**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**

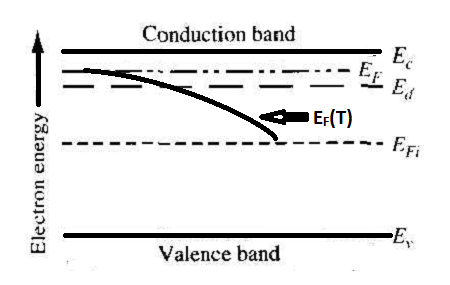
**Unit-1\_ (CO1):** Identify the energy band in solids and electron occupation probability

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| SOLUTION | S.No. |
| 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) =6.625x10-34 J.s. and mass of electron (m)= 9.1x10-31 kg. ]  **Solution:** We know that energy of electron is Given by [Particle in Box]  En= n2h2/8mL2 , where n=1,2,3……..etc.  Given l= 0.05 nm but 1nm=10-9 m  For least energy n=1  Therefore, E1 = h2/8mL2 now put h =6.625x10-34 and m = 9.1x10-31 kg. and L=0.05x10-9 m  E1 = {6.625x10-34}2/8x9.1x10-31x[5x10-11]2  E1=0.0241157x10-15 jule  E1= 0.0241157x10-15/1-6x10-19  E1= 0.015072x104  **E1= 150.7 eV** | 1 |
| Q-2. An electron is bound in a one dimensional potential box which has a width 2.5x10-10 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) =6.625x10-34 J.s. and mass of electron (m) = 9.1x10-31 kg.]  **Solution:** We know that energy of electron is Given by [Particle in Box]  En= n2h2/8mL2, where n=1,2, 3……..etc.  Given L= 2.5x10-10 m.  For lowest two energy n=1 & n=2 for n=1 Energy E1 and for n=2 energy E2=4E1  Therefore, E1= h2/8mL2 now put h =6.625x10-34 and m = 9.1x10-31 kg.and L=2.5x10-10 m.  E1 = {6.625x10-34}2/8x9.1x10-31x[2.5x10-10]2  E1=0.0964629x10-17 jule  E1= 0.0602893x100  E1= 6.02893 eV  & E2=4x6.02893  E2= 24.11 eV  **Lowest two permitted energy are=6.02 eV and 24.11 eV** | 2 |
| Q-3. Find the minimum energy of an electron moving in one dimension in an infinitely high potential box of width 1Å. [Given Planck’s Constant (h) =6.625x10-34 J.s. and mass of electron (m) = 9.1x10-31 kg.]  **Solution:** We know that energy of electron is Given by [Particle in Box]  En= n2h2/8mL2, where n=1,2, 3……..etc.  Given 1Å. But 1Å=1x10-10 m  For minimum energy n=1 we have to find E1  Therefore, E1= h2/8mL2 now put h =6.625x10-34 and m = 9.1x10-31 kg.and L=1x10-10 m.  E1 = {6.625x10-34}2/8x9.1x10-31x[1x10-10]2  E1=0.602893x10-17 jule  E1=0.602893x10-17/1.6x10-19  **E1=37.68 eV**  **Minimum energy of electron = 37.68 eV** | 3 |
| 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  Eav = 3EF /5, where EF is Fermi energy of electron  Therefore, Eav= 3x5/5=3 eV  **Average energy of electron= 3.0 eV** | 4 |
| 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  kBTF = EF i.e. TF = EF/ kB  ½ mvF2 = kBTF i.e. vF = (kBTF/m)1/2  vF = (EF/m)1/2  **vF = (2x1.6x10-19/9.1x10-31)1/2**  VF=0.351648x106  VF= 3.516x105 m/s  **Velocity of electron =3.516x105 m/s** | 5 |
| 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    when (i) energy is greater than Fermi Energy  i.e. E> EF , f(E) =0  and (ii) when energy is less than Fermi Energy  i.e. E< EF , f(E) =1 | 6 |
| 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  E0= 3xEF/5  E0 =3x10/5=4 eV  **Fermi energy of electron= 4.0 eV** | 7 |
| 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    Physical Significance of Wave-function: By [analogy](https://www.merriam-webster.com/dictionary/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, Ψ2, 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 Ψ2.  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:    Every acceptable wave function can be normalized by multiplying it by an appropriate constant | 8 |
