Semiconductor Devices

Chapter 5
Carrier Transport Phenomena

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Carrier Transport Mechanisms

- Drift: Due to the Electric field

- Diffusion: Due to the Carrier concetration gradient

- Recombination-Generation (R-G)

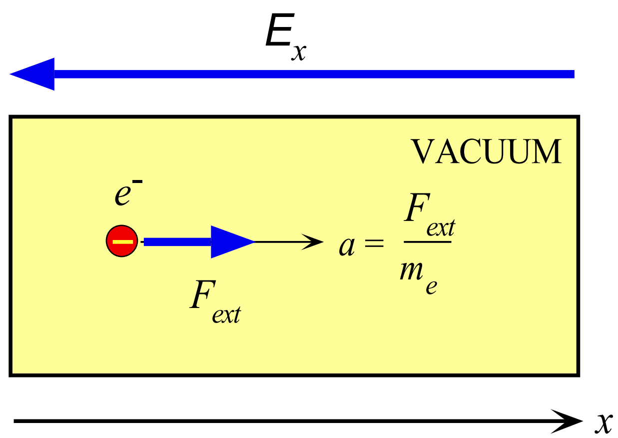
Carrier Transport Mechanisms

- **Drift: Due to the Electric field**

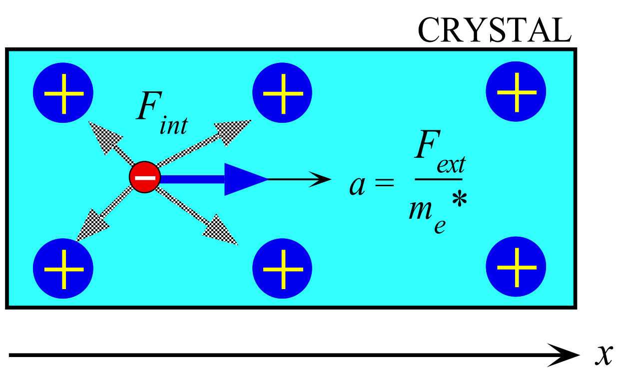
- Diffusion: Due to the Carrier concetration gradient

- Recombination-Generation (R-G)

Electron effective mass (m_n^*)



(a)



(b)

$$F_{ext} = m_e a$$

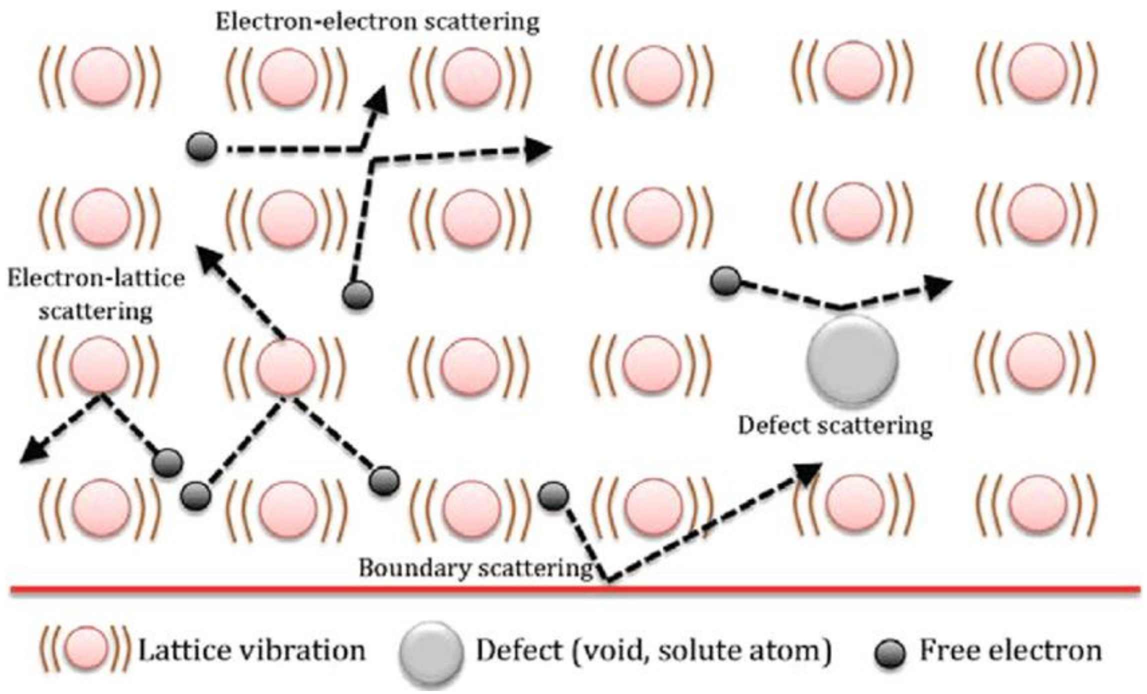
$$a = \frac{F_{ext}}{m_e}$$

$$F_{total} = F_{ext} - F_{int} = m_e^* a$$

$$a = \frac{F_{total}}{m_e^*}$$

<u>*What about velocity?*</u>

Scattering



- ✓ Si lattice vibration by thermal energy
  (Lattice scattering or Phonon scattering)

- ✓ Other scattering mechanisms:
  - Ionized impurity scattering or Defect scattering or Coulombic scattering
  - Electron-Electron scattering
  - Surface (roughness) scattering or Boundary scattering

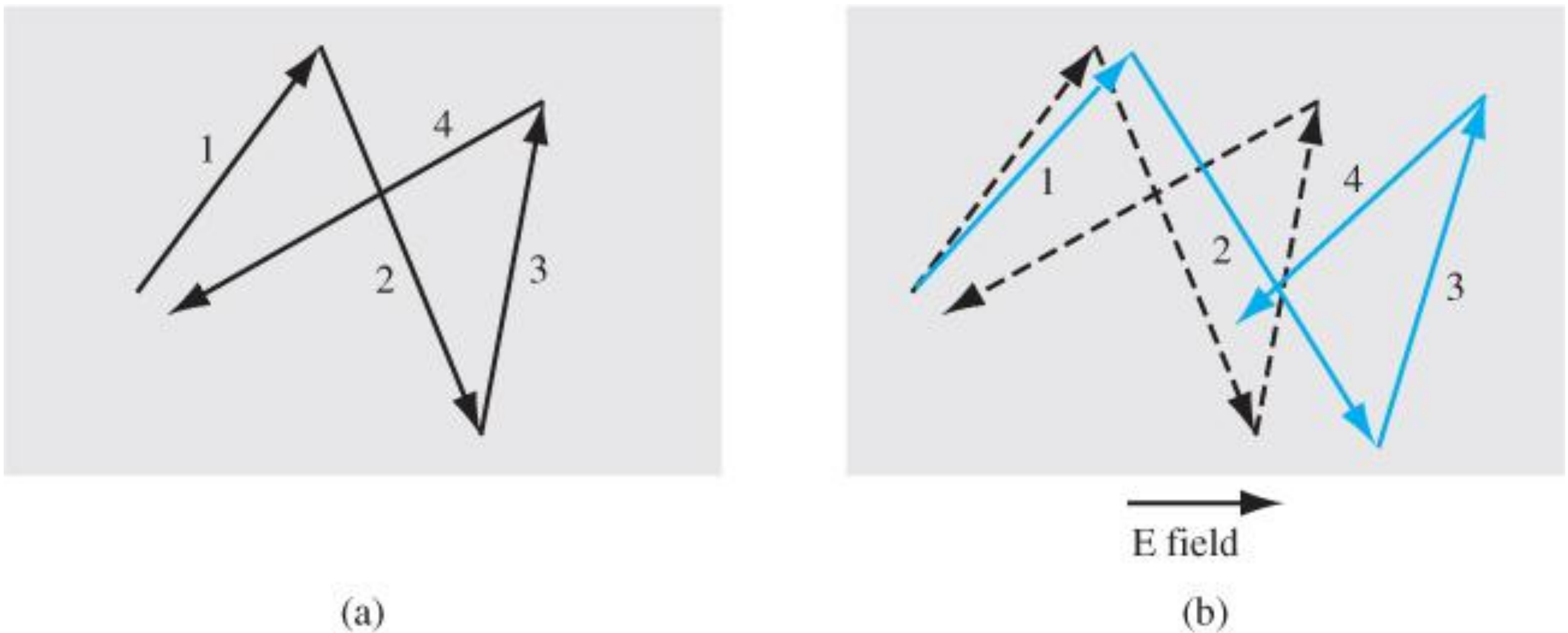


Figure 5.1 | Typical random behavior of a hole in a semiconductor (a) without an electric field and (b) with an electric field.

