MOSFET Physical Operation

Dr. José Ernesto Rayas Sánchez

Some figures of this presentation were taken from the instructional resources of the following textbooks:

B. Razavi, *Design of Analog CMOS Integrated Circuits*. New York, NY: McGraw Hill, 2001.

A. S. Sedra and K. C. Smith, *Microelectronic Circuits*. New York, NY: Oxford University Press, 2003.

A. R. Hambley, *Electronics: A Top-Down Approach to Computer-Aided Circuit Design*. Englewood Cliffs, NJ: Prentice Hall, 2000.

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Outline

- Introduction
- MOSFET physical structure
- MOSFET symbols
- MOSFET physical operation
- I-V characteristics
- Regions of operation
- Channel length modulation effect
- Body effect
- Strong inversion VS weak inversion

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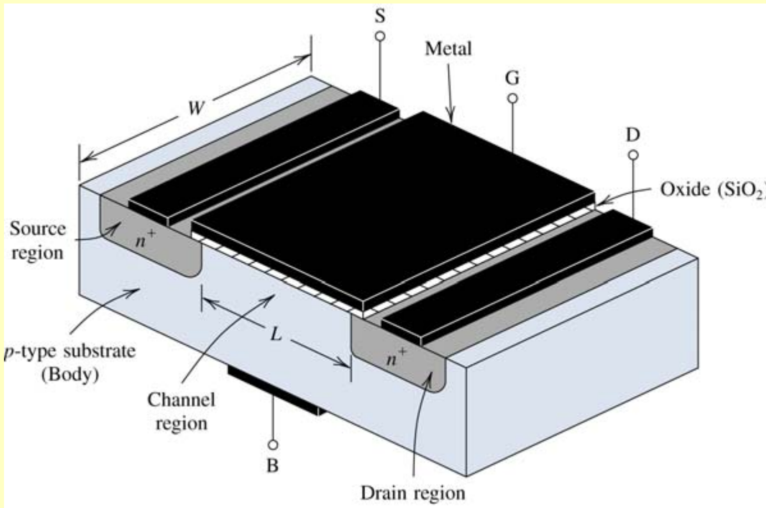
Introduction

- There are many types of FET technologies: MOS, CMOS, JFET, E-MOS, D-MOS, V-MOS, etc.
- MOSFETs are easier to fabricate and can be made smaller than BJTs
- Resistors and capacitors can be easily implemented in ICs using MOSFET technology
- Most of the logic and memory circuits can be implemented using MOSFET technology
- Most of the VLSI circuits are currently implemented in MOSFET technology

Terminology

- FET: Field Effect Transistor
- MOSFET: Metal Oxide Semiconductor FET
- JFET: Junction FET
- E-MOSFET: Enhancement MOSFET
- D-MOSFET: Depletion MOSFET
- V-MOSFET: MOSFET type V

E-MOSFET Physical Structure

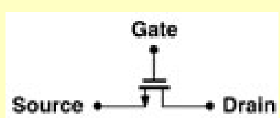


Typical dimensions: $0.1\mu\text{m} \le L \le 10\mu\text{m}$

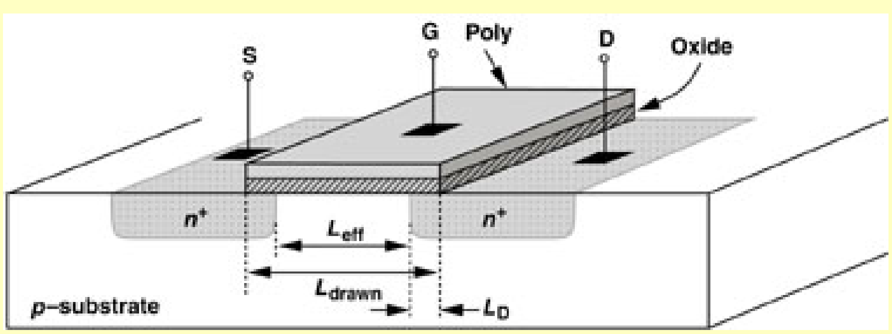
$2\mu\text{m} \le W \le 500\mu\text{m}$ $\quad 0.005\mu\text{m} \le H(\text{SiO}_2) \le 0.1\mu\text{m}$

E-MOSFET Physical Structure (cont)

Symbol:



Polysilicon (“poly”) is used for the gate:

