

The average drift velocity of an electron is also proportional to the electric field for small fields. However, since the electron is negatively charged, the net motion of the electron is opposite to the electric field direction. We can then write

$$v_{dr} = \mu_n E \quad (4.7)$$

where μ_n is the *electron mobility* and is a positive quantity. Equation (4.6) may now be written as

$$J_{ndrf} = (-en)(-\mu_n E) = e\mu_n n E \quad (4.8)$$

The conventional drift current due to electrons is also in the same direction as the applied electric field even though the electron movement is in the opposite direction.

Electron and hole mobilities are functions of temperature and doping concentrations, as we will see in the next section.

Since both electrons and holes contribute to the drift current, the total *drift current density* is the sum of the individual electron and hole drift current densities, so we may write

$$J_{drf} = e(\mu_n n + \mu_p p)E \quad (4.9)$$

Example 4.1

Objective To calculate the drift current density in a semiconductor for a given electric field.

Consider a gallium arsenide sample at $T = 300$ K with doping concentrations of $N_a = 0$ and $N_d = 10^{16}$ cm $^{-3}$. Assume complete ionization and assume electron and hole mobilities given in Table 4.1. Calculate the drift current density if the applied electric field is $E = 10$ V/cm.

Since $N_d > N_a$, the semiconductor is *n* type and the majority carrier electron concentration, from Chapter 4 is given by

$$n = \frac{N_d - N_a}{2} + \sqrt{\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2} \approx 10^{16} \text{ cm}^{-3}$$

The minority carrier hole concentration is

$$p = \frac{n_i^2}{n} = \frac{(1.8 \times 10^6)^2}{10^{16}} = 3.24 \times 10^{-4} \text{ cm}^{-3}$$

For this extrinsic *n*-type semiconductor, the drift current density is

$$J_{drf} = e(\mu_n n + \mu_p p)E \approx e\mu_n N_d E$$

Then

$$J_{drf} = (1.6 \times 10^{-19})(8500)(10^{16})(10) = 136 \text{ A/cm}^2$$

Comment Significant drift current densities can be obtained in a semiconductor applying relatively small electric fields. We may note from this example that the drift current will usually be due primarily to the majority carrier in an extrinsic semiconductor.

4.1.2 Mobility Effects

In the last section, we defined mobility, which relates the average drift velocity of a carrier to the electric field. Electron and hole mobilities are important semiconductor parameters in the characterization of carrier drift, as shown in Eq. (4.9).

Figure 4.1(a) shows a schematic model of the random thermal velocity and motion of a hole in a semiconductor with zero electric field. There is a mean time between collisions which may be denoted by τ_{cp} . If a small electric field (E -field) is applied as indicated in Fig. 4.1(b), there will be a net drift of the hole in the direction of the E -field, and the net drift velocity will be a small perturbation on the random thermal velocity, so the time between collisions will not be altered appreciably.

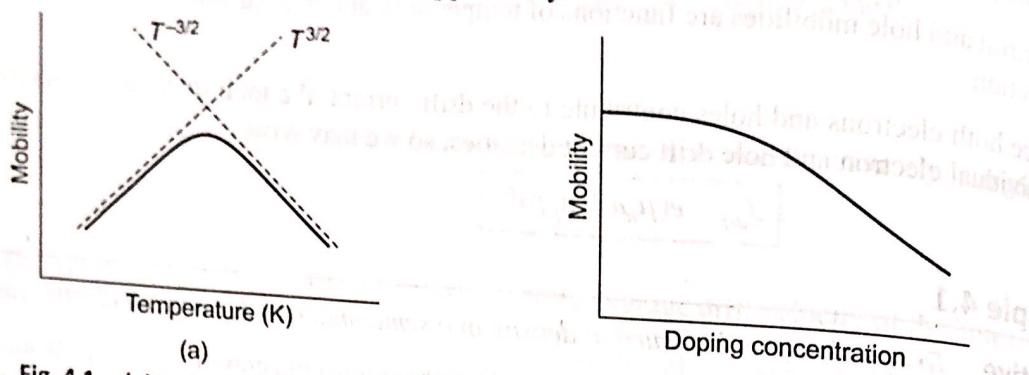


Fig. 4.1 (a) Variation of mobility with temperature, showing both types of scattering
 (b) Variation of mobility with doping concentration

Hole mobility is given as

$$\mu_p = \frac{v_{dp}}{E} = \frac{e\tau_{cp}}{m_p^*} \quad (4.1)$$

where, m_p^* is the conduction effective mass of holes.

