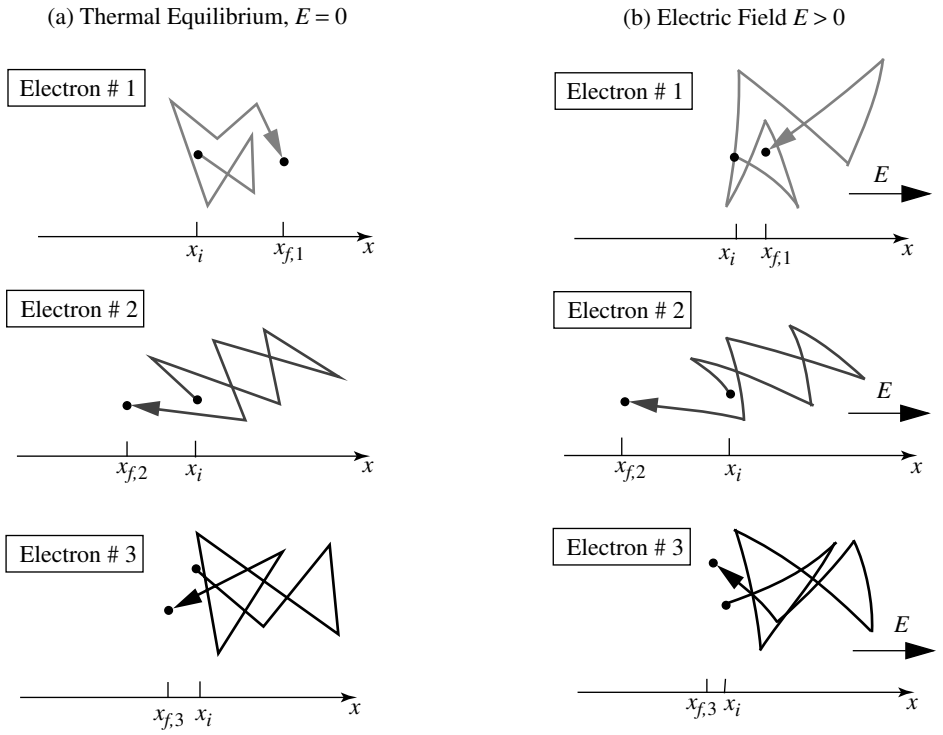
I. Carrier Transport: Drift

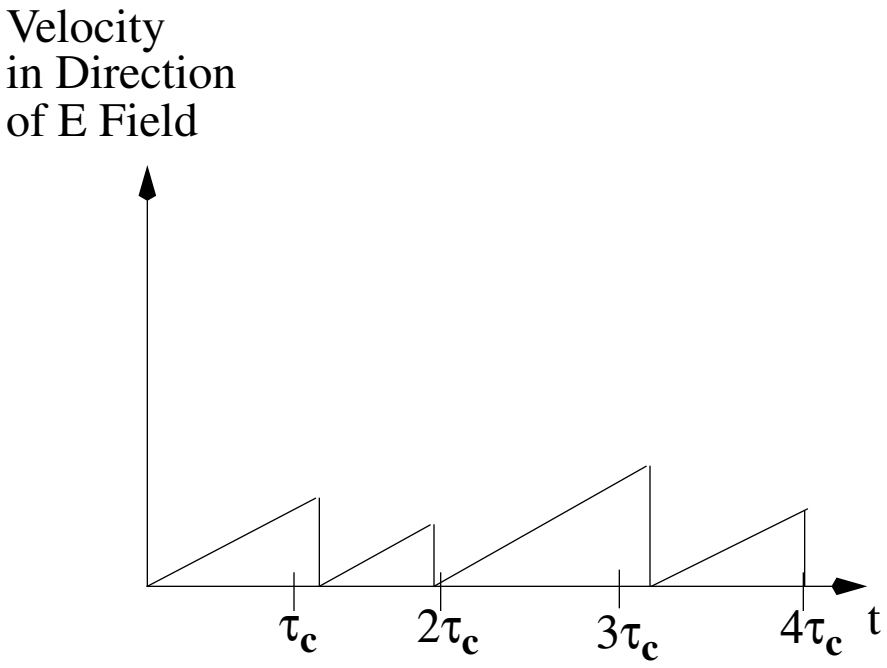
A. Drift Velocity



* x_i = initial position * $x_{f,\,n}$ = final position of electron n after 7 collisions

- Electrons drifting in an Electric Field move (on average) with a drift velocity which is proportional to the Electric Field, E.

