ELECTRICAL PROPERTIES

Introduction

The objective of this chapter is to explore the electrical properties of materials, i.e. their responses to an applied electric field. We begin with the phenomenon of electrical conduction: the parameters by which it is expressed, the mechanism of conduction by electrons, and how the electron energy band structure of a material influences its ability to conduct. These principles are extended to metals, semiconductors and insulators. Particular attention is given to the dielectric characteristics of insulating materials. The final sections are devoted to the peculiar phenomena of Ferro electricity and piezoelectricity.

The electrical conductivity is one of the properties of materials that vary most widely and the best conductors such as copper and silver have values of about $10^8 \Omega^{-1} m^{-1}$ and a good insulator such as polystyrene has conductivity $10^{-15} \Omega^{-1} m^{-1}$. In a metal, the current is carried by conduction electrons, and hence the name *electronic conduction*.

30 Minutes

ENERGY BAND STRUCTURES IN SOLIDS (Board Teaching & PPT)

In an isolated atom electron occupy well defined energy states, when atoms come together to form a solid, their valence electrons interact with each other and with nuclei due to Coulomb forces. Inter atomic spacing is small in solids compared with liquids and gases. Due to this closeness of atoms, energy levels of the atoms are disturbed. Energy levels of the valence electrons are most affected. Each energy level splits up into a number of closely spaced levels. These split energy levels form a continuous band called energy band as shown in fig 3.13.

Energy level is the discrete energy of an electron in an atom. But energy band is the energy of the same electron when it is in a solid. At large separation distances, each atom is independent of all the others, so they have energy levels. But the atoms come close to each other, electrons respond to the influence of other nuclei and electrons. So each atomic level splits into N levels each of which may be occupied by pairs of electrons of opposite spins. The extent of splitting depends on inter atomic separation.

1

Firstly outer most electron shells are disturbed.

In each energy band, energy levels are discrete; the difference between adjacent states is infinitesimally small. At the equilibrium spacing, band formation may not occur for electron sub shells nearestthe nucleus as shown in fig 3.13. Further gaps exist between adjacent bands. The electron does not have any energy with in energy gap.
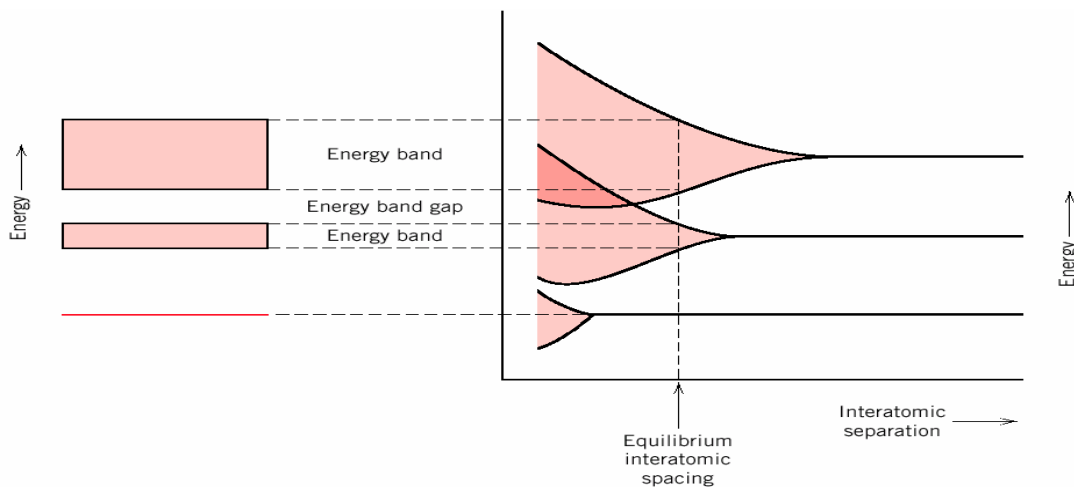

Figure 3.13: Electron energy versus inter atomic separation for an aggregate of atoms

ENERGY BAND STRUCTURES AND CONDUCTIVITY

There are four types of band structures which are possible at 0 K. The highest filled state at 0 K is called Fermi Energy (E_F). The two important energy bands are:

Valence band: Valence band is the wide range of energies possessed by the valence electrons.The highest filled energy band where the electrons are present at 0 K.

