

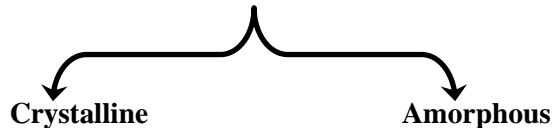
Chapter 3

Electronics

Day – 1

1. Solids and Semiconductor

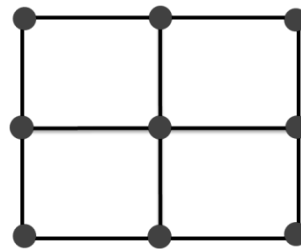
Solids



1.1 Crystalline

Atoms or molecules are arranged in definite and regular way also definite external geometrical shape.

Example:- Quartz, mica, sugar, NaCl etc.

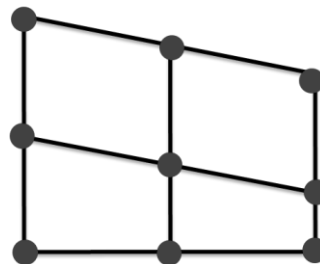


Crystalline

1.2 Amorphous

Atoms or molecules are arranged in indefinite and irregular way also no definite external geometrical shape.

Example:- Glass, Rubber etc.

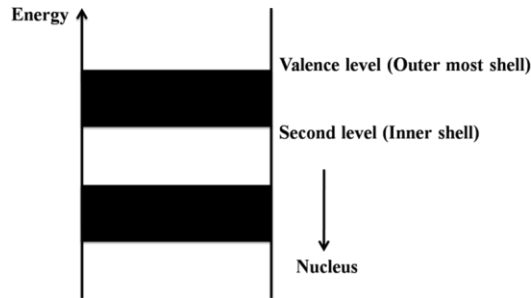


Amorphous

1.3 Band Theory of a Crystalline Solid

Valence level (Outer most shell)

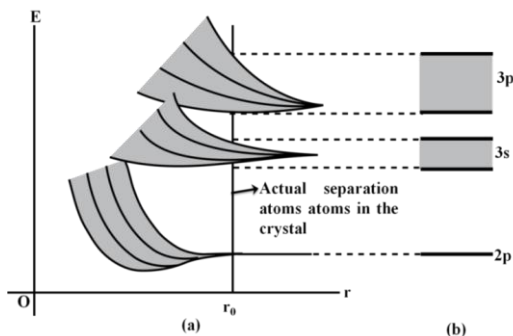
Second level (Inner shell)



1.4 Energy Bands

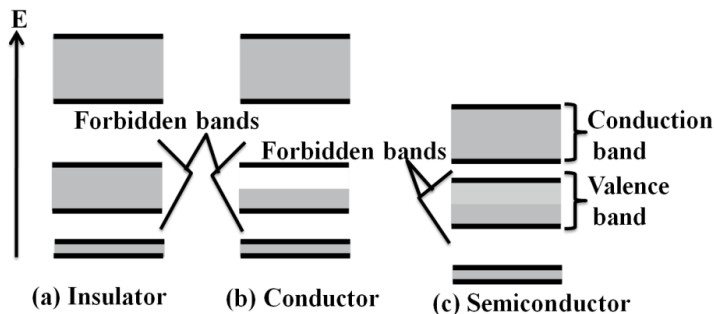
The energy band concept is a great help in understanding several properties of solids. To introduce the idea, suppose we have a large number N of identical atoms, far enough apart that their interactions are negligible. Every atom has the same energy-level diagram. We can draw an energy-level diagram for the entire system. It looks just like the diagram for a single atom, but the exclusion principle, applied to the entire system, permits each state to be occupied by N electrons instead of just one.

Now we begin to push the atoms uniformly closer together. Because of the electrical interactions and the exclusion principle, the wave functions begin to distort, especially those of the outer, or valence, electrons. The corresponding energies also shift, some upward and some downward, by varying amounts, as the valence electron wave functions become less localized and extend over more and more atoms. Thus the valence states that formerly gave the system a state with a sharp energy level that could accommodate N electrons now give a band containing N closely spaced levels. Ordinarily, N is very large, somewhere near the order of Avogadro's number (10^{24}), so we can accurately treat the levels as forming a continuous distribution of energies within a band. Between adjacent energy bands are gaps or forbidden regions where there are no allowed energy levels. The inner electrons in an atom are affected much less by nearby atoms than are the valence electrons, and their energy levels remain relatively sharp.



