The Currents in Semiconductors

1- Drift Current and Conductivity

For semiconductors, both electrons and holes contribute to electric current. The **current density**, J_p, is the charge per second crossing a unit area plane normal to the direction of current flow. As shown in Figure 18, the current density of holes is given by:

$$J_{p,\text{drift}} = p_o\, q\, v_{dp} \;\ldots\ldots\ldots (1)$$

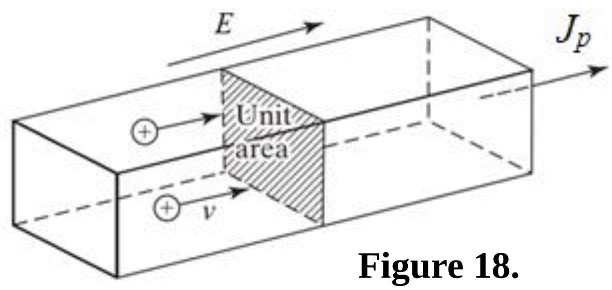

Figure 18.

The current density of electrons is given by:

$$J_{n,\text{drift}} = -n_o\, q\, v_{dn} \;\ldots\ldots\ldots (2)$$

where n_o is the concentration of electrons, p_o is the concentration of holes and q is the electron charge. <u>The unit of current density is (A/cm^2)</u>.

In term of mobility, equations (1) and (2) become:

$$J_{p,\text{drift}} = p_o\, q\, \mu_p E \;\ldots\ldots\ldots (3)$$

$$J_{n,\text{drift}} = n_o\, q\, \mu_n E \;\ldots\ldots\ldots (4)$$

The total drift current density is the sum of the electron and the hole components:

$$J = J_{n,\text{drift}} + J_{p,\text{drift}} = q\,(n_o\, \mu_n + p_o\, \mu_p)\, E \;\ldots\ldots.. (5)$$

The relation between the conductivity, σ, and the drift current density, J, is given by

$$J = \sigma\, E \;\ldots\ldots. (6)$$

From equations (5) and (6), the conductivity is,

$$\sigma = \sigma_n + \sigma_p = q\,(n_o\, \mu_n + p_o\, \mu_p) \;\ldots\ldots.. (7)$$

The reciprocal of conductivity is resistivity, which is denoted by ρ. We can write the formula for resistivity as

$$\rho = \frac{1}{\sigma} = \frac{1}{q\,(n_o\,\mu_n + p_o\,\mu_p)} \dots\dots\dots (8)$$

-- The standard units of σ is A/V·cm (or S/cm, S being siemens)

-- The standard units of ρ is **Ω**·cm

If we have a bar of semiconductor material with a volt applied that produces a current I, then we can write:

$$J = \frac{I}{A} = \sigma\,E \dots\dots (9)$$

where E is the electric field and is given by

$$E = \frac{V}{L}$$

Equation (9) can be written:

$$\frac{I}{A} = \sigma\,\frac{V}{L}$$

$$V = \left(\frac{L}{\sigma\,A}\right) I = \left(\frac{\rho\,L}{A}\right) I = RI$$

$$R = \rho\frac{L}{A} \dots\dots\dots.. (10)$$

where L is the length of the sample, A is the area of the sample.

Example: Mobilities of electrons and holes for intrinsic silicon are 0.64 m^2/V.s 0.36 m^2/V.s, respectively. If the electron and hole densities are equal to 1.6×10^{19} m^{-3}. What is the conductivity of silicon?

Solution: For intrinsic silicon, $n_o = p_o = 1.6\times10^{19}\ m^{-3}$

$$\sigma = q\,(n_o\,\mu_n + p_o\,\mu_p) = 1.6 \times 10^{-19} \times 1.6 \times 10^{19} \times (0.64 + 0.36) = 2.6\ \mathrm{S/m}$$

2- **Diffusion Current**

In addition to the drift current, there is a second component of current called the **diffusion current**. *Diffusion current is generally not an important consideration in metals because of their high conductivities. The low conductivity and the ease of creating nonuniform carrier densities make diffusion an important process in semiconductors.*

Diffusion is the result of particles undergoing thermal motion. It is the familiar process by which particles move from a point of higher particle density toward a point of lower density, as shown in Figure 19. *The aroma of a cup of coffee travels across a room by the diffusion of flavor molecules through the air.*

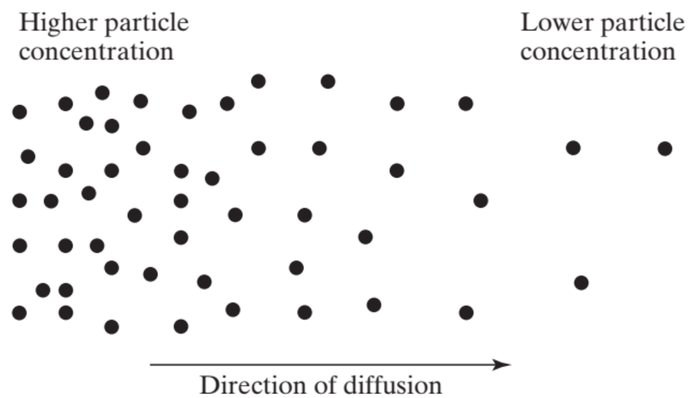

Figure 19.

