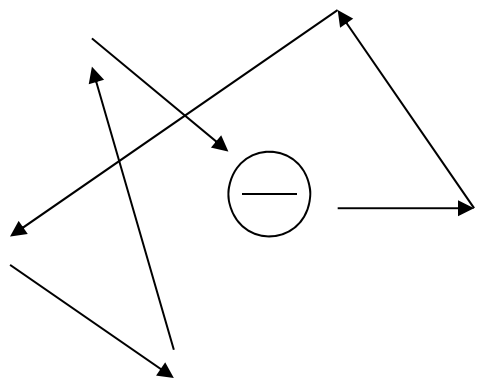
Drift and Diffusion Current

EECS 320

Introduction to Semiconductor Devices

Thermal Motion Of Carriers

Electrons move randomly in crystal with zero net displacement

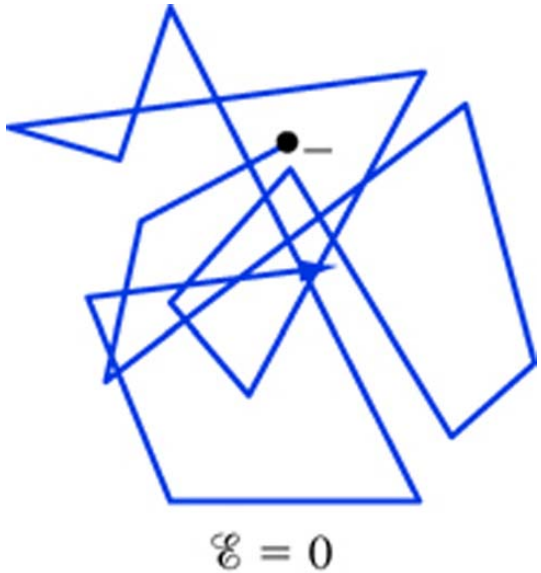


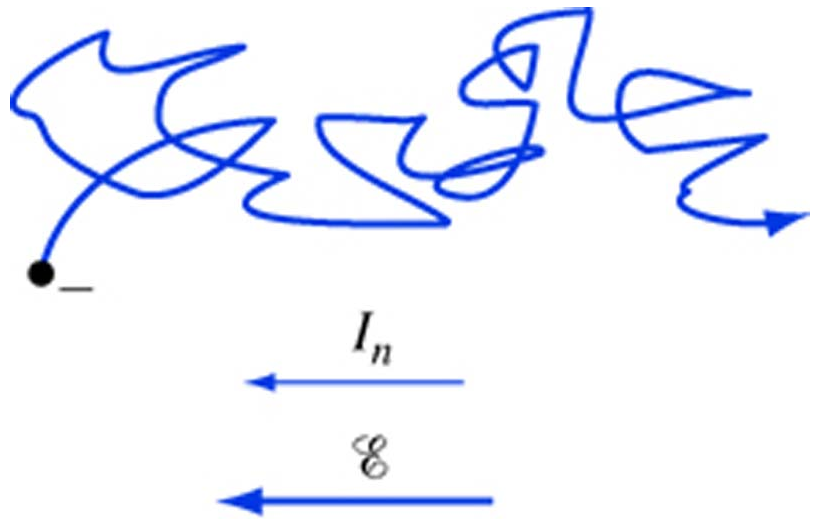
This is the thermal motion of carriers

V_{th} typically ~10^7 cm/s for most semiconductors!

