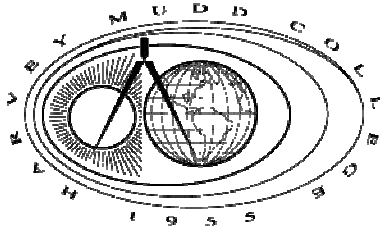
Introduction to CMOS VLSI Design

Lecture 3: CMOS Transistor Theory

David Harris



Harvey Mudd College

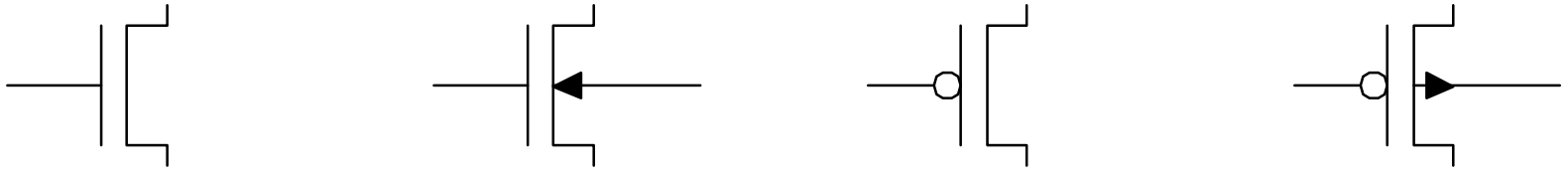
Spring 2004

Outline

- Introduction
- MOS Capacitor
- nMOS I-V Characteristics
- pMOS I-V Characteristics
- Gate and Diffusion Capacitance
- Pass Transistors
- RC Delay Models

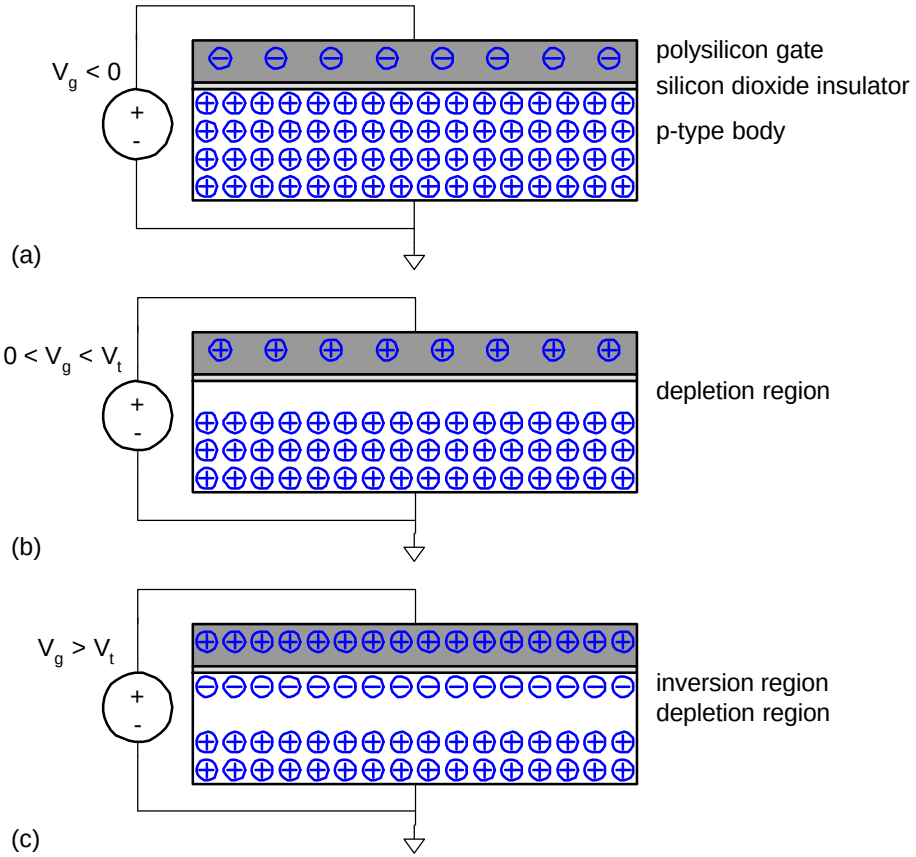
Introduction

- 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
- Also explore what a “degraded level” really means



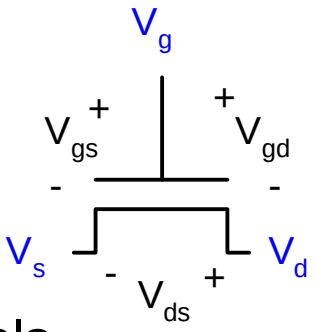
MOS Capacitor

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



Terminal Voltages

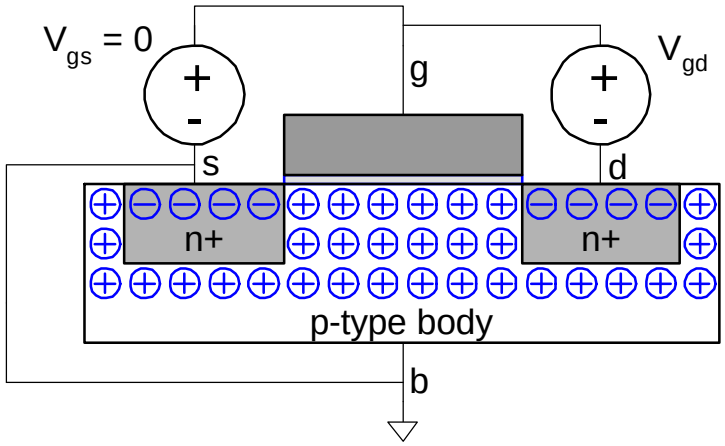
- Mode of operation depends on V_g, V_d, V_s
  - $V_{gs} = V_g - V_s$
  - $V_{gd} = V_g - V_d$
  - $V_{ds} = V_d - V_s = V_{gs} - V_{gd}$