1.5 Insulators and Semiconductors

The nature of the energy bands determines whether the material is an electrical conductor or an insulator. In insulators and semiconductors at absolute zero temperature the valence electrons completely fill the highest occupied band, called the valence band.



The next higher band, called the **conduction band**, is completely empty at absolute zero.

The energy gap separating the valence band and the conduction band may be of the order of 1 to 5 eV. This situation is shown in figures. The electrons in a full valence band are not free to move in response to an applied electric field. To move, an electron would have to go to a different quantum state with slightly different energy, but it can't do that because all the neighboring states are already occupied. The only way such an electron can move is to jump into the conduction band. This would require an additional energy of a few electron volts or so, and that much energy is not ordinarily available. The situation is like a completely filled floor below an empty floor in a parking garage; none of the cars can move because there is no place to go. If a car could jump up to the empty floor, it could move!

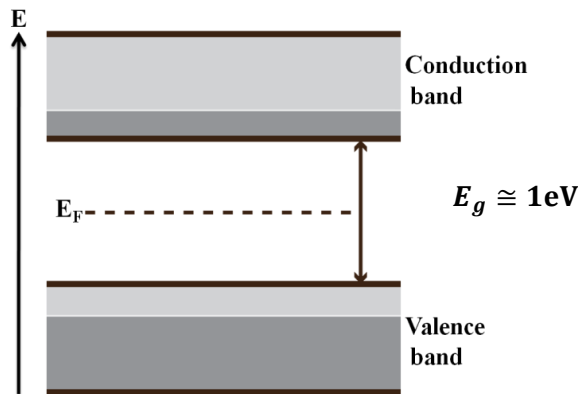
However, at any temperature above absolute zero there is some probability that an electron can gain enough energy from thermal motion to jump to the conduction band.

A distinguishing characteristic of all conductors, including metals, is that the valence band is only partly filled. The metal sodium is an example. An analysis of the energy-level diagram of figure shows that for an isolated sodium atom, the six $3p$ lowest excited states for the valence electron are about 2.1 eV above the two $3s$ ground states. But in solid sodium the $3s$ and $3p$ bands spread out enough that they actually overlap, forming a single band. Because each sodium atom has only one valence electron but eight $3s$ and $3p$ state, that single band is only $1/8$ filled. The situation is similar to the one shown in figure. Electrons in states near the top of the filled portion of the band have many adjacent unoccupied states available, and they can easily gain or lose small amounts of energy in response to an applied electronic field. Therefore these electrons are mobile and can contribute to electrical and thermal conductivity. Metallic crystals always have partly filled bands. The concept of energy bands is very useful in understanding the properties of semiconductors, which we will study in a later section.

1.6 Semiconductors

A semiconductor has an electrical resistivity that is intermediate between those of good conductors and of good insulators. The tremendous importance of semiconductors in present-day electronics stems in part from the fact that their electrical properties are very sensitive to very small concentrations of impurities. We'll discuss the basic concepts using the semiconductor elements silicon (Si) and germanium (Ge) as examples.

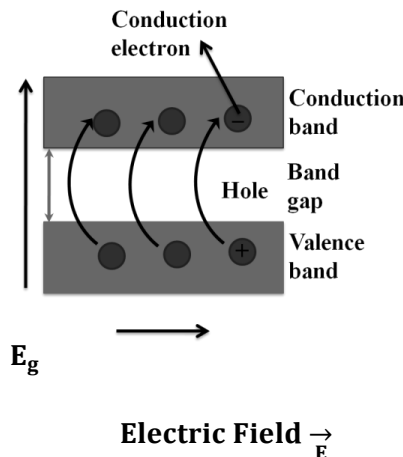
Silicon and germanium are in Group IV of the periodic table. Each has four electrons in the outermost electron subshells ($3s^2 3p^2$ for Si, $4s^2 4p^2$ for Ge). Both crystallize in the diamond structure with covalent bonding; each atom lies at the center of a regular tetrahedron, forming a covalent bond with each of four nearest neighbors at the corners of the tetrahedron. Because all the valence electrons are involved in the bonding, at absolute zero the band structure has a completely filled valence band separated by an energy gap from an empty conduction band. This distribution makes these materials insulators at very low temperatures; their electrons have no nearby states available into which they can move in response to an applied electric field.



