the atoms are arranged very close to each other such that the energy levels of the outermost orbital electrons are affected. But the energy level of the innermost electrons is not affected by the neighbouring atoms.

The three energy bands in solids are

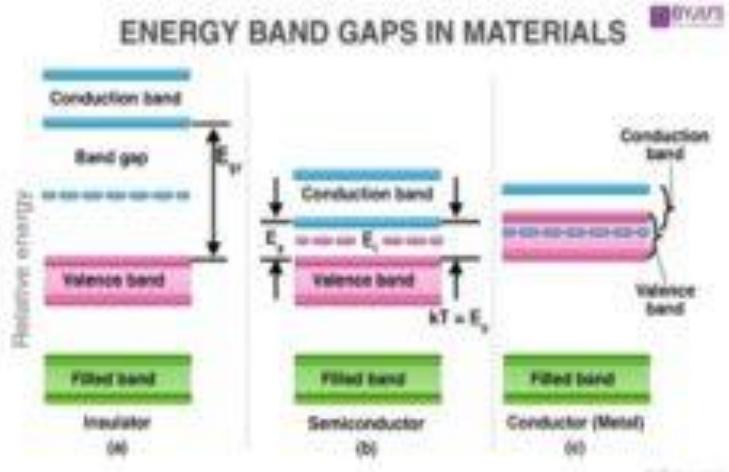


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- Valence band
- Conduction band
- Forbidden band

Bond theory solids

- In atoms, electrons are filled in respective energy orbits following Pauli's exclusion principle.
- In molecules, Two atomic orbitals combine together to form a molecular orbit with two distinct energy levels.
- In solids, 10^{23} stacked up lines confined in a tiny space would look like a band. Thereby forming energy continuum called energy bands.
- This theory helps to visualise the difference between conductor, semiconductors and insulator by plotting available energies for an electron in a material.



Conductors:

Metals are conductors in which there is no forbidden energy gap between the conduction band (CB) and valence band (VB). No extra energy required to transfer the electron from VB to CB.

Semiconductors:

In a semiconductor, the valence band is completely filled with electrons while the conduction band is empty. The energy gap between the bands is less. For electrons to jump from the valence band to the conduction band, room temperature needs to be maintained. If the temperature is 0K, there is no transfer of electrons from the valence band to the conduction band.

Insulators:

In insulators, the valence band is completely filled while the conduction band is empty. This results in a large energy gap. Since the energy gap between the conduction band and the valence band is more, there is no movement of electrons from the valence band to the conduction band.

Solids can be categorized into three main groups on the basis of band gaps as

A. Insulators

B. Semiconductor

C. Conductor.

A. Insulators

- The forbidden energy gap (E_g) is greater than 3eV
- do not conduct electricity
- number of electrons is just enough to completely fill a number of allowed energy bands.
- Above these bands there exists a series of completely empty bands.
- At ordinary temperatures electron can't be thermally excited across this gap from the valence band to the conduction band.
- As the bands are either completely filled or empty, no electric current flow.

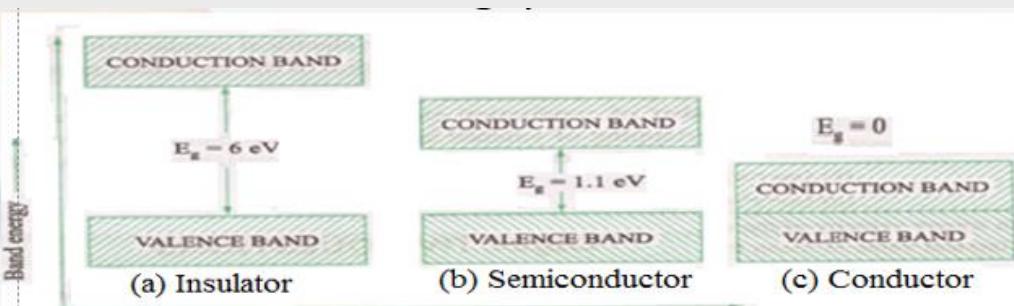
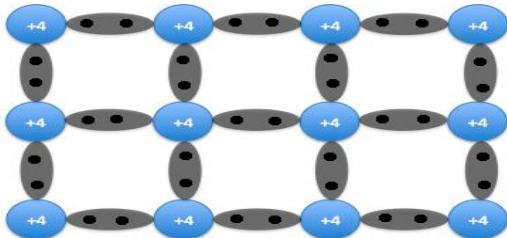


Fig. 1 Energy band diagram of (a) Insulator, (b) Semiconductor and (c) Conductor

- The topmost filled band is known as the valence band
- The lowermost empty band known as the conduction band
- The gap between valence band and conduction band is known as forbidden energy gap (E_g)

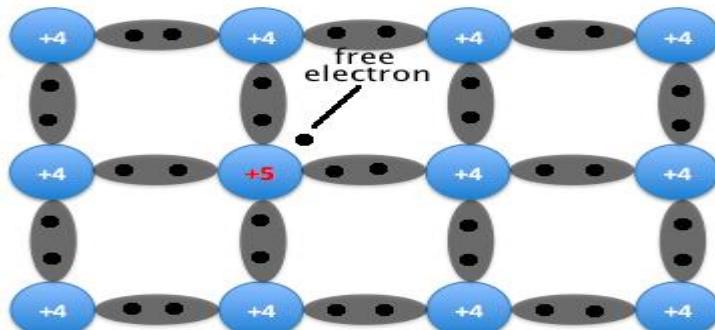
Unit- 2_(CO2): Understand the physics of semiconductor and develop the ability to choose the appropriate semiconductor for engineering applications

Questions	S.No.	Mark
<p>Q-1. Which types of charge carries are available in n-type of semiconductors? Justify your answer.</p> <p>Solution: In a pure (intrinsic) Si or Ge semiconductor, each nucleus uses its four valence electrons to form four covalent bonds with its neighbors (see figure below). Each ionic core, consisting of the nucleus and non-valent electrons, has a net charge of +4, and is surrounded by 4 valence electrons. Since there are no excess electrons or holes In this case, the number of electrons and holes present at any given time will always be equal.</p>	1	2



An intrinsic semiconductor. Note each +4 ion is surrounded by four electrons.

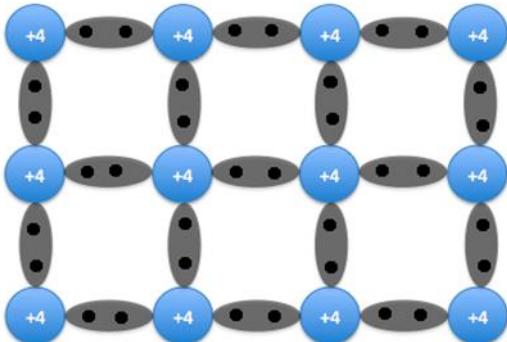
When one of the lattice atoms replace it by an atom with five valence electrons, such as the Group 5 atoms arsenic (As) or phosphorus (P). In this case, the impurity adds five valence electrons to the lattice where it can only hold four. This means that there is now one excess electron in the lattice (see figure below). Because it donates an electron, a Group 5 impurity is called a donor. Note that the material remains electrically neutral.



A semiconductor doped with a donor. A free electron is now present.

Donor impurities donate negatively charged electrons to the lattice, so a semiconductor that has been doped with a donor is called an n-type semiconductor; "n" stands for negative. Free electrons outnumber holes in an n-type material, so the electrons are the majority carriers and holes are the minority carriers.

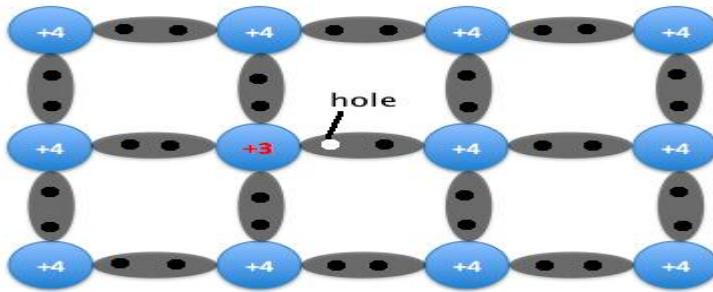
Q-2. Which types of charge carries are available in p-type of semiconductors? Justify your answer
Solution: In a pure (intrinsic) Si or Ge semiconductor, each nucleus uses its four valence electrons to form four covalent bonds with its neighbors (see figure below). Each ionic core, consisting of the nucleus and non-valent electrons, has a net charge of +4, and is surrounded by 4 valence electrons. Since there are no excess electrons or holes In this case, the number of electrons and holes present at any given time will always be equal.



An intrinsic semiconductor. Note each +4 ion is surrounded by four electrons.

Now, if one of the atoms in the semiconductor lattice is replaced by an element with three valence electrons, such as a Group 3 element like Boron (B) or Gallium (Ga), the electron-hole balance will be changed. This impurity will only be able to contribute three valence electrons to the lattice, therefore leaving one excess hole (see figure below). Since holes will "accept" free electrons, a Group 3 impurity is also called an acceptor.

2 2



A semiconductor doped with an acceptor. An excess hole is now present.

Because an acceptor donates excess holes, which are considered to be positively charged, a semiconductor that has been doped with an acceptor is called a p-type semiconductor; "p" stands for positive. Notice that the material as a whole remains electrically neutral. In a p-type semiconductor, current is largely carried by the holes, which outnumber the free electrons. In this case, the holes are the majority carriers, while the electrons are the minority carriers.

Q-3. Define the relaxation time and Drift velocity of an electron in a semiconductor

Solution: An electron experiences a collision with a probability per unit time $1/\tau$. This means that on the average an electron travels for time τ after it undergoes a collision and before its next collision

Relaxation Time: the average time between two successive collisions is τ . This time is known as relaxation time (τ).

The average distance traversed by a free electron between two successive collision s with positive ions is called the mean free path (λ).

In absence of external electric field, the random motion of free electrons is equally probable in all directions. As a result, there is no net current in the absence of electric field.

Drift Velocity: When an external electric field is applied, the electrons are accelerated in a direction opposite to that of electric field. Hence they acquire an average velocity in a direction opposite to that of electric field which is superimposed over the random motion. This velocity is known as the drift velocity (v_d).

Q-4. What is the wavelength corresponding to the bandgap of GaAs (1.42eV) approximately?

Solution: we know from band theory and quantum theory that ,

$$E_g = hc/\lambda, \text{ therefore}$$

$$\lambda = hc/E_g$$

Where Planck's constant (h) = 6.625×10^{-34} J.s. and velocity of light $C=3 \times 10^8$ m/s

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

$$\lambda=8.747 \times 10^{-7} \text{ m}$$

$$\lambda=874.7 \text{ nm}$$

Q-5. Outline the nature of charge on an intrinsic semiconductor on addition of neutral pentavalent or trivalent atoms

Solutions: In a semiconductor, electric charge and hence, electric current is carried by free charge carriers. If free charge carriers are more in number, electric current can flow easily and conductivity of the semiconductor increases.

An intrinsic semiconductor is made up of purely one element which has a valence shell with 4 valence electrons (such as silicon and germanium). These 4 valence electrons bond with 4 valence electrons of their neighbouring atom to complete their octet. Therefore, since the electrons are bound, there is a deficit of free charge carriers.

Pentavalent impurities (like P,As) have 5 electrons in their valence shell. When they are added to an intrinsic semiconductor, 4 electrons of the pentavalent atom bond with 4 electrons of the atom of the semiconductor to form an octet. Thus, one electron remains free and becomes a free charge carrier. This increases the conductivity of the intrinsic semiconductor.

Trivalent impurities (like Ga, In) have 3 valence electrons in their outer shell. When added to intrinsic semiconductors, the 3 electrons try to bond with 4 electrons by breaking bonds and jumping between two

electrons. This results in a void in one of the bonds at all times. This void is known as a hole. Since it is a deficit of electrons, it acts as a positive free charge carrier. This also increases the conductivity of the intrinsic semiconductor.

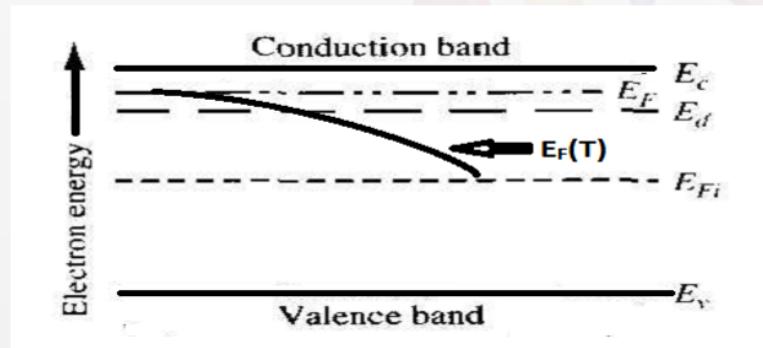
Hence, it is true that addition of either trivalent or pentavalent impurity to an intrinsic semiconductor increases its conductivity.

It is noted that not only electrons are considered charge carriers in semiconductors and hence, since only pentavalent impurities provide extra electrons, only they increase conductivity. Holes are also considered free charge carriers, as movement of electrons in one direction leads to movement of holes in the other direction, that is, in essence, they carry positive charge in a direction opposite to the negative charge carried by the electrons. Therefore, trivalent impurities also increase the conductivity of an intrinsic semiconductor by providing for the formation of holes in the semiconductor.

Q-6. Discuss the variation of Fermi-level position with temperature and doping concentration in Extrinsic semiconductors.

Solution:

In n-type semiconductor: At 0 K all allowed energy levels in the valence band are filled by electrons. All donor levels are filled by unbound electrons. The conduction band is free. So charge carriers do not exist, and the semiconductor behaves as an insulator. At 0 K the Fermi level is between the donor levels and the bottom of the conduction band as shown below.



Energy level diagram of N-type semiconductor. $E_F(T)$ shows the effect of temperature on Fermi energy

When the temperature is raised, by absorption of suitable energies, some donor atoms are ionised, so that their electrons are elevated to the conduction band. If the density of ionised donor atom is N_d and the density of electron-hole pairs in the intrinsic semi-conductors is n_i at room temperature T, then $N_d \gg n_i$. The Fermi energy is given by

$$E_F = E_C - k T \log_e \left(\frac{N_C}{N_d} \right)$$

$$\text{where } N_C = 2 \left[\frac{2\pi m_e^* k T}{h^2} \right]^{3/2}$$

This shows that in an N-type semiconductor the Fermi-level lies below the bottom of the conduction band. As temperature rises, the Fermi level goes on falling below E_C . When the temperature is sufficiently raised, the electrons and holes generated due to thermal agitation increase significantly and at a stage become fully dominant over the extrinsic carriers. Then the Fermi level approaches the middle of forbidden energy gap.

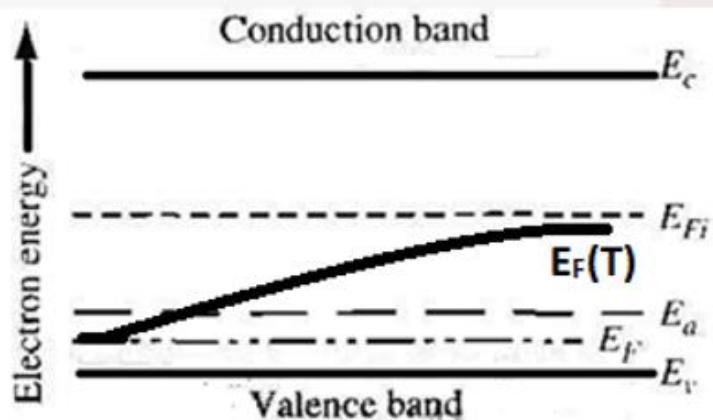
In P-type semiconductor: The energy band diagram of a P-type semiconductor is shown in the Figure. The acceptor level is shown by E_a near the top of the valence band, the Fermi level by E_F . At absolute zero, all the holes are in acceptor levels, but as the temperature rises, the electrons from valence band jump into

6 2

acceptor level on the absorption of energy ($E_A - E_V$) by each electron. As a result, these electrons are trapped in the acceptor levels and an equal number of holes are created in the valence band. These holes provide conduction currents. At the room temperature, almost all acceptor atoms trap electrons and thus the number of holes available in the valence band is almost equal to the number of impurity atoms added.

The variation of Fermi energy with temperature is given by:

$$E_F = E_V + kT \log_e \left(\frac{N_V}{N_a} \right) \text{ where } N_V = 2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{3/2}$$



Energy diagram of P-type Semiconductor. $E_F(T)$ shows the effect of temperature on Fermi energy.

This shows that Fermi level lies above the top of the valence band. The position of Fermi level depends upon the temperature and the number of impurity atoms. When the number of impurity atoms increases, the number of holes in the valence band will increase and the Fermi level will shift towards the valence band. When the concentration of acceptor impurity atoms is sufficiently high, the number of holes will be far greater than the conduction electrons and the Fermi level may even lie in the valence band. As the temperature is sufficiently increased, electrons from the valence band are excited to the conduction band and finally the P-type crystal will start behaving like an intrinsic semi-conductor when the number of electrons in the conduction band will be nearly equal to the valence holes. Thus at extremely high temperatures the Fermi level shifts towards the middle of forbidden energy gap.

