

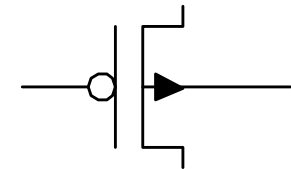
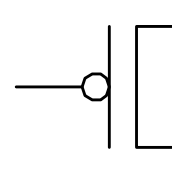
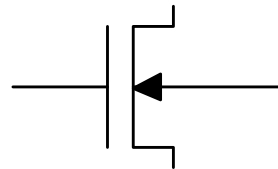
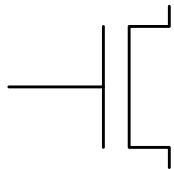
Lecture 3: CMOS Transistor Theory

Outline

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

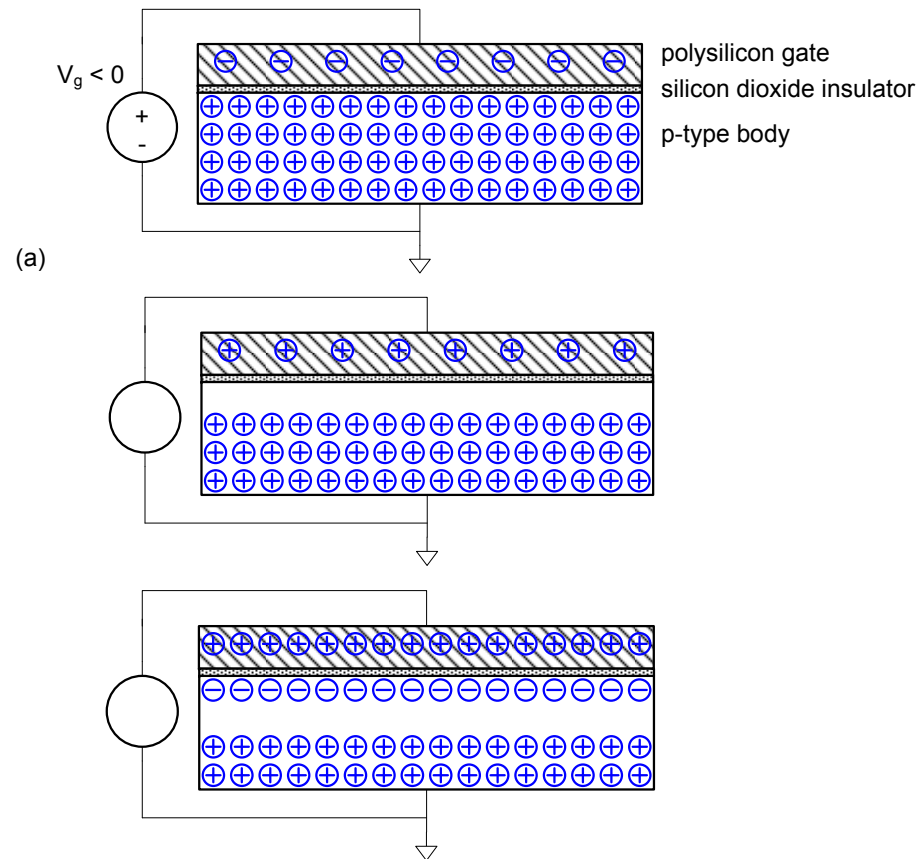
Introduction

- ❑ 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

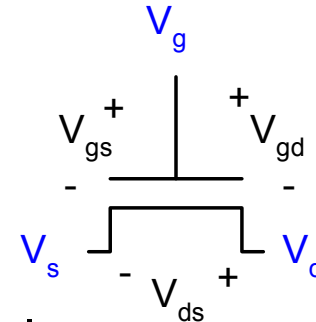
- ❑ Gate and body form MOS capacitor
- ❑ Operating modes
 - Accumulation
 - Depletion
 - Inversion