Application Of Electric Field

Electrons/holes respond to electric field

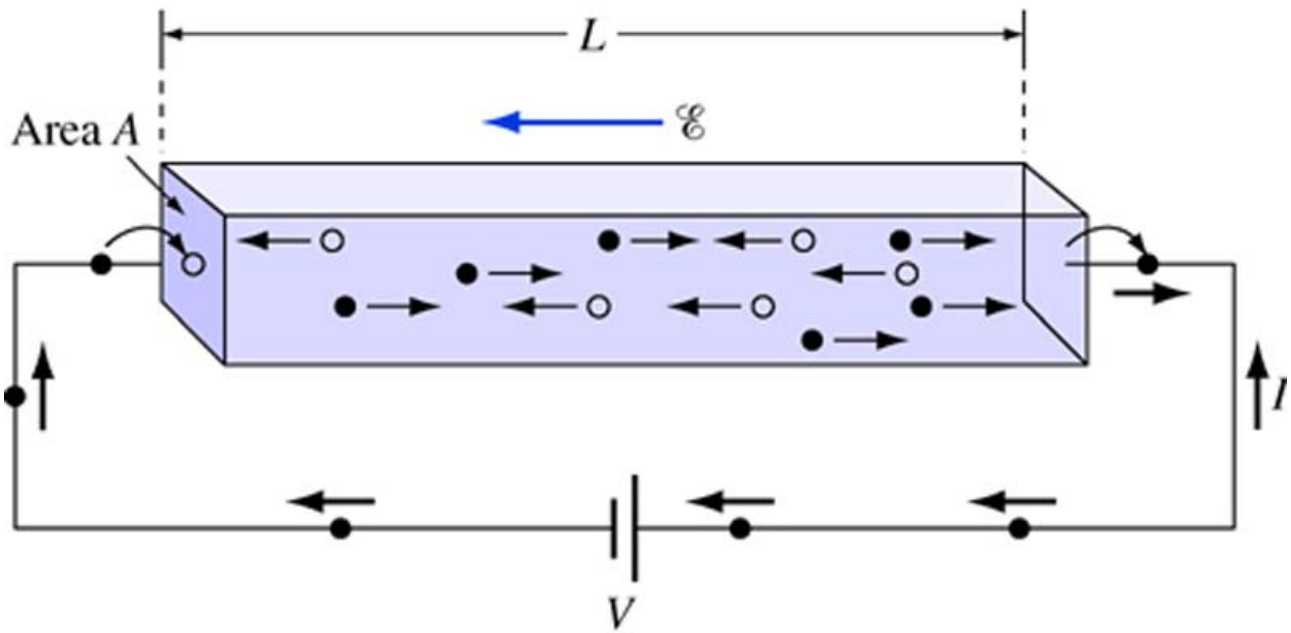




- Note that carriers are in motion without electric field (thermal energy)
- Carriers are accelerated by electric field
- Carriers scatter from crystal imperfections
- Average velocity obtained between scattering (v_{drift})

Drift Current

Drift current due to electrons and holes



$$R = \frac{V}{I} = \frac{\rho L}{A} = \frac{EL}{JA}$$

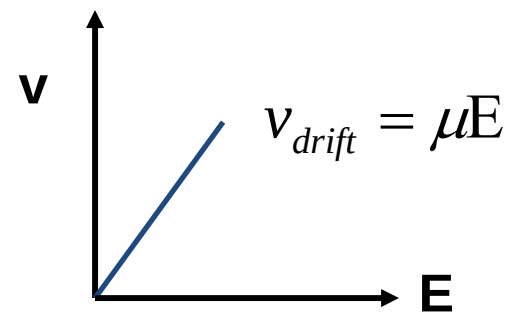
$$J_{drift} = \sigma E = \frac{E}{\rho}$$

$$J_{(drift)} = J_{n(drift)} + J_{p(drift)}$$

Conductivity and Mobility

Define mobility: proportionality between v_{drift} and E, represents carrier scattering

$$J_{drift} = \sigma E = qnv_{dn} + qpv_{dp}$$



$$\mu_n = -\frac{v_{dn}}{E} \qquad \mu_p = \frac{v_{dp}}{E}$$

$$\sigma = \frac{qnv_{dn} + qpv_{dp}}{E}$$

μ depends on mean time between scattering τ and m^*

$$\mu = \frac{q\tau}{m^*} \qquad \frac{1}{\tau} = \sum_i \frac{1}{\tau_i}$$

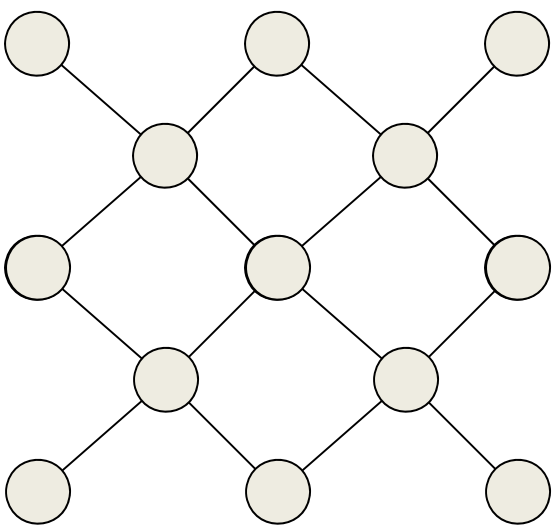
Conductivity depends on both carrier density and mobility

$$\sigma = qn\mu_n + qp\mu_p$$

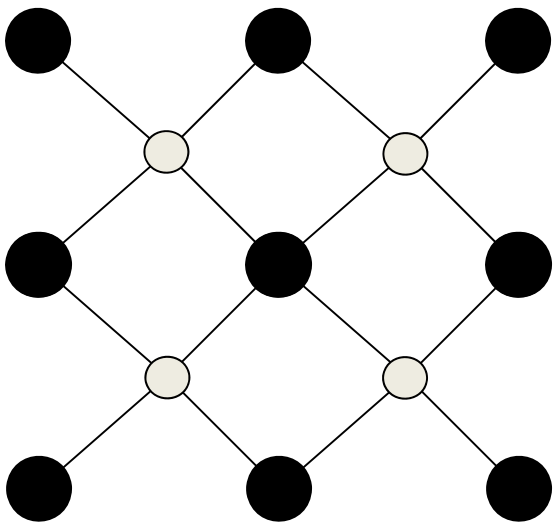
Mobility

Mobility depends on effective mass and scattering time

- Effective mass is a material parameter that accounts for periodicity of the crystal potential



