and hence

\[ v = \mu E, \tag{2.14} \]

where \( \mu \) is called the “mobility” and usually expressed in \( \text{cm}^2/(\text{V} \cdot \text{s}) \). For example in silicon, the mobility of electrons, \( \mu_n = 1350 \text{ cm}^2/(\text{V} \cdot \text{s}) \), and that of holes, \( \mu_p = 480 \text{ cm}^2/(\text{V} \cdot \text{s}) \). Of course, since electrons move in a direction opposite to the electric field, we must express the velocity vector as

\[ \vec{v}_e = -\mu_n \vec{E}. \tag{2.15} \]

For holes, on the other hand,

\[ \vec{v}_h = \mu_p \vec{E}. \tag{2.16} \]

**Example 2.5**

A uniform n-type piece of silicon that is 1 \( \mu \text{m} \) long senses a voltage of 1 V. Determine the velocity of the electrons.

**Solution**

Since the material is uniform, we have \( E = V/L \), where \( L \) is the length. Thus, \( E = 1000 \text{ V/cm} \) and hence \( v = \mu_n E = 1.35 \times 10^6 \text{ cm/s} \). In other words, electrons take \( (1 \mu \text{m})/(1.35 \times 10^6 \text{ cm/s}) = 0.74 \text{ ns} \) to cross the 1-\( \mu \text{m} \) length.

With the velocity of carriers known, how is the current calculated? We first note that an electron carries a negative charge equal to \( q = 1.6 \times 10^{-19} \text{ C} \). Equivalently, a hole carries a positive charge of the same value. Now suppose a voltage \( V_1 \) is applied across a uniform semiconductor bar having a free electron density of \( n \) (Fig. 2.10). Considering a cross section of the bar at \( x = x_1 \) and taking two “snapshots” at \( t = t_1 \) and \( t = t_1 + 1 \text{ second} \), we note that the total charge in \( v \) meters passes the cross section in 1 second if the electrons move at a velocity of \( v \text{ m/s} \). In other words, the current is equal to the total charge enclosed in \( v \) meters of the bar’s length. Since the bar has a width of \( W \), we have:

\[ I = -v \cdot W \cdot h \cdot n \cdot q, \tag{2.17} \]