Drift Velocity (Cont.)



$$v = at = \pm\frac{qE}{m_n}t$$

$$v_{ave} = \left(-\frac{q\tau_c}{m_n}\right)E$$

- m_n is an effective mass to take into account quantum mechanics
- Lump it into a quantity we call mobility μ_n (units:cm^2/V-s)

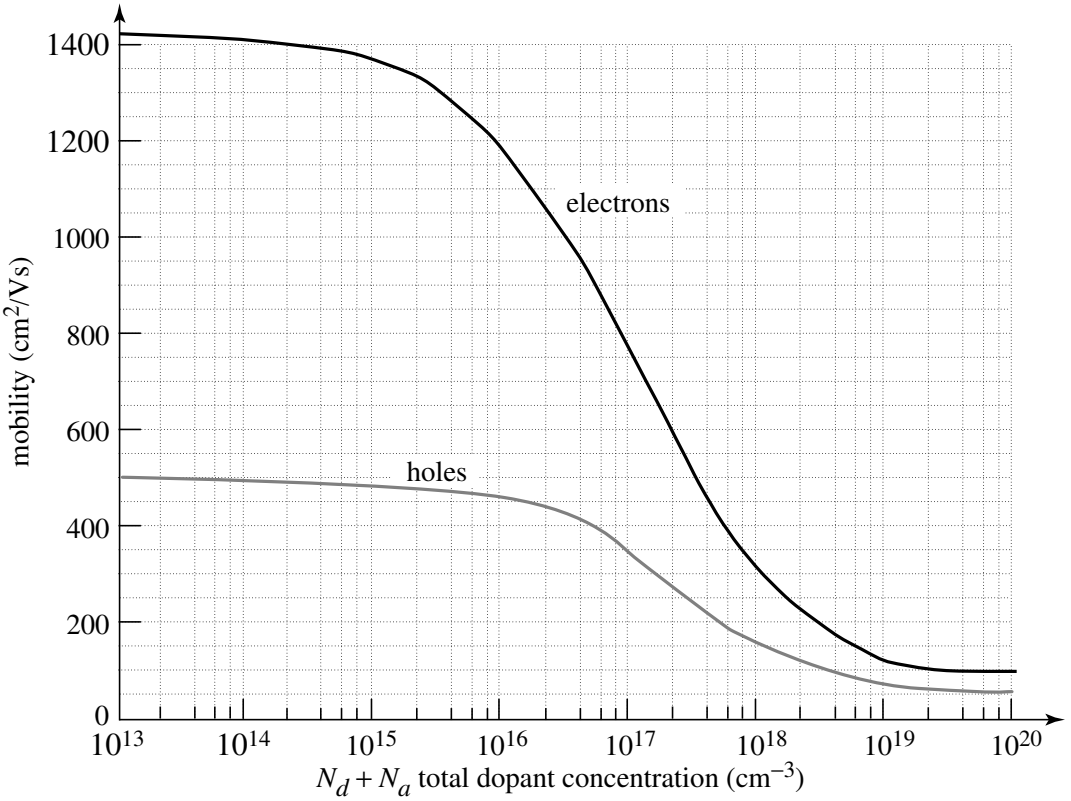
$$\boxed{v_d = -\mu_n E}$$

B. Electron and Hole Mobility

- Mobility DECREASES with INCREASING doping concentration - Impurity scattering
- Mobility DECREASES with INCREASING Temperature - Lattice scattering
- "typical values" for bulk silicon -- 300 K

$\mu_n = 1000\ \text{cm}^2/(\text{Vs})$

$\mu_p = 400\ \text{cm}^2/(\text{Vs})$



Temperature = 300 K

C. Drift Current Density

- Electrons drift against electric field
- Electrons carry negative charge
- $J_n^{dr} = (-q)\, n\, v_{dn}$ units: $Ccm^{-2}\, s^{-1} = Acm^{-2}$