Silicon

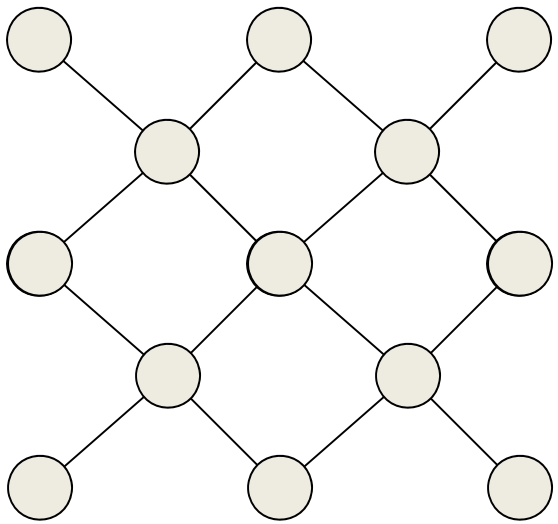


Gallium Arsenide

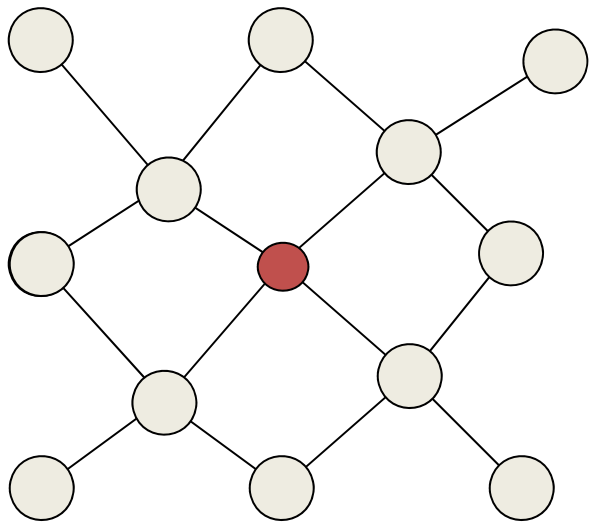
Mobility

Mobility depends on effective mass and scattering time

- Scattering time depends on impurity concentrations, temperature, carrier concentrations, crystal defects, etc.



Pure, T = 0K



T > 0K, with Impurity

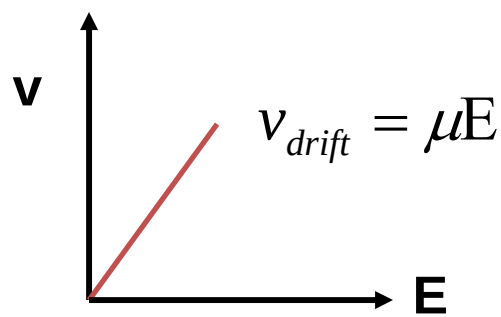
Mobility

Mobility depends on m^* and τ

- τ depends on scattering processes
- Use Mathieson's rule for net scattering time
- Scattering processes include phonon, ionized impurity, defects, carrier-carrier, alloy, etc.
- At low fields, mobility is constant