Semiconductor

1.7 Holes

When an electron is removed from a covalent bond, it leaves a vacancy behind. An electron from a neighboring atom can move into this vacancy, leaving the neighbor with the vacancy. In this way the vacancy, called a **hole**, can travel through the material and serve as an additional current carrier. It's like describing the motion of a bubble in a liquid. In a pure, or intrinsic, semiconductor, valence-band holes and conduction-band electrons are always present in equal numbers. When an electric field is applied, they move in opposite directions. Thus a hole in the valence band behaves like a positively charged particle, even though the moving charges in that band are electrons. The conductivity that we just described for a pure semiconductor is called ***intrinsic conductivity***. Another kind of conductivity, to be discussed in the next subsection, is due to impurities.

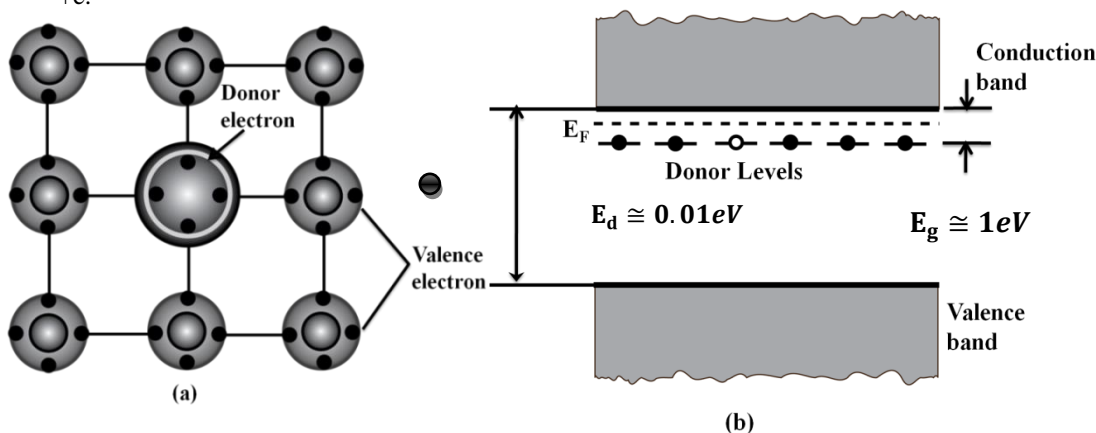


The valence band at absolute zero is like a completely filled floor. No cars (electrons) can move because there is nowhere for them to go. But if one car is moved to the vacant floor above, it can move freely, just as electrons can move freely in the conduction band. Also the empty space that it leaves permits cars to move on the nearly filled floor, thereby moving the empty space just as holes move in the normally filled valence band.

1.8 Impurities

Suppose we mix into melted germanium ($Z = 32$) a small amount of arsenic ($Z = 33$), the next element after germanium in the periodic table. This deliberate addition of Impurity elements is called **doping**. Arsenic is in Group V; it has five valence electrons. When one of these electrons is removed, the remaining electron structure is essentially identical to that of germanium. The only difference is that it is smaller; the arsenic nucleus has a charge of $+33e$ rather than $+32e$, and it pulls the electrons in a little more. An arsenic atom can comfortably take the place of a germanium atom as a substitutional impurity. Four of its five valence electrons form the necessary nearest-neighbor covalent bonds.

The fifth valence electron is very loosely bound; it doesn't participate in the covalent bonds, and it is screened from the nuclear charge of $+33e$ by the 32 electrons, leaving a net effective charge of about $+e$.

