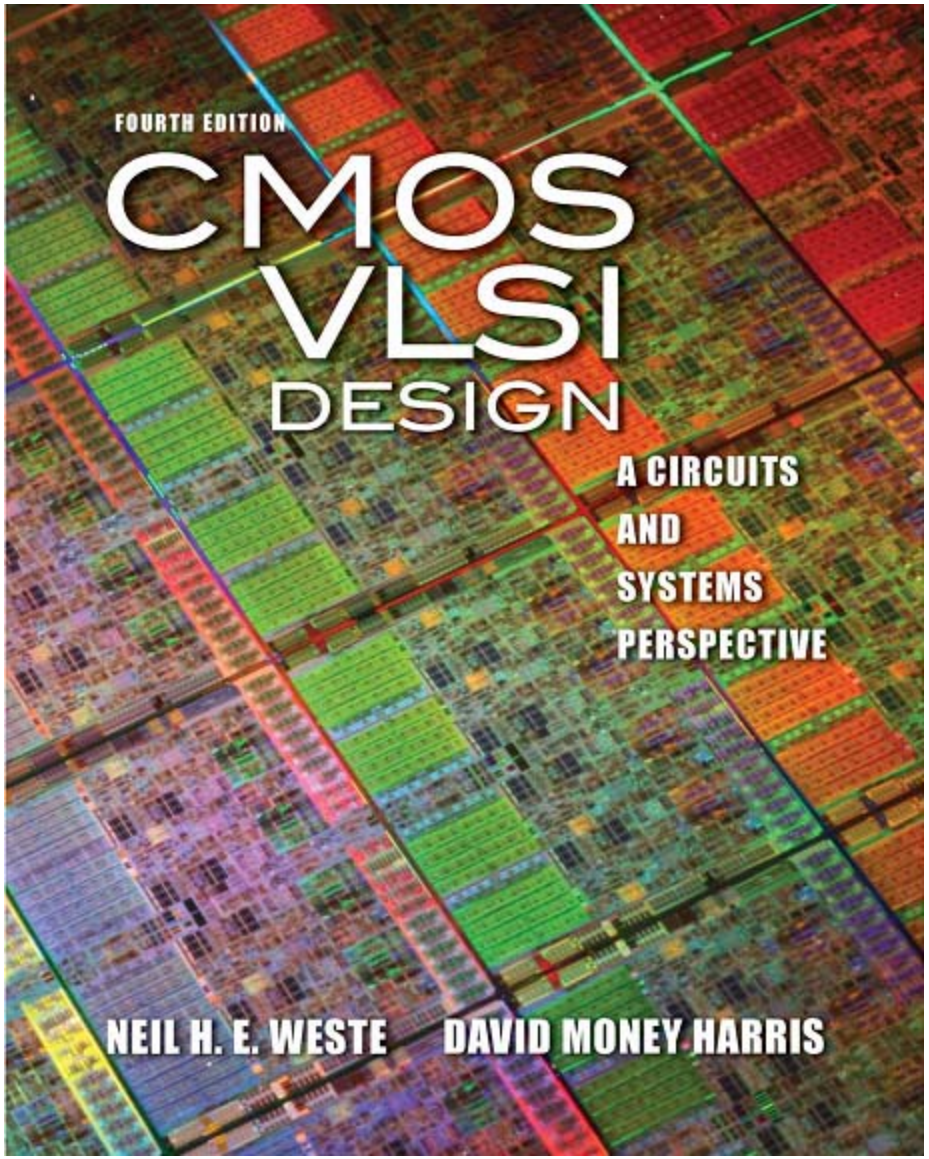


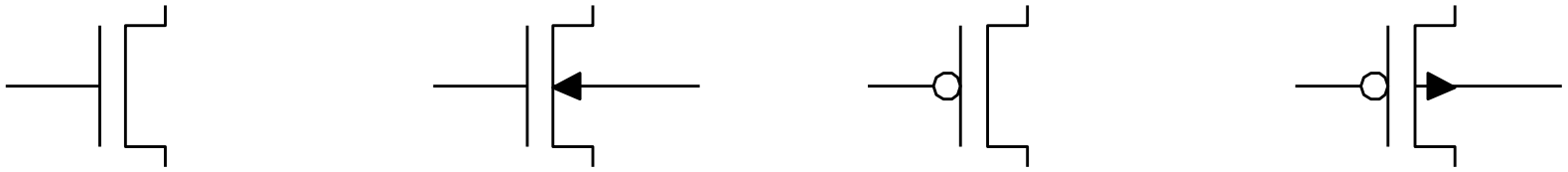
Lecture 3: CMOS Transistor Theory

Outline

- Introduction
- MOS Capacitor
- nMOS I-V Characteristics
- pMOS I-V Characteristics
- Gate and Diffusion Capacitance

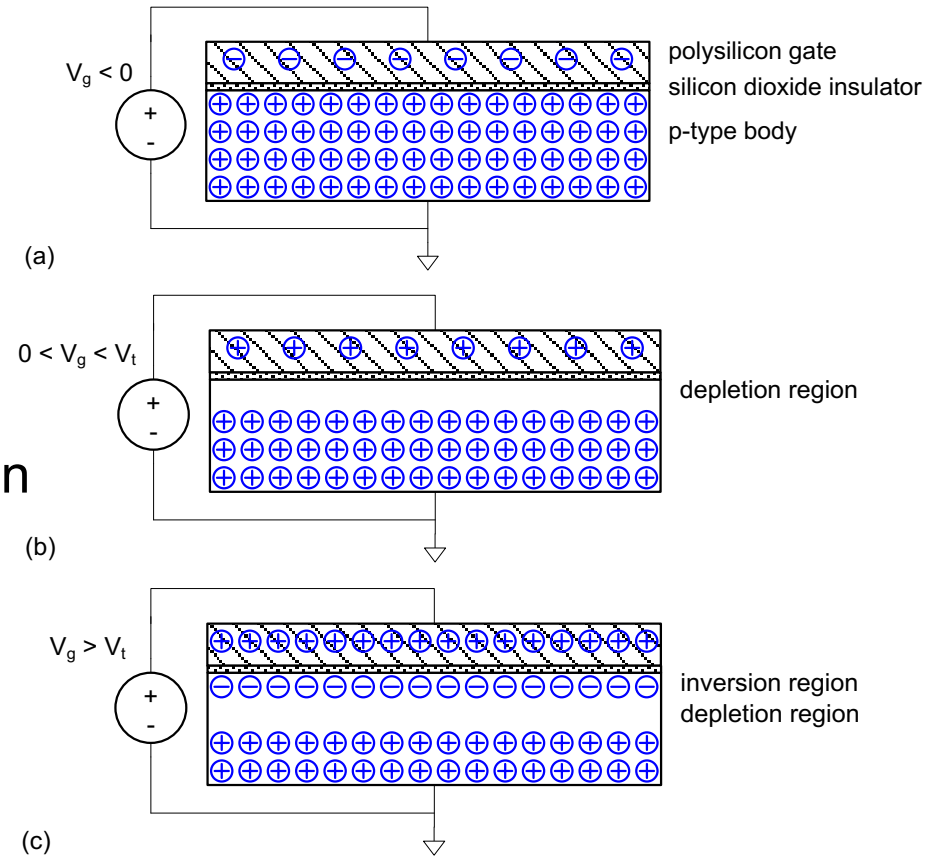
Introduction

- So far, we have treated transistors as ideal switches
- An ON transistor passes a finite amount of current
  - Depends on terminal voltages
  - Derive current-voltage (I-V) relationships
- Transistor gate, source, drain all have capacitance
  - $I = C (\Delta V/\Delta t) \rightarrow \Delta t = (C/I) \Delta V$
  - Capacitance and current determine speed



