MOSFET Current-Voltage Characteristics

COE 360

Principles of VLSI Design

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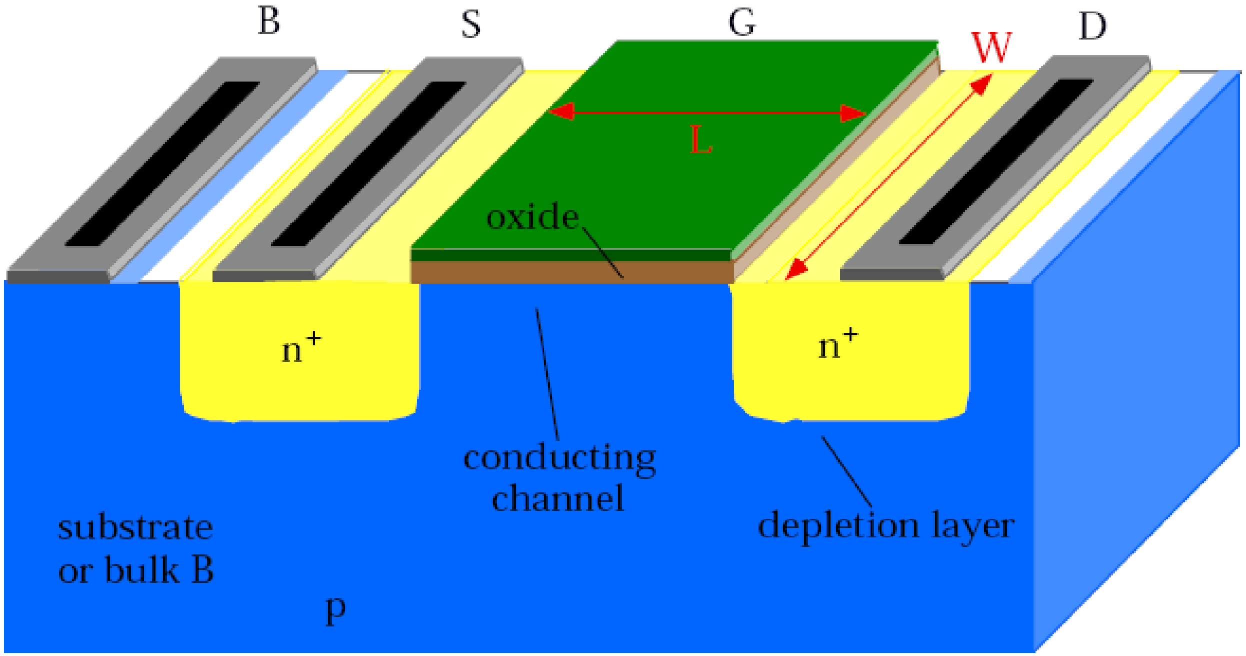
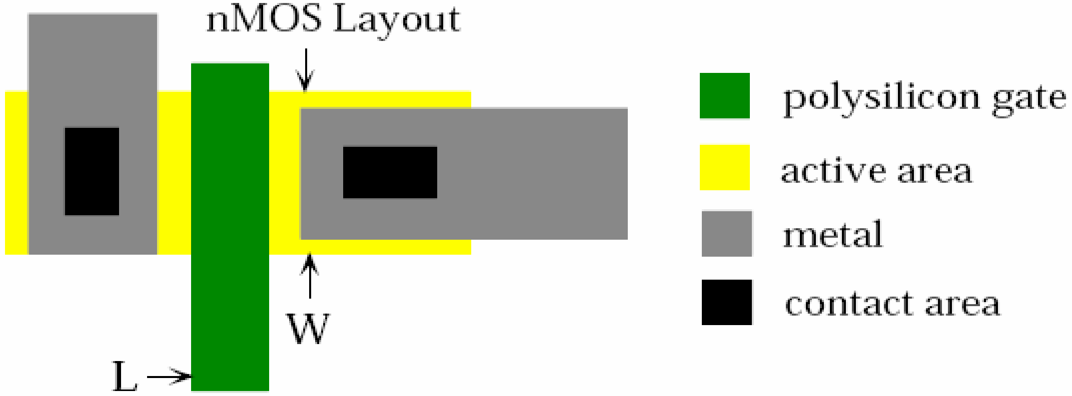
Outline

- MOS Operation Regions
- MOS Current-Voltage Characteristics
- Linear Region Current Equation
- Saturation Region Current Equation
- Channel Length Modulation
- Effective Channel Length and Width