| Q-9. Explain the idea of wave function for a quantum particle. Write the basic characteristics of well-behaved wave function  **Solution:** **wave function**, in [quantum mechanics](https://www.britannica.com/science/quantum-mechanics-physics), variable quantity that mathematically describes the [wave](https://www.britannica.com/science/wave-physics) characteristics of a [particle](https://www.britannica.com/science/particle-matter). The value of the wave [function](https://www.britannica.com/science/function-mathematics) 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](https://www.merriam-webster.com/dictionary/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, Ψ2, 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 Ψ2.  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:    Every acceptable wave function can be normalized by multiplying it by an appropriate constant  **Characteristics for a suitable wave-function-(Well-Behaved Wave Functions)**  In order for Ψ(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. | 9 |
| Q-10. Draw the E-K diagram of a semiconductor based on band theory of solids. Explain the Brillouin zones in a solid.  **Solution:** the E-K diagram of a semiconductor is shown below  C:\Users\Admin\Desktop\download.jpg    **In one dimensional periodic lattice, the energy discontinuities occur when the wave number k satisfies the condition k = nπ/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 ±π/a, then these line segments are known as Brillouin zones**  **The first segment  is called the First Brillouin zone.** | 10 |
| 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**  **P is a measure of the quantity V0b, which is the area of potential barrier, called barrier strength**  where P=   * **Equation (7) is satisfied only for those values of αa 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 αa will, therefore, represent the wave like solutions and are accessible. The other values of αa will be inaccessible.** * **In Fig. 3, the part of the vertical axis lying between the horizontal lines represents the range acceptable. As α2 is proportional to the energy E, the abscissa (αa) will be a measure of the energy** * **Clearly there are regions for αa where the value of  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.**     **The energy spectrum of the electron consists of alternate regions of allowed energy and forbidden energy**   1. **The width of the allowed energy band increases as the value of αa (i.e., energy) increases.** 2. **It is to be noted that P is a measure of the potential barrier strength.**   **Case 1: When P→∞, 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 αa = 0 or, αa = nπ,**  **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→0, corresponds to no barrier, the electron can be considered to be moving freely through the potential wells.**    **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.** | 11 |
| Q-12. Define the density of energy state in a solid. Find the expression for density of states.  **Solution:**    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, EF is the energy of the highest filled level at absolute zero.          **The last expression is the formula of density of energy states.** | 12 |
| 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 ≤ 0 and x ≥ L, the potential energy is infinite. The wave function for the particle in the nth state is given by ψn=A Sin (nπx/L). Find the expression for the normalized wave function.  **Solution:** The wave function for the particle in the nth state is given by ψn=A Sin (nπx/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.      **Where n=1,2,3,4………etc.**  2: Particle in a box wavefunctions. | Download Scientific Diagram | 13 |
| 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 ≤ 0 and x ≥ L, the potential energy is infinite. Solving Schrodinger’s equation, obtain energy Eigen values  **Solution:**      **En= n2h2/8mL2 , where n=1,2,3……..etc.**  **This is the expression of energy Eigen Values** | 14 |
| 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   * 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, 1023 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.   **Energy Band Gaps in Materials**  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 | 15 |