$$J_n^{dr} = (-q)\, n\, (-\mu_n E) = q\, n\, \mu_n E$$

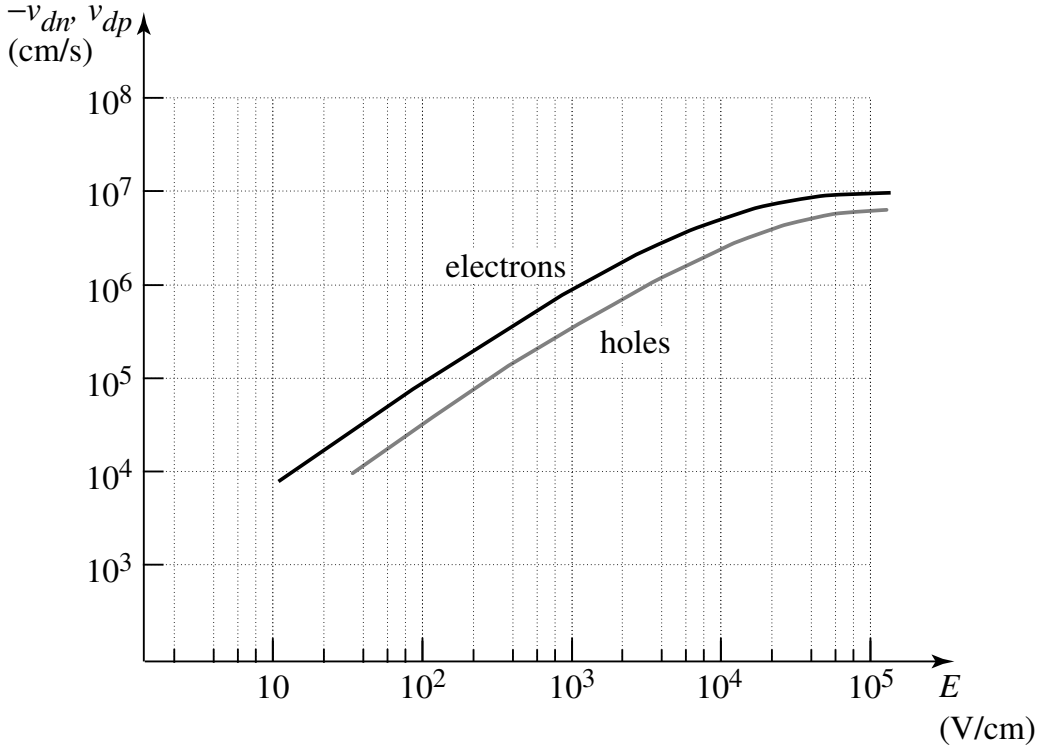
- Holes drift with electric field
- $v_{dp} = \mu_p E$
- $J_p^{dr} = (+q)\, p\, v_{dp}$

$$J_p^{dr} = q\, p\, \mu_p E$$

Caution:: The linear relationship between field and drift velocity breaks down for high electric fields.

D. Velocity Saturation

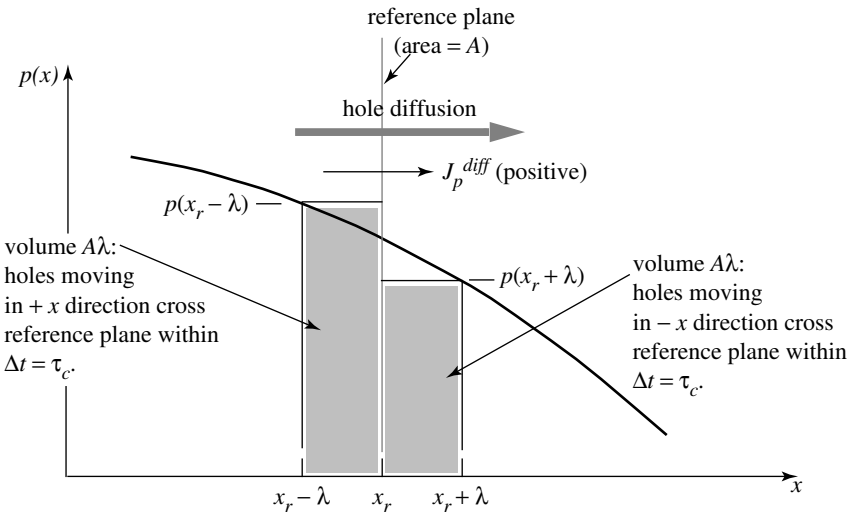
- At electric fields greater >~ 10^4 V/cm
- Drift velocities saturate --> max. out at around 10^7 cm/s.
- Velocity saturation is very common in VLSI devices, due to sub-micron dimensions



II. Carrier Transport: Diffusion

A. Diffusion

- *Diffusion* is a transport process driven by gradients in the concentration of particles in random motion undergoing frequent collisions.
- Average carrier velocity = $v_{th} = 10^7$ cm/s
- Average interval between collisions = $\tau_c = 10^{-13}$ s = 0.1 picoseconds
- mean free path = $\lambda = v_{th}\,\tau_c = 10^{-6}$ cm = 10 nm



- Since their motion is random, half of the carriers in each volume will pass through the plane before their next collision.