Q-7. Distinguish between elemental and compound semiconductors with examples.

Solution: There are different ways of classifying semiconductors depending on the property being measured. One classification that is fairly straight forward is

1. Elemental semiconductors
2. Compound semiconductor

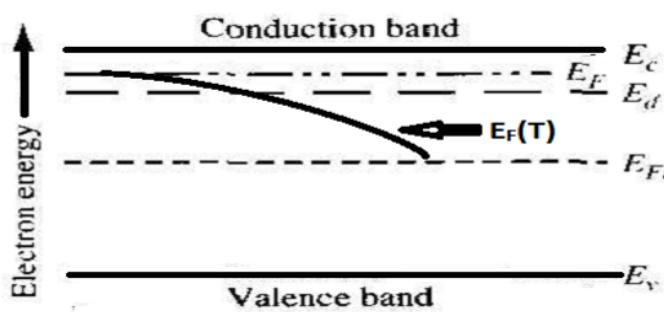
	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A
	5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.00674	8 O Oxygen 15.9994
12 IIB 2B	13 Al Aluminum 26.981539	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.066
30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.64	33 As Arsenic 74.92159	34 Se Selenium 78.96
48 Cd Cadmium 112.411	49 In Indium 114.818	50 Tin Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6
80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98037	84 Po Polonium [208.9824]

- Elemental semiconductors (Si and Ge) belong to group IV A of the periodic table. C which is on top of the group is an insulator (diamond) with energy band gap of 5.5 eV while Sn and Pb are metals.
- Compound semiconductors can be formed by combining elements of groups IIIA and VA. Examples include GaAs, GaP, GaN, InSb. AlN is also a III-V but its band gap is around 6.2 eV making it an insulator. Similarly II-VI compound semiconductors can be formed, examples include ZnO, ZnS, CdSe, CdTe.

Q-8. Draw and interpret the graph for the Fermi Energy variation with temperature for P and N type semiconductors.

Solutions:

In n-type semiconductor: At 0 K all allowed energy levels in the valence band are filled by electrons. All donor levels are filled by unbound electrons. The conduction band is free. So charge carriers do not exist, and the semiconductor behaves as an insulator. At 0 K the Fermi level is between the donor levels and the bottom of the conduction band as shown below.



Energy level diagram of N-type semiconductor. $E_F(T)$ shows the effect of temperature on Fermi energy

8 5

When the temperature is raised, by absorption of suitable energies, some donor atoms are ionised, so that their electrons are elevated to the conduction band. If the density of ionised donor atom is N_d and the density of electron-hole pairs in the intrinsic semi-conductors is n_i at room temperature T, then $N_d \gg n_i$. The Fermi energy is given by

$$E_F = E_C - kT \log_e \left(\frac{N_C}{N_d} \right)$$

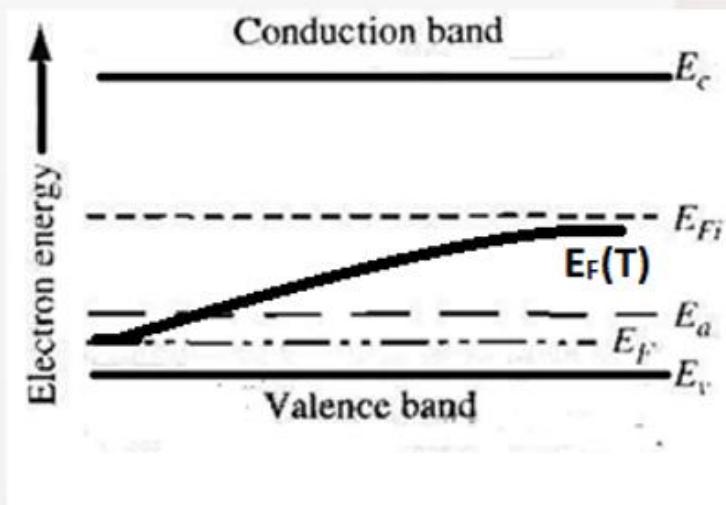
$$\text{where } N_C = 2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{3/2}$$

This shows that in an N-type semiconductor the Fermi-level lies below the bottom of the conduction band. As temperature rises, the Fermi level goes on falling below E_C . When the temperature is sufficiently raised, the electrons and holes generated due to thermal agitation increase significantly and at a stage become fully dominant over the extrinsic carriers. Then the Fermi level approaches the middle of forbidden energy gap.

In P-type semiconductor: The energy band diagram of a P-type semiconductor is shown in the Figure. The acceptor level is shown by E_a near the top of the valence band, the Fermi level by E_F . At absolute zero, all the holes are in acceptor levels, but as the temperature rises, the electrons from valence band jump into acceptor level on the absorption of energy ($E_A - E_V$) by each electron. As a result, these electrons are trapped in the acceptor levels and an equal number of holes are created in the valence band. These holes provide conduction currents. At the room temperature, almost all acceptor atoms trap electrons and thus the number of holes available in the valence band is almost equal to the number of impurity atoms added.

The variation of Fermi energy with temperature is given by:

$$E_F = E_V + kT \log_e \left(\frac{N_V}{N_a} \right) \text{ where } N_V = 2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{3/2}$$



Energy diagram of P-type Semiconductor. $E_F(T)$ shows the effect of temperature on Fermi energy.

This shows that Fermi level lies above the top of the valence band. The position of Fermi level depends upon the temperature and the number of impurity atoms. When the number of impurity atoms increases, the number of holes in the valence band will increase and the Fermi level will shift towards the valence band. When the concentration of acceptor impurity atoms is sufficiently high, the number of holes will be far greater than the conduction electrons and the Fermi level may even lie in the valence band. As the temperature is sufficiently increased, electrons from the valence band are excited to the conduction band

and finally the P-type crystal will start behaving like an intrinsic semi-conductor when the number of electrons in the conduction band will be nearly equal to the valence holes. Thus at extremely high temperatures the Fermi level shifts towards the middle of forbidden energy gap.

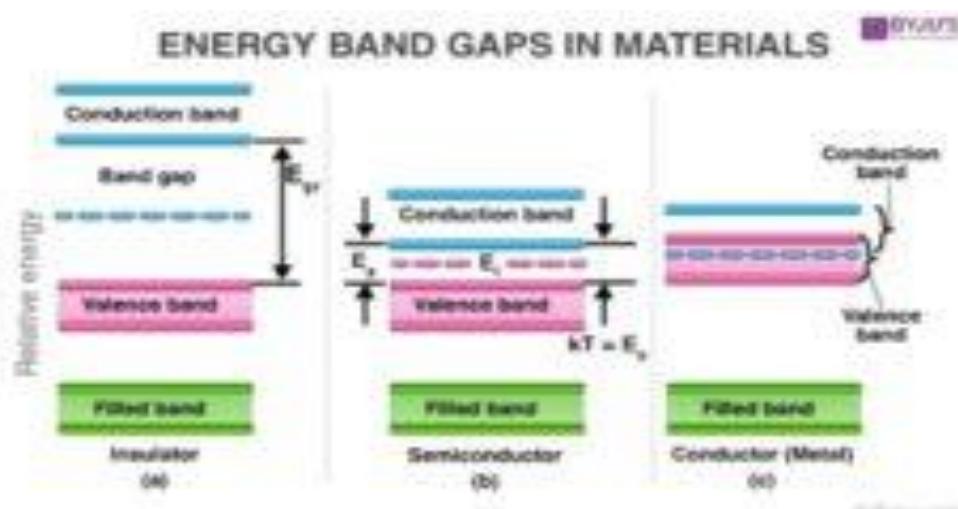
Q-9. Based on band theory of solids, distinguish between conductors, semiconductors, and insulators. The band theory of solids is different from the others because the atoms are arranged very close to each other such that the energy levels of the outermost orbital electrons are affected. But the energy level of the innermost electrons is not affected by the neighbouring atoms.

The three energy bands in solids are

- Valence band
- Conduction band
- Forbidden band

Bond theory solids

- In atoms, electrons are filled in respective energy orbits following Pauli's exclusion principle.
- In molecules, Two atomic orbitals combine together to form a molecular orbit with two distinct energy levels.
- In solids, 10^{23} stacked up lines confined in a tiny space would look like a band. Thereby forming energy continuum called energy bands.
- This theory helps to visualise the difference between conductor, semiconductors and insulator by plotting available energies for an electron in a material.



Conductors:

Metals are conductors in which there is no forbidden energy gap between the conduction band (CB) and valence band (VB). No extra energy required to transfer the electron from VB to CB.

Semiconductors:

In a semiconductor, the valence band is completely filled with electrons while the conduction band is empty. The energy gap between the bands is less. For electrons to jump from the valence band to the conduction band, room temperature needs to be maintained. If the temperature is 0K, there is no transfer of electrons from the valence band to the conduction band.

Insulators:

In insulators, the valence band is completely filled while the conduction band is empty. This results in a large energy gap. Since the energy gap between the conduction band and the valence band is more, there is no movement of electrons from the valence band to the conduction band.

Q-10. Define the Fermi energy and Fermi distribution function. Plot the Fermi distribution function at two different temperatures.

Solution:

The Fermi-Dirac distribution applies to fermions, particles with half-integer spin which must obey the Pauli Exclusion Principle. It gives the probability, $F(E)$, for the occupation of a particular energy level E by an electron is given by

9 5

$$F(E) = \frac{1}{1 + \exp[(E - E_F)/k_B T]}$$

At $T = 0$ K, $F(E) = 1$ for $E < E_F$

$F(E) = 0$ for $E > E_F$

Where k_B is the Boltzmann's constant, T is the absolute temperature, E is the energy of the particular energy level E , and E_F is the Fermi energy

It can be seen that for $T = 0$, all the states up to energy E_F are filled with electrons and all the states above E_F are vacant. At $E = E_F$ the occupation probability is $\frac{1}{2}$.

Thus the Fermi energy can be defined as the energy of the highest filled level at absolute zero. At a finite temperature, the electron may get the energy of order $k_B T$ and go to higher vacant state, and so

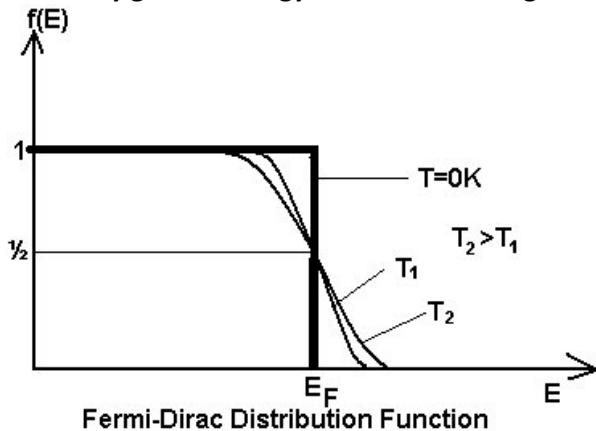


Figure shows the Fermi- function plot at three different temperatures { $T_2 > T_1 > T_0$ }

Q-11. Distinguish between elemental and compound semiconductors with two examples

Solution: -Elemental Semiconductors: Elemental semiconductors (Si and Ge) belong to group IVA of the periodic table. C which is on top of the group is an insulator (diamond) with energy band gap of 5.5 eV while Sn and Pb are metals.



Compound Semiconductors : Compound semiconductors can be formed by combining elements of groups IIIA and VA. Examples include GaAs, GaP, GaN, InSb. AlN is also a III-V but its band gap is around 6.2 eV making it an insulator. Similarly II-VI compound semiconductors can be formed, examples include ZnO, ZnS, CdSe, CdTe.

Q-12. Distinguish between intrinsic and extrinsic types of semiconductor with examples. Outline the nature of charge in an intrinsic semiconductor on addition of neutral trivalent impurity atoms.

Solution: The importance of semiconductors is further increased due to the fact that the conductivity and the effective band gaps of these materials can be modified by the introduction of impurities which strongly affect their electronic and optical properties. The process of introduction of impurities in

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12 8

semiconductors is called doping. Depending on the nature of impurities added, the semiconductors are classified as :

- (a) Pure or intrinsic semiconductors
- (b) Doped or extrinsic semiconductors

The intrinsic semiconductors are pure semiconductors in which no impurity atoms are added. The most common intrinsic semiconductors are Silicon (Si) and Germanium (Ge), which belong to Group IV of the periodic table. The atomic numbers of Si and Ge are 14 and 32, which yields their electronic configuration as $1s^2 2s^2 2p^6 3s^2 3p^2$ and $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^2$, respectively.

This indicates that both Si and Ge have four electrons each in their outer-most i.e. valence shell (indicated by red colour). These electrons are called valence electrons and are responsible for the conduction-properties of the semiconductors. Here it is seen that each valence electron of a Si atom pair with the valence electron of the adjacent Si atom to form a covalent bond.

After pairing, the **intrinsic semiconductor** becomes deprived of free charge carriers which are nothing but the valence electrons. Hence, at 0K the valence band will be full of electrons while the conduction band will be empty (as shown in figure 2 , in next slide). At this stage, no electron in the valence band would gain enough energy to cross the forbidden energy gap of the semiconductor material. **Thus the intrinsic semiconductors act as insulators at 0K.**

However, at room temperature, the thermal energy may cause a few of the covalent bonds to break, thus generating the free electrons as shown in Figure 3a. The electrons thus generated get excited and move into the conduction band from the valence band, overcoming the energy barrier (Figure 2b). During this process, each electron leaves behind a hole in the valence band. The electrons and holes created in this way are called intrinsic charge carriers and are responsible for the conductive properties exhibited by the intrinsic semiconductor material.

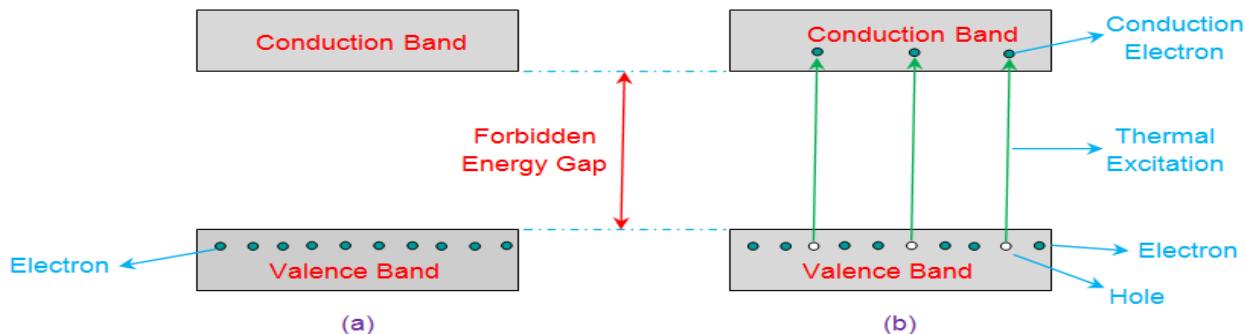
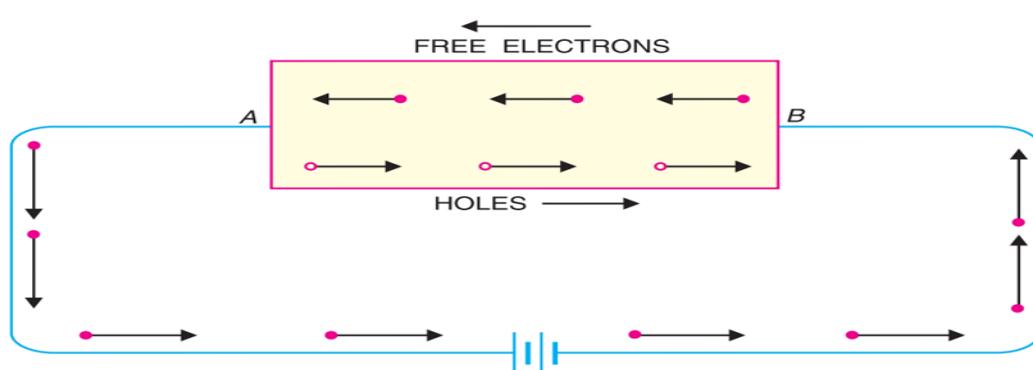


Figure 2 Energy Band Diagram of Intrinsic Semiconductor at (a) 0K (b) Temperature > 0K

In an intrinsic semiconductor, even at room temperature, hole-electron pairs are created

Under the influence of electric field, conduction through the semiconductor is by both free electrons and holes. Therefore, the total current inside the semiconductor is the sum of currents due to free electrons and holes.



The impurity mixed intrinsic semi-conductors are called extrinsic semiconductors. The process of adding impurity is called doping. The purpose of adding impurities is either to increase the number of free electrons or holes in the semi-conductor crystal.

Depending on the type of impurity added, the extrinsic semi conductor are classified as:

N-type semi-conductors:

electrons are majority charge carriers.

This is achieved by doping with pentavalent impurity atoms such as Phosphorus.