Conduction band: Conduction band is the wide range of energies possessed by the conduction electrons. A partially filled or empty energy band where the electrons can increase their energies by going to higher energy levels within the band when an electric field is applied.

Energy Band Structures and Conductivity for metals

In metals (conductors), highest occupied band is partially filled or bands overlap. Conduction occurs by promoting electrons into conducting states that starts right above the Fermi level. The conducting states are separated from the valence band by an infinitesimal amount. Energy provided by an electric field is

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sufficient to excite many electrons into conducting states.

Ex: Copper atomic number is 29, its electronic configuration is - $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^1$. Each copper atom has one 4s electron. For a solid consisting of N atoms, the 4s band can accommodate 2N electrons. Thus only half of the 4s band states are filled. This is shown in fig 3.14(a).

For the second band structure, there is an overlap of filled band (valence band) and empty band (conduction band). Ex: Magnesium atomic number is 12, its electronic configuration is $1s^2 2s^2 2p^6 3s^2$. Each magnesium atom has two 3s electrons. In a solid of magnesium, the 3s and 3p bands are overlapped. This is shown in fig 3.14(b).
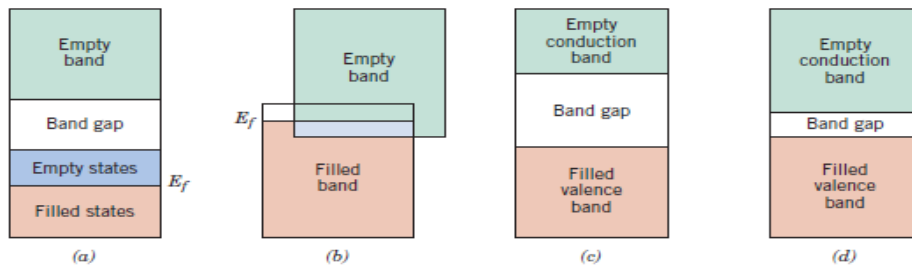

Figure 18.4 The various possible electron band structures in solids at 0 K. (*a*) The electron band structure found in metals such as copper, in which there are available electron states above and adjacent to filled states, in the same band. (*b*) The electron band structure of metals such as magnesium, wherein there is an overlap of filled and empty outer bands. (*c*) The electron band structure characteristic of insulators; the filled valence band is separated from the empty conduction band by a relatively large band gap (>2 eV). (*d*) The electron band structure found in the semiconductors, which is the same as for insulators except that the band gap is relatively narrow (<2 eV).

Figure 3.14: The various possible electron band structures in solids at 0 K. (a) The electron band structure found in metals such as copper, in which there are available electron states above and adjacent to filled states, in the same band. (b) The electron band structure of metals such as magnesium, wherein there is an overlap of filled and empty outer bands. (c) The band structures of insulators. (d) The band structure of semiconductors.

Energy Band Structures and Conductivity for Semiconductors and insulators:

As shown in fig 3.14, (c) and (d) band structures are similar. The valence band is completely filled with electrons. There is large energy gap between filled valence band and empty conduction band. Ex: Insulators. If the energy gap between valence and conduction band is small than i.e. semiconductor. Electrical conduction requires that electrons be able to gain energy in an electric field. To become free, electrons must be promoted (excited) across the band gap. The excitation energy can be provided by heat or light. In semiconductors and insulators, electrons have to jump across the band gap into conduction band to find conducting states above E_f.The energy needed for the jump may come from heat or from irradiation at sufficiently small wavelength (photo excitation).

The difference between semiconductors and insulators is that in semiconductors electrons can reach the

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conduction band at ordinary temperatures, where in insulators they cannot. An electron promoted into the conduction band leaves a hole(positive charge) in the valence band, that can also participate in conduction. Holes exist in metals as well, but are more important in semiconductors and insulators.

10 Minutes

Verify

1. In terms of electron energy band structure, discuss reasons for the difference in electrical conductivity between metals, semiconductors, and insulators.