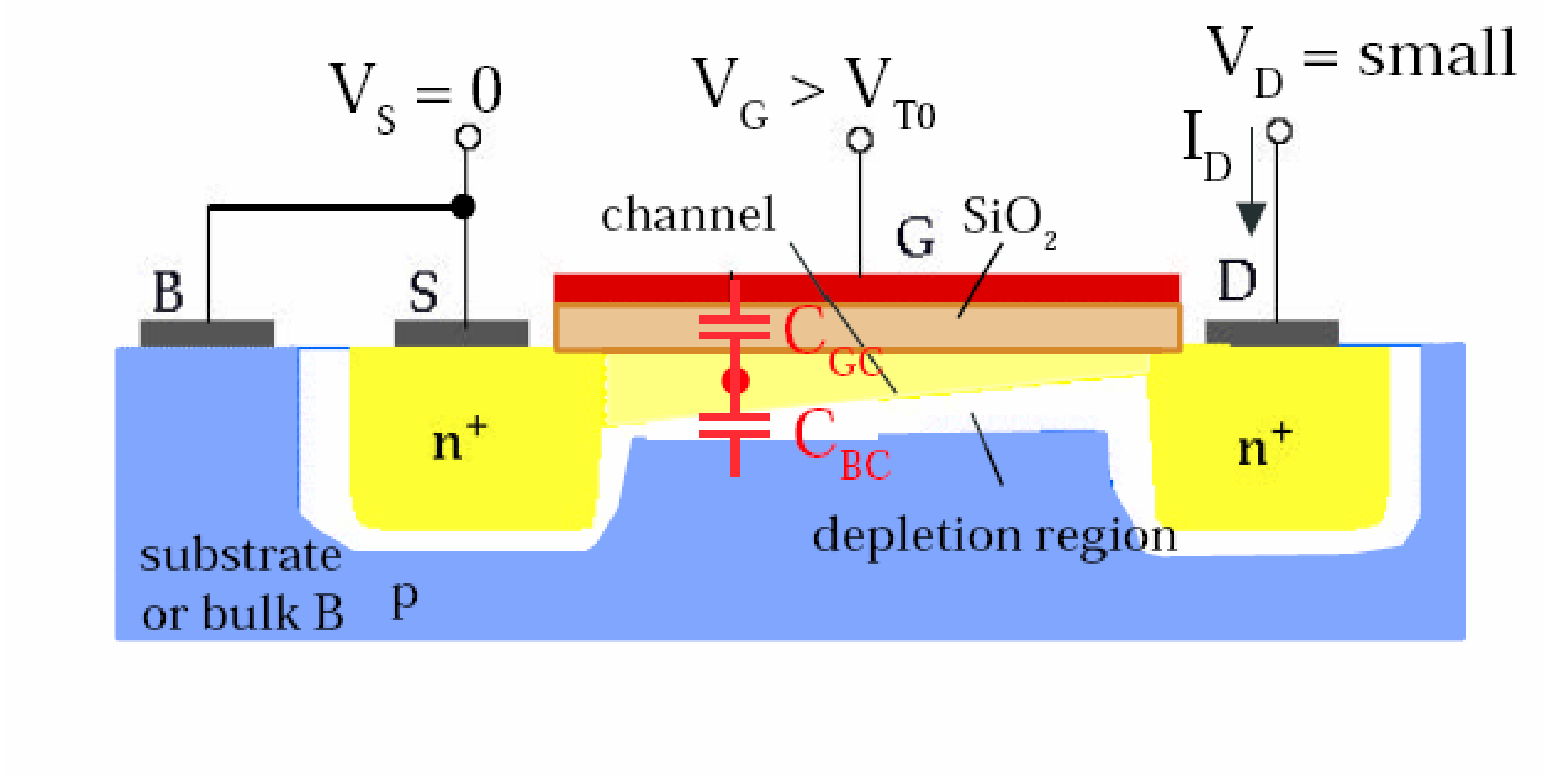
Based on Slides of Kenneth R. Laker, University of Pennsylvania