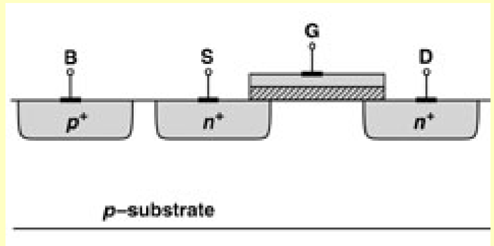


$$L_{eff} = L_{drawn} - 2L_D \qquad L = L_{eff}$$

Substrate Connections in NMOS and PMOS

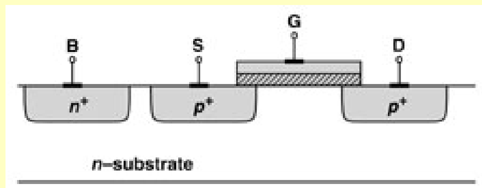
NMOS transistor:

B must be connected to the most negative voltage

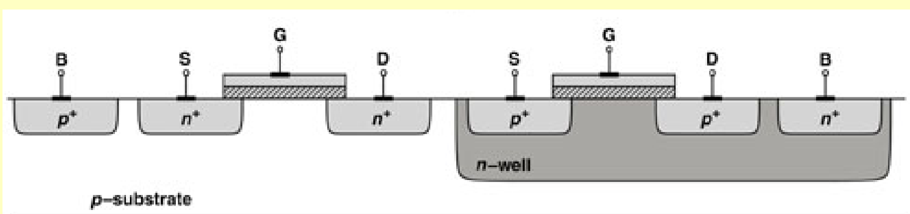


PMOS transistor:

B must be connected to the most positive voltage



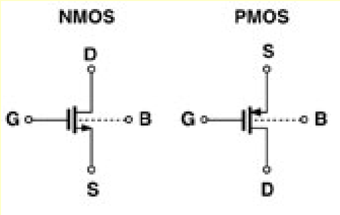
n-Well CMOS Technology Process

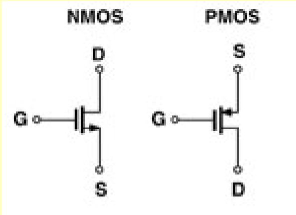


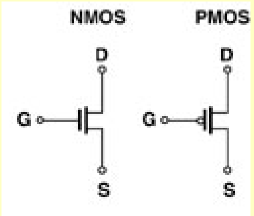
NMOS transistor PMOS transistor

(wells can also be used to fabricate resistors)

