Announcements:
- HW#5 online and due Friday via Gradescope
- Lab#3 this week
  - Due week after next (since next week is the first midterm exam)
- Midterm 1: Friday, Oct. 5, from 5-6:30 p.m., in 277 Cory
- Lab Sections on different grading curves
  - Fairer for earlier lab sections
- Will be collecting names and student ID numbers for those who do not yet have access to the lab
- Lecture Topics:
  - MOSFETs
    - Channel Length Modulation
    - Body Effect
  - Bipolar Junction Transistor (BJT)
    - Regions of Operation
- Last Time:
  - Started into channel length modulation
  - Now, continue with this ...

\( \text{Saturation Region:} \quad (V_{DS} \geq V_{GS} - V_{TH} \Rightarrow 0) \)

As \( V_{DS} \) increases, the voltage across the gate-to-substrate capacitance near the drain:

\( (V_{GS} - V_{TH} - V_{DN}) \rightarrow 0 \)

At this point, \( i_{DS} \) has reached its maximum!

\[ \text{Ideal} \]

Plug in \( V_{GS} - V_{TH} - V_{DN} = 0 \rightarrow V_{DS} = V_{GS} - V_{TH} \) into the \( i_{DS} \) equation:

\[ i_{DS} = \frac{1}{2} \mu_{n} C_{ox} \frac{W}{L} (V_{GS} - V_{TH})^2 \quad \text{for} \quad V_{DS} = V_{GS} - V_{TH} \]
as $V_{DS}$ increases, $i_{DS}$ remains constant; however, due to 2nd-order effects, $i_{DS}$ actually still rises a bit

Reason: channel length modulation

Example: $V_{GS} = 1V, V_{DS} = 4V \rightarrow V_{DS} - V_{TH} = 0.3V \rightarrow L_{sat} = 1V - V_{TH} = 0.7V$

$Q = \frac{C_L}{L} (V_{GS} - V_{TH})$

$\Delta L = L - L'$ (i.e., it gets smaller)

\[ i_{DS} = \frac{1}{2} \mu \frac{W}{L} \left( V_{GS} - V_{TH} \right)^2 \]

for short-channel devices

\[ \lambda \leq \text{channel length modulation parameter} \quad (0.001 \text{ } \text{V}^{-1} \leq \lambda \leq 0.1 \text{ } \text{V}^{-1}) \]
Body Effect (Substrate Sensitivity)

- threshold voltage, $V_{TN}$, is a function of substrate bias voltage: $V_{SB}$
- Region: (simple region)
  - as $V_{SB} \rightarrow$ max, channel depletion region gets larger (i.e., it can hold more charge)
  - need more $V_{GS}$ to permit $I_{ch}$ to flow

For a typical NMOS Transistor:

- $-5V \leq V_{GS} \leq 5V$ but usually $0.7V$
- $V_{TH} = \phi_T$ for enhancement mode NMOS
- $V_{TH} = -\phi_T$ for depletion mode NMOS

$0 \leq \phi \leq 3.3V \rightarrow$ typically $0.5V$

$0.3V \leq 2\phi_T \leq 1V \rightarrow$ for $V_{GS}$, generally $0.6V$

PMOS Transistors

- Basically, the reverse of NMOS transistors
- Physics basically the same, but the carriers are now $h^+$ and the voltage polarities reverse

$V_{PP} = \phi_T$ for enhancement $\phi_T$

$V_{PP} = (-\phi_T)$ for depletion $\phi_T$

$V_{PP} = (-\phi_T)$ for depletion region

$V_{PP} = \phi_T$ for enhancement region
PMOS Transistor Model Summary

\[ i_{SD} = \frac{1}{2} \mu_p C_{ox} W \left( V_{GS} - V_{TP} \right)^2 \left( 1 + \lambda N_{SD} \right) \]

1. **Cutoff Region:** \( N_{SG} \leq -V_{TP} \)
   - \( i_{SD} = 0 \)

2. **Linear (or Triode) Region:** \( N_{SG} + V_{TP} \geq N_{SD} \geq 0 \)
   - \( i_{SD} = K_p \left( N_{SG} + V_{TP} - \frac{N_{SD}}{2} \right) N_{SD} \)
   - \( = \frac{1}{2} \mu_p C_{ox} W \left( N_{SG} + V_{TP} - \frac{N_{SD}}{2} \right) N_{SD} \)

3. **Saturation Region:** \( N_{SD} \geq N_{SG} + V_{TP} \geq 0 \)
   - \( i_{SD} = \frac{1}{2} \mu_p C_{ox} W \left( N_{SG} + V_{TP} \right)^2 \left( 1 + \lambda N_{SD} \right) \)
   - \( = \frac{K_p}{2} \left( N_{SG} + V_{TP} \right)^2 \left( 1 + \lambda N_{SD} \right) \)

where for all regions:

- \( K_p \) = \( k_t W \) / \( L \)
- \( i_G = 0 \) and \( i_B = 0 \)
- \( V_{TP} = V_{TO} - \gamma \left( \sqrt{V_{GS} + 2 \phi_f} - \sqrt{2 \phi_f} \right) \)
- \( \mu_p \) = hole mobility in the channel
- \( C_{ox} \) = gate oxide per unit area
- \( V_{TO} \) = threshold voltage w/ \( V_{SB} = 0 \)
- \( \gamma \) = body effect parameter
- \( 2 \phi_f \) = built-in surface potential \( \approx 0.6 \)
MOSFET CV Curve

Simple Theory

Depletion Region (Fixed Neg. Charge)

Inversion Charge (Free Neg. Charge)

Thus, the inversion charge thins down towards the drain.

Q'(x = 0) = \text{Cox}(V_{GS} - V_{TH})

Q'(x = L) = \text{Cox}(V_{GS} - V_{TN} - V_{DS})

Thus, the inversion charge thins down towards the drain.

@ x = 0:

\[ C_G = \text{Cox} \]

\[ C_{Gd} = \text{Cox} \]

\[ C_{Gd} = \frac{dQ}{dV} = \frac{dQ_n}{dV} \text{ when inversion charge can keep up with the frequency} \]