Faculty of Engineering

ECE 335: Electronic Engineering

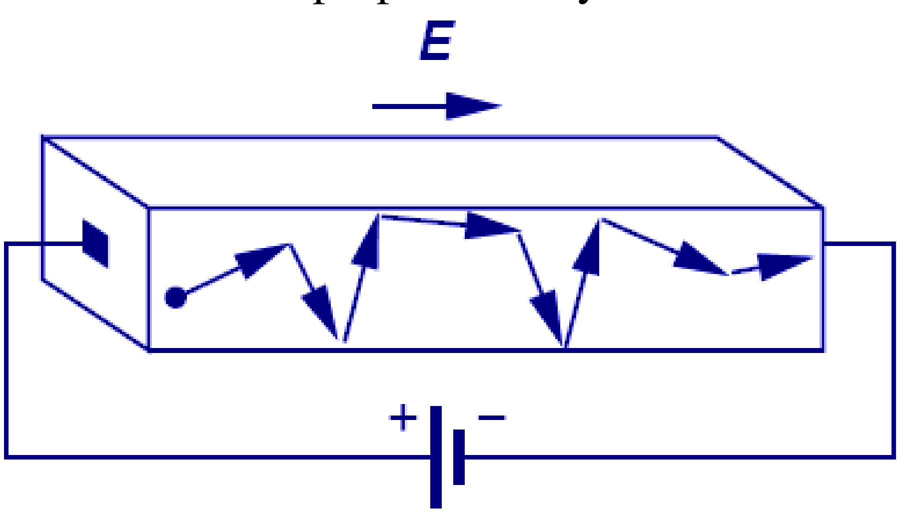
Lecture 4:
Semiconductors - Carrier Transport

Carrier Transport

1. Carrier Drift
2. Carrier Diffusion

Carrier Drift

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



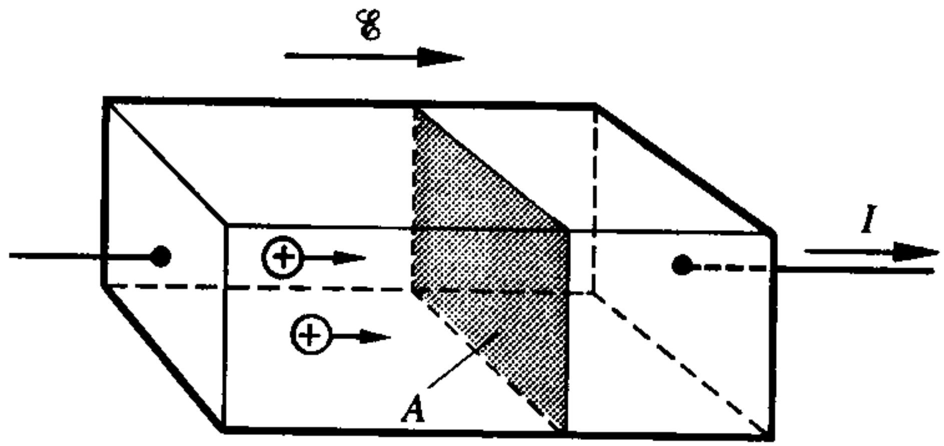
Hole velocity $\vec{v}_h = \mu_p \vec{E}$

$\vec{v}_e = -\mu_n \vec{E}$ Electron velocity

Notation:
$\mu_p \equiv$ hole mobility ($cm^2/V \cdot s$)
$\mu_n \equiv$ electron mobility ($cm^2/V \cdot s$)

Drift Current

- Drift current is proportional to the carrier velocity and carrier <u>concentration</u>:



$v_h\ t\ A$ = volume from which all holes cross plane in time t

$p\ v_h\ t$ A = # of holes crossing plane in time t

$q\ p\ v_h\ t$ A = charge crossing plane in time t

$q\ p\ v_h\ A$ = charge crossing plane per unit time = hole current

➔ **Hole current per unit area (*i.e.* current density) $J_{p,drift} = q\ p\ v_h$**

Conductivity and Resistivity

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

$$J_{p,drift} = qp\mu_p E \qquad J_{n,drift} = -qn(-\mu_n E)$$

$$J_{tot,drift} = J_{p,drift} + J_{n,drift} = qp\mu_p E + qn\mu_n E$$

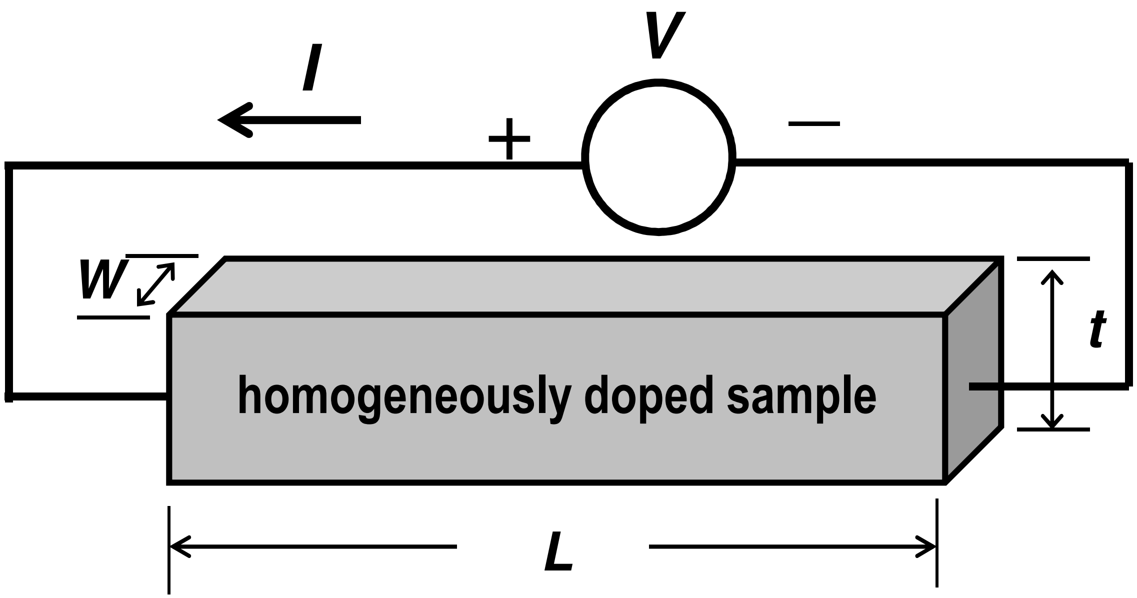
$$J_{tot,drift} = q(p\mu_p + n\mu_n)E \equiv \sigma E$$