2. Explain formation of energy band structure considering decrease in inter atomic spacing in to account.

   3. Define equilibrium spacing.

Session 11

Process of electrical conduction in metals, conductivity, mobility and Matthiessen's rule

30 Minutes

Process of electrical conductivity in metals (Board Teaching)

It is defined as the voltage apply to a conductor which is equal to the product of current passing through the conductor times its resistance. This law is independent of size and shape of the conductor under consideration. However, it can alsobe expressed in terms of current density J and electric field E. The current density in the direction of electric field is defined as the amount of charge flowing across a unit area of cross section per unit time in a conductor. If n is a number of electrons crossing a unit area in unit time then the amount of charge is equal to "$- ne$". Average velocity of electrons is the drift velocity. The flow of charge per unit time through unit area of the conductor is equal to the product of electon charge times the drift velocity of the electrons which is current density

$$J = -nev_d.$$

$$J = \frac{ne^2\tau}{m}\ E$$

Or

$$J = \sigma E$$

It follows that the electric current density is proportional to the applied electric field. This equation is known as Ohm's law and proportionality constant is called electrical conductivity σ.

(iv) Electrical conductivity

In general the electrical conductivity is a property of a conducting material which allows the flow of current.

$$\sigma = \frac{ne^2\tau}{m}$$

This is one of the central results of the classical free electron theory of metals. This formula is not useful for calculating the conductivity of a given metal, since it contains an unknown term called relaxation time. The theory itself has important implications. This picture of electron gas undergoing constant scattering and is still used. For a particular metal n, e and m are constants. Therefore, the electrical conductivity depends on the relaxation time 'τ'. Thus in the absence of collision process the relaxation time is infinite and hence the conductivity becomes infinite. The electrical conductivity can also be expresses in terms of mobility.

$$\sigma = ne\mu$$

Thus in general the electrical conductivity of a metal depends on two factors. They are n and μ.

(v) Electrical Resistivity (ρ)

Electrical resistivity is a measure of how strongly a materialopposes the flow of electric current. A low resistivity indicates a material that readily allows the movement of electric charge. The S.I. unit of electrical resistivity is Ω-m. It is commonly represented by a Greek letter ρ.

(vi) Electrical conductivity (σ)

It is the ability of a substance to conduct an electric current. It is the inverse of the resistivity.

Ohms law

Ohm's law can be rewritten in terms of the current density J = I/A as: J = σ E. Ohm's law can be expressed in both microscopic and macroscopic forms.

  (Macroscopic form)

  (Microscopic form)

Electrical conductivity varies between different materials by over 27 orders of magnitude.

Metals: $\sigma > 10^5$ $(\Omega.m)^{-1}$

Semiconductors: $10^{-6} < \sigma < 10^5$ $(\Omega.m)^{-1}$

Insulators: 10^{-6} $(\Omega.m)^{-1} < \sigma < 10^{-20}(\Omega.m)^{-1}$

One of the best materials for electrical conduction (low resistivity) is silver, but its use is restricted due to the high cost. Most widely used conductor is copper: inexpensive, abundant, high σ, but rather soft – cannot be used in applications where mechanical strength is important.

Metal	*Electrical Conductivity* $[(\Omega\text{-}m)^{-1}]$
Silver	6.8×10^7
Copper	6.0×10^7
Gold	4.3×10^7
Aluminum	3.8×10^7
Iron	1.0×10^7
Brass (70 Cu–30 Zn)	1.6×10^7
Platinum	0.94×10^7
Plain carbon steel	0.6×10^7

Table 3.1: Room temperature electrical conductivities for eight common metals and alloys

Solid solution alloying and cold working improve strength but decrease conductivity. If hardeningis preferred, Cu-Be alloy is used. When weight is important one uses aluminum, which is half as good as Cu and more resistant to corrosion. Heating elements require low (high R), and resistance to high temperature oxidation: nickel chromium alloy.

Drift velocity of electrons :

When an electric field E is applied to a conductor, the electrons modify their random motion and move with an average drift velocity v_d in a direction opposite to that of the electric field and an electric current is established in the conductor. The flow of current in a conductor is an indication that the electron in it moves in a specific direction. As a result, Maxwell-Boltzmann distribution function of the electrons in the conductor undergoes a change. The directional motion of the electrons is due to the applied electric field. The group of electrons within the conductor drifts in the direction opposite to the applied electric field. This motion is called a drift motion and the associated velocity of the electron is called drift velocity.

