

# **Lecture 5: CMOS Transistor Theory**

# Assignment for 9/12

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- ☐ Complete Lab2
- ☐ Text book reading sections 2.1T 2.3 (30 pages)

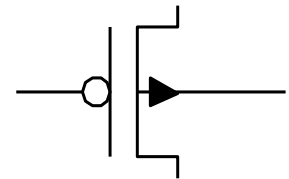
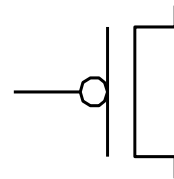
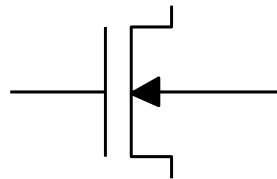
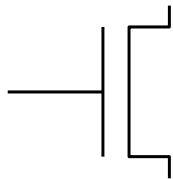
# Outline

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

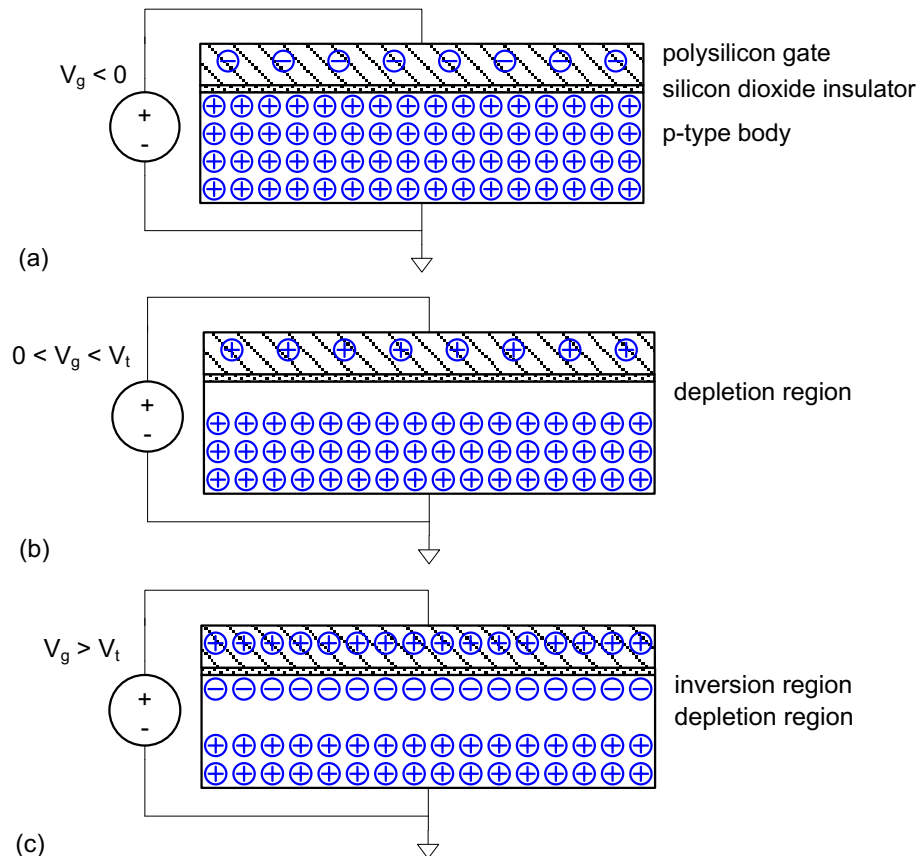
# Introduction

- ❑ 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



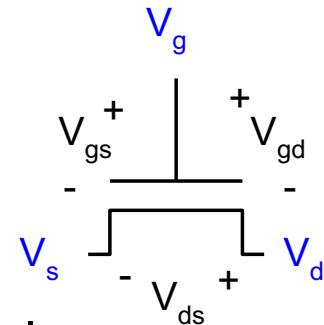
# MOS Capacitor

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



# Terminal Voltages

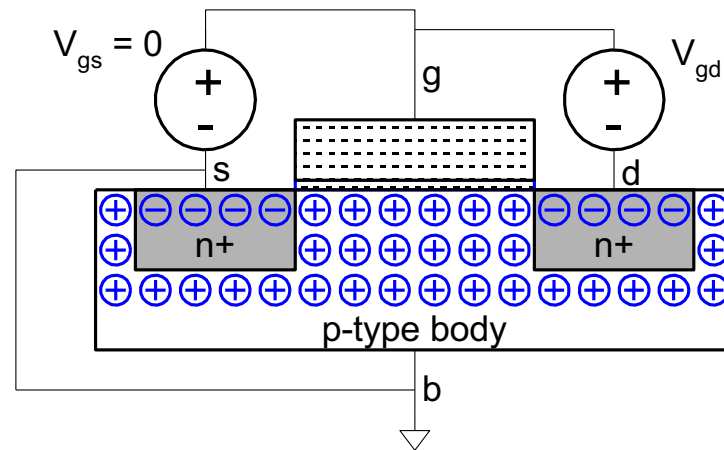
