Lecture 14: Diode On & MOSFETs I

Announcements:
- HW#5 online and due Friday via Gradescope
- Lab#2 prelab due this week
- Lab#1 experimental part also due this week
- Lab#2 experimental part due next week
- Lab#3 next week
  - Materials for Lab#3 online
  - Prelab due before lab in 2nd week

Lecture Topics:
- Diode Physics & Operation
  - Forward Bias
- Diode Fabrication
- MOSFETs
  - Structure and Operation
  - Cutoff
  - Linear Region

Last Time:
- Starting forward-biased diodes
- Now, continue with this …

The Diode Equation
\[ I_D = I_S \left[ \exp \left( \frac{qV_D}{nkT} \right) - 1 \right] = I_S \left[ \exp \left( \frac{V_D}{nVT} \right) - 1 \right] \]

\( I_S \) = reverse saturation current [A]
\( q = 1.602 \times 10^{-19} \) C
\( k = \text{Boltzmann constant} = 1.38 \times 10^{-23} \) J/K
\( T = \text{absolute temperature} [K] \)
\( V_T = kT = 25 \text{ mV} \)

Last Time

This Time

⇒ now, get some insight into where this equation comes from
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 is $V_R + \phi_j$, and

\[ W_d = x_n + x_p = \sqrt{\frac{2\varepsilon \varepsilon_0}{q}(N_A + N_B)(\phi_j + V_R)} = W_{do} \sqrt{1 + \frac{V_R}{\phi_j}} \]

\[ Q_n = qN_o x_n A = q \left( \frac{N_A N_B}{N_A + N_B} \right) W_d A \Rightarrow Q_n = f(V_R) \]

Thus, this is a nonlinear capacitor!
Diode Depletion Region Potential Barrier:
- (going deeper than needed, but this can help some of you make sense of what it happening)
- (you get a fuller picture in EE130)
- Plot the potential curve across the depletion region
- Potential curve determines carrier populations

\[ V_D = -\frac{n_D}{N_A} \exp \left( \frac{V_D}{V_T} \right) \]

To get correct, take the stage of the minority carrier concentration distribution:
On n-side: \( n_D = \frac{n_p(x_D)}{N_A} \exp \left( \frac{V_D}{V_T} \right) \)
On p-side: \( n_D = \frac{n_p(x_D)}{N_A} \exp \left( \frac{V_D}{V_T} \right) \)

Change density, \( n \)

\[ J_p = -q_D \frac{\partial \phi}{\partial x} = -q_D \left[ \frac{n_p - n_D}{n_p - n_N} \right] \]
**Transistor Operation → The Basic Goal**

**Overall Goal:** A device for which

1. With $N_{GS} = N_C - N_A$ small:
   
   $\begin{align*}
   V_{dd} & \downarrow \downarrow V_s \downarrow = 0 \\
   S & \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \\
   \Rightarrow & \text{open circuit → no current flow from D → S}
   \end{align*}$

2. With $N_{GS} > V_t \equiv \text{"threshold voltage"}$
   
   A resistor for which the current from D → S is a function of applied voltages

   $V_{dd}$
   $V_s$
   $S$
   $G$
   $D$
   $\downarrow \downarrow \downarrow \downarrow \downarrow \downarrow \downarrow$
   $V_t = f(N_{GS}, N_{DS})$
   $\Rightarrow \text{in effect, we have a switch controlled by voltage at } G$
### NMOS Transistor Mathematical Model

1. **Cutoff Region:** \( V_{GS} \leq V_{TN} \)
   
   \[ i_G = i_B = 0; \quad i_{DS} = 0 \]

2. **Linear (or Triode) Region:** \( V_{GS} - V_{TN} \geq V_{DS} \geq 0 \)
   
   \[ i_G = i_B = 0; \quad i_{DS} = \frac{1}{2} \mu A C_{ox} \frac{W}{L} \left( V_{GS} - V_{TN} \right)^2 \left( 1 + \frac{V_{DS}}{V_{TH}} \right) \]
   
   \[ = \frac{K_n}{2} \left( V_{GS} - V_{TN} \right)^2 \left( 1 + \frac{V_{DS}}{V_{TH}} \right) \]

3. **Saturation Region:** \( V_{DS} \geq V_{GS} - V_{TN} \geq 0 \)
   
   \[ i_G = i_B = 0; \quad i_{DS} = \frac{1}{2} \mu A C_{ox} \frac{W}{L} \left( V_{GS} - V_{TN} \right)^2 \left( 1 + \frac{V_{DS}}{V_{TH}} \right) \]
   
   \[ = \frac{K_n}{2} \left( V_{GS} - V_{TN} \right)^2 \left( 1 + \frac{V_{DS}}{V_{TH}} \right) \]
\[ K_n = \frac{k_i \cdot W}{L} = \mu_n C_{ox} \cdot \frac{W}{L} \]

\[ i_G = I_B = 0 \quad \text{for all regions} \]

\[ V_{TN} = f(N_{SB}) = V_{T0} + \gamma \left( \sqrt{V_{SB}} + 2\phi_f - \sqrt{2\phi_f} \right) \]

- \( \mu_n \): e\text{-}mobility in the channel
- \( C_{ox} \): gate oxide per unit area
- \( V_{T0} \): threshold voltage w/ \( V_{SB} = 0V \)
- \( \gamma \): body effect parameter
- \( 2\phi_f \): built\text{-}in surface potential \( \approx 0.6V \)

**MOS Transistor Regions of Operation**

Before starting: reminder of a simple capacitor

![Simple Capacitor Diagram](image)