

# Semiconductor Materials and Devices

## (반도체 재료 및 소자)

### Chapter 5. Carrier transport phenomena

**Young Min Song**

Assistant Professor

School of Electrical Engineering and Computer Science

Gwangju Institute of Science and Technology

<http://www.gist-foel.net>

[ymsong@gist.ac.kr](mailto:ymsong@gist.ac.kr), [ymsong81@gmail.com](mailto:ymsong81@gmail.com)

A207, ☎2655

## Drift Current Density

Drift current : the net drift of charges due to the electric field

For holes,

$$J_{p|drf} = (ep)v_{dp} \quad v_{dp} : \text{drift velocity of hole}$$

$$v_{dp} = \mu_p E \quad \mu_p : \text{hole mobility}$$

$$J_{drf} = \rho v_d$$

$\rho$  : charge density  
 $v_d$  : drift velocity

Mobility : determine how well the charged particle will move due to an electric field

$$F = m_p^* a = eE \quad \rightarrow \quad J_{p|drf} = (ep)v_{dp} = e\mu_p pE$$

Similarly, for electrons

$$v_{dn} = -\mu_n E \quad \rightarrow \quad J_{n|drf} = \rho v_{dn} = (-en)v_{dn}$$

$$\rightarrow J_{n|drf} = (-en)(-\mu_n E) = e\mu_n nE$$

Total drift current density:

$$J_{drf} = e(\mu_n n + \mu_p p)E$$

**Table 5.1** | Typical mobility values at  $T = 300$  K and low doping concentrations

	$\mu_n$ (cm <sup>2</sup> /V-s)	$\mu_p$ (cm <sup>2</sup> /V-s)
Silicon	1350	480
Gallium arsenide	8500	400
Germanium	3900	1900

## Mobility Effects

$$F = m_p^* \frac{dv}{dt} = eE \quad v = \frac{eEt}{m_p^*} \quad \tau_{cp}, \tau_{cn} : \text{mean time between collisions}$$

$$\Rightarrow \mu_p = \frac{v_{dp}}{E} = \frac{e\tau_{cp}}{m_p^*} \quad \mu_n = \frac{e\tau_{cn}}{m_n^*}$$

Lattice scattering(Phonon scattering) :

Lattice vibration → disruption in perfect periodic potential → interaction between electrons/holes and lattice atoms

$$\mu_L \propto T^{-3/2}$$

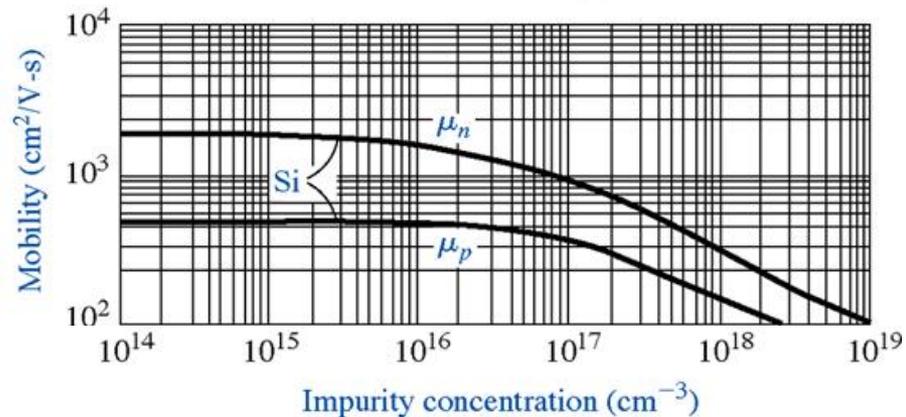
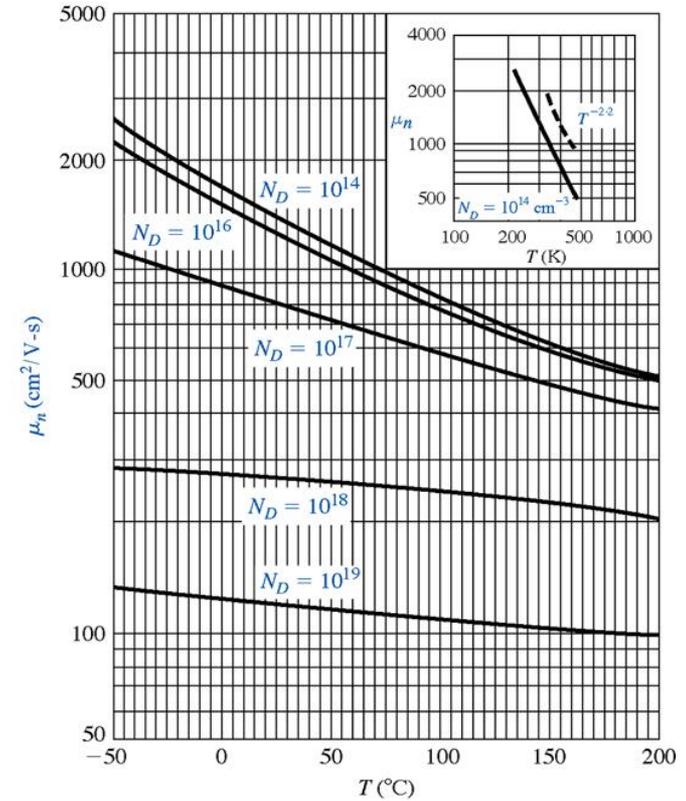
Impurity scattering :