Due to the electric field E an electron inside the metal experiences a force and this force F is equal to the product of electric charge and electric field.

$$F = -e * E$$

where '−e' is the charge of the electron. As a result, the electron acquires acceleration. According to newtons second law of motion, the force experienced by the electron is given by

$$F = m * a$$

where 'a' is the acceleration of the electron and m is the mass of the electron. Eliminating F from the above equations gives the acceleration of the electron under the influence of electric field −eE=ma.

$$a = \frac{-eE}{m}$$

It is clear from the above equation that the electrons are accelerated indefinitely because of growth of their velocity due to electric field i.e. its drift velocity v_d increases with time. However the electrons are not accelerated indefinitely because during their motion the electrons collide with impurities and lattice imperfections in the crystal. Here Drude assumed that the conduction electron acquires random motion after collision with impurities and lattice imperfections. In the collision process the electron loses the energy and after collision it again gains energy from the electric field. The velocity of the electrons after collision does not depend upon its velocity before collision. When the electron collides with the lattice imperfection it stops momentarily and moves in another direction with a new velocity. Thus electrons acquire random motion even in the presence of electric field. This problem can be solved by considering these collisions are similar to the collision process of an ideal gas in a container. The collision process introduces the concept of relaxation time, which influences the conductivity in the metals. The average time between successive collisions of electron with the lattice imperfection is called relaxation time and is denoted by τ.

The acceleration of the electron due to collision with impurities is given by $-v_d/\tau$ (negative sign is due to the acceleration is opposite to the direction of electric field). Now, the acceleration is equal to sum of the acceleration due to electric field and acceleration due to collision with impurities.

$$a = \frac{-eE}{m} - \frac{vd}{\tau}$$

After sometime the acceleration of the electrons due to the electric field and acceleration due to collision should compensate with each other but leads to steady state condition of the electron gas. As a result the acceleration of electron becomes zero

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$$\frac{-eE}{m} - \frac{vd}{\tau} = 0$$

The drift velocity of the electron is then obtained by arranging the above equation.

$$v_d = \frac{-e\tau E}{m}$$

Thus the electrons in a conductor attain a constant drift velocity under the application of the electric field. The drift velocity is proportional to applied electric field and the proportionality constant is called the electron mobility μ.

(ii) Electron Mobility (μ) :

The electron mobility is defined as the drift velocity v_d per unit applied electric field E.

$$\mu = \frac{vd}{E}$$

Substituting the value of dirft velocity in the above equation we get

$$\mu = \frac{-e\tau}{m}$$

The above equation shows that mobility of an electron depends on the relaxation time and hence it depends on temperature.

10 Minutes

Verify

1. Draw energy band structure for Copper and Magnesium.

2. Write microscopic and macroscopic forms of Ohm's law

3. Define drift velocity and mobility of electron and write the expression of electrical conductivity in metals.
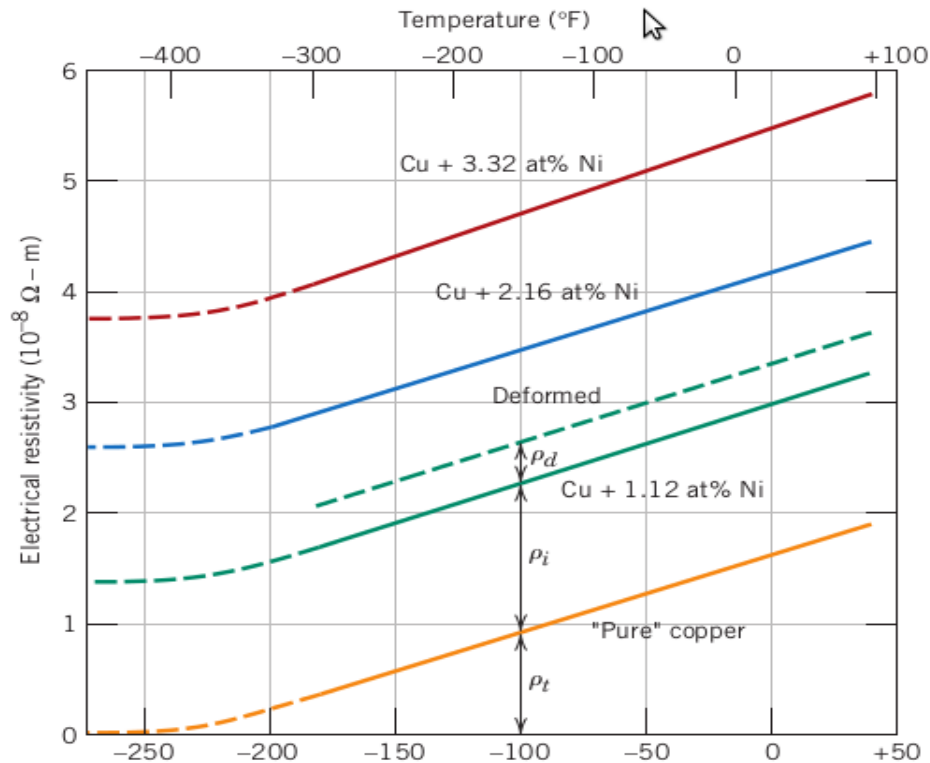
30 Minutes