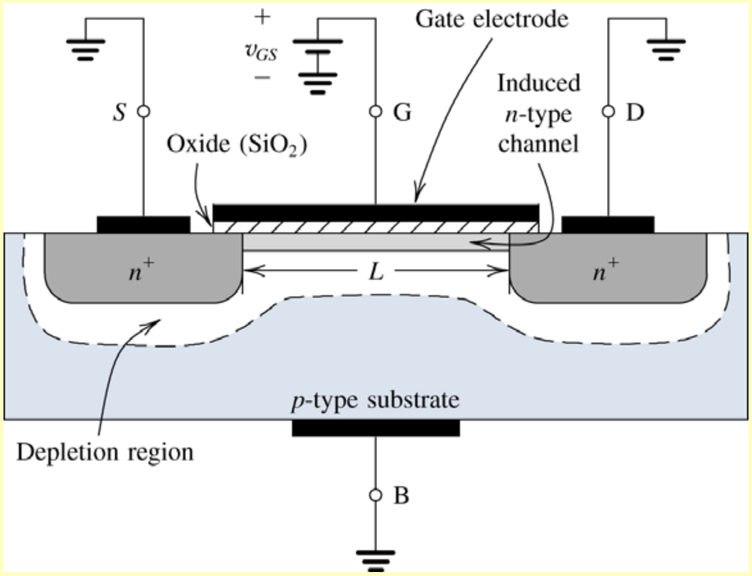
Symbols for E-MOS Transistors



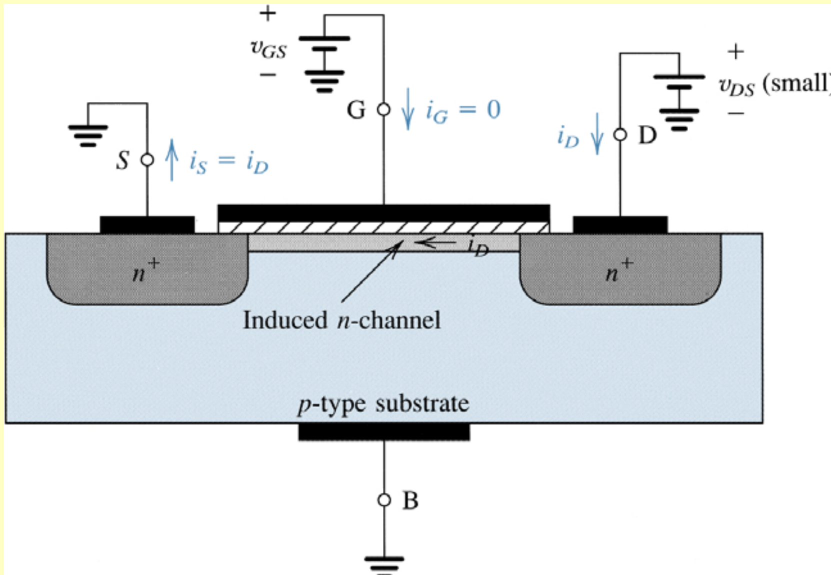




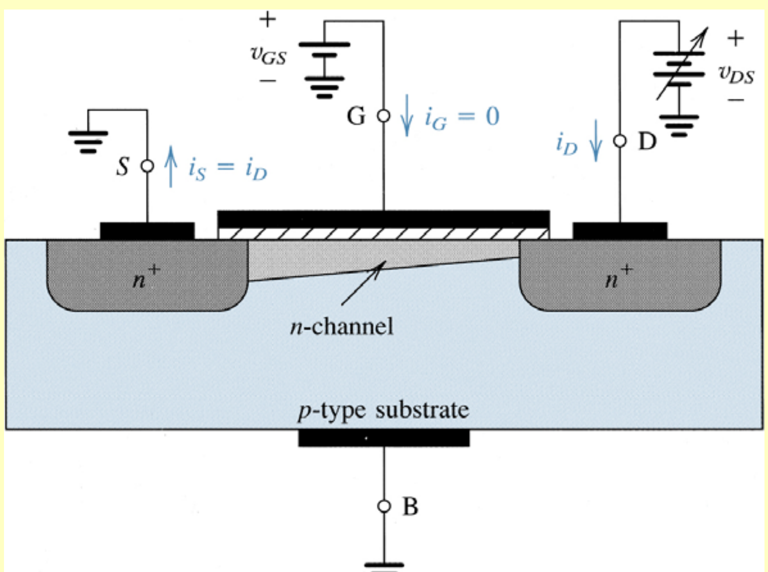
E-MOSFET Operation ($v_{GS} > V_{TH}$, $v_{DS} = 0$)



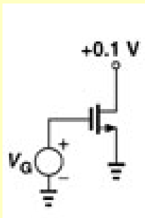
E-MOSFET Operation ($v_{GS} > V_{TH}$, v_{DS} small)



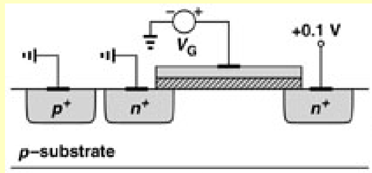
E-MOSFET Operation ($v_{GS} > V_{TH}$, v_{DS} large)



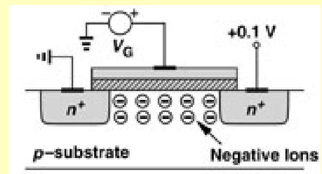
The Inversion Layer (Channel Formation)