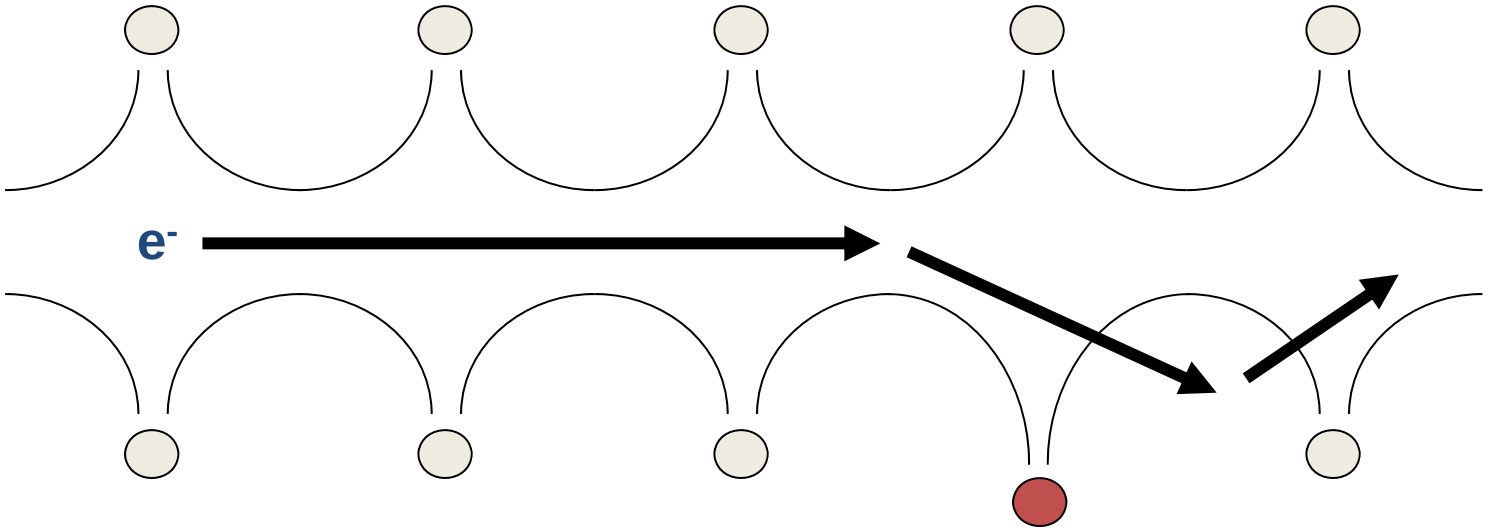
$$\mu = \frac{q\tau}{m^*}$$

$$\frac{1}{\tau} = \sum_i \frac{1}{\tau_i}$$



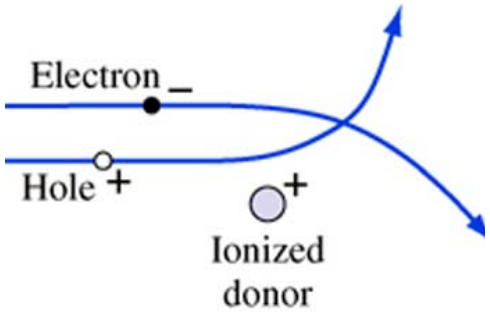
Mobility Dependence On Doping