Carrier Velocity and Mobility

Mean Time between Collision (related to Scattering)

$$F = m_n^* \frac{dv_{dn}}{dt} = -qE, \qquad \boldsymbol{v_{dn}} = -\frac{qEt_{mn}}{m_n^*} = -\boldsymbol{\mu_n E}\ [\mathbf{cm^2/V \cdot s}] \qquad \mu_n = \frac{qt_{mn}}{m_n^*}$$

Electron Velocity

Electron Mobility

$$F = m_p^* \frac{dv_{dp}}{dt} = +qE, \qquad \boldsymbol{v_{dp}} = +\frac{qEt_{mp}}{m_p^*} = +\boldsymbol{\mu_p E}\ [\mathbf{cm^2/V \cdot s}] \qquad \mu_p = \frac{qt_{mp}}{m_p^*}$$

Hole Velocity

Hole Mobility

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

	μ_n (cm²/V-s)	μ_p (cm²/V-s)
Silicon	1350	480
Gallium arsenide	8500	400
Germanium	3900	1900

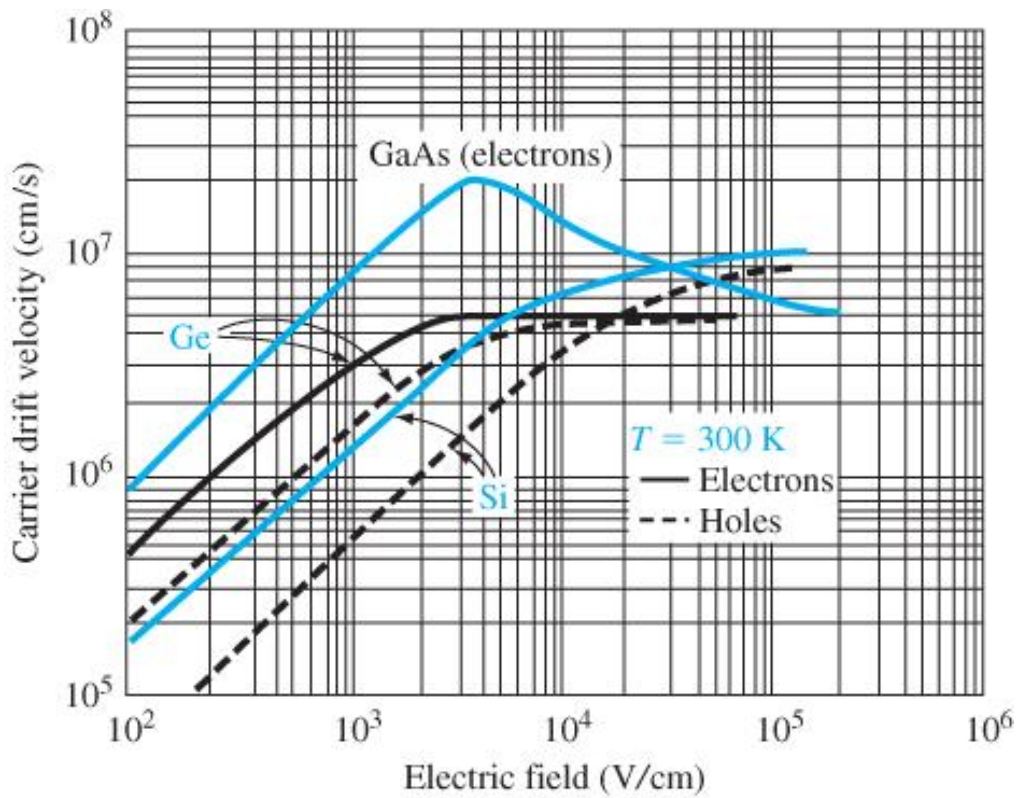
Carrier Velocity and Velocity Saturation

Mean Time between Collision (related to Scattering)

$$v_{dn} = -\frac{qEt_{mn}}{m_n^*} = -\mu_n E \; [\mathrm{cm^2/V \cdot s}] \qquad \mu_n = \frac{qt_{mn}}{m_n^*}$$

Electron Velocity

Electron Mobility



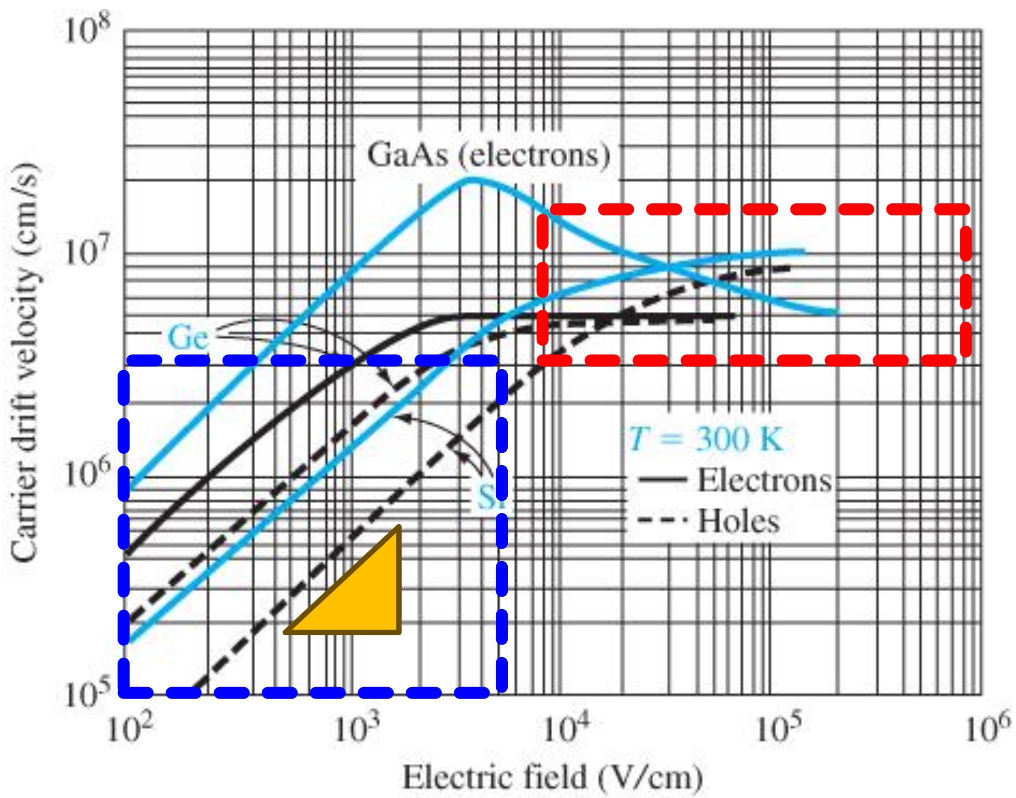
Carrier Velocity and Velocity Saturation

Mean Time between Collision (related to Scattering)

$$v_{dn} = -\frac{qEt_{mn}}{m_n^*} = -\mu_n E \; [\mathrm{cm^2/V \cdot s}] \qquad \mu_n = \frac{qt_{mn}}{m_n^*}$$

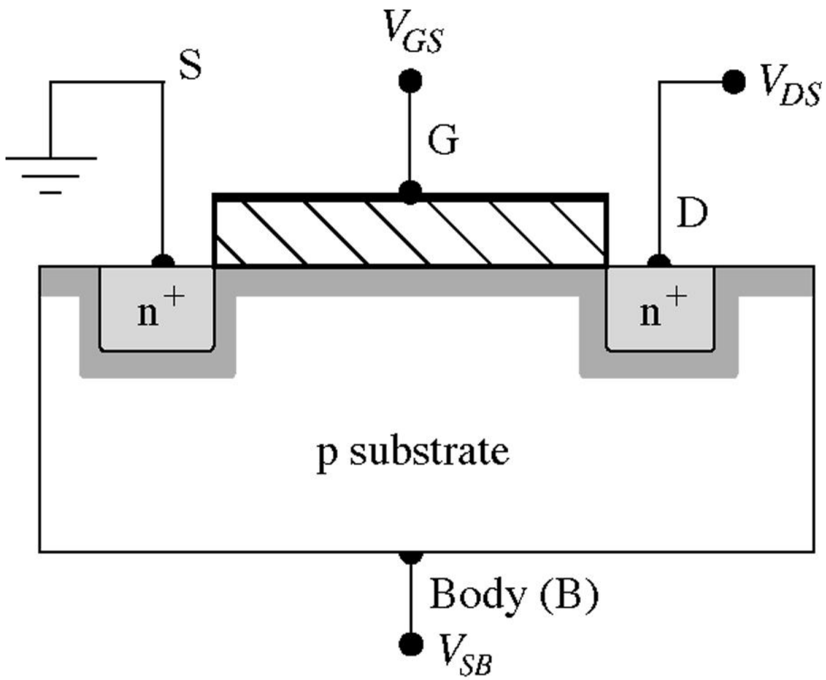
Electron Velocity

Electron Mobility



Velocity Saturation due to scattering

$Slope = \mu_n$



(a)