NMOS Transistor Structure

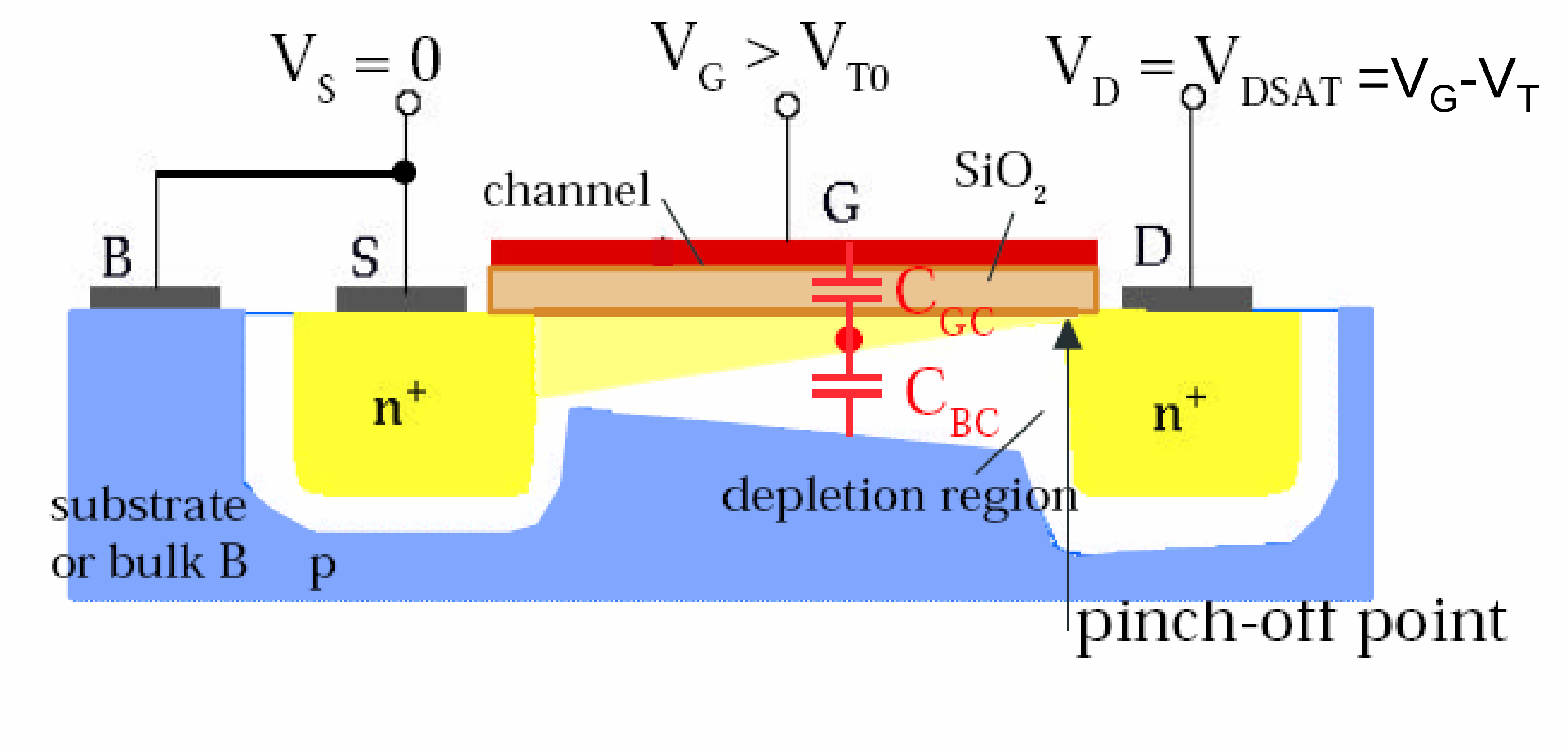




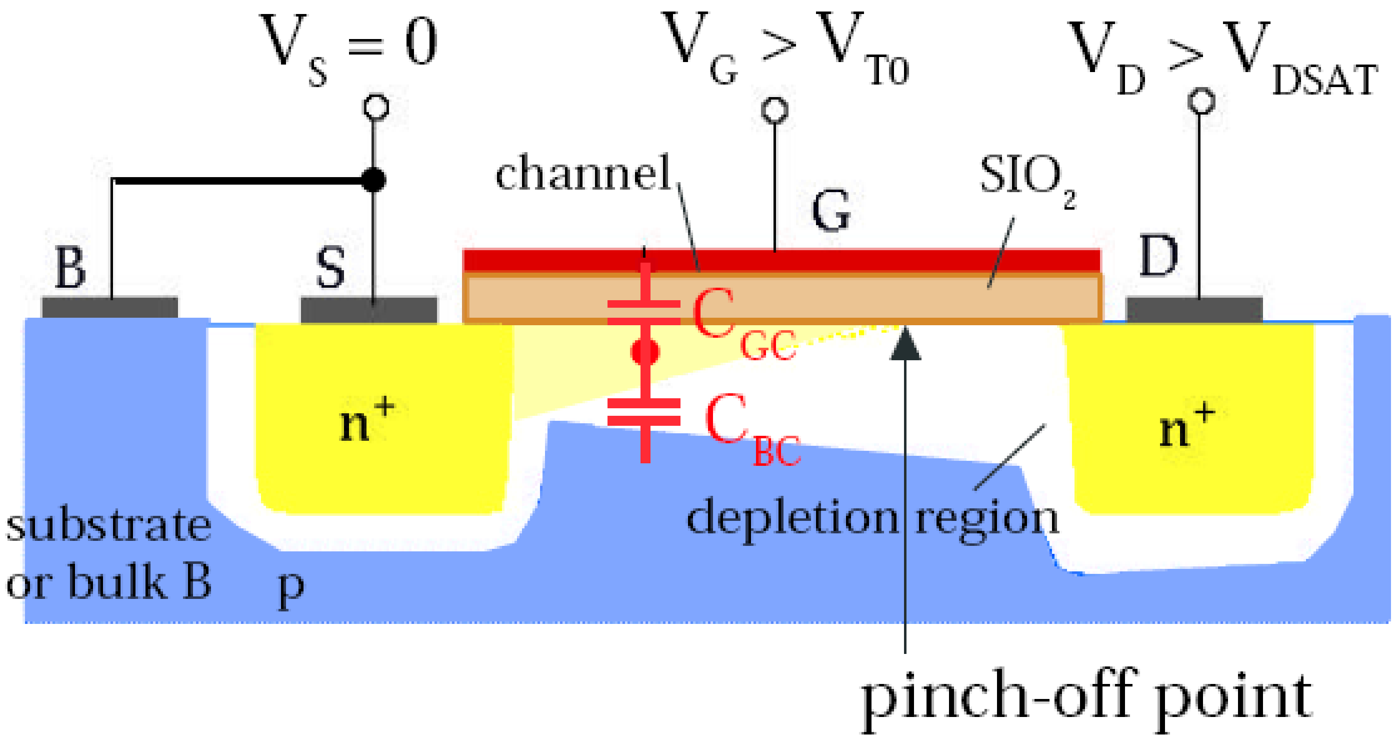
NMOS Transistor in Linear Region