Mobility shows clear dependence on doping

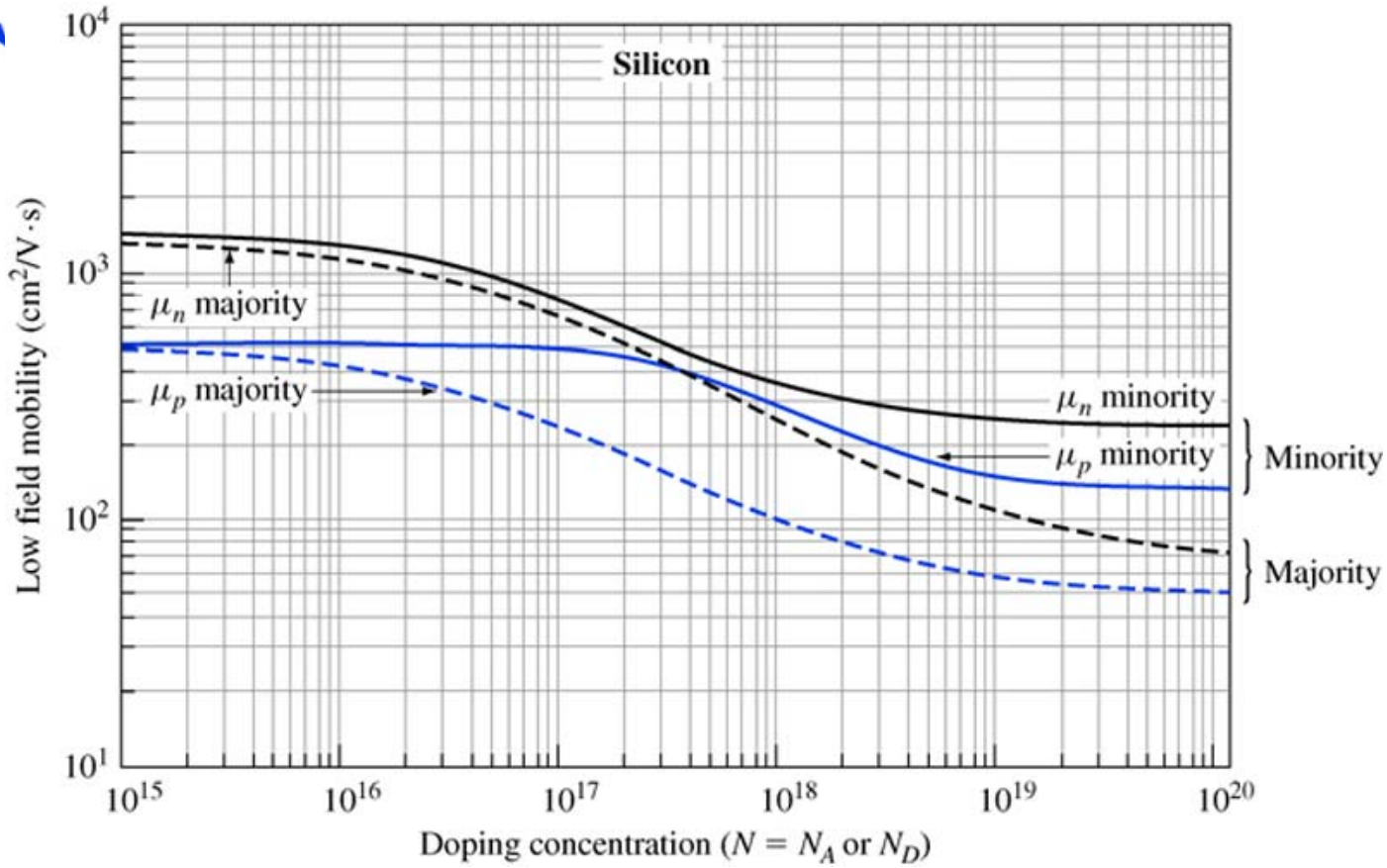


- Dopants are impurities in the crystal and cause local changes to the crystal potential seen by a moving electron