Example:

Length; 0.1 μm, V_{DS}; 1V

E=1$\times$10^5 V/cm
(already saturated)

Carrier Mobility vs. Scattering

Mean Time between Collision (related to Scattering)

$$\mu_n = \frac{q t_{mn}}{m_n^*}$$

- ✓ Si lattice vibration by thermal energy (**Lattice scattering** or Phonon scattering)
  - ➢ Under the dominance of **Lattice scattering**, Mobility **decreases** as increasing *T.*

$$\mu_l = \mu_{l0} \frac{1}{\left(\frac{T}{T_0}\right)^{\frac{3}{2}}} \propto T^{-\frac{3}{2}}$$

- ✓ Other scattering mechanisms:
  - **Ionized impurity scattering** or Coulombic scattering
  - Electron-Electron scattering
  - Surface (roughness) scattering or Boundary scattering
  - ➢ Under the dominance of **Impurity scattering**, Mobility **increases** as increasing *T.*

$$\mu_i = \mu_{i0} \left(\frac{T}{T_0}\right)^{+\frac{3}{2}} \propto T^{+\frac{3}{2}}$$

Carrier Mobility vs. Scattering (Dopant or Impurity Concentration)

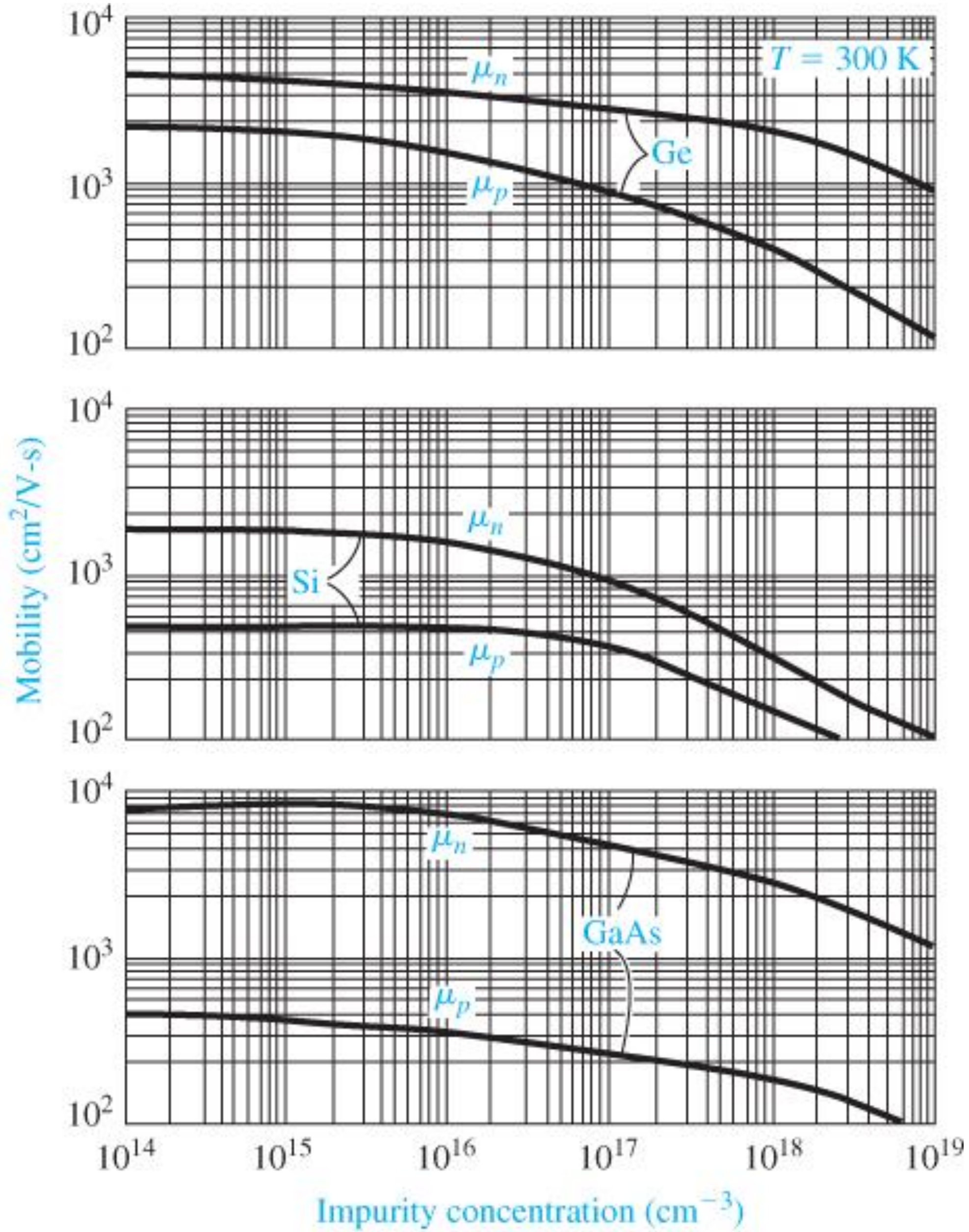
$$\mu_n = \frac{q t_{mn}}{m_n^*}$$

- Under the dominance of Impurity scattering, Mobility increases as increasing *T.*

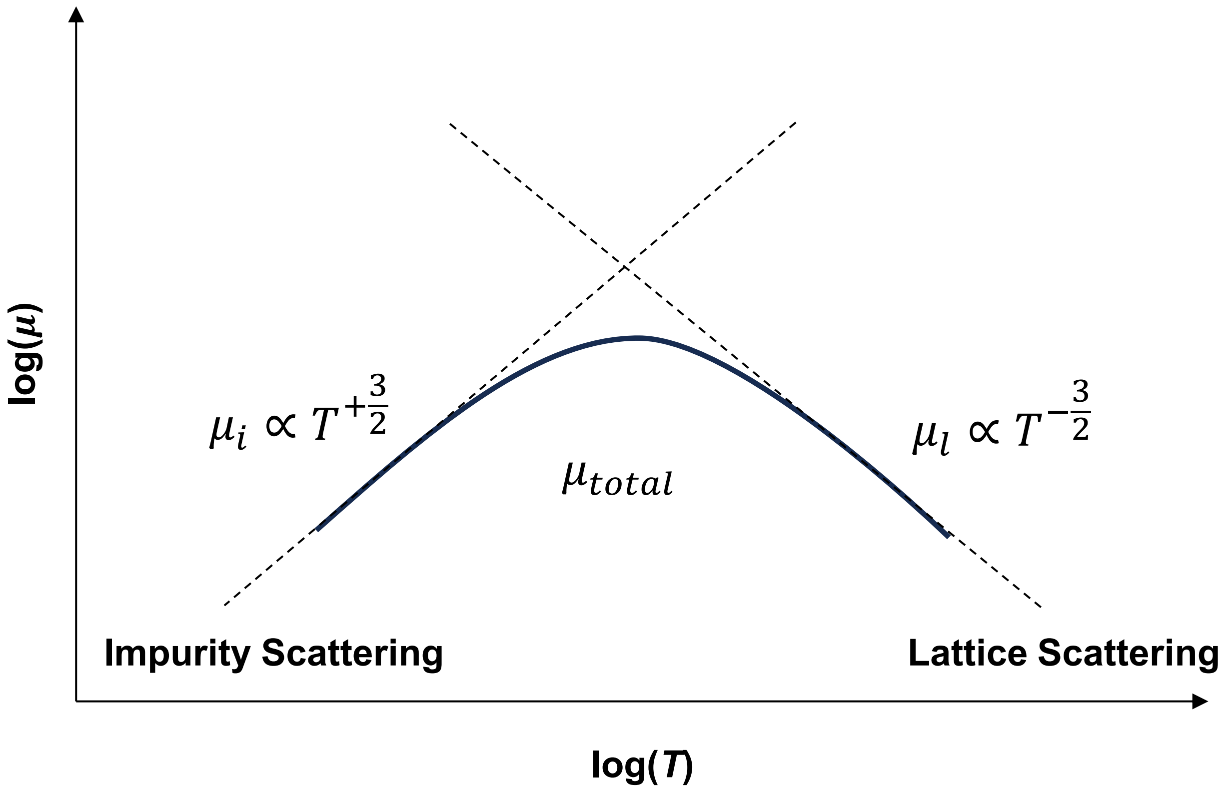
$$\mu_i = \mu_{i0}\left(\frac{T}{T_0}\right)^{+\frac{3}{2}} \propto T^{+\frac{3}{2}}$$

- Under the dominance of **Impurity scattering**, Mobility **decreases** as increasing **Dopant concentration** (N_d or N_a).

