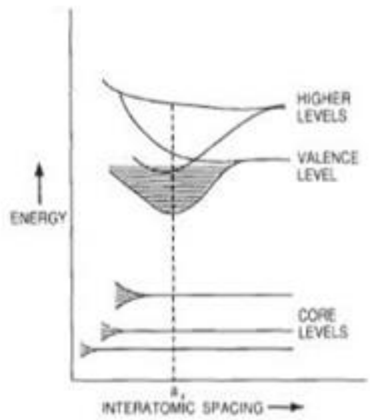
# Unit 2 Model Questions and Answers

**1. Describe the formation of energy bands in solids.**

Ans. A solid contains large number of atoms packed together. In each isolated atom, the electron energy levels are discrete, as shown in the following figure. As the atoms approach one another, the wave functions start to overlap and the individual levels split, as a consequence of an extension of the Pauli's exclusion principle (that says that to a collective solid no two electrons can exist in the same quantum state). Level splitting and broadening occur first for the valence or outer electrons, since their electron clouds are the first to overlap. At the equilibrium inter atomic distance in the solid, where the system energy is minimized, some of the levels have broadened into bands of energy levels. The bands span different ranges of energy, depending on the atoms and specific electron levels involved. Sometimes as in metals, bands of high energy overlap. Insulators and semiconductors have energy gaps of varying width between bands where electron states are not allowed.




The most important bands are:

Valence band – the last filled energy level at T = 0 K.
Conduction band – the first unfilled energy level at T = 0 K.

**2. Define bands in solids and explain the valence band, the conduction band and the forbidden energy gap.**

Ans. Inside a solid crystal, each electron has a different energy level because of slightly different patterns of the surrounding charges. These electron energy levels form a continuous energy variation called as the Energy Bands. There are three important bands in solids, viz. valence band, conduction band and the forbidden energy band (or the band gap).

**Valence band** – This is the last filled energy level of a solid at T = 0 K.

**Conduction band** – This is the first unfilled energy level of a solid at T = 0 K.

**Forbidden energy band or the Band Gap -** A band gap is the distance between the valence band and the conduction band in a semiconductor or an insulator. Essentially, the band gap represents the minimum energy that is required to excite an electron from the valence band to the conduction band, where it can participate in conduction.

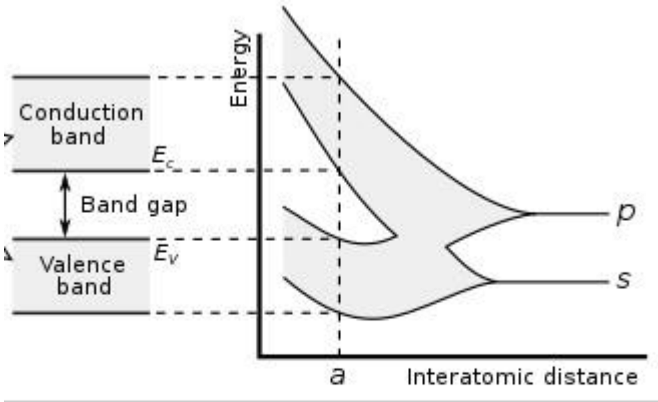



Fig. Formation of valence band, conduction band and the band gap.

**3. Differentiate solids according to energy band structure.**

Ans. According to the energy band structures, solids are broadly classified into three categories:

i. **Conductors:** In this type of materials there is no forbidden energy gap. The valence band and conduction band overlap with each other. Large number of free electrons are available and such metals have low resistivity *(~ $10^{-6}$ Ω-cm)*. For example, metals.

ii. **Insulators:** Insulators are materials with very large band gap (≥ 5.5 eV). Their valence electrons are very tightly bound and have hardly any electron in the conduction band. They are high resistivity *(~ $10^{11}$ – $10^{19}$ Ω-m)* material. For example, glass or bakelite.

iii. **Semiconductors:** This type of materials has resistivity between conductors and insulators *(~$10^{-5}$ – $10^{6}$ Ω-m)*. They have a small band gap (≤ 2.3 eV). With increase in temperature electrons in the valence band acquire enough energy to move to the conduction band. Thus, resistivity of the semiconductor decreases with increasing temperature. For example, Si and Ge.

