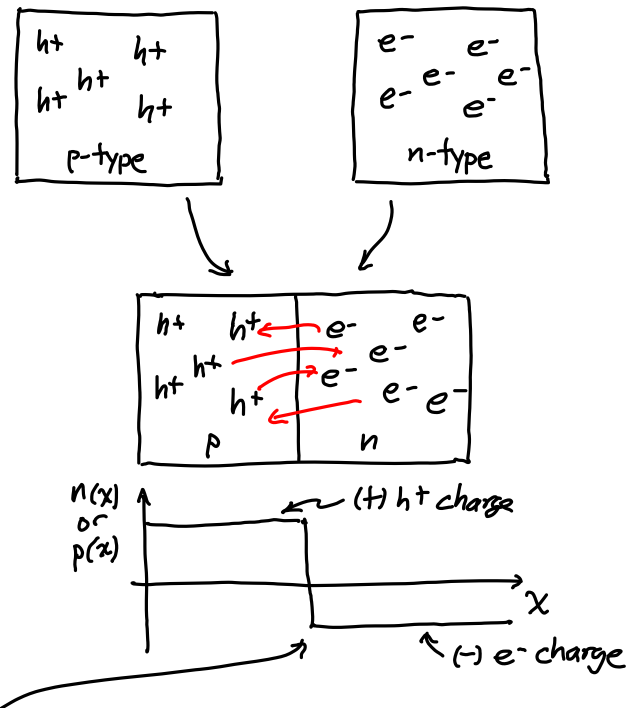
Lecture 12: Diodes & Transistors

- **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 online
- Midterm 1 ~2.5 weeks away, on Friday, Oct. 5
    - We have 5-6:30 p.m., 277 Cory
- UC Police Dept. slow at giving people access to the lab, for not just this class
    - Unclear why, but I guess we need to be patient
- \-
- Lecture Topics:
    - Diode Regions of Operation
        - Zero Bias
        - Forward Bias
        - Reverse Bias
    - Diode Fabrication
    - MOSFET Overview
- \-
- **Last Time**:
- Looking at diode regions of operation
- Now, continue with this …

Diode

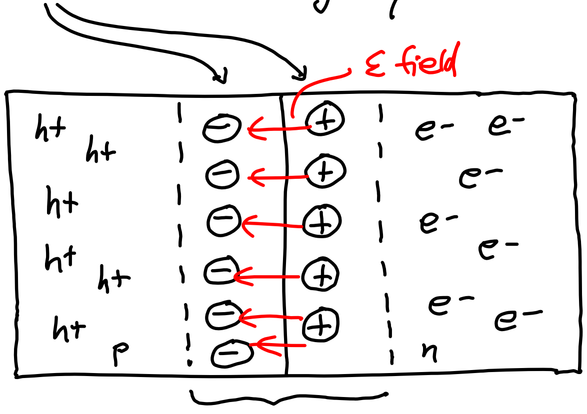
⇒ merely a pn-junction, i.e., a result of bringing p-type and n-type material into contact w/ one another



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

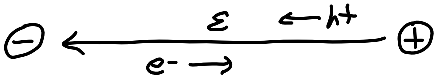
pn Junction

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



depletion region → region of static charge devoid of carriers

Eventually, an ε field develops that opposes further movement of mobile charge (e⁻ & h+)



(opposites attract; likes repel)

The Diode Equation

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

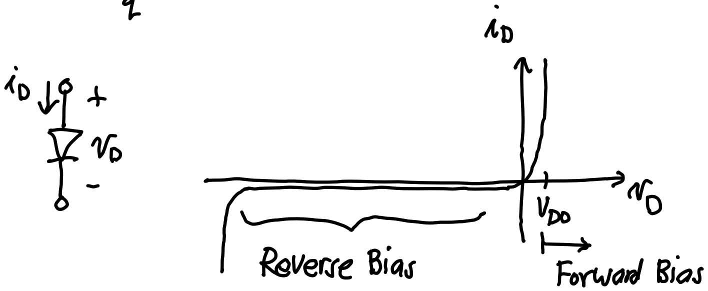
$I_S \triangleq$ reverse saturation current [A]

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

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

T = absolute temperature [K]