$N_d \uparrow$ ➔ $\mu_i \downarrow$

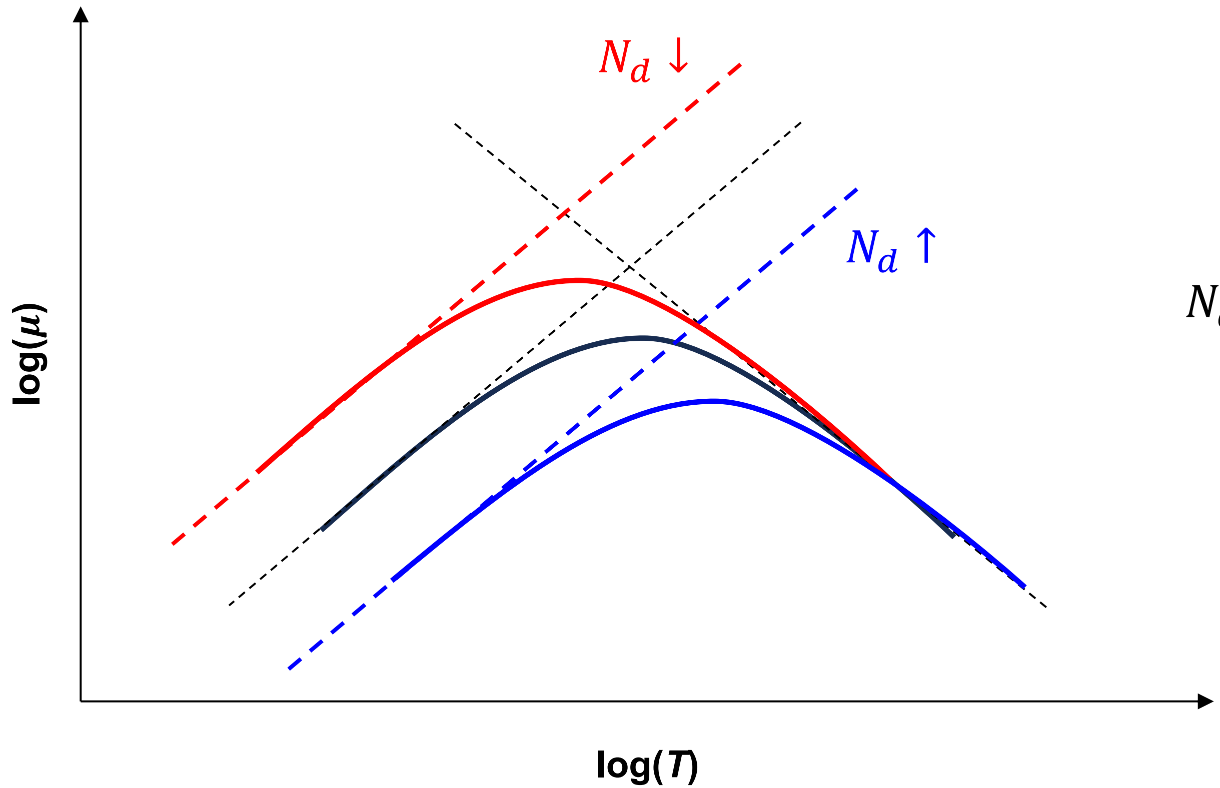


Carrier Mobility vs. Temperature



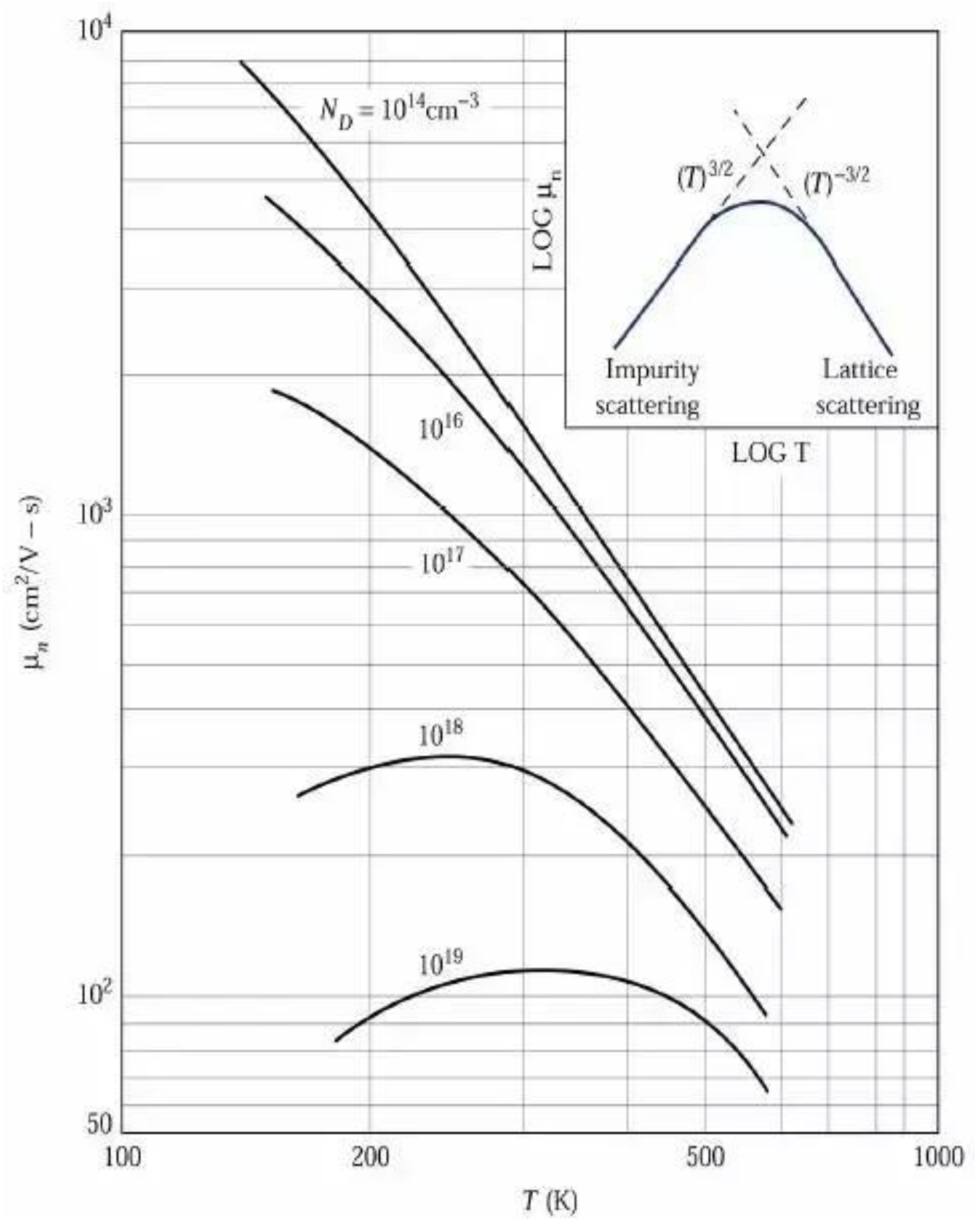
$$\frac{1}{\mu_{total}} = \frac{1}{\mu_1} + \frac{1}{\mu_2} + \frac{1}{\mu_3} + \frac{1}{\mu_4} = \frac{1}{\mu_l} + \frac{1}{\mu_i}$$