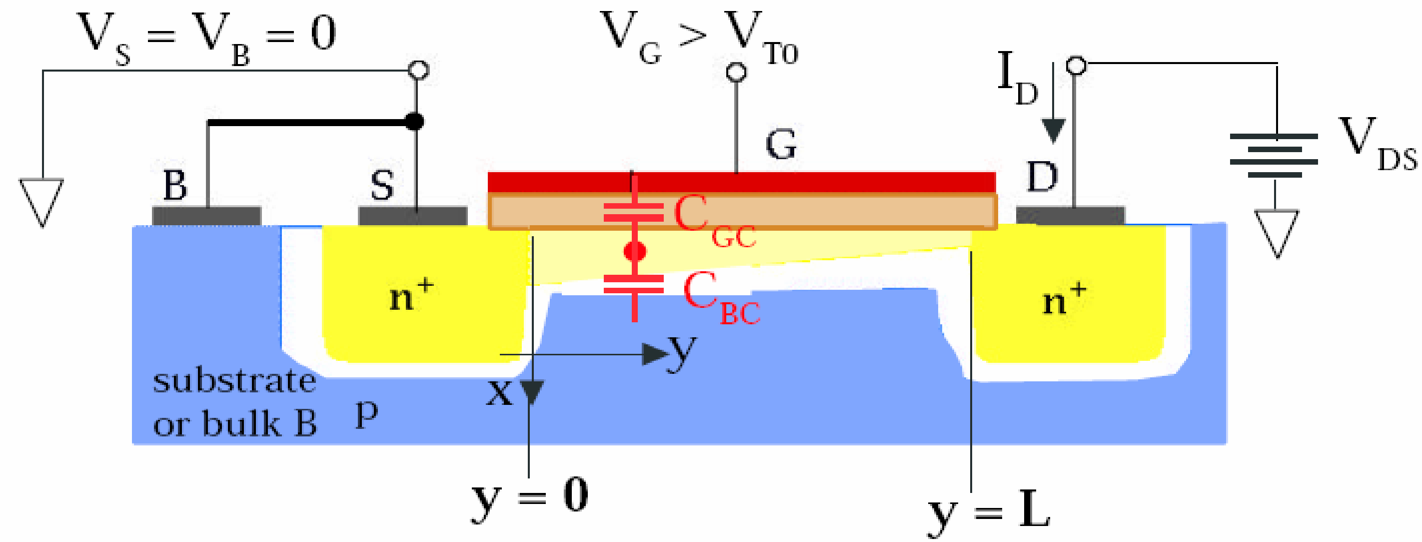
NMOS Transistor at Edge of Saturation

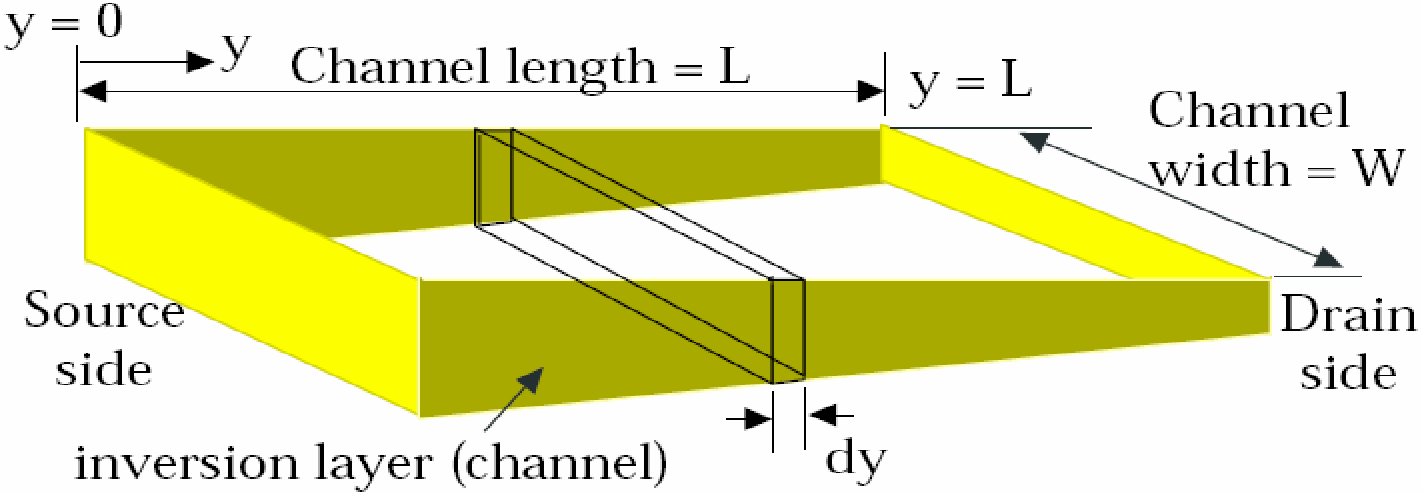


NMOS Transistor in Saturation