Coulomb interaction between electrons/holes and ionized impurity atoms

$$\mu_I \propto \frac{T^{+3/2}}{N_I}$$

$dt/\tau$  : probability of scattering event during the differential time  $dt$

$$\frac{dt}{\tau} = \frac{dt}{\tau_I} + \frac{dt}{\tau_L} \Rightarrow \frac{1}{\mu} = \frac{1}{\mu_I} + \frac{1}{\mu_L}$$



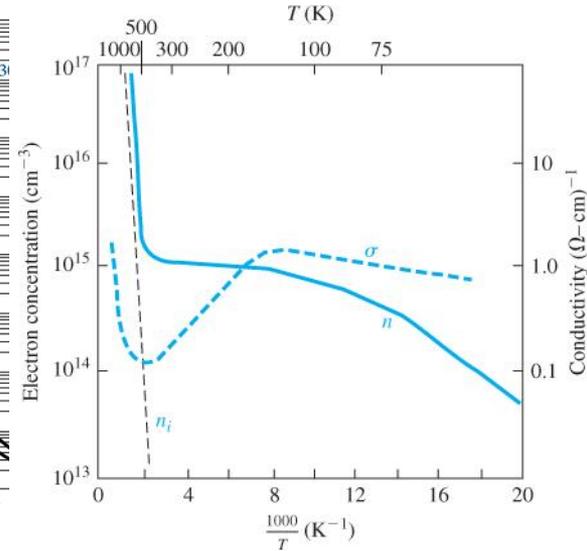
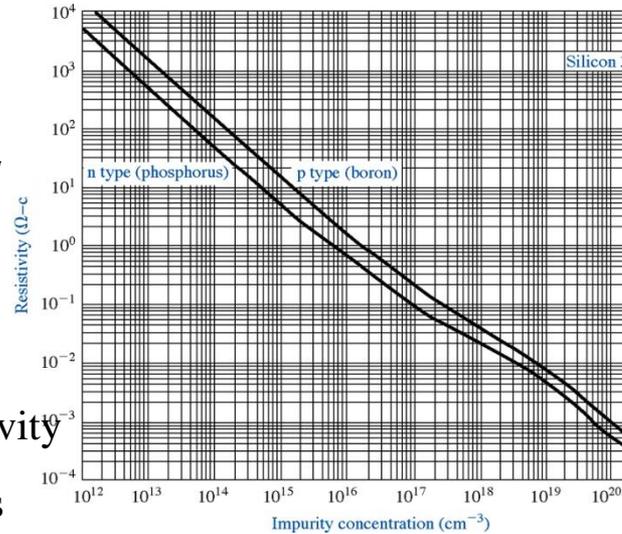
# Conductivity