P-type semi-conductors:

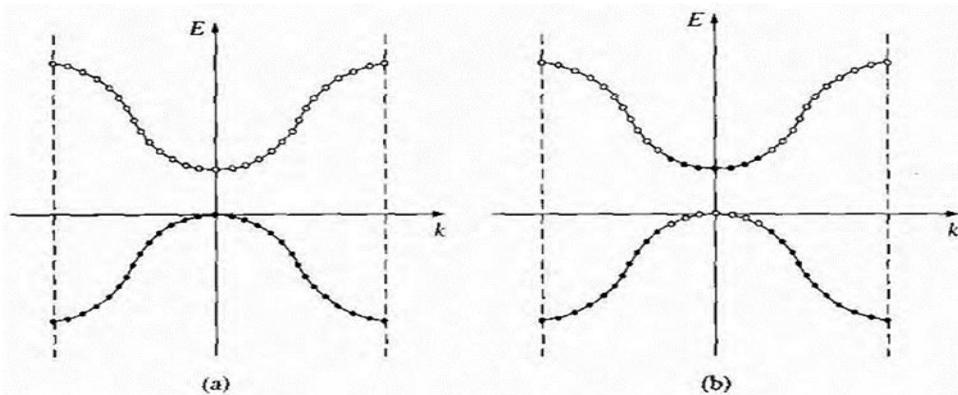
holes are majority charge carriers.

This is achieved by doping with trivalent impurity atoms such as Aluminium

Q-13. Distinguish between the direct and indirect band gap semiconductors with one examples.

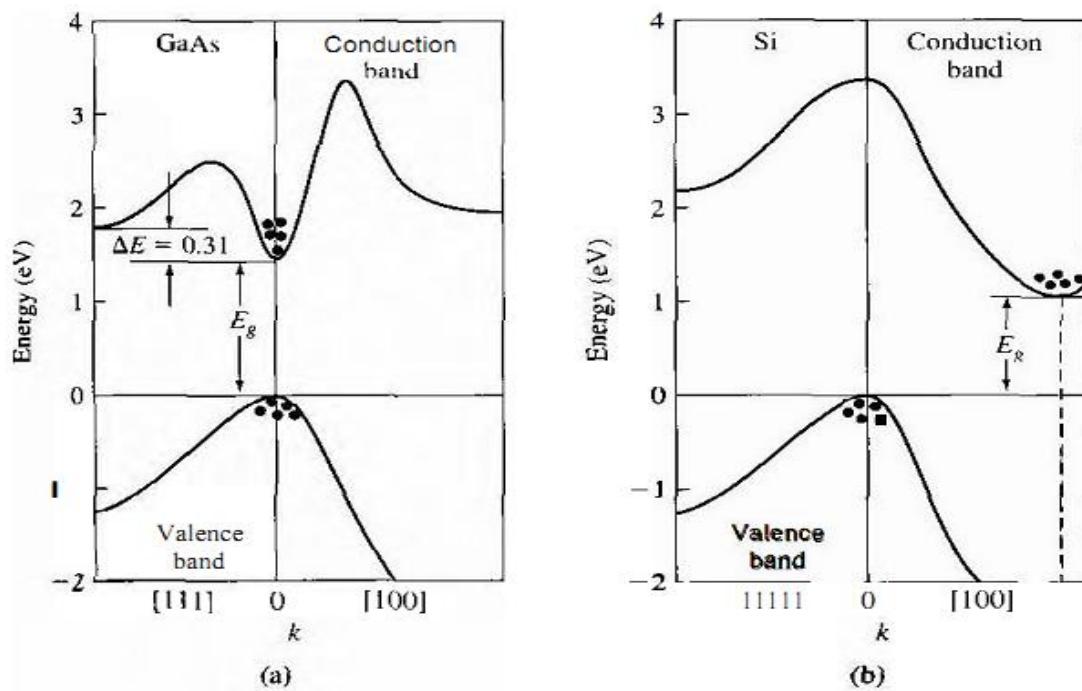
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Solution: Figure shows the E versus k diagram of the conduction and valence bands for an intrinsic semiconductor at $T = 0 \text{ K}$. The energy states in the valence band are completely full and the states in the conduction band are empty. Figure shows these same bands for $T > 0 \text{ K}$, in which some electrons have gained enough energy to jump to the conduction band and have left empty states in the valence band. In absence of any external forces, the electron and "empty state" distributions are symmetrical with k .



The E versus k diagram of the conduction and valence bands of a semiconductor at (a) $T = 0 \text{ K}$ and (b) $T > 0 \text{ K}$.

Figure shows the E versus k diagram for Ga-As and Si.

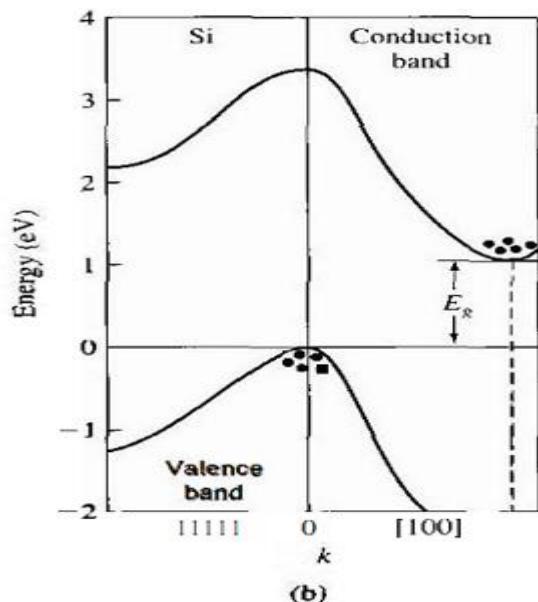


In Ga-As, the valence band maximum and the conduction band minimum both occur at $k = 0$. The electrons in the conduction band tend to settle at the minimum conduction band energy which is at $k = 0$. Similarly, holes in the valence band tend to congregate at the uppermost valence band energy. In Ga-As, the minimum conduction band energy and maximum valence band energy occur at the same k value.

A semiconductor with this property is said to be a **direct band gap semiconductor**; transitions between the two allowed bands can take place with no change in crystal momentum. This direct nature has

significant effect on the optical properties of the material. Ga-As and other direct bandgap materials are ideally suited for use in semiconductor lasers and other optical devices.

The E versus k diagram for silicon is shown in Figure b. The maximum in the valence band energy occurs at $k = 0$ as before. The minimum in the conduction band energy occurs not at $k = 0$, but along the [100] direction. The difference between the minimum conduction band energy and the maximum valence band energy is still defined as the bandgap energy. **A semiconductor whose maximum valence band energy and minimum conduction band energy do not occur at the same k value is called an indirect bandgap semiconductor.**



When electrons make a transition between the conduction and valence bands, we must invoke the law of conservation of momentum. A transition in an indirect bandgap material must necessarily include an interaction with the crystal so that crystal momentum is conserved. Germanium is also an indirect bandgap material, whose valence band maximum occurs at $k = 0$ and whose conduction band minimum occurs along the [111] direction. GaAs is a direct bandgap semiconductor, but other compound semiconductors such as GaP and AlAs, have indirect bandgaps.

Q-14. Describe the P and N types semiconductors and indicate the Fermi level and energy level of impurity atoms in band diagram

14 8

Solution: Depending on the type of impurity added, the extrinsic semi conductor are classified as:

N-type semi-conductors:

electrons are majority charge carriers.

This is achieved by doping with pentavalent impurity atoms such as Phosphorus.

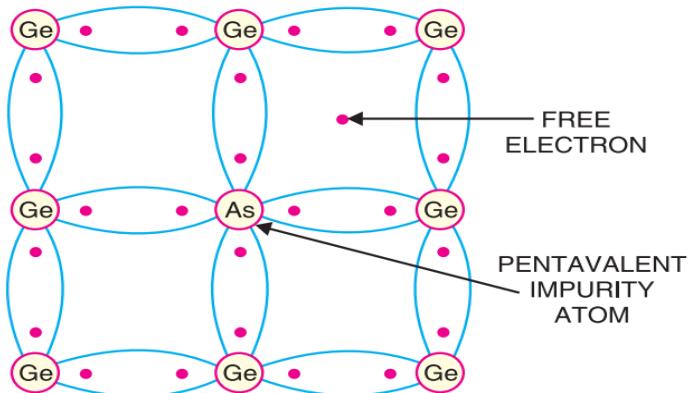
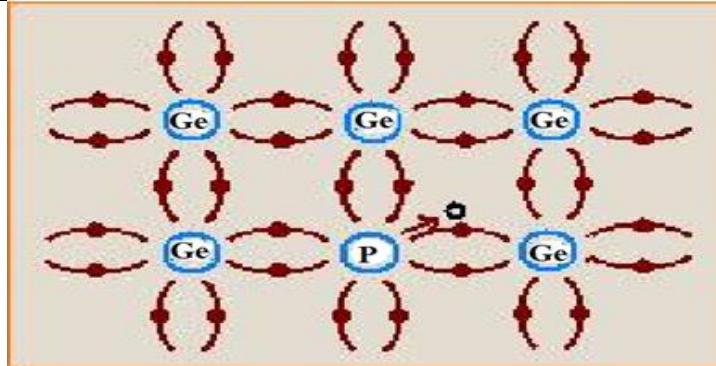
P-type semi-conductors:

holes are majority charge carriers.

This is achieved by doping with trivalent impurity atoms such as Aluminium.

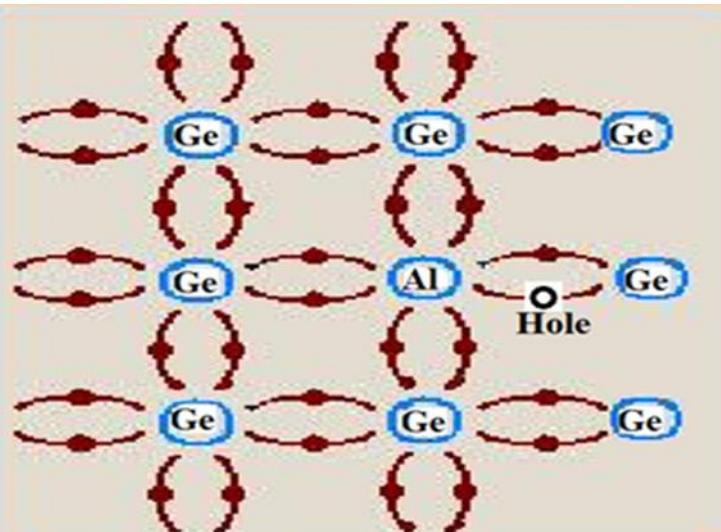
When a small amount of pentavalent impurity (phosphorus, bismuth, arsenic, antimony) is doped in pure semi-conductor then the conductivity of crystal increases due to surplus electrons and such a doped semi-conductor is called N-type semi-conductors while the impurity atoms are called donors, because they donate free electrons for conduction to the semiconductor crystal.

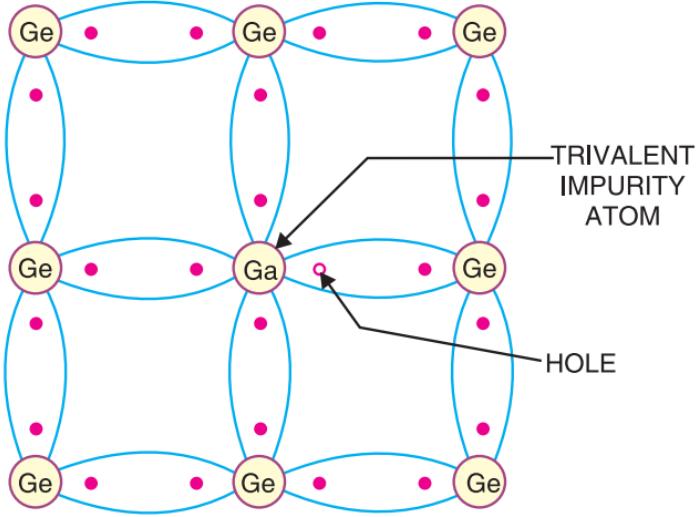
To explain the formation of N-type semiconductor, consider that a pentavalent impurity phosphorus is added to a pure germanium crystal. Each impurity atom with five valence electrons replaces a germanium atom. The four valence electrons of impurity atom form covalent bonds with electrons of neighbouring germanium atoms, while the fifth electron becomes surplus. Therefore for each impurity atom added one electron will be available for germanium crystal to cause conduction.



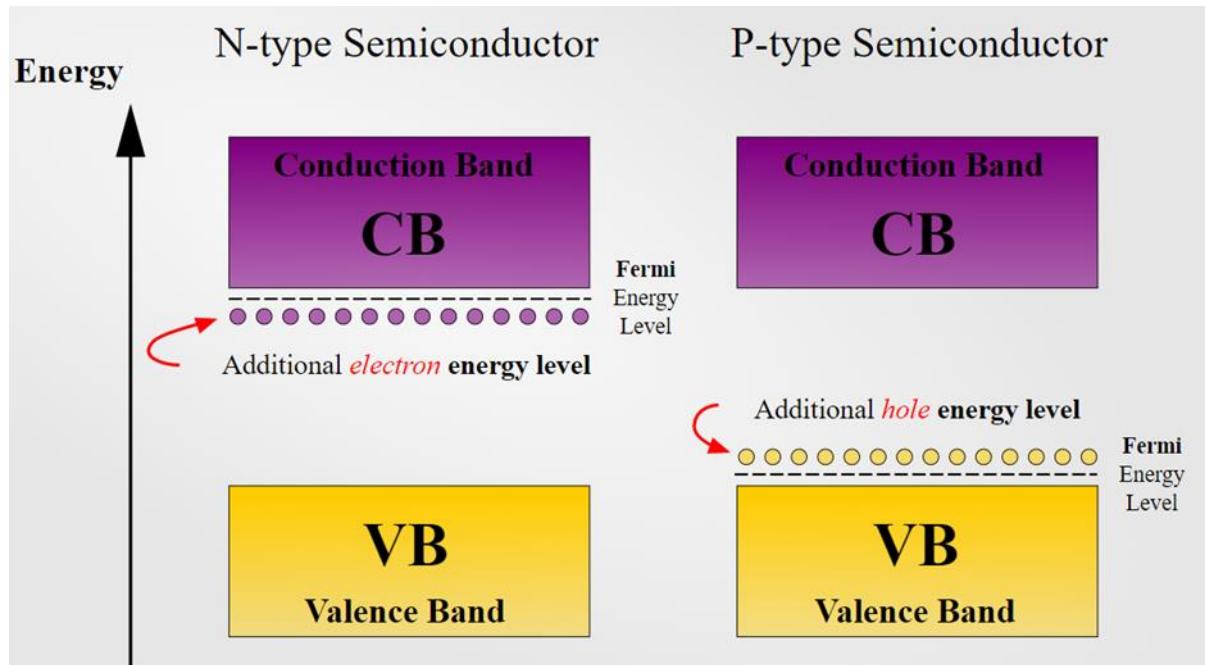
When a small amount of trivalent impurity like gallium, indium, aluminium or boron is doped in a pure semi-conductor, then the conductivity of crystal increases due to the deficiency of electrons (i.e., holes) and such a doped semi-conductor is called P-type semi-conductors, while the impurity atoms are called acceptors because the holes created can accept the electrons.

To explain the formation of P-type semi-conductor, consider that a trivalent impurity (Aluminium or Ga) is added to pure germanium crystal. Each impurity atom with three valence electrons replaces a germanium atom. Three valence electrons of Aluminium can form only three single covalent bonds with neighbouring germanium atoms. In the formation of fourth covalent bond there is a deficiency of electron with Aluminium. This deficiency acts like a positive charge and is called a hole. Therefore for each impurity atom added, a hole is created. A small amount of trivalent impurity provides millions of holes to cause conduction.





Fermi level and impurity atoms (Donor/ Acceptors) level in n type and p-type of semi-conductors



Q-15. Explain the extrinsic semiconductor. Using suitable diagram, discuss how the Fermi level changes with change of temperature in extrinsic semiconductors.

Solution:

Extrinsic Semiconductors (Definition) - An extrinsic semiconductors are those semiconductors that come into existence when a measured and small amount of chemical impurity is added to intrinsic semiconductors. It is also known as doped semiconductor or impurity semiconductors. The doping of the semiconductors increases its conductivity. The process of deliberately adding a desirable impurity is known as doping and the impurity atoms are called dopants. Extrinsic semiconductors are further classified into two types - N-Type semiconductors and P-type semiconductors.

At lower temperatures the quasi Fermi level is between conduction and donor energy level for n type semiconductor and between valence and acceptor energy level for a p type semiconductor but as temperature increases gradually, the quasi Fermi level falls in case of n type and rises gradually in case of p type semiconductor and after a certain temperature, the quasi fermi level becomes equal to half of the band gap of the semiconductor and at that point, the quasi Fermi level is same as the Fermi level for an intrinsic one and hence, the extrinsic semiconductor acts as an intrinsic one.

The Fermi Level: Extrinsic Semiconductor

Fermi Level Position: Extrinsic Semiconductor

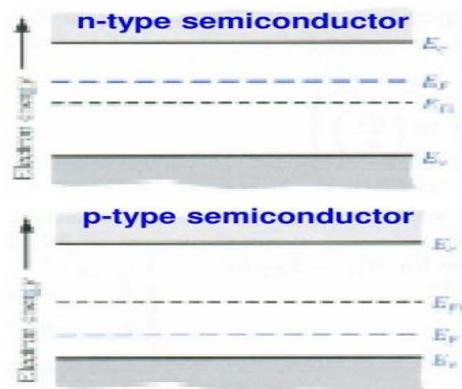
We can now determine the position of the Fermi energy level as a function of the doping concentrations.

