Lecture 11: Diodes

- 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 will be online soon
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- Lecture Topics:
  - Semiconductor Currents
  - Diode Operation
    - Zero Bias
    - Forward Bias
    - Reverse Bias
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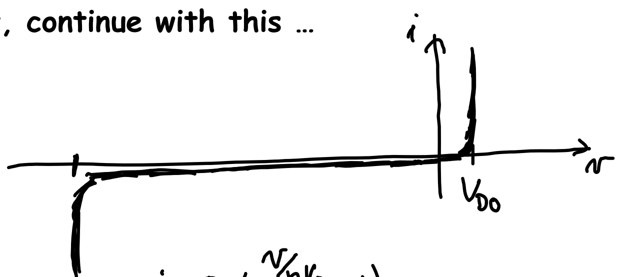
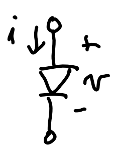
- Last Time:
- Started looking into currents in semiconductors
- Now, continue with this …





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

$I_s \triangleq$ saturation current

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

$n = 1 \text{ a } 2$ ← discrete diodes
↑ IC diodes

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

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

- 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:

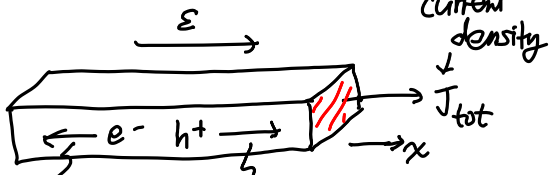
Predominantly n-type ($N_D >> N_A$): $n \cong N_D \rightarrow p = \frac{n_i^2}{N_D}$

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

Types of Currents in Semiconductors

⇒ two possible current components: drift & diffusion current

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



move in opposite direction to field $\mathcal{E}$ — move in direction of field $\mathcal{E}$

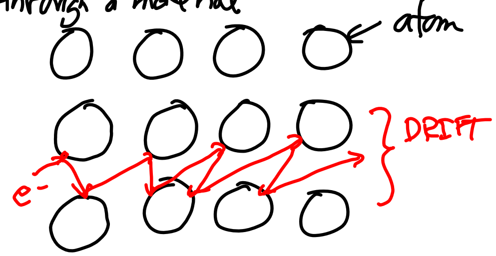
unit charge $= 1.602\times10^{-19}$ C

For e^-'s: $J_n^{drift} = Q_n v_n = (-qn)(-\mu_n\mathcal{E})$ ⟶ ✱

Q_n: charge density of e^-'s [C/cm^3]; v_n: velocity of the e^-'s [cm/s]; $\mathcal{E}$: electric field

$\mu_n \triangleq$ mobility of e^-'s $\approx 500\,\text{cm}^2/\text{V}\cdot\text{s}$

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



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

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

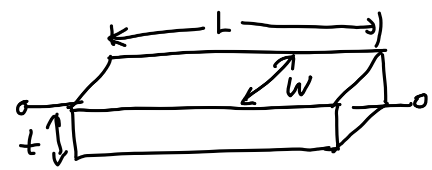
Q_p: charge density of h^+'s [C/cm^3]; v_p: velocity of h^+'s [cm/s]; μ_p: h^+ mobility $\approx 250\,\text{cm}^2/\text{V}\cdot\text{s}$

And the total drift current:

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

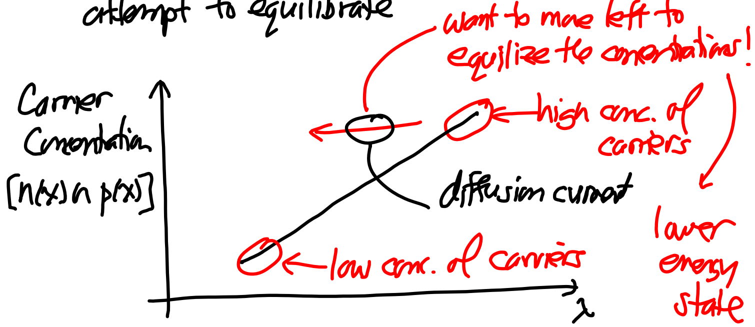
$\sigma \triangleq$ conductivity $= q(n\mu_n + p\mu_p) = \frac{1}{\rho}$ (ρ: resistivity)