Mobility Dependence On Doping

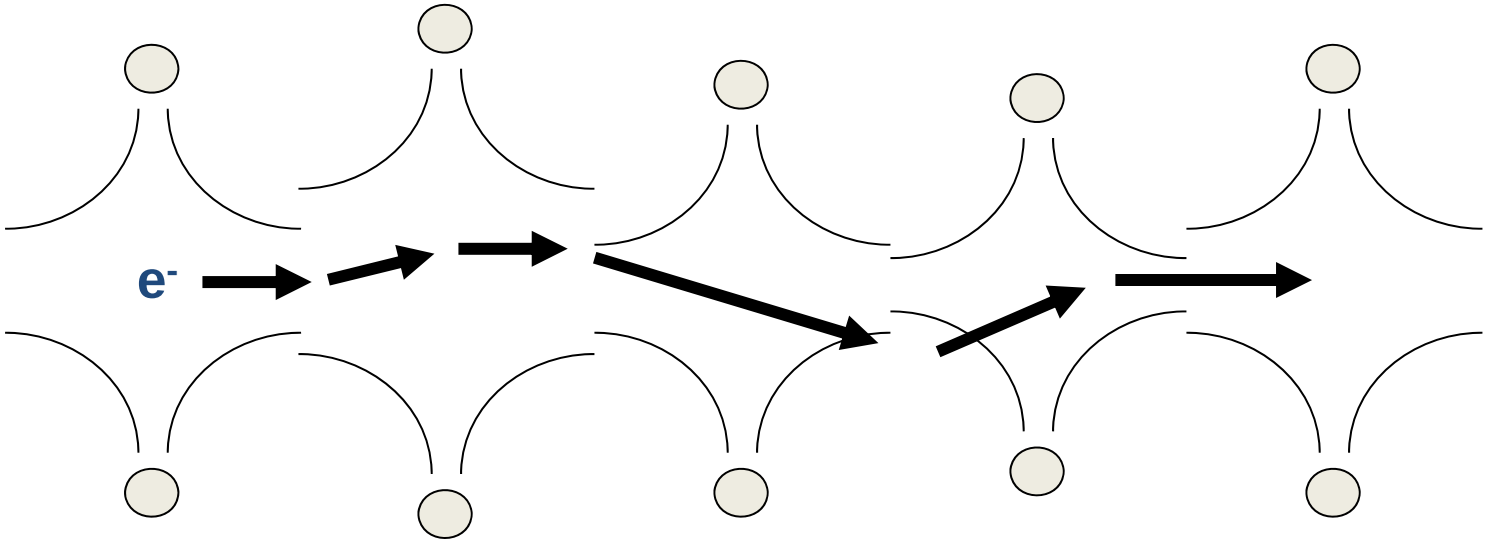


Ionized dopants result in an increase in carrier scattering



Mobility Dependence on Temperature

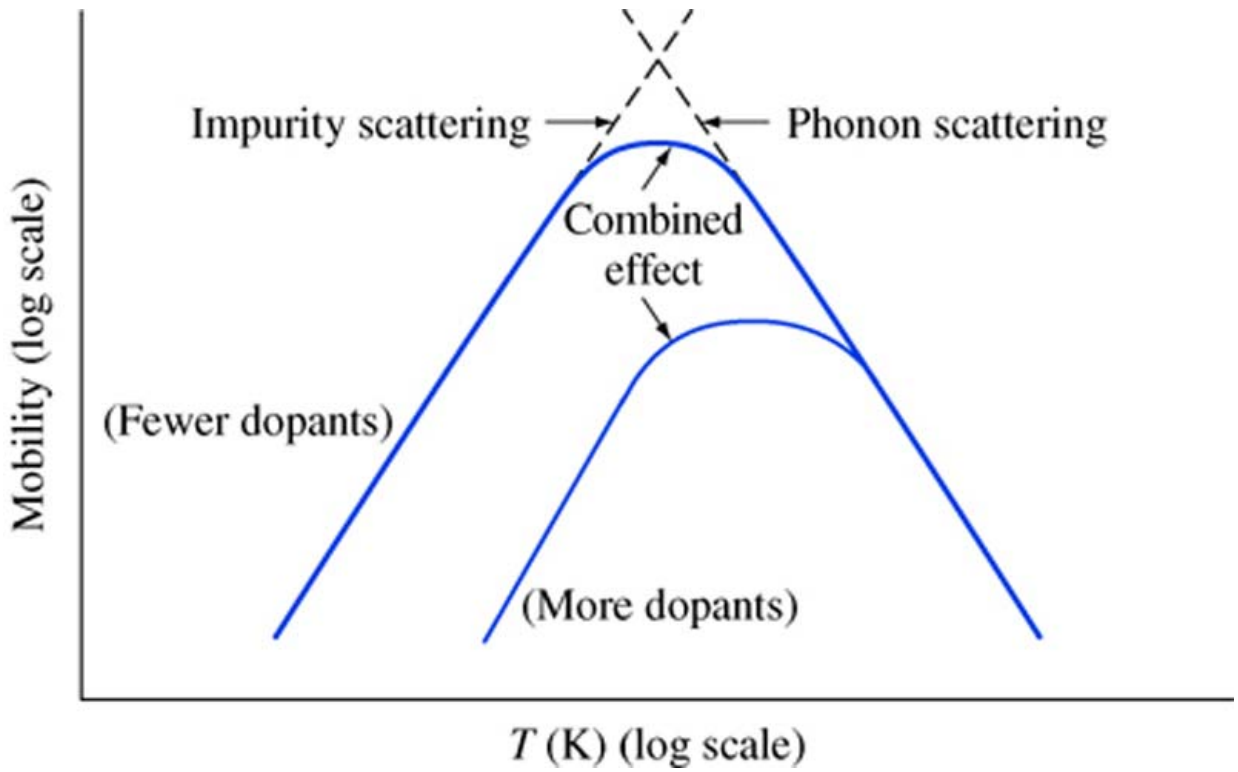
Mobility shows clear dependence on temperature



- Vibration of crystal atoms due to temperature causes a varying crystal potential as seen by a moving electron