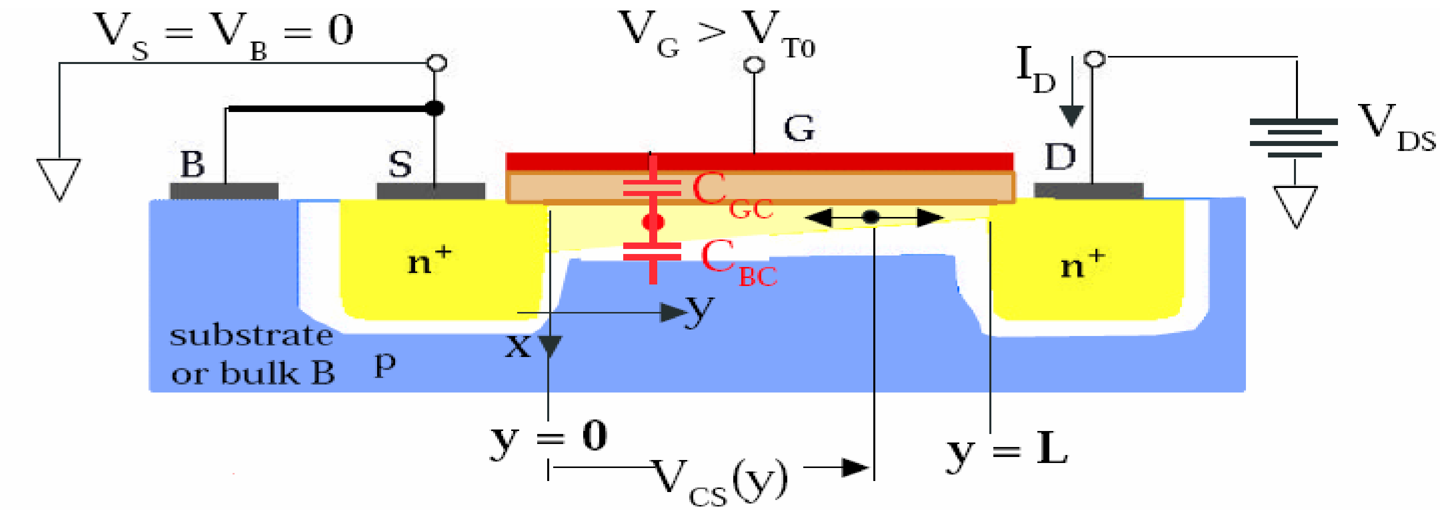


MOS Current-Voltage Characteristics





MOS Current-Voltage Characteristics



Boundary conditions:

$$V_{CS}(y = 0) = V_S = 0$$

$$V_{CS}(y = L) = V_{DS}$$

Assumptions:

$$V_{T0}(y) = V_{T0}$$

$$V_{GS} > V_{T0}$$

$$V_{GD} = V_{GS} - V_{DS} > V_{T0}$$

Mobile charge in channel:

$$Q_I(y) = -C_{ox}[V_{GS} - V_{CS}(y) - V_{T0}]$$

$$\mu_n Q_I(y) = \left(\frac{cm^2}{V \cdot s}\right)\left(\frac{c}{cm^2}\right) = \frac{c/s}{V} = \frac{I}{V}$$

$$dR = -\frac{dy}{W}\left(\frac{1}{\mu_n Q_I(y)}\right)$$

μ_n = electron mobility
= $cm^2/Vsec$
[μ –> U0 in SPICE]

MOS Current-Voltage Characteristics

$$Q_I(y) = -C_{ox}[V_{GS} - V_{CS}(y) - V_{T0}]$$

$$dR = -\frac{dy}{W}\left(\frac{1}{\mu_n Q_I(y)}\right)$$

$$dV_{CS} = I_D dR = -\frac{I_D}{W\mu_n Q_I(y)} dy$$

Boundary conditions:

$$V_{CS}(y = 0) = V_S = 0$$

$$V_{CS}(y = L) = V_{DS}$$

Integrating along the channel

$0 \leq y \leq L$

and $0 \leq V_{CS} \leq V_{DS}$

$$\int_0^L I_D dy = -W\mu_n \int_0^{V_{DS}} Q_I(y) dV_{CS}$$

$$\int_0^L I_D y = W\mu_n C_{ox} \int_0^{V_{DS}} [V_{GS} - V_{CS} - V_{T0}] dV_{CS}$$

$$Iy\Big|_{y=0}^{y=L} = W\mu_n C_{ox}\Big[(V_{GS} - V_{T0})V_{CS} - V_{CS}^2/2\Big]\Big|_{V_{CS}=0}^{V_{CS}=V_{DS}}$$

$$= W\mu_n C_{ox}[(V_{GS} - V_{T0})V_{DS} - V_{DS}^2/2]$$

$$I_D = \frac{\mu_n C_{ox}}{2}\frac{W}{L}[2(V_{GS} - V_{T0})V_{DS} - V_{DS}^2]$$

MOS Current-Voltage Characteristics

$$I_D = \frac{\mu_n C_{ox}}{2}\frac{W}{L}[2(V_{GS} - V_{T0})V_{DS} - V_{DS}^2]$$

$$= \frac{k'}{2}\frac{W}{L}[2(V_{GS} - V_{T0})V_{DS} - V_{DS}^2]$$

$$k' = \mu_n C_{ox}$$

[k' -> KP in SPICE]

$$= \frac{k}{2}[2(V_{GS} - V_{T0})V_{DS} - V_{DS}^2]$$

$$k = k'\frac{W}{L}$$

MOS Current-Voltage Characteristics

❖ Example

For an n-MOS transistor with $\mu_n = 600\ cm^2/Vsec$, $C_{ox} = 7 \times 10^{-8}\ F/cm^2$ $W = 20\ \mu m$, $L = 2\ \mu m$, $V_{T0} = 1.0\ V$, plot the relationship between I_D and V_{DS}, V_{GS}.

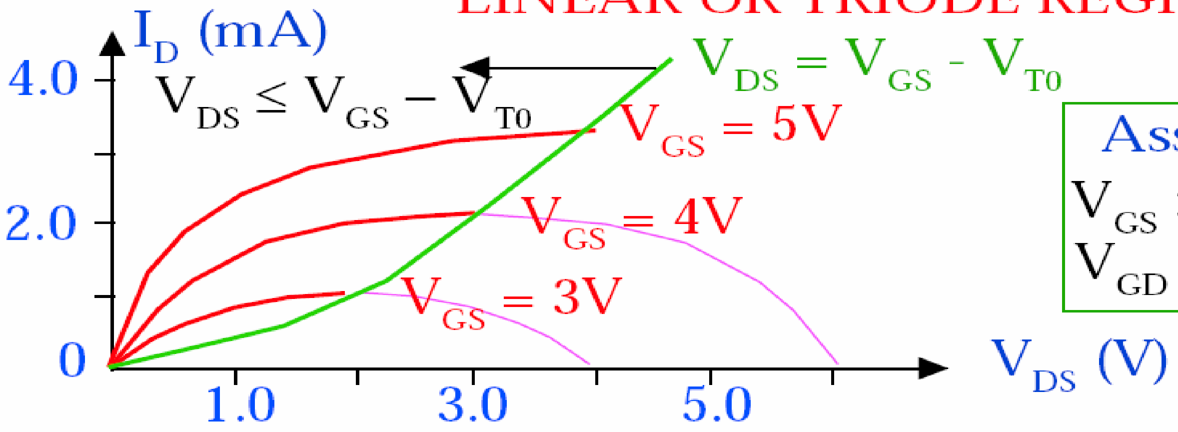
$$I_D = \frac{k}{2}[2(V_{GS} - V_{T0})V_{DS} - V_{DS}^2] \quad \text{where} \quad k = \mu_n C_{ox}\frac{W}{L}$$