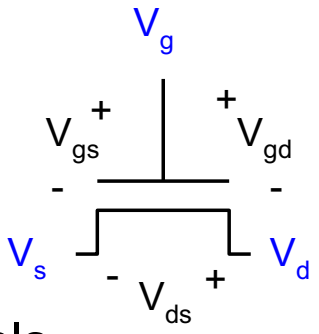
MOS Capacitor

- Gate and body form MOS capacitor
- Operating modes
  - Accumulation
  - Depletion
  - Inversion
- Threshold voltage is when inversion begins



Terminal Voltages

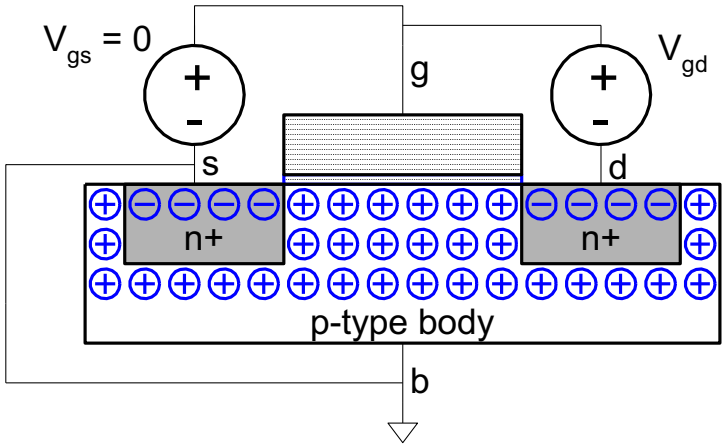
- Mode of operation depends on V_g, V_d, V_s
  - $V_{gs} = V_g - V_s$
  - $V_{gd} = V_g - V_d$
  - $V_{ds} = V_d - V_s = V_{gs} - V_{gd}$



- Source and drain are symmetric diffusion terminals
  - By convention, source is terminal at lower voltage
  - Hence $V_{ds} \geq 0$
- nMOS body is grounded. First assume source is 0 too.
- Three regions of operation
  - *Cutoff*
  - *Linear*
  - *Saturation*