ELECTRICAL RESISTIVITY OF METALS :

The resistivity ρ is defined by scattering events due to the imperfections and thermal vibrations. Total resistivity ρ_{tot} can be described by the Matthiessen's rule:

$\rho_{total} = \rho_{thermal} + \rho_{impurity} + \rho_{deformation}$, Where $\rho_{thermal}$ - from thermal vibrations, $\rho_{impurity}$ - from impurities, $\rho_{deformation}$ - from deformation-induced defects resistivity increases with temperature, with deformation, and with alloying.

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Graphical explanation to electrical resistivity in metals:

One of the best materials for electrical conduction (low resistivity) is silver, but its use is restricted due to the high cost. Most widely used conductor is copper: inexpensive, abundant, high σ, but rather soft – cannot be used in applications where mechanical strength is important.

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temperature oxidation: nickel chromium alloy.

10 Minutes

Verify

1) Discuss the origin of electrical resistance in metals.
2) Explain variation of electrical resistance of a metal with change of temperature?
3) Compare the influence of temperature, impurity concentration and deformation on electrical resistance of metals.

Session 12 : Semiconductors and conductivity

30 Minutes

Classification - conductivity (Board Teaching)

SEMI CONDUCTORS

INTRODUCTION (10 min)

The electrical conductivity of the semiconducting materials is not as high as that of the metals. Nevertheless they have some unique electrical characteristics that render them especially useful. The electrical properties of these materials are extremely sensitive to the presence of even minute concentrations of impurities.

Intrinsic Semiconductors (20 min):

Intrinsic semiconductors - electrical conductivity is defined by the electronic structure of pure material.

Extrinsic semiconductors - electrical conductivity is defined by impurity atoms.

Intrinsic semiconductors

Highly pure semiconductors with no impurities are called intrinsic semiconductors. In such a material there are no charge carriers at 0K. Since the valence band is filled and the conduction band is empty. At higher temperatures, the electrons reaching the conduction band due to thermal excitation leave equal number of holes in valence band. In intrinsic semiconductor, the number of free electrons is equal to the number of holes. The bond structure and band structures of intrinsic semiconductors are shown in below fig 3.15.
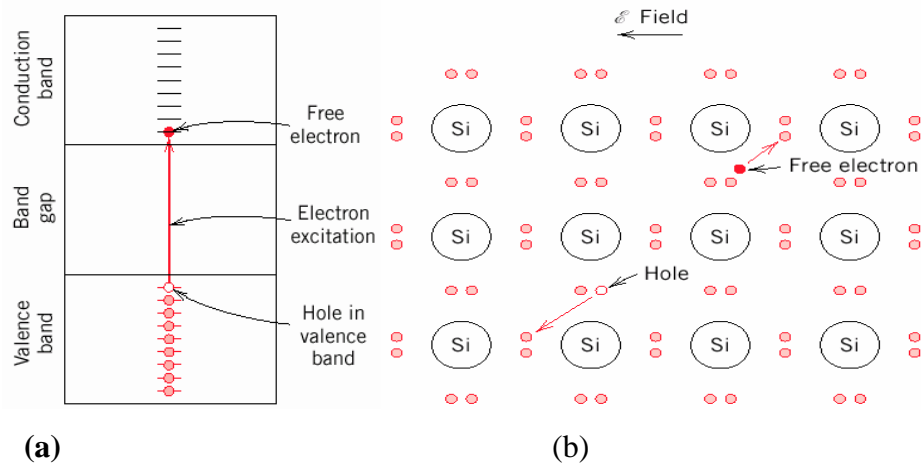
Examples: Si, Ge, GaP, GaAs, InSb, CdS, ZnTe