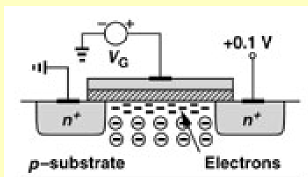
If $V_G = 0\text{V}$

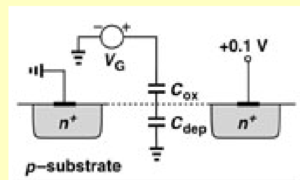


If $0 < V_G < V_{TH}$

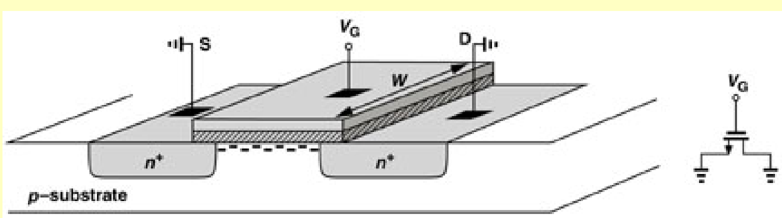


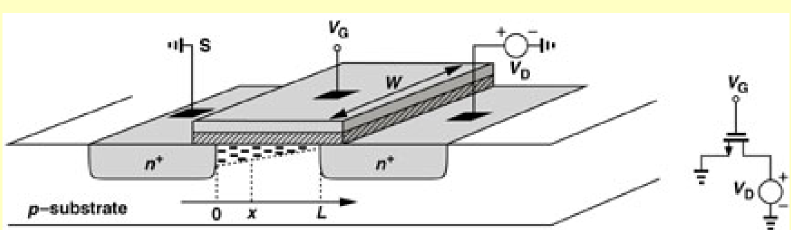
If $V_G > V_{TH}$





Increasing V_{DS}

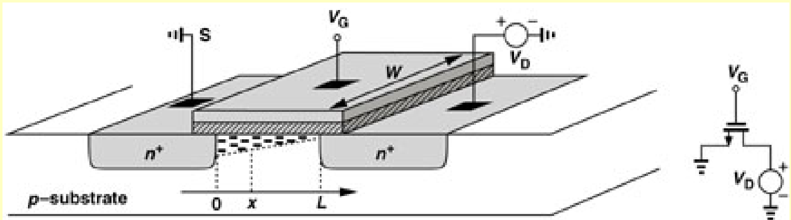




Channel thickness depends on $v_{GS} - V(x)$

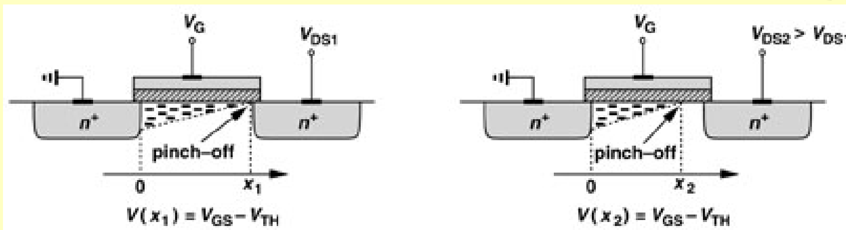
where $V(x=0) \approx 0$ and $V(x=L) \approx V_D$

Increasing V_{DS} (cont)



Channel density at x depends on $v_{GS} - V(x)$

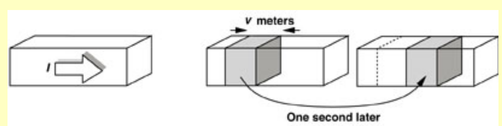
where $V(x=0) \approx 0$ and $V(x=L) \approx V_D$

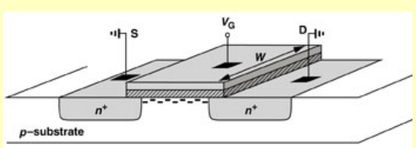


Minimum channel density occurs when $v_{GS} - V(x) = V_{TH}$

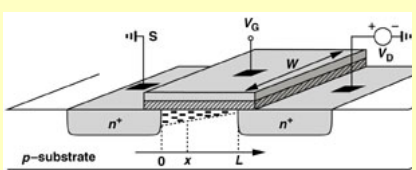
Derivation of I-V Characteristics

$$I = Q_d v$$





$$Q_d = -WC_{OX}(v_{GS} - V_{TH})$$



$$Q_d = -WC_{OX}\left[v_{GS} - V(x) - V_{TH}\right]$$

$$i_{DS} = Q_d v = -WC_{OX}\left[v_{GS} - V(x) - V_{TH}\right]v$$

Since $v = \mu E$ and $E(x) = -\dfrac{dV(x)}{dx}$

$$i_{DS} = WC_{OX}\left[v_{GS} - V(x) - V_{TH}\right]\mu_n \frac{dV(x)}{dx}$$

Derivation of I-V Characteristics (cont)

$$i_{DS} = WC_{OX}\mu_n[v_{GS} - V(x) - V_{TH}]\frac{dV(x)}{dx}$$

$$\int_0^L i_{DS}dx = \int_0^{v_{DS}} WC_{OX}\mu_n[v_{GS} - V(x) - V_{TH}]dV$$

Since i_{DS} is constant along the channel length,

$$i_{DS} = \mu_n C_{OX}\frac{W}{L}\left[(v_{GS} - V_{TH})v_{DS} - \frac{1}{2}v_{DS}^2\right]$$

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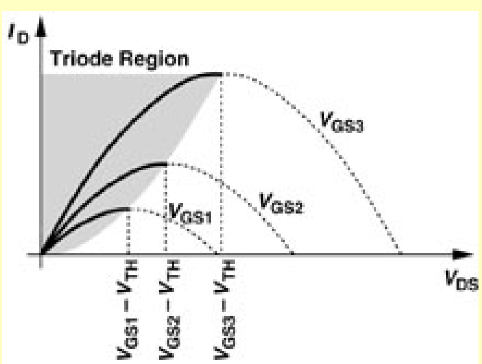
I-V Characteristics – Triode Region

$$i_{DS} = \mu_n C_{OX}\frac{W}{L}\left[(v_{GS} - V_{TH})v_{DS} - \frac{1}{2}v_{DS}^2\right]$$



