ESE370: Circuit-Level Modeling, Design, and Optimization for Digital Systems

Lec 7: September 16, 2015
MOS Transistor Operating Regions
Part 1

Today
- PN Junction
- MOS Transistor Topology
- Threshold
- Operating Regions
  - Resistive
  - Saturation
  - Subthreshold (next class)
  - Velocity Saturation (next class)

Last Time – MOS model
- Refinement
  - Depletion region → excess carriers depleted

Bulk/Body Contact
- MOS actually has four contacts
- Also effects fields
- Usually common across transistors
  - Grid for nmos, V_{dd} for pmos

No Field
- V_{GS}=0, V_{DS}=0
Apply $V_{GS}>0$

- Accumulate negative charge
  - Repel holes (fill holes)

Channel Evolution -- Increasing $V_{gs}$

Gate Capacitance

- Changes based on operating region.
  - Depletion capacitance dependent on width of depletion region and potential at oxide-silicon border

Channel Evolution -- Increasing $V_{gs}$

Inversion

- Surface builds electrons
  - Inverts to n-type
  - Draws electrons from n$^+$ source terminal
Threshold

- Voltage where strong inversion occurs: \( V_{th} \)
- \( V_{th} \approx 2\phi_F \)
- Engineer by controlling doping \( N_A \):
  \[
  \phi_F = \phi_T \ln \left( \frac{N_A}{n_i} \right)
  \]

Linear Region

- \( V_{GS} > V_{th} \) and \( V_{DS} \) small
- \( C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} \)

\[
I_{DS} = \mu_n C_{ox} \frac{W}{L} \left[ (V_{GS} - V_{th})V_{DS} - \frac{V_{DS}^2}{2} \right]
\]

MOSFET – IV Characteristics

-\( V_{DS} < V_{GS} - V_{TH} \)
-\( V_{GS} = V_{th} + 7 \text{V} \)
-\( V_{DS} = V_{th} \)
-\( V_{DS} = V_{GS} - V_{TH} \)

Dimensions

- Channel Length (\( L \))
- Channel Width (\( W \))
- Oxide Thickness (\( T_{ox} \))
Preclass

1. $I_{ds}$ for identical transistors in parallel?

2. $I_{ds}$ for identical transistors in series?
   - (Vds small)

Transistor Strength (W/L)

$$C_{ox} = \frac{\varepsilon_{ox}}{L_{ox}}$$

$$I_{DS} = \mu_n C_{OX} \left( \frac{W}{L} \right) \left[ (V_{GS} - V_{th})V_{DS} - \frac{V_{DS}^2}{2} \right]$$

$L_{\text{drawn}}$ vs. $L_{\text{effective}}$

- Doping not perfectly straight
- Spreads under gate
- Effective $L$ smaller than draw gate width

Channel Voltage

- Voltage varies along channel
- Think of channel as resistor
Preclass

- What is voltage in the middle of a resistive medium?
  - (halfway between terminals)

Voltage in Channel

- Think of channel as resistive medium
  - Length = L
  - Area = Width * Depth (inversion)

- What is voltage in the middle of the channel?
  - L/2 from S and D?

Channel Voltage

- Voltage varies along channel
- If think of channel as resistor
  - Serves as a voltage divider between $V_S$ and $V_D$

Voltage along Channel

- What does voltage along the channel look like?

Voltage along Channel

- What does voltage along the channel look like?
What does voltage along the channel look like?

![Diagram of voltage along the channel with labels: S (source), G (gate), and D (drain) with n⁺ regions and a depletion region.]

Channel Field

- When voltage gap $V_C-V_s$ drops below $V_{th}$, drops out of inversion
  - If $V_{DS} = V_{GS} - V_{th}$, $V_{DS} = V_{th}$

![Diagram of channel field with labels: S (source), G (gate), and D (drain) with n⁺ regions and a depletion region.]

Pinch Off

- When voltage along the channel drops below $V_{th}$, the channel drops out of inversion
  - Occurs when: $V_{GS} - V_{DS} < V_T$ → $V_{DS} < V_{GS} - V_{th}$
  - Conclusion: current cannot increase with $V_{DS}$ once $V_{DS} > V_{GS} - V_T$

![Diagram of pinch off with labels: S (source), G (gate), and D (drain) with n⁺ regions and a depletion region.]

Saturation

- In saturation, $V_{DS\text{-effective}} = V_s = V_{GS} - V_T$
  
  $I_{DS} = \mu_n C_{OX} \left( \frac{W}{L} \right) \left[ (V_{GS} - V_T) V_{DS} - \frac{V_{DS}^2}{2} \right]$

  - Becomes:
    
    $I_{DS} = \mu_n C_{OX} \left( \frac{W}{L} \right) \left[ (V_{GS} - V_T)^2 - \frac{(V_{GS} - V_T)^2}{2} \right]$

    $I_{DS} = \frac{\mu_n C_{OX} W}{2} \left( \frac{V_{GS} - V_T}{L} \right)$

![Diagram of MOSFET IV characteristics with various curves indicating saturation and breakdown regions.]

MOSFET – IV Characteristics

- When $V_{DS} < V_{GS} - V_{th}$, linear region
- When $V_{DS} = V_{GS} - V_{th}$, saturation region
- When $V_{DS} = V_{GS} - V_T$, breakdown region
- When $V_{GS} - V_{th} = V_{th}$, output region

![Graph with axes labeled: Drain current (in Ampere), Drain to source voltage (in Volt), VDS, VGS. Curves showing various regions: linear, saturation, breakdown, output.]
Approach

- Identify Region
- Drives governing equations
  - See preclass reference
- Use region and equations to understand operation

Big Idea

- 3 Regions of operation for MOSFET
  - Subthreshold
  - Linear
  - Saturation

Admin

- Text 3.3.2 – highly recommend read!!
  - Second half on Friday
- HW4 out
  - Get started over weekend
  - Long and time-consuming