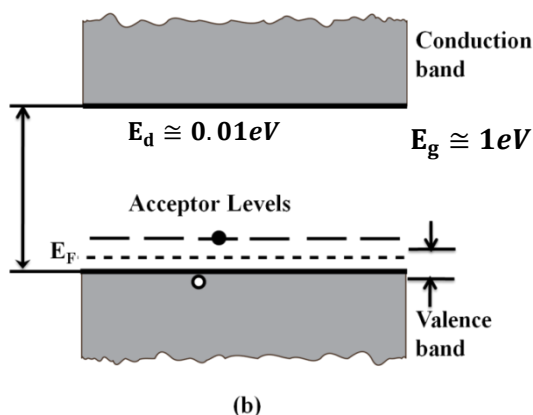
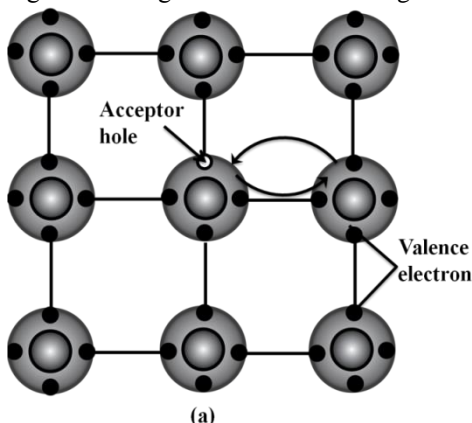


We might guess that the binding energy would be of the same order of magnitude as the energy of the $n = 4$ level in hydrogen, that is, $\left(\frac{1}{4}\right)^2 (13.6\text{ eV}) = 0.85\text{ eV}$. In fact, it is much smaller than this, only about 0.01 eV , because the electron probability distribution actually extends over many atomic diameters and the polarization of intervening atoms provides additional screening.

The energy level of this fifth electron corresponds in the band picture to an isolated energy level lying in the gap, about 0.01 eV below the bottom of the conduction band. This level is called a **donor level**, and the impurity atom that is responsible for it is simply called a **donor**. All Group V elements, including N, P, As, Sb, and Bi, can serve as donors.

However, a concentration of donors as small as one part in 108 can increase the conductivity so drastically that conduction due to impurities becomes by far the dominant mechanism. In this case the conductivity is due almost entirely to negative charge (electron) motion. We call the material an ***n-type semiconductor***, with n-type impurities.

Adding atoms of an element in Group III (B, Al, Ga, In, Tl), with only three valence electrons, has an analogous effect. An example is gallium ($Z=31$); as a substitutional impurity in germanium, the gallium atom would like to form four covalent bonds, but it has only three outer electrons. It can, however, steal an electron from a neighboring germanium atom to complete the required four covalent bonds. The resulting atom has the same electron configuration as Ge but is somewhat larger because gallium's nuclear charge is smaller, $+31e$ instead of $+32e$.

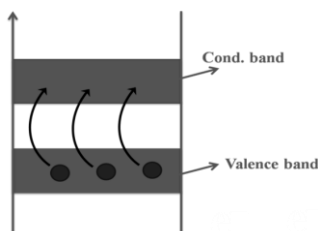


This theft leaves the neighboring atom with a hole, or missing electron. The hole acts as a positive charge that can move through the crystal just as with intrinsic conductivity. The stolen electron is bound to the gallium atom in a level called an **acceptor level** about 0.01 eV above the top of the valence band. The gallium atom, called an **acceptor**, thus accepts an electron to complete its desire for four covalent bonds. This extra electron gives the previously neutral gallium atom a net charge of $-e$. The resulting gallium ion is not free to move. In a semiconductor that is doped with acceptors, we consider the conductivity to be almost entirely due to positive charge (hole) motion. We call the material a **p-type semiconductor**, with p-type impurities. Some semiconductors are doped with both n- and p-type impurities. Such materials are called **compensated semiconductor**.

Caution:- Saying that a material is a p-type semiconductor does not mean that the material has a positive charge; ordinarily, it would be neutral. Rather, it means that its majority carriers of current are positive holes (and therefore its minority carriers are negative electrons). The same idea holds for an n-type semiconductor; ordinarily, it will not have a negative charge, but its majority carriers are negative electrons.

