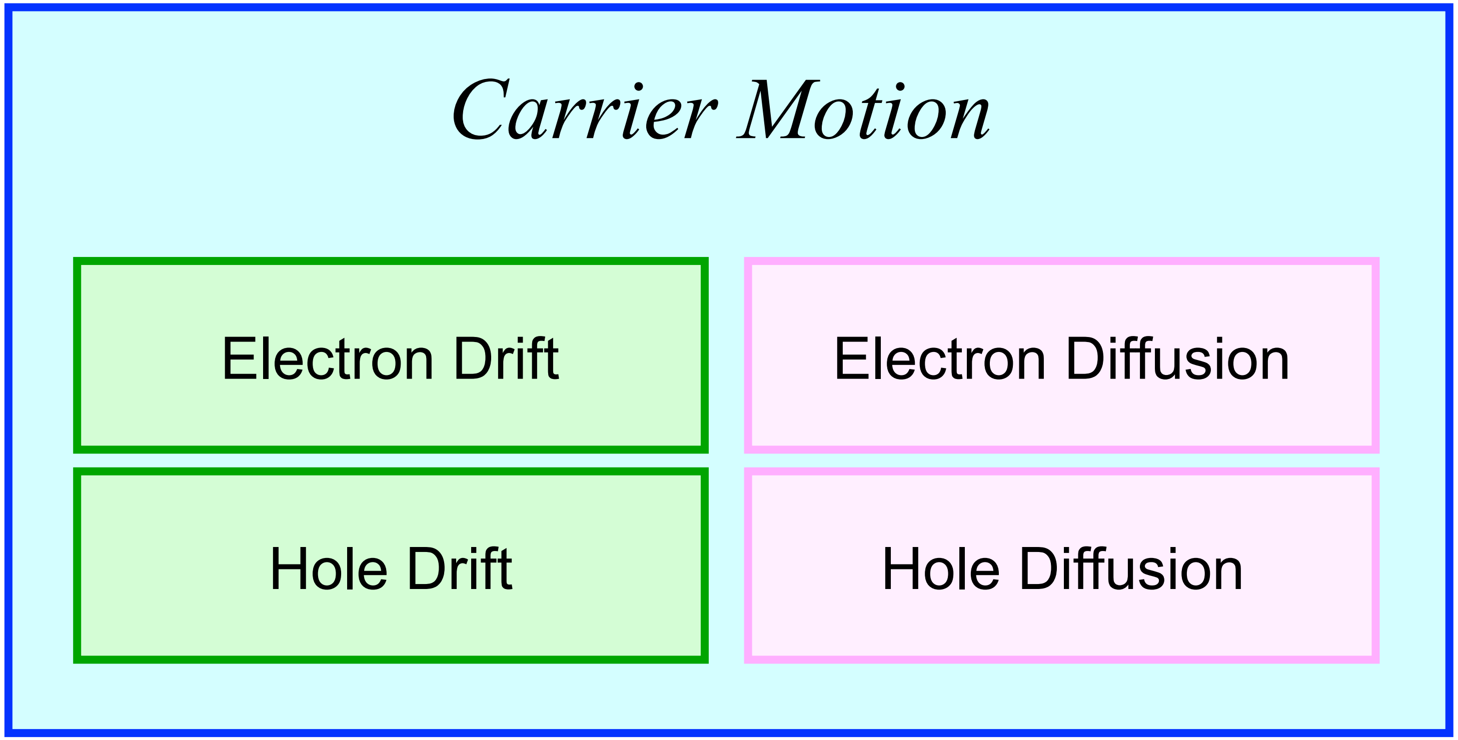
Carrier Action

Drift and Diffusion Currents

Carrier Dynamics



Carrier Motion

Electron Drift

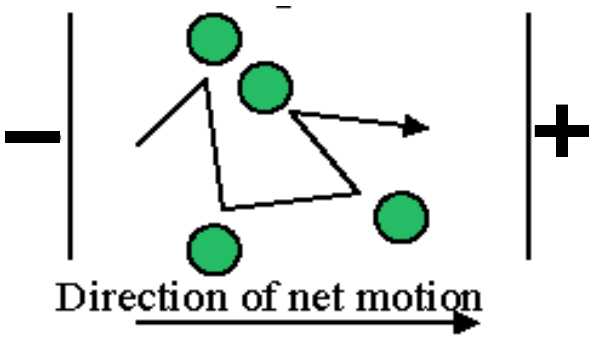
Electron Diffusion

Hole Drift

Hole Diffusion

Drift

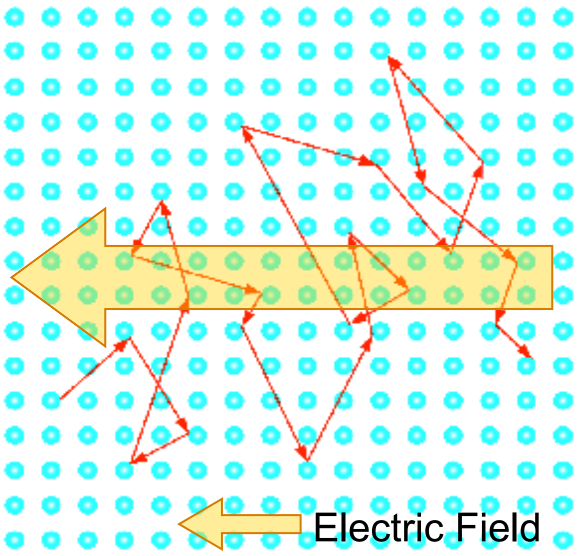
- ❑ Direction of motion
  - ➢ Holes move in the direction of the electric field. (⊕➪⊖)
  - ➢ Electrons move in the opposite direction of the electric field. (⊖➪⊕)
  - ➢ Motion is highly non-directional on a local scale, but has a net direction on a macroscopic scale.
  - ➢ Average net motion is described by the drift velocity, v_d [cm/sec].
  - ➢ Net motion of charged particles gives rise to a current.



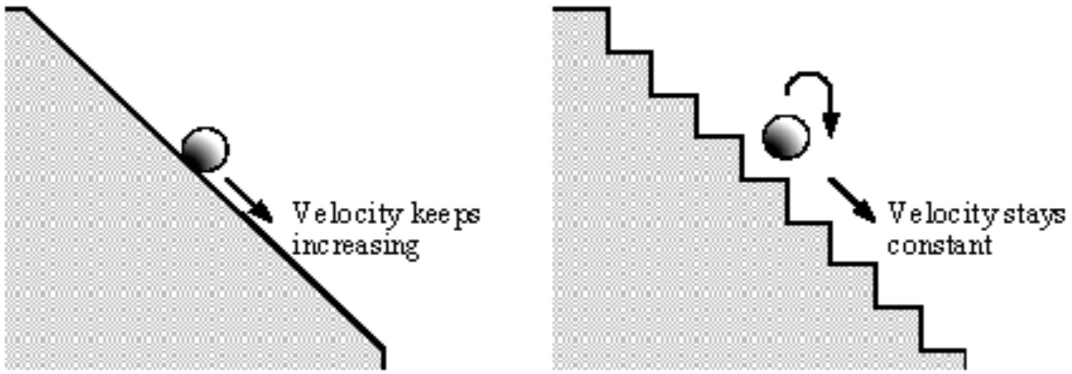
Instantaneous velocity is extremely fast

Drift

☐ Drift of Carriers



Drift of electron in a solid



The ball rolling down the smooth hill speeds up continuously, but the ball rolling down the stairs moves with a constant average velocity.

Average drift velocity:

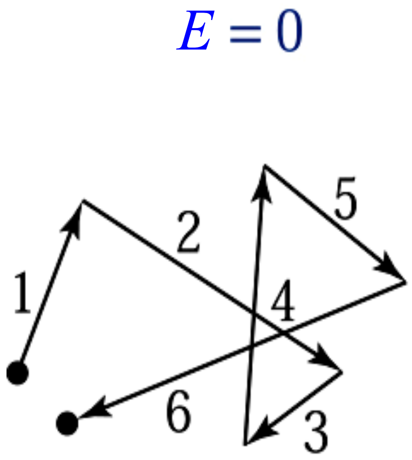
$$\langle \mathbf{v} \rangle\big|_{electron} = -\mu_n \mathbf{E}$$

$$\langle \mathbf{v} \rangle\big|_{hole} = \mu_p \mathbf{E}$$

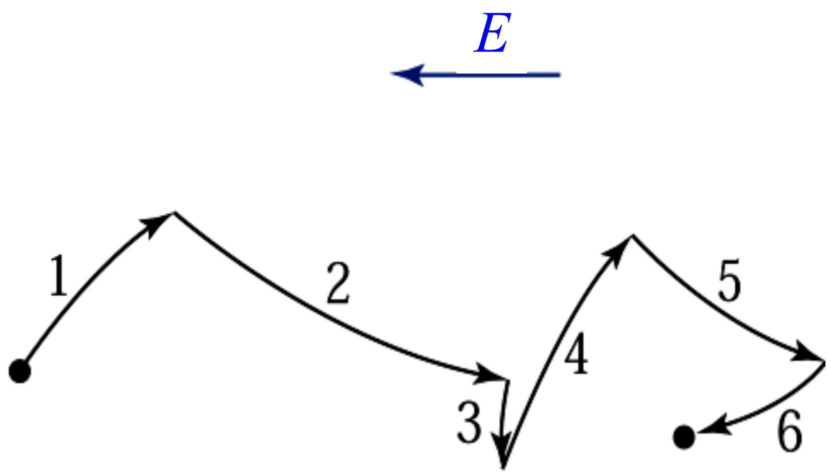
$\mu\ [cm^2/Vsec]$: mobility

Drift

- Schematic path of an electron in a semiconductor.

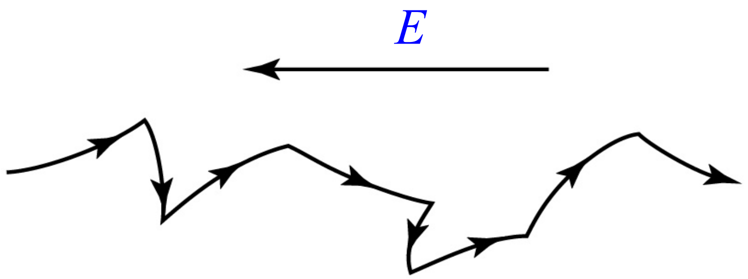


Random thermal motion.