- 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*

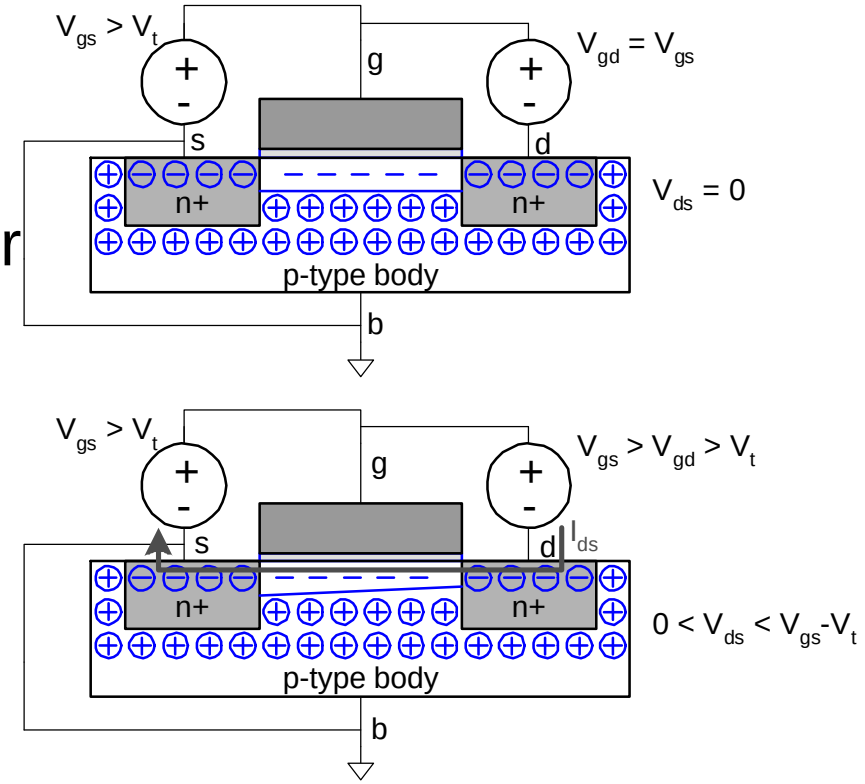
nMOS Cutoff

- No channel
- $I_{ds} = 0$



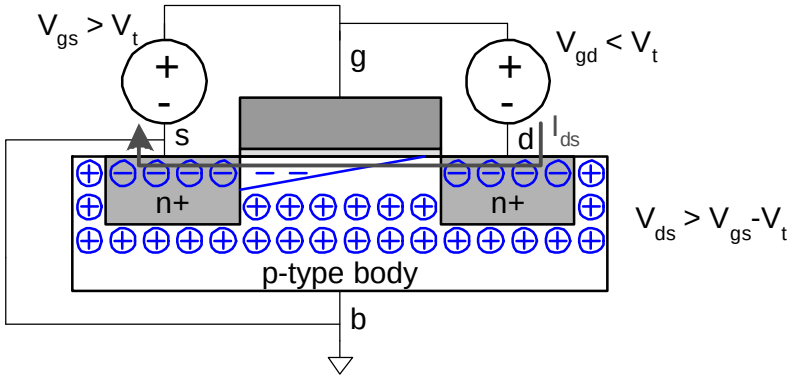
nMOS Linear

- 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

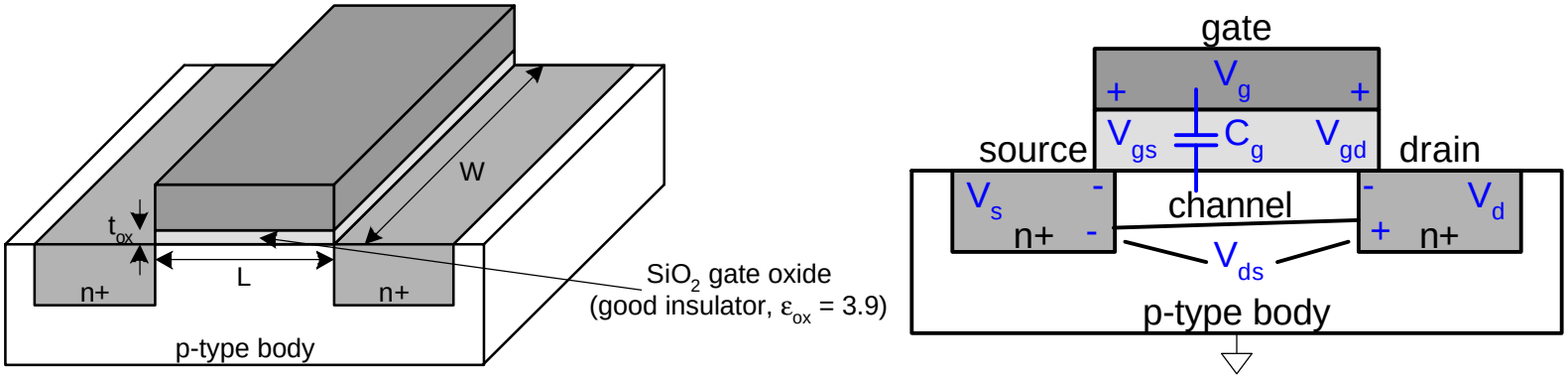


I-V Characteristics

- 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
- $Q_{channel}$ =



Channel Charge