Similarly, electron mobility is given by

$$\mu_n = \frac{e\tau_{cn}}{m_n^*} \quad (4.1)$$

where τ_{cn} is the mean time between collisions for an electron, m_n^* the conduction effective mass of electrons. As $m_n^* < m_p^*$, electron mobility is higher than hole mobility.

There are two types of collision or scattering mechanisms that dominate in a semiconductor and affect carrier mobility: phonon or lattice scattering, and ionized impurity scattering.

Phonon Scattering

The atoms in a semiconductor crystal have a certain amount of thermal energy at temperatures above absolute zero that causes the atoms to randomly vibrate about their lattice position within the crystal. The lattice vibrations cause a disruption in the perfect periodic potential function. A perfect periodic potential in a solid allows electrons to move unimpeded, or with no scattering, through the crystal. But the thermal vibrations cause a disruption of the potential function, resulting in an interaction between the electrons or holes and the vibrating lattice atoms. This *lattice scattering* is also referred to as *phonon scattering*.

Since lattice scattering is related to the thermal motion of atoms, the rate at which the scattering occurs is a function of temperature. If we denote μ_L as the mobility that would be observed if only lattice scattering existed, then the scattering theory states that to first order

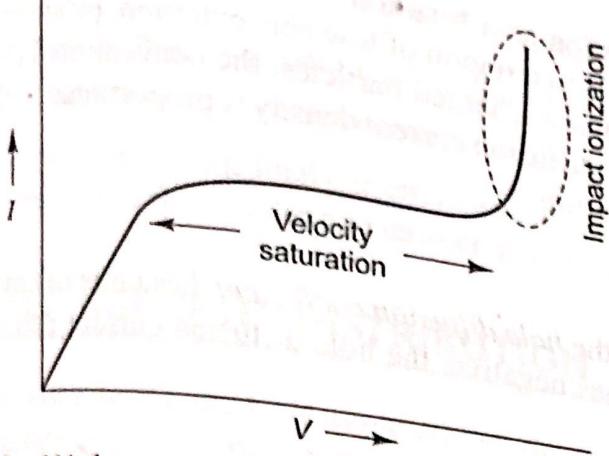


Fig. 4.9 V-I characteristics or intrinsic semiconductor. From, Eq. (4.5), $J = 2e n_r v_d$ for an intrinsic semiconductor
Then drift current will be much more as compared to the intrinsic one.

For an *n*-type semiconductor with $N_D \approx 10^{15} / \text{cm}^3$, the current will be more than the *p*-type one for the same condition as $\mu_n > \mu_p$.

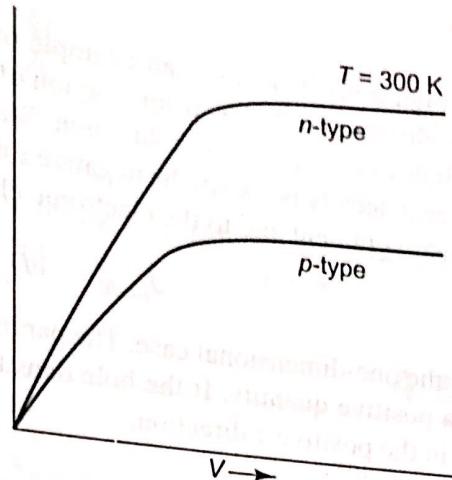


Fig. 4.10 V-I characteristics of a *p* and *n*-type Si bar having same physical size

CARRIER DIFFUSION

4.2

There is a second mechanism, in addition to drift, that can induce a current in a semiconductor. We may consider a classic physics example in which a container, as shown in Fig. 4.11, is divided into two parts by a membrane. The left side contains gas molecules at a particular temperature and the right side is initially empty. The gas molecules are in continual random thermal motion so that, when the membrane is broken, the gas molecules flow into the right side of the container. *Diffusion* is the process whereby particles flow from a region of high concentration toward a region of low concentration. If the gas molecules were electrically charged, the net flow of charge would result in a *diffusion current*.

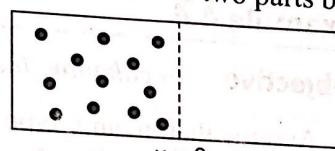


Fig. 4.11 Container divided by a membrane with gas molecules on one side

4.2.1 Diffusion Current Density

Figure 4.13(a) shows the variation of electron concentration with distance. Due to this concentration gradient diffusion current flows.

Electron diffusion current density \propto charge gradient,

$$J_{n/diff} \propto e \cdot \frac{dn}{dx}$$

$$J_{n/diff} = eD_n \frac{dn}{dx} \quad (4.21)$$

where D_n is called the *electron diffusion coefficient*, has units of cm^2/s , and is a positive quantity. If the electron density gradient becomes negative, the electron diffusion current density will be in the negative x direction.