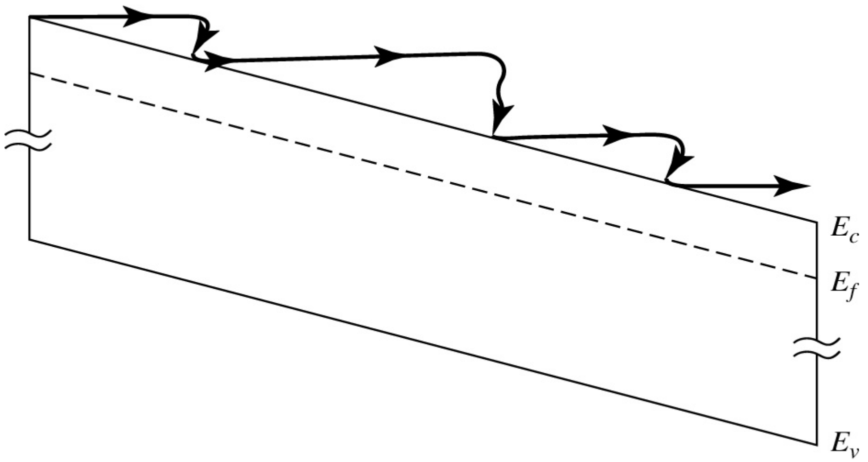


Combined motion due to random thermal motion and an applied electric field.

Drift



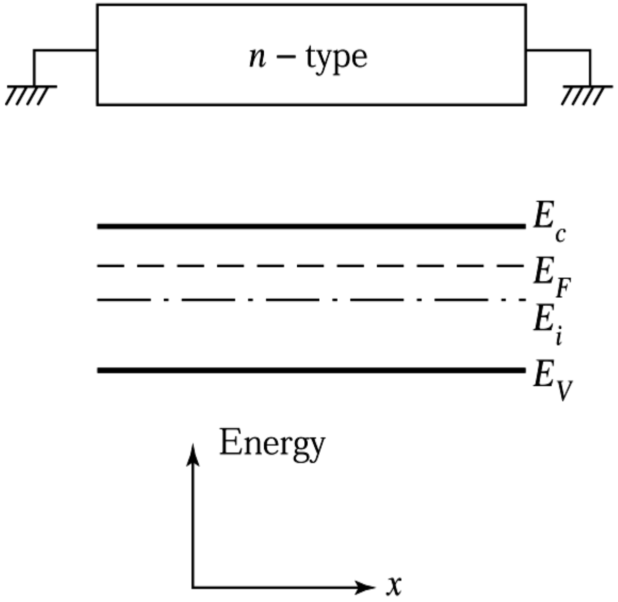
The motion of an electron in a solid under the influence of an applied field.



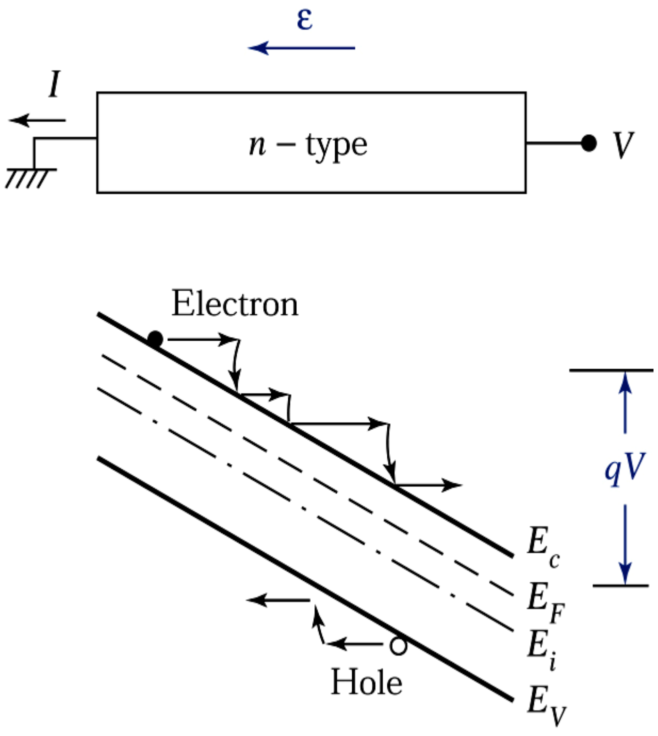
Energy-band representation of the motion, indicating the loss of energy when the electron undergoes a collision.

Drift

- ☐ Conduction process in an n-type semiconductor

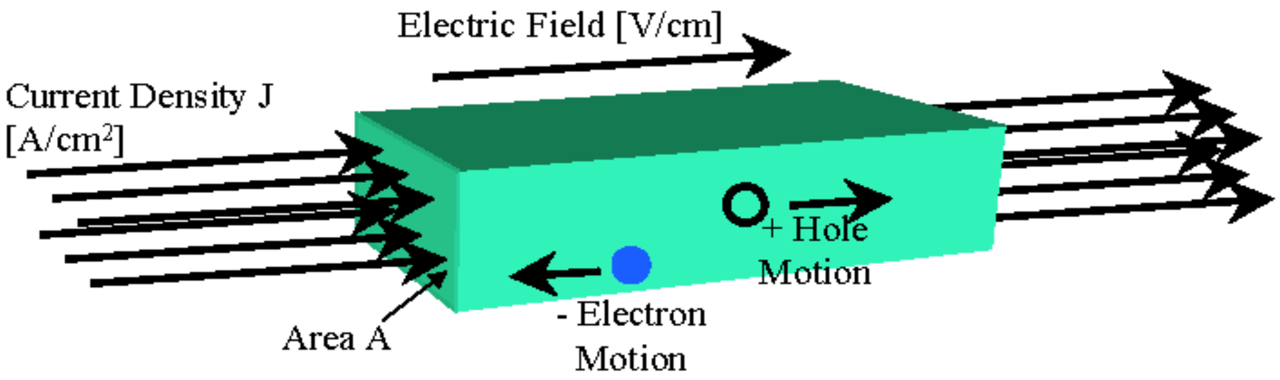


Thermal equilibrium



Under a biasing condition

Drift



Given current density J ($I = J \times Area$) flowing in a semiconductor block with face area A under the influence of electric field E, the component of J due to drift of carriers is:

$$\boxed{J_p\big|_{Drift} = q \cdot p \cdot v_d}$$

and

$$\boxed{J_n\big|_{Drift} = q \cdot n \cdot v_d}$$

Hole Drift Current Density

Electron Drift Current Density

Drift

- ☐ At Low Electric Field Values,

$$\boxed{J_p\Big|_{Drift} = q\cdot p\cdot \mu_p \cdot E}$$ and $$\boxed{J_n\Big|_{Drift} = q\cdot n\cdot \mu_n \cdot E}$$

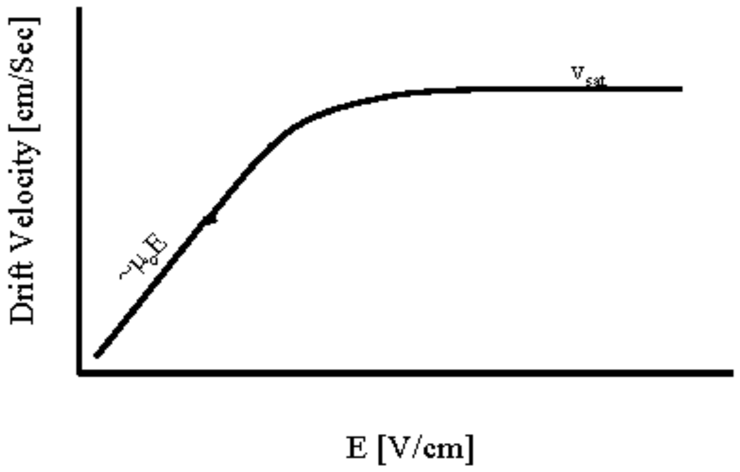
- ➢ $\mu\ [cm^2/V\cdot sec]$ is the "mobility" of the semiconductor and measures the ease with which carriers can move through the crystal.
- ➢ The drift velocity increases with increasing applied electric field. More generally, for Silicon and similar materials the drift velocity can be *empirically* given as:

$$v_d = \frac{\mu_0}{\left[1+\left(\dfrac{\mu_0 E}{v_{sat}}\right)^{\beta}\right]^{1/\beta}} \cong \begin{cases} \mu_0 E & when\ \ E \to 0 \\ v_{sat} & when\ \ E \to \infty \end{cases}$$