Carrier Mobility vs. Temperature

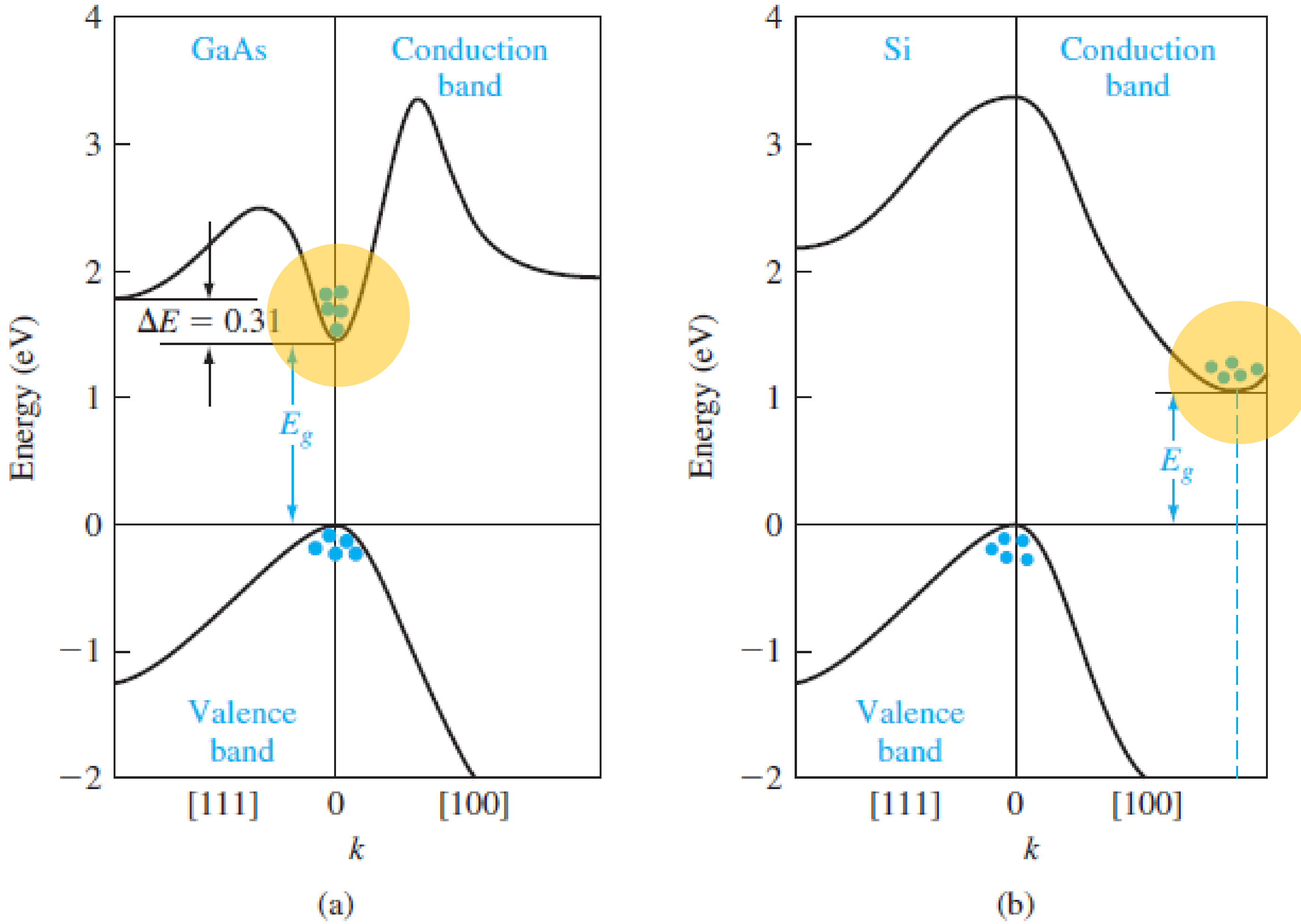


$N_d \uparrow \;\Rightarrow\; \mu_i \downarrow$

Carrier Mobility vs. Temperature



Electron effective mass (m_n^*)



$$m^* = \left(\frac{1}{\hbar^2}\frac{d^2E}{dk^2}\right)^{-1}$$

$$m^*_{\mathrm{GaAs}} < m^*_{\mathrm{Si}}$$

Carrier Mobility vs. Effective Mass

Mean Time between Collision (related to Scattering)

$$\mu_n = \frac{q t_{mn}}{m_n^*}$$

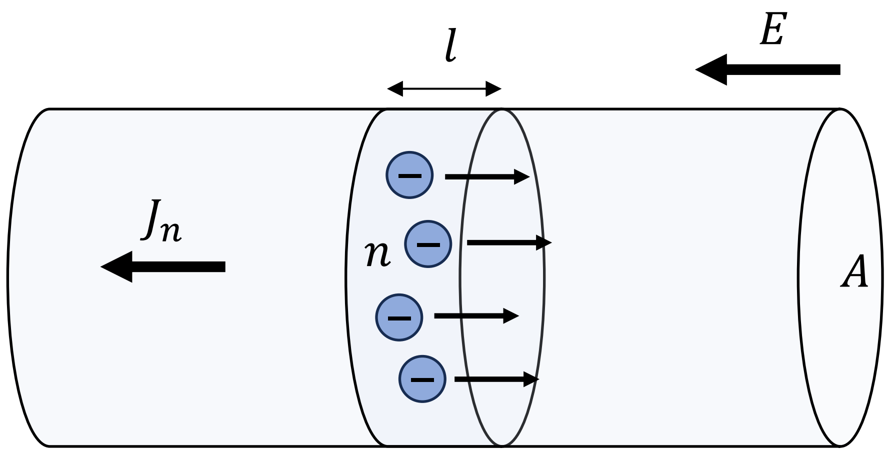
Table 4.1 | Effective density of states function and density of states effective mass values

	N_c (cm^{-3})	N_v (cm^{-3})	m_n^*/m_0	m_p^*/m_0
Silicon	2.8×10^{19}	1.04×10^{19}	1.08	0.56
Gallium arsenide	4.7×10^{17}	7.0×10^{18}	0.067	0.48
Germanium	1.04×10^{19}	6.0×10^{18}	0.55	0.37

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

	μ_n (cm^2/V-s)	μ_p (cm^2/V-s)
Silicon	1350	480
Gallium arsenide	8500	400
Germanium	3900	1900

Drift Current Density



Current **Charge** **Electron density**

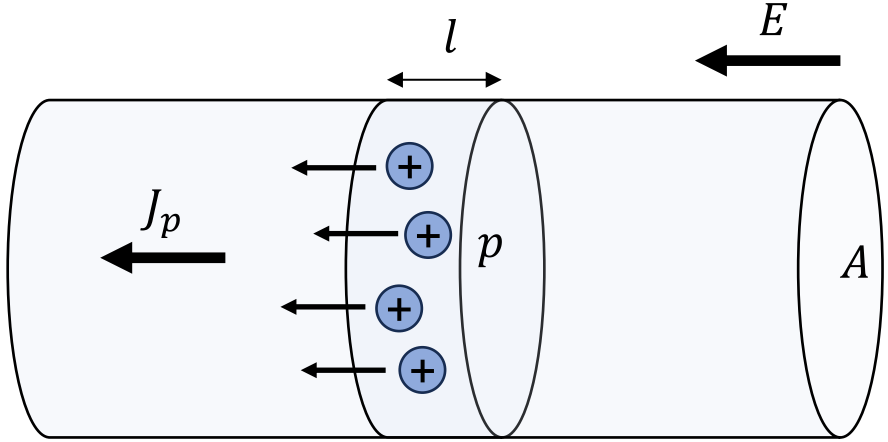
$$I_n = \frac{dQ}{dt}, \qquad Q = -qnlA$$