1.9 Holes

When electron jumps the energy graph into conduction band they leave an equal number of vacant energy state called holes in the valence band. Electrons in the conduction band and holes in valence band can be charge carriers



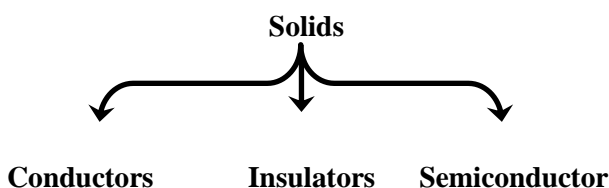
1.10 Classification of solids on the basis of band theory

Conductivity of solid:-

It will depend on the position of two highest bands and their electron occupation also the separation between their energy levels.

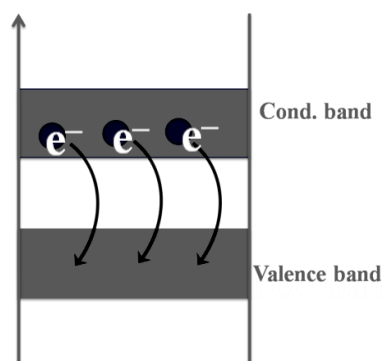
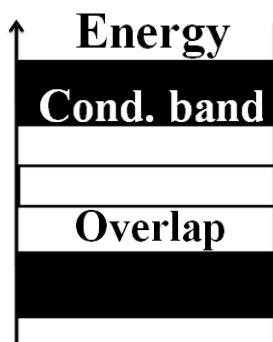
Valence band and conduction band:-

The band occupied by outer or valence electrons will be conduction band.



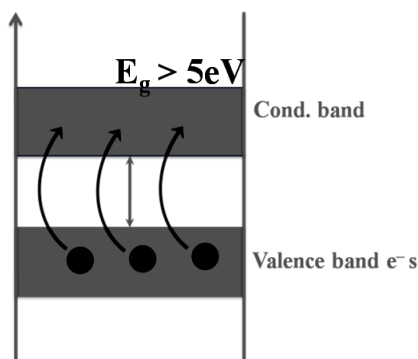
1.11 Conductors

- (i) Valence band is partly filled
- (ii) Conduction band overlaps to valence band



1.12 Insulators

At very high temperature semiconductor becomes conductor, α for semiconductors will be negative.

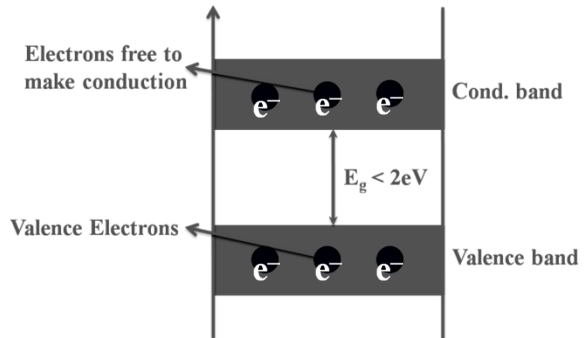


1.13 Semiconductors

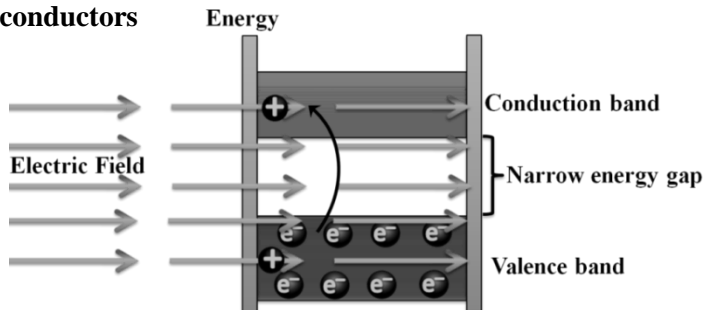
Conduction band overlaps valence band slightly.

Example:- Silicon (Si) $E_g = 1.1 \text{ eV}$, Germanium (Ge) $E_g = 0.67 \text{ eV}$

At ok semiconductor becomes ideal.