For n-type semiconductor

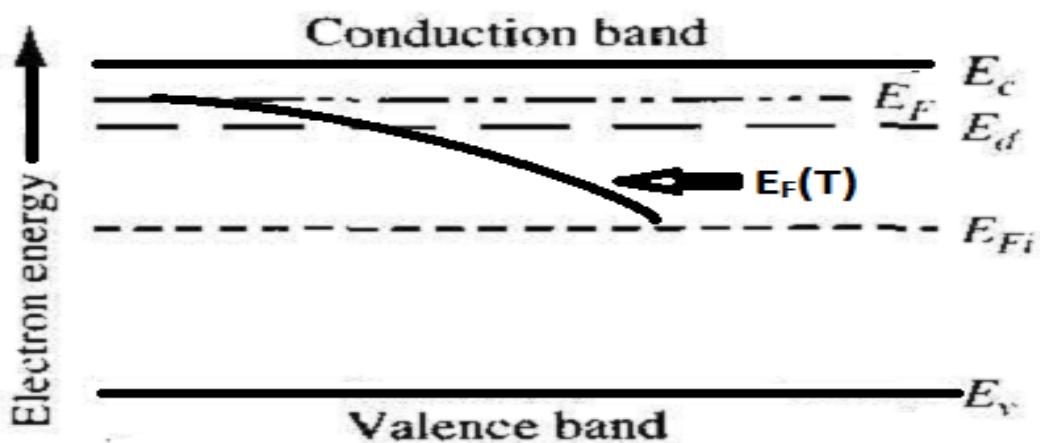
$$n_0 = N_C e^{-(E_c - E_F)/kT} \approx N_D$$
$$\Rightarrow E_c - E_F = kT \ln\left(\frac{N_C}{N_D}\right)$$

For p-type semiconductor

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



In n-type semiconductor: At 0 K all allowed energy levels in the valence band are filled by electrons. All donor levels are filled by unbound electrons. The conduction band is free. So charge carriers do not exist, and the semiconductor behaves as an insulator. At 0 K the Fermi level is between the donor levels and the bottom of the conduction band as shown below.



Energy level diagram of N-type semiconductor. $E_F(T)$ shows the effect of temperature on Fermi energy

When the temperature is raised, by absorption of suitable energies, some donor atoms are ionised, so that their electrons are elevated to the conduction band. If the density of ionised donor atom is N_d and the density of electron-hole pairs in the intrinsic semi-conductors is n_i at room temperature T, then $N_d \gg n_i$. The Fermi energy is given by This shows that in an N-type semiconductor the Fermi-level lies below the bottom of the conduction band. As temperature rises, the Fermi level goes on falling below E_c . When the temperature is sufficiently raised, the electrons and holes generated due to thermal agitation increase significantly and at a stage become fully dominant over the extrinsic carriers. Then the Fermi level approaches the middle of forbidden energy gap.

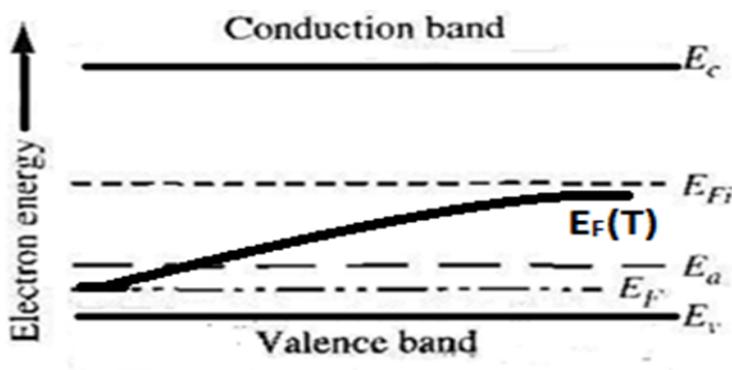
$$E_F = E_C - kT \log_e \left(\frac{N_C}{N_d} \right)$$

where $N_C = 2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{3/2}$

In P-type semiconductor: The energy band diagram of a P-type semiconductor is shown in the Figure. The acceptor level is shown by E_a near the top of the valence band, the Fermi level by E_F . At absolute zero, all the holes are in acceptor levels, but as the temperature rises, the electrons from valence band jump into acceptor level on the absorption of energy ($E_A - E_V$) by each electron. As a result, these electrons are trapped in the acceptor levels and an equal number of holes are created in the valence band. These holes provide conduction currents. At the room temperature, almost all acceptor atoms trap electrons and thus the number of holes available in the valence band is almost equal to the number of impurity atoms added.

The variation of Fermi energy with temperature is given by:

$$E_F = E_V + kT \log_e \left(\frac{N_V}{N_a} \right) \text{ where } N_V = 2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{3/2}$$



Energy diagram of P-type Semiconductor. $E_F(T)$ shows the effect of temperature on Fermi energy.

This shows that Fermi level lies above the top of the valence band. The position of Fermi level depends upon the temperature and the number of impurity atoms. When the number of impurity atoms increases, the number of holes in the valence band will increase and the Fermi level will shift towards the valence band. When the concentration of acceptor impurity atoms is sufficiently high, the number of holes will be far greater than the conduction electrons and the Fermi level may even lie in the valence band. As the temperature is sufficiently increased, electrons from the valence band are excited to the conduction band and finally the P-type crystal will start behaving like an intrinsic semi-conductor when the number of electrons in the conduction band will be nearly equal to the valence holes. Thus at extremely high temperatures the Fermi level shifts towards the middle of forbidden energy gap.

e of energy
two momenta
Hon occurs
radiative
emission

is low
o make
I- Si, Ge.

electrons
ugly gap

holes
gap

2)

For GaAs, $E_g = 1.42 \text{ eV}$ and the corresponding wavelength is:

$$\lambda = \frac{hc}{E_g} = \frac{(6.626 \times 10^{-34} \text{ Js})(3 \times 10^8 \text{ m s}^{-1})}{(1.42 \text{ eV} \times 1.602 \times 10^{-19} \text{ J/eV})}$$

$$\therefore \lambda = 8.74 \times 10^{-7} \text{ m or } 874 \text{ nm}$$

3)

Given, $\lambda = 414 \text{ nm}$

$$E = \frac{hc}{\lambda} = \frac{6.626 \times 10^{-34} \times 3 \times 10^8}{414 \times 10^{-9}}$$

$$E = 0.04801 \times 10^{-17} = 4.801 \times 10^{15} \text{ V}$$

Q5) Mobility of semiconductor n-p is:

$$M_p = \frac{G_p}{P_e} = G_p R_H = \frac{R_H}{P}$$

where $P = \text{resistivity} = 9 \times 10^{-3} \Omega \cdot \text{m}$

$$M_p = \frac{3.22 \times 10^{-4}}{9 \times 10^{-3}} = 0.357 \text{ m}^2/\text{V-s}$$

$m^2/\text{s} = 5 \text{ m}^2/\text{s}$

Since R_H is +ve, so the given semiconductor is **P-type**

where, $P = \text{hole concentration}$

$$6) R_H = \frac{1}{P e} = 1.904 \times 10^{21} \text{ m}^{-3}$$

$$P = \frac{1}{R_H e} = \frac{1}{3.22 \times 10^{-4} \times 1.6 \times 10^{-19}}$$

7) The charge carriers that are present in large quantity are called majority charge carriers. The majority charge carriers carry most of the electric charge or electric current in the semiconductor. Hence, majority charge carriers are mainly responsible for current flow in the semiconductor.

Whereas, the charge carriers that are present in small quantity are called minority charge carriers carry very small amount of electric charge or electric current in the semiconductor.

8) From the relation, $J = I/A$

$$I = n e A V_d$$

Also,

$$V_d = \frac{e E_r}{m} \Rightarrow I = n e A \left(\frac{e E_r}{m} \right) \\ = \frac{n e^2 A E_r}{m}$$

$$\text{or } I/A = \frac{n e^2 E_r}{m} = J$$

$$\text{Hence } P = \frac{m}{n e^2 \gamma}$$

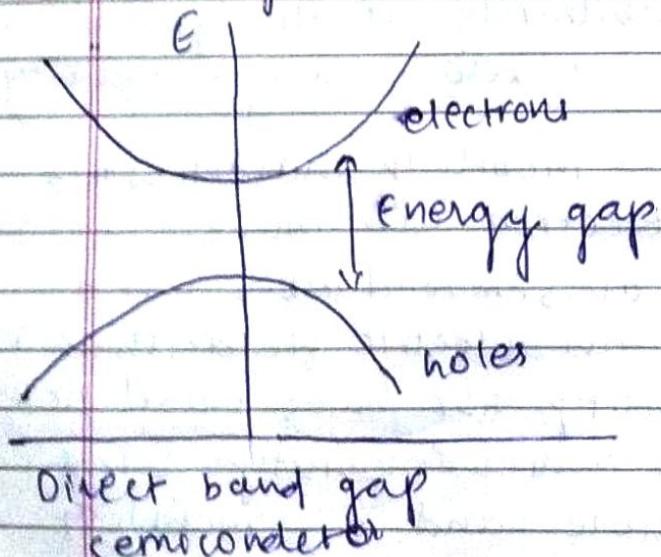
So, for current density J , conductivity $\sigma = (\gamma_p)$
where $J = \sigma E$

$$\text{Mobility } \mu = V_d/E = e \gamma/m$$

As temp. is constant ~~so~~ so relaxation time will be same and if we double the potential difference the mobility will change accordingly.

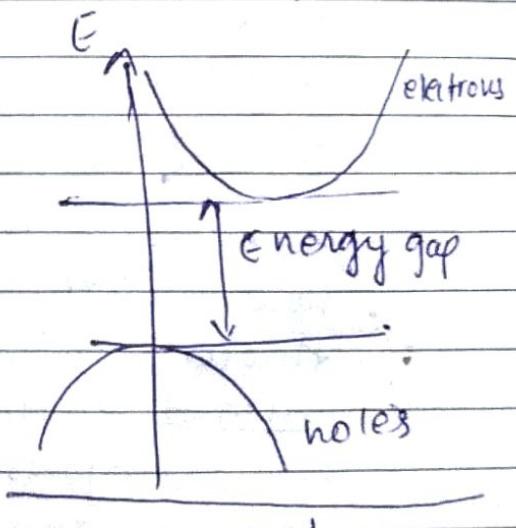
1) DIRECT Band gap

- ① It is one in which maximum energy level of valence band aligns with the minimum energy level of conduction band with respect to momentum.
- ② In this direct recombination takes place with energy equal to the difference between energy of recombining particles.
- ③ The probability of radiative recombination is very high.
- ④ Efficiency factor is high.
- ⑤ They are preferred for making optical devices like LEDs e.g.: GaAs



Indirect Band gap

- ① It is one in which maximum energy level of valence band and minimum energy level of valence band and minimum energy level of conduction band are not aligned with respect to momentum.
- ② In this due to a diff. in momentum, first momentum is conserved by release of energy and only when the two momenta are aligned, recombination occurs.
- ③ The probability of radiative recombination is almost negligible.
- ④ Efficiency factor is low.
- ⑤ Cannot be used to make optical device e.g.: Si, Ge.



Sankshi
Aivastava

10) The current density can be defined as the electric current carried by conductor per unit cross-sectional area of the semiconductor per unit conducting medium. We denote the current density with j and $j = I/A$. Here, I is the uniformly distributed current being carried by the conductor of the cross-sectional area A .

The mobility of charge carriers in current carrying conductors can be defined as the net average velocity with which the free electrons move towards the positive end of a conductor under the influence of an external electric field that is being applied.

Same as ques. no. 5

(11) It is the drift velocity :- It is the average velocity acquired by a charged particle (like an electron or proton) in the body due to an electric field. Usually, an e^- inside a conductor moves arbitrarily at the Fermi velocity, generating a zero average velocity.

Mobility :- In electro mobility characteristics how quickly an electron can move through a metal or semiconductors when plugged pulled by an electric field. There is an analogous quantity for holes called hole mobility. The term carrier mobility refers in general to both hole and e^- mobility.

- Equation of mobility (denoted by μ)

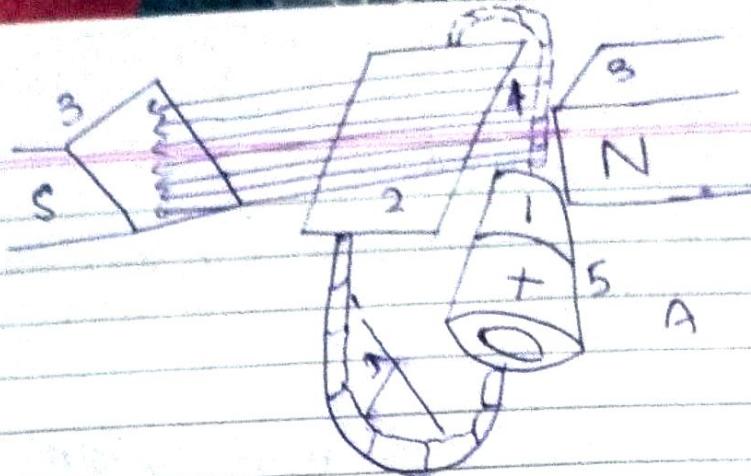
$$V_d = \mu E$$

$$V_d \propto E$$

$$\frac{V_d}{E} = \mu \text{ or } \mu = \frac{V_d}{E}$$

$V_d = \mu E$

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DATE
PAGE

Hall effect: It is a current carrying conductor (or semiconductor) is placed in the magnetic field \perp to the dirⁿ of current, the magnetic field exerts a transverse force (Korentz force) on the moving charge carriers which tends to push charge carriers to one side of the conductor. A build-up of charge at the sides of the conductors will balance this magnetic influence, producing a measurable voltage between the two sides of the conductor. This voltage is called Hall voltage (V_H) and this effect is called Hall effect.

Semi-Conductor

Ques - An electric field of 200 V/m is applied to a sample of n type semiconductor whose Hall coefficient is $-0.0145 \text{ m}^2/\text{Coulomb}$. Calculate the current density in the sample assuming mobility of electron equals to $0.36 \text{ V}^{-1}\text{A}^{-1}\text{s}^{-1}$.

Ay Electric field (E) = 200 V/m

Hall coefficient (R_H) = $-0.0145 \text{ m}^2/\text{C}$

Current density (J) = ?

Mobility of electrons (m_e) = $0.36 \text{ V}^{-1}\text{A}^{-1}\text{s}^{-1}$

$$m_e = \frac{J}{n e E}$$

$$m_e = \frac{J}{\frac{1}{R_H} \times e \times E}$$

$$\left(\because n = \frac{1}{R_H e} \right)$$

$$0.36 = \frac{J}{\frac{1}{0.0145} \times 200 \times 10000}$$

$$J = \frac{0.36 \times 2 \times 10^6}{145} = 4.965 \times 10^3 \text{ A/m}^2/\text{kg}$$

Ques-4:- The carrier concentration in n-type semiconductor is $10^{19}/\text{m}^3$. Determine the value of Hall effect coefficient.

Given:- $n = \text{electron concentration} = 10^{19}/\text{m}^3$
 R_H (Hall coefficient) = ?

$$R_H = -\frac{1}{ne}$$

$$R_H = -\frac{1}{10^{19} \times 1.6 \times 10^{-19}}$$

$$\underline{\underline{R_H = -0.625 \text{ m}^2/\text{C}}}$$

Ques 14:- Explain Hall effect & derive the expression for Hall coefficient. The carrier concentration in n-type semiconductor is 10^{19} m^{-3} . Determine the value of Hall coefficient.

Ans Hall effect explained in Ques - 13.

Derivation:-

$$F_H = F_m$$

$$F_H = e E_H$$

Now, at equilibrium the magnitude of Hall coefficient force & Lorentz force will be equal.

$$\text{i.e } e E_H = ev_d B \Rightarrow E_H = v_d B \quad \text{--- (1)}$$

Current Density,

~~$$J = -nev_d \quad \text{--- (2)}$$~~

divide eqⁿ (1) & (2)

$$\frac{E_H}{J} = \frac{v_d B}{-nev_d}$$

$$\Rightarrow \frac{E_H}{J} = \frac{B}{-ne}$$

$$\Rightarrow \boxed{E_H = R_H B J} \quad (\because R_H = \frac{1}{-ne})$$

$$R_H = \frac{E_H}{BJ} = -\frac{1}{ne}$$

R_H

$R_H = +ve$ for e^- & $-ve$ for holes.

$$\text{Given: } -n = 10^9 \text{ m}^{-3}$$

we know

$$R_H = \frac{1}{-ne}$$

$$R_H = \frac{1}{10^{10} \times 1.6 \times 10^{-19}}$$

$$R_H = \frac{1}{1.6} \text{ m}^2/\text{C}$$

$$R_H = 0.625 \text{ m}^2/\text{C} \quad \underline{\text{Ans}}$$

Ans

11

12

13

14

Ques-18:- Show that in an intrinsic semiconductor the conductivity of the material is given by the expression; $\sigma = en(\mu_e + \mu_p)$, where σ = conductivity, n = carrier density, μ_e = mobility of e^- , μ_p = mobility of holes & e = electronic charge. The intrinsic carrier density n_{in} of Ge at 27° is $2.4 \times 10^{17} m^{-3}$. Calculate its resistivity, if the electron & hole mobility are $0.35 m^2/Vs$ & $0.18 m^2/Vs$.