- The ***conductivity*** of a semiconductor is $\boxed{\sigma \equiv qp\mu_p + qn\mu_n}$
  - Unit: mho/cm
- The ***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} cm^{-3} and boron to a concentration of 10^{17} cm^{-3}. The electron mobility and hole mobility are 700 cm^2/Vs and 300 cm^2/Vs, respectively.

Electrical Resistance

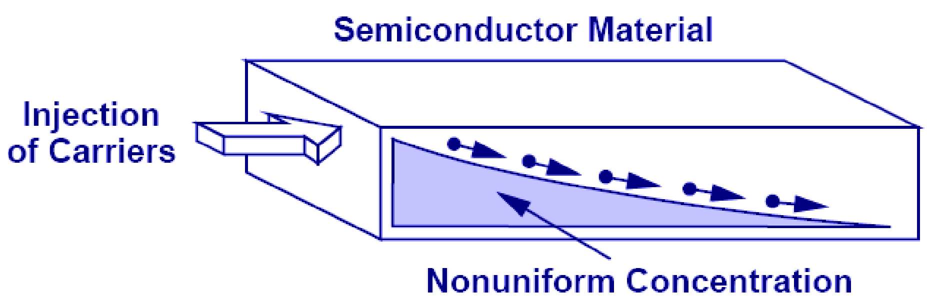


Resistance $$R \equiv \frac{V}{I} = \rho \frac{L}{Wt}$$ **(Unit: ohms)**

where ρ 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 <u>concentration gradient</u>.
  - The proportionality constant is the ***diffusion constant***.



$$J_p = -qD_p \frac{dp}{dx}$$

<u>Notation</u>:

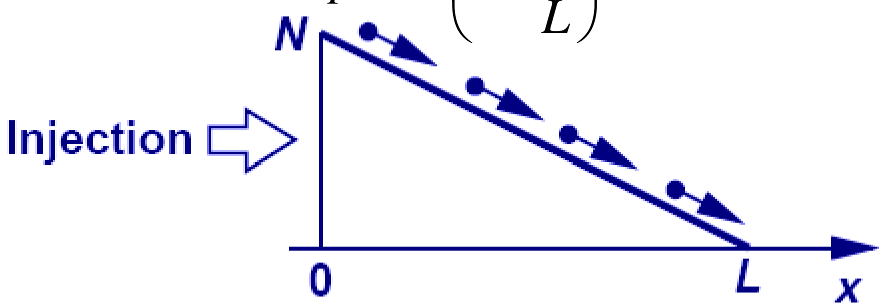
$D_p \equiv$ hole diffusion constant (cm^2/s)

$D_n \equiv$ electron diffusion constant (cm^2/s)

Diffusion Examples

- Linear concentration profile
  → constant diffusion current

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

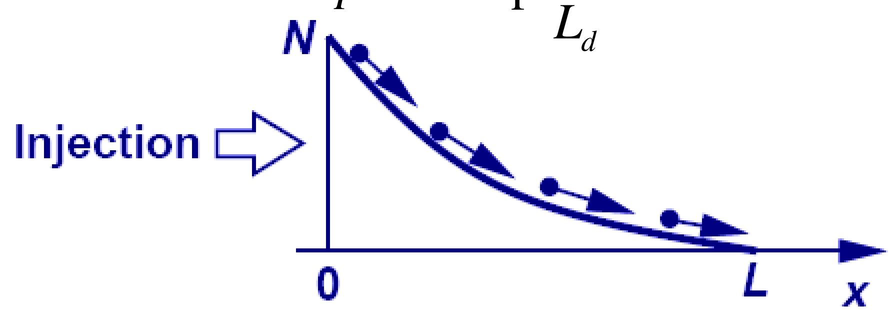


$$J_{p,diff} = -qD_p \frac{dp}{dx}$$

$$= qD_p \frac{N}{L}$$

- Non-linear concentration profile
  → varying diffusion current

$$p = N \exp \frac{-x}{L_d}$$



$$J_{p,diff} = -qD_p \frac{dp}{dx}$$

$$= \frac{qD_p N}{L_d} \exp \frac{-x}{L_d}$$

Diffusion Current

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

$$J_{p,diff} = -qD_p \frac{dp}{dx} \qquad J_{n,diff} = qD_n \frac{dn}{dx}$$

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

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

$$\boxed{J_{tot} = J_{p,drift} + J_{n,drift} + J_{p,diff} + J_{n,diff}}$$

The Einstein Relation

- The characteristic constants for drift and diffusion are related:

$$\frac{D}{\mu} = \frac{kT}{q}$$

- Note that $\frac{kT}{q} \cong 26\text{mV}$ at room temperature (300K)
  - This is often referred to as the **"thermal voltage"**.