The peak of each parabola occurs at $v_{DS} = v_{GS} - V_{TH}$

$$i_{DS,peak} = \frac{1}{2}\mu_n C_{OX}\frac{W}{L}(v_{GS} - V_{TH})^2$$

W/L "aspect ratio"

If $v_{GS} \geq V_{TH}$ and $v_{DS} \leq v_{GS} - V_{TH}$, $\rightarrow$ triode region

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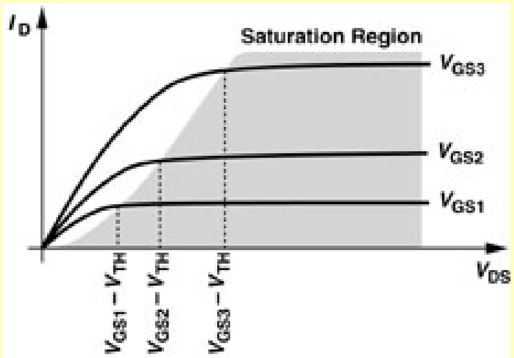
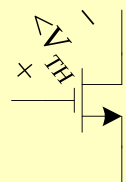
I-V Characteristics – Saturation Region

If $v_{GS} \geq V_{TH}$ and $v_{DS} > v_{GS} - V_{TH}$, $\rightarrow$ saturation region or active region, i_{DS} is approximately constant



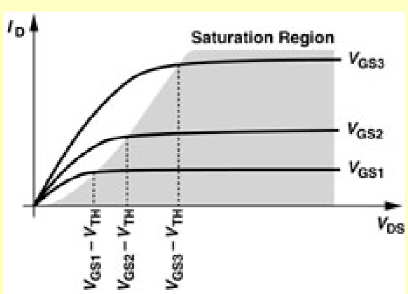
$$i_{DS} \approx \frac{1}{2}\mu_n C_{OX} \frac{W}{L'}(v_{GS} - V_{TH})^2$$

Condition for saturation:

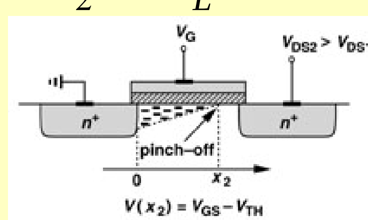


Saturation Region, Channel Length Modulation

If $v_{GS} \geq V_{TH}$ and $v_{DS} > v_{GS} - V_{TH}$, $\rightarrow$ saturation region or active region



$$i_{DS} = \frac{1}{2}\mu_n C_{OX} \frac{W}{L'}(v_{GS} - V_{TH})^2$$

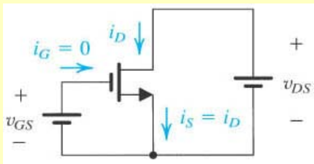


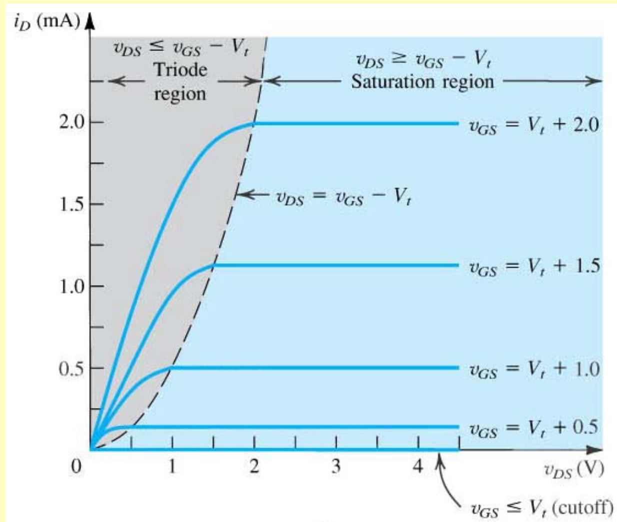
$$i_{DS} = \frac{1}{2}\mu_n C_{OX} \frac{W}{L}(v_{GS} - V_{TH})^2(1 + \lambda v_{DS})$$