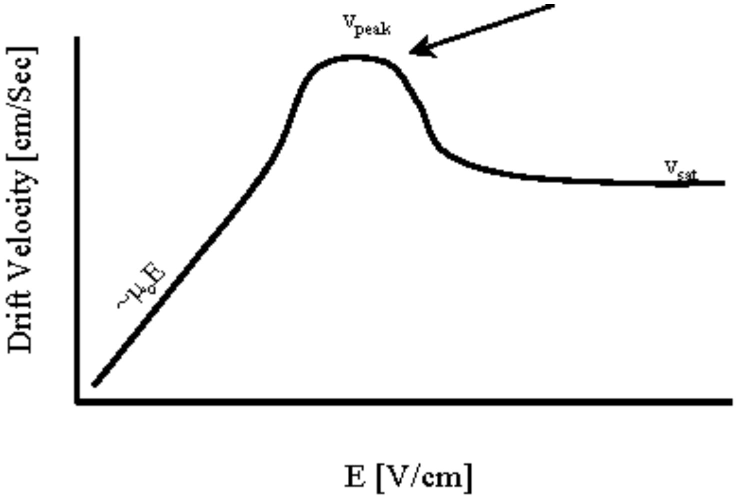
where v_{sat} is saturation velocity

Drift

❑ Drift velocity vs. Electric field



Si and similar materials



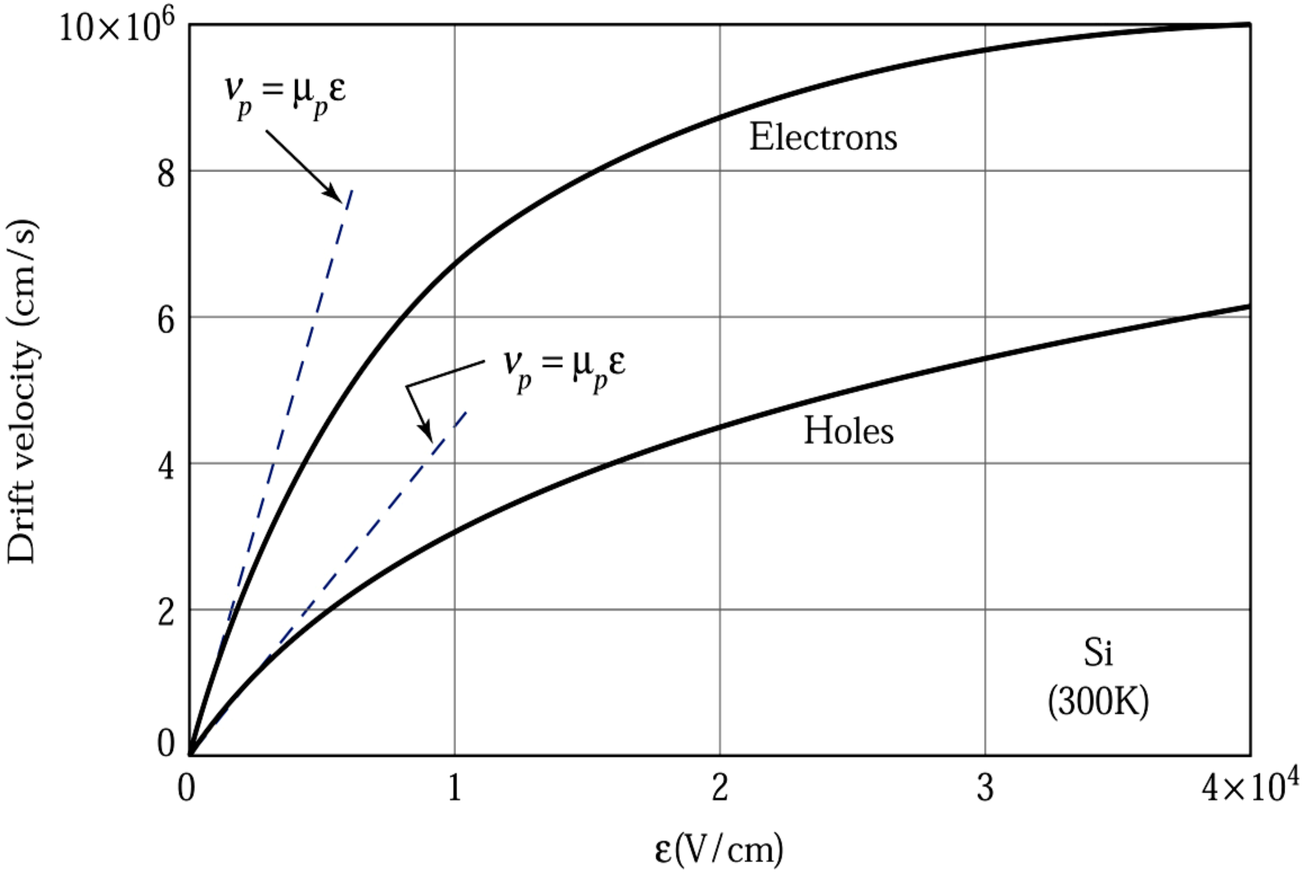
Designing devices to work here results in faster operation

GaAs and similar materials

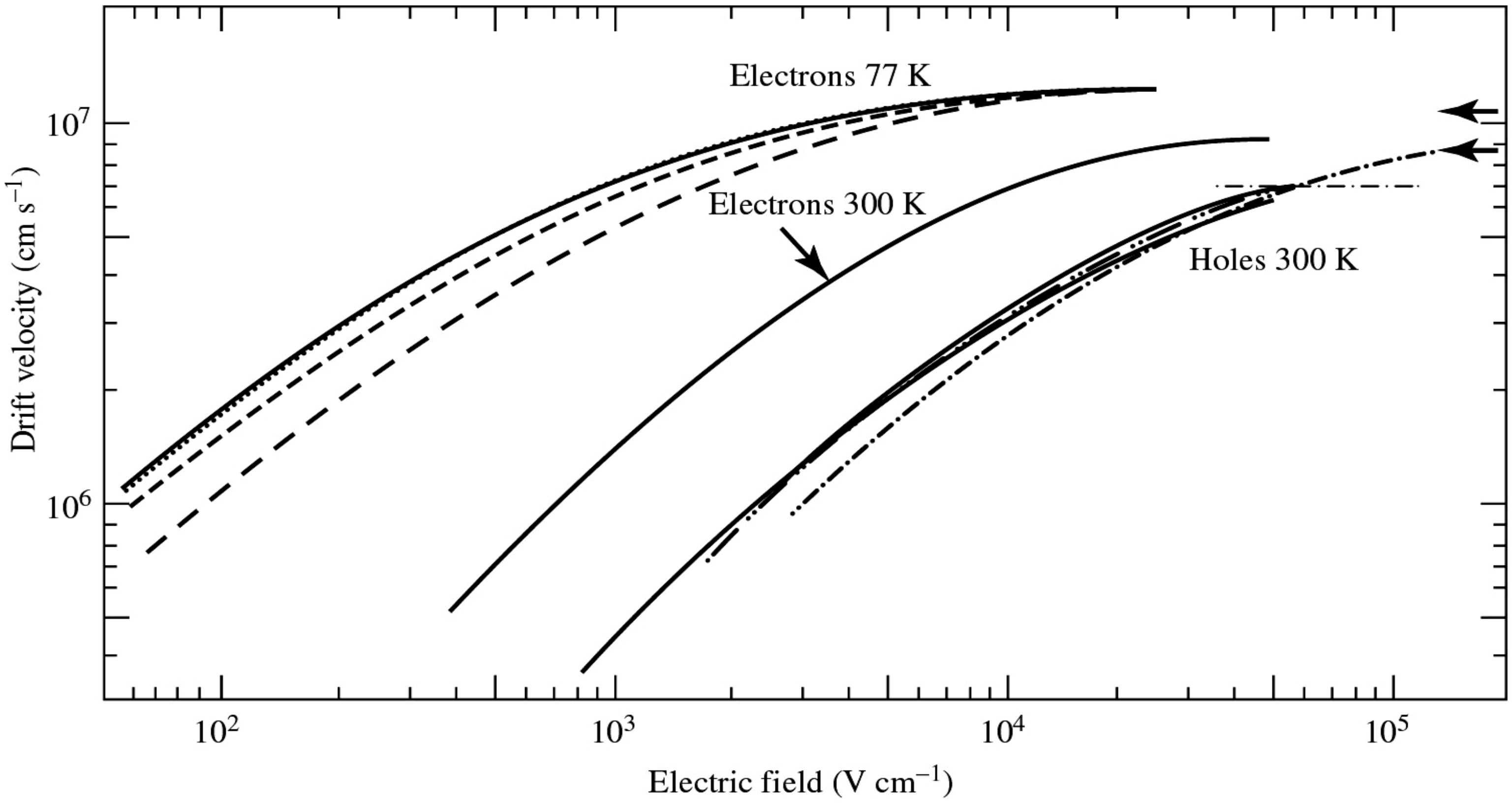
- Ohm's law is valid only in the low-field region where drift velocity is independent of the applied electric field strength.
- Saturation velocity is approximately equal to the thermal velocity (10^7 cm/s).

Drift

- ☐ Drift velocity vs. Electric field in Si.



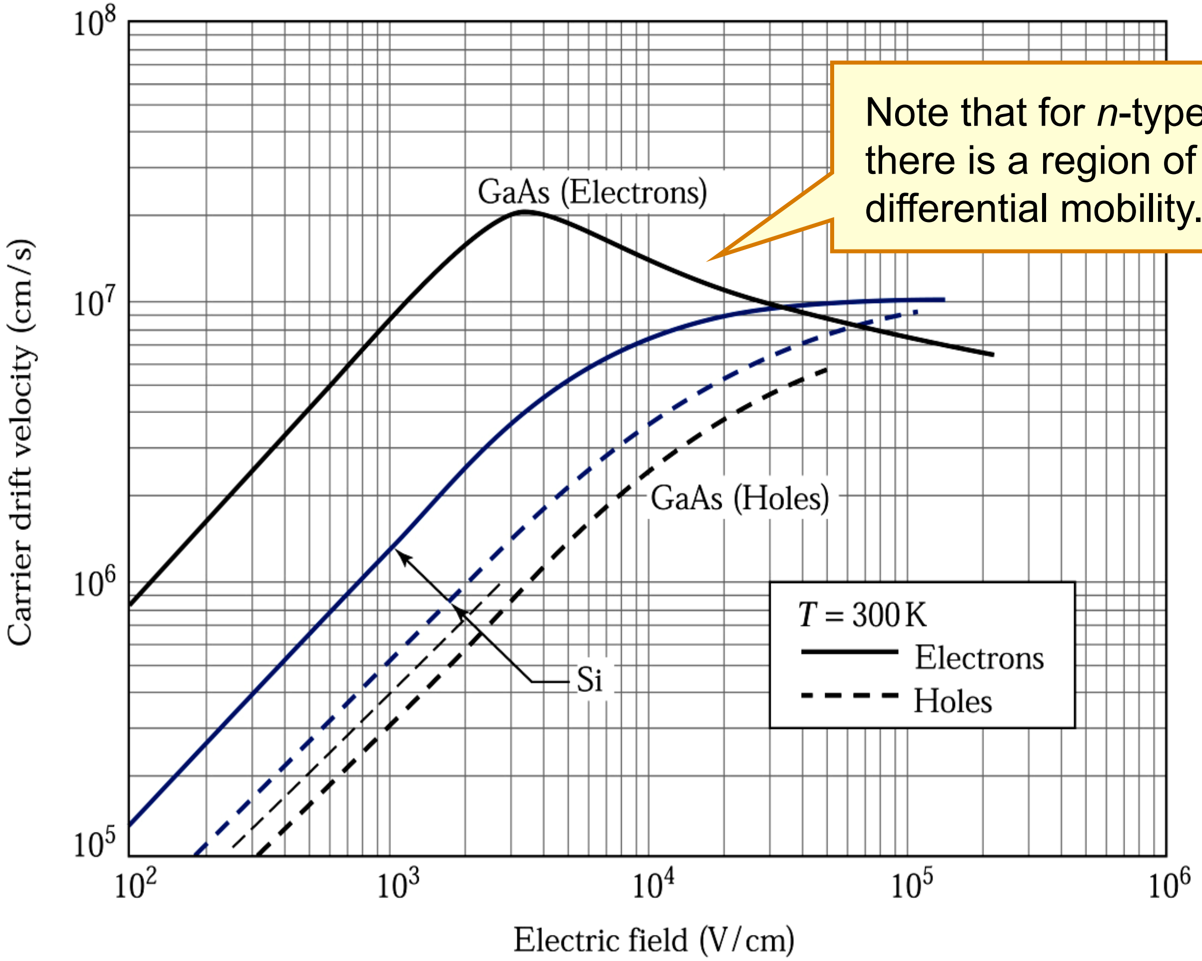
Drift



- Drift velocities of electrons (at 77 K and 300 K) and holes (at 300 K) in Silicon as functions of the applied field, showing velocity saturation at high fields.
- The presence of several curves indicates the variation in reported data.