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

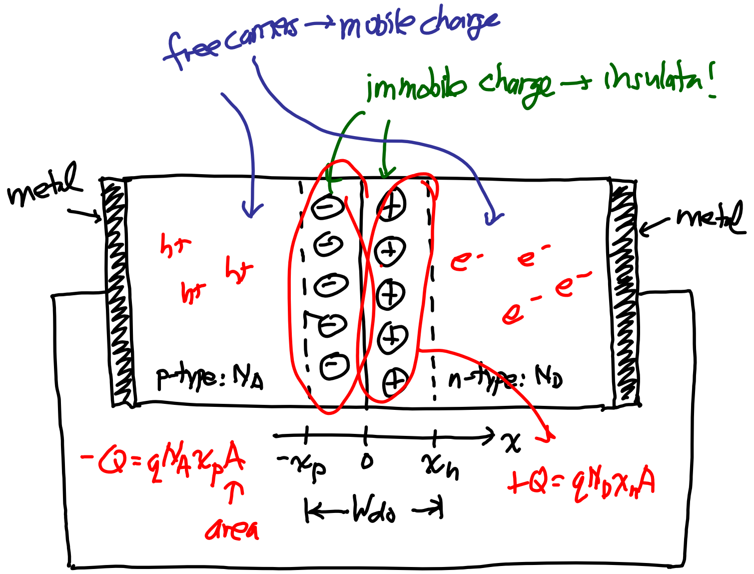


⇒ now, get some insight into where this equation comes from

Zero Bias $v_D = 0V \rightarrow i_D = 0A$

No current → iv characteristic not interesting.

However, there is capacitance:



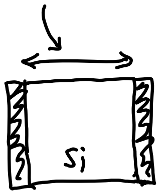
Separate oppositely charged regions → Electric field across the depletion region → Voltage Drop $= -\int E(x)dx$

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

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

The depletion layer width:

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



⇒ this is a capacitor:

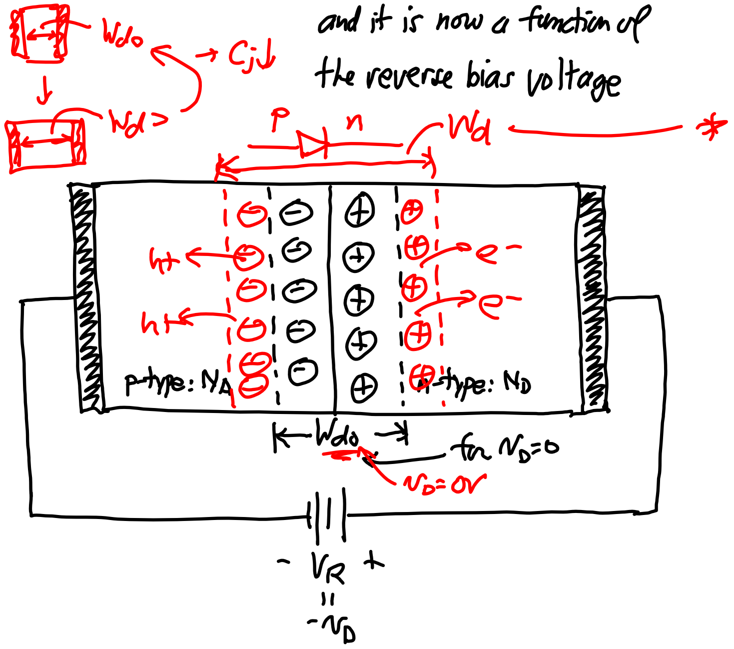
$$C_j = \frac{\epsilon_s A}{W_{do}} \quad \text{for } v_D = 0$$

ϵ_s = permittivity of silicon = 11.7

A = cross-sectional area of diode

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

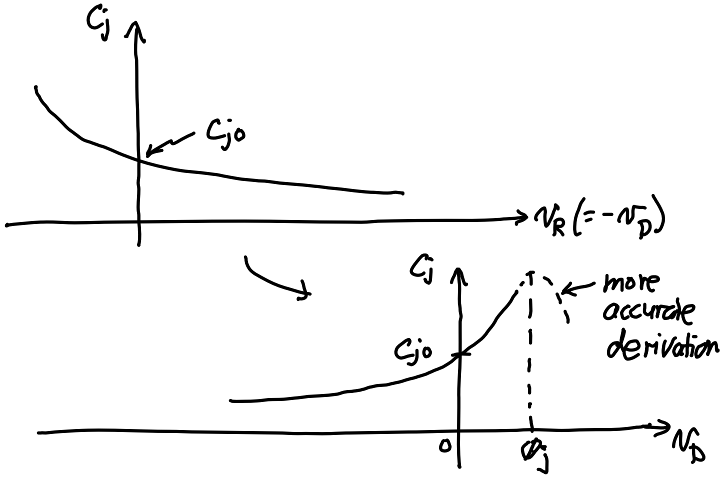


Again, the depletion region width is proportional to the potential dropped across the region. But now, the total potential drop = $V_R + \phi_j$ and