$$J_{drf} = e(\mu_n n + \mu_p p)E = \sigma E$$

$$\rho = \frac{1}{\sigma} = \frac{1}{e(\mu_n n + \mu_p p)}$$

Resistivity : Reciprocal of conductivity

depends on the carrier concentrations and mobilities



$$J = \frac{I}{A} \quad E = \frac{V}{L} \quad \frac{I}{A} = \sigma \left( \frac{V}{L} \right)$$

$$\Rightarrow V = \left( \frac{L}{\sigma A} \right) I = \left( \frac{\rho L}{A} \right) I = IR$$

For p-type,  $\sigma = e(\mu_n n + \mu_p p) \approx e\mu_p p$

$$\Rightarrow \sigma \approx e\mu_p N_a \approx \frac{1}{\rho} \quad \text{: primarily depends on the majority carrier}$$

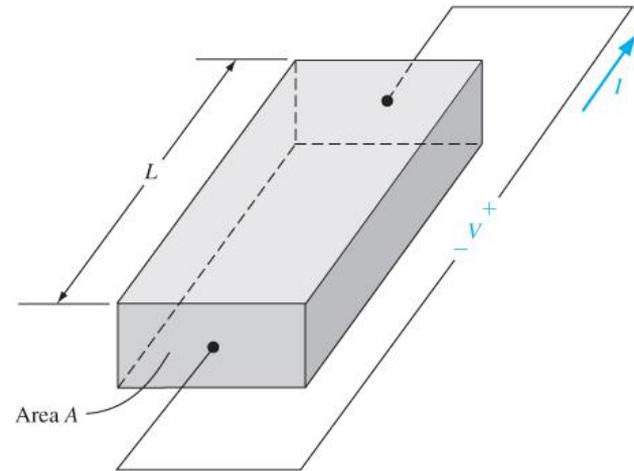


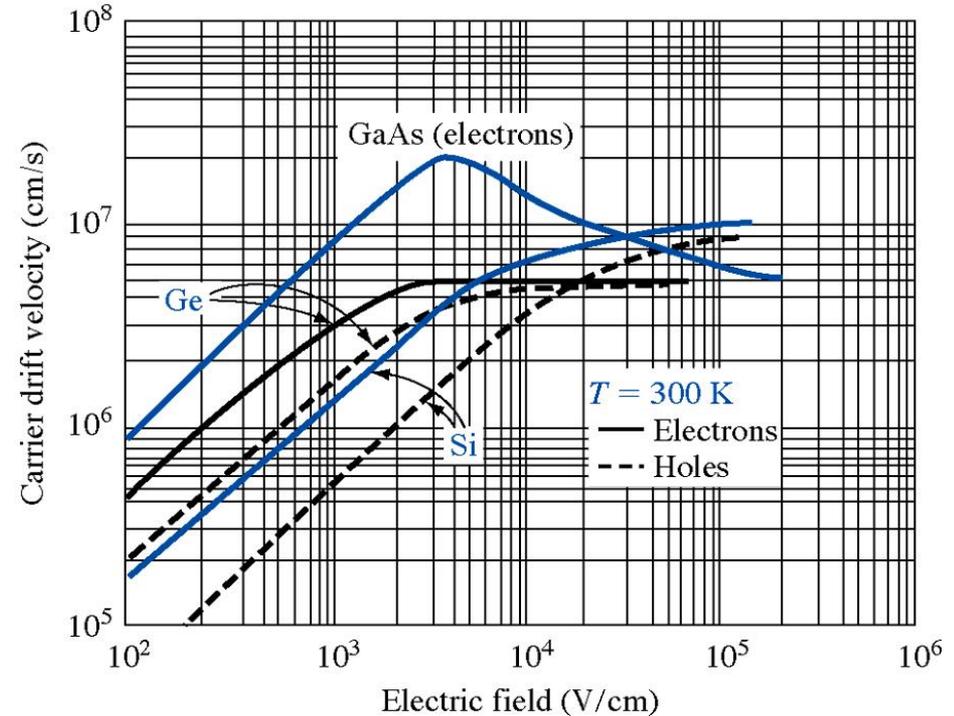
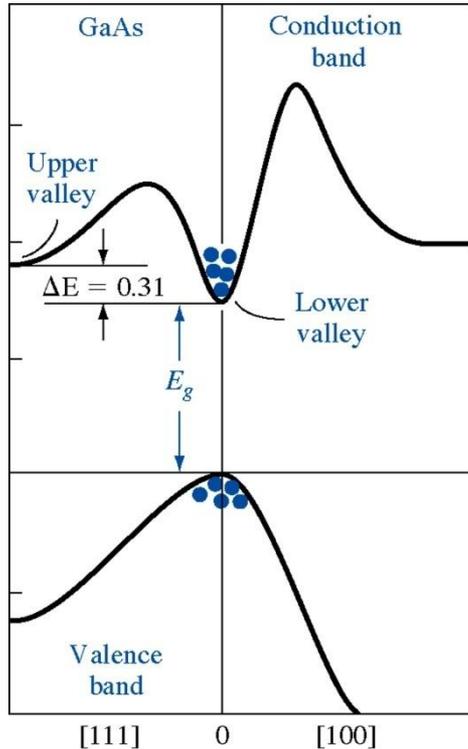
Figure 5.5 | Bar of semiconductor material as a resistor.