(a)   **(b)**

Figure 3.15: (a) For a semiconductor, occupancy of electron states after an electron excitation from the valence band into the conduction band in which both a free electron and a hole are generated. (b) Electron bonding model of electrical conduction in intrinsic silicon after excitation.

Number of electrons in the conduction band increases exponentially with temperature.E_g is the band-gap width. In an electric field, electrons and holes move in opposite direction and participate in conduction.Since both electrons and holes are charge carriers in an intrinsic semiconductor, the conductivity is

$$\sigma = n|e|\mu_e + p|e|\mu_h$$

where p is the hole concentration and μ_h the hole mobility.

Electrons are more mobile than holes, $\mu_e > \mu_h$In an intrinsic semiconductor, a hole is produced by thepromotion of each electron to the conduction band. Therefore, **n = p**and (only for intrinsic semiconductors)

$$\sigma = n|e|(\mu_e + \mu_h) = p|e|(\mu_e + \mu_h)$$

n (and p) increase exponentially with temperature, whereas μ_e and μ_h decrease (about linearly) with temperature.The conductivity of intrinsic semiconductors is increasing with temperature (different from metals)

$$\sigma = n|e|(\mu_e + \mu_h)$$

Extrinsic semiconductors

The application of intrinsic semiconductors is restricted due to its low conductivity. In electronic devices, high conducting semiconductors are more essential. The concentration of either electrons or holes in a semiconductor should be increased depending upon the requirements in the electronic devices.

This can be carried out simply by adding impurities (one atom in 10^7 host atoms) to the intrinsic semiconductors. The process of adding impurity to the intrinsic semiconductors is called doping. The doped semiconductor is called as extrinsic semiconductor. The concentration of electrons and holes are not equal in an extrinsic semiconductor.

Usually the doping material is either penta-valent atoms (P, AS, Sb, Bi) or trivalent atoms (B, Al, Ga, In). The penta-valent atom is called donor atom because it donates one electron to the conduction band of pure semiconductor. The trivalent doping atom is called acceptor atom because it accepts one electron from semiconductor atom. The added impurity is called dopant.

In Extrinsic semiconductors, electrical conductivity is defined by impurity atoms.

Example: Si is considered to be extrinsic at room T if impurity concentration is one impurity per 10^{12} lattice sites (remember our estimation of the number of electrons promoted to the conduction band by thermal fluctuations at 300 K) unlike intrinsic semiconductors, an extrinsic semiconductor may have different concentrations of holes and electrons. It is called p-type if p > n and n-type if n > p.

Thus there are two types of extrinsic semiconductors depending on the type of impurity added (10 min).

1. N-type extrinsic semiconductors

2. P-type extrinsic semiconductors

N-type extrinsic semiconductors:

Excess electron carriers are produced by substituting impurities that have more valence electron per atom than the semiconductor matrix.

Example: phosphorus (or As, Sb) with 5 valence electrons, is an electron donor in Si since only 4 electrons are used to bond to the Si lattice when it substitutes for a Si atom. Fifth outer electron of P atom is weakly bound in a donor state(~ 0.01 eV) and can be easily promoted to the conduction band.Impurities which produce extra conduction electrons are called donors,Elements in columns V and VI of the periodic table are donors for semiconductors in the IV column, Si and Ge.