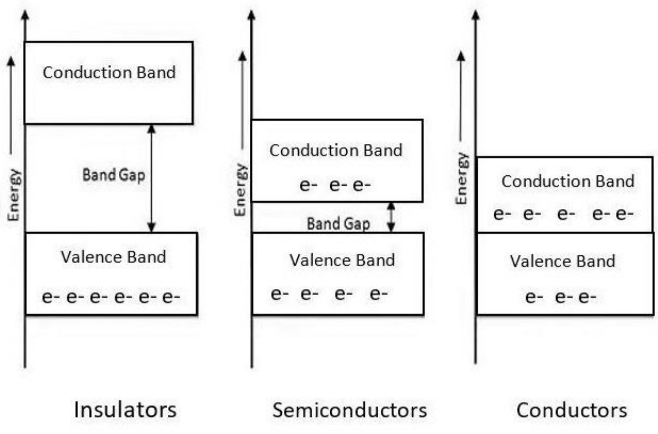



Fig. Band configurations for insulator, semiconductor and metal.

**4. Define semiconductors. What are their characteristics properties?**

Ans. Semiconductors are materials having resistivity between conductors and insulators *($\sim 10^{-5} - 10^{6}$ $\Omega$-m)*. They have a small band gap ($\leq$ 2.3 eV). With increase in temperature electrons in the valence band acquire enough energy to move to the conduction band. Thus, resistivity of the semiconductor decreases with increasing temperature. For example, Si and Ge.

**5. If you are going to design high speed electronic device, which type of semiconductor (i.e. n- type or p-type) you would prefer and why?**

Ans. We know that n-type semiconductors have electron as the majority carrier and p-type semiconductors have holes as majority carriers. Since the mobility of electron is about three times that of holes, n-type semiconductors will be preferred to make high speed electronic devices.

**6. Can an intrinsic semiconductor behave as an insulator at some temperature?**

Ans. Intrinsic semiconductors behave as insulators at T = 0K. At that temperature the valence band is completely filled and conduction band is completely empty. Thus no conduction is possible and the semiconductor will behave as an insulator.

**7. State the law of mass action for a semiconductor.**

Ans. This shows that for a given semiconductor, the product of electron and hole concentrations is a constant at a given temperature and is equal to the square of the intrinsic carrier concentration. This is known as the law of mass action and holds for both intrinsic and extrinsic semiconductors. If impurity atoms are added to a semiconductor to increase n, there will be corresponding decrease in p such that the product np remains constant. Thus we always have

$$\boldsymbol{np = n_i^2}$$

**8. What are intrinsic and extrinsic semiconductors? Show the positions of Fermi levels in them.**

**Or**

**Explain the intrinsic and extrinsic semiconductors with their band diagrams.**

Ans. **Intrinsic semiconductors** - A perfect semiconductor crystal with no impurities or lattice defects is called an intrinsic semiconductor. In such material there are no charge carriers at 0 K, since the valence band is filled with electrons and the conduction band is empty. At higher temperatures electron-hole pairs (EHP) are generated as valence band electrons are excited thermally across the band gap to the conduction band.

**Extrinsic semiconductors** - Addition of controlled quantity of impurity to an intrinsic semiconductor to increase the conductivity is called doping and the resultant semiconductor is known as extrinsic semiconductor. The impurity atoms occupy lattice positions. Two types of extrinsic semiconductors are produced depending upon the group of impurity atom. If a pentavalent impurity (donor impurity) like arsenic (As) or phosphorous (P) is added to pure semiconductor like Si or Ge, n-type semiconductor is formed. If a trivalent impurity (acceptor impurity), like boron (B) is added to a pure semiconductor like Si or Ge, p-type semiconductor is formed.