Drift

- ☐ Drift velocity vs. Electric field in Si and $GaAs$.



Note that for *n*-type GaAs, there is a region of negative differential mobility.

Drift

- ❑ Mobility

  - ➢ μ $[cm^2/Vsec]$ is the “mobility” of the semiconductor and measures the ease with which carriers can move through the crystal.
    - $\mu_n \sim 1360\ cm^2/Vsec$ for Silicon @ 300K
    - $\mu_p \sim 460\ cm^2/Vsec$ for Silicon @ 300K
    - $\mu_n \sim 8000\ cm^2/Vsec$ for GaAs @ 300K
    - $\mu_p \sim 400\ cm^2/Vsec$ for GaAs @ 300K

$$\mu_{n,p} = \frac{q\langle\tau\rangle}{m^*_{n,p}} \quad \left[cm^2/V\sec\right]$$

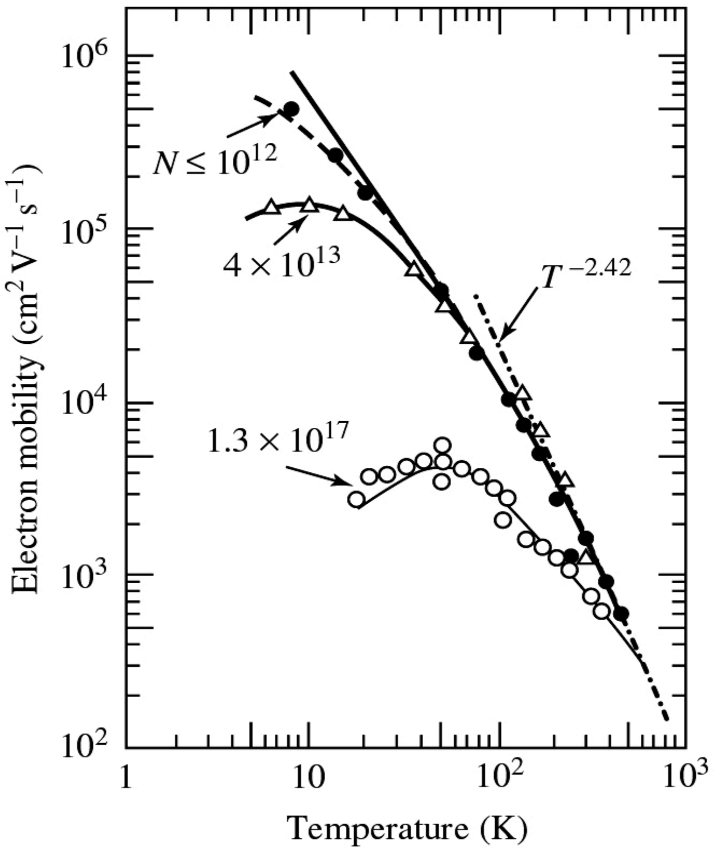
Average drift velocity:

$$\langle \mathbf{v}\rangle\big|_{electron} = -\mu_n \mathbf{E}$$

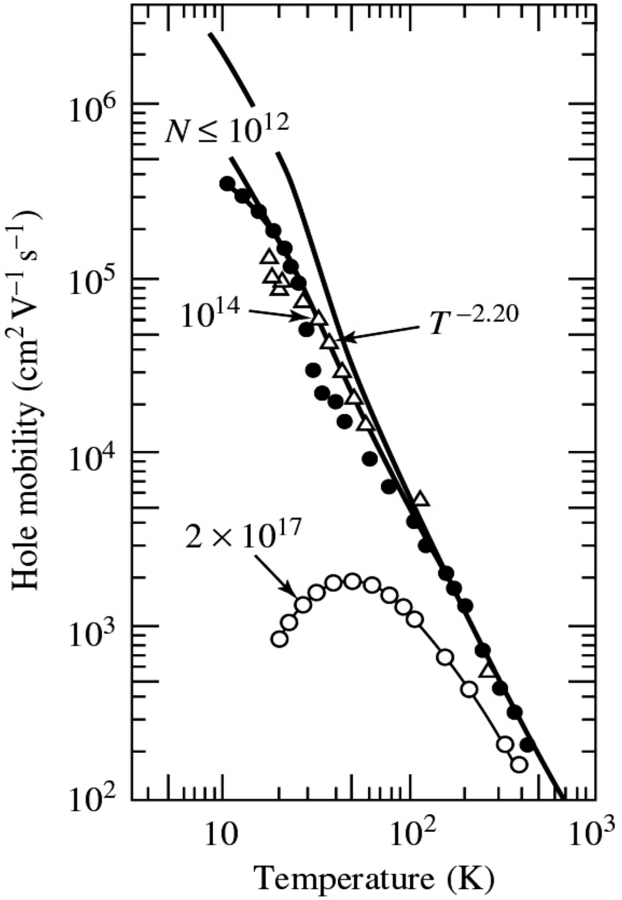
$$\langle \mathbf{v}\rangle\big|_{hole} = \mu_p \mathbf{E}$$

  - ➢ $<\tau>$ is the average time between “particle” collisions in the semiconductor.
  - ➢ Collisions can occur with lattice atoms, charged dopant atoms, or with other carriers.

Drift



Electrons



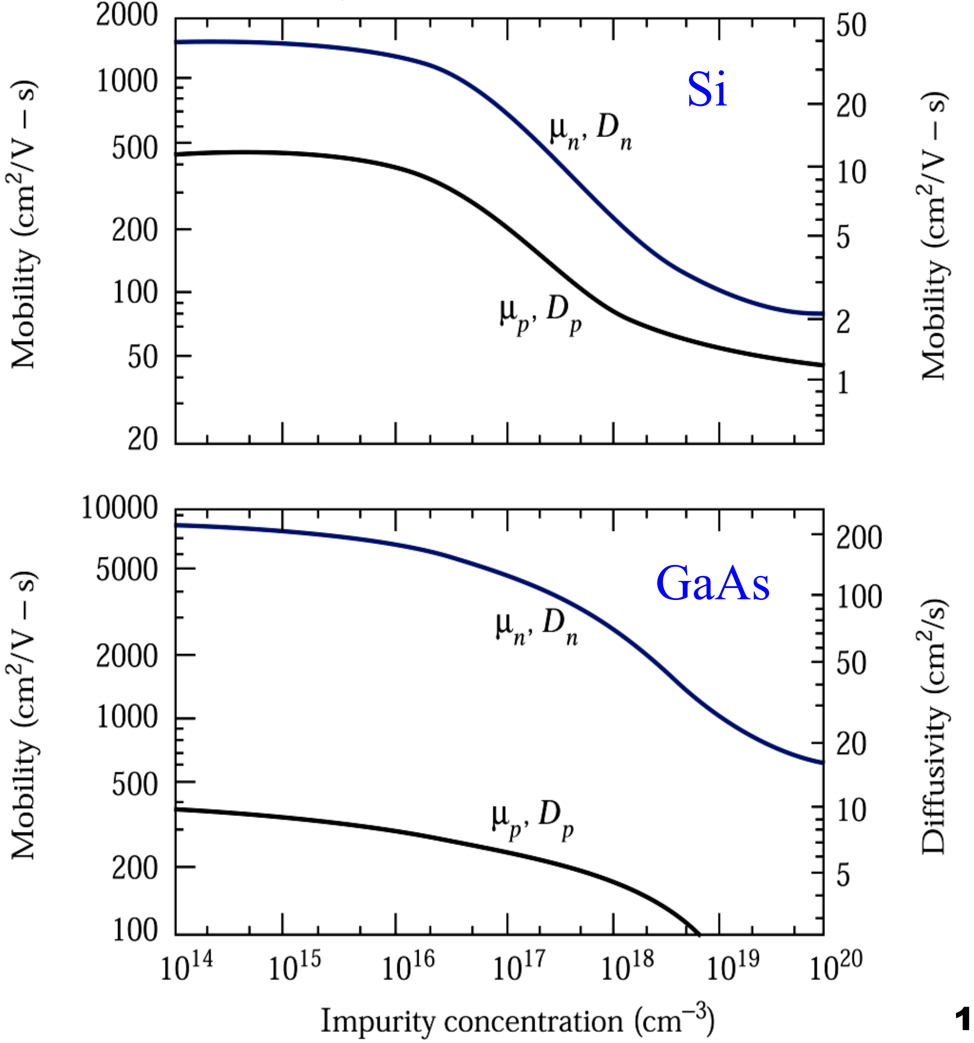
Holes

- Low-field mobility in Silicon as a function of temperature.
- The solid lines represent the theoretical predictions for pure lattice scattering.