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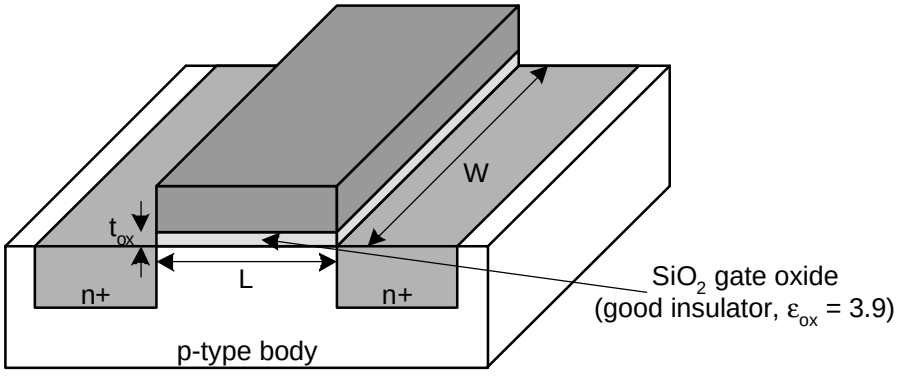
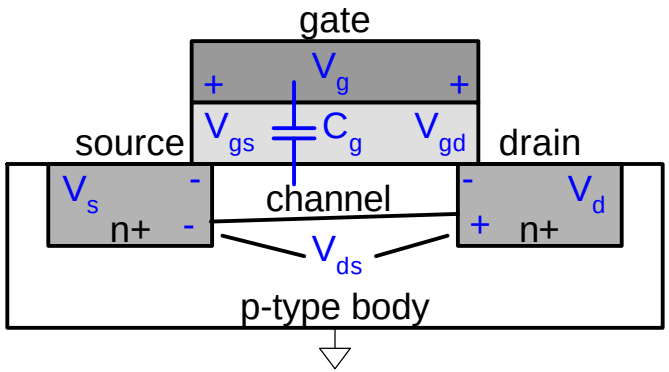
- $Q_{channel} = CV$
- C =





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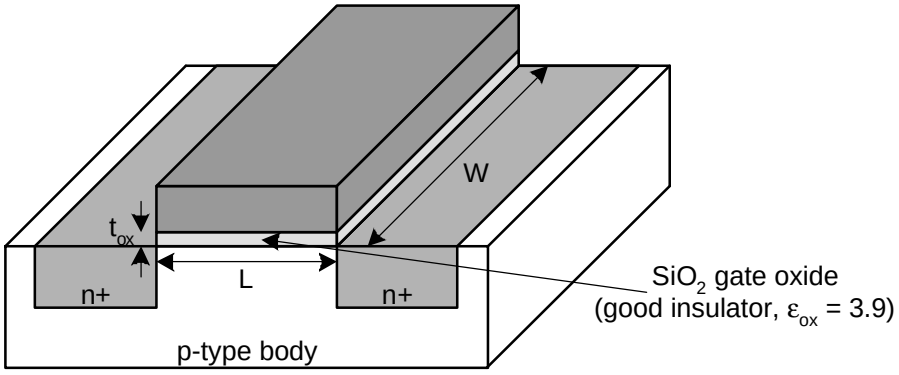
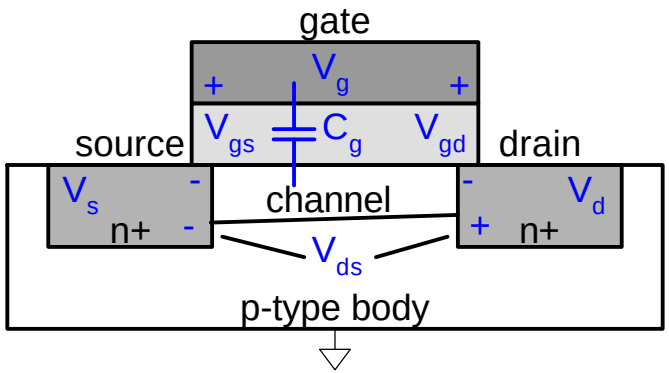
- $C = C_g = \varepsilon_{ox} WL/t_{ox} = C_{ox} WL$ $\qquad C_{ox} = \varepsilon_{ox} / t_{ox}$
- V =





