

# ECE 255

24 August 2017

When semiconductor materials are doped, they become extrinsic semiconductors displaying different properties. Due to the abundance presence of holes or electrons, they become much better conductors than intrinsic semiconductors. The holes and electrons are carriers of electricity when they move about. These carriers move around in a random walk fashion, colliding with the lattice or impurities in the material. On the average, random walk motion does not give rise to a net flow of current. Their motion is like the Brownian motion of molecules.

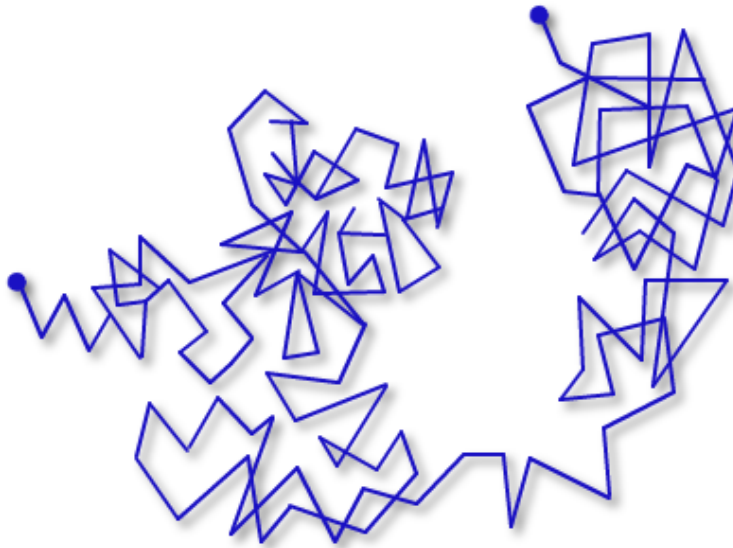


Figure 1: A random walk motion of a carrier particle.

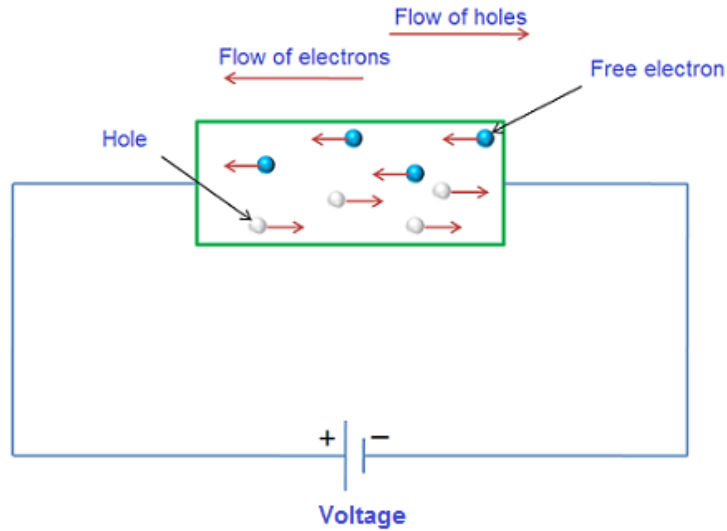
There are two ways to make these carriers move in a preferred direction on average: one by applying an electric field giving rise to drift current; and second, by causing the concentration of carriers to be non-uniform yielding diffusion current. These two kinds of current will be discussed next.

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# 1 Drift Current

An electric field applies a positive force on a positively charged particle. A hole effectively behaves like a positively charged particle, and will be pushed in the direction of the applied electric field. On the other hand, an electron will be driven in the opposite direction when an electric field is applied.



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Figure 2: The electrons and holes flow in opposite directions, on the average, in the presence of an electric field, or an applied potential difference.

Because of this, the holes and electrons will acquire an average drift velocity  $v_p$  and  $v_n$  proportional to the strength of the electric field  $E$ . In other words,

$$v_p = \mu_p E \quad (1.1)$$

$$v_n = -\mu_n E \quad (1.2)$$

where  $\mu_p$  and  $\mu_n$  are the mobilities of the holes and electrons respectively. They are indicators of how mobile the holes and electrons are. Typically, holes have mobility of  $\approx 480 \text{ cm}^2/\text{V}\cdot\text{s}$ , while electrons have mobility of  $\approx 1350 \text{ cm}^2/\text{V}\cdot\text{s}$ . Electrons are seen to be more mobile than holes, due to their lighter weight and no bond-breaking is associated with their movements.

