ECE 335: Electronic Engineering

Lecture 4:
Semiconductors - Carrier Transport
Carrier Transport

1. Carrier Drift
2. Carrier Diffusion
Carrier Drift

- The process in which charged particles move because of an electric field is called \textit{drift}.
- Charged particles within a semiconductor move with an average velocity proportional to the electric field.
  - The proportionality constant is the carrier \textit{mobility}.

\[ \vec{v}_h = \mu_p \vec{E} \]
\[ \vec{v}_e = -\mu_n \vec{E} \]

\textbf{Notation:}
\[ \mu_p \equiv \text{hole mobility (cm}^2\text{/V\cdot s)} \]
\[ \mu_n \equiv \text{electron mobility (cm}^2\text{/V\cdot s)} \]
Drift Current

- Drift current is proportional to the carrier velocity and carrier concentration:

$$v_h \, t \, A = \text{volume from which all holes cross plane in time } t$$

$$p \, v_h \, t \, A = \# \text{ of holes crossing plane in time } t$$

$$q \, p \, v_h \, t \, A = \text{charge crossing plane in time } t$$

$$q \, p \, v_h \, A = \text{charge crossing plane per unit time } = \text{hole current}$$

⇒ **Hole current per unit area (i.e. current density)** $J_{p,\text{drift}} = q \, p \, v_h$
Conductivity and Resistivity

• In a semiconductor, both electrons and holes conduct current:

\[ J_{p,\text{drift}} = q p \mu_p E \quad J_{n,\text{drift}} = -q n (-\mu_n E) \]

\[ J_{\text{tot,drift}} = J_{p,\text{drift}} + J_{n,\text{drift}} = q p \mu_p E + q n \mu_n E \]

\[ J_{\text{tot,drift}} = q (p \mu_p + n \mu_n) E \equiv \sigma E \]

• The \textit{conductivity} of a semiconductor is \[ \sigma \equiv q p \mu_p + q n \mu_n \]
  – Unit: mho/cm

• The \textit{resistivity} of a semiconductor is \[ \rho \equiv \frac{1}{\sigma} \]
  – Unit: ohm-cm
Resistivity Example

- Estimate the resistivity of a Si sample doped with phosphorus to a concentration of $10^{15} \text{ cm}^{-3}$ and boron to a concentration of $10^{17} \text{ cm}^{-3}$. The electron mobility and hole mobility are $700 \text{ cm}^2/\text{Vs}$ and $300 \text{ cm}^2/\text{Vs}$, respectively.
Electrical Resistance

\[ R \equiv \frac{V}{I} = \rho \frac{L}{Wt} \]  

(Unit: ohms)

where \( \rho \) is the resistivity
Carrier Diffusion

• Due to thermally induced random motion, mobile particles tend to move from a region of high concentration to a region of low concentration.
  – Analogy: ink droplet in water

• Current flow due to mobile charge diffusion is proportional to the carrier concentration gradient.
  – The proportionality constant is the diffusion constant.

\[ J_p = -qD_p \frac{dp}{dx} \]

**Notation:**
- \( D_p \equiv \) hole diffusion constant (cm\(^2\)/s)
- \( D_n \equiv \) electron diffusion constant (cm\(^2\)/s)
Diffusion Examples

- Linear concentration profile
  → constant diffusion current

\[ p = N \left( 1 - \frac{x}{L} \right) \]

\[ J_{p,\text{diff}} = -qD_p \frac{dp}{dx} = qD_p \frac{N}{L} \]

- Non-linear concentration profile
  → varying diffusion current

\[ p = N \exp\left(-\frac{x}{L_d}\right) \]

\[ J_{p,\text{diff}} = -qD_p \frac{dp}{dx} = \frac{qD_p N}{L_d} \exp\left(-\frac{x}{L_d}\right) \]
Diffusion Current

- Diffusion current within a semiconductor consists of hole and electron components:

\[
J_{p,\text{diff}} = -qD_p \frac{dp}{dx} \quad J_{n,\text{diff}} = qD_n \frac{dn}{dx}
\]

\[
J_{\text{tot, diff}} = q(D_n \frac{dn}{dx} - D_p \frac{dp}{dx})
\]

- The total current flowing in a semiconductor is the sum of drift current and diffusion current:

\[
J_{\text{tot}} = J_{p,\text{drift}} + J_{n,\text{drift}} + J_{p,\text{diff}} + J_{n,\text{diff}}
\]
The Einstein Relation

• The characteristic constants for drift and diffusion are related:

\[
\frac{D}{\mu} = \frac{kT}{q}
\]

• Note that \( \frac{kT}{q} \equiv 26\text{mV} \) at room temperature (300K)
  
  – This is often referred to as the “thermal voltage”.