SEMICONDUCTOR PHYSICS AND DEVICES

BASIC PRINCIPLES

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To my wife, Mimi,
for her patience, understanding,
and support during this project.

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relation between the mobility and diffusion coefficient, given by Equation (j-45), is known as the *Einstein relation.*

Example 5-6

Objective: To determine the diffusion coefficient given the carrier mobility.
Assume that the mobility of a particular carrier is 1000 $cm^2/V\text{-}sec$ at $T = 300°K$.

Solution: Using the Einstein relation, we have that

$$D = \left(\frac{kT}{e}\right)\mu = (0.0259)(1000) = 25.9 \text{ cm}^2/\text{sec}$$

Comment: Although this example is fairly simple and straightforward. it is important to keep in mind the relative order of magnitudes of the mobility and diffusion coefficient. The diffusion coefficient is approximately 40 times smaller than the mobility at room temperature.

Table 5-2 shows the diffusion coefficient values at $T = 300°K$ corresponding to the mobilities listed in Table 5-l for silicon. gallium arsenide, and germanium.

Table 5–2 Typical mobility and diffusion coefficient values at $T = 300°K$ ($\mu = cm^2/V\text{-}sec$ and $D = cm^2/sec$)

	μ_n	D_n	μ_p	D_p
Silicon	1350	35	480	12.4
Gallium arsenide	8500	220	400	10.4
Germanium	3900	101	1900	49.2

The relation between the mobility and diffusion coefficient given by Equation (5-45) contains temperature. It is important to keep in mind that the major temperature effects are a result of lattice scattering and ionized impurity scattering processes, as discussed in Section 5.1.2. As the mobilities are strong functions of temperature due to the scattering processes, the diffusion coefficients are also strong functions of temperature. The specific temperature dependence given in Equation (5-45) is a small fraction of the real temperature characteristic.

*5.4 THE HALL EFFECT

The Hall effect is a consequence of the forces that are exerted on moving charges by electric and magnetic fields. The Hall effect is used to distinguish whether a semiconductor is n-type or p-type[1] and is used to measure the

[1] We will assume an extrinsic semiconductor material in which the majority carrier concentration is much larger than the minority carrier concentration.

majority carrier concentration and majority carrier mobility. The Hall effect device, as discussed in this section, is used to experimentally measure semiconductor parameters. However, the Hall effect device is used extensively in engineering applications as a magnetic probe and in other circuit applications.

The force on a particle having a charge q and moving in a magnetic field is given by

$$F = qv \times B \tag{5-46}$$

where the cross product is taken between velocity and magnetic field so that the force vector is perpendicular to both the velocity and magnetic field.

Figure 5–13 illustrates the Hall effect. A semiconductor with a current I_x is placed in a magnetic field perpendicular to the current. In this case, the

Figure 5-13 Geometry for measuring the Hall effect

magnetic field is in the, z-direction. Electrons and holes flowing in the semiconductor will experience a force as indicated in the figure. The force on both electrons and holes is in the $(-y)$ direction. In a p-type semiconductor $(p_0 > n_0)$, there will be a buildup of positive charge on the $y = 0$ surface of the semiconductor and, in an n-type semiconductor $(n_0 > p_0)$, there will be a buildup of negative charge on the $y = 0$ surface. This net charge induces an electric field in the y-direction as shown in the figure. In steady state, the magnetic field force will be exactly balanced by the induced electric field

force. This balance may be written as

$$F = q[E + v \times B] = 0 \tag{5.47a}$$

which becomes

$$qE_y = qv_x B_z \tag{5.47b}$$

The induced electric field in the y-direction is called the Hall field. The Hall field produces a voltage across the semiconductor which is called the Hall voltage. We can write

$$V_H = +E_H W \tag{5-48}$$

where E_H is assumed positive in the $+y$ direction and V_H is positive with the polarity shown.

In a p-type semiconductor in which holes are the majority carrier. the Hall voltage will be positive as defined in Figure 5-13. In an n-type semiconductor in which electrons are the majority carrier, the Hall voltage will have the opposite polarity. The polarity of the Hall voltage is used to determine whether an extrinsic semiconductor is n-type or p-type.

Substituting Equation (5–48) into Equation (5-47). we have

$$V_H = v_x WB_z \tag{5-49}$$

For a p-type semiconductor, the drift velocity of holes can be written as

$$v_{dx} = \frac{J_x}{ep} = \frac{I_x}{(ep)(Wd)} \tag{5-50}$$

where e is the magnitude of the electronic charge. Combining Equations (5–50) and (5–49), we have

$$V_H = \frac{I_x B_z}{epd} \tag{5-51}$$

or, solving for the hole concentration, we obtain

$$p = \frac{I_x B_z}{edV_H} \tag{5-52}$$

The majority carrier hole concentration is determined from the current, magnetic field, and Hall voltage.