channel length modulation factor

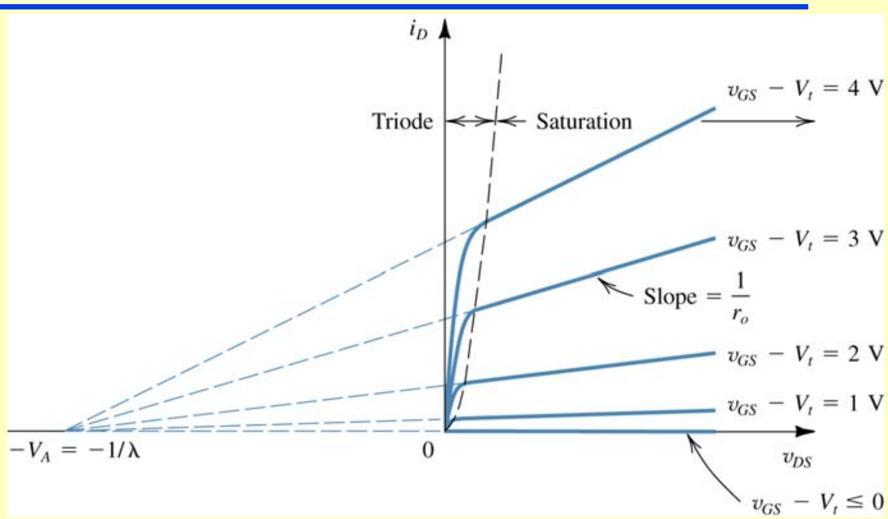
$\lambda \propto 1/L$

Regions of Operation





Saturation Region, Channel Length Modulation



$$i_{DS} = \frac{1}{2}\mu_n C_{OX}\frac{W}{L}(v_{GS} - V_{TH})^2(1 + \lambda v_{DS})$$

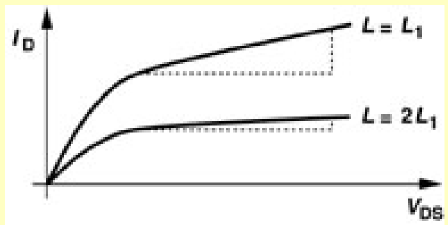
channel length modulation

Saturation Region, Channel Length Modulation

$$i_{DS} = \frac{1}{2}\mu_n C_{OX} \frac{W}{L}(v_{GS} - V_{TH})^2 (1 + \lambda v_{DS})$$

$(1 + \lambda v_{DS})$ → channel length modulation

Since $\lambda \propto 1/L$:

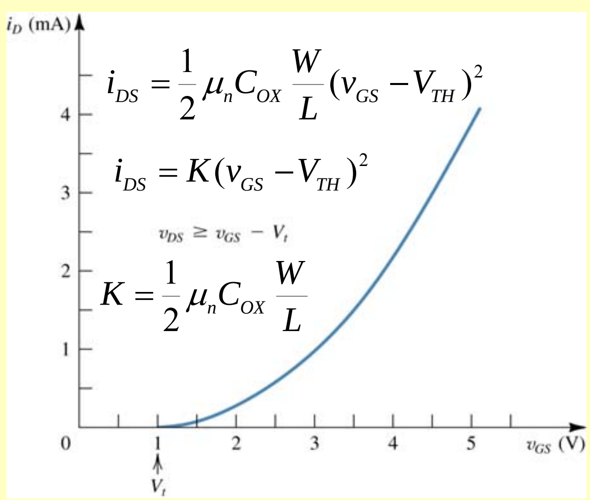


Larger MOSFETs are less sensitive to the channel length modulation effect

Transconductance Curve – Saturation Region

(it neglects the channel length modulation effect)

$v_{DS} > v_{GS} - V_{TH}$



$$i_{DS} = \frac{1}{2}\mu_n C_{OX} \frac{W}{L}(v_{GS} - V_{TH})^2$$

$$i_{DS} = K(v_{GS} - V_{TH})^2$$

$$K = \frac{1}{2}\mu_n C_{OX} \frac{W}{L}$$

Small Signal Transconductance, g_m

$$v_{DS} > v_{GS} - V_{TH}$$

$$i_{DS} = K(v_{GS} - V_{TH})^2$$

$$g_m \equiv \left.\frac{\partial i_{DS}}{\partial v_{GS}}\right|_{v_{GS}=V_{GS},\, v_{DS}=V_{DS}}$$

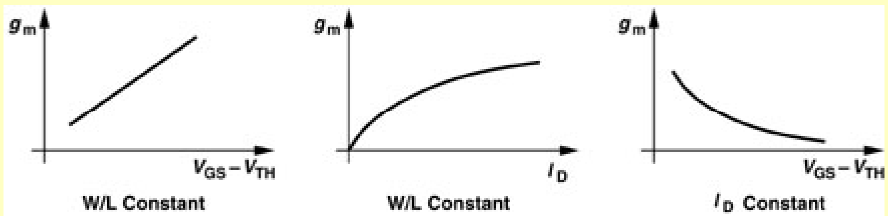
$$K = \frac{1}{2}\mu_n C_{OX}\frac{W}{L}$$

$$g_m = 2K(V_{GS} - V_{TH})$$

$$g_m = \frac{2I_{DS}}{V_{GS} - V_{TH}}$$

$$g_m = \sqrt{4KI_{DS}}$$

$$g_m = \sqrt{2\mu_n C_{OX}(W/L)I_{DS}}$$



How does g_m changes with V_{DS}?

