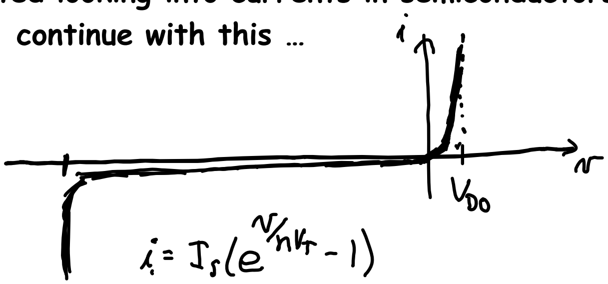
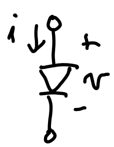
Lecture 11: Semiconductor Currents

- **Announcements**:
- HW#4 online and due Friday via Gradescope
- Lab#2 continues this week
  - Prelab is due at the beginning of lab
- Lab#3 next week
  - Materials for Lab#3 already online
- ------------------------------------
- Lecture Topics:
  - Doping
  - Semiconductor Currents
  - Diode Operation
    - Zero Bias
    - Forward Bias
    - Reverse Bias
- ------------------------------------
- **Last Time**:
- Started looking into currents in semiconductors
- Now, continue with this …



$$i = I_s\left(e^{v/nV_T} - 1\right)$$



$I_s \triangleq$ saturation current

$V_T = 25\,mV = \frac{kT}{q} \triangleq$ thermal voltage

$n = 1$ a 2 (1 ← IC diodes; 2 ← discrete diodes)

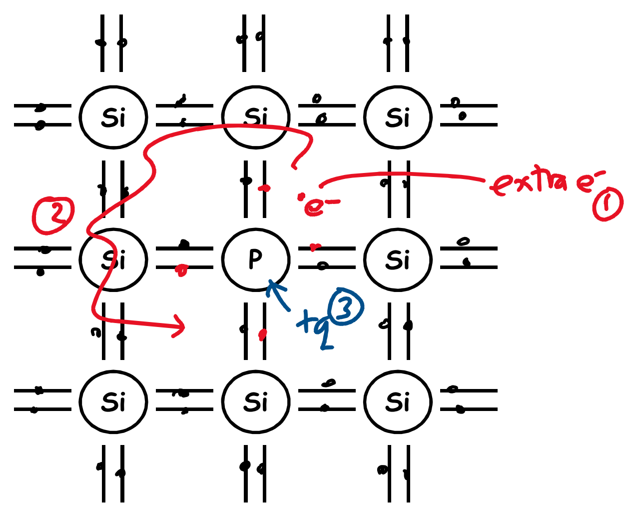
3. **Semiconductors**:

- Basically the same as insulators, except they require smaller temperatures to free e⁻s
- For most purposes, they are just like insulators … until they are doped, at which point they become like metals

- **Doping**:
- A semiconductor converts to a conductor when one adds certain impurities that substitute for Si atoms
- Type types of substitutional impurities
  - Donors
  - Acceptors

1. **Donors**:

- Elements with 5 valence e⁻'s, e.g., phosphorous (P) and Arsenic (As)



(1) – 4 e^-'s from P contribute to covalent bonds, leaving one extra e^-

(2) – extra e^- can now move around

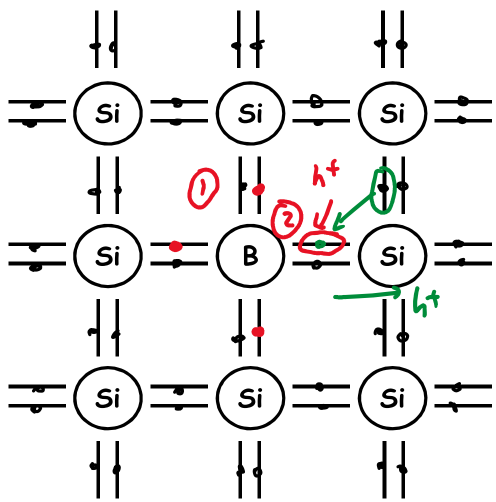
(3) – When e^- moves away from the donor atom (in this case, P), the donor atom effectively represents a (+) static charge

- The larger the concentration of donors N_D, the greater the number of e^-'s available to generate the e^- cloud, i.e., the better the conductor

$n = \#$ of free e^-'s $\sim N_D$ $[cm^{-3}]$

2. Acceptors:

- Elements w/ 3 valence e^-'s, e.g., Boron (B)



(1) – 3 e^-'s from B not enough to complete the valence shell → leaves a hole, h^+

(2) – h^+=absence of e^- = hole

(3) – e^- can move into this h^+, creating another h^+

(4) – h^+'s propogate this way under an applied electric field, generating current

- The larger the concentration of acceptors N_A, the greater the number of h^+'s available for current, i.e., the better the conductor

$p = \#$ free $h^+ \sim N_A$ $[cm^{-3}]$

- Thus, we can convert a semiconductor to a conductor by doping w/ donors (which generate an e^- cloud) or doping w/ acceptors (which generate a h^+ cloud)

- n_i = concentration of free e^-'s in intrinsic (undoped) Si = 1.45×10^{10} cm^{-3} ← at room temperature
- $p = n = n_i$ in intrinsic silicon
- As a rule of thumb, at any given location at equilibrium, $pn = n_i^2 = (1.45\times10^{10})^2$
- If a region is doped predominantly one type (p or n), then the carrier concentrations are as follows:

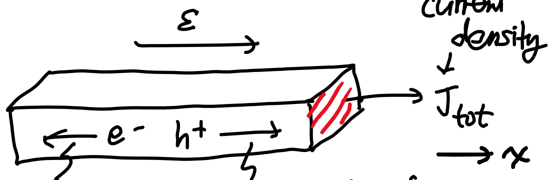
Predominantly n-type ($N_D \gg N_A$): $n \cong N_D \rightarrow p = \frac{n_i^2}{N_D}$