Ans If n_e, n_p represents electron & hole density & v_e, v_p their drift velocities,

$$I_e = e n_e A v_e$$

$$I_p = e n_p A v_p$$

$$\text{Total Current} = I_e + I_p$$

$$I = e n_e A v_e + e n_p A v_p$$

$$I = e(n_e v_e + n_p v_p)A \quad - \quad (1)$$

we know that $R = \frac{V}{I}$ ~~more~~ ~~per unit length~~

$$R = \rho \frac{l}{A}$$

$$\frac{V}{I} = \rho \frac{l}{A} \Rightarrow \rho = \frac{V A}{I l} = \frac{E A}{I} \quad (\because E = \frac{V}{l}) \quad - \quad (2)$$

E = electric intensity.

$$\sigma = \frac{1}{\rho}$$

$$\sigma = \frac{I}{E A} \quad (\because \text{from } (1))$$

$$\sigma = \frac{e(n_e v_e + n_p v_p)A}{E A} \quad (\because \text{from } (1))$$

$$\sigma = e \left[n_e \left(\frac{v_e}{E} \right) + n_p \left(\frac{v_p}{E} \right) \right]$$

$$\sigma = e(n_e v_e + n_p v_p) \quad (\because m = \frac{v}{E}, m = \text{mobility})$$

Hence Proved.

For intrinsic semiconductor $n_e = n_p = n$

$$\sigma = n_e (v_e + v_p) \quad \text{Hence Proved}$$

$$\text{Given:- } n = 2.4 \times 10^{17} \text{ m}^{-3}$$

$$\mu_e = 0.35 \text{ m}^2/\text{Vs}$$

$$\mu_p = 0.18 \text{ m}^2/\text{Vs}$$

We know that

$$\sigma = n e (\mu_e + \mu_p)$$

$$\sigma = 2.4 \times 10^{17} \times 1.6 \times 10^{-19} (0.35 + 0.18)$$

$$\sigma = 3.84 \times 10^{-2} (0.53)$$

$$\sigma = 2.03 \times 10^{-12}$$

$$\text{Here } \sigma = \frac{1}{\rho}$$

$$\text{Resistivity } (\rho) = \frac{1}{2.03 \times 10^{-12}} = 49.26 \text{ } \cancel{\Omega \text{m}}$$

COURSE: BBS01T1002 SEMICONDUCTOR PHYSICS

Syllabus for B.Tech. Sem -II

ETE- (Winter-2021-22)

Unit 1 Quantum and Band Theory of electron: Quantum free electron theory. Fermi Dirac distribution function and Fermi level, density of states, Energy band in solids, E-K diagram and Brillouin zone, effective mass, concept of holes.

Unit 2 Semiconductor: Types of semiconductor, Fermi level in semiconductor, effect of carrier concentration and temperature on fermi level, direct-indirect band gap semiconductors, compound semiconductors, Conductivity and mobility, recombination process, Hall effect and applications.

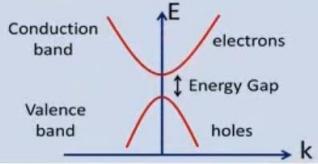
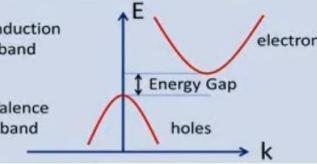
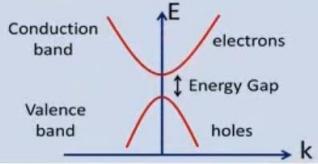
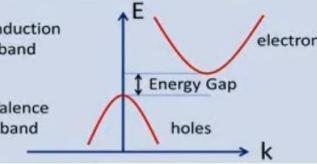
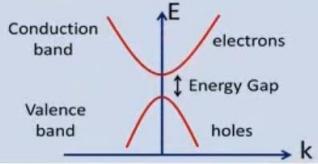
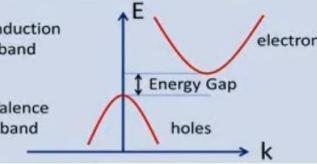
Unit 3 Applications of Diodes : Concept in optical transitions in bulk semiconductors-absorption process, recombination process, explanation for spontaneous emission-stimulated emission-transition rate, theory of p-n junction, p-n junction diode and its I-V characteristics, optoelectronics devices-LEDs, laser diode, Basics of Photovoltaics- photovoltaic effect, Determination of efficiency of PV cell.

Unit- 4 Low Dimension Physics and Nano-materials: Density of states in 0D, 1 D and 2D –Low dimensional systems: Quantum well, Quantum wire, Quantum dots, Nanomaterials and its properties, Classification of Nanomaterials, Carbon nanowires and nanotubes, Semiconductor nanomaterials, Graphene, Characterization techniques (basic ideas): Scanning Electron Microscopy and Transmission Scanning Electron microscopy

S.No.	Unit 1 [Quantum and Band Theory of electron]: Questions	Max Marks
1	Find the least energy of an electron moving in one dimensional infinitely high potential box of width 0.05 nm. [Given Planck's Constant (h) = 6.625×10^{-34} J.s. and mass of electron (m)= 9.1×10^{-31} kg.]	2
2	Find the least energy of an electron moving in one dimensional infinitely high potential box of width 0.05 nm	2
3	An electron is bound in a one dimensional potential box which has a width 2.5×10^{-10} m. Assuming the height of the box to be infinite, calculate the lowest two permitted energy values of the electron.[Given Planck's Constant (h)= 6.625×10^{-34} J.s. and mass of electron (m) = 9.1×10^{-31} kg.]	2
4	Find the minimum energy of an electron moving in one dimension in an infinitely high potential box of width 1 Å. [Given Planck's Constant (h)= 6.625×10^{-34} J.s. and mass of electron (m) = 9.1×10^{-31} kg.]	2
5	The Fermi Energy for a given solid is 5.0 eV at T=0K. What is the average energy of the electron in the metal at 0 K?	2
6	The Fermi level for potassium is 2.0 eV. Calculate the velocity of the electrons at the Fermi level.	2

7	What is the value of Fermi-Dirac distribution function for T=0, when (i) energy is greater than Fermi Energy and (ii) when energy is less than Fermi Energy.	2
8	Define the Fermi Energy. If the Fermi energy is 10eV, calculate the mean energy of electron at 0 Kelvin.	2
9	Write Schrodinger's time-independent equation for matter waves. Explain the physical significance of the wave function?	5
10	Explain the idea of wave function for a quantum particle. Write the basic characteristics of well-behaved wave function?	5
11	Draw the E-K diagram of a semiconductor based on band theory of solids. Explain the Brillouin zones in a solid.	5
12	What would be the band structure if the barrier strength is extremely high or negligible? Justify your answer with a suitable diagram.	8
13	Define the density of energy state in a solid. Find the expression for density of states.	8
14	An electron is in motion along a line between $x=0$ and $x=L$ with zero potential energy. At points for which $x \leq 0$ and $x \geq L$, the potential energy is infinite. The wave function for the particle in the n^{th} state is given by $\psi_n = A \sin(n\pi x/L)$. Find the expression for the normalized wave function.	8
15	An electron is in motion along a line between $x=0$ and $x=L$ with zero potential energy. At points for which $x \leq 0$ and $x \geq L$, the potential energy is infinite. Solving Schrodinger's equation, obtain energy Eigen values	8
16	Explain the energy band in solids and classify the materials based on energy gap.	8

S.No .	Unit- 2 [Semiconductor] : Questions	Max Marks
1	An electric field of 200 volt/m is applied to a sample of n type semiconductor whose Hall coefficient is $-0.0145 \text{ m}^2/\text{coulomb}$. Calculate the current density in the sample assuming mobility of electron equals to $0.36 \text{ V}^{-1} \text{ S}^{-1}$.	2
2	The carrier concentration in n-type semiconductor is $3.0 \times 10^{19}/\text{m}^3$. Determine the value of Hall coefficient. Given that $e = 1.6 \times 10^{-19} \text{ C}$	2
3	What is the wavelength corresponding to the bandgap of GaAs (1.42eV) approximately?	2
4	Calculate energy band gap of semiconducting material if it emits light of wavelength 414 nm.	2
5	The carrier concentration in n-type semiconductor is $10^{19}/\text{m}^3$. Determine the value of Hall coefficient.	2

6	Hall coefficient of a semiconductor is $3.22 \times 10^{-4} \text{ m}^3/\text{C}$. Its resistivity is $9 \times 10^{-3} \text{ ohm-meter}$. Calculate the mobility in the semiconductor.	2												
7	The Hall coefficient (R_H) of a semiconductor is $3.22 \times 10^{-4} \text{ m}^3/\text{C}$. Calculate the carrier concentration of the carriers. (Given that $e = 1.6 \times 10^{-19} \text{ C}$).	2												
8	In a p-n junction diode, explain a). Minority charge carrier b). Majority charge carrier	2												
9	Derive the expression of current density and Mobility of charge carriers for semiconductor	5												
10	<p>Distinguish between the direct and indirect band gap semiconductors using band diagram with one-one example.</p> <table border="1"> <thead> <tr> <th>Direct bandgap Semiconductors</th> <th>Indirect bandgap Semiconductors</th> </tr> </thead> <tbody> <tr> <td></td> <td></td> </tr> <tr> <td>Maximum of valence band and minimum of conduction band occur at same momentum values</td> <td>Maximum of valence band and minimum of conduction band occur at two different momentum values.</td> </tr> <tr> <td>Electron making a transition from valence band to conduction band need not undergo any change in its momentum.</td> <td>In order to make a transition from maximum point in valence band to minimum point in conduction band, the electron requires energy for the change in momentum in addition to the energy gap E_g</td> </tr> <tr> <td>The compound semiconductors such as GaAs, are direct gap semiconductors</td> <td>All elemental semiconductors such as Si, Ge, are indirect gap semiconductors</td> </tr> <tr> <td>These direct gap semiconductors are used in LED and Semiconductor Lasers.</td> <td>Not useful for LEDs and Semiconductor Lasers</td> </tr> </tbody> </table>	Direct bandgap Semiconductors	Indirect bandgap Semiconductors			Maximum of valence band and minimum of conduction band occur at same momentum values	Maximum of valence band and minimum of conduction band occur at two different momentum values.	Electron making a transition from valence band to conduction band need not undergo any change in its momentum.	In order to make a transition from maximum point in valence band to minimum point in conduction band, the electron requires energy for the change in momentum in addition to the energy gap E_g	The compound semiconductors such as GaAs, are direct gap semiconductors	All elemental semiconductors such as Si, Ge, are indirect gap semiconductors	These direct gap semiconductors are used in LED and Semiconductor Lasers.	Not useful for LEDs and Semiconductor Lasers	5
Direct bandgap Semiconductors	Indirect bandgap Semiconductors													
														
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These direct gap semiconductors are used in LED and Semiconductor Lasers.	Not useful for LEDs and Semiconductor Lasers													
11	Define current density and mobility of charge carriers for a semiconductor. Hall coefficient of a semiconductor is $3.22 \times 10^{-4} \text{ m}^3/\text{C}$. Its resistivity is $9 \times 10^{-3} \text{ ohm-meter}$. Calculate the mobility in the semiconductor.	5												
12	Explain the Hall effect and derive the expression for Hall coefficient.	5												
13	Define the drift velocity and mobility of an electron and find the expression of mobility in an intrinsic semiconductor.	8												
14	Discuss the Hall effect phenomenon in a semiconductor with the suitable diagram	8												
15	<p>Discuss the Hall effect phenomenon in a semiconductor with the suitable diagram also derive the expression for Hall coefficient. Write two application of Hall effect .</p>	8												
	<p>Hall effect is defined as the production of a voltage difference across an electrical conductor which is transverse to an electric current and with respect to an applied magnetic field it is perpendicular to the current. Edwin Hall discovered this effect in the year 1879.</p> <p>Hall field is defined as the field developed across the conductor and Hall voltage is the corresponding potential difference. This principle is observed in the charges involved in the electromagnetic fields.</p>													

Hall Effect Derivation

Consider a metal with one type charge carriers that are electrons and is a steady-state condition with movement of charges in the y-axis direction. Following is the derivation of Hall-effect:

$$eE_H = Bev \frac{eV_H}{d} = BevV_H = Bvd$$

(at equilibrium, force is downwards due to magnetic field which is equal to upward electric force)

Where,

- VH is Hall voltage
- EH is Hall field
- v is the drift velocity
- d is the width of the metal slab
- B is the magnetic field
- Bev is a force acting on an electron

$$I = -nevA$$

Where,

- I is an electric current
- n is no.of electrons per unit volume
- A is the cross-sectional area of the conductor

$$V_H = \frac{-Bi}{ne}$$

$$\frac{E_H}{JB} = -\frac{1}{ne}$$

Where,

$$\frac{E_H}{JB}$$

: Hall coefficient (R_H) is defined as the ratio between the induced electric field and to the product of applied magnetic field and current density. In semiconductors, R_H is positive for the hole and negative for free electrons.

$$R_H = -\frac{1}{ne}$$

$$\mu_H = \frac{v}{E} = \frac{J}{neE} = \sigma R_H = \frac{R_H}{\rho} (v)$$

Where,

- E is an electric field
- v is the drift velocity
- R_H is the Hall coefficient
- μ_H is the mobility of the hole

$$\frac{J_y}{J_x} = \sigma \frac{E_y}{J_x} = \mu_H B_z = \sigma R_H B_z$$

The ratio between density (x-axis direction) and current density (y-axis direction) is known as Hall angle that measures the average number of radians due to collisions of the particles.

$$R = \frac{V_H}{I} = \frac{B}{net}$$

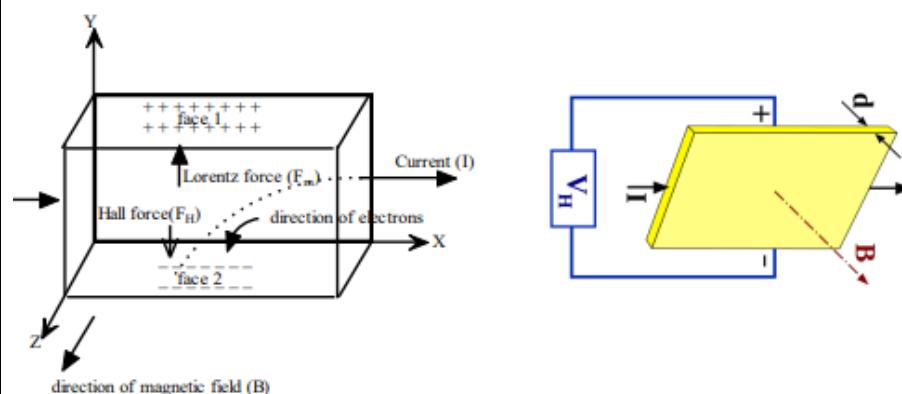
Where,

- R is Hall resistance

Applications of Hall effect

Hall effect finds many applications.

- It is used to determine if the given material is a semiconductor or insulator.
- It is used to measure the magnetic field and is known as a magnetometer
- They find applications in position sensing as they are immune to water, mud, dust, and dirt.
- They are used in integrated circuits as Hall effect sensors.



