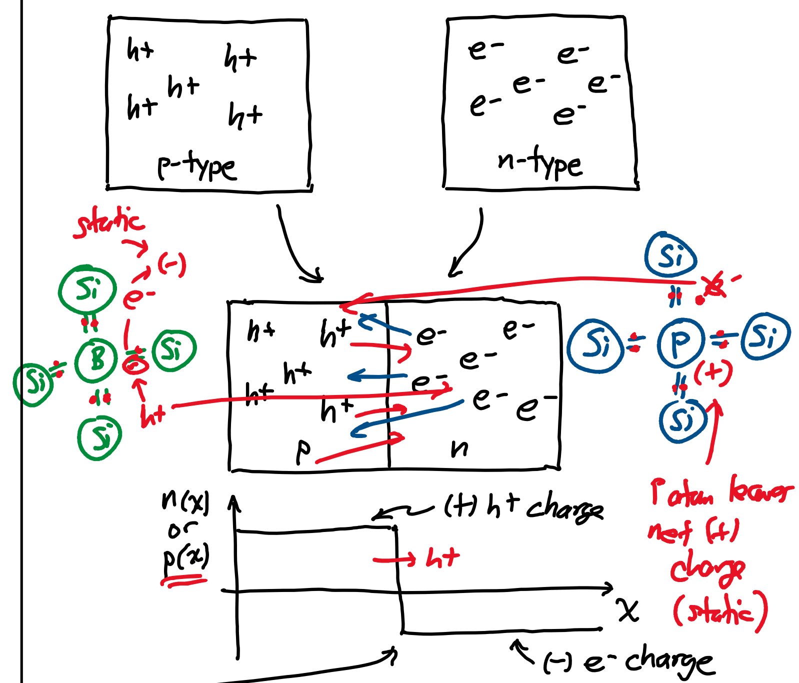
Lecture 12: Diodes

- **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 already online
- Midterm 1 ~2.5 weeks away, on Friday, Oct. 11
  - We have 7-9 p.m., 160 Kroeber Hall
- My Monday Office Hours will move to 5-6 p.m. on Oct. 14 and thereafter
- Projector overheated in our classroom; this is a recorded lecture
- ------------------------------------
- Lecture Topics:
  - Diode Operation
    - Zero Bias
    - Forward Bias
    - Reverse Bias
  - Diode Fabrication
  - MOSFET Overview
- ------------------------------------
- **Last Time**:
- Finished currents in semiconductors
- Now, start diode operation …

$\boxed{\text{Diode}}$

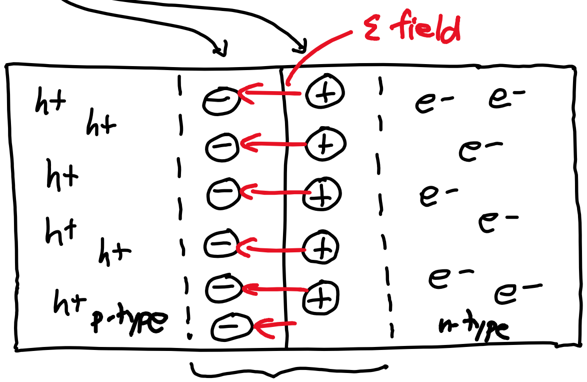
⇒ merely a pn-junction, i.e., a result of bringing p-type and n-type material into contact w/ one another



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

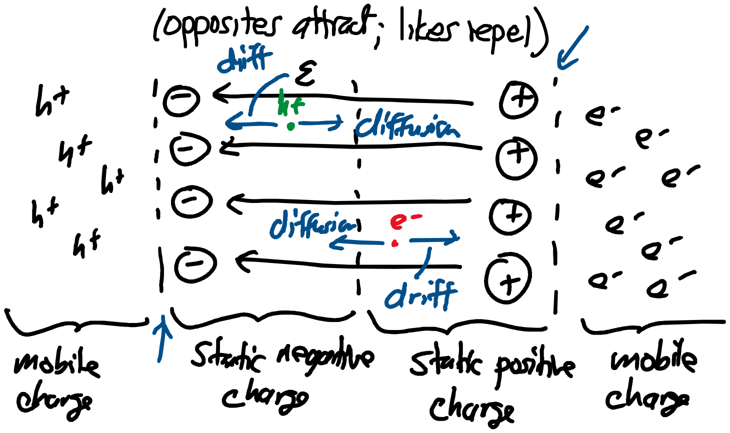
⇒ when they move they leave behind static charge regions (because those originally was a neutral region)