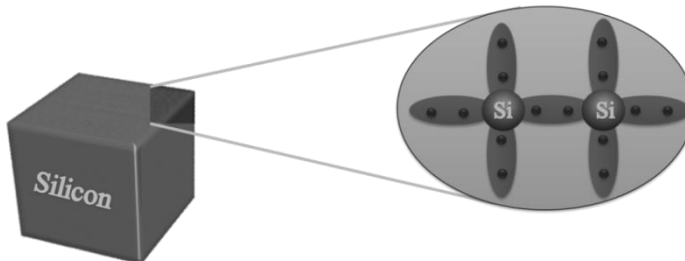


(1) Intrinsic or pure semiconductors

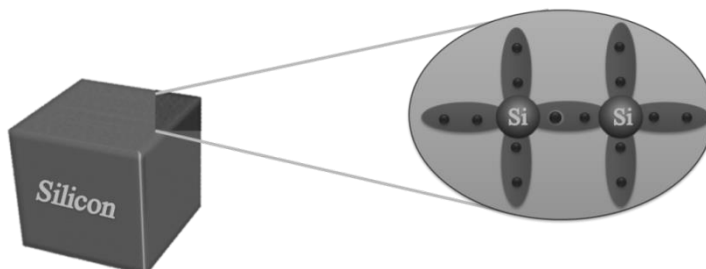


At low temperature (0K)

No free e^- no holes so behave like insulator



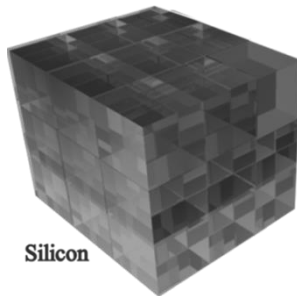
At room temperature



For intrinsic semiconductors

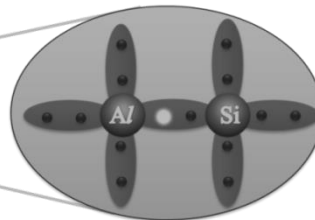
$$n_n = n_e$$

1.14 Extrinsic or doped semiconductors



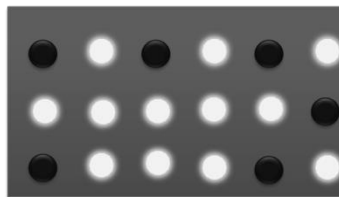
+ 3 valence (trivalent)
(B, Al, Ga, In)

(1) p – type semiconductors

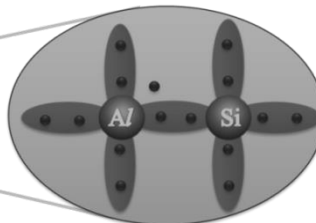


$n_h \gg n_e$ Electrically neutral

Doped with acceptor atoms

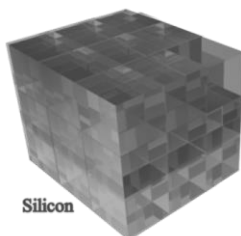


(2) n – type semiconductors

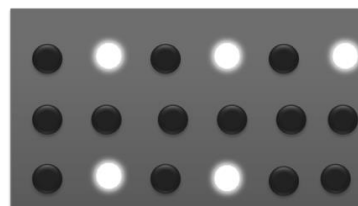


$n_e \gg n_h$ Electrically neutral

Doped with donor atoms



+ 5 valence (pentavalent)
(Antimony, p, or Arsenic)



1.15 Electrical properties of semiconductor

(i) Conductivity

$$\left. \begin{aligned} \text{Restivity } \rho &= \frac{m}{ne^2\tau} = \frac{E}{J} \\ \text{Conductivity } \sigma &= \frac{1}{\rho} = \frac{ne^2\tau}{m} \end{aligned} \right\} \text{Also } \sigma = \sigma_e + \sigma_n$$

(ii) Mobility:-

Drift speed of electron or holes per unit field

$$\mu = \frac{v_d}{E} = \frac{e\tau}{m} \quad \text{Here } v_d = \frac{e\tau}{m} E$$

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

$$\mu_n < \mu_e$$

Total Current

$$i = i_e + i_n$$

1.16 Resistivity

$$\sigma = n_e e \mu_e + n_n e \mu_n$$

$$\text{Also } \frac{1}{\rho} = e(n_e \mu_e + n_n \mu_n)$$

For intrinsic semiconductor

$$\begin{array}{c} n_e = n_n = n_i \Rightarrow \text{Concentration} \\ \downarrow \quad \downarrow \quad \downarrow \\ \text{Electron} \quad \text{Hole} \quad \text{Intrinsic} \\ \sigma = n_i e (\mu_e + \mu_n) \end{array}$$

Practice Question online