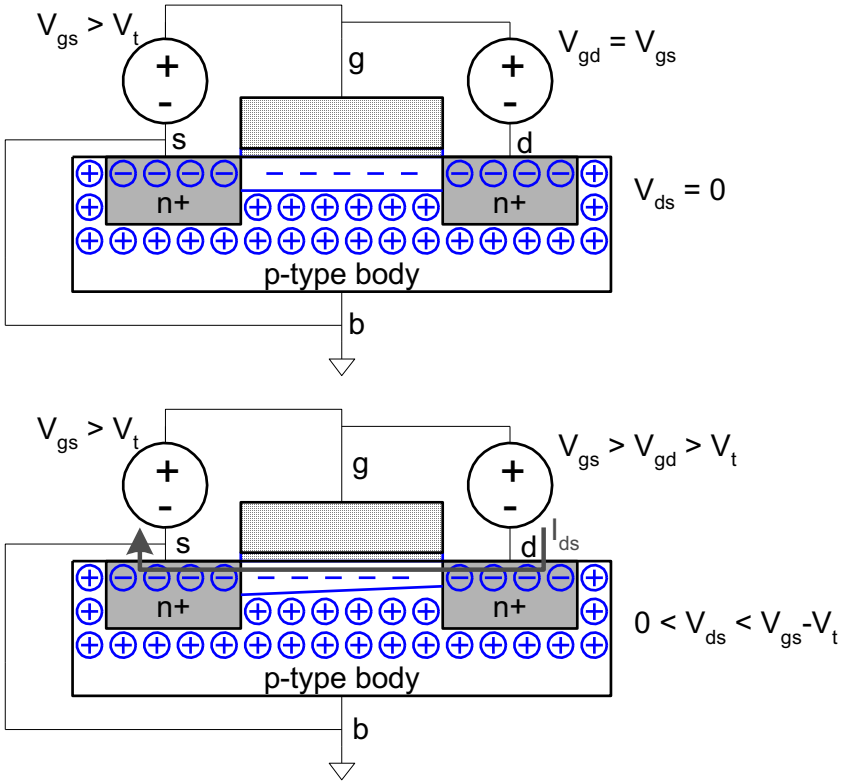
nMOS Cutoff

- $V_{gs} < V_t$
- No inversion, no channel
- $I_{ds} \approx 0$



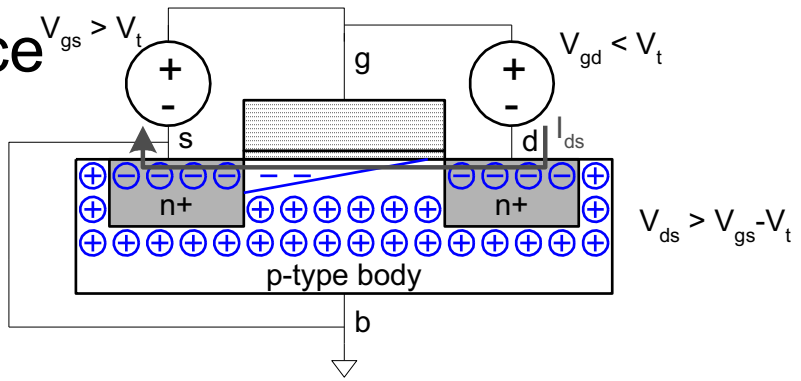
nMOS Linear

- $V_{gs} > V_t$
- But V_{ds} small
- Channel forms
- Current flows from d to s
  - e^- from s to d
- I_{ds} increases with V_{ds}
- Similar to linear resistor



nMOS Saturation

- $V_{gs} > V_t$
- $V_{ds} > V_{gs} - V_t$
- Channel pinches off
- I_{ds} independent of V_{ds}
- We say current *saturates*
- Similar to current source

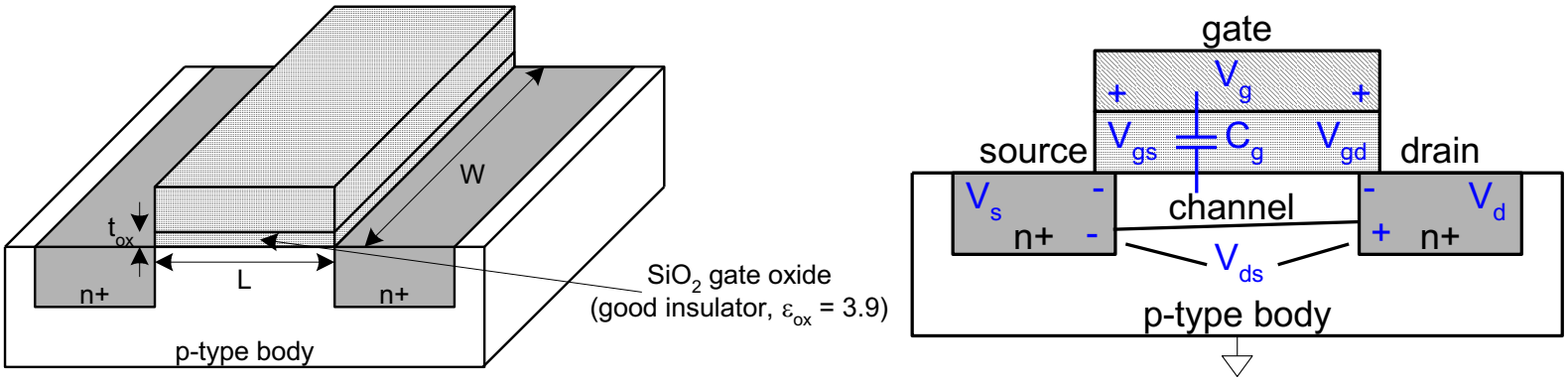


I-V Characteristics

- In Linear region, I_{ds} depends on
  - How much charge is in the channel?
  - How fast is the charge moving?