Terminal Voltages

- Mode of operation depends on V_g , V_d , V_s

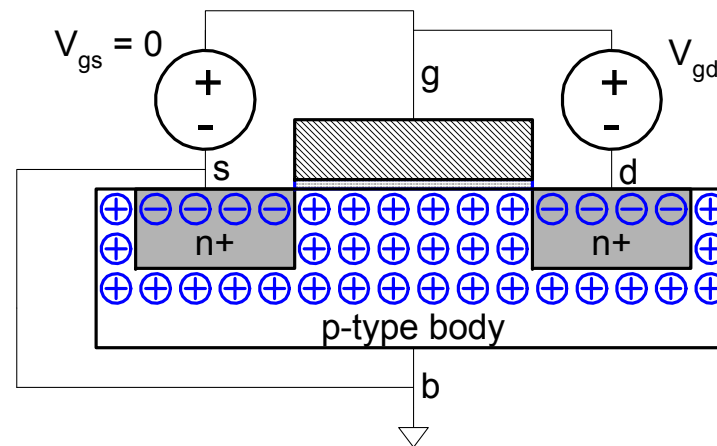
- $V_{gs} = V_g - V_s$
- $V_{gd} = V_g - V_d$
- $V_{ds} = V_d - V_s = V_{gs} - V_{gd}$



- 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*

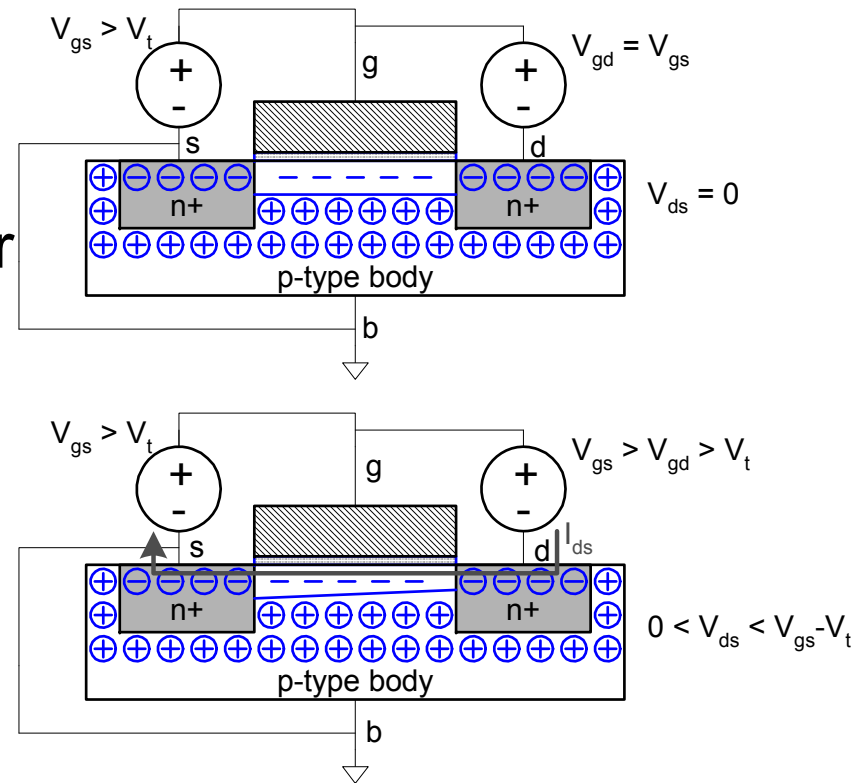
nMOS Cutoff

- ❑ No channel
- ❑ $I_{ds} \approx 0$



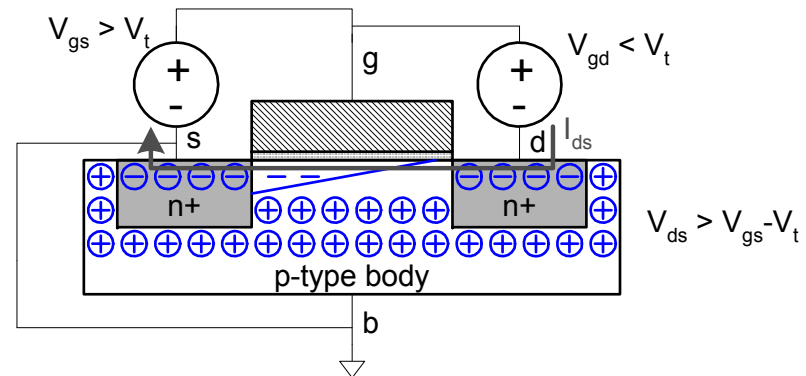
nMOS Linear

- ❑ 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

- ❑ Channel pinches off
- ❑ I_{ds} independent of V_{ds}
- ❑ We say current *saturates*
- ❑ Similar to current source