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

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

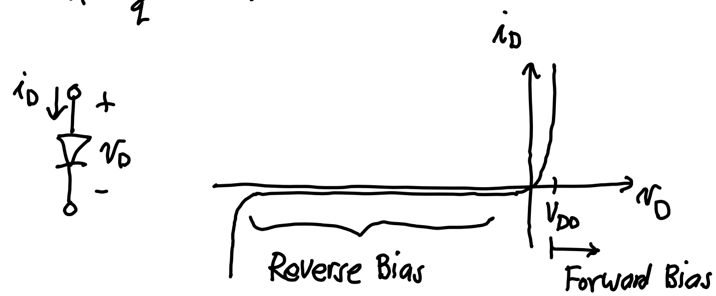
$I_S \triangleq$ reverse saturation current [A]

$q = 1.602 \times 10^{-19}$ C

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

T = absolute temperature [K]

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

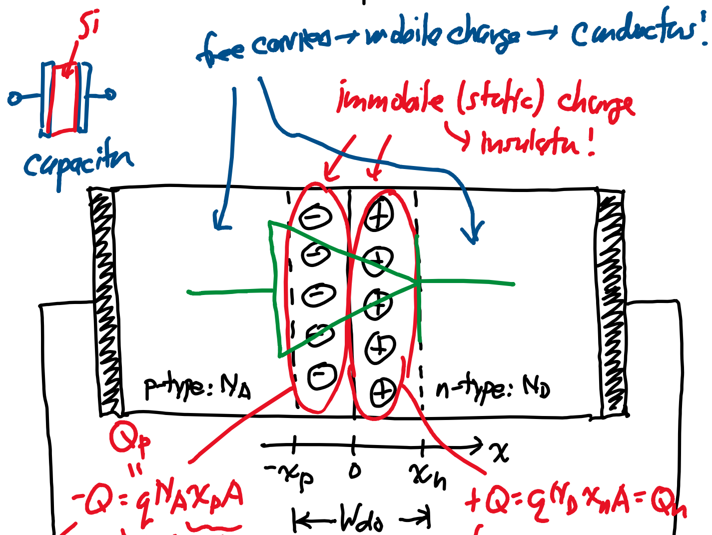


⇒ now, get some insight into where this equation comes from

$\boxed{\text{Zero Bias}}$ $v_D = 0V \rightarrow i_D = 0A$

No current → i-v characteristic not interesting.

However, there is capacitance:



$Q_p = -Q = \underbrace{q N_A}_{\text{charge/volume}} \underbrace{x_p A}_{\text{volume}}$ $\qquad +Q = q N_D x_n A = Q_n$

These must be equal:

$Q_p = qN_A x_p A = Q_n = qN_D x_n A$

$qN_A k_p W_{do} A = qN_D k_n W_{do} A \rightarrow k_p = \frac{N_D}{N_A} k_n$

$x_n + x_p = W_{do} = (k_n W_{do} + k_p W_{do}) = W_{do} \rightarrow k_n + k_p = 1$

$k_n = \frac{N_A}{N_A + N_D} \rightarrow Q_n = qN_D\left(\frac{N_A}{N_A+N_D}\right)W_{do}A$

$k_p = \frac{N_D}{N_A + N_D} \rightarrow Q_p = qN_A\left(\frac{N_D}{N_A+N_D}\right)W_{do}A$

$=$

$\Rightarrow Q_n = Q_p = q(N_A \| N_D) W_{do} A$

$\Rightarrow$ to get W_{do}, need:

Voltage Dropped Across the Depletion Region:

Separate oppositely charged regions → Electric field across the depletion region

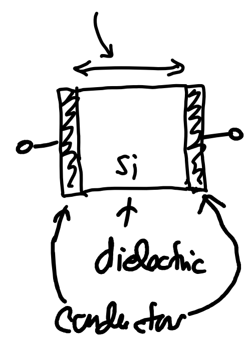
→ Voltage Drop $= -\int E(x)dx$

As you will see in EE 130: The voltage dropped from $x = -x_p$ to $x = x_n$ is:

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

The depletion layer width:

$$W_{do} = f(\phi_j) = x_n + x_p = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)\phi_j}$$



$\Rightarrow$ this is a capacitor:

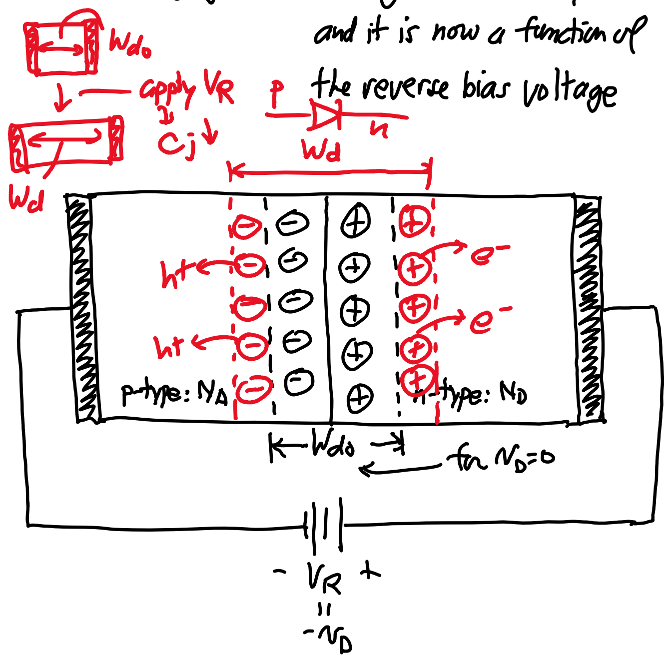
$C_j = \frac{\epsilon_s A}{W_{do}}$ for $v_D = 0$

ϵ_s = permittivity of silicon = 11.7

A = cross-sectional area of diode

$\boxed{\text{Reverse Bias}}$ $v_D < 0 \rightarrow i_D = -I_S$

Current negligible → but again, there is capacitance and it is now a function of the reverse bias voltage

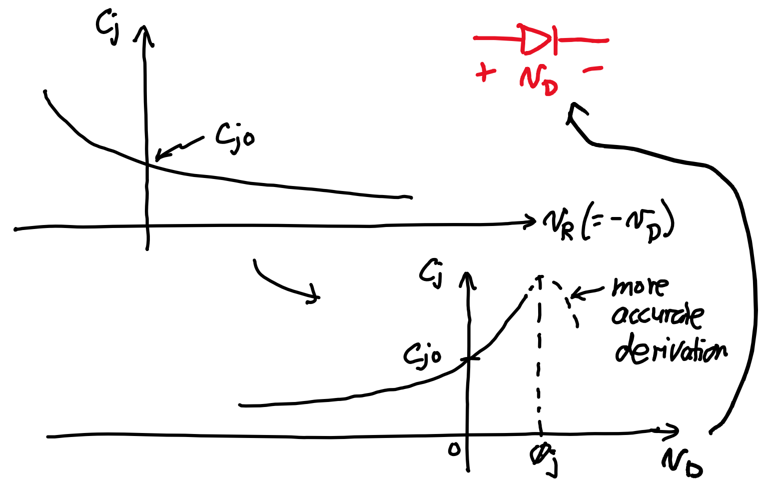


Again, the depletion region width is proportional to the potential dropped across the region. But now, the total potential drop $= V_R + \phi_j$ and

$$W_d = x_n + x_p = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)(\phi_j+V_R)} = W_{d0}\sqrt{1+\frac{V_R}{\phi_j}}$$

$$Q_n = qN_D x_n A = q\left(\frac{N_A N_D}{N_A+N_D}\right)\underbrace{W_d}_{f(V_R)} A \Rightarrow \underbrace{Q_n = f(V_R)}_{\text{Thus, this is a nonlinear capacitor!}}$$