Channel Charge

- MOS structure looks like parallel plate capacitor while operating in inversions
  - Gate – oxide – channel
- $Q_{channel}$ =
-
-



Carrier velocity

- Charge is carried by e-
- Electrons are propelled by the lateral electric field between source and drain
  - E =
- Carrier velocity *v* proportional to lateral E-field
  - *v* =
- Time for carrier to cross channel:
  - *t* =

nMOS Linear I-V

- Now we know
  - How much charge $Q_{channel}$ is in the channel
  - How much time *t* each carrier takes to cross

$$I_{ds} =$$

$$=$$

$$=$$

nMOS Saturation I-V

- If $V_{gd} < V_t$, channel pinches off near drain
  - When $V_{ds} > V_{dsat}$ =
- Now drain voltage no longer increases current

$$I_{ds} =$$

$$=$$

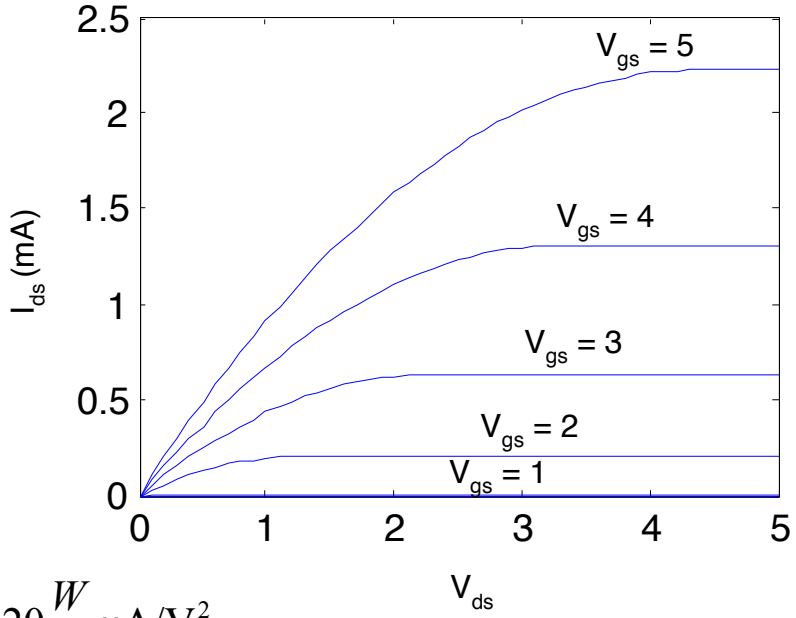
nMOS I-V Summary

- *Shockley* 1st order transistor models

$$I_{ds} = \begin{cases} 0 & V_{gs} < V_t \quad \text{cutoff} \\ \beta\left(V_{gs} - V_t - V_{ds}/2\right)V_{ds} & V_{ds} < V_{dsat} \quad \text{linear} \\ \frac{\beta}{2}\left(V_{gs} - V_t\right)^2 & V_{ds} > V_{dsat} \quad \text{saturation} \end{cases}$$

Example

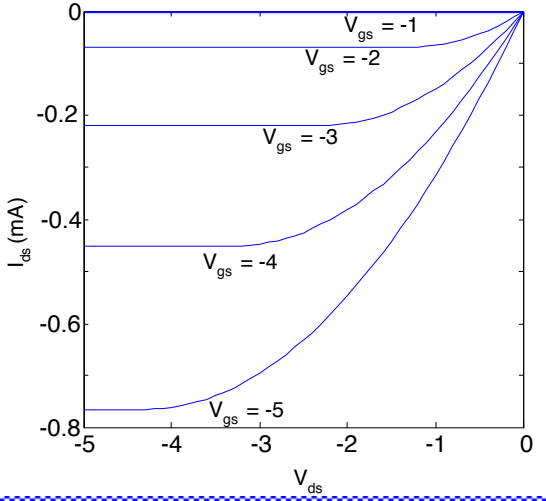
- We will be using a 0.6 μm process for your project
  - From AMI Semiconductor
  - t_{ox} = 100 Å
  - μ = 350 $cm^2/V*s$
  - V_t = 0.7 V
- Plot I_{ds} vs. V_{ds}
  - V_{gs} = 0, 1, 2, 3, 4, 5
  - Use W/L = 4/2 λ