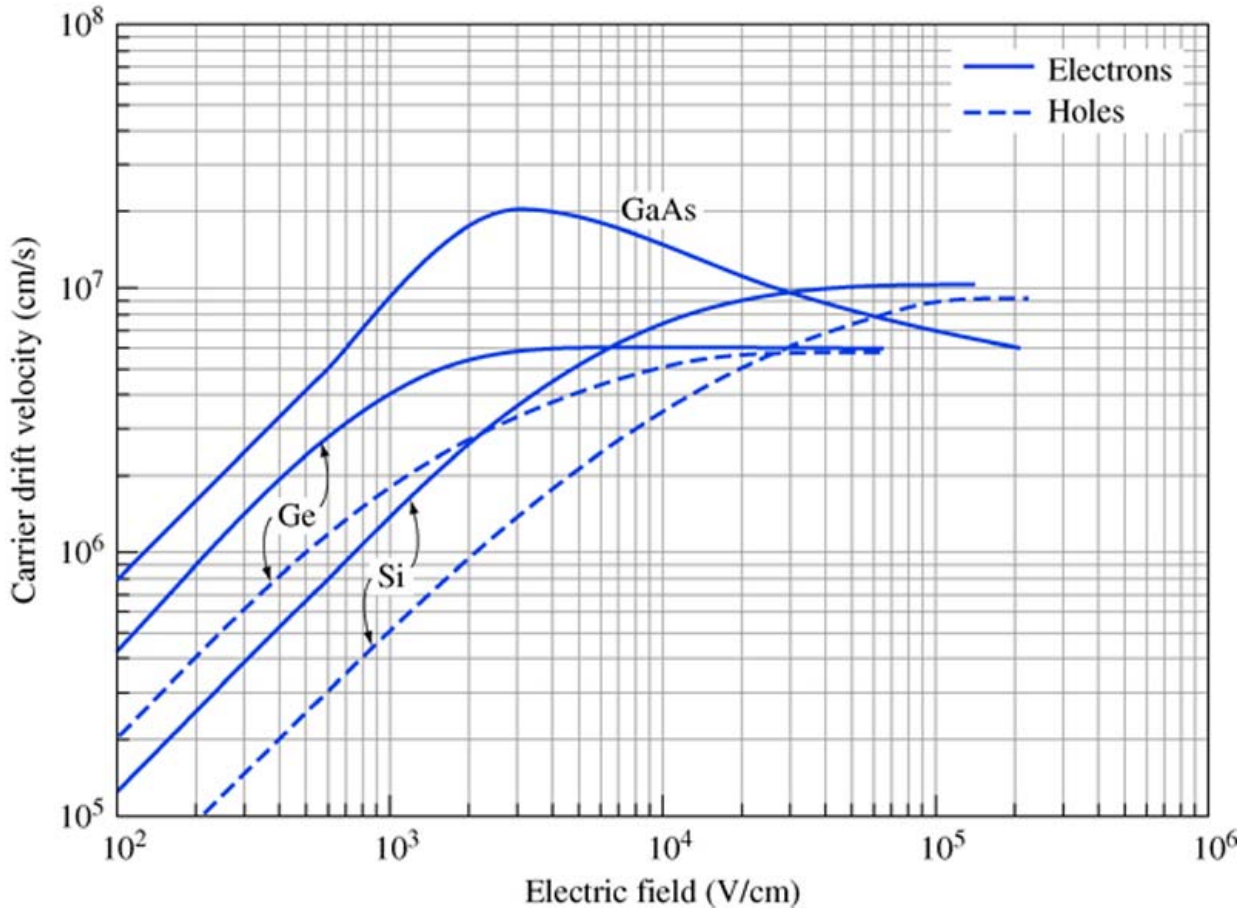
Mobility Dependence on Temperature

Scattering mechanisms have different temperature dependencies, need to determine dominant mechanism



High Field Mobility

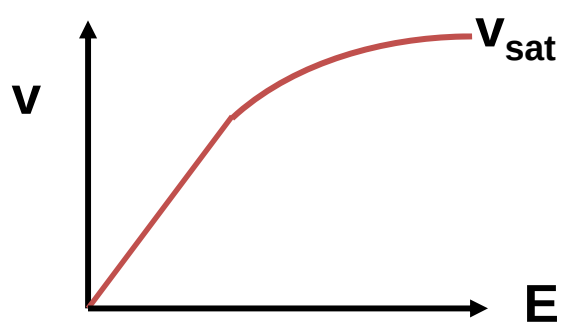
At high fields, mobility not constant, velocity "saturates"



Velocity Saturation

At high electric fields, mobility is no longer constant

- Drift velocity becomes comparable to thermal velocity
- When carriers achieve energy above ambient thermal energy, characterized as *hot carriers*
- Hot carriers are subject to additional scattering mechanisms such as optical phonons
- Velocity tends to saturate at high fields – analogous to terminal velocity in freefall



$$v_d = \frac{\mu_0 E}{\left[1 + \left(\frac{\mu_0 E}{v_{sat}}\right)^{\beta}\right]^{1/\beta}}$$

Drift Current

Drift Current

$$J_n = -nqv_{drift} = nq\mu_n E \qquad J_p = pqv_{drift} = pq\mu_p E$$

$$J = \sigma E$$

$$\boxed{J = J_n + J_p = \left(nq\mu_n + pq\mu_p\right)E}$$

Conductivity

$$\boxed{\sigma = nq\mu_n + pq\mu_p}$$

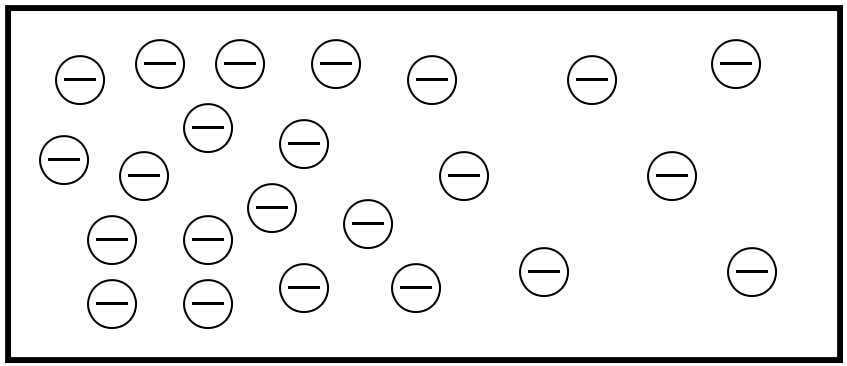
Conductivity depends on mobility and carrier concentration

How can you alter conductivity in a semiconductor?

