

Intrinsic sc in a pure semiconductor  $\rightarrow$  It is made up of tetravalent atom, that has 4 valence e<sup>-</sup>

Extrinsic sc  $\rightarrow$  Impure sc, because we add some impurity in it, at a controlled ratio.

The conductivity of Exsc is larger than Intrinsic sc.

Ex  $\rightarrow$  Intrinsic sc, Si,  $E_F = 0.6 \text{ eV}$   
Doping  $L = 1.0 \text{ eV}$

The process by which an impurity is added to a sc is known as Doping. Generally one impurity atom is added to a  $10^8$  atoms of a sc.

The purpose of adding impurity in sc crystal is to increase the no. of free e<sup>-</sup> & holes to make it conductive.

If of p-type

In a most pure sc, at room temp., the population of thermally excited charge carriers is so small.

For such as for Si  $\sim 1.5 \times 10^{10} / \text{cm}^3$

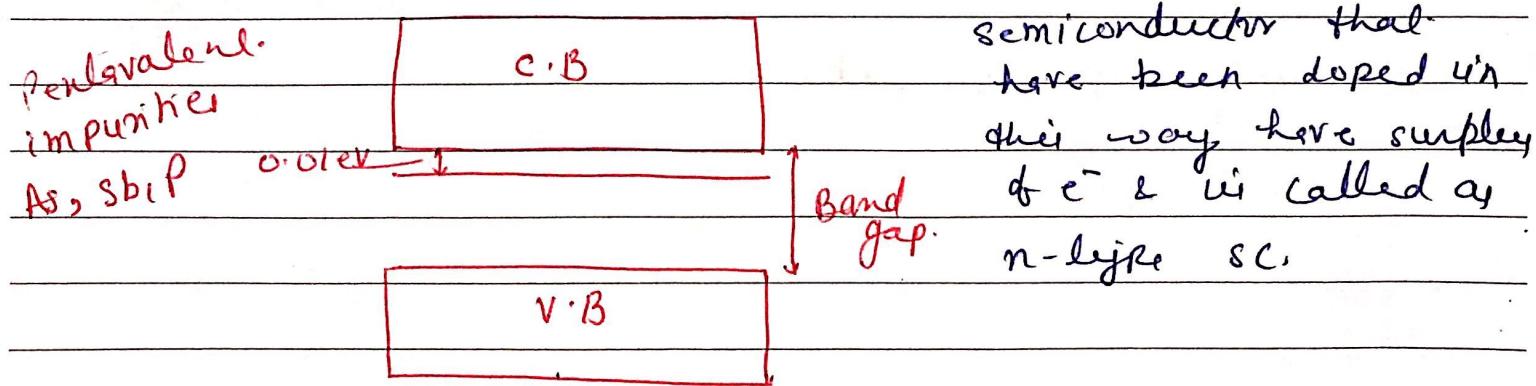
GaAs  $\sim 1.1 \times 10^6 / \text{cm}^3$

Metal  $\sim 10^{28} / \text{cm}^3$

in Si, which is a group IV element, & has 4 valence  $e^-$  per atom. In pure Si, the V.B is completely filled at 0 K. At finite temp the only charge carriers are  $e^-$  in the C.B & the holes in the V.B that arise as a result of thermal excitation of  $e^-$  to the C.B.

These charge carriers are called the intrinsic charge carriers, necessarily there are equal no. of holes &  $e^-$ . Pure Si is an **INTRINSIC SEMICONDUCTOR**.

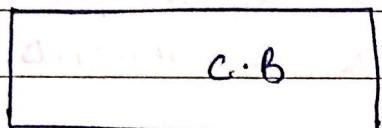
If a very small no. of atoms of a group V element such as phosphorus (P) are added to the Si as substitutional atoms in the lattice, additional valence  $e^-$  are introduced into the material. These addition  $e^-$  are bound only weakly to the parent impurity atom. & even at very low temp. can be promoted to the C.B of the semiconductor. This is often represented schematically in band diagrams by the addition of donor levels.



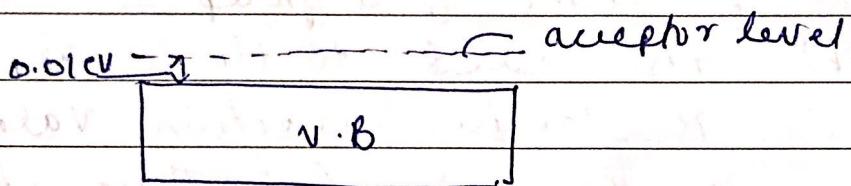
$$\text{for Si} = 0.05 \text{ eV} \quad \& \quad \text{As} = 0.01 \text{ eV}$$

conversely, if a group III element, such as Al is used to substitute few of the Si atoms, there will be deficit of valence  $e^-$ . This will introduce the  $e^-$  accepting level just above the top of the V.B.

s.c doped in this way is called the p-type s.c.



Doped s.c (either n-type or p-type) are known as extrinsic s.c.



\* It should be remembered that the case of an extrinsic s.c. there is no contribution to the total no. of charge carriers from the intrinsic  $e^-$  & holes, but at room temp this is very low in comparison to the no. of charge carriers introduced by the impurities.

### Trivalent-impurity like

B, Ga, Al

### Example 3.5

**Objective** To determine the energy at which the Boltzmann approximation may be considered valid.

Calculate the energy, in terms of  $kT$  and  $E_F$ , at which the difference between the Boltzmann approximation and the Fermi-Dirac function is 5 percent of the Fermi function.