## Velocity saturation

At low field :

$$v_d = \mu \cdot E \quad \mu \text{ is constant}$$

At high field, velocity is saturated  $\rightarrow$  the current density is also saturated.



For GaAs, the mobility is higher than silicon.

At low field, the situation is same as the case of silicon.

As the field increases, the differential mobility is negative!!  $\rightarrow$  negative differential resistance..

At lower valley, the effective mass is  $0.067m_0$ , and the effective mass is  $0.55m_0$  at the upper valley. (Small effective mass leads to large mobility)

The intervalley transfer at high field, results in the decreasing average drift velocity of electron

## Diffusion Current Density

Diffusion : Flow of particles from a region of high concentration toward a region of low concentration.

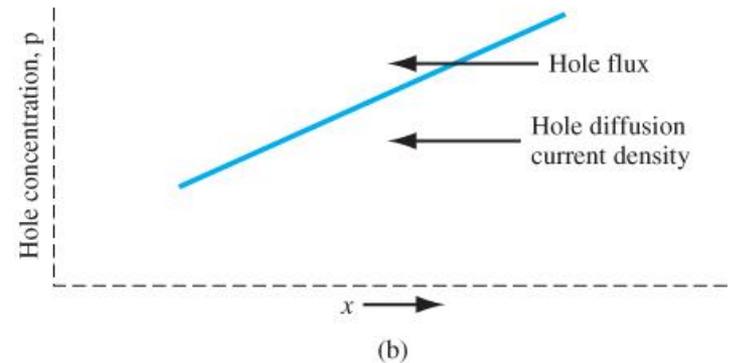
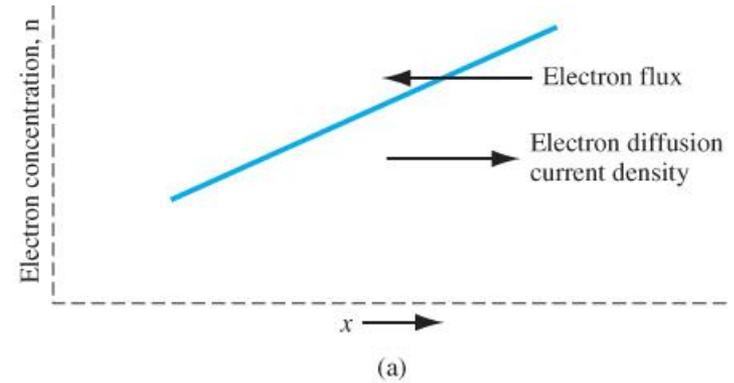
$$J_{nx|dif} = eD_n \frac{dn}{dx} \quad D_n : \text{electron diffusion coefficient}$$

$$J_{px|dif} = -eD_p \frac{dp}{dx} \quad D_p : \text{hole diffusion coefficient}$$