16	Show that in an intrinsic semiconductor the conductivity of the material is given by the expression; $\sigma = e n (\mu_e + \mu_h)$, where [σ =conductivity, n carrier density μ_e = mobility of electron and μ_h = mobility of hole and e = electronic charge]. The intrinsic carrier density of Ge at 27°C is $2.4 \times 10^{17} \text{ m}^{-3}$. Calculate its resistivity, if the electron and hole mobility are $0.35 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$ and $0.18 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$ respectively.	8
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S.N o.	Unit -3 [Applications of Diodes] : Questions	Max Mar ks
1	Write down the diode equation. How this equation is modified during forward bias?	2

	$I = I_0 \left(e^{\frac{qV}{kT}} - 1 \right) \dots \dots (1)$ <p>In forward biased condition, there will a large amount of current flow through the diode.</p> <p>Thus the diode current equation (equation 1) becomes</p> $I = I_0 e^{\frac{qV}{kT}}$	
2	<p>Explain avalanche breakdown and Zener breakdown in a p-n junction diode</p> <p>Avalanche Breakdown:</p> <p>This type of breakdown occurs in the presence of a high electric field. When we apply a high electric field in a reverse biased condition, the electrons start gaining high kinetic energy. These electrons start breaking other covalent bonds and start creating more hole-electron pairs. These pairs start crossing the depletion region and contribute to a high reverse reverse biased current. The breaking of bond is an irreversible process, and the p-n junction is completely destroyed after an avalanche breakdown.</p> <p>Zener Breakdown:</p> <p>Zener Breakdown is a controlled way of creating breakdown in p-n junction diodes. The p-n junction has to be heavily doped so that the electrons in the valence bond of p-type region can jump easily to the conduction band of n-type region. This temporary breakdown occurs due to the high electric field. As it does not contribute to a chain reaction, the effects of Zener breakdown is temporary.</p>	2
3	<p>Explain threshold voltage (knee voltage) and breakdown voltage in a p-n junction diode</p> <p>The forward voltage at which the current through the junction starts increasing rapidly, is called the knee voltage or cut-in voltage.</p> <p>The reverse voltage at which P-N junction of a diode breaks down with sudden rise in reverse current is known as break down voltage.</p>	2
4	<p>Define built-in-potential (potential barrier). What will be direction of internal electric field developed due to potential barrier in a zero biased p-n junction diode?</p> <p>A p-n junction is an interface or a boundary between two semiconductor material types, namely the p-type and the n-type, inside a semiconductor.</p> <p>Barrier Potential: The electric field that is produced in the depletion region acts as a barrier. External energy must be exerted to allow the electrons to get through the barrier of the electric field. The potential difference required for the electrons to be passed across the electric field is called the potential barrier. The barrier potential of a P-N junction depends on the type of material, amount of doping and temperature of the semiconductor. For silicon it is about 0.7V, for germanium, it is about 0.3V.</p>	2
5	<p>Describe the Forward and reverse biased p-n Junction along with proper circuit diagram.</p> <p>Forward Biased PN Junction</p> <p>A PN junction is said to be forward-biased when the p-type region of a junction is connected to the positive terminal of a voltage source and the n-type region is connected to the voltage source's negative terminal.</p> <p>In this forward-biased condition, due to the attraction of the positive terminal of the source, electrons that participated in covalent bond creation in the p-type material will be attracted towards the terminal.</p>	5

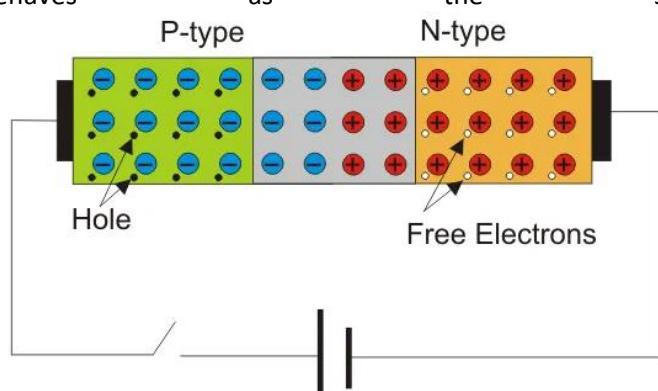
As a result, the number of covalent bonds is broken and electrons are shifted towards the positive terminal. This results in the electrons' concentration in the crystal closer to the terminal to increase, and these electrons recombine with holes here.

In this way, the number of holes increases in the portion of the p-type region away from the junction, and it is reduced in the portion of the p-type region nearer to the terminal as such holes are shifted from terminal to junction.

Due to the higher concentration of holes adjacent to the negative impurity ions layer, the electrons of negative ions come out and recombine with those holes and create new holes in the layer. Consequently, the width of this negative ions layer is reduced, and finally, this layer vanishes.

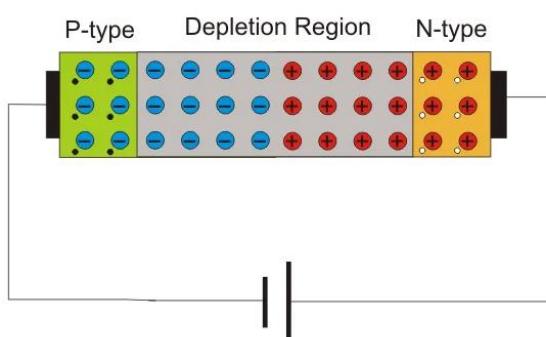
In these ways, both layers of ions disappear, and there will be no more depletion layer. After the depletion layer disappeared, free electrons from the n-type region can easily drift to the p-type region and holes from the p-type region to the n-type region in the crystal.

Hence, ideally, there will be no obstruction of flowing current, and the PN junction behaves as the short circuit.



Reverse Biased PN Junction

When the positive terminal of a voltage source is connected to the n-type region and the negative terminal of the source is connected to the p-type region. The PN junction is said to be in reverse biased condition.



6	In a PN junction diode, explain: a). Minority charge carrier b). Majority charge carrier c). Break down voltage.	5
	The charge carriers that are present in large quantity are called majority charge carriers . The majority charge carriers carry most of the electric charge or electric	

	<p>current in the semiconductor. Hence, majority charge carriers are mainly responsible for electric current flow in the semiconductor.</p> <p>The charge carriers that are present in small quantity are called minority charge carriers. The minority charge carriers carry very small amount of electric charge or electric current in the semiconductor.</p> <p>The reverse voltage at which P-N junction of a diode breaks down with sudden rise in reverse current is known as break down voltage.</p>	
7	Describe the formation of depletion layer in p-n junction diode. Draw and explain the V-I characteristics of a p-n Junction diode.	5
8	<p>Link answer</p> <p>Interpret the recombination and generation of electron-hole pairs in a semiconductor. Find the wavelength corresponding to the band gap of GaAs (1.42eV) approximately?</p>	5
	<p>Generation of carriers (free electrons and holes) The process by which free electrons and holes are generated in pair is called generation of carriers.</p> <p>When electrons in a valence band get enough energy, then they will absorb this energy and jumps into the conduction band. The electron which is jumped into a conduction band is called free electron and the place from where electron left is called hole. Likewise, two type of charge carriers (free electrons and holes) gets generated.</p> <p>Recombination of carriers (free electrons and holes) The process by which free electrons and the holes get eliminated is called recombination of carriers. When free electron in the conduction band falls in to a hole in the valence band, then the free electron and hole gets eliminated.</p>	

Energy gap of semiconductor is given by:

$$E_g = \frac{hc}{\lambda}$$

where, h is the Planck's constant, c is the speed of light, and λ is the wavelength of radiation.

We are given that, $E_g = 1.44\text{eV}$

$$1\text{eV} = 1.602 \times 10^{-19}\text{J}$$

$$\Rightarrow 1.44\text{eV} = 2.31 \times 10^{-19}\text{J}$$

$$c = 3.0 \times 10^8\text{m/s}$$

$$h = 6.63 \times 10^{-34}\text{m}^2\text{kg/s}$$

Substitute the values to find the wavelength of radiation:

$$\Rightarrow \lambda = \frac{hc}{E_g} = \frac{6.63 \times 10^{-34}\text{m}^2\text{kg/s} \times 3.0 \times 10^8\text{m/s}}{2.31 \times 10^{-19}\text{J}} = 8.61 \times 10^{-7}\text{m} = 861\text{nm}$$

Hence, the wavelength of the emitted radiation from GaAs which has band gap of 1.44 eV is 861 nm.

9 Discuss in detail that an ideal p-n junction diode act as short circuit in forward biased mode and open circuit in a reverse biased mode.

8

Reverse Biased PN Junction Diode

When a diode is connected in a **Reverse Bias** condition, a positive voltage is applied to the N-type material and a negative voltage is applied to the P-type material.

The positive voltage applied to the N-type material attracts electrons towards the positive electrode and away from the junction, while the holes in the P-type end are also attracted away from the junction towards the negative electrode.

The net result is that the depletion layer grows wider due to a lack of electrons and holes and presents a high impedance path, almost an insulator and a high potential barrier is created across the junction thus preventing current from flowing through the semiconductor material.

This condition represents a high resistance value to the PN junction and practically zero current flows through the junction diode with an increase in bias voltage. However, a very small **reverse leakage current** does flow through the junction which can normally be measured in micro-amperes, (μA).

One final point, if the reverse bias voltage V_r applied to the diode is increased to a sufficiently high enough value, it will

cause the diode's PN junction to overheat and fail due to the avalanche effect around the junction. This may cause the diode to become shorted and will result in the flow of maximum circuit current

Forward Biased PN Junction Diode

When a diode is connected in a **Forward Bias** condition, a negative voltage is applied to the N-type material and a positive voltage is applied to the P-type material. If this external voltage becomes greater than the value of the potential barrier, approx. 0.7 volts for silicon and 0.3 volts for germanium, the potential barriers opposition will be overcome and current will start to flow.

This is because the negative voltage pushes or repels electrons towards the junction giving them the energy to cross over and combine with the holes being pushed in the opposite direction towards the junction by the positive voltage. This results in a characteristics curve of zero current flowing up to this voltage point, called the "knee" on the static curves and then a high current flow through the diode with little increase in the external voltage

The application of a forward biasing voltage on the junction diode results in the depletion layer becoming very thin and narrow which represents a low impedance path through the junction thereby allowing high currents to flow. The point at which this sudden increase in current takes place is represented on the static I-V characteristics curve above as the "knee" point.

This condition represents the low resistance path through the PN junction allowing very large currents to flow through the diode with only a small increase in bias voltage. The actual potential difference across the junction or diode is kept constant by the action of the depletion layer at approximately 0.3v for germanium and approximately 0.7v for silicon junction diodes.

Since the diode can conduct "infinite" current above this knee point as it effectively becomes a short circuit, therefore resistors are used in series with the diode to limit its current flow. Exceeding its maximum forward current specification causes the device to dissipate more power in the form of heat

than it was designed for resulting in a very quick failure of the device

Junction Diode Summary

The PN junction region of a **Junction Diode** has the following important characteristics:

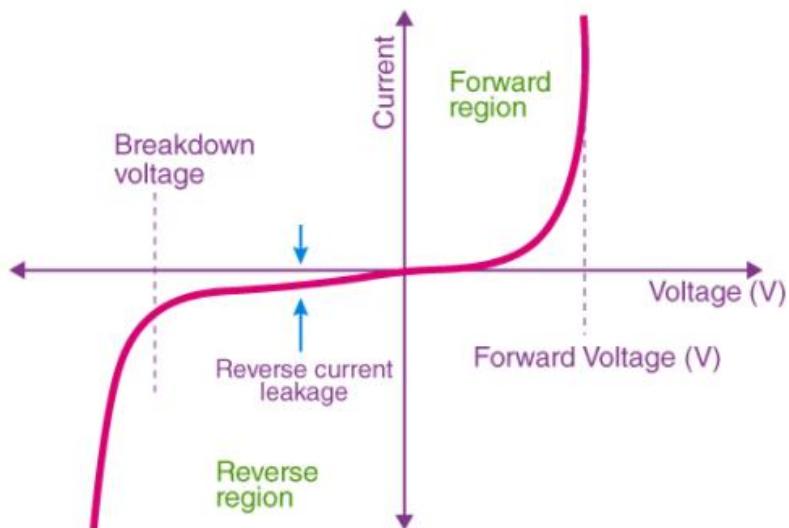
- Semiconductors contain two types of mobile charge carriers, "Holes" and "Electrons".
- The holes are positively charged while the electrons negatively charged.
- A semiconductor may be doped with donor impurities such as Antimony (N-type doping), so that it contains mobile charges which are primarily electrons.
- A semiconductor may be doped with acceptor impurities such as Boron (P-type doping), so that it contains mobile charges which are mainly holes.
- The junction region itself has no charge carriers and is known as the depletion region.
- The junction (depletion) region has a physical thickness that varies with the applied voltage.
- When a diode is **Zero Biased** no external energy source is applied and a natural **Potential Barrier** is developed across a depletion layer which is approximately 0.5 to 0.7v for silicon diodes and approximately 0.3 of a volt for germanium diodes.
- When a junction diode is **Forward Biased** the thickness of the depletion region reduces and the diode acts like a short circuit allowing full circuit current to flow.
- When a junction diode is **Reverse Biased** the thickness of the depletion region increases and the diode acts like an open circuit blocking any current flow, (only a very small leakage current will flow).

10	Describe the formation of depletion layer in p-n junction diode. Draw and explain the V-I characteristics of a p-n Junction diode. Is current flowing through the p-n junction diode due to majority charge carries? Justify your answer.	8
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	The <u>depletion region</u> is caused by the diffusion of charges. Because of the concentration gradient holes diffuse from p-side to the n-side across the junction while electrons diffuse from the n-side to the p-side. The holes and the electrons	
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diffusing towards each other combine near the junction. In doing so positive and negative ions are formed. The pair of positive and negative ions at the junction forms the dipole. The region containing the dipoles and completely depleted of mobile charge carriers is called the depletion region.

V-I Characteristics of P-N Junction Diode



No, current flowing through the p-n junction diode is not due to majority charge carrier

EXPLANATION:

- In forward biasing, the applied voltage V of the battery mostly drops across the depletion region and the voltage drops across the p-side and n-side of the p-n junction is negligibly small.
- It is due to the fact that the resistance of the depletion region is very high as it has no free charge carriers.
- Due to concentration difference, holes try to diffuse from p-side to the n-side.
- But the electric field at the junction exerts a force on the holes towards left as they come to the depletion layer. Only those holes which start moving towards the right with a high kinetic energy are able to cross the junction.
- Similarly diffusion of electrons takes place from right to left. This diffusion results in an electric current from the p-side to the n-side known as diffusion current. Therefore option 3 is correct.

11 Discuss the different types of biasing of p-n junction diode and its applications
[Click link](#)

5

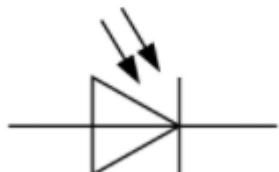
12 Explain the construction and working of photo diode.

What is Photodiode?

A photodiode is a PN-junction diode that consumes light energy to produce an electric current. They are also called a photo-detector, a light detector, and a photo-sensor. Photodiodes are designed to work in reverse bias condition. Typical photodiode materials are Silicon, Germanium and Indium gallium arsenide.

Symbol of Photodiode

The following image shows the symbol of a photodiode:



Photodiode Working

A photodiode is subjected to photons in the form of light which affects the generation of electron-hole pairs. If the energy of the falling photons ($h\nu$) is greater than the energy gap (E_g) of the semiconductor material, electron-hole pairs are created near the depletion region of the diode. The electron-hole pairs created are separated from each other before recombining due to the electric field of the junction. The direction of the electric field in the diode forces the electrons to move towards the n-side and consequently the holes move towards the p-side. As a result of the increase in the number of electrons on the n-side and holes on the p-side, a rise in the electromotive force is observed. Now when an external load is connected to the system, a current flow is observed through it.

The more the electromotive force created, the greater the current flow. The magnitude of the **electromotive force** created depends directly upon the intensity of the incident light. This effect of the proportional change in photocurrent with the change in light intensity can be easily observed by applying a reverse bias.

Since photodiodes generate current flow directly depending upon the light intensity received, they can be used as photodetectors to detect optical signals. Built-in lenses and optical filters may be used to enhance the power and productivity of a photodiode.

Applications of Photodiode

- Photodiodes are used in solar cell panels.
- Photodiodes are used in logic circuits.
- Photodiodes are used in the detection circuits.
- Photodiodes are used in character recognition circuits.

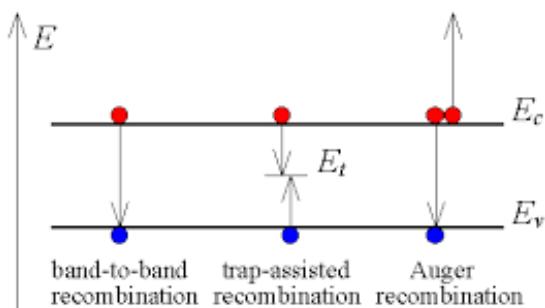
13

Interpret the recombination and generation of electron hole pairs in a semiconductor.

8

Recombination Process

- Recombination of electrons and holes is a process by which both carriers annihilate each other: the electrons fall in one or multiple steps into the empty state which is associated with the hole. Both carriers eventually disappear in the process.
- The energy difference between the initial and final state of the electron is given off. This leads to one possible classification of the recombination processes: In the case of radiative recombination this energy is emitted in the form of a photon, in the case of non-radiative recombination it is passed on to one or more phonons and in Auger recombination it is given off in the form of kinetic energy to another electron.
- Another classification scheme considers the individual energy levels and particles involved. These different processes are further illustrated with the figure below.



Recombination Process

Band-to-band recombination occurs when an electron falls from its state in the conduction band into the empty state in the valence band which is associated with the hole. This band-to-band transition is typically also a radiative transition in direct bandgap semiconductors.

Trap-assisted recombination occurs when an electron falls into a "trap", an energy level within the bandgap caused by the presence of a foreign atom or a structural defect. Once the trap is filled it can not accept another electron. The electron occupying the trap energy can in a second step fall into an empty state in the valence band, thereby completing the recombination process. One can envision this process either as a two-step transition of an electron from the conduction band to the valence band or also as the annihilation of the electron and hole which meet each other in the trap. We will refer to this process as [Shockley-Read-Hall \(SRH\) recombination](#).