B. Diffusion Current Density- Holes

- Current density = (charge) x (# carriers per second per area):

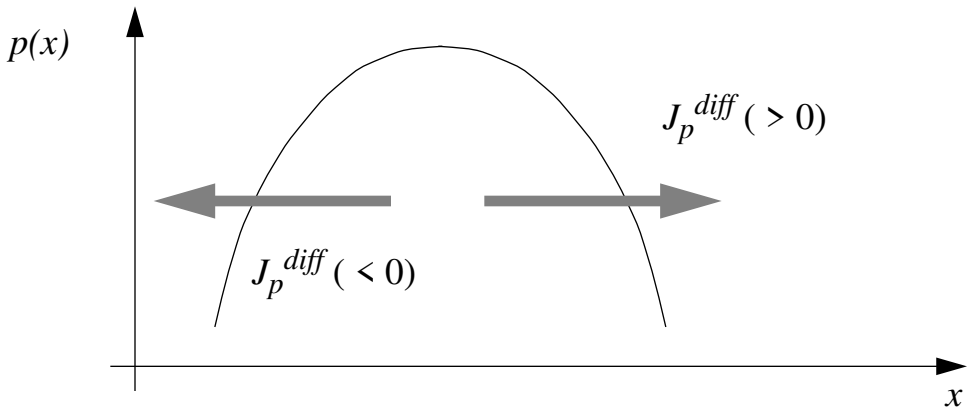
$$J_p^{diff} = q\left[\frac{\frac{1}{2}\left[p\left(x-\lambda\right)\right]A\lambda - \frac{1}{2}\left[p(x+\lambda)\right]A\lambda}{A\tau_c}\right]$$

:

- If we assume the mean free path is much smaller than the dimensions of our device, then we can consider $\lambda = dx$ and use a Taylor expansion on $p(x - \lambda)$ and $p(x + \lambda)$:

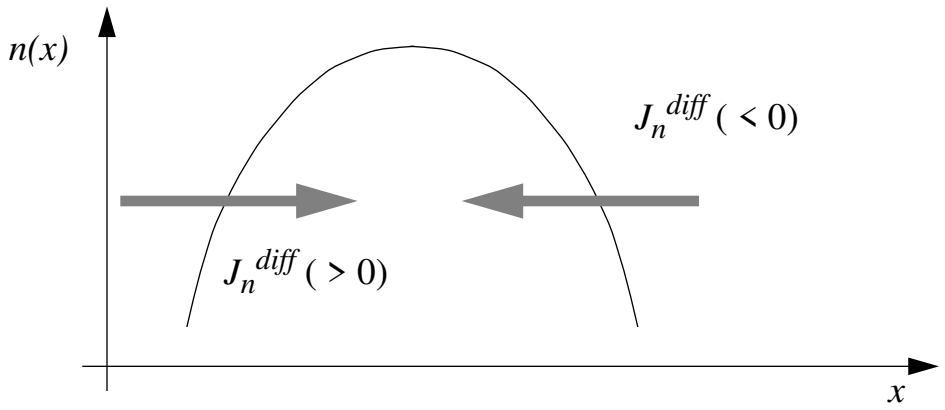
- $J_p^{diff} = -qD_p\frac{dp}{dx}$ where $D_p = \lambda^2 / \tau_c$ is the diffusion coefficient

- Holes diffuse down the concentration gradient and carry positive charge.



C. Diffusion Current Density - Electrons

- Electrons diffuse down the concentration gradient, yet carry negative charge --> electron diffusion current density points in the direction of the gradient



D. Einstein Relation

- Both mobility and the diffusion constant are related to the mean time between collisions τ_c. There is a relation between these important quantities called the Einstein Relationship.

$$\frac{D_p}{\mu_p} = \frac{kT}{q} \qquad \text{and} \qquad \frac{D_n}{\mu_n} = \frac{kT}{q}$$

III. Total Current Density

$$J_n = J_n^{dr} + J_n^{diff} = qn\mu_n E + qD_n \frac{dn}{dx}$$

$$J_p = J_p^{dr} + J_p^{diff} = qp\mu_p E - qD_p \frac{dp}{dx}$$

- Fortunately, we will be able to eliminate one or the other component in finding the internal currents in microelectronic devices.