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

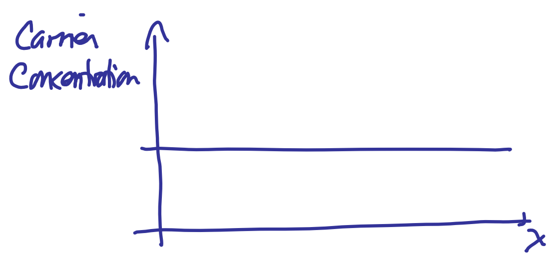


⇒ thus, resistance is basically a drift current phenomenon

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



⇓ if carriers had their way...



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

h^+ diffusion:

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

e^- diffusion:

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

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

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

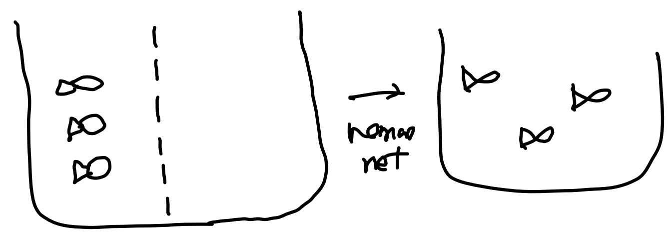
Boltzmann Const.

$V_T = \frac{kT}{q} = 25mV$ @ $25°C$

The total current @ location x:

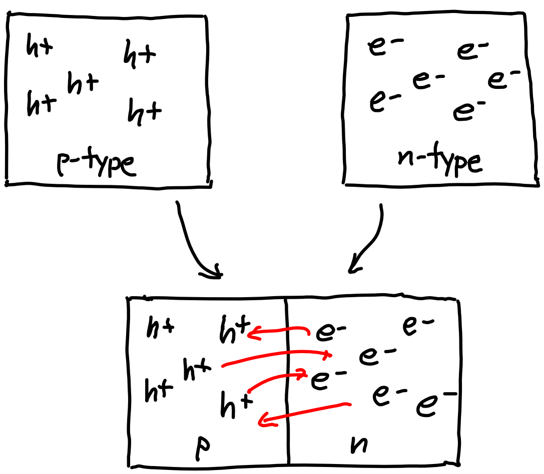
$$\boxed{J_{tot} = J_{tot}^{drift} + J_{tot}^{diff}}$$

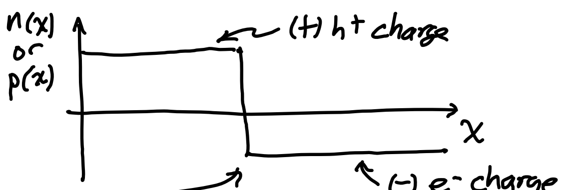
Fish Tank Diffusion



Diode

⇒ merely a pn-junction, i.e., a result of bringing p-type and n-type material into contact w/ one another

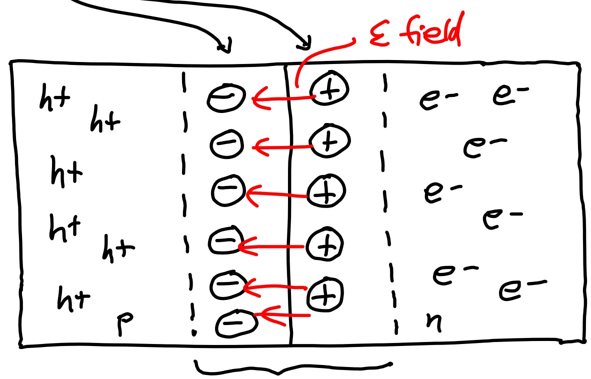




huge gradient in free charge @ the interface
↳ corresponds to high energy state
↳ ∴ system tries to equilibrate to a low energy state
↙
e-'s move to the left, h+ move to the right