Ohmic Region

$$i_{DS} = \mu_n C_{OX} \frac{W}{L}\left[(v_{GS} - V_{TH})v_{DS} - \frac{1}{2}v_{DS}^2\right]$$

If $v_{GS} \geq V_{TH}$ and v_{DS} is small ($v_{DS} << v_{GS} - V_{TH}$),

→ ohmic region or deep triode region

$$i_{DS} = \mu_n C_{OX} \frac{W}{L}(v_{GS} - V_{TH})v_{DS}$$

$$r_{DS} = \frac{v_{DS}}{i_{DS}} \approx \frac{1}{\mu_n C_{OX} \frac{W}{L}(v_{GS} - V_{TH})} = \frac{1}{2K(v_{GS} - V_{TH})}$$

para v_{DS} pequeño

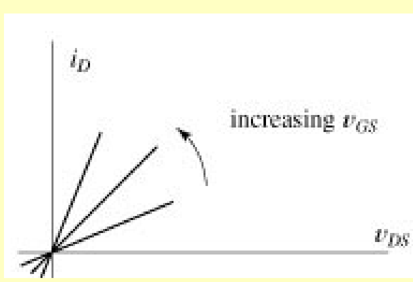
Ohmic Region (cont)

If $v_{GS} \geq V_{TH}$ and v_{DS} is small ($v_{DS} << v_{GS} - V_{TH}$),

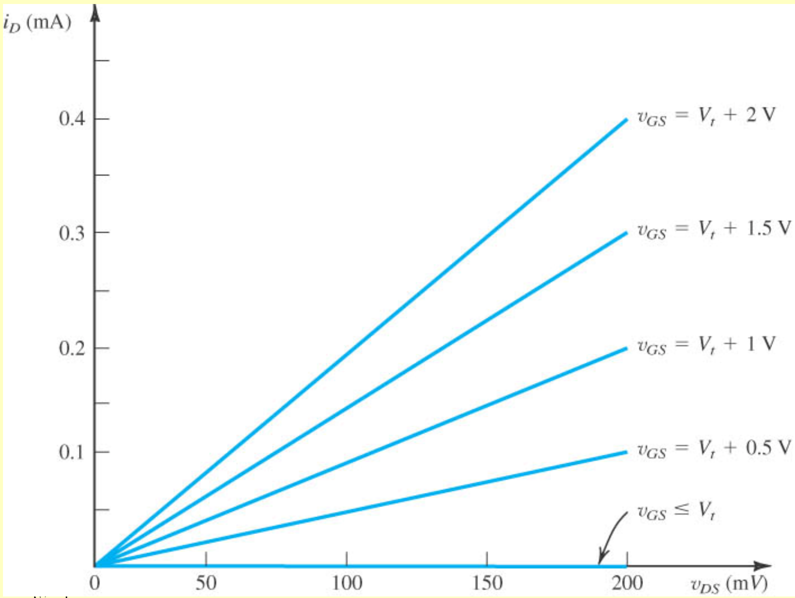
→ ohmic region or deep triode region

$$r_{DS} = \frac{v_{DS}}{i_{DS}} \approx \frac{1}{\mu_n C_{OX} \frac{W}{L}(v_{GS} - V_{TH})} = \frac{1}{2K(v_{GS} - V_{TH})}$$

for v_{DS} small



Ohmic Region (cont)



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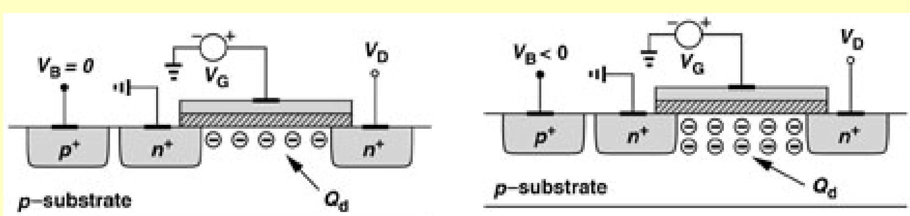
Body Effect

Usually, $V_B = V_S$

If $V_B < V_S$ then V_{TH} increases



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Subthreshold Conduction (Weak Inversion)