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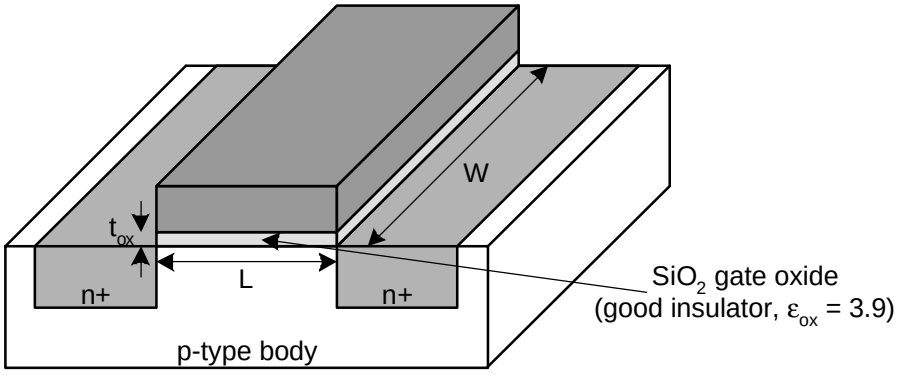
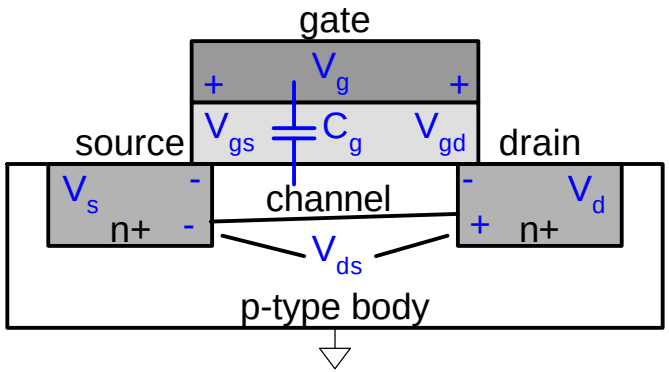
- $C = C_g = \varepsilon_{ox} WL/t_{ox} = C_{ox} WL$ $\qquad C_{ox} = \varepsilon_{ox} / t_{ox}$
- $V = V_{gc} - V_t = (V_{gs} - V_{ds}/2) - V_t$





Carrier velocity

- Charge is carried by e-
- Carrier velocity *v* proportional to lateral E-field between source and drain
- *v* =

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- $E = V_{ds}/L$
- Time for carrier to cross channel:
  - $t =$

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- Time for carrier to cross channel:
  - $t = L / v$

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 Linear I-V

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$$I_{ds} = \frac{Q_{\text{channel}}}{t}$$

$$=$$

nMOS Linear I-V

- Now we know
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  - How much time *t* each carrier takes to cross

$$I_{ds} = \frac{Q_{\text{channel}}}{t}$$

$$= mC_{\text{ox}} \frac{W}{L}\left(V_{gs} - V_t - V_{ds}/2\right)V_{ds}$$

$$= b\left(V_{gs} - V_t - V_{ds}/2\right)V_{ds}$$

$$b = mC_{\text{ox}} \frac{W}{L}$$

nMOS Saturation I-V

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

$$I_{ds} =$$

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$$I_{ds} = b\left(V_{gs} - V_t - V_{dsat}/2\right)V_{dsat}$$

$$= \frac{b}{2}\left(V_{gs} - V_t\right)^2$$

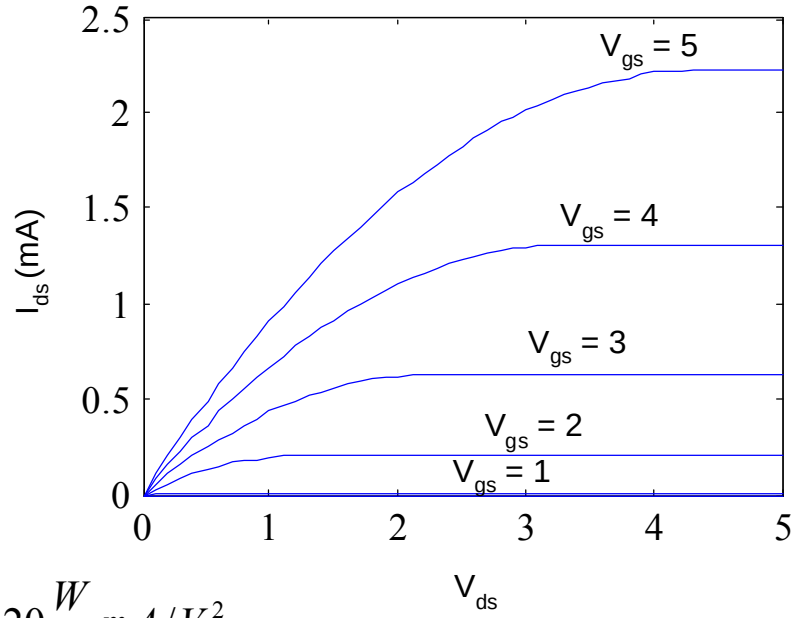
nMOS I-V Summary

- *Shockley* 1st order transistor models

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

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



$$b = mC_{ox}\frac{W}{L} = (350)\left(\frac{3.9 \bullet 8.85 \cdot 10^{-14}}{100 \cdot 10^{-8}}\right)\left(\frac{W}{L}\right) = 120\frac{W}{L} mA/V^2$$