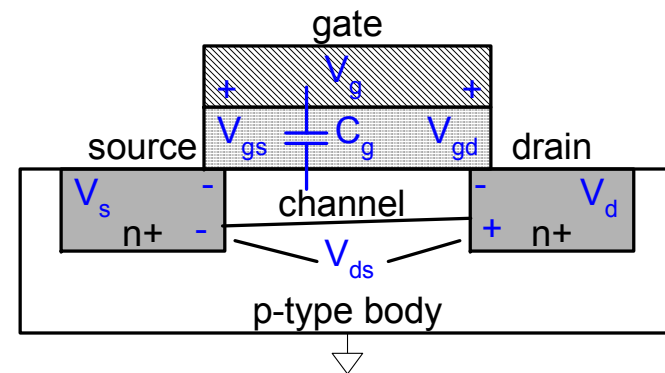
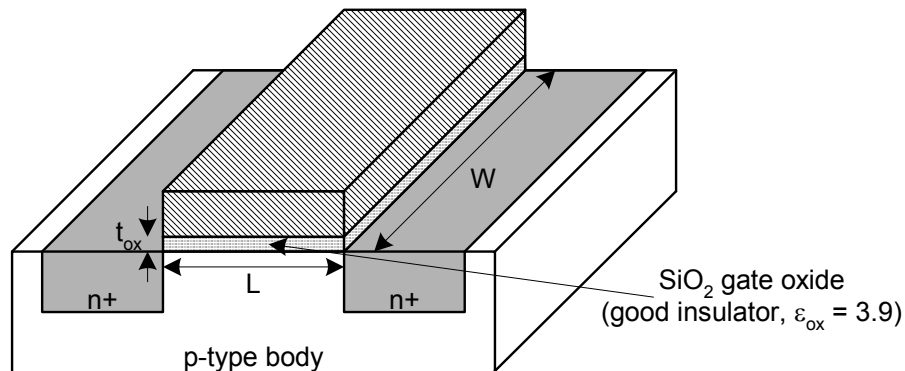
I-V Characteristics

- 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 inversion
 - Gate – oxide – channel