- Above threshold conduction, for $v_{GS} \geq V_{TH}$

$$v_{DS} \geq v_{GS} - V_{TH} \qquad i_{DS} = K(v_{GS} - V_{TH})^2$$

→ strong inversion

- Subthreshold conduction, for $v_{GS} \leq V_{TH}$

$$i_{DS} = I_0 e^{\frac{v_{GS}}{\xi V_T}}$$ → weak inversion

$$\xi > 1$$

$$V_T = \frac{KT}{q} \approx 25\text{mV (@ room temp)}$$

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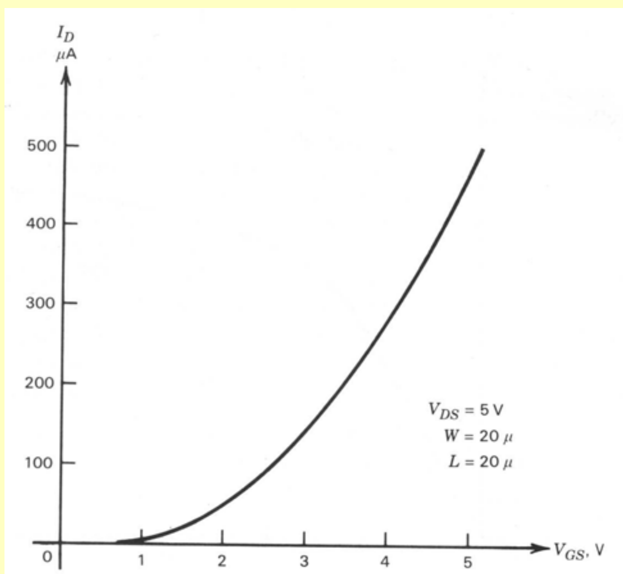
Strong Inversion – Weak Inversion



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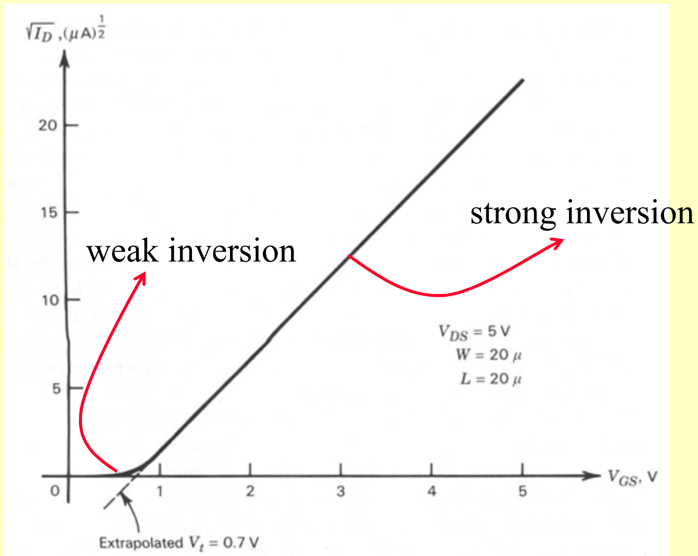
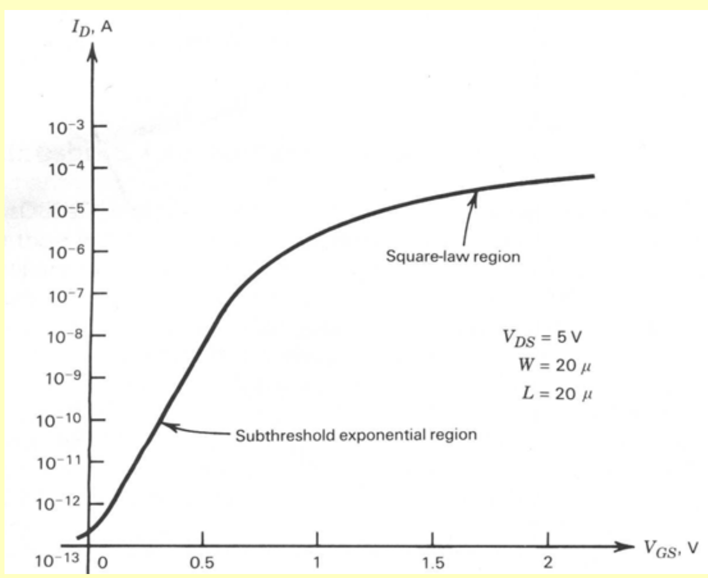
Strong Inversion – Weak Inversion (cont)



Strong Inversion – Weak Inversion (cont)



Strong Inversion – Weak Inversion (cont)