Predominantly p-type ($N_A \gg N_D$): $p \cong N_A \rightarrow n = \frac{n_i^2}{N_A}$

Types of Currents in Semiconductors

⇒ two possible current components:

① Drift Current – current that flows upon application of an ε-field across a material w/ free charge carriers (like e^-'s and/or h^+'s)



move in opposite direction to field ε

move in direction of field ε

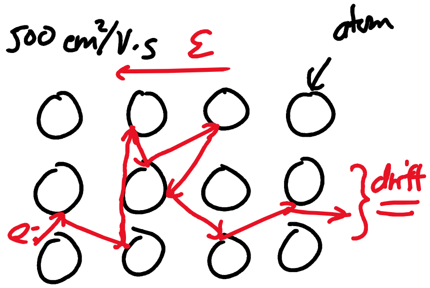
For e^-'s:

$$J_n^{drift} = Q_n v_n = (-qn)(-\mu_n \mathcal{E}) \longrightarrow *$$

- Q_n: charge density of e^-'s [C/cm³]
- v_n: velocity of the e^-'s [cm/s]
- q: unit charge ≙ 1.602×10^{-19}C
- $\mathcal{E}$: electric field

μ_n ≙ mobility of e^-'s ~ 500 cm²/V·s

↳ models the fact that e^-'s collide their way thru a material



$$* \; \boxed{J_n^{drift} = qn\mu_n\mathcal{E} \quad [A/cm^2]} \leftarrow \text{Drift current for } e^-\text{'s under electric field } \mathcal{E}$$

For h^+:

$$J_p^{drift} = Q_p v_p = (+qp)(+\mu_p\mathcal{E}) = \boxed{qp\mu_p\mathcal{E} = J_p^{drift}}$$

- Q_p: charge density of h^+'s [C/cm³]
- v_p: velocity of h^+'s [cm/s]
- μ_p: h^+ mobility ≈ 250 cm²/V·s

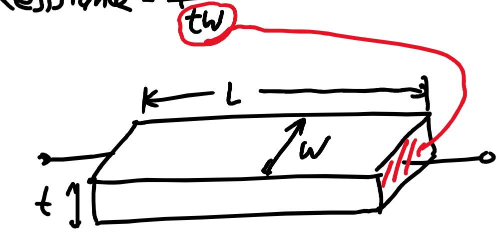
And the total drift current:

$$J_{tot}^{drift} = J_n^{drift} + J_p^{drift} = q(n\mu_n + p\mu_p)\mathcal{E} = \sigma\mathcal{E}$$

$$\sigma ≙ \text{conductivity} = q(n\mu_n + p\mu_p) = \frac{1}{\rho}$$

(ρ = resistivity)

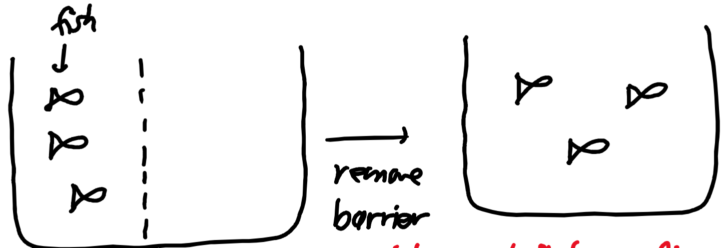
$$\text{Resistance} = \frac{\rho L}{tW}$$



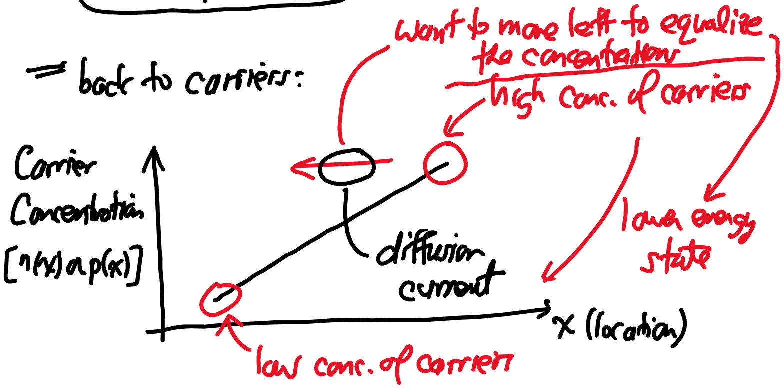
⇒ thus, resistance is basically a drift current phenomenon

② **Diffusion Current** – current that flows when there is a gradient in carrier concentration and the carriers attempt to equilibrate

Ex. Fish Tank: (diffusion)



⇒ back to carriers:



⇓ if carriers had their way

⇒ Diffusion current is proportional to the negative of the carrier gradient:

h+ diffusion:

$$J_p^{diff} = (+q)D_p\left(-\frac{\partial p}{\partial x}\right) = -qD_p\frac{\partial p}{\partial x} \quad [A/cm^2]$$

e- diffusion:

$$J_n^{diff} = (-q)D_n\left(-\frac{\partial n}{\partial x}\right) = +qD_n\frac{\partial n}{\partial x} \quad [A/cm^2]$$

D_n = e- diffusivity $= \mu_n \frac{kT}{q} = \mu_n V_T$

D_p = h+ diffusivity $= \mu_p \frac{kT}{q} = \mu_p V_T$

$V_T = \frac{kT}{q} = 25mV$ @ 25°C (k: Boltzmann Const., T: temperature)

The total current @ location x:

$$J_{tot} = J_{tot}^{drift} + J_{tot}^{diff}$$

$$J_{tot}^{diff} = J_p^{diff} + J_n^{diff}$$