Distinction between metals, insulators, and intrinsic semiconductors:-

Let us consider a particular energy band which we shall assume to be filled with electrons up to a certain value K_1, as indicated in fig (1). As far as the influence of an external electric field is concerned one would like to know with how many 'free' electrons the N electrons in the band are equivalent. It would be possible to draw conclusion about the conductivity associated with this band. The effective number of 'free' electrons in the band is in accordance with the preceding section equal to

$$N_{eff} = \sum f_k \quad \text{——} (1)$$

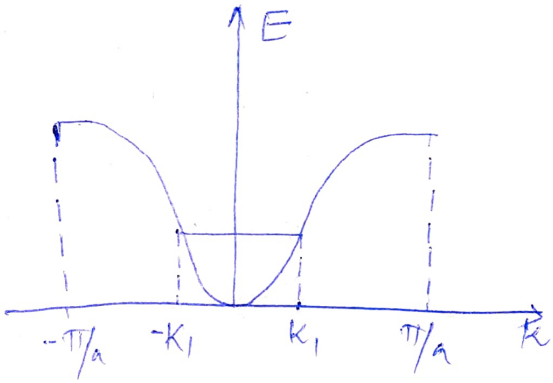


Fig.-(1) Energy band filled up to states $|K_1$ at T=0.

Where the summation extends over all occupied states in the band.

Now according to $dn = L\,dK/2\pi$ —— (2).

the number of states in an interval dK (excluding the spin) for a one-dimensional lattice of length L is equal to $L\,dK/2\pi$. Because two electrons occupy each of these states in the shaded region of fig (1), one may write instead of (2)

$$N_{eff} = (L/\pi)\int_{-K_1}^{+K_1} f_K\,dK = (2Lm/\pi\hbar^2)\int_0^{K_1}(d^2E/dK^2)\,dK \quad \text{——— (3)}$$

We used

$$f_K = m/m^* = (m/\hbar^2)(d^2E/dK^2) \quad \text{——— (4)}$$

where, f_K is a measure for the extent to which an electron in states K is free
m^* is effective mass. and is equal to $\hbar^2/(d^2E/dK$
m is mass of free electron.

Thus, from eq^n (3) the effective number of electron in the band is:

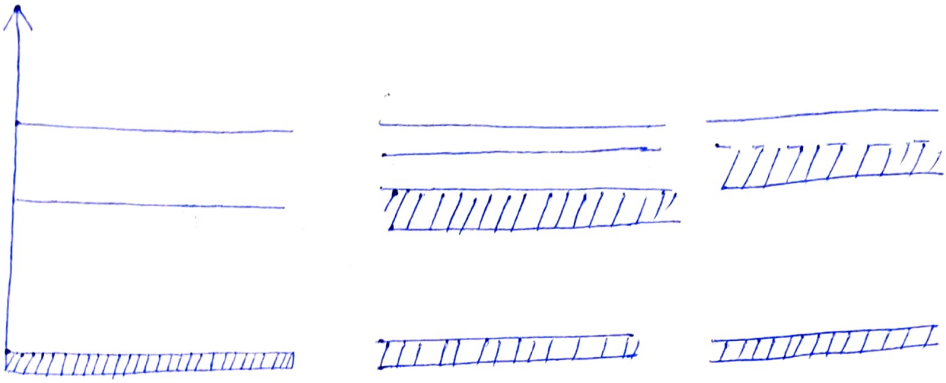
$$N_{eff} = (2Lm/\pi\hbar^2)\,(dE/dK)_{K=K_1} \quad \text{——— (5)}$$

From this result we write the following conclusions:

(i) The effective number of electrons in a completely filled band vanishes, because dE/dK vanishes at the top of the band.

(ii) The effective number of electrons reaches a maximum for a band filled to the inflection point of the E(K) curve, because then dE/dK is a maximum.

From the above discussion it follows that a solid for which a certain number of energy bands are completely filled, the other bands being completely empty, is an insulator [See in fig (2a)] on the other hand, a solid containing an energy band which is incompletely filled has metallic character (Fig 2(c)). It will be evident that the situation depicted by fig (2a) can occur actually only at absolute zero when the crystal is in its lowest energy state.

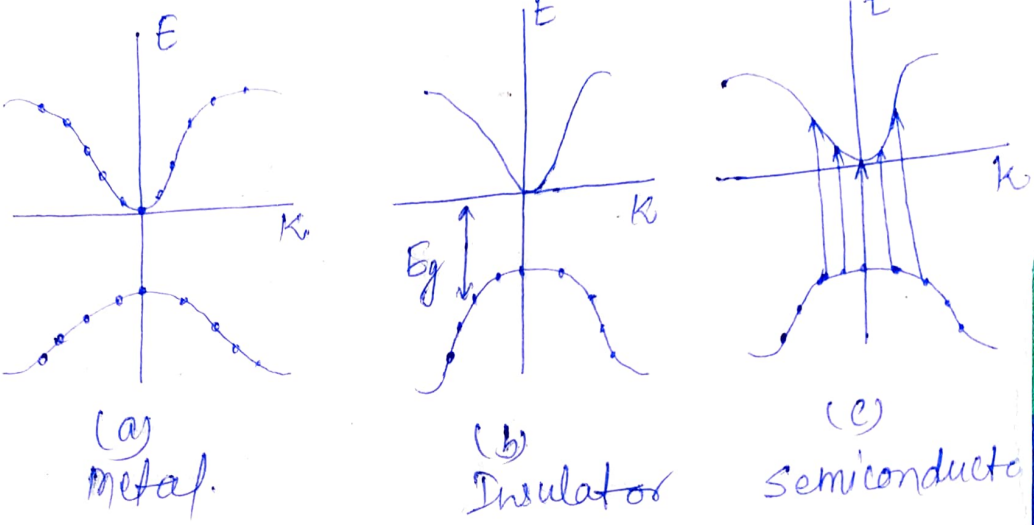


Insulator 2(a) | Semiconductor 2(b) | Metal 2(c)

Fig-(2). Electron distribution at $T=0$ is an Insulator, intrinsic semiconductor and metal. the shaded regions are occupied by electrons.

At temperatures different from zero, some electrons from the upper filled band will be excited into the next empty band ("conduction band") and conduction becomes possible. If the forbidden energy gap is of the order of several electron volts, however the solid will remain an "insulator" for all practical purposes. An example is diamond, for which the forbidden gap is about 7 ev. For a small gap width, say about 1 ev, the number of thermally excited electrons may become appreciable and in this case one speaks of an intrinsic semiconductor. Examples are germanium and silicon. It is evident that the distinction between insulators and intrinsic semiconductors is only a quantitative one. In fact, all intrinsic semiconductors are Insulators at $T=0$, whereas all Insulators may be considered semiconductors at $T>0$.

It may be noted here that the conductivity of semiconductors in general increases with increasing temperature, whereas the conductivity of metals decreases with increasing temp. ~~The properties of these materials will~~ be further discussed in later chapters.



(a) Metal. (b) Insulator (c) Semiconductor

A substance in which the number of valence electrons per unit cell is odd is necessarily a metal, since it takes an even number of electrons to fill a band completely. But when the number is even, the substance may be either an insulator or a metal, depending on whether the bands are disparate or overlapping.