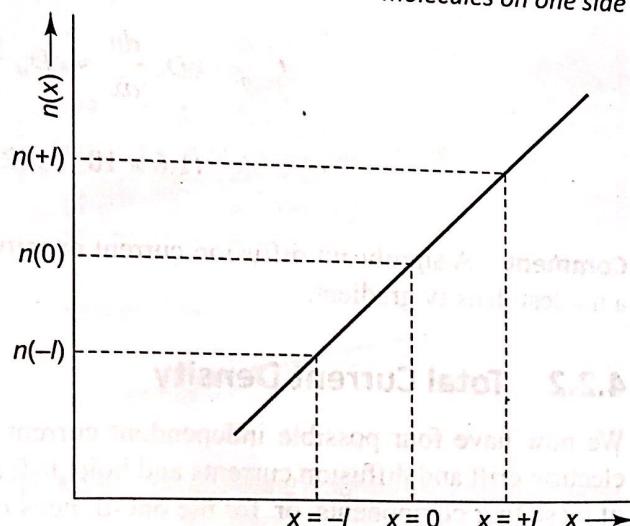


Fig. 4.12 Electron concentration versus distance

Figure 4.13(b) shows an example of a hole concentration as a function of distance in a semiconductor. The diffusion of holes, from a region of high concentration to a region of low concentration, produces a current density in the negative x direction. Since holes are positively charged particles, the conventional diffusion current density is also in the negative x direction. The hole diffusion current density is proportional to the density gradient and to the electronic charge, so we may write

$$J_{p\text{dif}} = -eD_p \frac{dp}{dx} \quad (4)$$

for the one-dimensional case. The parameter D_p is called the *hole diffusion coefficient*, has units of cm^2/s , is a positive quantity. If the hole density gradient becomes negative, the hole diffusion current density will be in the positive x direction.

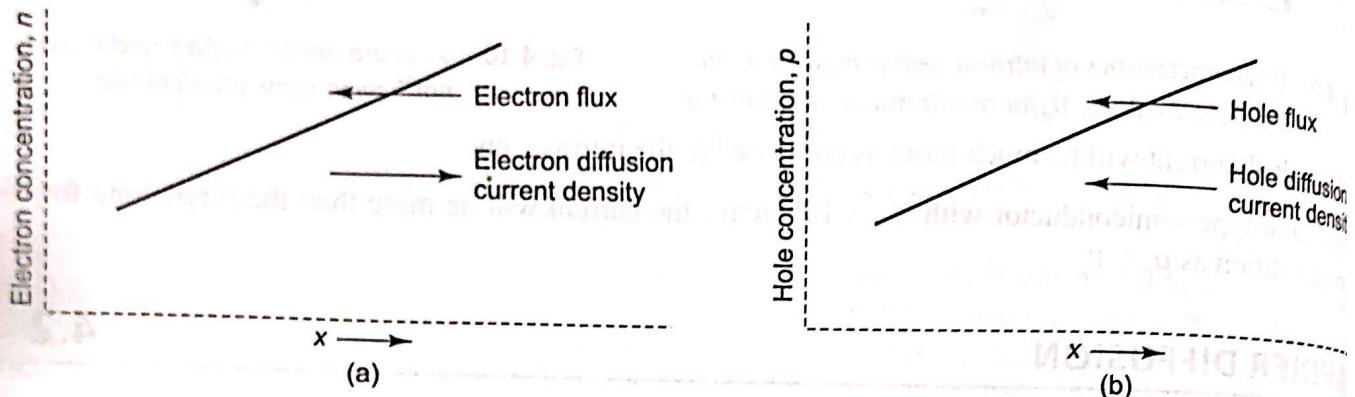


Fig. 4.13 (a) Diffusion of electrons due to a density gradient (b) Diffusion of holes due to a density gradient

Example 4.4

Objective To calculate the diffusion current density given a density gradient.

Assume that, in an n -type gallium arsenide semiconductor at $T = 300$ K, the electron concentration varies linearly from 1×10^{18} to $7 \times 10^{17} \text{ cm}^{-3}$ over a distance of 0.10 cm. Calculate the diffusion current density if the electron diffusion coefficient is $D_n = 225 \text{ cm}^2/\text{s}$.