$$I_n = \frac{d(-qnlA)}{dt} = qnA\frac{dl}{dt} = -qnAv_{dn}$$

Current density

$$J_{n|drf} = \frac{I_n}{A} = -qnv_{dn} = -qn(-\mu_n E) = qn\mu_n E$$

Drift Current Density



Current **Charge** **Electron density**

$$I_p = \frac{dQ}{dt}, \qquad Q = qplA$$

$$I_p = \frac{d(qplA)}{dt} = qpA\frac{dl}{dt} = qpAv_{dp}$$

Current density

$$J_{p|drf} = \frac{I_p}{A} = qpv_{dp} = qp(+\mu_p E) = qp\mu_p E$$

Drift Current and Conductivity

$$J_{n|drf} = -qnv_{dn} = qn\mu_n E \qquad J_{p|drf} = qpv_{dp} = qp\mu_p E$$

$$J_{drf} = J_{n|drf} + J_{p|drf} = q(n\mu_n + p\mu_p)E \ [\mathrm{A/cm^2}]$$

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

Conductivity

$$\sigma = qn\mu_n + qp\mu_p \ [1/\Omega \cdot \mathrm{cm}]$$

Resistance and Ohm's Law

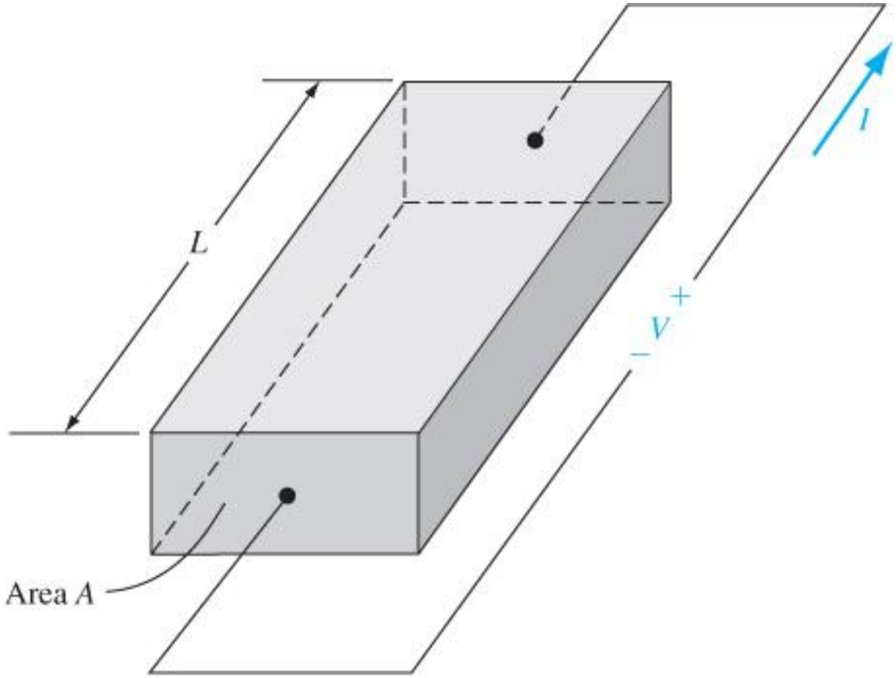


Figure 5.5 | Bar of semiconductor material as a resistor.

Resistance

$$R\ [\Omega] = \frac{V}{I} = \rho\ \frac{L}{A}$$

Resistivity

$$\rho = \frac{1}{\sigma}\ [\Omega \cdot \mathrm{cm}]$$

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

:Ohm's Law

Resistivity and Doping Concentration

$$\rho = \frac{1}{\sigma}\ [\Omega \cdot \mathrm{cm}]$$

$$\sigma = qn\mu_n + qp\mu_p\ [1/\Omega \cdot \mathrm{cm}]$$

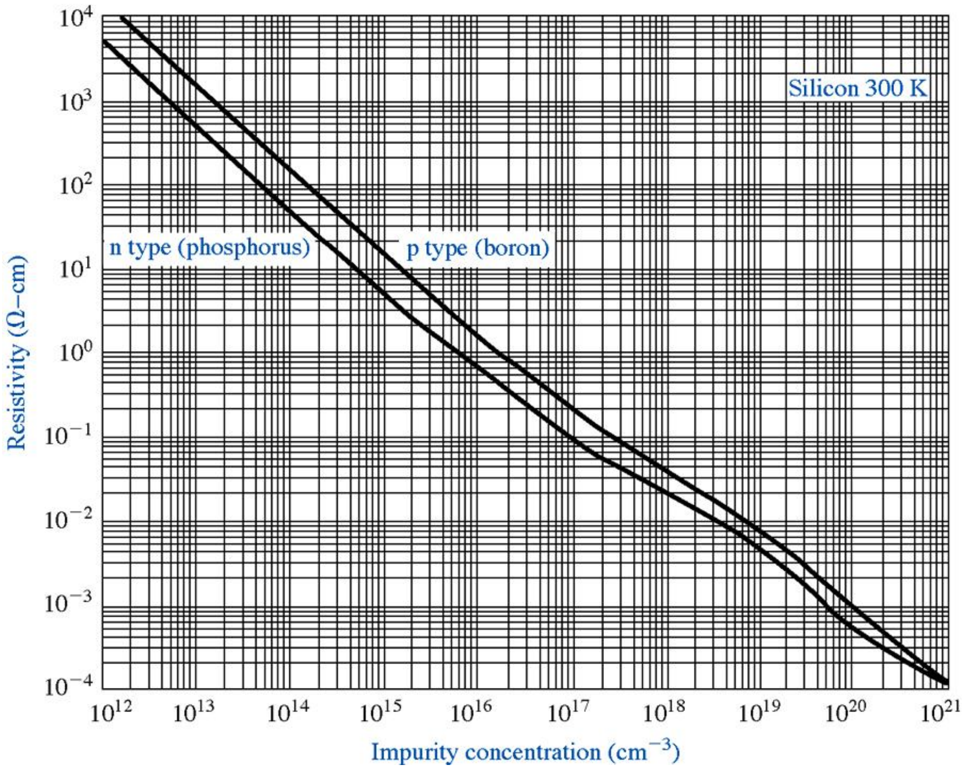
$$\rho = \frac{1}{\sigma} = \frac{1}{qn\mu_n + qp\mu_p}$$

For n-type

$$\boldsymbol{\rho} \cong \frac{1}{q\boldsymbol{n}\mu_n}$$

For p-type

$$\boldsymbol{\rho} \cong \frac{1}{q\boldsymbol{p}\mu_p}$$



Resistivity and Doping Concentration with Mobility

$$\rho = \frac{1}{\sigma} \; [\Omega \cdot \mathrm{cm}]$$

$$\sigma = qn\mu_n + qp\mu_p \; [1/\Omega \cdot \mathrm{cm}]$$

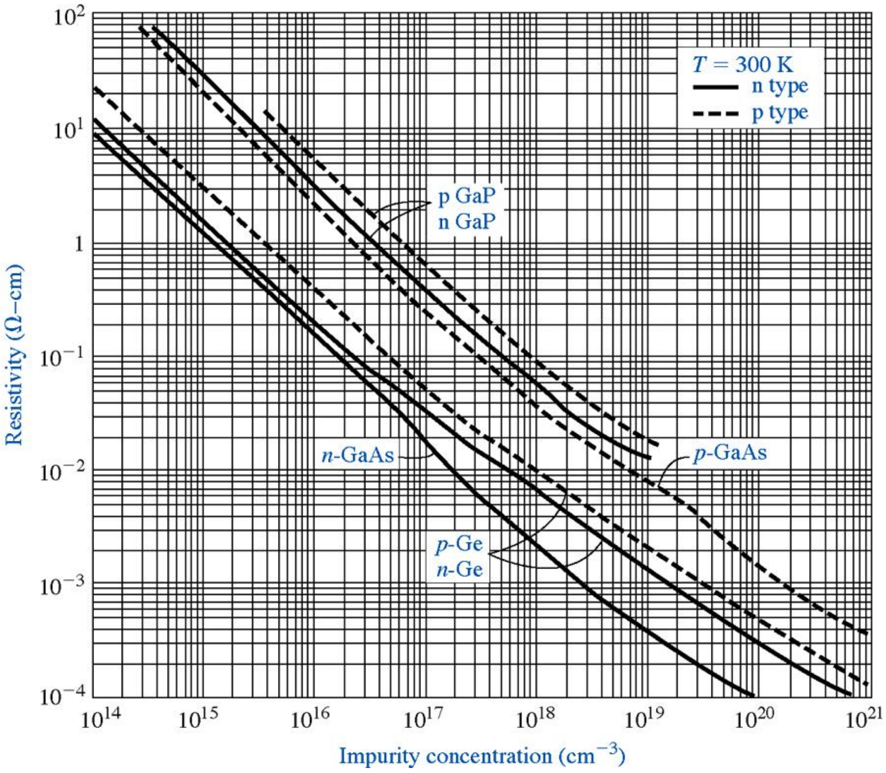
$$\rho = \frac{1}{\sigma} = \frac{1}{qn\mu_n + qp\mu_p}$$

For n-type

$$\boldsymbol{\rho} \cong \frac{1}{qn\boldsymbol{\mu_n}}$$

For p-type

$$\boldsymbol{\rho} \cong \frac{1}{qp\boldsymbol{\mu_p}}$$



	μ_n $[\mathrm{cm}^2/\mathrm{V \cdot s}]$	μ_p $[\mathrm{cm}^2/\mathrm{V \cdot s}]$
Silicone	1450	480
Germanium	3900	1900
Gallium Arsenide (GaAs)	8500	400
Gallium Phosphide (GaP)	110	75

Carrier Transport Mechanisms

- Drift: Due to the Electric field

- **Diffusion: Due to the Carrier concetration gradient**

- Recombination-Generation (R-G)

Diffusion Current

- Carriers (particles) move from “High” to “Low” concentration.