pMOS I-V

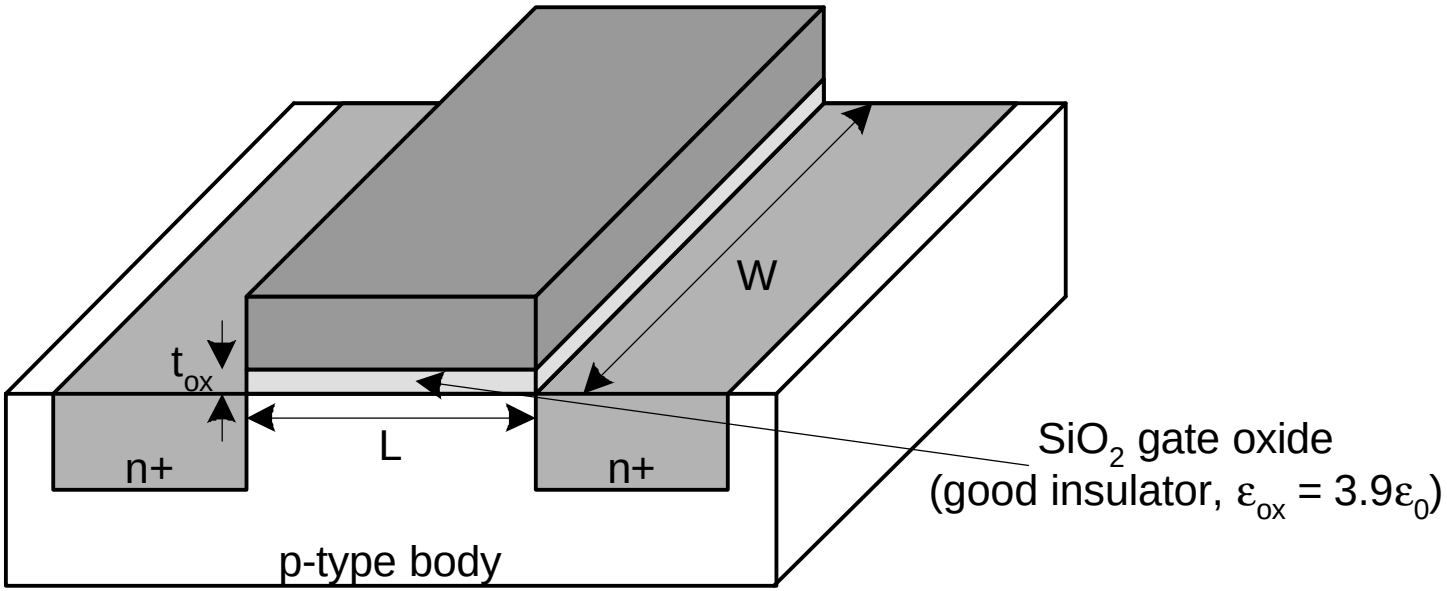
- All dopings and voltages are inverted for pMOS
- Mobility μ_p is determined by holes
  - Typically 2-3x lower than that of electrons μ_n
  - 120 $cm^2/V*s$ in AMI 0.6 μm process
- Thus pMOS must be wider to provide same current
  - In this class, assume $\mu_n / \mu_p = 2$
  - *** plot I-V here

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

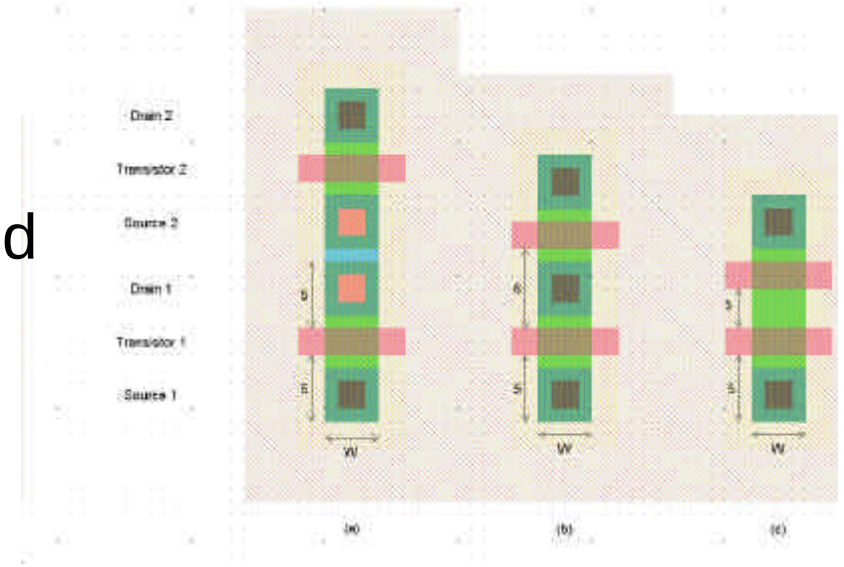
Gate Capacitance

- 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



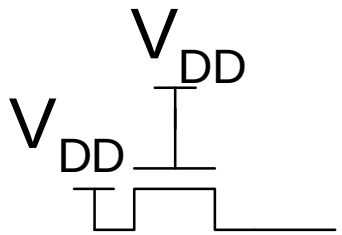
Diffusion Capacitance

- 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



Pass Transistors

- We have assumed source is grounded
- What if source > 0?
  - e.g. pass transistor passing V_{DD}