- ❑ Mode of operation depends on  $V_g$ ,  $V_d$ ,  $V_s$ 
  - $V_{gs} = V_g - V_s$
  - $V_{gd} = V_g - V_d$
  - $V_{ds} = V_d - V_s = V_{gs} - V_{gd}$
- ❑ Source and drain are symmetric diffusion terminals
  - By convention, source is terminal at lower voltage
  - Hence  $V_{ds} \geq 0$
- ❑ nMOS body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



# nMOS Cutoff

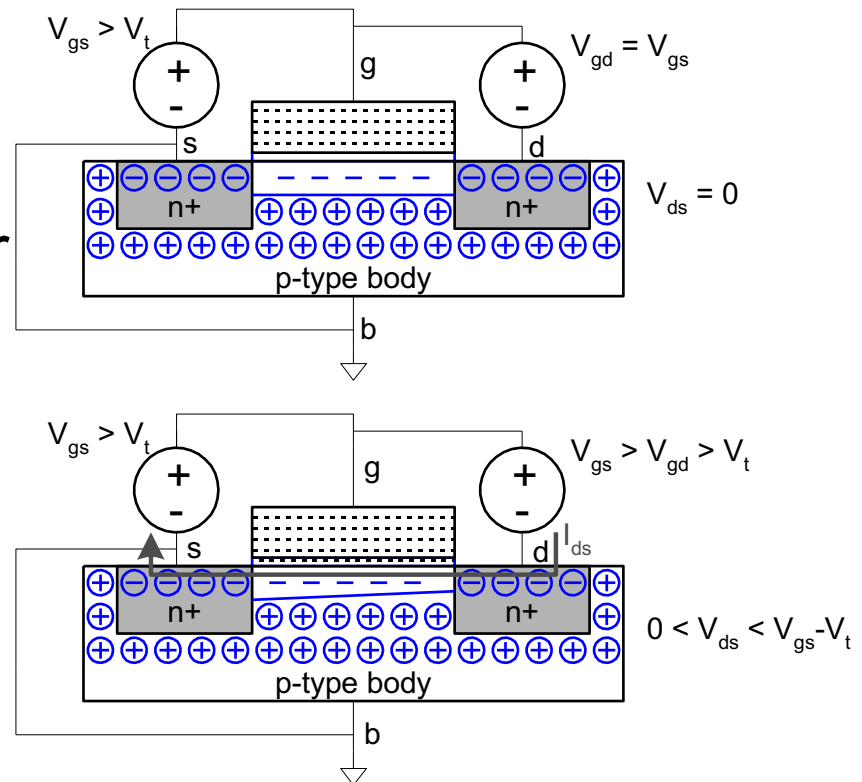
❑ No channel

❑  $I_{ds} \approx 0$



# nMOS Linear

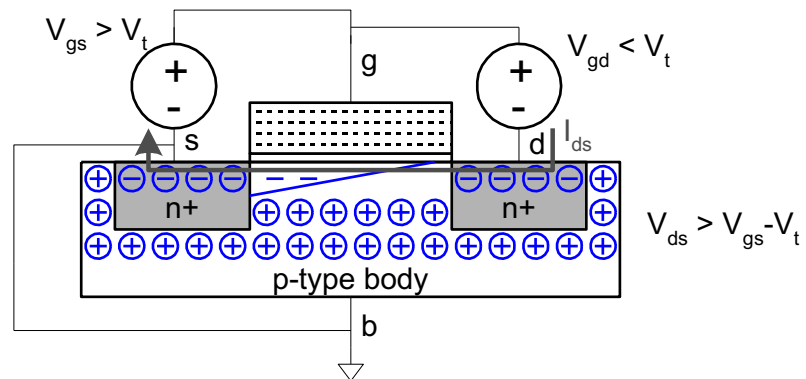
- ❑ Channel forms
- ❑ Current flows from d to s
  - $e^-$  from s to d
- ❑  $I_{ds}$  increases with  $V_{ds}$
- ❑ Similar to linear resistor