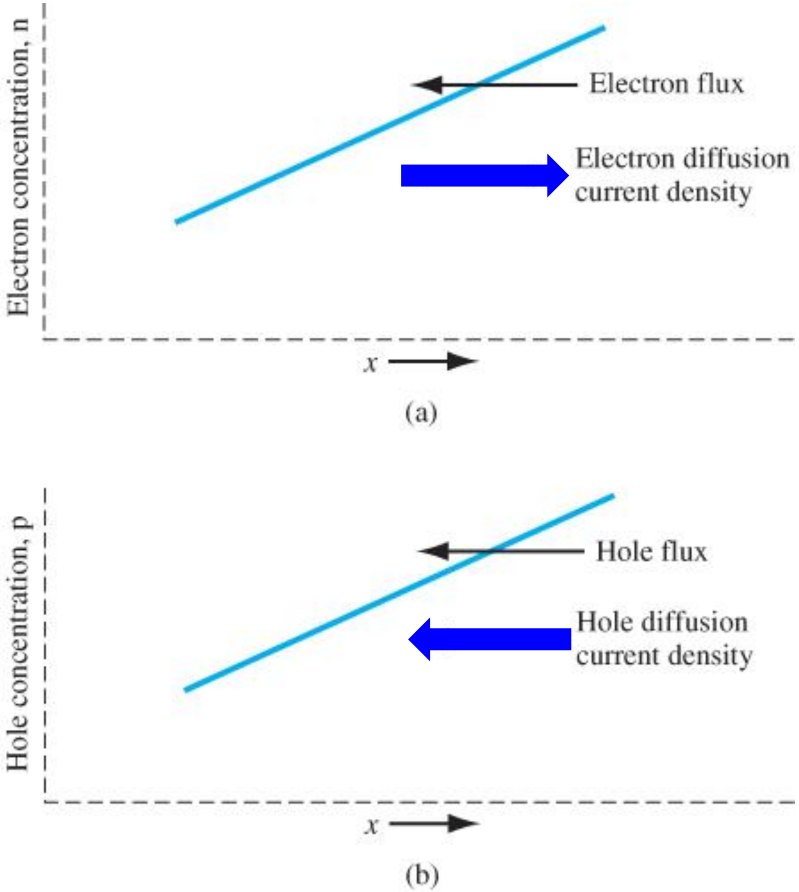


Figure 5.11 | (a) Diffusion of electrons due to a density gradient. (b) Diffusion of holes due to a density gradient.

Diffusion constant $[\mathrm{cm}^2/s]$

$$J_{n|dif} = -qD_n\left(-\frac{dn}{dx}\right) = qD_n\frac{dn}{dx}$$

$$J_{p|dif} = qD_p\left(-\frac{dp}{dx}\right) = -qD_p\frac{dp}{dx}$$

Total Current Density

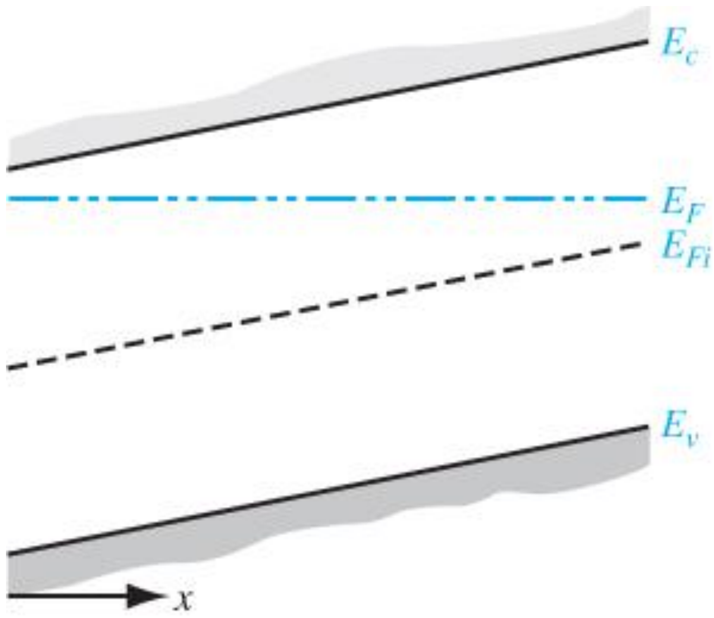
$$J_{total} = J_{drf} + J_{diff} = (J_{n|drf} + J_{p|drf}) + (J_{n|diff} + J_{p|diff})$$

Drift (n) Diffusion (n)

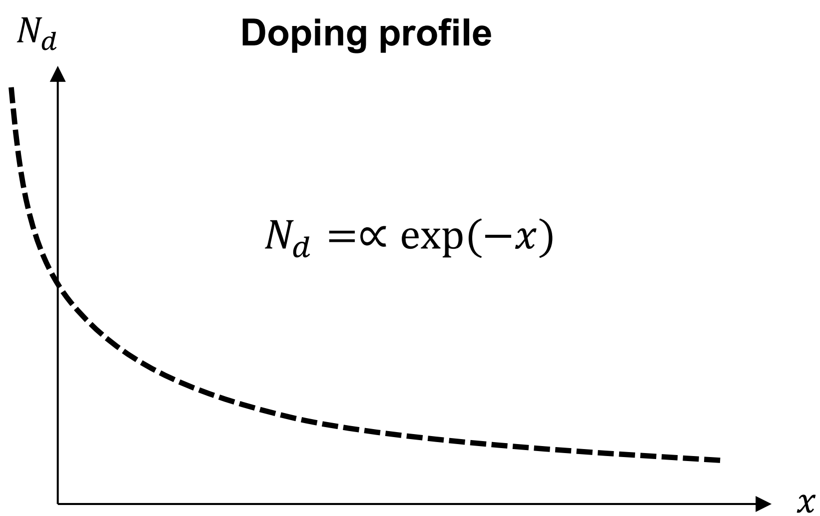
$$J_{total} = qn\mu_n\boldsymbol{E} + qp\mu_p\boldsymbol{E} + qD_n\frac{\boldsymbol{dn}}{\boldsymbol{dx}} - qD_p\frac{\boldsymbol{dp}}{\boldsymbol{dx}}$$

Drift (p) Diffusion (p)