Drift

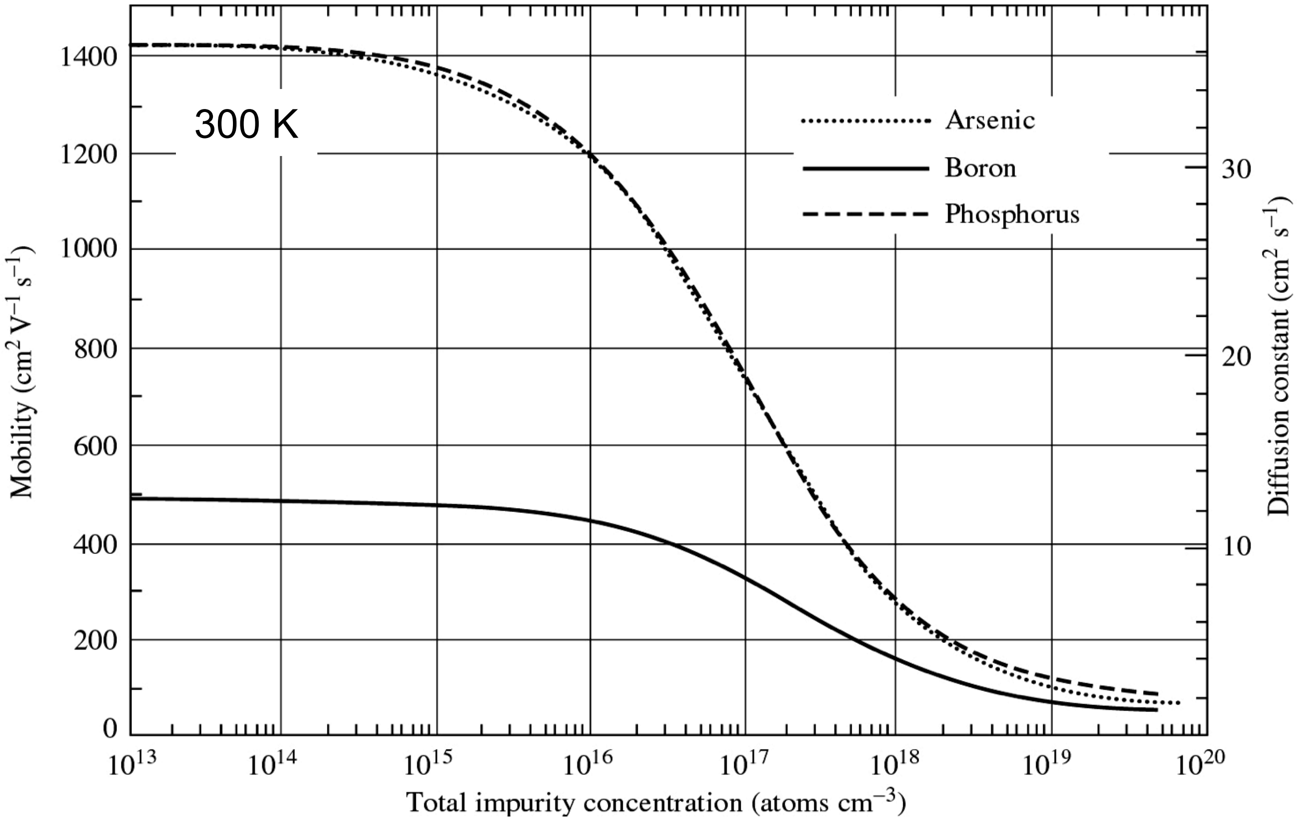
- ❑ Effect of Doping concentration on Mobility

Mobilities and diffusivities in Si and GaAs at 300 K as a function of total impurity concentration (N_A+N_D).



Drift

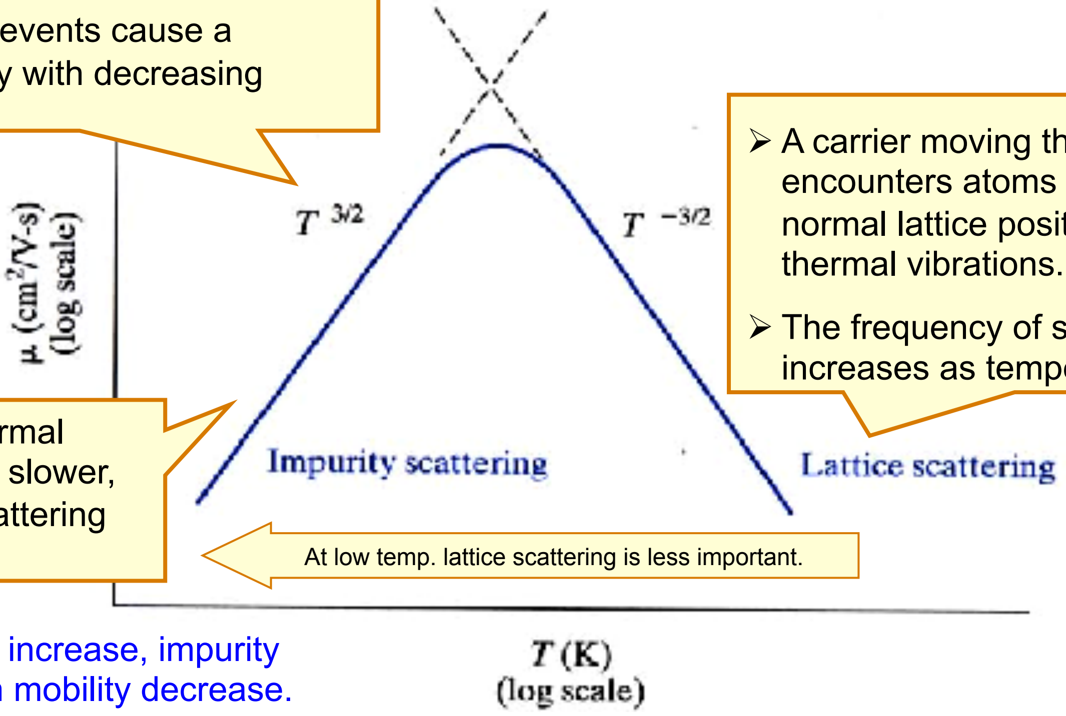
- ❑ Effect of Doping concentration on Mobility



- ➢ Electron and hole mobilities in *Silicon* as functions of the total dopant concentration.

Drift

❑ Effect of Temperature on Mobility



- Since the slowing moving carrier is likely to be scattered more strongly by an interaction with charged ion.
- Impurity scattering events cause a decrease in mobility with decreasing temperature.

- A carrier moving through the lattice encounters atoms which are out of their normal lattice positions due to the thermal vibrations.
- The frequency of such scattering increases as temperature increases.

- At low temperature, thermal motion of the carriers is slower, and ionized impurity scattering becomes dominant.

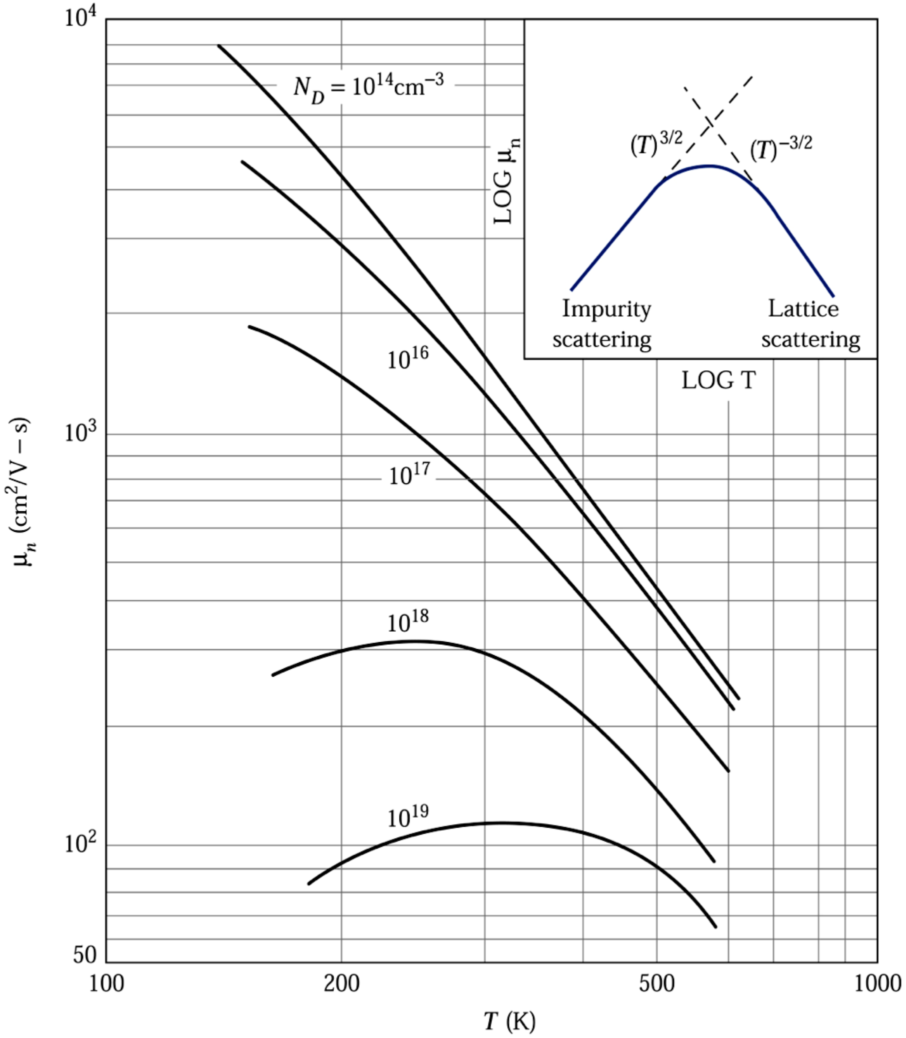
At low temp. lattice scattering is less important.

As doping concentration increase, impurity scattering increase, then mobility decrease.

Temperature dependence of mobility with both lattice and impurity scattering.

Drift

- ❑ Effect of Temperature on Mobility



- ➢ Electron mobility in silicon versus temperature for various donor concentrations.
- ➢ Insert shows the theoretical temperature dependence of electron mobility.