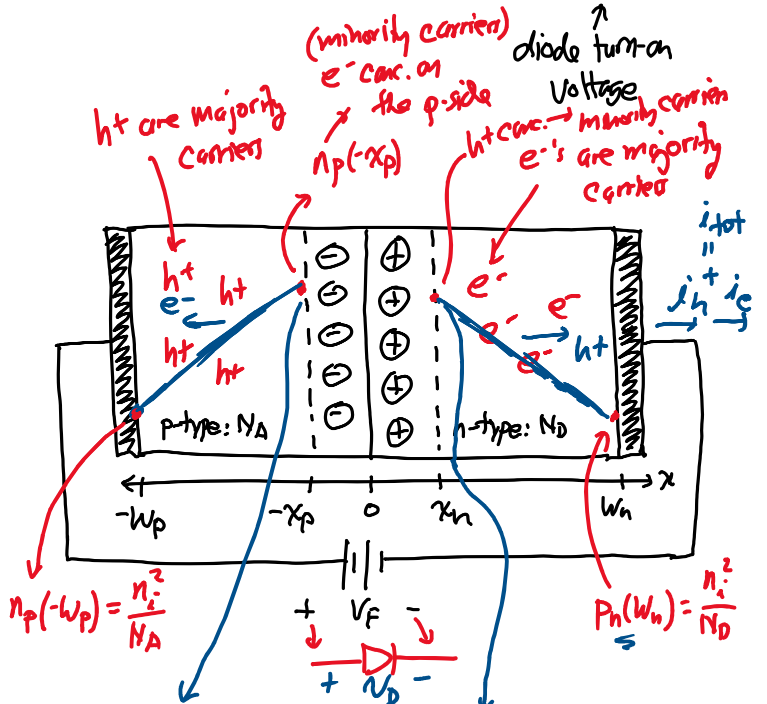
$$\boxed{C_j = \frac{dQ_n}{dV_R} = \frac{C_{j0}}{\sqrt{1+\frac{V_R}{\phi_j}}} \ ; \ C_{j0} = \frac{\epsilon_s A}{W_{d0}} \qquad [V_R = -V_D] \Rightarrow C_j = \frac{C_{j0}}{\sqrt{1-\frac{V_D}{\phi_j}}}}$$



Forward Bias

Case $v_D > 0$.

$\Rightarrow$ most interested in case where $v_D \geq V_{D0}$.



Injected e⁻'s on the p-side:

$$n_p(-x_p) = \frac{n_i^2}{N_A}\exp\left(\frac{v_D}{V_T}\right)$$

Injected h+ on the n-type side:

$$p_n(x_n) = \frac{n_i^2}{N_D}\exp\left(\frac{v_D}{V_T}\right)$$

To get currents, take the slopes of the minority carrier distributions:

On the n-side → h+ diffusion current:

$$J_p^{diff} = -qD_p\frac{\partial p}{\partial x} = -qD_p\left[\frac{p_n(W_n) - p_n(x_n)}{W_n - x_n}\right]$$

$$\Rightarrow J_p^{diff} = \underbrace{qD_p\frac{n_i^2}{N_D}\frac{1}{(W_n - x_n)}}_{\text{contributes to the saturation current, } I_S}\left[\exp\left(\frac{v_D}{V_T}\right) - 1\right]$$

On p-side → e⁻ diffusion current:

$$J_n^{diff} = qD_n\frac{\partial n}{\partial x} = qD_n\left[\frac{n_p(-x_p) - n_p(-W_p)}{-x_p + W_p}\right]$$

$$\Rightarrow \boxed{J_n^{diff} = qD_n\frac{n_i^2}{N_A}\frac{1}{(-x_p + W_p)}\left[\exp\left(\frac{v_D}{V_T}\right) - 1\right]}$$

… and for total current density:

$$J_{tot} = J_p^{diff} + J_n^{diff} = I_S\left[\exp\left(\frac{v_D}{V_T}\right) - 1\right]$$

$$\text{where } I_S = qn_i\left[\frac{D_p}{N_D}\frac{1}{(W_n - x_n)} + \frac{D_n}{N_A}\frac{1}{(W_p - x_p)}\right]$$

Actual Diode