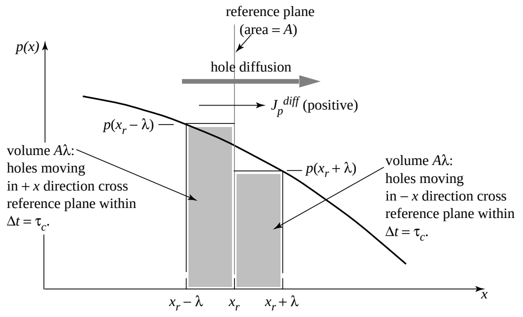
Carrier Transport: Diffusion

Diffusion is a transport process driven by gradients in the concentration of particles in random motion and undergoing frequent collisions -- such as ink molecules in water ... or holes and electrons in silicon.

Mathematics: find the number of carriers in a volume $A\lambda$ on either side of the reference plane, where λ is the mean free path between collisions.

- Some numbers: 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 = 0.01 μm



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

Carrier Transport:
Diffusion Current Density

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

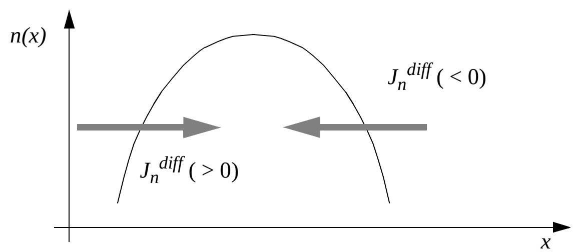
$$J_p^{diff} = q\left[\frac{\frac{1}{2}p(x-\lambda)A\lambda - \frac{1}{2}p(x+\lambda)A\lambda}{A\tau_c}\right]$$

- If we assume that λ is much smaller than the dimensions of our device, then we can consider $\lambda = dx$ and use Taylor expansions :

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

Carrier Transport by Diffusion (cont.)

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



- Total current density: add drift and diffusion components for electrons and for holes --

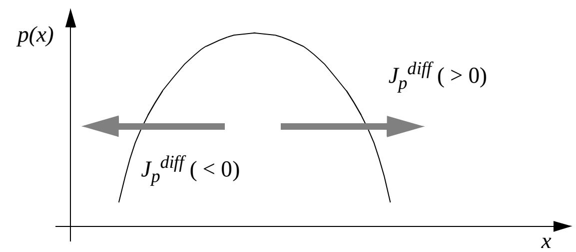
$$J_n = J_n^{dr} + J_n^{diff} = qn\mu_n E + qD_n \frac{dn}{dx}$$

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

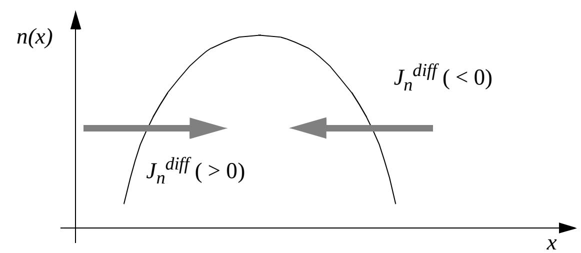
- Fortunately, we will be able to eliminate one or the other component in finding the internal currents in microelectronic devices.

Carrier Transport by Diffusion

- Holes diffuse “down” the concentration gradient and carry a positive charge --> hole diffusion current has the *opposite* sign to the gradient in hole concentration *dp/dx*



- Electrons diffuse down the concentration gradient, yet carry a negative charge --> electron diffusion current density has the *same* sign as the gradient in electron concentration *dn/ dx*.



Electron Diffusion Current Density

- Similar analysis leads to

$$J_n^{diff} = qD_n \frac{dn}{dx},$$

where D_n is the electron diffusion coefficient (units: cm^2/s)

- Numerical values of diffusion coefficients: use Einstein's relation

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

- The quantity kT/q has units of volts and is called the *thermal voltage*, V_{th}:

$$V_{th} = \frac{kT}{q} = 25 - 26 \text{ mV},$$

at "room temperature," with 25 mV for a cool room (62 ^{o}F) and 26 mV for a warm room (83 ^{o}F).

We will pick 25 mV or 26 mV depending on which gives the "roundest" numbers.

Total Current Densities

- Add drift and diffusion components for electrons and for holes --

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

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

- Fortunately, we will be able to eliminate one or the other component of the electron or the hole current in our analysis of semiconductor devices.
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