

2.7.5. The Hall Effect

The Hall effect describes the behavior of the free carriers in a semiconductor when applying an electric as well as a magnetic field. The experimental setup shown in Figure 2.7.7, depicts a semiconductor bar with a rectangular cross section and length L . A voltage V_x is applied between the two contacts, resulting in a field along the x -direction. The magnetic field is applied in the z -direction.

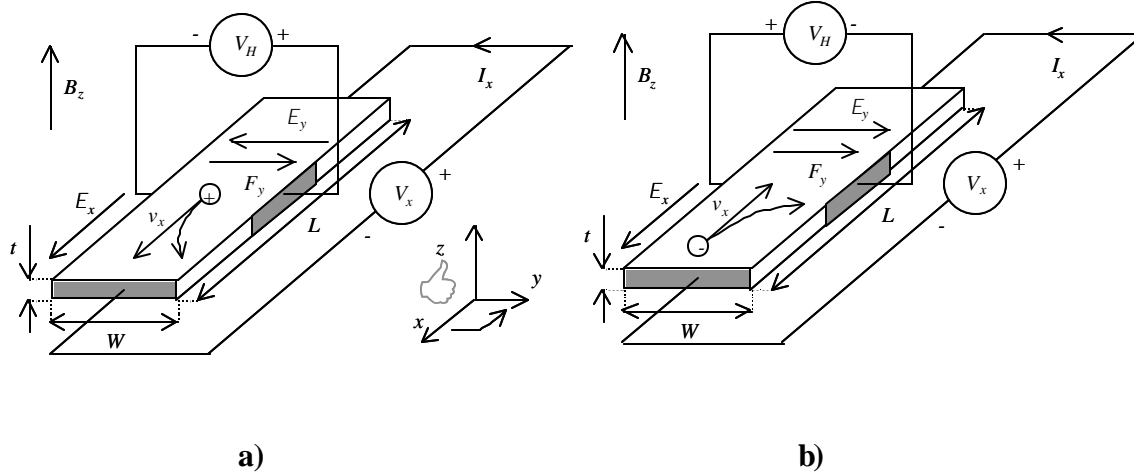


Figure 2.7.7 Hall setup and carrier motion for a) holes and b) electrons.

As shown in Figure 2.7.7 a), the holes move in the positive x -direction. The magnetic field causes a force to act on the mobile particles in a direction dictated by the right hand rule. As a result there is a force, F_y , along the positive y -direction, which moves the holes to the right. In steady state this force is balanced by an electric field, E_y , so that there is no net force on the holes. As a result there is a voltage across the sample, which can be measured with a high-impedance voltmeter. This voltage, V_H , is called the Hall voltage. Given the sign convention as shown in Figure 2.7.7, the hall voltage is positive for holes.

The behavior of electrons is shown in Figure 2.7.7 b). The electrons travel in the negative x -direction. Therefore the force, F_y , is in the positive y -direction due to the negative charge and the electrons move to the right, just like holes. The balancing electric field, E_y , now has the opposite sign, which results in a negative Hall voltage.

To calculate the Hall field, we first calculate the Lorentz force acting on the free carriers:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \quad (2.7.33)$$

We now assume that the carriers can only flow along the x -direction and label their velocity v_x . The Lorentz force then becomes:

$$\vec{F} = q\vec{E} + q \begin{vmatrix} \vec{e}_x & \vec{e}_y & \vec{e}_z \\ v_x & 0 & 0 \\ 0 & 0 & B_z \end{vmatrix} = qE_x \vec{e}_x + q(E_y - v_x B_z) \vec{e}_y + qE_z \vec{e}_z \quad (2.7.34)$$

Since the carriers only flow along the x -direction, the net force must be zero along the y and z direction. As a result, the electric field is zero along the z direction and:

$$F_y = q(E_y - v_x B_z) = 0 \quad (2.7.35)$$

which provides a relation between the electric field along the y -direction and the applied magnetic field, which can also be rewritten as a function of the current density, J_x , using (2.7.8):

$$E_y = v_x B_z = \frac{J_x}{qp_{p0}} B_z \quad (2.7.36)$$

This electric field is called the Hall field. The Hall coefficient, R_H , is defined as the Hall field divided by the applied current density and magnetic field:

$$R_H = \frac{E_y}{J_x B_z} = \frac{1}{qp_{p0}} \quad (2.7.37)$$

Once the Hall coefficient is obtained one easily finds the hole density:

$$p_{p0} = \frac{1}{qR_H} = \frac{J_x B_z}{qE_y} \quad (2.7.38)$$

The carrier mobility can also be extracted from the Hall coefficient:

$$\mathbf{m}_p = \frac{J_x}{qp_{p0} E_x} = \frac{R_H}{\mathbf{r}} \quad (2.7.39)$$

Where \mathbf{r} is the resistivity of the semiconductor.

The Hall coefficient can be calculated from the measured current, I_x , and measured voltage, V_H :

$$R_H = \frac{V_H}{I_x B_z} \frac{tL}{W} \quad (2.7.40)$$

A measurement of the Hall voltage is often used to determine the type of semiconductor (n -type or p -type) the free carrier density and the carrier mobility. Repeating the measurement at different temperatures allows one to measure the free carrier density as well as the mobility as a function of temperature. Since the measurement can be done on a small piece of uniformly doped material it is by far the easiest measurement to determine the carrier mobility. It should be noted that the scattering mechanisms in the presence of a magnetic field are different and that the measured Hall mobility can differ somewhat from the drift mobility. A measurement of the carrier density versus temperature provides information regarding the ionization energies of the donors and acceptor that are present in the semiconductor as described in section 2.6.4.4. While the interpretation of the Hall measurement is straightforward in the case of a single dopant, multiple types of impurities and the presence of electrons and holes can make the interpretation non-trivial.