Lecture 17: PMOS and Bipolar Transistors I

Announcements:
- HW#6 online and due Friday via Gradescope
- Lab#2 experimental part due this week
- Lab#3 prelab due next week
- Lab#3 experimental part due the week of 10/19

Lecture Topics:
- MOSFETs
  - Body Effect
  - PMOS
- Bipolar Junction Transistor (BJT)
  - Regions of Operation
  - Cutoff
  - Forward-Active

Last Time:
- Derived the saturation region MOSFET equation
- Now, continue with 2nd order effects ...

Saturation Region - \( V_{DS} > V_{GS} \cdot V_{TN} > 0 \)

As \( V_{DS} \to \) the voltage across the gate-to-substrate

capacitor near the drain:

\( (V_{GS}-V_{TN}-V_{DS}) \to 0 \) @ the drain edge

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

\( V_{DS} > V_{GS} \cdot V_{TN} \)

\( i_{DS} = \frac{1}{2} \mu_C (N_{GS} - V_{TN}) \cdot \frac{(N_{GS} - V_{TN})}{L} \) \( V_{GS} = V_{GS} \cdot V_{TN} \)

\( i_{DS} = \frac{1}{2} \mu_C (N_{GS} - V_{TN})^2 \) \( V_{GS} = V_{GS} \cdot V_{TN} \)

onset of Saturation
\[ i_{DS} = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})^2 \]

This is the linear region. In the saturation region,

\[ \Delta L = \frac{2}{N_{DS}} \]

Use boundary theorem:

\[ (L + \Delta L) = (1 + \lambda N_{DS}) L \]

\[ \lambda = \frac{\Delta L}{L} = \frac{2}{N_{DS}} \]

This is the channel length modulation parameter:

\[ 0.001 \leq \lambda \leq 0.1 \text{V}^{-1} \]

For a long-channel device:

\[ N_{DS} \rightarrow V_{DS} - V_{TH} \]

For a short-channel device:

\[ N_{DS} \rightarrow \text{symmetric device?} \]
Body Effect (Substrate Sensitivity):

- Threshold voltage $V_{TN}$ is a function of the substrate bias voltage $v_{SB}$
- Reason: (simple version)
  - As $v_{SB}$ ↑ ⇔ maximum channel depletion region gets larger (i.e., it can hold more charge)
  - Need more $V_{GS}$ to invert the channel ⇒ $V_{TN}$ ↑

![Diagram](https://via.placeholder.com/150)

Governing Threshold Voltage Equation

$$V_{TN} = V_{T0} + \theta (\sqrt{N_{SB} - 2\phi_f} - \sqrt{2\phi_f})$$

Where $V_{T0}$ = voltage of $V_{TN}$ for $N_{SB} = 0V$ [V]

$\theta$ = body effect parameter [\sqrt{V}]  

$2\phi_f$ = surface potential parameter [V]

Remarks: (for a typical NMOS transistor)

1. $-5V \leq V_{T0} \leq 5V$ → but usually 0.7V
   - $V_{T0}$: (+) → enhancement mode NMOS
   - $V_{T0}$: (-) → depletion mode NMOS (but out of the scope of this class)

2. $0 \leq \theta \leq 3 \sqrt{V}$ → typically, $0.5 \sqrt{V}$

3. $0.3V \leq 2\phi_f \leq 1V$ → for us, generally 0.6V
• Basically, the reverse of NMOS transistors
• Physics basically the same, but the carriers are now \( h^+ \) and the voltage polarities reverse

\[ V_{DD}, \quad e^- \text{ (for depletion PMOS)} \]

\[ V_{DD}, \quad e^- \text{ (for enhancement PMOS)} \]

**PMOS Transistor Model Summary**

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

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

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

\[ k_p = k_p l = \mu_p C_{ox} \frac{W}{L} \]

\[ i_G = 0 \] and \[ i_B = 0 \]

\[ V_{TP} = V_{TO} - \gamma (\sqrt{V_{BS} + 2 \phi_f} - \sqrt{2 \phi_f}) \]

\[ \mu_p \] = hole mobility in the channel

\[ C_{ox} \] = gate oxide per unit area

\[ V_{TO} \] = threshold voltage w/ \( V_{SB} = 0 \) V

\[ \gamma \] = body effect parameter

\[ 2 \phi_f \] = built-in surface potential \( \approx 0.6V \)
Regions of BJT Operation

<table>
<thead>
<tr>
<th>EBJ</th>
<th>CBJ</th>
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<tbody>
<tr>
<td>R</td>
<td>R</td>
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<tr>
<td>F</td>
<td>F</td>
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</tbody>
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- **EEJ** - Forward bias, Re-reverse bias
- **EBJ** - Cutoff (both diodes off)
- **CBJ** - Reverse Active (widely used in analog amplifiers)
- **EBJ** - Saturated

**⇒ Or graphically:**

- npn
  - Reverse Active
  - Saturation
  - Cut-off

- pnp
  - Reverse Active
  - Saturation
  - Cut-off

**⇒ BOTH diodes reverse-biased**

- No current flow.
  - $i_B = 0$, $i_C = 0$, $i_E = 0$

**⇒ Cutoff Region: (npn transistor)**

- $V_{BE} = L^-$
- $V_{BC} = L^-$

- BOTH diodes reverse-biased

- **Ideal model**
  - Includes the tiny reverse currents

- **Real model**
Forward-Active Region: (nnp transistor)

BEJ forward-biased (i.e., diode on)

BCJ reverse-biased (i.e., diode off)

Minority Carrier Concentrations:

\[ N_{BE} = \text{(+)} \quad N_{BC} = \text{(-)} \quad N_{CB} = \text{(+) \, (n)} \]