# nMOS Saturation

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



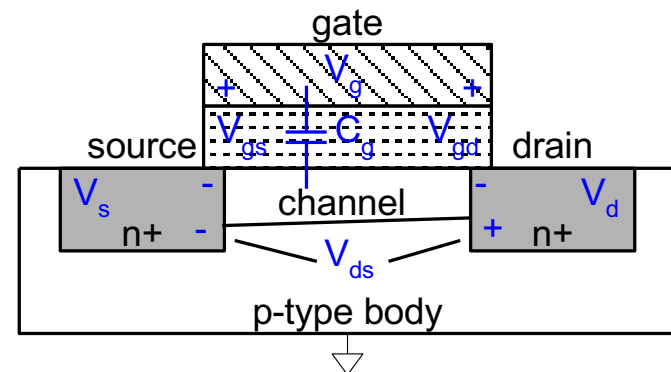
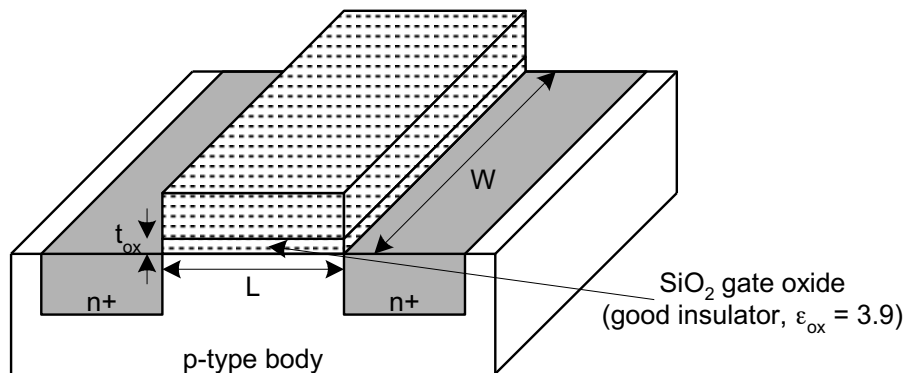
# I-V Characteristics

- ❑ 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 inversions
  - 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  $Q_{\text{channel}}$  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

$$I_{ds} =$$

=

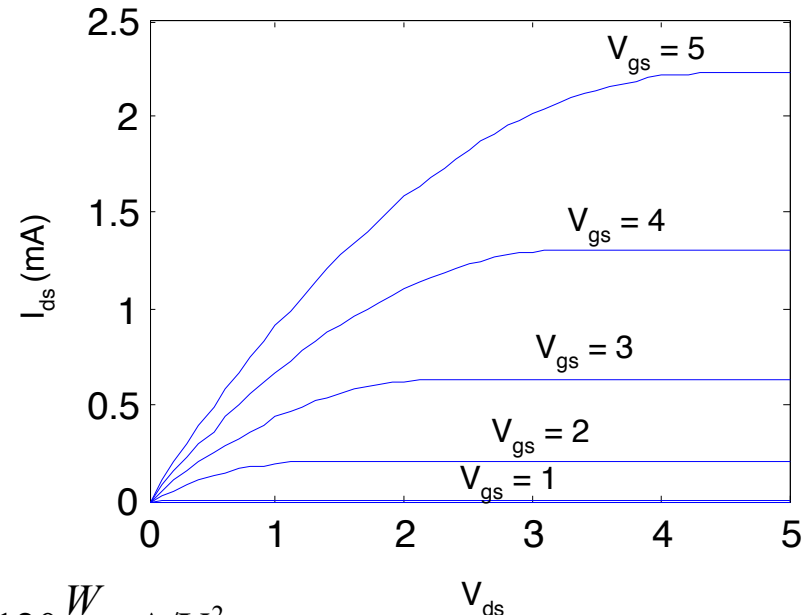
# nMOS I-V Summary

□ Shockley 1<sup>st</sup> 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  $0.6\ \mu\text{m}$  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  $I_{\text{ds}}$  vs.  $V_{\text{ds}}$ 
  - $V_{\text{gs}} = 0, 1, 2, 3, 4, 5$
  - Use  $W/L = 4/2\ \lambda$