For an n-type semiconductor, the Hall voltage is given by

$$V_H = -\frac{I_x B_z}{ned} \tag{5-53}$$

so that the electron concentration is

$$n = -\frac{I_x B_z}{edV_H} \tag{5-54}$$

We may note that the Hall voltage is negative for the n-type semiconductor;

therefore, the electron concentration determined from Equation (5–54) is actually a positive quantity.

Once the majority carrier concentration has been determined. we can calculate the low-field majority carrier mobility. For a p-type semiconductor, we can write

$$J_x = ep\mu_p \mathrm{E}_x \tag{5-55}$$

The current density and electric field can be converted to current and voltage so that Equation (5–55) becomes

$$\frac{I_x}{Wd} = \frac{ep\mu_p V_x}{L} \tag{5-56}$$

The hole mobility is then given by

$$\mu_p = \frac{I_x L}{epV_x Wd} \tag{5-57}$$

Similarly for an n-type semiconductor, the low-field electron mobility is determined from

$$\mu_n = \frac{I_x L}{en\ V_x\ Wd} \tag{5-58}$$

Example 5-7

Objective: To determine the majority carrier concentration and mobility given Hall effect parameters.

Consider the geometry shown in Figure 5-13. Let $L = 10^{-1}$ cm, $W = 10^{-2}$ cm. and $d = 10^{-3}$ cm. Also assume that $I_x = 1.0$ mA, $V_x = 12.5$ volts, $B_z = 500$ gauss $= 5 \times 10^{-2}$ tesla, and $V_H = -6.25$ mV.

Solution: A negative Hall voltage for this geometry implies that we have an n-type semiconductor. Using Equation (5–54), we can calculate the electron concentration as

$$n = \frac{-(10^{-3})(5 \times 10^{-2})}{(1.6 \times 10^{-19})(10^{-5})(-6.25 \times 10^{-3})} = 5 \times 10^{21}\ \mathrm{m}^{-3} = 5 \times 10^{15}\ \mathrm{cm}^{-3}$$

The electron mobility is then determined from Equation (5-58) as

$$\mu_n = \frac{(10^{-3})(10^{-3})}{(1.6 \times 10^{-19})(5 \times 10^{21})(12.5)(10^{-4})(10^{-5})} = 0.10\ \mathrm{m}^2/\mathrm{V\text{-}sec}$$

or

$$\mu_n = 1000\ \mathrm{cm}^2/\mathrm{V\text{-}sec}$$

Comment: It is important to note that the MKS units must be used consistently in the Hall effect equations to yield correct results.

5.5 SUMMARY AND REVIEW

In this chapter we have considered carrier transport, the process by which charge moves in a semiconductor to produce current. We explored the theory of the two transport mechanisms, drift and diffusion.

We first considered drift. The motion or drift of electrons and holes due to electric fields leads to drift currents. The drift current density in a semiconductor is a function of the concentration of electrons and holes and is also a function of the average drift velocity of these charge carriers. The net flow of electrons and holes. due to an applied electric field. is in opposite directions because of the difference in charge, but the drift currents generated by the electrons and holes are in the same direction as the electric field.

The average drift velocity of a carrier is a function of the electric field and carrier mobility. Carrier mobility is an indicator of how well an electron or hole will drift through the semiconductor. and a function of the scattering or collision processes within the semiconductor. Two scattering mechanisms are lattice scattering and impurity scattering. Lattice scattering occurs because atoms in a semiconductor contain a certain amount of thermal energy in the form of atomic vibrations. The interatomic distance between atoms is then fluctuating. the perfect periodic potential function is altered, and the motion of the carrier through the semiconductor is disrupted. Since this scattering mechanism is a function of the thermal motion of atoms, the associated component of mobility is a strong function of temperature. Mobility decreases as temperature increases. Impurity scattering occurs because donor and acceptor impurities are ionized: a coulomb interaction occurs between the charged impurities and electrons and holes. When carriers drift into the vicinity of a charged impurity atom they will be deflected or scattered. Mobility decreases as the impurity concentration increases.

Conductivity and resistivity are parameters used extensively in semiconductor material specifications, resistivity being the reciprocal of conductivity. These parameters are functions of electron and hole concentrations and mobilities.

We then considered diffusion. Diffusion of electrons and holes in a semiconductor leads to diffusion currents proportional to the gradients in electron and hole concentrations. The constant of proportionality is the electron diffusion coefficient or hole diffusion coefficient. The diffusion coefficients indicate how well the charge carriers diffuse in a semiconductor. The carrier diffusion coefficient and mobility are not independent parameters, but are related by the Einstein relation.

The Hall effect is used to experimentally determine conductivity type, majority carrier concentration, and majority carrier mobility. A magnetic field is applied perpendicular to a current in the semiconductor. A moving charge particle in a magnetic field experiences a force perpendicular to both the magnetic field and direction of motion. An electric field, the Hall field, is induced in the semiconductor due to these forces. The induced field pro-