## Total Current Density

$$J = en\mu_n E_x + ep\mu_p E_x + eD_n \frac{dn}{dx} - eD_p \frac{dp}{dx}$$

$$J = en\mu_n E + ep\mu_p E + eD_n \nabla n - eD_p \nabla p$$

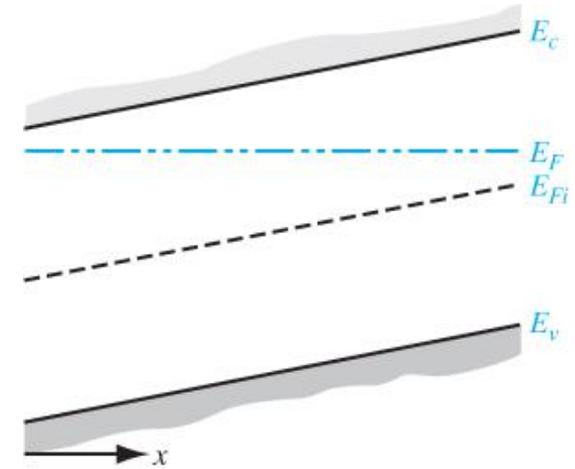


**Figure 5.11** | (a) Diffusion of electrons due to a density gradient. (b) Diffusion of holes due to a density gradient.

## Induced Electric Field

Nonuniformly doped n-type semiconductor in equilibrium

- Fermi energy level is constant
- Diffusion of majority carriers
- Separation of positive and negative charge induces an electric field in a direction to oppose the diffusion process
- The induced electric field prevents any further separation of charge (the mobile carrier concentration is not exactly equal to the fixed impurity concentration)



**Figure 5.12** | Energy-band diagram for a semiconductor in thermal equilibrium with a nonuniform donor impurity concentration.

$$\phi = +\frac{1}{e}(E_F - E_{Fi}) \quad E_x = -\frac{d\phi}{dx} = \frac{1}{e} \frac{dE_{Fi}}{dx}$$

$\phi$  : electric potential

$E_x$  : electric field in one dimension

$$n_0 = n_i \exp\left[\frac{E_F - E_{Fi}}{kT}\right] \approx N_d(x) \quad E_F - E_{Fi} = kT \ln\left(\frac{N_d(x)}{n_i}\right) \quad -\frac{dE_{Fi}}{dx} = \frac{kT}{N_d(x)} \frac{dN_d(x)}{dx}$$

$$\Rightarrow E_x = -\left(\frac{kT}{e}\right) \frac{1}{N_d(x)} \frac{dN_d(x)}{dx}$$

Induced electric field due to the nonuniform doping concentration.

## Einstein Relation

Nonuniformly doped semiconductor in equilibrium. (no external forces)

→ No electron and hole current !!

$$J_n = 0 = en\mu_n E_x + eD_n \frac{dn}{dx} \qquad J_n = 0 = e\mu_n N_d(x)E_x + eD_n \frac{dN_d(x)}{dx}$$

$$0 = -e\mu_n N_d(x) \left( \frac{kT}{e} \right) \frac{1}{N_d(x)} \frac{dN_d(x)}{dx} + eD_n \frac{dN_d(x)}{dx} \qquad \left\{ E_x = - \left( \frac{kT}{e} \right) \frac{1}{N_d(x)} \frac{dN_d(x)}{dx} \right.$$

$$\Rightarrow \frac{D_n}{\mu_n} = \frac{kT}{e} \qquad \frac{D_p}{\mu_p} = \frac{kT}{e} \qquad \frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{kT}{e} \qquad \text{The diffusion coefficient and mobility are not independent parameters!!}$$