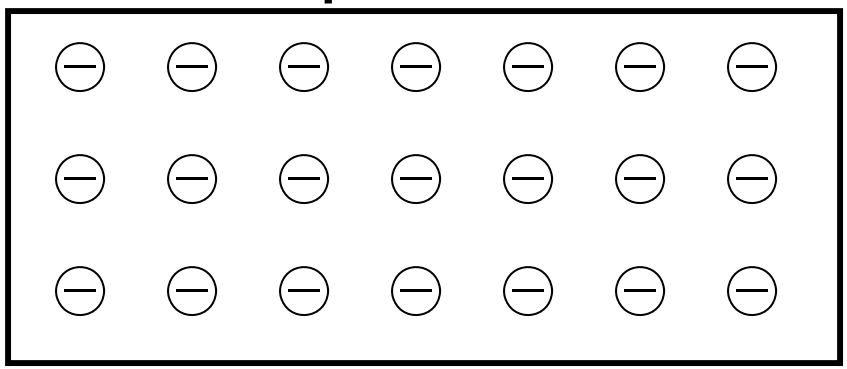
Diffusion

Carriers flow from high to low concentration

Electron diffusion →



Equilibrium

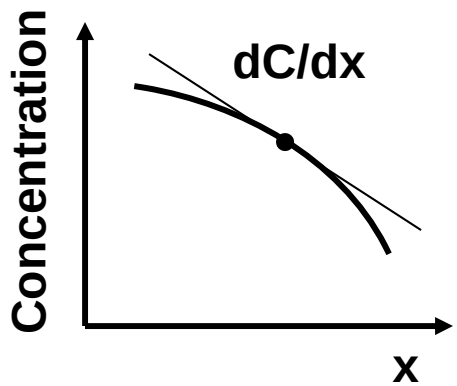


Diffusion Current

Diffusion process described by

- Fick's law: flux given by F=-D$\Delta\eta$
- Diffusion constant, D
- Diffusion process dependent on material properties

Diffusion current given by diffusion constant and concentration gradient



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

$$J_n = qD_n \frac{dn}{dx}$$

Einstein Relation

Constants for diffusion and drift are related

Examine current in semiconductor at equilibrium

$$J_n = q\mu_n nF + qD_n \frac{dn}{dx} = 0$$

$$q\mu_n n_i \exp\left(\frac{E_f - E_i}{kT}\right)\frac{1}{q}\frac{dE_i}{dx} = -\frac{q}{kT}D_n n_i \exp\left(\frac{E_f - E_i}{kT}\right)\left(\frac{dE_f}{dx} - \frac{dE_i}{dx}\right) = 0$$

$$\frac{dE_f}{dx} = 0 \text{ at equilibrium}$$

$$\boxed{\frac{D_n}{\mu_n} = \frac{kT}{q}}$$

Drift Diffusion & E_f

$$J_n = q\mu_n nF + qD_n \frac{dn}{dx}$$

$$= q\mu_n nF + q\left(\frac{kT}{q}\right)\mu_n \frac{dn}{dx}$$

$$= q\mu_n nF + kT\mu_n \frac{dn}{dx}$$

$$= q\mu_n n\frac{1}{q}\frac{dE_i}{dx} + kT\mu_n \frac{d}{dx}\left(N_c e^{(E_f - E_c)/kT}\right)$$

$$= \mu_n n\frac{dE_i}{dx} + \mu_n N_c e^{(E_f - E_c)/kT}\left(\frac{dE_f}{dx} - \frac{dE_c}{dx}\right)$$

$$= \mu_n n\frac{dE_i}{dx} + \mu_n n\left(\frac{dE_f}{dx} - \frac{dE_i}{dx}\right)$$

$$= \mu_n n\frac{dE_f}{dx}$$

More Generally, and not dependent on Boltzmann Statistics:

$$J_n = \mu_n n\nabla E_{fn}$$

$$J_p = \mu_p p\nabla E_{fp}$$

Summary

- For this class, we will assume electron and hole currents are given by:

$$1-D$$

$$J_n = q\mu_n nF + qD_n \frac{dn}{dx} = \mu_n n \frac{dE_{fn}}{dx}$$

$$J_p = q\mu_p pF - qD_p \frac{dp}{dx} = \mu_p p \frac{dE_{fp}}{dx}$$

$$3-D$$

$$\vec{J}_n = q\mu_n n\vec{F} + qD_n \nabla n = \mu_n n \nabla E_{fn}$$

$$\vec{J}_p = q\mu_p p\vec{F} - qD_n \nabla p = \mu_p p \nabla E_{fp}$$