We can write

$$\frac{\exp\left[\frac{-(E - E_F)}{kT}\right] - \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}}{\frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}} = 0.05$$

If we multiply both numerator and denominator by the  $1 + \exp()$  function, we have

$$\exp\left[\frac{-(E - E_F)}{kT}\right] \cdot \left\{1 + \exp\left[\frac{E - E_F}{kT}\right]\right\} - 1 = 0.05$$

which becomes

$$\exp\left[\frac{-(E - E_F)}{kT}\right] = 0.05$$

or

$$(E - E_F) = kT \ln\left(\frac{1}{0.05}\right) \approx 3kT$$

**Comment** As seen in this example and in Fig. 3.8, the  $E - E_F \gg kT$  notation is somewhat misleading. The Maxwell-Boltzmann and Fermi-Dirac functions are within 5 percent of each other when  $E - E_F \approx 3kT$ .

The actual Boltzmann approximation is valid when  $\exp[(E - E_F)/kT] \gg 1$ . However, it is still common practice to use the  $E - E_F \gg kT$  notation when applying the Boltzmann approximation. We will use this Boltzmann approximation in our discussion of semiconductors in the next chapter.

## CHARGE CARRIERS IN SEMICONDUCTORS

### 3.2

Current is the rate at which charge flows. In a semiconductor, two types of charge carriers, the electron and the hole, can contribute to a current. Since the current in a semiconductor is determined largely by the number of electrons in the conduction band and the number of holes in the valence band, an important characteristic of the semiconductor is the density of these charge carriers. The density of electrons and holes is related to the density of states function and the Fermi distribution function, both of which we have considered. A qualitative discussion of these relationships will be followed by a more rigorous mathematical derivation of the thermal-equilibrium concentration of electrons and holes.

### 3.2.1 Equilibrium Distribution of Electrons and Holes

The distribution (with respect to energy) of electrons in the conduction band is given by the density of allowed quantum states times the probability that a state is occupied by an electron. This statement is written in equation form as

$$n(E) = g_c(E)f_F(E)$$

where  $f_F(E)$  is the Fermi-Dirac probability function and  $g_c(E)$  is the density of quantum states in the conduction band. The total electron concentration per unit volume in the conduction band is then found by integrating Eq. (3.6) over the entire conduction-band energy.

Similarly, the distribution (with respect to energy) of holes in the valence band is the density of allowed quantum states in the valence band multiplied by the probability that a state is *not* occupied by an electron. We may express this as

$$p(E) = g_v(E)[1 - f_F(E)]$$

The total hole concentration per unit volume is found by integrating this function over the entire valence band energy.

To find the thermal-equilibrium electron and hole concentrations, we need to determine the position of the Fermi energy  $E_F$  with respect to the bottom of the conduction-band energy  $E_c$  and the top of the valence-band energy  $E_v$ . To address this question, we will initially consider an intrinsic semiconductor. An ideal intrinsic semiconductor is a pure semiconductor with no impurity atoms and no lattice defects in the crystal (e.g., pure silicon). We have argued in the previous chapter that, for an intrinsic semiconductor at  $T = 0$  K, all energy states in the valence band are filled with electrons and all energy states in the conduction band are empty of electrons. The Fermi energy must, therefore, be somewhere between  $E_c$  and  $E_v$ . (The Fermi energy does not need to correspond to an allowed energy.)

As the temperature begins to increase above 0 K, the valence electrons will gain thermal energy. A few electrons in the valence band may gain sufficient energy to jump to the conduction band. As an electron jumps from the valence band to the conduction band, an empty state, or hole, is created in the valence band. In an intrinsic semiconductor, then, electrons and holes are created in pairs by the thermal energy so that the number of electrons in the conduction band is equal to the number of holes in the valence band.

Figure 3.9(a) shows a plot of the density of states function in the conduction band  $g_c(E)$ , the density of states function in the valence band  $g_v(E)$ , and the Fermi-Dirac probability function for  $T > 0$  K when  $E_F$  is approximately halfway between  $E_c$  and  $E_v$ . If we assume, for the moment, that the electron and hole effective masses are equal, then  $g_c(E)$  and  $g_v(E)$  are symmetrical functions about the midgap energy (the energy midway between  $E_c$  and  $E_v$ ). We noted previously that the function  $f_F(E)$  for  $E > E_F$  is symmetrical to the function  $1 - f_F(E)$  for  $E < E_F$  about the energy  $E = E_F$ . This also means that the function  $f_F(E)$  for  $E = E_F + dE$  is equal to the function  $1 - f_F(E)$  for  $E = E_F - dE$ .

Figure 3.9(b) is an expanded view of the plot in Fig. 3.9(a) showing  $f_F(E)$  and  $g_c(E)$  above the conduction band energy  $E_c$ . The product of  $g_c(E)$  and  $f_F(E)$  is the distribution of electrons  $n(E)$  in the conduction band given by Eq. (3.6). This product is plotted in Fig. 3.9(a). Figure 3.9(c) is an expanded view of the plot in Fig. 3.9(a) showing  $[1 - f_F(E)]$  and  $g_v(E)$  below the valence band energy  $E_v$ . The product of  $g_v(E)$  and  $[1 - f_F(E)]$  is the distribution of holes  $p(E)$  in the valence band given by Eq. (3.7). This product is also plotted in Fig. 3.9(a). The areas under these curves are then the total density of electrons in the conduction band and the total density of holes in the valence band. From this we see that if  $g_c(E)$  and  $g_v(E)$  are symmetrical, the Fermi energy must be at the midgap energy in order to obtain equal electron and hole concentrations. If the