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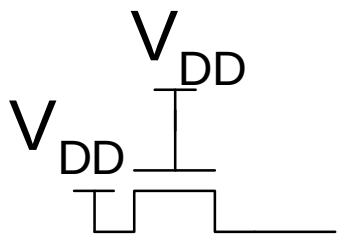
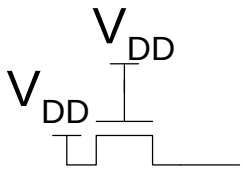
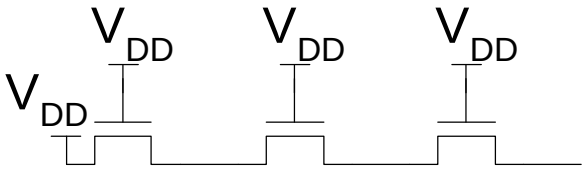
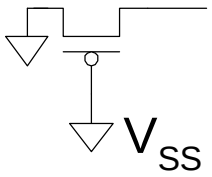


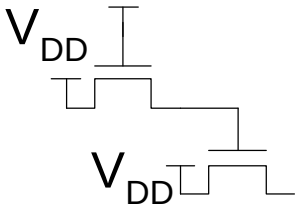
- $V_g = V_{DD}$
  - If $V_s > V_{DD}-V_t$, $V_{gs} < V_t$
  - Hence transistor would turn itself off
- nMOS pass transistors pull no higher than $V_{DD}-V_{tn}$
  - Called a degraded “1”
  - Approach degraded value slowly (low I_{ds})
- pMOS pass transistors pull no lower than V_{tp}

Pass Transistor Ckts









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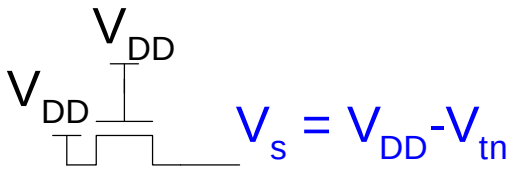
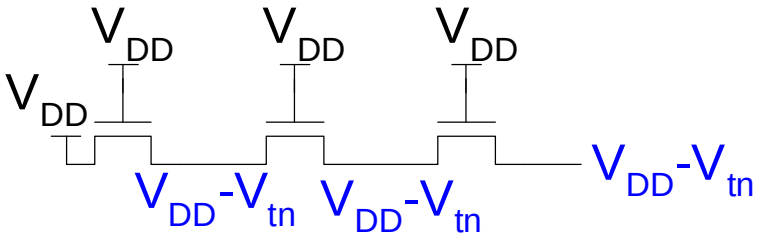
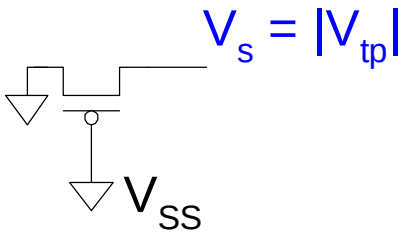
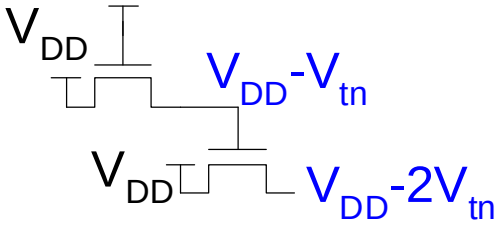






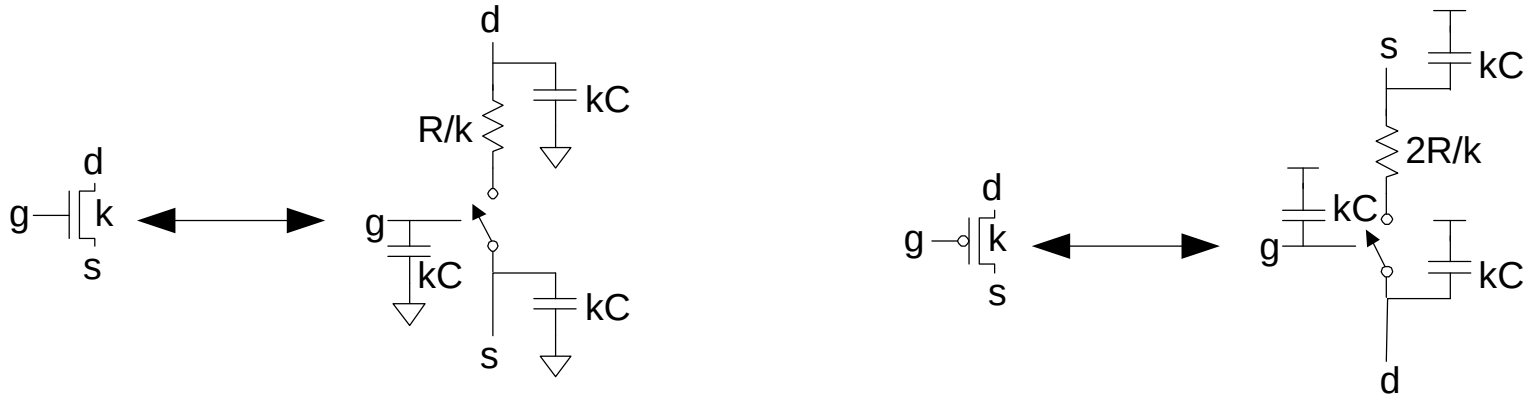


Effective Resistance

- Shockley models have limited value
  - Not accurate enough for modern transistors
  - Too complicated for much hand analysis
- Simplification: treat transistor as resistor
  - Replace $I_{ds}(V_{ds}, V_{gs})$ with effective resistance R
    - $I_{ds} = V_{ds}/R$
  - R averaged across switching of digital gate
- Too inaccurate to predict current at any given time
  - But good enough to predict RC delay