Resistivity and Conductivity

☐ Ohms' Law

$$J = \sigma \cdot E = \frac{E}{\rho} \quad \left[A/cm^2\right]$$ Ohms Law

$$\sigma \quad [1/ohm \cdot cm]$$ Conductivity

$$\rho \quad [ohm \cdot cm]$$ Resistivity

Resistivity and Conductivity

- ☐ Adding the Electron and Hole Drift Currents (at low electric fields)

$$J = J_p\big|_{Drift} + J_n\big|_{Drift} = q(\mu_p p + \mu_n n)\cdot E \qquad \textit{Drift Current}$$

$$\sigma = q(\mu_p p + \mu_n n) \qquad \textit{Conductivity}$$

$$\rho = \frac{1}{\sigma} = 1/\left[q(\mu_n n - \mu_p p)\right] \qquad \textit{Resistivity}$$

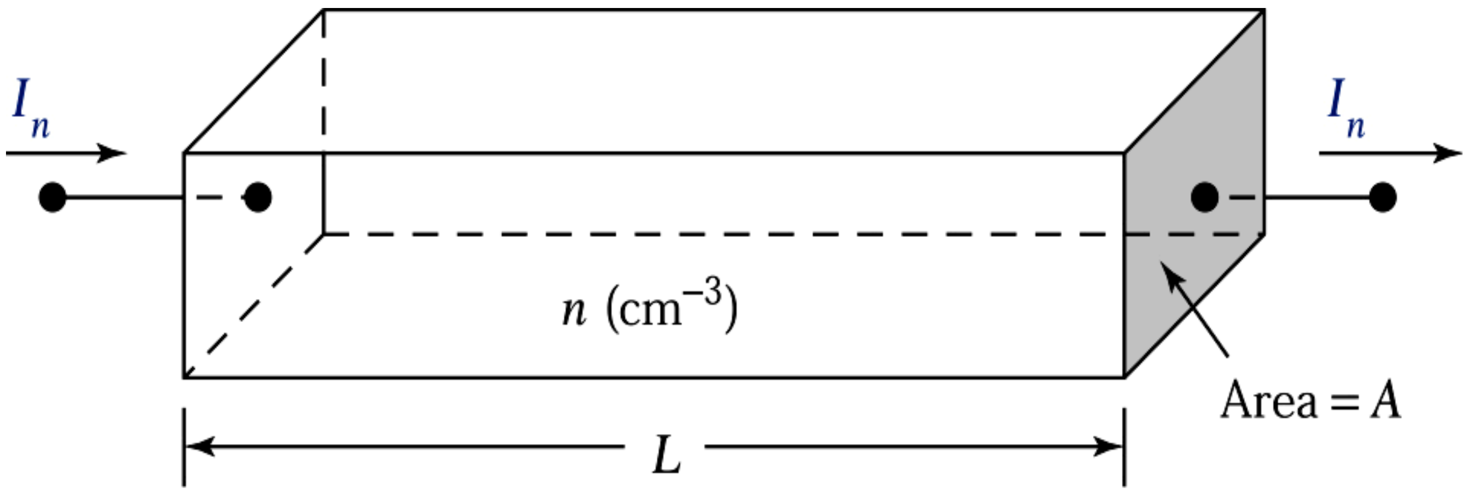
- But since μ_n and μ_p change very little and n and p change several orders of magnitude:

$$\sigma \cong q\,\mu_n n \qquad \textit{for n-type with } n>>p$$

$$\sigma \cong q\,\mu_p p \qquad \textit{for p-type with } p>>n$$

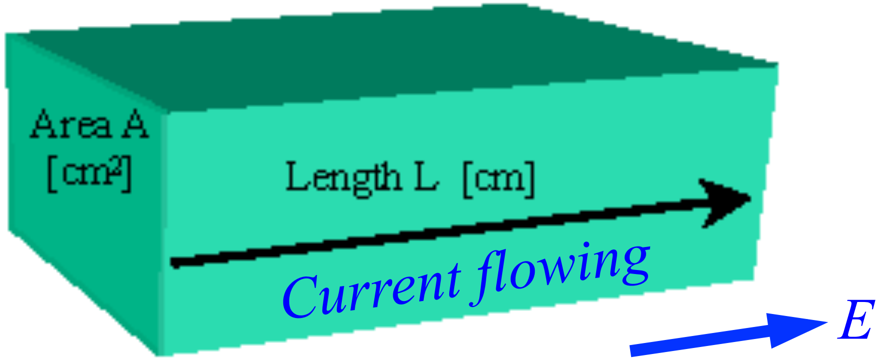
Current conduction

- ❑ Current conduction in a uniformly doped semiconductor bar with length L and cross-sectional area A.



Resistivity and Conductivity

- ☐ Do not confuse !!!
  - ❖ Resistance and Resistivity
  - ❖ Conductance and Conductivity

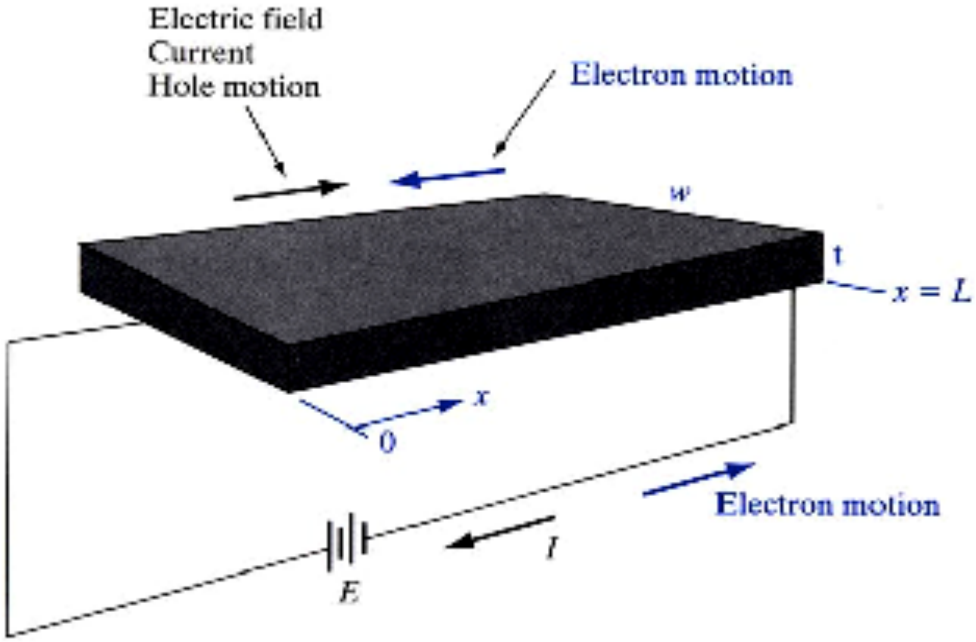


- ➢ Resistance to current flow along length L.

$$R = \frac{\rho \cdot L}{A}\left[\frac{ohm \cdot cm \cdot cm}{cm^2}\right] = [ohm] \quad \text{Resistance}$$

Resistivity and Conductivity

- Schematic Illustration of Sheet Resistance



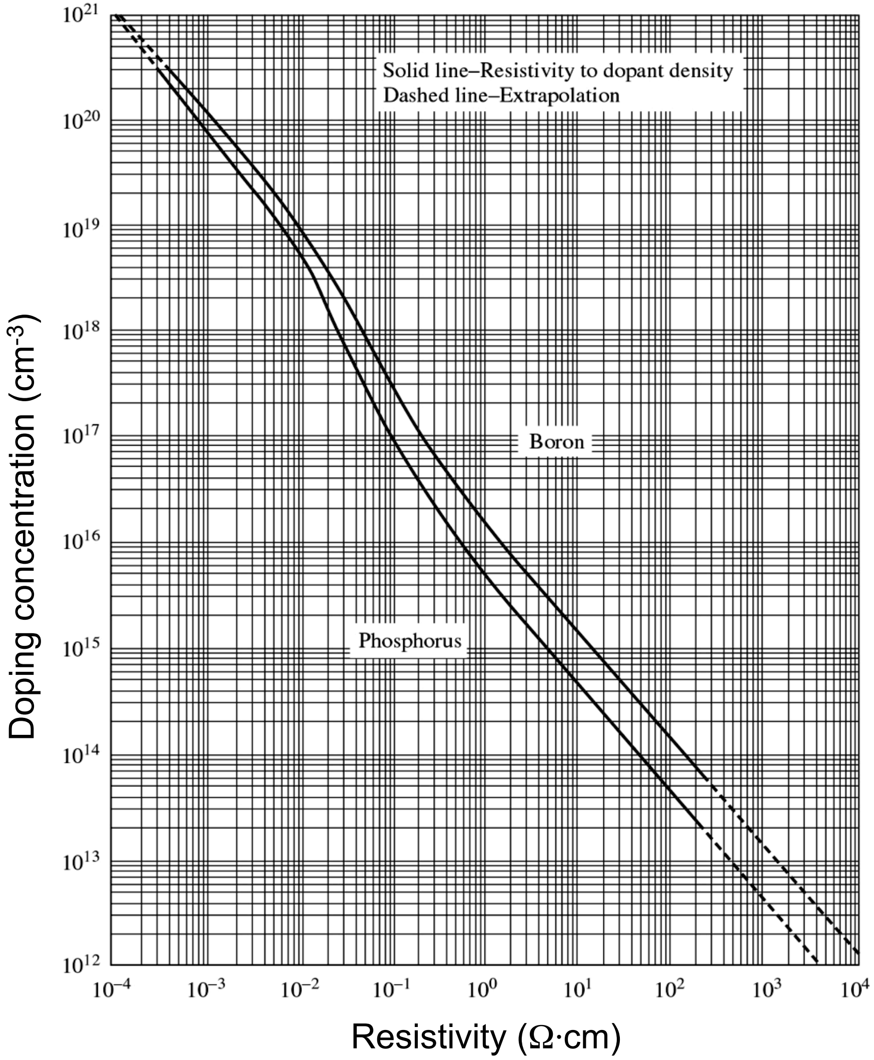
Drift of electrons and holes in a semiconductor bar.

$$R = \frac{\rho L}{wt} = \frac{L}{wt}\frac{1}{\sigma}$$

$$R = \frac{\rho L}{wt} = \frac{\rho}{t}\frac{L}{w} = R_{\square}\frac{L}{w}$$

$R_{\square}$: sheet resistance ($\Omega/\square$)