- ❑ $Q_{\text{channel}} =$



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

$$I_{ds} =$$

=

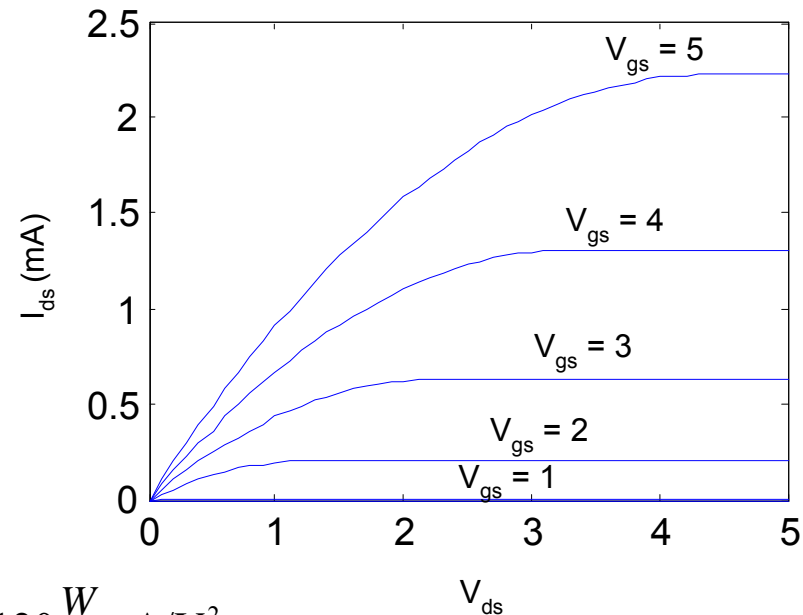
nMOS I-V Summary

- Shockley 1st order transistor models

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

Example

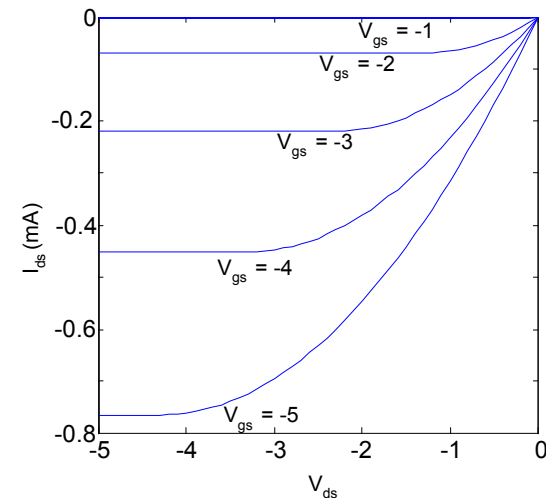
- ❑ We will be using a 0.6 μm process for your project
 - From AMI Semiconductor
 - $t_{\text{ox}} = 100 \text{ \AA}$
 - $\mu = 350 \text{ cm}^2/\text{V}\cdot\text{s}$
 - $V_t = 0.7 \text{ V}$
- ❑ Plot I_{ds} vs. V_{ds}
 - $V_{\text{gs}} = 0, 1, 2, 3, 4, 5$
 - Use $W/L = 4/2 \lambda$



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

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 cm²/V•s in AMI 0.6 μm process
- ❑ Thus pMOS must be wider to provide same current
 - In this class, assume
$$\mu_n / \mu_p = 2$$

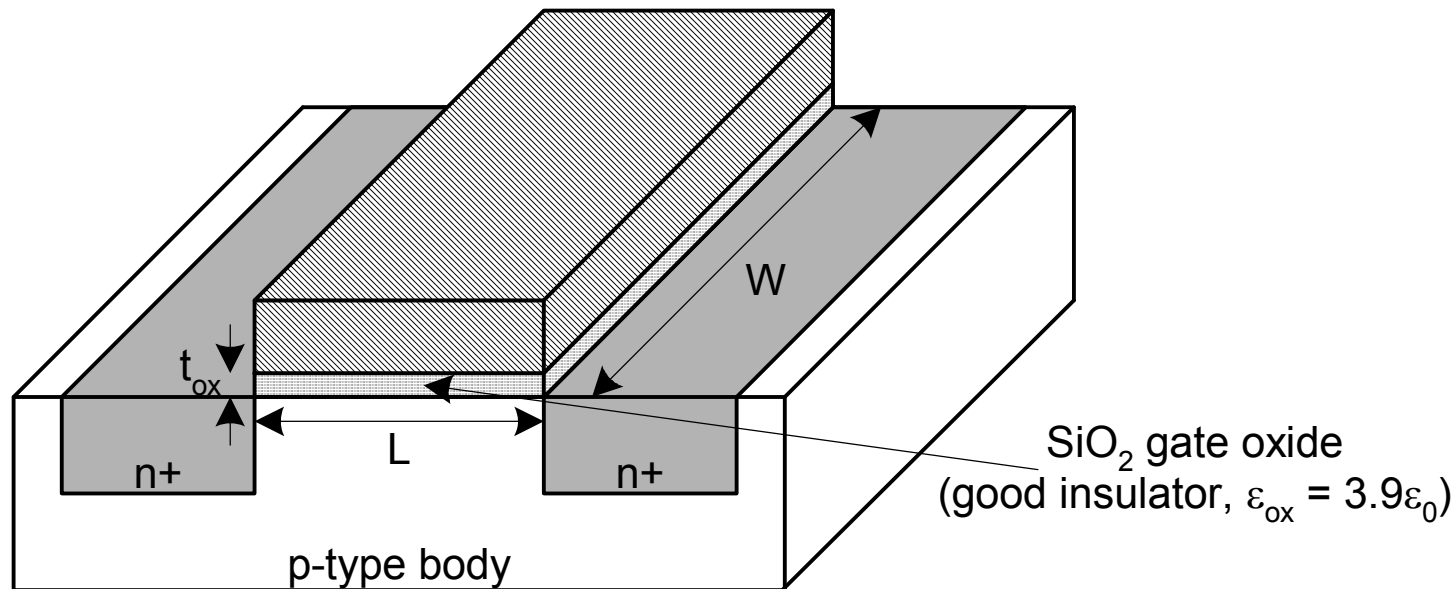


Capacitance

- ❑ 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
- $C_{gs} = \epsilon_{ox} WL/t_{ox} = C_{ox} WL = C_{permicron} W$
- $C_{permicron}$ is typically about 2 fF/ μm



Diffusion Capacitance

- ❑ 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
 - $\frac{1}{2} C_g$ for uncontacted
 - Varies with process