The average current density is given by  $I/A$  in terms of amperes per unit area. If the average charge density  $Q$  is known, then the average current density due to the charge moving at velocity  $v$  is  $Qv$ . The drift current due to electrons

is then

$$\begin{aligned} J_n^{\text{drift}} &= Q_n v_n = (-qn)(-\mu_n E) \\ &= q\mu_n n E \quad \text{A/cm}^2 \end{aligned} \quad (1.3)$$

$$\begin{aligned} J_p^{\text{drift}} &= Q_p v_p = (+qp)(+\mu_p E) \\ &= q\mu_p p E \quad \text{A/cm}^2 \end{aligned} \quad (1.4)$$

where  $q$  is one electron charge which is  $1.6 \times 10^{-19}$  coulomb. The total current then is the sum of these two currents, namely,

$$J_{\text{total}}^{\text{drift}} = J_n^{\text{drift}} + J_p^{\text{drift}} = q(n\mu_n + p\mu_p)E \quad (1.5)$$

Consequently, one can define

$$J = \sigma E \quad (1.6)$$

where  $J$  is the total current driven by the electric field  $E$ , and  $\sigma$  is the effective conductivity of the medium. The conductivity is then

$$\sigma = q(n\mu_n + p\mu_p) \quad (\Omega \cdot \text{cm})^{-1} \quad (1.7)$$

Similarly, the resistivity is

$$\rho = \frac{1}{\sigma} = \frac{1}{q(n\mu_n + p\mu_p)} \quad (\Omega \cdot \text{cm}) \quad (1.8)$$

Note that both the electrons and holes contribute to the total current. Whichever is the dominant carrier of the current depends on the concentrations of the carriers  $n$  or  $p$ . For a  $p$ -doped material,  $p \gg n$ , and for an  $n$ -doped material,  $n \gg p$ .

For intrinsic, undoped silicon, Si,  $n = p = n_i = p_i \approx 10^{10}/\text{cm}^3$  at room temperature. Using the mobility that  $\mu_p = 480 \text{ cm}^2/(\text{V}\cdot\text{s})$ , and that  $\mu_n = 1350 \text{ cm}^2/(\text{V}\cdot\text{s})$ , one arrives at

$$\rho = \frac{1}{q(n\mu_n + p\mu_p)} \approx 2 \times 10^5 \quad \Omega \cdot \text{cm} \quad (1.9)$$

For extrinsic doped silicon, let  $N_A = 10^{16}/\text{cm}^3$ , and that  $N_D = 2 \times 10^{15}/\text{cm}^3$ , then

$$p \approx N_A \approx 10^{16}/\text{cm}^3, \quad n = \frac{n_i^2}{p} \approx 10^4/\text{cm}^3 \quad (1.10)$$

Consequently,

$$\rho = \frac{1}{q(n\mu_n + p\mu_p)} \approx 1.6 \quad \Omega \cdot \text{cm} \quad (1.11)$$