$F = C/V$

$$k = \mu_n C_{ox}\frac{W}{L} = (600\,cm^2/Vsec)(7x10^{-8}\,F/cm^2)\frac{20\,\mu m}{2\,\mu m} = 0.42\,mA/V^2$$

$$I_D = 0.21 mA/V^2[2(V_{GS} - 1.0)V_{DS} - V_{DS}^2]$$

LINEAR OR TRIODE REGION



Assumptions:

$V_{GS} > V_{T0}$

$V_{GD} = V_{GS} - V_{DS} > V_{T0}$

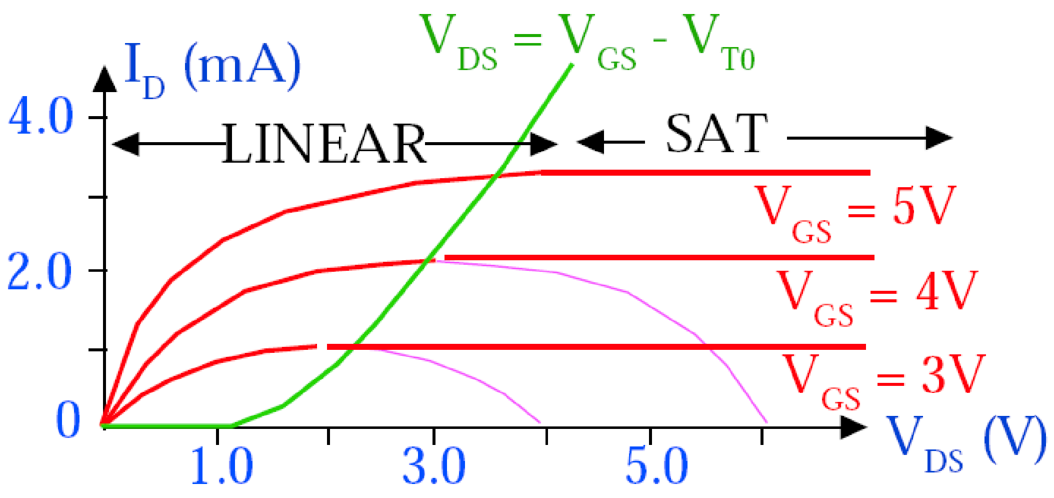
MOS Current-Voltage Characteristics

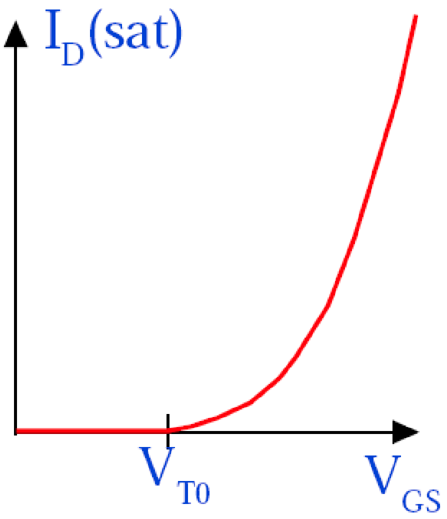
$V_{DS} \geq V_{GS} - V_{T0} = V_{DSAT}$ SATURATION REGION

$$I_D = \frac{\mu_n C_{ox}}{2}\frac{W}{L}[2(V_{GS} - V_{T0})V_{DS} - V_{DS}^2]\Big| \quad @V_{DS} = V_{DSAT} = V_{GS} - V_{T0}$$

$$= \frac{\mu_n C_{ox}}{2}\frac{W}{L}[2(V_{GS} - V_{T0})(V_{GS} - V_{T0}) - (V_{GS} - V_{T0})^2]$$