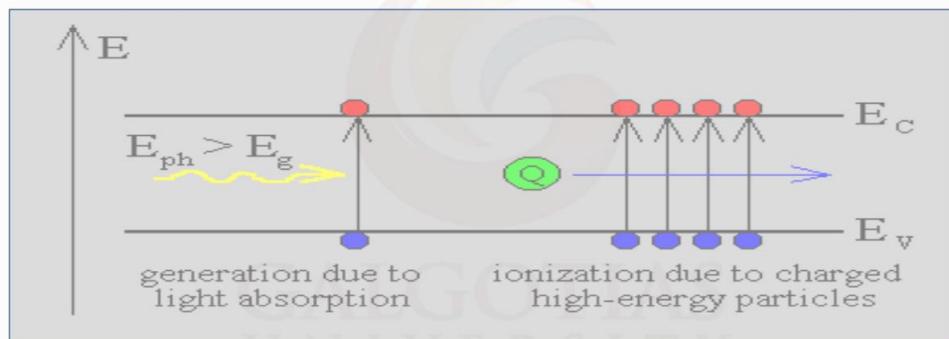
Auger recombination is a process in which an electron and a hole recombine in a band-to-band transition, but now the resulting energy is given off to another electron or hole. The involvement of a third particle affects the recombination rate so that we need to treat Auger recombination differently from band-to-band recombination.

Recombination Process

Each of these recombination mechanisms can be reversed leading to carrier generation rather than recombination. A single expression will be used to describe recombination as well as generation for each of the above mechanisms.

In addition there are **generation mechanisms** which do not have an associated recombination mechanism: generation of carriers by light absorption or a high energy electron/particle beam. These processes are also referred to as ionization processes. Impact ionization which is the generation mechanism associated with Auger recombination also belongs to this category. The generation mechanisms are illustrated with the figure below:

Recombination Process



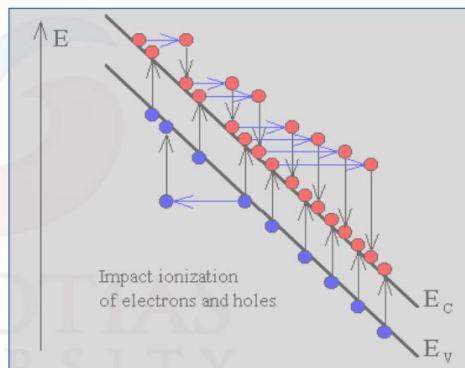
Carrier generation due to light absorption and ionization due to high-energy particle beams

Recombination Process

Carrier **generation due to light absorption** occurs if the photon energy is large enough to lift an electron from the valence band into an empty state in the conduction band, generating one electron-hole pair. The photon energy needs to be at least equal to the bandgap energy to satisfy this condition. The photon is absorbed in this process and the excess energy, $E_{ph} - E_g$ is added to the electron and the hole in the form of kinetic energy.

Carrier generation or **ionization due to a high energy beam** consisting of *charged* particles is similar except that the available energy can be much larger than the bandgap energy so that multiple electron-hole pairs can be formed. The high-energy particle gradually loses its energy and eventually stops. This generation mechanism is used in semiconductor-based nuclear particle counters. As the number of ionized electron-hole pairs varies with the energy of the particle, one can also use such detector to measure the particle energy.

Finally there is a generation process called **impact ionization**, the generation mechanism which is the counterpart of Auger recombination. Impact ionization is caused by an electron (hole) with an energy which is much larger (smaller) than the conduction (valence) band edge. The detailed mechanism is illustrated with the figure.



Impact ionization and avalanche multiplication of electrons and holes in the presence of a large electric field.

The excess energy is given off to generate an electron-hole pair through a band-to-band transition. This generation process causes avalanche multiplication in semiconductor diodes under high reverse bias: As one carrier accelerates in the electric field it gains energy. The kinetic energy is given off to an electron in the valence band, thereby creating an electron-hole pair. The resulting two electrons can create two more electrons which generate four more causing an avalanche multiplication effect. Electrons as well as holes contribute to avalanche multiplication. A simple model for the recombination-generation mechanisms states that the recombination-generation rate is proportional to the excess carrier density. It acknowledges the fact that no recombination takes place if the carrier density equals the thermal equilibrium value. The resulting expression for the recombination of electrons in a p-type semiconductor is given by:

$$U_p = G_p - R_p = \frac{p_n - p_{n0}}{\tau_p} \quad \text{and similarly for holes in an n-type semiconductor:} \quad U_n = G_n - R_n = \frac{n_p - n_{p0}}{\tau_n}$$

where the parameter t can be interpreted as the average time after which an excess minority carrier recombines. We will show for each of the different recombination mechanisms that the recombination rate can be simplified to this form when applied to minority carriers in a "quasi-neutral" semiconductor. The above expressions are therefore only valid under these conditions. The recombination rates of the majority carriers equals that of the minority carriers since in steady state recombination involves an equal number of holes and electrons. As a result the recombination rate of the **majority** carriers depends on the excess **minority** carrier density which are the limiting factor in this situation. Recombination in a depletion region and in situations where the hole and electron density are close to each other can **not** be described with the simple model and the more elaborate expressions for the individual recombination mechanisms must be used.

Carrier generation due to light absorption

Carriers can be generated in semiconductors by illuminating the semiconductor with light. The energy of the incoming photons is used to bring an electron from a lower energy level to a higher energy level. In the case where an electron is removed from the valence band and added to the conduction band, an electron-hole pair is generated. A necessary condition for this to happen is that the energy of the photon, E_{ph} , is larger than the bandgap energy, E_g . As the energy of the photon is given off to the electron, the photon no longer exists.

Assuming that each absorbed photon creates one electron-hole pair, the electron and hole generation rates are given by:

$$G_{p,light} = G_{n,light} = \alpha \frac{qP_{opt}(x)}{E_{ph}A} \quad \text{where } \alpha \text{ is the absorption coefficient of the material at the energy of the incoming photon.}$$

14	<p>Describe the working of light emitting diode (LED) with its energy band diagram. In a LED, the semiconductor material has band gap of 1.1 eV. Calculate the wavelength of light emitted by the LED</p>	8
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	<p style="text-align: center;">LED</p> <p style="text-align: center;">LED is an abbreviation used for Light Emitting Diode.</p>  <p style="text-align: center;">It is basically a pn junction diode that has the ability to give off light when certain voltage is applied to it.</p>	
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LED (Light Emitting Diode) is an optoelectronic device which works on the principle of electro-luminance. Electro-luminance is the property of the material to convert electrical energy into light energy and later it radiates this light energy. In the same way, the semiconductor in LED emits light under the influence of electric field.

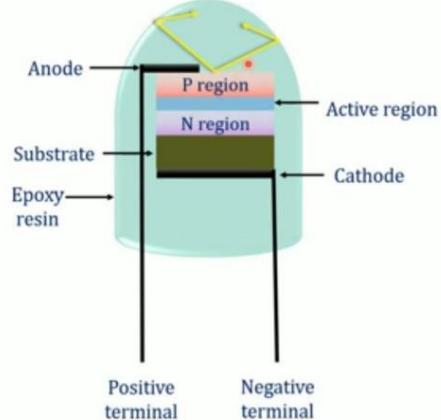
A Light emitting diode (LED) is essentially a pn junction diode. When carriers are injected across a forward-biased junction, it emits incoherent light. Most of the commercial LEDs are realized using a highly doped 'n' and a 'p' Junction.

BASIS OF LED CONSTRUCTION

LED is formed by merging p and n type semiconductor material.

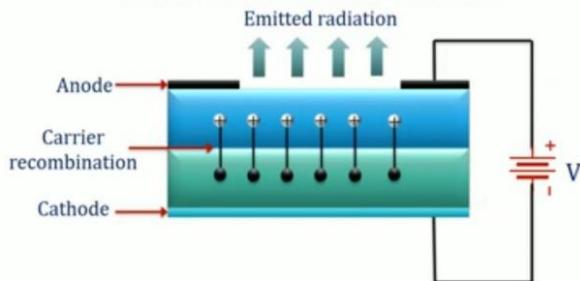
However, the material used for its construction is usually **GaAs, GaAsP or GaP**.

It is majorly a forward biased device.

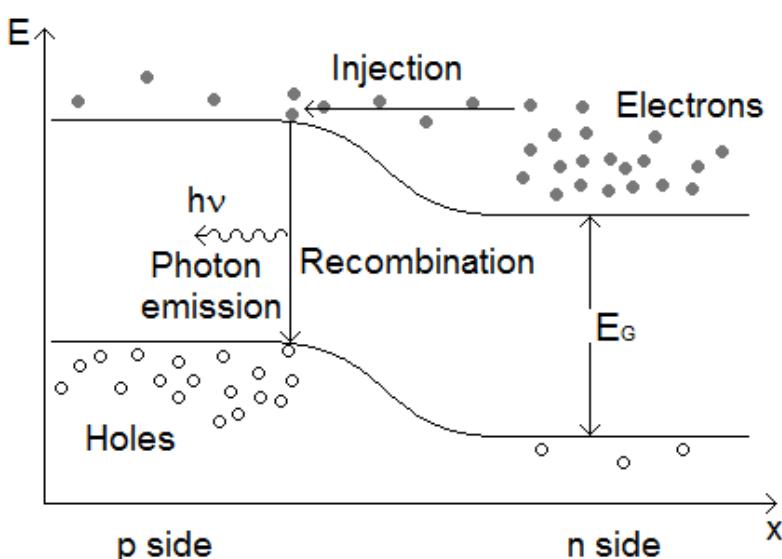


WORKING PRINCIPLE OF LED

LED works on the principle of **Electroluminescence**.



Electroluminescence is the property by which semiconductor material converts **electrical energy** into **light energy**.



energy band diagram

Applications of LED:

LED have a lot of applications. Following are few examples.

- Devices, medical applications, clothing, toys
- Remote Controls (TVs, VCRs)
- Lighting • Indicators and signs
- Optoisolators and optocouplers

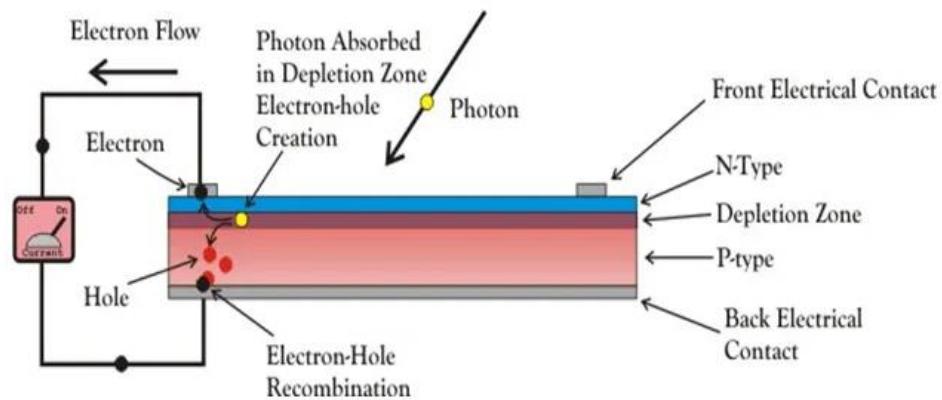
Advantages of LED:

1. **Temperature Range:** It can be operated over a wide range of temperature ranging from 0°C - 70°C
2. **Switching Time:** The Switching time of LEDs is in order of 1ns. Thus, they are useful in dynamic operations where a large number of arrays are used.
3. **Low Power Consumption:** They consume less power and they can be used even if the dc power supplied is low.
4. **Better Controlling:** The radiant power of LEDs is the function of the current flowing in it. Thus, the light intensity of LED can be controlled easily.
5. **Economical and Reliable:** LEDs are cheap and they possess a high degree of reliability.
6. **Small Size and Portability:** They are small in size and can be stacked together for the formation of alphanumeric displays.
7. **Higher Efficiency:** The efficiency of LEDs to convert power to light energy is 10-50 times greater than that of the tungsten lamp. The response time of LED is 0.1?S while in the case of tungsten lamp it is in tens or hundreds of milliseconds.

Disadvantages of LED

8. **Oversupply or Overcurrent:** The LEDs may get damaged when the current is increased beyond a certain limit.
9. **Overheating due to radiant power:** It gets overheated with an excessive increase in radiant power. This may lead to damage of LED.

15	Discuss principle and working of solar cell also explain Voltage -current characteristic curve and fill factor of solar cell.	8
	Solar cells and photo-detectors are devices that convert an optical input into current. A solar cell is an example of a photovoltaic device, i.e., a device that generates voltage when exposed to light. The photovoltaic effect was	



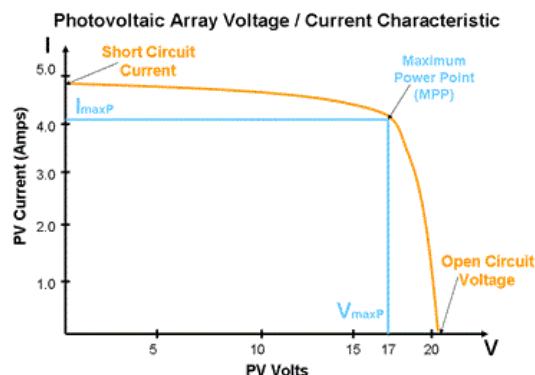
Working Principle of Solar Cell

When light reaches the **p-n junction**, the light photons can easily enter in the junction, through very thin p-type layer. The light energy, in the form of photons, supplies sufficient energy to the junction to create a number of electron-hole pairs. The incident light breaks the thermal equilibrium condition of the junction. The free electrons in the depletion region can quickly come to the n-type side of the junction.

Similarly, the holes in the depletion can quickly come to the p-type side of the junction. Once, the newly created free electrons come to the n-type side, cannot further cross the junction because of barrier potential of the junction.

Similarly, the newly created holes once come to the p-type side cannot further cross the junction became of same barrier potential of the junction. As the concentration of electrons becomes higher in one side, i.e. n-type side of the junction and concentration of holes becomes more in another side, i.e. the p-type side of the junction, the p-n junction will behave like a small battery cell. A voltage is set up which is known as photo voltage. If we connect a small load across the junction, there will be a tiny current flowing through it.

V-I Characteristics of a Photovoltaic Cell



The product of open circuit voltage V_{OC} and short circuit current I_{SC} is known as ideal power.

$$\text{Ideal Power} = V_{OC} \times I_{SC}$$

The maximum useful power is the area of the largest rectangle that can be formed under the V-I curve. If V_m and I_m are the values of voltage and current under this condition, then

$$\text{Maximum useful power} = V_m \times I_m$$

The ratio of the maximum useful power to ideal power is called the fill factor

$$\therefore \text{Fill factor} = \frac{V_m \times I_m}{V_{OC} \times I_{SC}}$$

$$\text{Efficiency of solar cell} = \frac{\text{Output power}}{\text{Input power}}$$

Advantages of Solar cell:

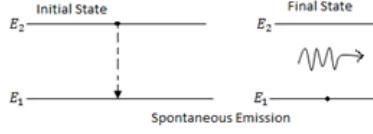
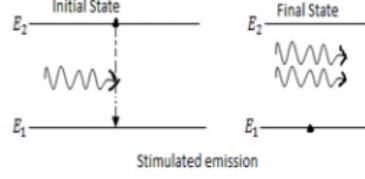
- It uses renewable energy
- No pollution so it is environment friendly
- It lasts for many years
- No maintenance cost

Disadvantages of Solar cell:

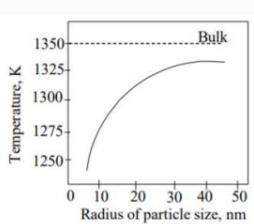
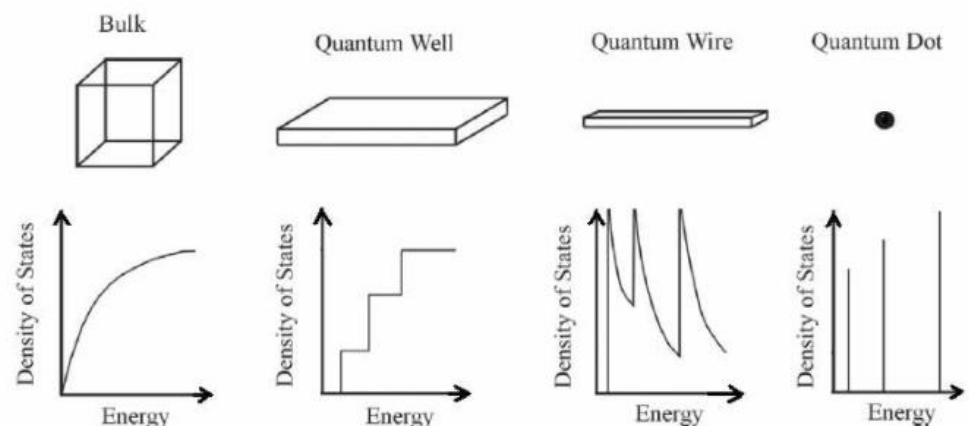
- Energy is not produced during rainy, cloudy days and during night times.
- Cost of installation is high.