It is known that the rate of particle movement by diffusion is proportional to the concentration gradient. If the electron concentration is not uniform, there will be an electron diffusion current, which is proportional to the gradient of the electron concentration.

$$J_{n,\text{diffusion}} \propto \frac{\mathrm{d}n}{\mathrm{d}x}$$

$$J_{n,\text{diffusion}} = q\, D_n \frac{\mathrm{d}n}{\mathrm{d}x} \dots\dots\dots\dots (11)$$

We have introduced the proportional constant qDn. q is the electron charge (1.6×10^{-19} C), and Dn is called the electron **diffusion constant**. The larger the Dn is, the faster the electrons diffuse.

For holes,

$$J_{p,\text{diffusion}} = -q\, D_p \frac{\mathrm{d}p}{\mathrm{d}x} \ldots \ldots \ldots \ldots (12)$$

Equation (12) has a negative sign, while Eq. (11) has a positive sign. Instead of memorizing the signs, memorize Figure 20. In Figure 20, (a) shows a positive $\mathrm{d}n/\mathrm{d}x$ (n increases as x increases) and (b) shows a positive $\mathrm{d}p/\mathrm{d}x$. In (a), electrons diffuse to the left (toward the lower concentration point). Because electrons carry negative charge, the diffusion current flows to the *right*. In (b), holes diffuse to the left, too. Because holes are positively charged, the hole current flows to the *left*, i.e., the current is negative.

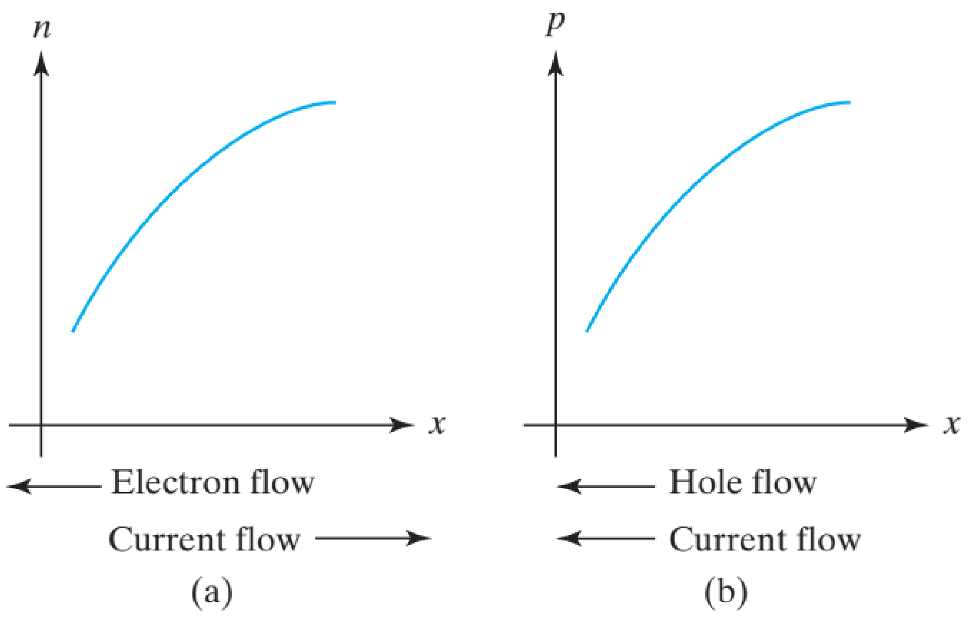

Figure 20.

In general, both drift and diffusion may contribute to the current. Therefore,

$$J_n = J_{n,\mathrm{drift}} + J_{n,\mathrm{diffusion}} = qn\mu_n E + q\, D_n \frac{\mathrm{d}n}{\mathrm{d}x} \dots\dots\dots (13)$$

$$J_p = J_{p,\mathrm{drift}} + J_{p,\mathrm{diffusion}} = qn\mu_p E - q\, D_p \frac{\mathrm{d}p}{\mathrm{d}x} \dots\dots\dots (14)$$

$$J = J_n + J_p \dots\dots\dots (15)$$

<u>Einstein Relationship Between D and μ</u>

Because the semiconductor is at equilibrium, there cannot be any J_n (or J_p). From Eq.(13),

$$J_n = 0 = qn\mu_n E + q\, D_n \frac{\mathrm{d}n}{\mathrm{d}x} \dots\dots\dots (16)$$

$$n = N_c . exp\left(\frac{-(E_c - E_F)}{kT}\right) \dots\dots (17)$$

$$\frac{\mathrm{d}n}{\mathrm{d}x} = \frac{-N_c}{kT} . exp\left(\frac{-(E_c - E_F)}{kT}\right) \frac{\mathrm{d}E_c}{\mathrm{d}x} \dots\dots (18)$$

From eq.(17), eq. (18) becomes

$$\frac{\mathrm{d}n}{\mathrm{d}x} = \frac{-n}{kT}\frac{\mathrm{d}E_c}{\mathrm{d}x} = \frac{-n}{kT} qE \dots\dots (19)$$

Substitute eq.(19) in eq.(16):

$$0 = qn\mu_n E - q\, D_n \frac{n}{kT} qE$$

$$\boxed{D_n = \frac{kT}{q}\mu_n} \dots\dots\dots (18)$$

For holes,

$$\boxed{D_p = \frac{kT}{q}\mu_p} \dots\dots\dots.(19)$$

are known as the **Einstein relationship**.

Example: Consider the hole mobility of Si is 410 $cm^2.V^{-1}.s^{-1}$. What is the hole diffusion constant in a piece of silicon at 300 K?

Solution:

$$D_p = \frac{kT}{q}\mu_p = 0.026 \times 410 = 11\ cm^2/s$$