Resistivity



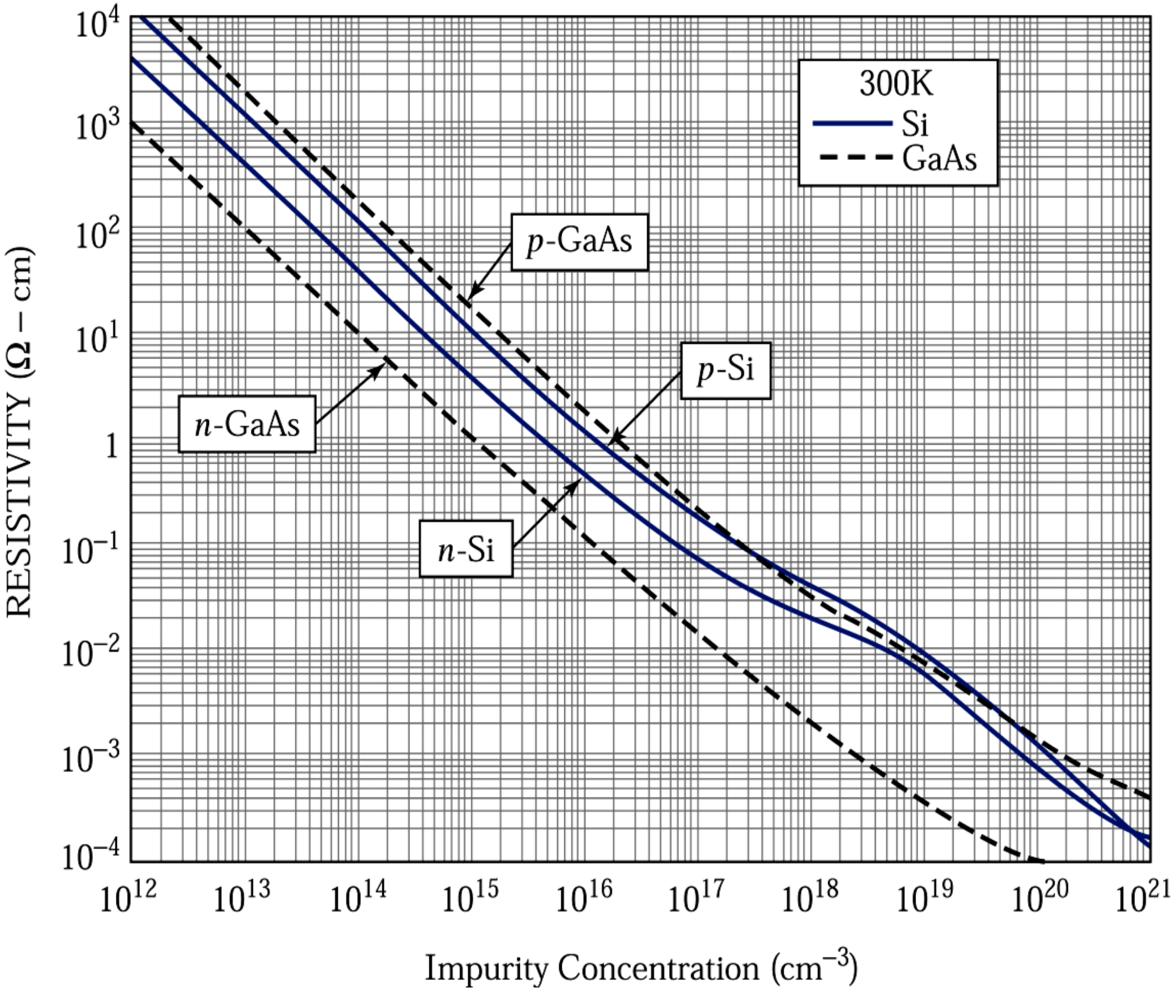
- <u>Dopant density</u> versus <u>resistivity</u> at 296 K for silicon doped with phosphorus and with boron.

The curves can be used with little error to represent conditions at 300 K.

[W. R. Thurber, R. L. Mattis, and Y. M. Liu, National Bureau of Standards Special Publication 400–64, 42 (May 1981).]

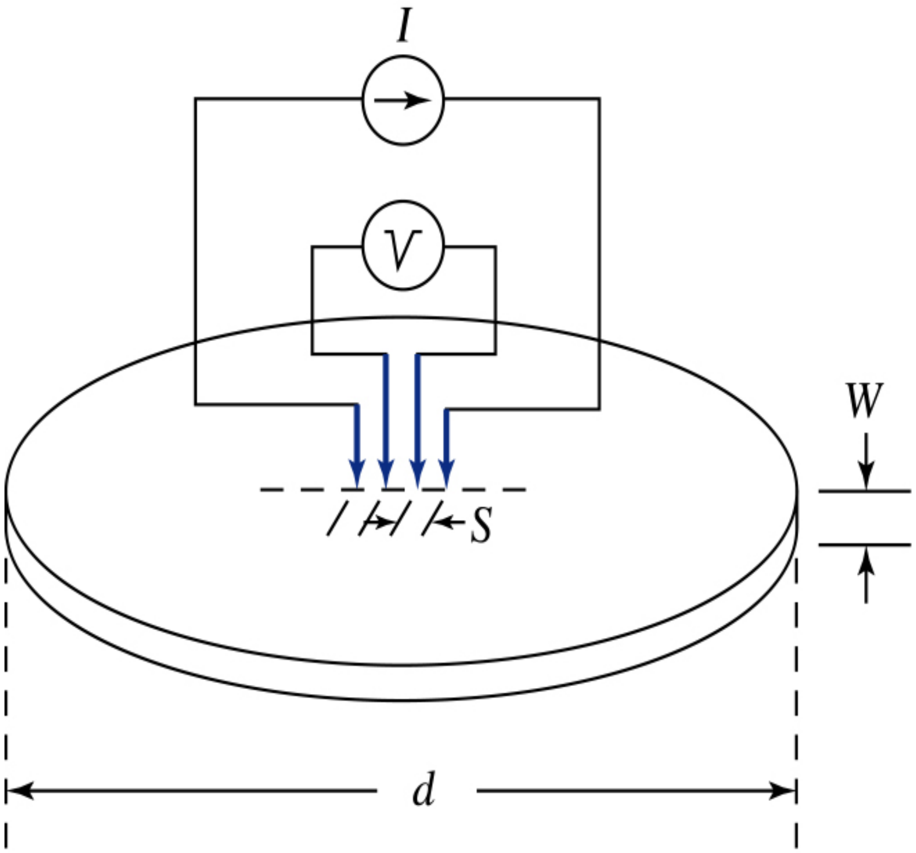
Resistivity

- Resistivity vs. Impurity concentration for Si and GaAs



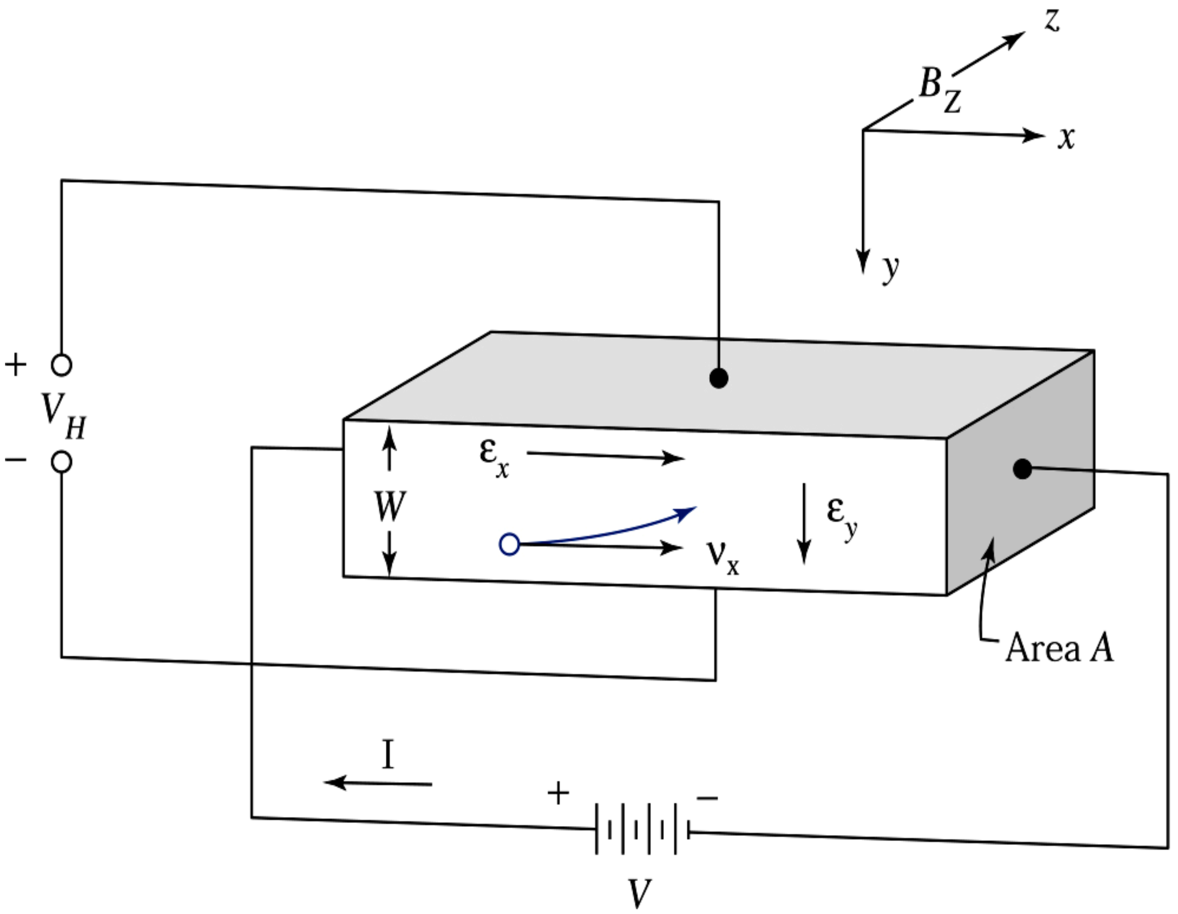
Resistivity

- Measurement of resistivity using a Four-point probe.

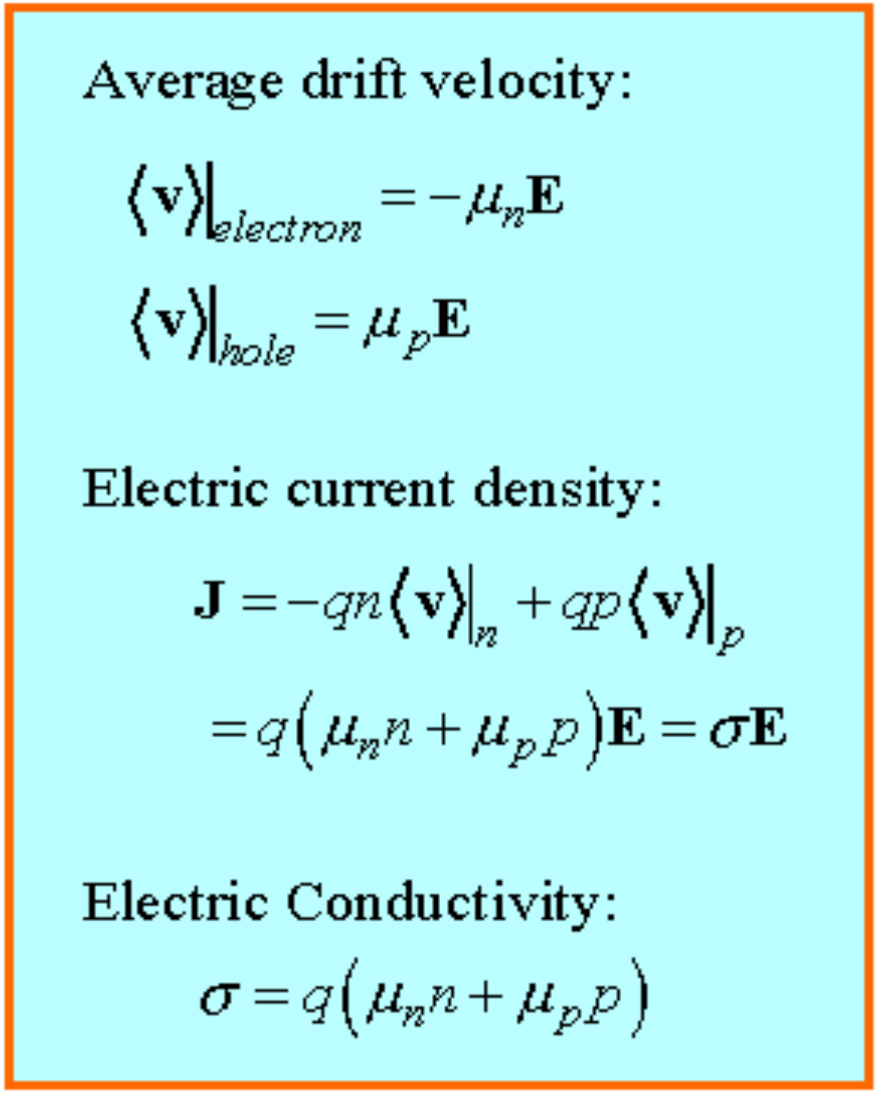


Hall effect

- ☐ Basic setup to measure carrier concentration using the Hall effect.



