

11. SEMICONDUCTORS

Semiconductor physics is of obvious importance, as it is the basis for the development of modern electronics. In this lecture we will go through the basis of semiconductor physics. The main part will deal with the conductivity, both the intrinsic one and the extrinsic one due to doping.

1. Basic features of semiconductors (K p. 187-191, 200-205).

Semiconductors are classified as having an electrical resistivity between 10^{-4} and $10^7 \Omega\text{m}$ at room temperature. Some types of semiconductors are the elemental ones (Group IV: Si, Ge.), the III-V ones (InSb, Ga As...) and II-VI ones (ZnS, CdS...). Semiconductors have a filled valence band and an empty conduction band, with a bandgap less than 4 eV. Hence pure semiconductors are insulators at zero temperature, but at higher temperatures electrons can be excited over the bandgap and give rise to the **intrinsic** conductivity (there is also a contribution from holes in the valence band). Impurities or doping also gives a so called **extrinsic** contribution to the conductivity.

The band structure of silicon and germanium are discussed in K p. 202-205. Some other semiconductors were discussed in the lecture on band structure in the context of s-p hybridization. The band gap can be either direct or indirect. In the former case the edges of the valence and conduction band occur at the same point in the Brillouin zone, while in the latter case they are at different values of \mathbf{k} .

The bandgap can be determined by optical absorption, K p. 188-191. The optical absorption is approximately vertical in the band structure scheme, i.e. the initial and final states are at the same \mathbf{k} -value. The direct bandgap is easily seen as a sudden onset of optical absorption. In the indirect case, a phonon has to be involved in order to conserve \mathbf{k} . Hence the indirect absorption is weaker, but still allows a detailed analysis of the bandgap as well as the energies of the phonons involved in the process.

The bandgap, E_g , can also be obtained from the temperature dependence of the electrical conductivity, as seen below.

2. Intrinsic conductivity (K p. 205-209).

We assume that the band edges, i.e the regions close to the maximum of the valence band and the minimum of the conduction band, have a parabolic dependence on \mathbf{k} , just as in the case of free electrons. The number of electrons excited to the conduction band is given by the Fermi-Dirac (FD) distribution.

First we calculate the density of states in the conduction band, and by integration of it (multiplied with the FD function) we obtain the electron concentration, n (K p. 205-206).

The same argument is applied to hole states in the valence band. Analogously we obtain the density of hole states and the hole concentration, p (K p. 206). It is seen that the product np is exponentially dependent on the bandgap divided by $k_B T$. It is a constant at a given temperature.

In the intrinsic case $n=p$ (we denote this by n_i) and an expression for the Fermi level, μ , is easily obtained (K p. 207-208). At zero temperature it is in the middle of the bandgap.

Rule of thumb: At $T=300$ K and if the effective masses of electrons and holes are equal to the free electron mass, then $n_0=p_0=2.5 \cdot 10^{25} \text{ m}^{-3}$.

The conductivity is obtained as the sum of two free-electron like contributions from electrons and holes, respectively. In semiconductors one defines electron and hole mobilities instead of working with relaxation times. The mobility is defined as the magnitude of the drift velocity divided by the electric field (K p. 208).

The electrical conductivity of an intrinsic semiconductor is obtained from the product of the charge carrier concentration, the mobility, $\mu_{e,h}$, and e .

$$\sigma_i = e (\mu_e + \mu_h) (\sqrt{n_0 p_0}) \exp(-E_g/2k_B T)$$

Here the n_0 and p_0 have very weak temperature dependences, proportional to $T^{3/2}$. The conductivity is thermally activated with activation energy equal to half the bandgap.

3. Doping and extrinsic conductivity (K p. 209-214).

The number of conduction electrons in an intrinsic semiconductor decreases very quickly as the bandgap increases. For an insulator with bandgap $> 4\text{eV}$, n will be less than 1 m^{-3} at room temperature. This situation will never be reached in practise, however, since the presence of impurities also affects the electron (and hole) concentration. It is very difficult to prepare materials with impurity content less than 10^{17} m^{-3} .

The electrical conductivity of semiconductors can be controlled by deliberate doping with impurities. We consider the situation in the elemental semiconductors, which have four valence electrons. There are two kinds of doping:

- a) **Donor doping.** The donor atom has one valence electron more than the atom it will substitute for. The extra electron is situated in a localized donor state close to the conduction band and can easily be excited. The ionization energy and the radius of the orbit of the extra electron are given in K. p. 210-211. The donor levels are usually an energy (E_d) 10-50 meV below the conduction band, while the orbit radii are in the range 30-80 Å. The semiconductor is called n-type.
- b) **Acceptor doping.** The acceptor atom has one valence electron less than the atom it will substitute. Localized acceptor states occur close to the top of the valence band at an energy, E_a , above it. Valence electrons can easily be excited there giving rise to an increased conductivity due to holes in the valence band. The semiconductor is p-type.
- c) **Compensation.** One can also dope with both donors and acceptors. Because the product np is a constant at a given temperature, doping with equal amounts of donors and acceptors will give us back the intrinsic situation. This is of importance because impurity conduction in a semiconductor can be compensated by the controlled introduction of dopants of the opposite type (K. p. 207).