The band-diagrams for intrinsic and extrinsic semiconductors are as follows:

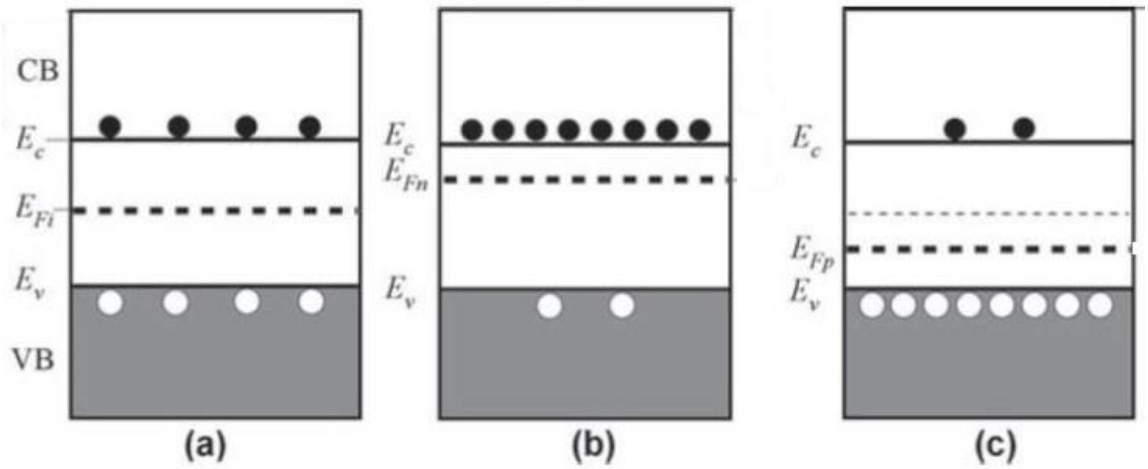



Fig. Positions of Fermi levels in (a) intrinsic, (b) n-type and (c) p-type semiconductors.

**9. Define the following terms: (a) Doping, (b) Dopant, (c) Donors, (d) Acceptors, (e) Mobility of a charge carrier and (f) drift velocity.**

Ans. **Doping:** Addition of controlled quantity of impurity to an intrinsic semiconductor to increase the conductivity is called doping and the resultant semiconductor is known as extrinsic semiconductor.

**Dopant:** The impurities that are added to pure or intrinsic semiconductors to increase their conductivity are known as dopants.

**Donor impurity:** If a pentavalent impurity like arsenic (*As*) or phosphorous (*P*) is added to pure semiconductor like *Si* or *Ge*, each *As* atom forms covalent bonds with neighboring four Si atoms with four of its valance electrons. Fifth valance electron remains loosely bound to the parent impurity atom and cannot form covalent bond. This extra electron can now contribute to the conductivity of the semiconductor. Such impurities that increases conductivity by donating electron are known as donor impurities and the semiconductor is now known as an n-type material.

**Acceptor impurity:** If a trivalent impurity like boron (*B*) is added to a pure semiconductor like *Si* or *Ge*, p-type semiconductor is formed. Each *B* atom forms covalent bonds with neighboring three *Si* atoms with three valance electrons and falls short of one electron for completing fourth covalent bonds. As a result, a vacancy is left in the bonding. With a small amount of thermal energy, this incomplete bond can be transferred to other atoms as the bonding electrons exchange positions. The impurity atoms thus supply holes which are ready to accept electrons. Hence the impurity is known as acceptor impurity.

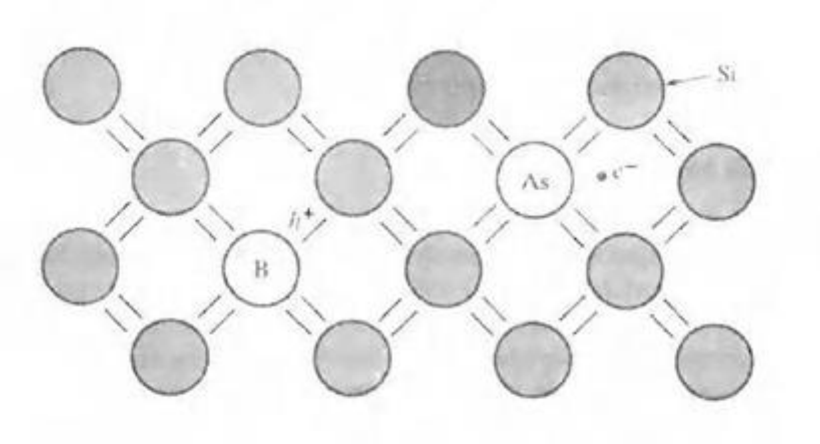



Fig. Donor and acceptor atoms in the covalent bond model of Si-crystal.

