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Lecture for M. Sc. Physics IV Semester students

Paper-I: Condense matter physics-II

Unit-3 Carrier Concentration

The hole concentration is thus given by

$$p = \int_{-\infty}^{0} f_h(E) g_h(E)\, dE \tag{10}$$

when we substitute for $f_h(E)$ and $g_h(E)$ from the above equatio and carry out the integral as in the electron case, we obtain

$$p = 2\left(\frac{m_h k_B T}{2\pi h^2}\right)^{3/2} e^{-E_F/k_B T} \tag{11}$$

The electron and hole concentration have thus far bee treated as independent quantities. The two concentrations are in fact equal, because the electrons in the conduction band are due t excitations from the valence band across the energy gap, and for each electron thus excited a hole is created in the valence band. Therefore

$$n = p \tag{12}$$

If we substitute n and p from eqs. (6) and (11), respectively, into (12), we obtain an equation involving the only unknown E_F. The solution of this equation is

$$E_F = \frac{1}{2} E_g + \frac{3}{4} k_B T \log\left(\frac{m_h}{m_e}\right) \qquad (13)$$

Since $k_B T \langle\langle E_g$ under usual circumstances, the second term on the RHS of eq (13) is very small compared with the first, and the energy level is close to the middle of the energy gap. This is consistent with earlier assertions that both the bottom of conduction band and the top of valence band are far from the Fermi level.

The concentration of electrons may now be evaluated explicitly by using the above value of E_F. Substitution of eq (13) into eq (6) yields

$$n = 2\left(\frac{k_B T}{2\pi\hbar^2}\right)^{3/2} (m_e m_h)^{3/4} e^{-E_g / k_B T} \qquad (14)$$

The important feature of this expansion is that n increases very rapidly (exponentially) with temperature, particularly by virtue of the exponential factor. Thus as the temperature is raised, a vastly greater number of electrons is excited across the gap.

One can evaluate the numerical value of n by substituting values $E_g = 1eV$, $m_e = m_h = m_0$ and $T = 300\,K$. One finds $n \approx 10^{15}$ electrons/c typical value of carrier concentration in semiconductors.

Extrinsic semiconductors

The contribution of impurities, in fact, frequently exceeds thos carriers that are supplied by interband excitation. When this is so, th sample is in the extrinsic region.

Two different types of extrinsic regions may be distinguished. The first occurs when the donor concentration greatly exceeds the acceptor concentration, that is, when $N_d \gg N_a$. In this case, the concentration of electrons may be evaluated quite readily. Since the donor's ionization energy (the binding energy) is quite small, all the donors are essentiall ionized, their electrons going into the conduction band. Therefore to a good approximation

$$n = N_d \tag{15}$$

The hole concentration is small under this conditions. To calculate this concentration, we make the following useful observation. We note that eq (6) is still valid even in the case of a doped sample. Only when we use eq (12) to evaluate E_F was the discussion restricted to an intrinsic case. Similarly, eq (11) is also valid whether the sample is pure or doped. If we multiply these two equations, we find that

$$np = 4\left(\frac{k_B T}{2\pi\hbar^2}\right)^3 (m_e m_h)^{3/2} e^{-E_g/k_B T} \qquad (16)$$

Note that the product np is independent of E_F, and hence of the amount and type of doping; the product np depends only on temperature.

We know that the intrinsic concentration n_i may be defined as

$$n_i = n = p \qquad (17)$$

Hence from eqs (16) and (17) we have

$$np = n_i^2 \qquad (18)$$

This equation means that, if there is no change in temperature, the product np is a constant, independent of the doping. If the electron concentration is increased by varying the doping, the hole concentration decreases, and vice versa.

When the doping is primarily of the donar type $n \approx N_d$ as shown by eq (15), according to eq (18), the concentration of holes is

$$p = \frac{n_i^2}{N_d} \qquad (19)$$

Since we are in the extrinsic region, $n_i \langle\langle N_d$ and hence $p \langle\langle N_d = n$. Thus the concentration of electrons is much larger than that of holes.

For a strongly n-type sample $n \rangle\rangle p$, while for a weakly n-type sample, $n \geq p$.

The other type of extrinsic region occurs where $N_a \rangle\rangle N_d$, that is, the doping is primarily by acceptors. Using an argument similar to above, one then has

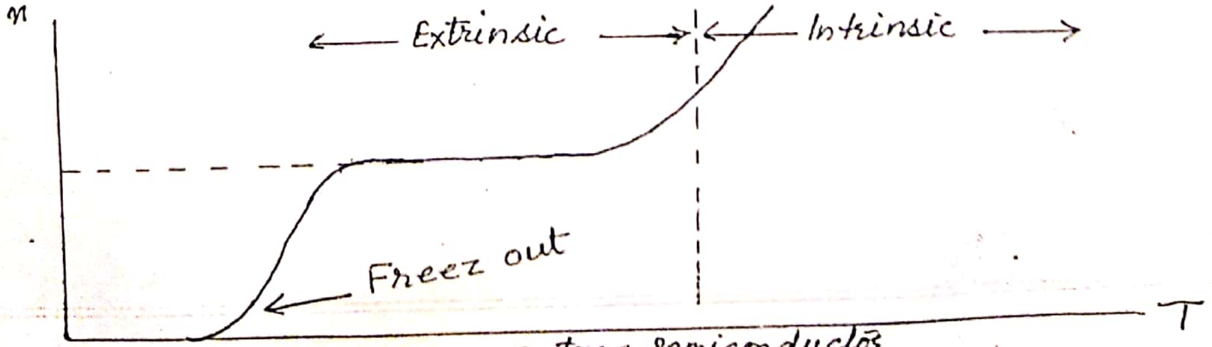
$$p \approx N_a \qquad (20)$$

i.e. all the acceptors are ionized. The electron concentration, which is small, is given by

$$n = \frac{n_i^{2}}{N_a} \tag{21}$$

Such a material is called a p-type semiconductor. It is characterized by a preponderance of holes (acceptors).

In discussing ionization of donors/acceptors, we assume that the temperature is sufficiently high so that all of these are ionized. This is certainly true at room temperature. But if the temperature is progressively lowered, a point is reached at which the thermal energy becomes too small to cause electron excitation. In that case, the electrons falls from the conduction band into the donor level, and the conductivity of the sample diminishes dramatically. This is referred to as freez out, in that the electrons are now "frozen" at their impurity sites. We can estimate the temperature at which freez out takes place from the equation $E_d \approx k_B T$ which gives a temperature of about $100^\circ K$.



n-type semiconductor

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