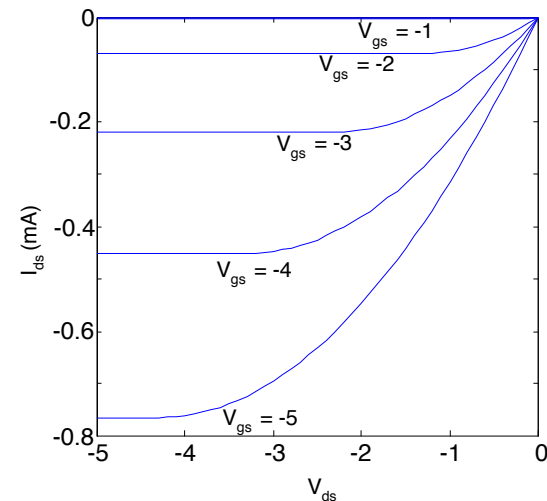


$$\beta = \mu C_{\text{ox}} \frac{W}{L} = (350) \left( \frac{3.9 \times 8.85 \cdot 10^{-14}}{100 \cdot 10^{-8}} \right) \left( \frac{W}{L} \right) = 120 \frac{W}{L} \mu\text{A}/\text{V}^2$$



# pMOS I-V

- ❑ All dopings and voltages are inverted for pMOS
  - Source is the more positive terminal
- ❑ Mobility  $\mu_p$  is determined by holes
  - Typically 2-3x lower than that of electrons  $\mu_n$
  - 120 cm<sup>2</sup>/V•s in AMI 0.6  $\mu$ m process
- ❑ Thus pMOS must be wider to provide same current
  - In this class, assume
$$\mu_n / \mu_p = 3$$

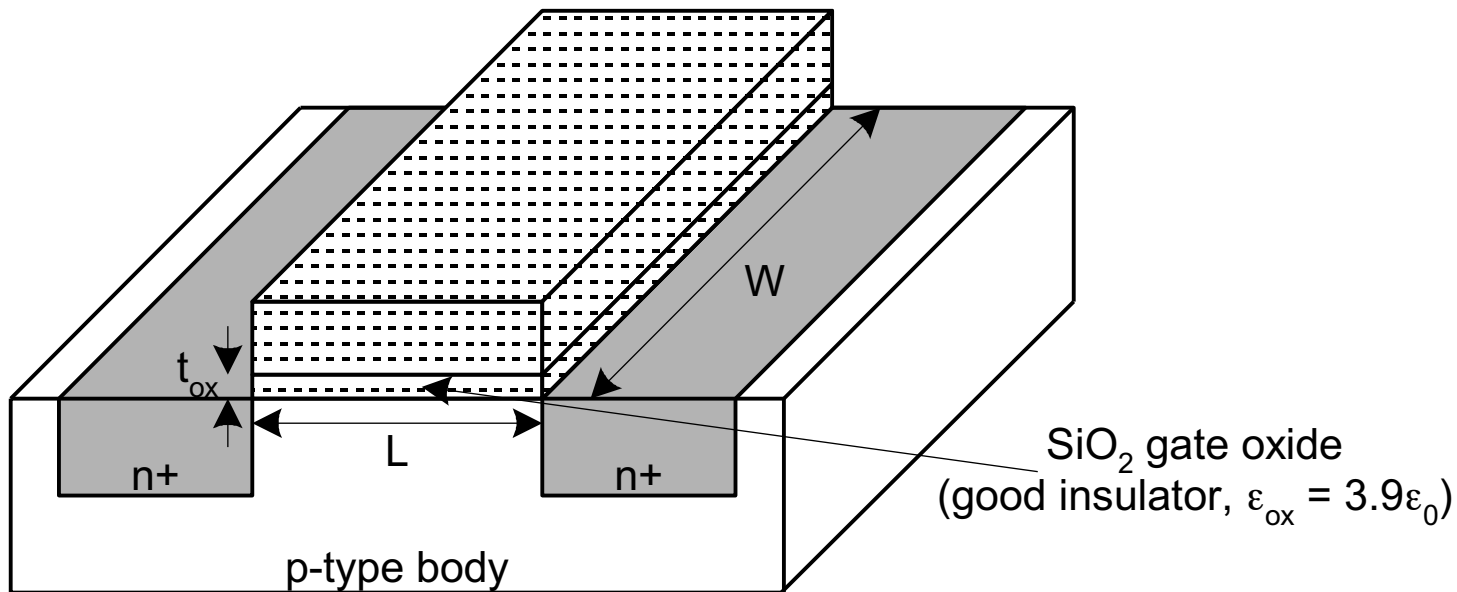


# Capacitance

- ❑ 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/ $\mu\text{m}$



# 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