**Mobility of a charge carrier:** It is defined as the drift velocity per unit electric field. S.I. unit for μ is $m^2$/V.sec.

**Drift velocity:** The extra (i.e. other than thermal diffusion) velocity acquired by the carriers in the presence of applied electric field is called drift velocity ($v_d$). It is proportional to the strength of the applied electric field, $\boldsymbol{E}$, i.e.

$$v_d \propto \boldsymbol{E} \qquad \text{or} \qquad v_d = \mu \boldsymbol{E}$$

where the constant of proportionality, $\mu$, is called the mobility of the charge carrier.

**10. Differentiate between n-type and p-type semiconductors.**

Ans. Depending on what type of impurity is added to an intrinsic semiconductor to increase the conductivity, the resulting extrinsic semiconductors are classified into two categories.

If a pentavalent impurity (donor impurity) like arsenic (As) or phosphorous (P) is added to pure Gr-IV semiconductor like Si or Ge, n-type semiconductor is formed. Here the electrons are majority carrier and the Fermi level lies close to the conduction band.

If a trivalent impurity (acceptor impurity), like boron (B) is added to a pure Gr-IV semiconductor like Si or Ge, p-type semiconductor is formed. In this case, holes are the majority carriers and the Fermi level lies close to the valence band.

**11. What are Fermi Function (or, Fermi-Dirac distribution law) and Fermi level?**

Ans. The Fermi function states that the distribution of electrons over a range of allowed energy levels at thermal equilibrium is

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

Where $k$ is Boltzmann's constant (= 8.62 x $10^{-5}$ eV/K = 1.38 x $10^{-23}$ J/K), $T$ is the absolute temperature. The function $f(E)$, the Fermi-Dirac distribution function, gives the probability that an available energy state at $E$ will be occupied by an electron at absolute temperature $T$.

The quantity $E_F$ is called the Fermi level. For an energy $E$ equal to the Fermi level energy $E_F$, the occupation probability is

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

Thus an energy state at Fermi level has a probability of occupancy by an electron equal to ½.

12. **Show that for an intrinsic semiconductor, at low temperature, Fermi level lies at the half of the energy band gap.**

Ans. Let us consider an intrinsic semiconductor at T K. The concentration of electrons in the conduction band is

$$n = N_c \exp[-\left(\frac{E_c-E_F}{kT}\right)]$$

Where, $N_C = 2(2\pi m_n kT/h^2)^{3/2}$ is the effective density of electrons at the conduction band edge $(E_C)$. $m_n$ = effective mass of the e, $k$ = Boltzmann's constant, $h$ = Planck's constant

Where, $N_V=2(2\pi m_p kT/h^2)^{3/2}$ represents the effective density of holes at the valence band edge, $E_v$. $m_p$ = effective mass of the hole.

For an intrinsic semiconductor,

$$n = p = n_i$$

Therefore,

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

Or $$\exp\left(\frac{2E_F-E_c-E_v}{kT}\right) = \frac{N_v}{N_c} \quad \text{or} \quad \frac{2E_F-E_c-E_v}{kT} = \ln(\frac{N_v}{N_c})$$

Or $$E_F = E_i = \frac{E_c+E_v}{2} + \frac{kT}{2}\ln(\frac{N_v}{N_c})$$

Putting the values of $N_v$ and $N_c$ we get

$$E_F = \frac{E_c+E_v}{2} + \frac{3}{4}\text{kTln}(\frac{m_p}{m_n})$$ [Since $ln(x^y) = yln(x)$

At T = 0 K

$$E_F = \frac{E_c+E_v}{2}$$

i.e. the Fermi level lies in the middle of the conduction and the valence band. This is also true for other temperatures provided $m_p = m_n$. However, in general $m_p > m_n$ and the Fermi level is raised slightly as T exceeds 0 K.