$$\beta = \mu C_{ox}\frac{W}{L} = (350)\left(\frac{3.9\times 8.85\cdot 10^{-14}}{100\cdot 10^{-8}}\right)\left(\frac{W}{L}\right) = 120\frac{W}{L}\,\mu A/V^2$$

pMOS I-V

- All dopings and voltages are inverted for pMOS
  - Source is the more positive terminal
- Mobility μ_p is determined by holes
  - Typically 2-3x lower than that of electrons μ_n
  - 120 $cm^2/V \cdot s$ in AMI 0.6 μm process
  - In advanced nodes, $\mu_p \approx \mu_n$
- Thus pMOS must be wider to provide same current
  - In this class, assume $\mu_n / \mu_p = 2$

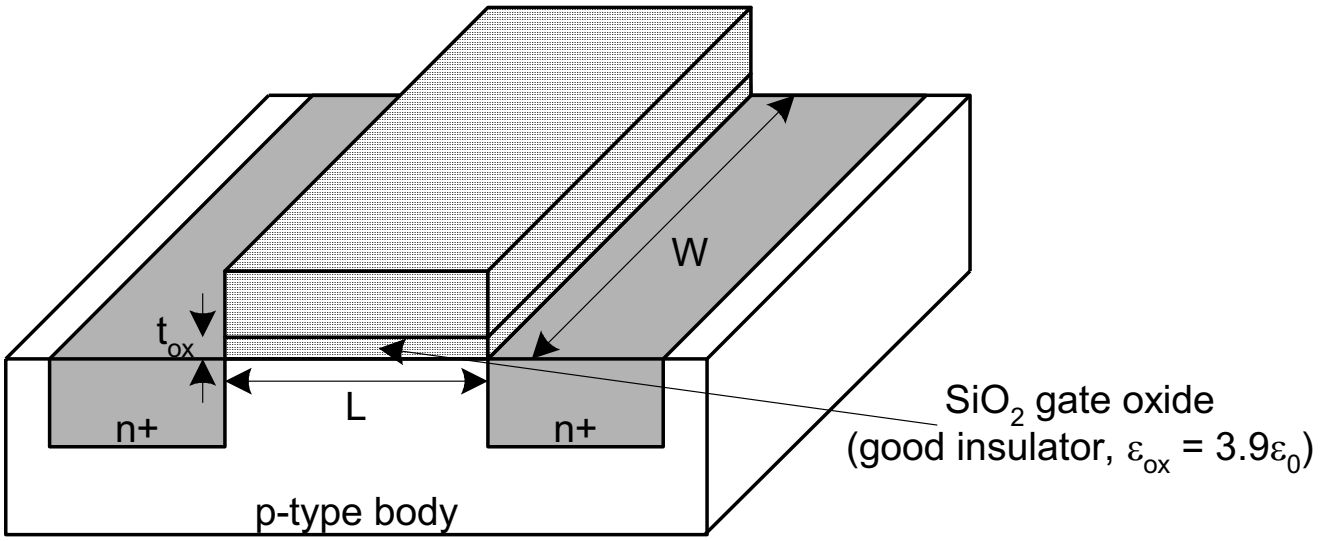


Capacitance

- Any two conductors separated by an insulator have capacitance
- Gate to channel capacitor is very important
  - Creates channel charge necessary for operation
- Source and drain have capacitance to body
  - Across reverse-biased diodes
  - Called diffusion capacitance because it is associated with source/drain diffusion

Gate Capacitance

- Approximate channel as connected to source
- $C_{gs} = \varepsilon_{ox}WL/t_{ox} = C_{ox}WL = C_{permicron}W$
- $C_{permicron}$ is typically about 2 fF/μm



Diffusion Capacitance

- Source/drain diffusion to body C_{sb}, C_{db}
- Undesirable, called *parasitic* capacitance
- Capacitance depends on area and perimeter
  - Use small diffusion nodes
  - Comparable to C_g for contacted diff
  - ½ C_g for uncontacted
  - Varies with process