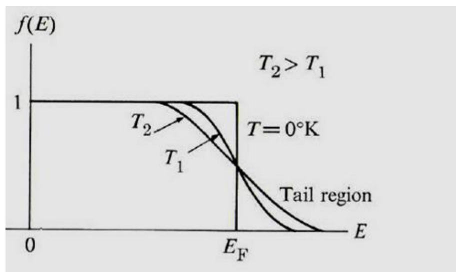
CARRIER CONCENTRATION: INTRINSIC SEMICONDUCTORS

In the field of semiconductors, electrons and holes are usually referred to as free carriers, or simply carriers, because it is these particles which are responsible for carrying the electric current. The number of carriers is an important property of a semiconductor, as this determines its electrical conductivity. In order to determine the number of carriers, we need some of the basic results of statistical mechanics. The most important result in this regard is the Fermi-Dirac (FD) distribution function

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

This function gives the probability that an energy level E is occupied by an electron when the system is at temperature T. The function is plotted versus E in figure below



The Fermi–Dirac distribution function.

Here we see that, as the temperature rises, the unoccupied region below the Fermi level Ep becomes longer, which implies that the occupation of high energy states increases as the temperature is raised, a conclusion which is most plausible, since increasing the temperature raises the overall energy of the system. Note also that f (E):] at the Fermi level (E: E) regardless of the temperature. That is, the probability that the Fermi level is occupied is always equal to onehalf.

In semiconductors it is the tail region of the FD distribution which is of of particular interest. In that region the inequality $(E - E_v) > k_B T$ holds true and one may thereby neglect the term unity in the-denominator. The FD distribution then reduces to the form

$$f(E) = e^{E_F/k_B T} e^{-E/k_B T}$$

which is the familiar Maxwell-Boltzmann, or classical, distribution. This simple distribution therefore suffices for the discussion of electron statistics in semiconductors.

The energy of an electron in the conduction band is

$$\epsilon_k = E_c + \hbar^2 k^2/2m_e$$

where Ec is the energy at the conduction band edge. Here m_e is the effective mass of an electron. By using the expression of density of states from the free electron theory, given by

$$D(\epsilon) \equiv \frac{dN}{d\epsilon} = \frac{V}{2\pi^2} \cdot \left(\frac{2m}{\hbar^2}\right)^{3/2} \cdot \epsilon^{1/2} \ .$$

Therefore, we have electron state density

$$D_e(\epsilon) = \frac{1}{2\pi^2}\left(\frac{2m_e}{\hbar^2}\right)^{3/2}(\epsilon - E_c)^{1/2}$$

The concentration of electrons in the conduction band is

$$n = \int_{E_c}^{\infty} D_e(\epsilon) f_e(\epsilon) d\epsilon = \frac{1}{2\pi^2}\left(\frac{2m_e}{\hbar^2}\right)^{3/2} \exp(\mu/k_B T) \times \int_{E_c}^{\infty} (\epsilon - E_c)^{1/2} \exp(-\epsilon/k_B T) d\epsilon \ ,$$

which integrates to give

$$n = 2\left(\frac{m_e k_B T}{2\pi\hbar^2}\right)^{3/2} \exp[(\mu - E_c)/k_B T] \ .$$

It is useful to calculate the equilibrium concentration of holes p. The distribution function f_h for holes is related to the electron distribution function f_e by $f_h = 1 - f_e$, because a hole is the absence of an electron. We have

$$f_h = 1 - \frac{1}{\exp[(\epsilon - \mu)/k_B T] + 1} = \frac{1}{\exp[(\mu - \epsilon)/k_B T] + 1} \cong \exp[(\epsilon - \mu)/k_B T] \ ,$$

provided $(\mu - \epsilon) \gg k_B T$.

If the holes near the top of the valence band behave as particles with effective mass m_h, the density of hole states is given by

$$D_h(\epsilon) = \frac{1}{2\pi^2}\left(\frac{2m_h}{\hbar^2}\right)^{3/2}(E_v - \epsilon)^{1/2}$$

where E_v is the energy at the valence band edge. So the hole concentration would be given by;

$$p = \int_{-\infty}^{E_v} D_h(\epsilon) f_h(\epsilon) d\epsilon = 2\left(\frac{m_h k_B T}{2\pi\hbar^2}\right)^{3/2} \exp[(E_v - \mu)/k_B T]$$

Therefore,

$$np = 4\left(\frac{k_B T}{2\pi\hbar^2}\right)^3 (m_e m_h)^{3/2} \exp(-E_g/k_B T)$$

Where, $E_g = E_c - E_v$, is the band gap energy

In an intrinsic semiconductor the number of electrons is equal to the number of holes, because the thermal excitation of an electron leaves behind a hole in the valence band. Thus from (43) we have, letting the subscript i denote intrinsic. Therefore

$$n_i = p_i = 2\left(\frac{k_B T}{2\pi\hbar^2}\right)^{3/2} (m_e m_h)^{3/4} \exp(-E_g/2k_B T) .$$

The intrinsic carrier concentration depends exponentially on $E_g/2kBT$, where E_g is the energy gap. The Fermi level as measured from the top of the valence band,

$$\exp(2\mu/k_B T) = (m_h/m_e)^{3/2} \exp(E_g/k_B T) \;;$$
$$\mu = \tfrac{1}{2} E_g + \tfrac{3}{4} k_B T \ln(m_h/m_e) \;.$$

If $m_h = m_e$, then and the Fermi level is in the middle of the forbidden gap.

Mobility of Electrons and Holes

The mobility is the magnitude of the drift velocity of a charge carrier per unit electric field: $\mu = |v|/E$. The mobility is defined to be positive for both electrons and holes, although their drift velocities are opposite in a given field. By writing μ_e or μ_h with subscripts for the electron or hole mobility we can avoid any confusion between chemical potential and as the mobility.

In a semiconductor, the **mobility of electrons is higher than that of the holes**. It is mainly because of their different band structures and scattering mechanisms.

Electrons travel in the conduction band whereas holes travel in the valence band. When an electric field is applied, holes cannot move as freely as electrons due to their restricted movent. The elevation of electrons from their inner shells to higher shells results in the creation of holes in semiconductors. Since the holes experience stronger atomic force by the nucleus than electrons, holes have lower mobility.

The mobility of a particle in a semiconductor is more if;

- Effective mass of particles is lesser
- Time between scattering events is more

For intrinsic silicon at 300 K, the mobility of electrons is 1500 $cm^2 (V\cdot s)^{-1}$ and the mobility of holes is 475 $cm^2 (V\cdot s)^{-1}$.

The electrical conductivity is the sum of the electron and hole contributions:

$$\sigma = (ne\mu_e + pe\mu_h)$$

where n and p are the concentrations of electrons and holes. In the drift velocity of a charge q was found to be $v = q\tau E/m$, whence

$$\mu_e = e\tau_e/m_e \ ; \qquad \mu_h = e\tau_h/m_h$$

where τ is the relaxation time.

Why does the Resistivity of Semiconductors go down with Temperature?

The difference in resistivity between conductors and semiconductors is due to their difference in charge carrier density.The resistivity of semiconductors decreases with temperature because the number of charge carriers increases rapidly with increase in temperature making the fractional change i.e. the temperature coefficient negative.