**Table 5.2** | Typical mobility and diffusion coefficient values at  $T = 300$  K ( $\mu = \text{cm}^2/\text{V}\cdot\text{s}$  and  $D = \text{cm}^2/\text{s}$ )

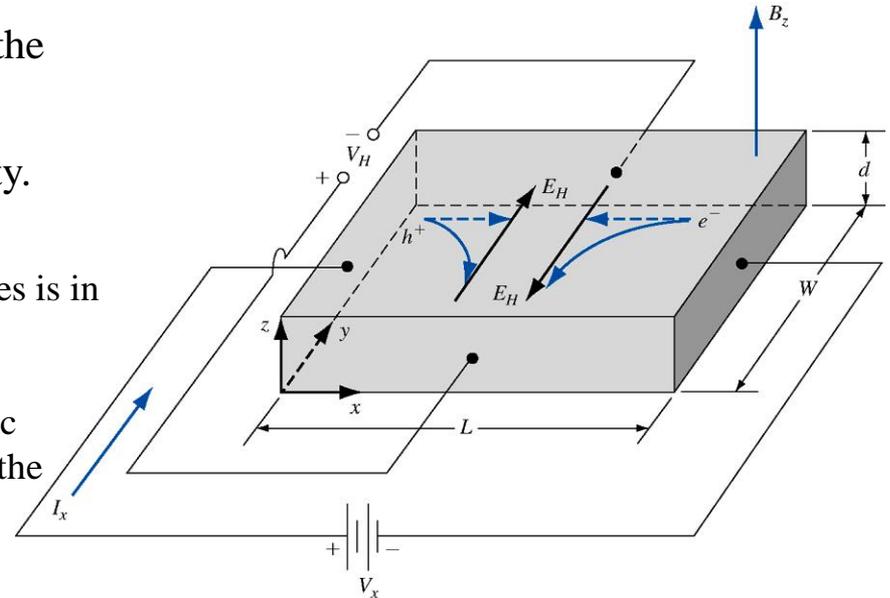
	$\mu_n$	$D_n$	$\mu_p$	$D_p$
Silicon	1350	35	480	12.4
Gallium arsenide	8500	220	400	10.4
Germanium	3900	101	1900	49.2

The Hall effect is used to distinguish whether a semiconductor is n-type or p-type and to measure the majority carrier concentration and mobility.

Magnetic probe : measure the magnetic flux density.

$F = qv \times B$  The force on both electrons and holes is in the (-y) direction

The buildup of positive/negative charge induces an electric field (Hall field) in (+y) direction to exactly balance out the force due to the magnetic field.



$F = q[E + v \times B] = 0 \Rightarrow qE_y = qv_x B_z$

Hall Voltage :  $V_H = +E_H W$   $E_H$  is positive in +y direction  $\Rightarrow V_H = v_x W B_z$

$V_H > 0 \rightarrow$  p-type  
 $V_H < 0 \rightarrow$  n-type

For p-type,  $v_{dx} = \frac{J_x}{ep} = \frac{I_x}{(ep)(Wd)} \Rightarrow V_H = \frac{I_x B_z}{epd} \Rightarrow p = \frac{I_x B_z}{edV_H}$

For n-type,  $V_H = -\frac{I_x B_z}{ned} \Rightarrow n = -\frac{I_x B_z}{edV_H}$

Carrier concentration is determined from current, B-field and Hall voltage.

For mobility measure,  $J_x = ep\mu_p E_x \Rightarrow \frac{I_x}{Wd} = \frac{ep\mu_p V_x}{L} \Rightarrow \mu_p = \frac{I_x L}{epV_x Wd}$   $\mu_n = \frac{I_x L}{enV_x Wd}$

# Hall Measurement