Now we consider the carrier concentrations. The concentration of donor atoms is denoted N_d and of acceptor atoms N_a . The charged species are denoted by the appropriate charge as a superscript. The requirement of charge neutrality gives:

$$p + N_d^+ = n + N_a^-.$$

The requirement $np = n_i^2$ gives, rewriting p with the help of the relation above:

$$n = 1/2 (N_d^+ - N_a^-) + 1/2 ((N_d^+ - N_a^-)^2 + 4 n_i^2)^{1/2}$$

We discuss the case of n-type semiconductors, i.e. $N_d > N_a$. For p-type ones we have to consider a similar equation for p . We have different cases:

1. At very high temperatures ($k_B T \gg E_g$), the thermally excited intrinsic charge carriers are dominating over those supplied by the doping. Hence the electrical conductivity exhibits the intrinsic value given in sec. 2.
2. We lower T ($k_B T \gg E_d$), so that $N_d - N_a > n_i$. This means that all donors are ionized. Now $n = N_d - N_a$ and independent of temperature. The electrical conductivity is also approximately constant in this range. It only exhibits the weak temperature dependence of the mobility, $\sigma = ne \mu_e(T)$.
3. At still lower temperatures ($k_B T \sim E_d$), not all donors are ionized. This is the situation around room temperature for most semiconductors. In this case we must again apply FD statistics. We assume only donor doping and neglect any acceptor impurities. The concentration of neutral (not ionized) donor atoms is given by:

$$N_d^0 = N_d f_{FD}(E_c - E_d) = N_d / (\exp[(E_c - E_d - \mu) / k_B T] + 1),$$

where E_c is the conduction band edge and E_d is the energy from the donor level to the conduction band. From neutrality $n = N_d^+ = N_d - N_d^0$, we immediately obtain:

$$n = N_d / (\exp[(\mu - E_c + E_d) / k_B T] + 1).$$

In many situations the Fermi level is larger than the difference $E_c - E_d$ and the term unity in the denominator can be neglected. However we use below the full expression and obtain for the electron concentration

$$n / (N_d - n) = \exp[(E_c - E_d - \mu) / k_B T].$$

Or, by using the general expression for the electron concentration, K p.206, eq.(39), we obtain, (NOTE: This expression and its analogue for holes are valid irrespective of whether we have an intrinsic situation, or doping!)

$$n^2 / (N_d - n) = n_0 \exp[-E_d / k_B T].$$

4. If $k_B T \ll E_d$, then $N_d \gg n$ and we arrive at the low temperature expression in Kittel, p. 213.

$$n = (N_d n_0)^{1/2} \exp[-E_d / 2 k_B T].$$

One can also study the evolution of the Fermi level with temperature. We put the general expression for n , K p.206, eq.(39), equal to our expressions above. In the low temperature region (4) we then obtain:

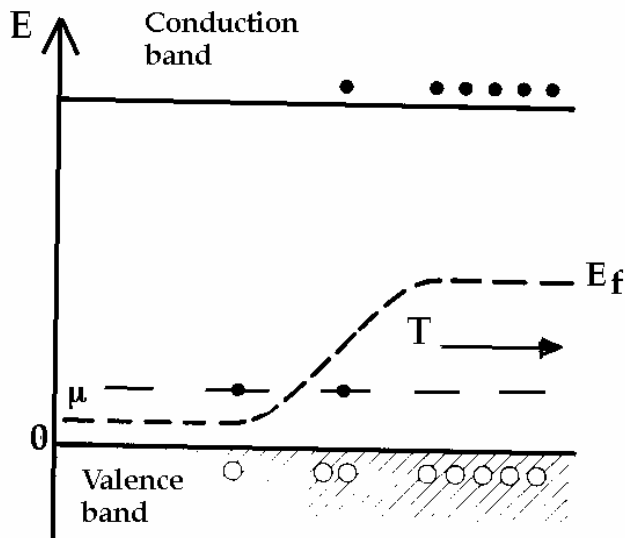
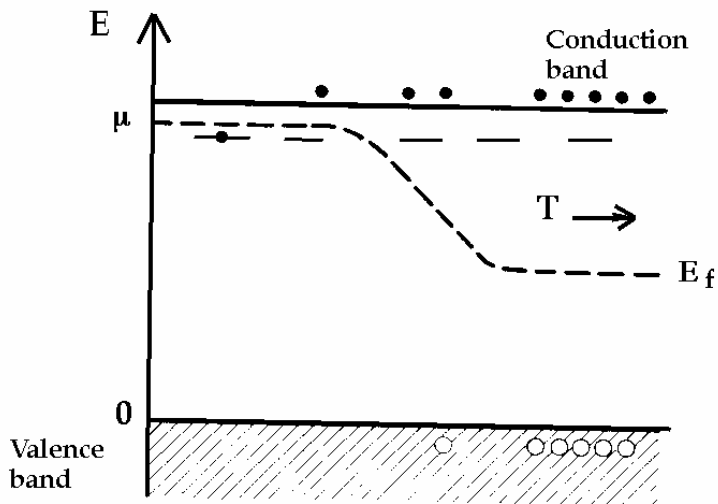
$$\mu = E_c - E_d/2 + 1/2 k_B T \ln(N_d/n_0).$$

It is seen that the Fermi level at absolute zero is situated half way between the donor levels and the conduction band edge. As the temperature increases the Fermi level will sink towards the middle of the bandgap. In region (3) the expression for μ becomes in general complicated. In region (2) we again obtain a simple expression, namely

$$\mu = E_g - k_B T \ln(n_0/(N_d - N_a)).$$

At very high temperatures the intrinsic situation is again attained. We have considered here n-doped semiconductors, but an analogous treatment can easily be developed for the p-type case.

The temperature dependence of the Fermi level for n- and p-type semiconductors is depicted in the Figures below (adapted from Myers).



Links to applets –simple simulations of some of the features detailed above:

<http://jas.eng.buffalo.edu/education/semicon/fermi/levelAndDOS/index.html>

<http://jas.eng.buffalo.edu/education/semicon/fermi/bandAndLevel/fermi.html>