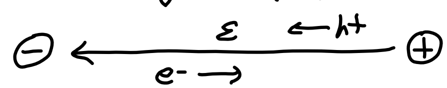
pn Junction

⇒ when they move they leave behind static charge regions (because there originally was a neutral region)



depletion region → region of static charge devoid of carriers

Eventually, an ℰ field develops that opposes further movement of mobile charge (e^- & h^+)



(opposites attract; likes repel)

The Diode Equation

$$i_D = I_S\left[\exp\left(\frac{qv_D}{nkT}\right)-1\right] = I_S\left[\exp\left(\frac{v_D}{nV_T}\right)-1\right]$$

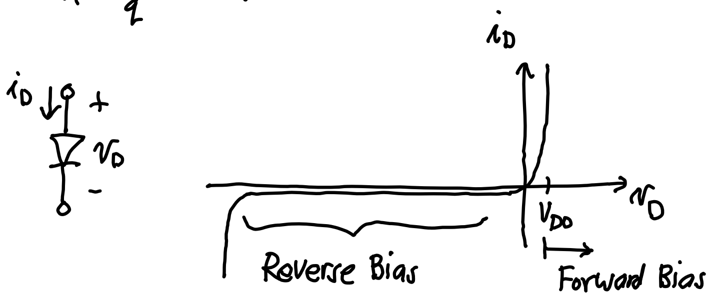
$I_S \triangleq$ reverse saturation current [A]

$q = 1.602\times10^{-19}\,C$

k = Boltzmann constant = 1.38×10^{-23} J/K

T = absolute temperature [K]

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



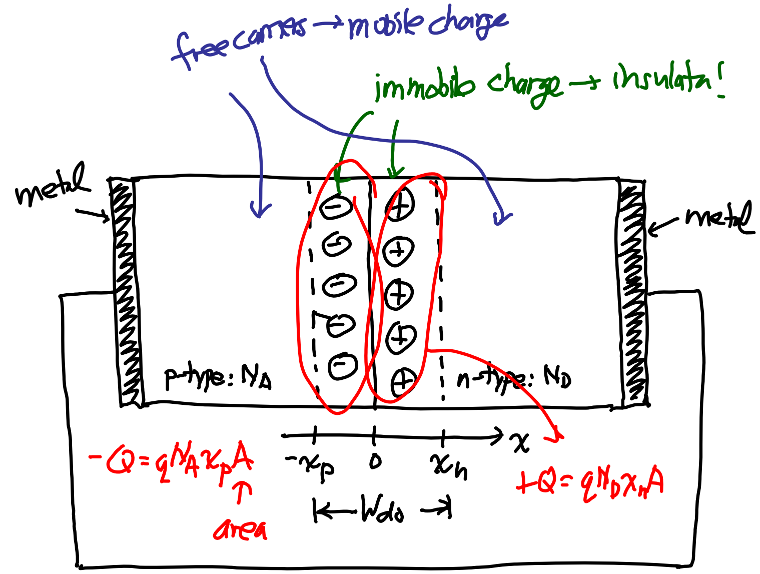
⇒ now, get some insight into where this equation comes from

Zero Bias

$v_D = 0V \to i_D = 0A$

No current → i-v characteristic not interesting.

However, there is capacitance:



Separate oppositely charged regions → Electric field across the depletion region

→ Voltage Drop = $-\int E(x)dx$

As you will see in EE130: The voltage dropped from $x = -x_p$ to $x = x_n$ is:

$$\phi_j \triangleq \text{built-in potential} = V_T \ln\left(\frac{N_AN_D}{n_i^2}\right) \quad \left[= -\int_{-x_p}^{x_n} E(x)\,dx\right]$$