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

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

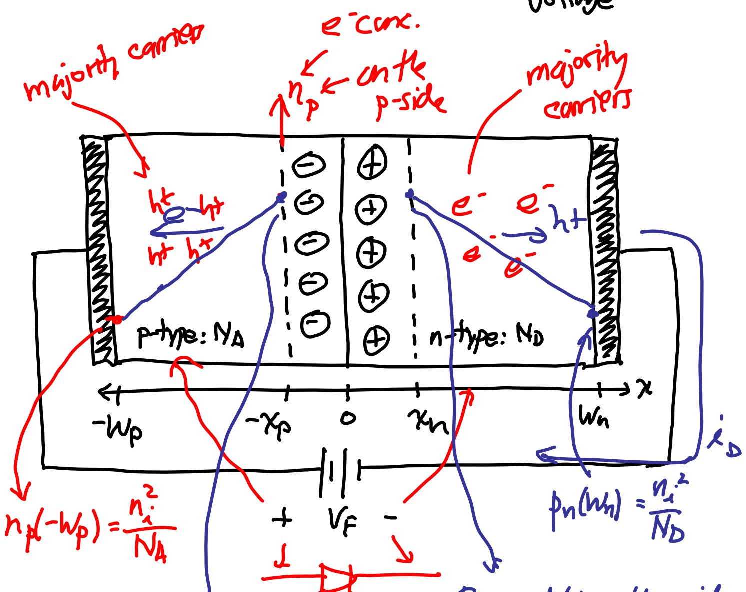
$$\boxed{C_j = \frac{dQ_n}{dV_R} = \frac{C_{jo}}{\sqrt{1+\frac{V_R}{\phi_j}}} \; ; \; C_{jo} = \frac{\epsilon_s A}{W_{do}} \quad \rightarrow \quad C_j = \frac{C_{jo}}{\sqrt{1-\frac{V_D}{\phi_j}}}}$$



Forward Bias Case $V_D > 0$.

$\Rightarrow$ most interested in case where $V_D \geq V_{DO}$.

$\uparrow$ diode turn-on voltage



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-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 n-side → h^+ diffusion current:

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

$$\Rightarrow J_p^{diff} = qD_p \frac{n_i^2}{N_D} \frac{1}{(W_n - x_n)} \left[\exp\left(\frac{v_D}{V_T} \right) - 1 \right]$$

On p-side → e⁻ diffusion current:

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

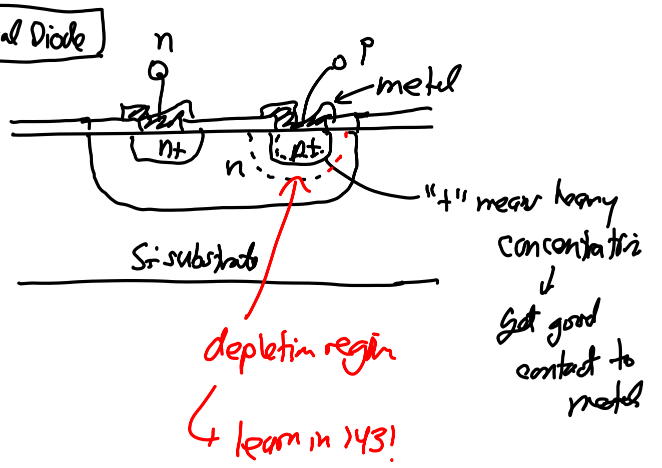
$$\Rightarrow \boxed{J_n^{diff} = qD_n \frac{n_i^2}{N_A} \frac{1}{(-x_p + W_p)} \left[\exp\left(\frac{v_D}{V_T} \right) - 1 \right]}$$

... 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



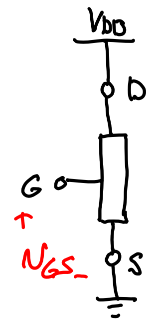
"+" means heavy concentration
↓
get good contact to metal

depletion region

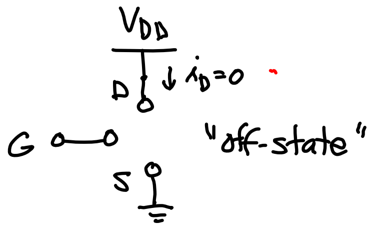
↳ learn in 143!

Transistor Operation → The Basic Goal

Overall Goal: A device for which

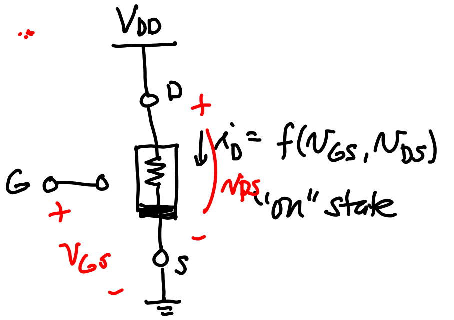


① With $v_{GS} = v_G - v_S$ = small:



⇒ open ckt. → no current flow from D→S

② With $v_{GS} > V_t \triangleq$ "threshold voltage":

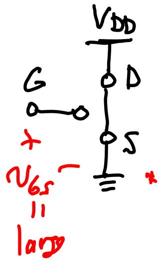


$i_D = f(v_{GS}, v_{DS})$

"on" state

A resistor for which the current from D→S is a function of applied voltages

for high enough voltage:



⇒ in effect, we have a switch controlled by voltage at G