Drift velocity, Resistivity, and Conductivity



Average drift velocity:

$$\langle \mathbf{v} \rangle \big|_{electron} = -\mu_n \mathbf{E}$$

$$\langle \mathbf{v} \rangle \big|_{hole} = \mu_p \mathbf{E}$$

Electric current density:

$$\mathbf{J} = -qn \langle \mathbf{v} \rangle \big|_n + qp \langle \mathbf{v} \rangle \big|_p$$

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

Electric Conductivity:

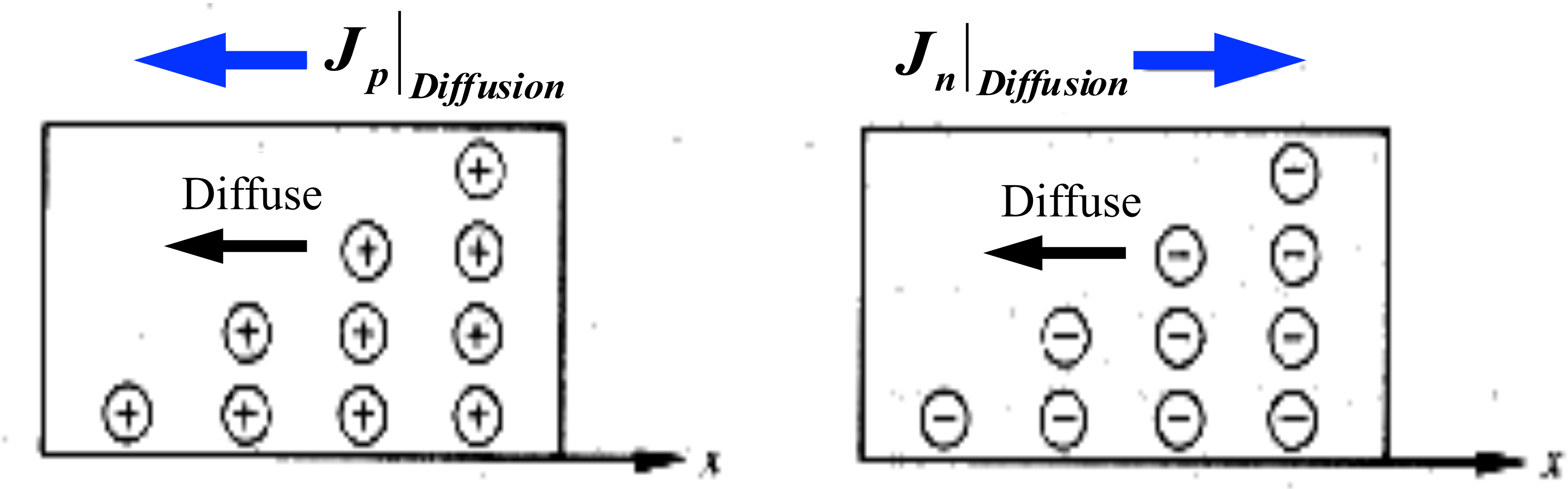
$$\sigma = q\left(\mu_n n + \mu_p p\right)$$

Diffusion

- Nature attempts to reduce concentration gradients to zero.

  Example: a bad odor in a room, a drop of ink in a cup of water.

  - In semiconductors, this “flow of carriers” from one region of higher concentration to lower concentration results in a “Diffusion Current”.



Visualization of electron and hole diffusion on a macroscopic scale.

Diffusion

- ☐ Fick' s law

  - Diffusion as the flux, F, (of particles in our case) is proportional to the gradient in concentration.

$$\boxed{F = -D\nabla\eta}$$

η : Concentration

D : Diffusion Coefficient

  - For electrons and holes, the diffusion current density (Flux of particles times ± q)

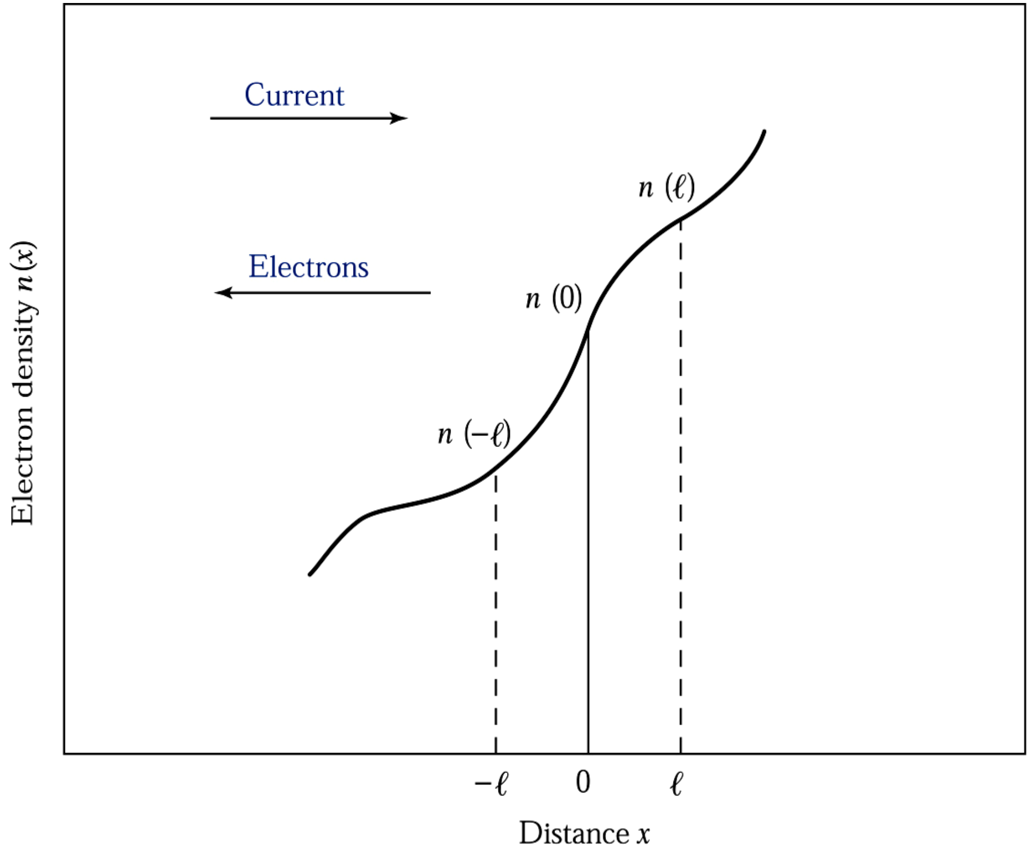
$$J_p\Big|_{Diffusion} = -q\cdot D_p\nabla p$$

$$J_n\Big|_{Diffusion} = q\cdot D_n\nabla n$$

The opposite sign for electrons and holes

Diffusion

- ❑ Electron diffusion current



- ➢ Electron concentration vs. distance; l is the mean free path.
- ➢ The directions of electron and current flows are indicated by arrows.

Total Current

- ☐ Total Current = Drift Current + Diffusion Current

$$J_p = J_p\Big|_{Drift} + J_p\Big|_{Diffusion} = q \cdot \mu_p p E - q \cdot D_p \nabla p$$

$$J_n = J_n\Big|_{Drift} + J_n\Big|_{Diffusion} = q \cdot \mu_n n E + q \cdot D_n \nabla n$$

$$J = J_p + J_n$$

Einstein relation: drift and diffusion

(i.e. relation between mobility μ and diffusion coefficient D)

Total current in semiconductor (1D Case, n-type):

$$\boxed{J_n(x) = \underbrace{e\mu_n n(x)E(x)}_{\text{drift}} + \underbrace{eD_n \frac{dn(x)}{dx}}_{\text{diffusion}}}$$

Diffusion coefficient– depends on carrier scattering

The mobility also depends on carrier scattering! It means that both μ and D must be related somehow!

Einstein relation: drift and diffusion

We know that the diffusion coefficient D is:

$$D_n = v_{th} l \longrightarrow l = v_{th} \tau_c$$

$$D_n = v_{th}^2 \tau_c \qquad \mu_n = \frac{e\tau_c}{m_n^*}$$

Drift
(carrier mobility)

$$\boxed{D_n = v_{th}^2 \left(\frac{\mu_n m_n^*}{e} \right)}$$

Einstein relation: drift and diffusion

Kinetic energy of carriers for 1 degree of freedom due to thermal movement is ½ kT , so we will have:

$$\frac{1}{2} m_n^* v_{th}^2 = \frac{1}{2} kT \qquad v_{th}^2 = \frac{kT}{m_n^*}$$

$$\boxed{D_n = v_{th}^2 \left(\frac{\mu_n m_n^*}{e} \right) = \left(\frac{kT}{m_n^*} \right) \left(\frac{\mu_n m_n^*}{e} \right)}$$

$$\boxed{D_n = \left(\frac{kT}{e} \right) \mu_n}$$

same for holes:

$$\boxed{D_p = \left(\frac{kT}{e} \right) \mu_p}$$

Einstein relation