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

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| Questions | S.No. | Marks |
| Q-1. Which types of charge carries are available in n-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.  **Intrinsic semiconductor.jpg**  ***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.**  **N-type semiconductor.jpg**  ***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.** | 1 | 2 |
| 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.**  **P-type semiconductor.jpg**  *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. | 2 | 2 |
| 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/τ. 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 (vd). | 3 | 2 |
| 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 ,  Eg= hc/λ, therefore  λ =hc/Eg  Where Planck’s constant (h) =6.625x10-34 J.s. and velocity of light C=3x10-8 m/s  1eV=1.6x10-19 joule  **λ=8.747x10-7 m**  **λ=874.7 nm** | 4 | 2 |
| 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 note 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. | 5 | 2 |
| Q-6. Discuss the variation of Fermi- level position with temperature and doping concentration in Extrinsic semiconductors.  Solution:    **In P-type semiconductor:** The energy band diagram of a P-type semiconductor is shown in the Figure. The acceptor level is shown by Ea near the top of the valence band, the Fermi level by EF. 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 (EA-EV) 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.    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. | 6 | 2 |
| 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     * *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. | 7 | 2 |
| Q-8. Draw and interpret the graph for the Fermi Energy variation with temperature for P and N type semiconductors.  Solutions:    **In P-type semiconductor:** The energy band diagram of a P-type semiconductor is shown in the Figure. The acceptor level is shown by Ea near the top of the valence band, the Fermi level by EF. 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 (EA-EV) 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.    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. | 8 | 5 |
| 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, 1023 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.   **Energy Band Gaps in Materials**  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. | 9 | 5 |
| Q-10. Define the Fermi energy and Fermi distribution function. Plot the Fermi distribution function at two different temperatures.  **Solution:**    **Where kB is the Boltzmann's constant, T is the absolute temperature, E is the energy of the particular energy level E, and EF is the Fermi energy**  **It can be seen that for T = 0, all the states up to energy EF are filled with electrons and all the states above EF are vacant. At E = EF the occupation probability is ½.**  **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 kBT and go to higher vacant state, and so**    **Figure shows the Fermi- function plot at three different temperatures { T2 > T1 > T0 }** | 10 | 5 |
| Q-11. Distinguish between elemental and compound semiconductors with two examples  **Solution:** -**Elemental Semiconductors:** *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 : 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. | 11 | 5 |
| 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 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 1s2 2s2 2p6 3s2 3p2 and 1s2 2s2 2p6 3s2 3p6 4s2 3d10 4p2, 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.  energy band diagram of intrinsic semiconductor  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 semiconductor. 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 | 12 | 8 |
| Q-13. Distinguish between the direct and indirect band gap semiconductors with one examples.  **Solution:** Figure shows the E versus k diagram of the conduction and valence bands for an intrinsic semiconductor at T = 0 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 K, in which some electrons have gained enough energy to jump to the conduction band and have left empty states in the valence hand. 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 K and (b) T > 0 K.*  *Figure shows the E versus k diagram for Ga-As and Si.*    In Ga-As, the valence band maximum and the conduction hand 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, hut 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. | 13 | 8 |
| Q-14. Describe the P and N types semiconductors and indicate the Fermi level and energy level of impurity atoms in band diagram  **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 imputrity 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 | 14 | 8 |
| Q-15. Explain the extrinsic semiconductor. Using suitable diagram, discuss how the Fermi level changes with change of temperature in extrinsic semiconductors.  **Solution:**  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. | 15 | 8 |

**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. EF(T) shows the effect of temperature on Fermi energy*

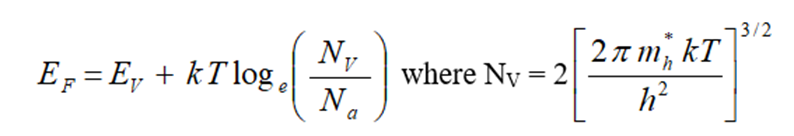
When the temperature is raised, by absorption of suitable energies, some donor atoms are ionised, so that their electrons are elevated to the conduction band. If the density of ionised donor atom is Nd and the density of electron-hole pairs in the intrinsic semi-conductors is ni at room temperature T, then Nd >> ni. 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 EC. 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.

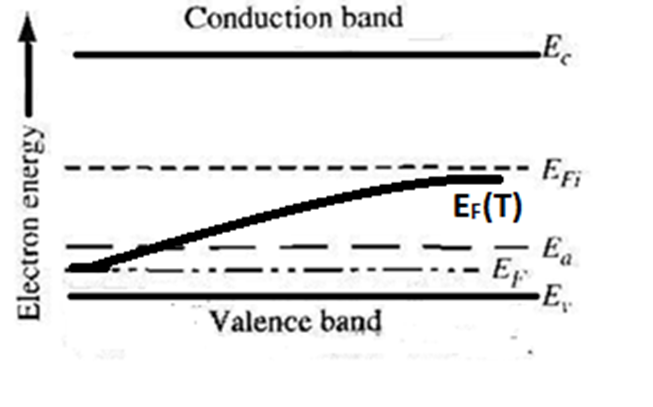


where NC = 2

**In P-type semiconductor:** The energy band diagram of a P-type semiconductor is shown in the Figure. The acceptor level is shown by Ea near the top of the valence band, the Fermi level by EF. 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 (EA-EV) 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:





*Energy diagram of P-type Semiconductor. EF(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.