Applications of Solar cell:

- It is used in calculators and in wrist watches
- Used in storage batteries
- Street lights
- Portable power supplies
- Satellites

16	<p>Differentiate between spontaneous and stimulated emission and write two -two properties of Coherent and incoherent waves. Also write two uses of coherent waves.</p>			8
	SR No	<p>Spontaneous emission</p>	<p>Stimulated emission</p>	
	1	<p>The transition of an electron from the excited state to the ground state happens as a result of the natural tendency of the electron without the action of any external agent. The radiation produced as a result of such transitions is called as spontaneous radiation.</p>	<p>Stimulated emission of radiation is the process whereby photons are used to generate other photons that have exact phase and wavelength as that of parent photon.</p>	
	2	<p>This phenomenon is found in LEDs, Fluorescent tubes.</p>	<p>This is the key process of formation of laser beam.</p>	
	3	<p>There is no population inversion of electrons in LEDs.</p>	<p>Population inversion is achieved by various ‘pumping’ techniques to get amplification giving the LASER its name “Light amplification by stimulated emission of radiation.”</p>	
	4	<p>No external stimuli required.</p>	<p>Thus stimulated emission is caused by external stimuli.</p>	
	5			
	<p>Figure 3.5: Spontaneous Emission</p>		<p>Figure 3.6: Stimulated Emission</p>	
	<p>Coherent light is light where the beam occurs for all the photons at the same time. There will be no sudden change in the phase within the beam. For example, the light produced by the laser is both coherent and monochromatic</p> <p>Characteristics of Coherent Sources</p> <ul style="list-style-type: none"> • The waves generated have a constant phase distinction. • The waves are of one frequency. • The waves ought to have identical amplitude. <p>For example, a laser</p>		<p>Incoherent light is a type of light source where there is a frequent and random change in the phase between the photons. For example, conventional light sources such as night bulbs, fluorescent tubes and metal filament lamps produce incoherent lightweight waves. All standard sources are incoherent sources</p> <ul style="list-style-type: none"> • Coherent light waves are usually stronger compared to the incoherent source of light waves. • Furthermore, coherent light waves are unidirectional and Incoherent light waves are Omni-directional. 	

S.N o.	Unit- 4 [Low Dimension Physics and Nano-materials]: Questions	Max Mar ks
1	Draw the ray diagram of transmission scanning electron microscopy (TSEM)	2
	<p>The diagram illustrates the optical path of an electron beam in a TSEM. It starts at the 'Electron source' at the top, which emits a beam that passes through the 'Condenser lens' and 'Condenser aperture'. The beam then hits the 'Sample'. After passing through the 'Objective lens' and 'Objective aperture', the beam reaches the 'Selected area aperture'. The beam continues through the 'Intermediate lens' and 'Projective lens' before finally hitting the 'Screen' at the bottom. Various lenses and apertures are represented by rectangles with internal cross-hatching, and the beam path is shown as a dashed line.</p>	
2	Explain the difference between back scattered and secondary electrons, and their use in SEM.	2
	<p>In SEM, two types of electrons are primarily detected:</p> <ul style="list-style-type: none"> • Backscattered electrons (BSE) • Secondary electrons (SE) <p>Backscattered electrons are reflected back after elastic interactions between the beam and the sample. Secondary electrons, however, originate from the atoms of the sample. They are a result of inelastic interactions between the electron beam and the sample.</p> <h2>Secondary electrons</h2> <p>In contrast, secondary electrons originate from the surface or the near-surface regions of the sample. They are a result of inelastic interactions between the primary electron beam and the sample and have lower energy than the backscattered electrons. Secondary electrons are very useful for the inspection of the topography of the sample's surface</p>	

3	<p>Explain the 0D, 1D and 2D structure of Nano-materials with examples.</p> <p>Three-dimensional (3D) structure or bulk structure: No quantization of the particle motion occurs, i.e., the particle is free.</p> <p>Two-dimensional (2D) structure or quantum well : Quantization of the particle motion occurs in one direction, while the particle is free to move in the other two directions.</p> <p>One-dimensional (1D) structure or quantum wire (Nano wires): Quantization occurs in two directions, leading to free movement along only one direction.</p> <p>Zero-dimensional (0D) structure or quantum dot (sometimes called “quantum box”): Quantization occurs in all three directions</p>	2
4	<p>How melting point and colours are changing by reducing the size of materials at the Nano scale?</p> <p>B. Thermal Properties</p> <p>The melting point of a material directly correlates with the bond strength. In bulk materials, the surface to volume ratio is small and hence the surface effects can be neglected. However, in nanomaterials the melting temperature is size dependent and it decreases with the decrease particle size diameters.</p> <p>The reason is that in nanoscale materials, surface atoms are not bonded in direction normal to the surface plane and hence the surface atoms will have more freedom to move.</p> <p>D. Optical Properties</p> <p>Because of the quantum confinement in nanomaterials, the emission of visible light can be tuned by varying the nanoscale dimensions. It is observed that the size reduction in nanomaterials shifts the emission of peak towards the shorter wavelength (blue shift).</p> 	2
5	<p>Compare graphically the density of states for quantum wire, Quantum dot and Quantum well.</p>  <p>The figure shows four panels. Top row: Bulk (3D cube), Quantum Well (2D rectangle), Quantum Wire (1D line), Quantum Dot (0D point). Bottom row: Density of States vs Energy graphs. Bulk: smooth curve. Quantum Well: discrete steps. Quantum Wire: multiple overlapping peaks. Quantum Dot: single sharp peak.</p>	2
6	<p>Explain different electron sources used in Scanning electron Microscopy (SEM).</p> <ol style="list-style-type: none"> 1. Tungsten filament 2. Solid state crystal (Cerium hexaboride or Lanthanum hexaboride) 3. Field emission gun (FEG) 	2

7	Write two different electron sources used in scanning electron microscopy (SEM) Same as 6	2	
8	Explain the structure and types of bonding of the graphene and write four applications. <u>Graphene</u> is a two-dimensional carbon allotrope. It is composed of carbon atoms positioned in a hexagonal design, which can be said to resemble a chicken wire Application-sensor,battery,election emission display	2	
9	Explain quantum well. quantum wire and quantum dots Ans-3,5	5	
10	<p>Explain the single and multi-wall carbon nano tubes.</p> <p>Single-walled carbon nanotubes (SWNTs) are seamless cylinders comprised of a layer of graphene. They have unique electronic properties which can change significantly with the chiral vector, C = (n, m), the parameter that indicates how the graphene sheet is rolled to form a carbon nanotube.</p> <ul style="list-style-type: none"> • Single-walled isolated and bundled carbon Nanotubes powder • 2 nm (diameter, measured by HRTEM) x several µm (length, measured by TEM / SEM) • Carbon purity : > 70 % (by TGA) • Metal oxide impurity: < 30 % (by TGA) • High specific surface area (> 1000 m²/g by BET) 	<p>Multi-walled carbon nanotubes (MWNTs) consist of multiple rolled layers of graphene. MWNTs have not been well-defined due to their structural complexity and variety when compared to SWNTs. Nonetheless, MWNTs exhibit advantages over SWNTs, such as ease of mass production, low product cost per unit, and enhanced thermal and chemical stability. In general, the electrical and mechanical properties of SWNTs can change when functionalized, due to the structural defects occurred by C=C bond breakages during chemical processes. However, intrinsic properties of carbon nanotubes can be preserved by the surface modification of MWNTs, where the outer wall of MWNTs is exposed to chemical modifiers.</p> <ul style="list-style-type: none"> • Thin multi-walled (avg. 7~9 walls) carbon nanotubes powder • 9.5 nm (diameter, by TEM) x 1.5 µm (length, by TEM) • Carbon purity : > 95 % (by TGA) • Metal oxide impurity: < 5 % (by TGA) • High level of purity 	5

11	Describe the electronic, optical, and mechanical properties of graphene.	5
	<p>Electronic prop.-</p> <ul style="list-style-type: none"> the movement of electrons is very fluid. allowing for an easy movement of electrons without the need to input energy into the system. The electronic mobility of graphene is very high and the electrons act like photons <p>Mechanical prop.</p> <ul style="list-style-type: none"> Graphene is one of the strongest materials ever discovered with a tensile strength of 1.3×10^{11} Pa <p>Graphene also has great optical, thermal and mechanical properties. Single sheet graphene is a highly transparent material but each layer in thickness absorbs up to 2.3% of white light, with less than 0.1% reflectance.</p>	
12	What are CNTs? Describe the single and multi-wall carbon nano tubes	8
	<p>A carbon nanotube is a carbon allotrope that resembles a tube of carbon atoms. Carbon nanotubes are extremely robust and difficult to break, but they are still light.</p> <p>Because of their exceptional mechanical, electrical, and thermal properties, carbon nanotubes are one of the most investigated nanomaterials. Multiwall carbon nanotubes feature several concentric cylindrical lattices of carbon atoms, whereas single wall carbon nanotubes have only one cylinder of carbon atoms.</p> <p>Buckytube is another name for carbon nanotubes. Two-dimensional graphite is folded or rolled into a cylindrical shape structure to create nanotubes. Inside, nanotubes are hollow. The nanotube has a diameter of 1-3 nanometers.</p> <p>Refer-10</p>	
13	Discuss the principle and working of Transmission Scanning Electron Microscope (TSEM).	8
	<p>TEM is a microscopy technique capable of providing very high resolution images down to a level of several Angstroms ($\sim 0.19\text{nm}$). It images thin (100s nms) samples via the interaction of electrons as they pass through a specimen. Detecting a range of resultant secondary signals allows for the study of nano-scale morphological and chemical features of materials down to near atomic levels.</p> <p>Applications</p> <ul style="list-style-type: none"> Bright field imaging Electron diffraction Dark field imaging Energy Dispersive X-ray Spectroscopy (EDS) Electron Energy Loss Spectroscopy (EELS) Scanning Transmission Electron Spectroscopy (STEM) Nanotomography (3D profiling) 	

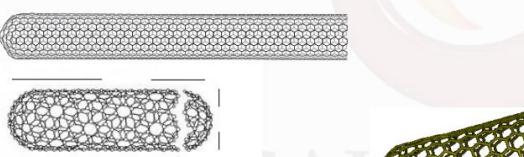
How does TEM work?

An electron source at the top of the microscope emits electrons that travel through a vacuum in the column of the microscope. Electromagnetic lenses are used to focus the electrons into a very thin beam and this is then directed through the specimen of interest. The electrons passing through the specimen then impact on a detector. Traditional bright field imaging relies on incident electrons being scattered and disappearing from the beam depending upon the compositional density and crystal orientation of the sample. The intensity of un-scattered electrons gives rise to a "shadow image" of the specimen, with different parts of a specimen displayed in varied darkness according to density. By rotating a sample, and taking multiple images at each rotation, it is also possible to build a 3D representation of the specimen (tomography).

The crystal structure of samples with regular atomic structure (crystalline material) may also be analysed via electron diffraction. Positive interference in the back focal plane leads to discrete spots of electron localisation, which can then be visualised by mapping the back focal plane to the imaging apparatus. The diffraction patterns can then be used to analyse the crystal structure of the specimen.

X-ray emission consequent to the interaction of the primary electron beam with the sample, can also be detected by an energy-dispersive spectrometer (EDS) within the TEM. As the resulting X-ray energies are characteristic of the atomic structure of the element they originated from, the spectra generated can be used to identify the constituent elements.

It is also possible to measure the loss of energy from the inelastic scattering of electrons in specimen transmission (EELS). This information can be used to infer elemental composition, chemical bonding, valence and conduction band electronic properties.

14	<p>Describe Carbon nanowires and nanotubes and explain their electronic and mechanical properties.</p> <p><i>"Nanotechnology is the understanding and control of matter at dimensions of roughly 1 to 100 nanometers, where unique phenomena enable novel applications."</i></p> <p><i>"Encompassing nanoscale science, engineering and technology, nanotechnology involves imaging, measuring, modeling, and manipulating matter at this length scale."</i></p> <p>Carbon nanotubes or CNTs are a class of 1D material formed by sheets of Graphene rolled into hollow tubes of small (0.5–5nm) diameter. They were first discovered by Sumio Iijima in 1991.</p> <p>CNT can be classified as single-walled CNT (SWCNT) or multiwalled CNT (MWCNT). A multiwall carbon nanotube consists of several concentric tubes of Graphene nested inside each other.</p> 	8
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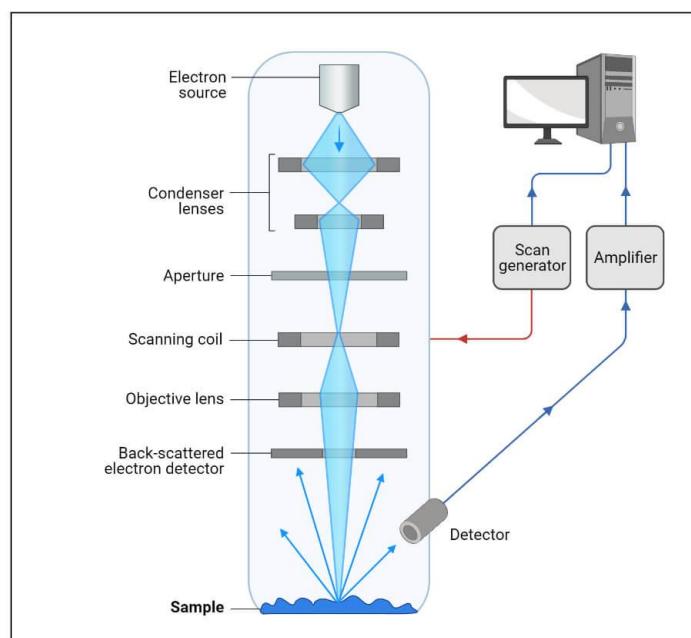
	<p>Electrical properties:</p> <ol style="list-style-type: none"> Chirality of carbon changes the electrical conductivity Change in conductivity from Metallic to semiconducting by insertion of pentagons and heptagons in SWNT. Band gap variation with doping Resistance is independent of tube length <p>Optical activity- The optical activity (to rotate polarized light) of chiral nanotubes disappears if the nanotubes become larger</p> <p>Thermal property-</p> <ol style="list-style-type: none"> A distinct anisotropic thermal behaviour Along the axis have high thermal conductivity Quantization effects are much pronounced with, 2 nm diameter of CNT <p>Mechanical property-</p> <ol style="list-style-type: none"> CNTs have a very large Young modulus (elastic modulus- measure of stiffness) in their axial direction. The nanotube as a whole is very flexible because of the great length. Therefore, these compounds are potentially suitable for applications in composite materials that need anisotropic properties. <p>Anisotropy is the property of substances to exhibit variations in physical properties along different molecular axes. It is seen in crystals, liquid crystals and, less commonly, in liquids.</p>	
15	<p>Describe the Chirality of Carbon nanotubes (CNTs). Write four application of a Carbon nanotubes.</p> <p>Chirality of CNT:</p> <p>Armchair carbon nanotubes (a)- In comparison to the zig - zag tubes, the Graphene sheet is turned by 30° before rolling up. The perfect boundary is an edge consisting of the sides of the last row of six -membered rings. It is good conductor.</p> <p>Chiral carbon nanotubes (c)- If the angle of turning the Graphene layer before rolling up is between 0 ° and 30, chiral nanotubes are obtained. They are characterized by a line in parallel with the unity vector a_1 that spirals up around the tube. Consequently two enantiomeric forms exist for these species. It is a semiconductor.</p> <p>Zigzag carbon nanotubes (b)- The Graphene layer is rolled up in a way to make the ideal ends of an open tube be a zigzagged edge.</p> <ul style="list-style-type: none"> CNT composites used for electrostatically applying paints to car components They can form transparent, conducting and flexible polymer composite Used in field emission device Used in tips of atomic force microscopy CNT with higher charge carrier mobility ($20000 \text{ cm}^2 / \text{V s}$) finds application in transistors, replacing the metal oxides Hydrogen storage material Precise mass and charge measurements (Addition of single atom or charge to CNT is detected by measuring the change in resonant frequency) Large non linear absorption of Light(NLO material) Used in optical switches In Lithium ion batteries: N-doped CNT show good Li^+ ion storage capacity than normal graphite Sensors: N doped MWNT shows fast response (milliseconds) to toxic gases and organic solvents In field effect transistors 	8
16	<p>Explain the basic principle of Scanning Electron Microscope (SEM). Describe the working of SEM using its basic diagram.</p> <p>Scanning Electron Microscope (SEM) is a type of electron microscope that scans surfaces of microorganisms that uses a beam of electrons moving at low energy to focus and scan specimens. The development of electron microscopes was due to the inefficiency of the wavelength of light microscopes. electron microscopes have very short wavelengths in</p>	8

comparison to the light microscope which enables better resolution power.

Principle of Scanning Electron Microscope (SEM)

Unlike the Transmission Electron Microscope which uses transmitted electrons, the scanning electron Microscope uses emitted electrons. The Scanning electron microscope works on the principle of applying kinetic energy to produce signals on the interaction of the electrons. These electrons are secondary electrons, backscattered electrons, and diffracted backscattered electrons which are used to view crystallized elements and photons. Secondary and backscattered electrons are used to produce an image. The secondary electrons are emitted from the specimen play the primary role of detecting the morphology and topography of the specimen while the backscattered electrons show contrast in the composition of the elements of the specimen.

Scanning Electron Microscopy (SEM)



END