The diffusion current density is given by

$$\begin{aligned} J_{n\text{dif}} &= eD_n \frac{dn}{dx} \approx eD_n \frac{\Delta n}{\Delta x} \\ &= (1.6 \times 10^{-19}) (225) \left(\frac{1 \times 10^{18} - 7 \times 10^{17}}{0.10} \right) = 108 \text{ A/cm}^2 \end{aligned}$$

Comment A significant diffusion current density can be generated in a semiconductor material with a modest density gradient.

4.2.2 Total Current Density

We now have four possible independent current mechanisms in a semiconductor. These components are electron drift and diffusion currents and hole drift and diffusion currents. The total current density is the sum of these four components, or, for the one-dimensional case,

Total current density = Electron drift current + hole drift current + electron diffusion current + hole diffusion current.

$$J = en\mu_n E_x + ep\mu_p E_x + eD_n \frac{dn}{dx} - eD_p \frac{dp}{dx} \quad (4.23)$$

This equation may be generalized to three dimensions as

$$J = en\mu_n E + ep\mu_p E + eD_n \nabla n - eD_p \nabla p \quad (4.24)$$

The expression for the total current in a semiconductor contains four terms. Fortunately in most situations, we will only need to consider one term at any one time at a particular point in a semiconductor.

GRADED IMPURITY DISTRIBUTION

4.3

In most cases so far, we have assumed that the semiconductor is uniformly doped. In many semiconductor devices, however, there may be regions that are nonuniformly doped. We will investigate how a nonuniformly doped semiconductor reaches thermal equilibrium and, from this analysis, we will derive the Einstein relation, which relates mobility and the diffusion coefficient.

4.3.1 Induced Electric Field

Consider a semiconductor that is nonuniformly doped with donor impurity atoms. If the semiconductor is in thermal equilibrium, the Fermi energy level is constant through the crystal so the energy-band diagram may qualitatively look like that shown in Fig. 4.14. The doping concentration decreases as x increases in this case. There will be a diffusion of majority carrier electrons from the region of high concentration to the region of low concentration, which is in the $+x$ direction. The flow of negative electrons leaves behind positively charged donor ions. The separation of positive and negative charge induces an electric field that is in a direction to oppose the diffusion process. When equilibrium is reached, the mobile carrier concentration is not exactly equal to the fixed impurity concentration and the induced electric field prevents any further separation of charge. In most cases of interest, the space charge induced by this diffusion process is a small fraction of the impurity concentration, thus the mobile carrier concentration is not too different from the impurity dopant density.

The electric potential ϕ is related to electron potential energy by the charge ($-e$), so we can write

$$\phi = +\frac{1}{e}(E_F - E_{Fi}) \quad (4.25)$$

The electric field for the one-dimensional situation is defined as

$$E_x = -\frac{d\phi}{dx} = \frac{1}{e} \frac{dE_{Fi}}{dx} \quad (4.26)$$

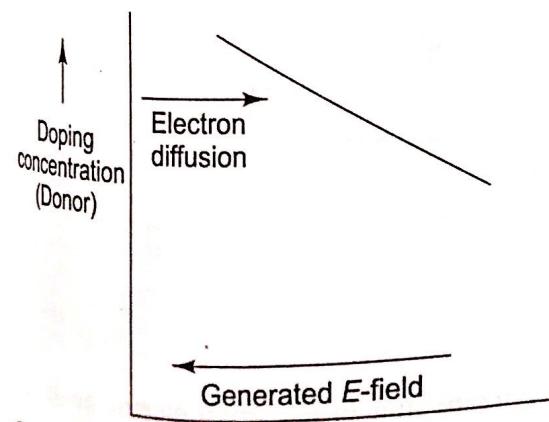


Fig. 4.14a

Variation of doping concentration with distance

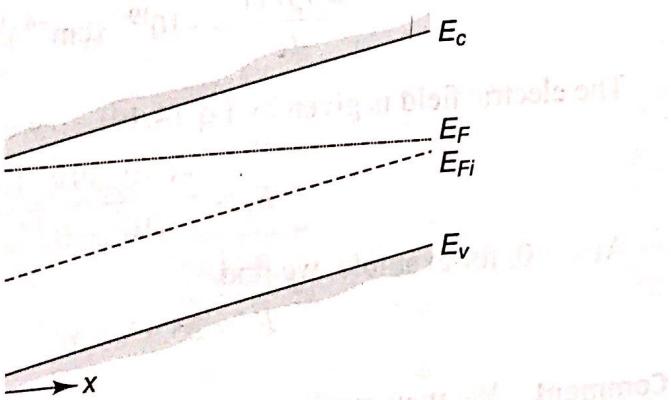


Fig. 4.14b Energy-band diagram for a semiconductor in thermal equilibrium with a nonuniform donor impurity concentration