Graded Impurity Distribution



Doping profile



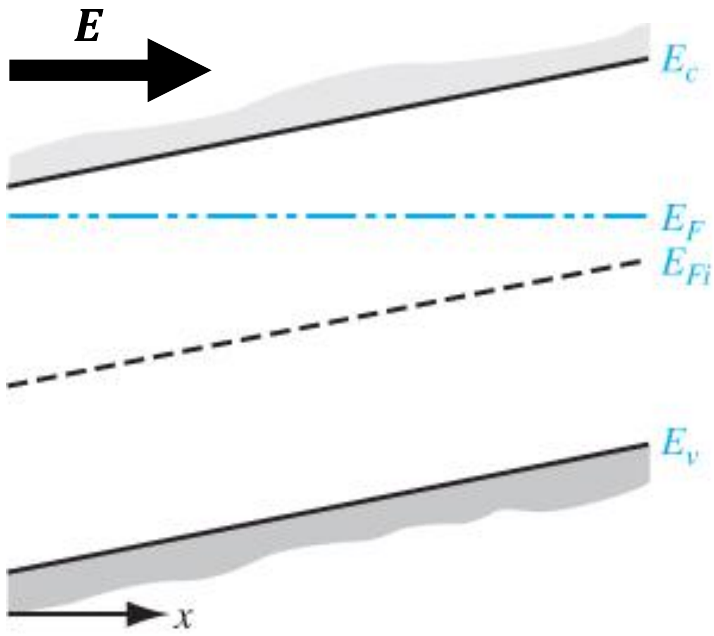
$$N_d = \propto \exp(-x)$$

$$E_c - E_F = ax + b$$

$$n_0 = N_d = N_c \exp\left[\frac{-(\boldsymbol{E_c - E_F})}{kT}\right]$$

$$N_d = N_c \exp\left[\frac{-ax - b}{kT}\right] \propto \exp(-x)$$

Graded Impurity Distribution



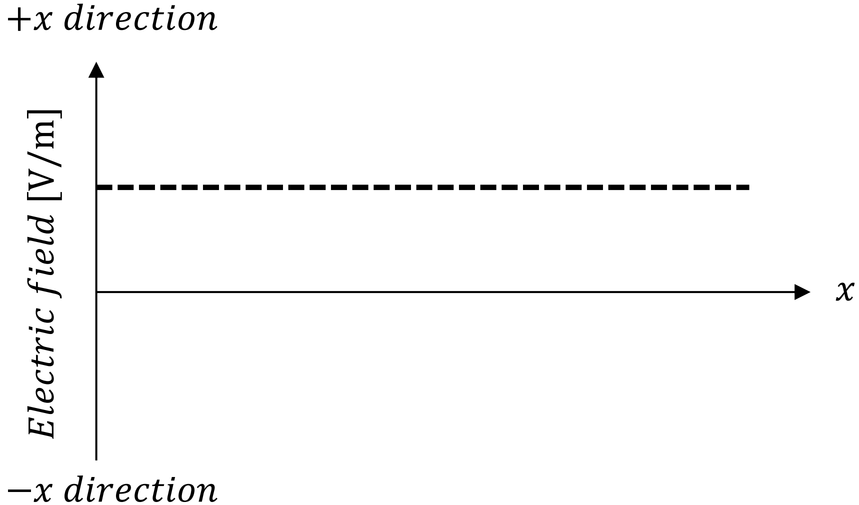
Electric field $[\mathrm{V/m}]$

Electric potential $[\mathrm{V}]$
= Built-in potential

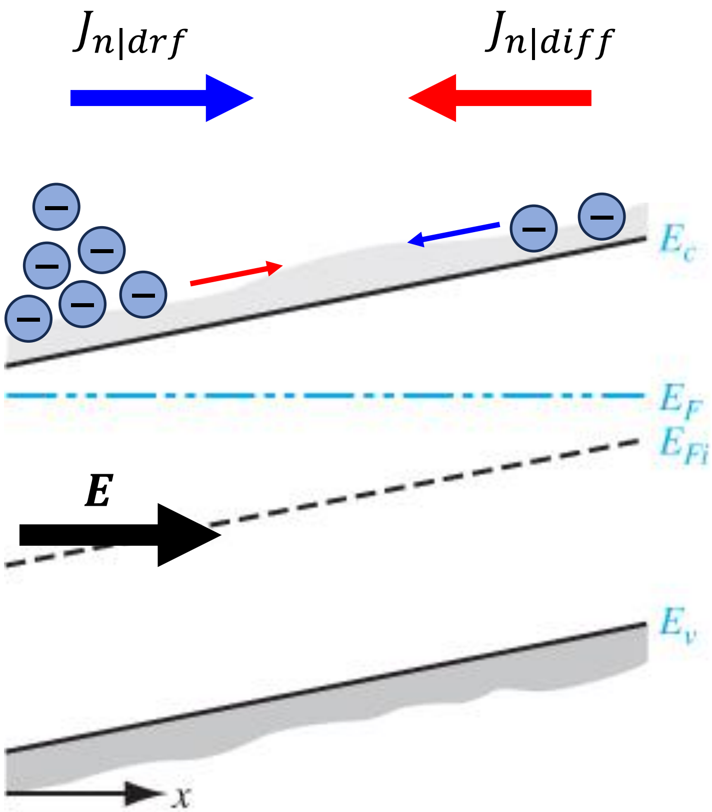
$$E = -\frac{dV}{dx} = \frac{1}{q}\frac{dE_c(x)}{dx} = constant$$

slope

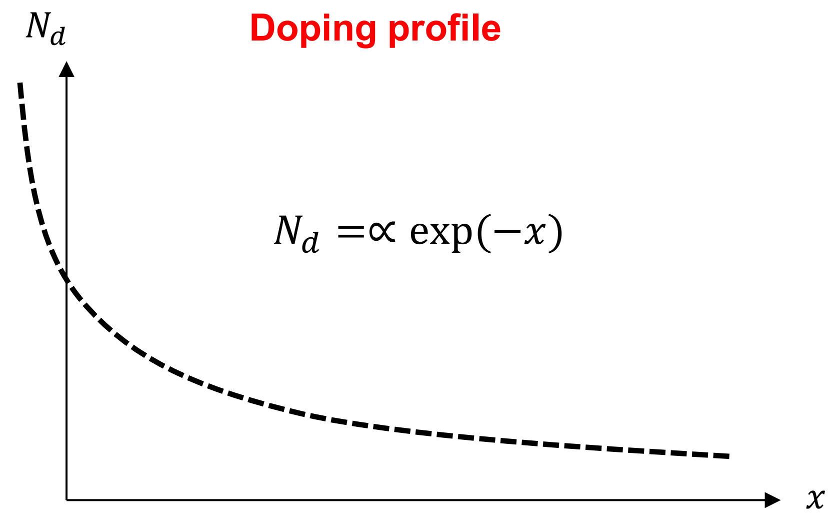
Electric field profile

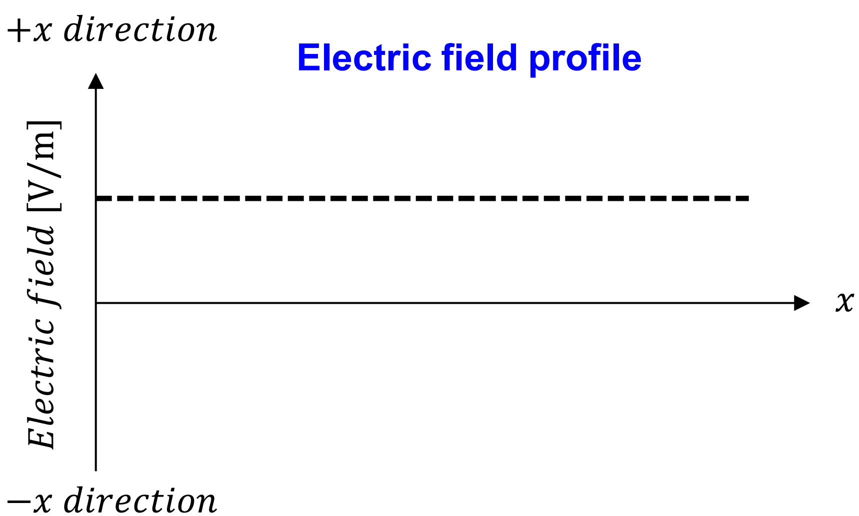


Net Current in Graded Impurity Distribution



$$J_{total} = J_{n|drf} + J_{n|diff} = 0$$





Einstein's Relationship

$$J_{total} = 0\ (at\ thermal\ equilibrium\ state)$$

$$J_{total}(x) = J_n(x) + J_p(x) = J_{n|drf}(x) + J_{n|diff}(x) + J_{p|drf}(x) + J_{p|diff}(x)$$

$$J_n(x) = J_{n|drf}(x) + J_{n|diff}(x) = qn(x)\mu_n E + qD_n \frac{dn(x)}{dx} = 0$$

$$J_p(x) = J_{p|drf}(x) + J_{p|diff}(x) = qp(x)\mu_p E - qD_p \frac{dp(x)}{dx} = 0$$

<u>For n-type</u> $$E = -\frac{D_n}{\mu_n}\frac{1}{n(x)}\frac{dn(x)}{dx}$$

<u>For p-type</u> $$E = \frac{D_p}{\mu_p}\frac{1}{p(x)}\frac{dp(x)}{dx}$$

Einstein's Relationship

For n-type

$$E = -\frac{D_n}{\mu_n}\frac{1}{n(x)}\frac{dn(x)}{dx}$$

$$n(x) = N_c \exp\left[\frac{-(E_c(x) - E_F)}{kT}\right]$$

$$\frac{dn(x)}{dx} = \frac{d}{dx}\left(N_c \exp\left[\frac{-(E_c(x) - E_F)}{kT}\right]\right) = -\left(\frac{1}{kT}\right) N_c \exp\left[\frac{-(E_c(x) - E_F)}{kT}\right]\frac{dE_c(x)}{dx}$$

$$= -\left(\frac{1}{kT}\right) N_c \exp\left[\frac{-(E_c(x) - E_F)}{kT}\right]\frac{dE_c(x)}{dx}$$

$$E = -\frac{dV}{dx} = \frac{1}{q}\frac{dE_c(x)}{dx} = constant$$

$$= -\left(\frac{1}{kT}\right) n(x)(qE)$$

$$E = -\frac{D_n}{\mu_n}\frac{1}{n(x)}\frac{dn(x)}{dx} = -\frac{D_n}{\mu_n}\frac{1}{n(x)}\left[-\left(\frac{1}{kT}\right) n(x)(qE)\right]$$

⇨ $$\frac{D_n}{\mu_n} = \frac{kT}{q}[V]$$ Thermal voltage

Einstein's Relationship

$$\Rightarrow \quad \frac{D_n}{\mu_n} = \frac{kT}{q}\,[V] \quad \text{Thermal voltage}$$

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

	μ_n	D_n	μ_p	D_p
Silicon	1350	35	480	12.4
Gallium arsenide	8500	220	400	10.4
Germanium	3900	101	1900	49.2