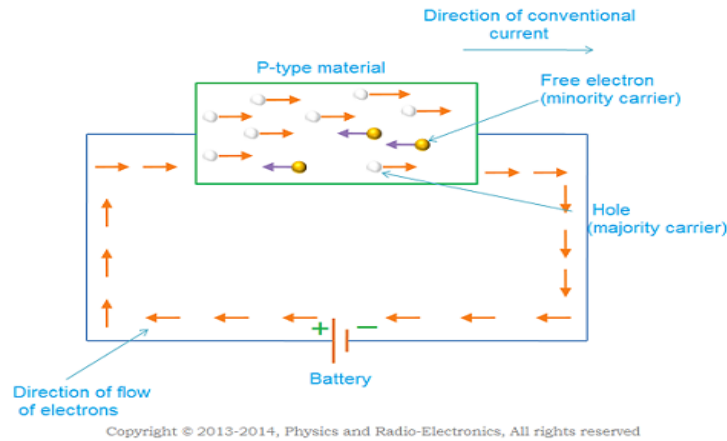


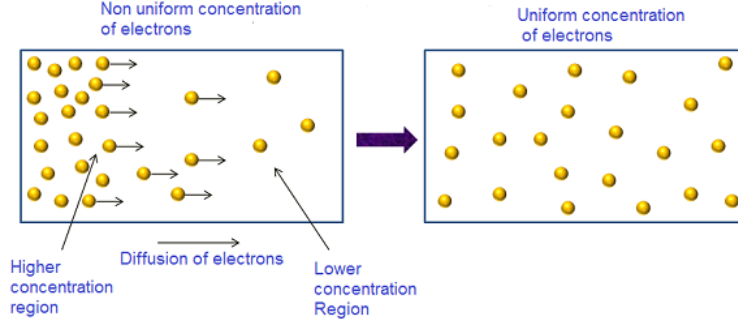
Figure 3: The pictorial representation of the total current in a doped  $p$ -type semiconductor. The majority carrier is hole here, even though both holes and electrons contribute to the total current.

## 2 Diffusion Current

Another way that the carriers can move about in a preferred direction is due to diffusion. Diffusion is a common phenomenon seen in gases. In gases, the kinetic theory of gas is used to explain this phenomenon. Gas molecules are constantly moving around and colliding with each other. In a region where the gas concentration is high, the rate at which gas molecules collide with each other is higher, and consequently, forces the gas molecules to move away from regions of high concentration to regions of low concentration.

However, the carriers in a semiconductor do not actually collide with each other as in gas molecules. To begin, one notes that a semiconductor material is actually charge neutral. But instead, in a semiconductor, each carrier particle, like a hole (electron) is either positively (negatively) charged. Therefore, they repel each other, and in regions of high concentration of carriers of the same kind, they tend to repel each other more than the region of low concentration. Consequently, at equilibrium, the carrier concentration will be evenly distributed. The uneven distribution of carrier concentration gives rise to the flow of these carriers is attributed to diffusion.

Hence, one can safely assume that the diffusion current is due to the uneven concentration of the carriers. In one dimension, if the electron carrier concentration is  $n(x)$ , then the diffusion current is proportional to  $\frac{dn}{dx}$  the gradient of



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Figure 4: The carriers flow from the region of high concentration to region of low concentration due to repulsion between the carriers.

the concentration. Therefore,

$$J_n^{\text{diff}} = (-q)D_n \left( -\frac{dn}{dx} \right) = +qD_n \frac{dn}{dx} \quad (2.1)$$

$$J_p^{\text{diff}} = (+q)D_p \left( -\frac{dp}{dx} \right) = -qD_p \frac{dp}{dx} \quad (2.2)$$

$$(2.3)$$

where  $D_n$  and  $D_p$  are diffusion coefficients for the electron and hole respectively. Diffusion coefficient has a unit of  $\text{cm}^2/\text{s}$ .

### Diffusion Current and Recombination Rate

A possible uneven concentration of hole is

$$p(x) = p_0 e^{-x/L_p} \quad (2.4)$$

$$\frac{dp}{dx} = -\frac{1}{L_p} p_0 e^{-x/L_p} \quad (2.5)$$

This implies that the diffusion current, hole concentration, and the gradient are proportional to each other, or that  $\frac{dp}{dx} \sim p(x) \sim J_p^{\text{diff}}$ . Recombination of electrons and holes can give rise to a gradient of the hole concentration. Such recombination rate is proportional to  $np$ . If  $n$  is the majority carrier, recombination affects its concentration very little, but if  $p$  is a minority carrier, it is much affected by recombination. A case where the diffusion current is proportional to the concentration will have an exponentially decaying solution.

In general, the total current is again the contribution from both types of carriers, namely,

$$J_{\text{total}}^{\text{diff}} = qD_n \frac{dn}{dx} - qD_p \frac{dp}{dx} \quad (2.6)$$

When drift and diffusion currents co-exist, the total current is then

$$J_n = J_n^{\text{drift}} + J_n^{\text{diff}} = q\mu_n nE + qD_n \frac{dn}{dx} \quad (2.7)$$

$$J_p = J_p^{\text{drift}} + J_p^{\text{diff}} = q\mu_p pE - qD_p \frac{dp}{dx} \quad (2.8)$$

The total current is the sum of these two currents, namely,  $J = J_n + J_p$ .