RC Delay Model

- Use equivalent circuits for MOS transistors
  - Ideal switch + capacitance and ON resistance
  - Unit nMOS has resistance R, capacitance C
  - Unit pMOS has resistance 2R, capacitance C
- Capacitance proportional to width
- Resistance inversely proportional to width

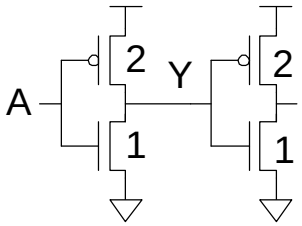


RC Values

- Capacitance
  - $C = C_g = C_s = C_d = 2$ fF/μm of gate width
  - Values similar across many processes
- Resistance
  - $R \approx 6$ KΩ*μm in 0.6um process
  - Improves with shorter channel lengths
- Unit transistors
  - May refer to minimum contacted device (4/2 λ)
  - Or maybe 1 μm wide device
  - Doesn't matter as long as you are consistent

Inverter Delay Estimate

- Estimate the delay of a fanout-of-1 inverter



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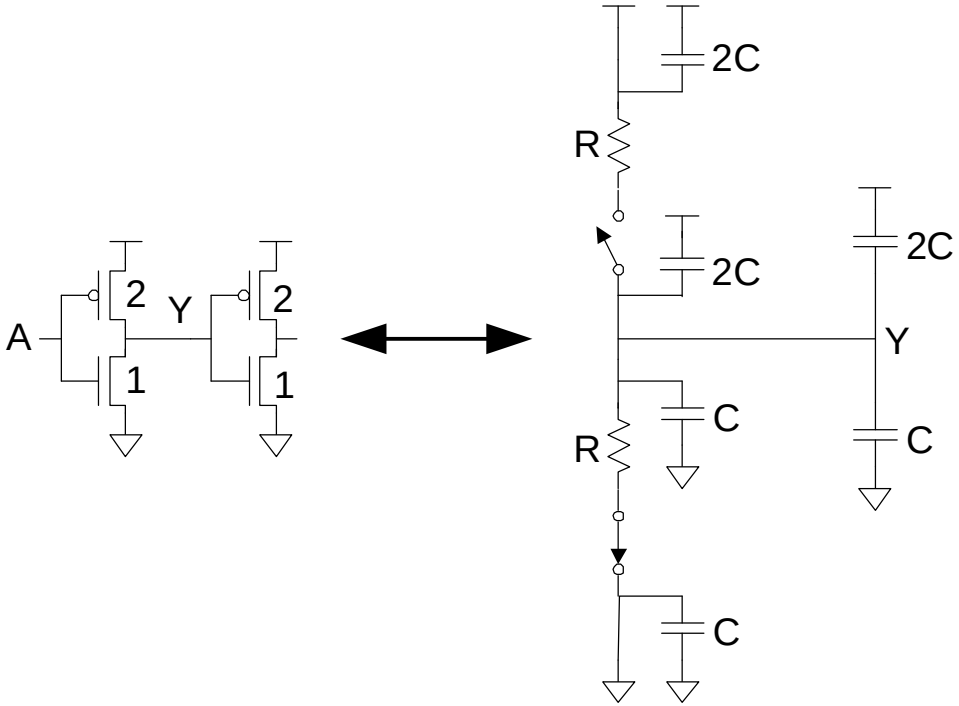

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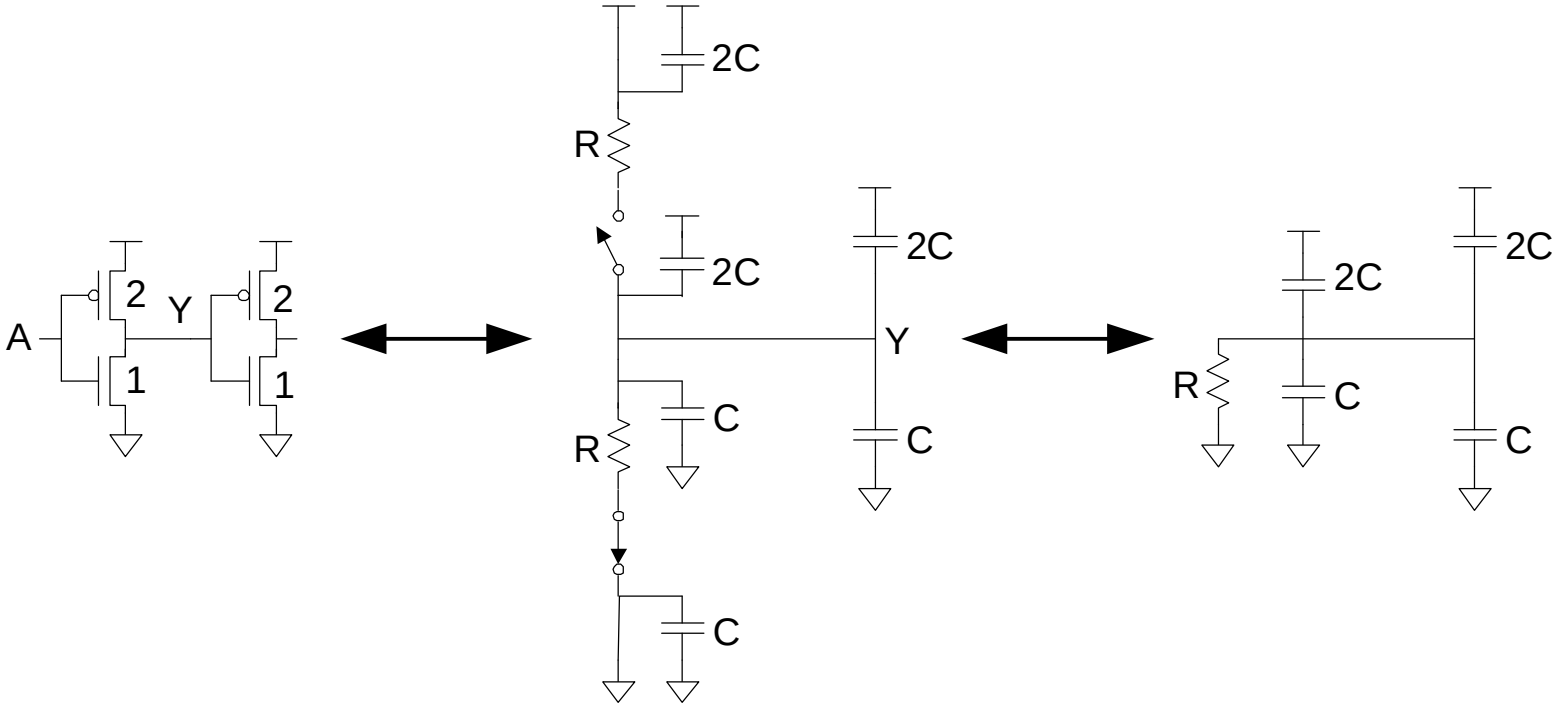