The hole created in donor state is far from the valence band and is immobile. Conduction occurs mainly by the donated electrons thus n-type.
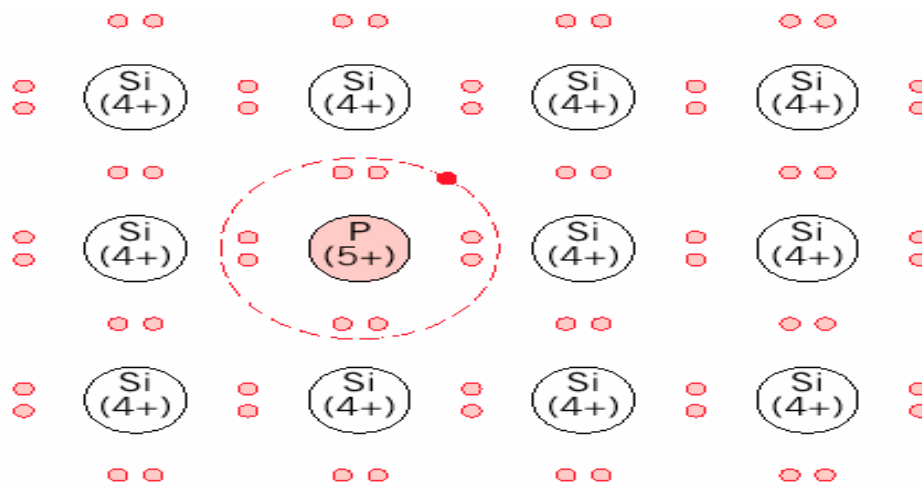
Figure 3.16: Extrinsic n-type semi conduction model (electron bonding). An impurity atom such as phosphorus, having five valence electrons, may substitute for a silicon atom.
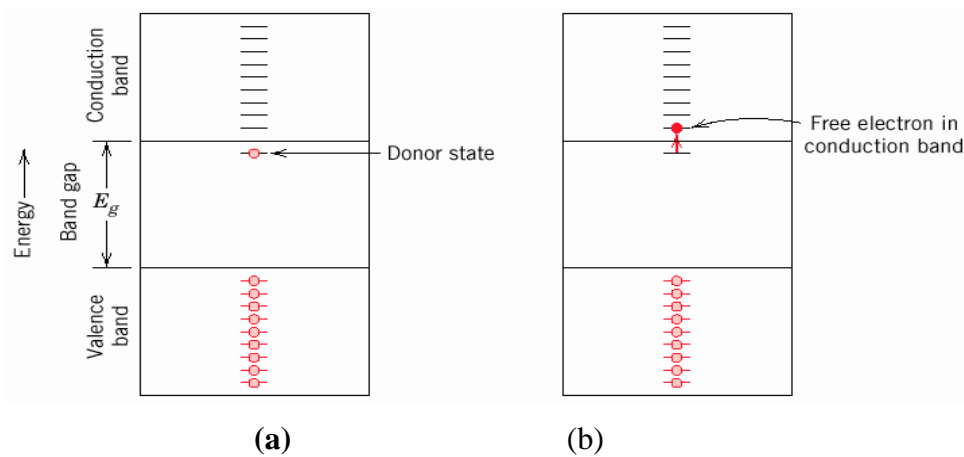

(a) **(b)**

Figure 3.17: (a) Electron energy band scheme for a donor impurity level located within the band gap and just below the bottom of the conduction band. (b) Excitation from a donor state in which a free electron is generated in the conduction band.

P-type extrinsic semiconductors:

Excess holes are produced by substituting impurities that have fewer valence electrons per atom than the matrix. A bond with the neighbors is incomplete and can be viewed as a holeweakly bound to the impurity atom. Elements in columns III of the periodic table (B, Al, Ga) are donors for semiconductors in the IV column, Si and Ge. Impurities of this type are called acceptors.
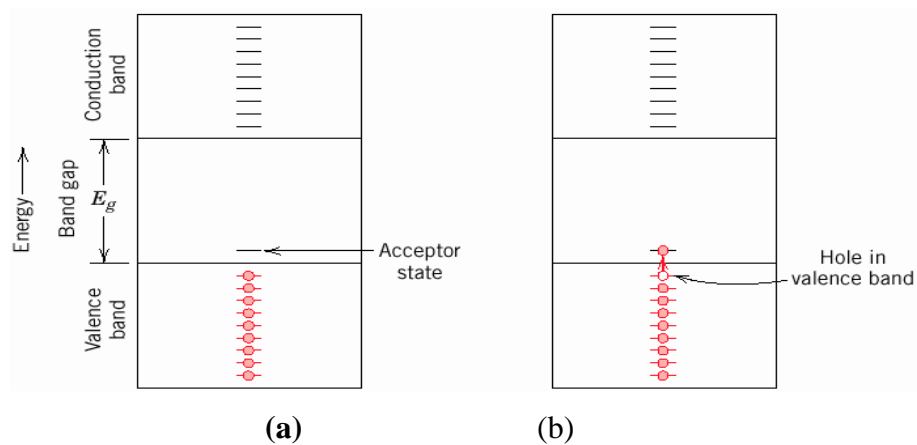
Figure 3.18: (a) Energy band scheme for an acceptor impurity level located within the band gap and just above the top of the valence band. (b) Excitation of an electron into the acceptor level leaving behind a hole in the valence band.
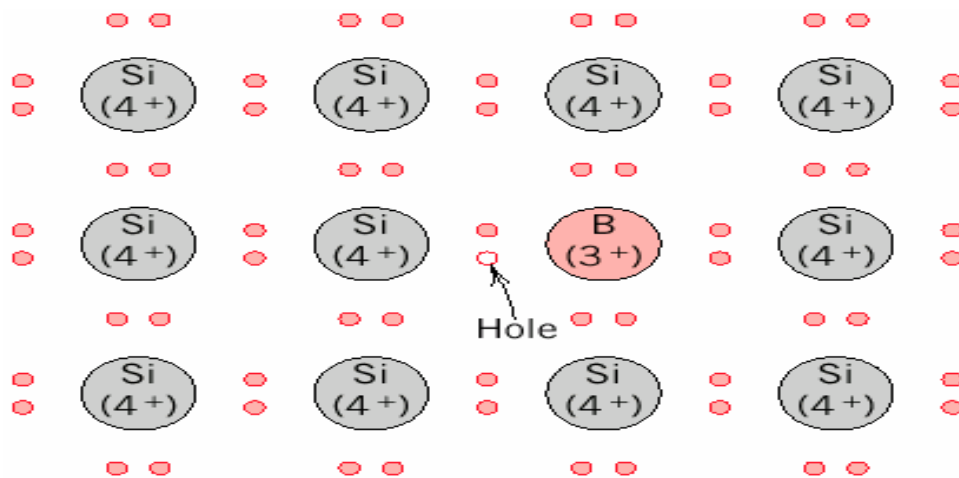

Figure 3.19: Extrinsic p-type semi conduction model (electron bonding). An impurity atom such as boron having three valence electrons, may substitute for a silicon atom.

The energy state that corresponds to the hole (acceptor state) is close to the top of the valence band. An electronmay easily jump from the valence band to complete the bondleaving a hole behind. Conduction occurs mainly by theholes (thus p-type). For extrinsic p-type semiconductors

$\sigma = p|e|\mu_p$

10 Minutes

Verify

1) Explain the conductivity and resistivity of different types of semiconductors.

14

2) Compare the temperature dependence of the conductivity for metals and intrinsic semiconductors. Briefly explain the difference in behavior.

3) Draw energy band stucture of n-type and p-type semiconductors.

4) Compare the temperature dependence of the conductivity for metals and intrinsic semiconductors. Briefly explain the difference in behavior.

30 Minutes

Factors effecting conductivity of semiconductors

1) Temperature effect on concentration of charge carrier in intrinsic and extrinsic semiconductors.
2) Effect of concentration of charge carriers on mobility of charge carriers.
3) Effect of temperature on mobility of charge carriers

(Please refer Callister's Materials science and engineering - An Introduction)

10 Minutes

Verify

1. State the reason for increase of electrical conductivity with increase of temeperature in intrinsic semiconductor.

2. State the reason for decrease of mobility with increase of concentration of charge carriers and temperature.

3. Explain the resons for no change in carrier concentration with increase of temperature in extrinsic region.

Session 13: Basic definitions in Dielectrics, relations and Polarization

30 Minutes

DIELECTRICS (Board Teaching)

All dielectric materials are electrical insulators. But all electric insulators need not be dielectrics. Ex: Vacuum is an insulator but it is not dielectric.The distinction between a dielectric material and an insulator lies in the application. The insulating materials are used to resist the flow of current through