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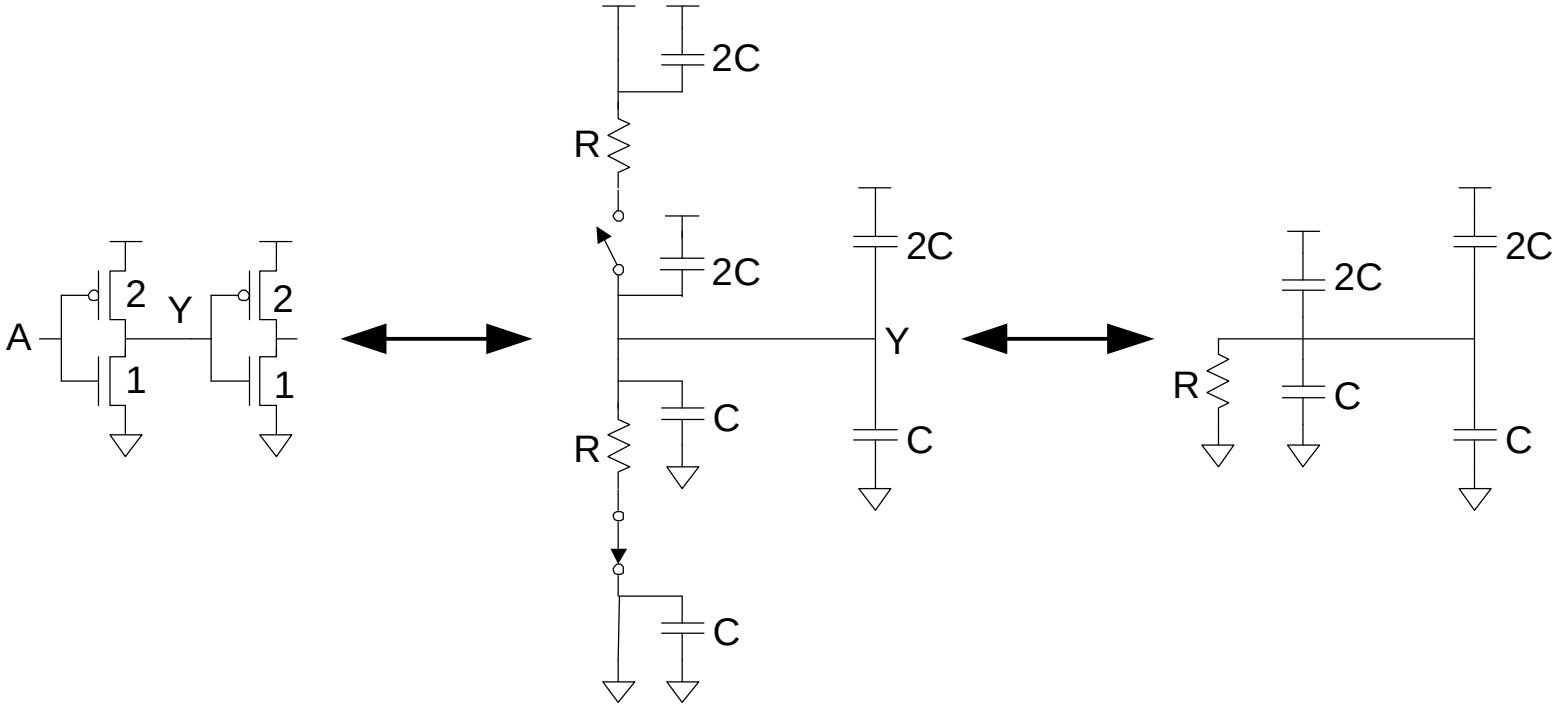

d = 6RC