$$I_D(sat) = \frac{\mu_n C_{ox}}{2}\frac{W}{L}(V_{GS} - V_{T0})^2$$





Channel Length Modulation

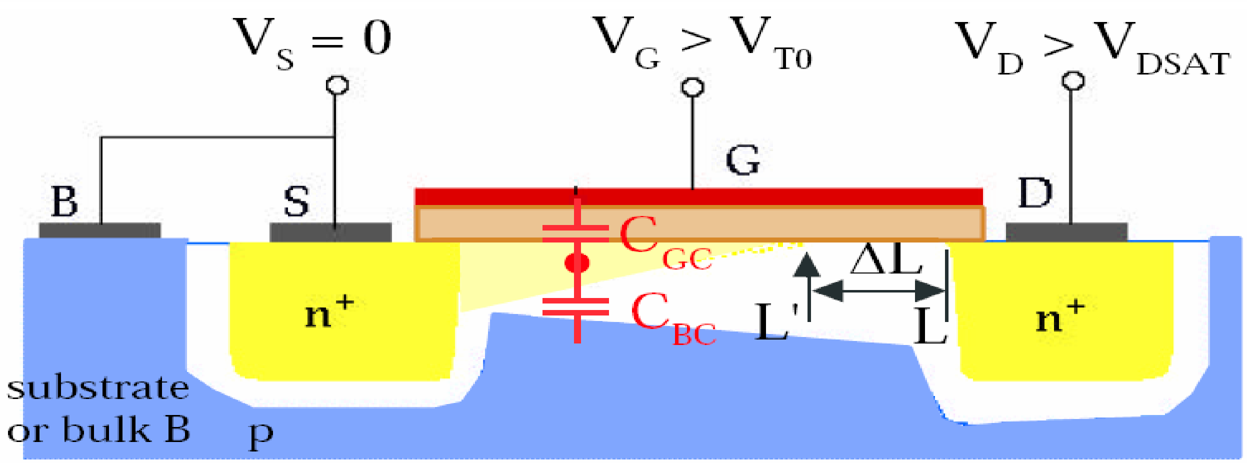
Boundary conditions:

$$Q_I(y) = -C_{ox}[V_{GS} - V_{CS}(y) - V_{T0}]$$

$$V_{CS}(y=0) = V_S = 0 \rightarrow Q_I(y=0) = -C_{ox}[V_{GS} - V_{T0}]$$

$$V_{CS}(y=L) = V_{DS} \rightarrow Q_I(y=L) = -C_{ox}[V_{GS} - V_{DS} - V_{T0}]$$

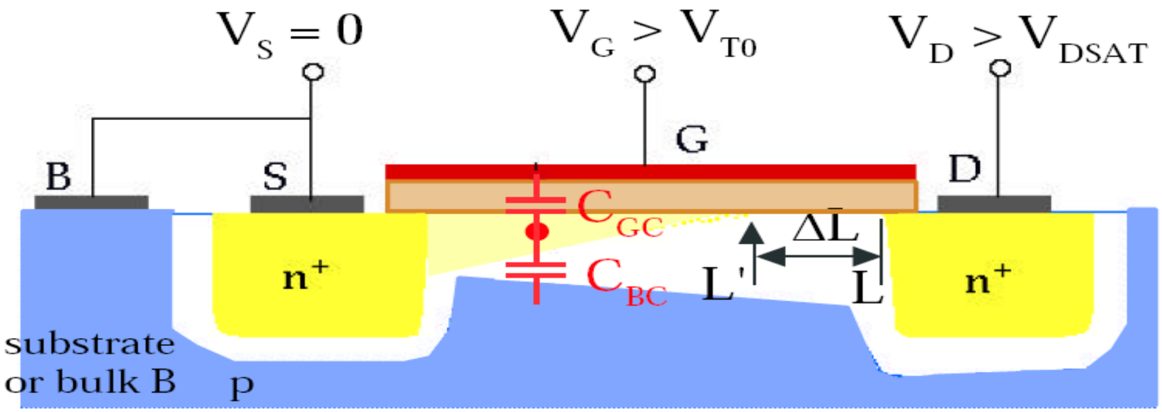
$$= 0 \ @ \ V_{DS} = V_{DSAT}$$



$$L' = L - \Delta L$$ effective channel length

$$V_{CS}(y = L') = V_{DSAT}$$

Channel Length Modulation



$$I_D(sat) = \frac{\mu_n C_{ox}}{2}\frac{W}{L'}(V_{GS} - V_{T0})^2 = \frac{\mu_n C_{ox}}{2}\frac{W}{L(1-\frac{\Delta L}{L})}(V_{GS} - V_{T0})^2$$

where $\Delta L \propto \sqrt{V_{DS} - V_{DSAT}}$

emperical relation: $\frac{1}{1-\frac{\Delta L}{L}} = 1 + \lambda V_{DS}$ [λ -> LAMBDA in SPICE]

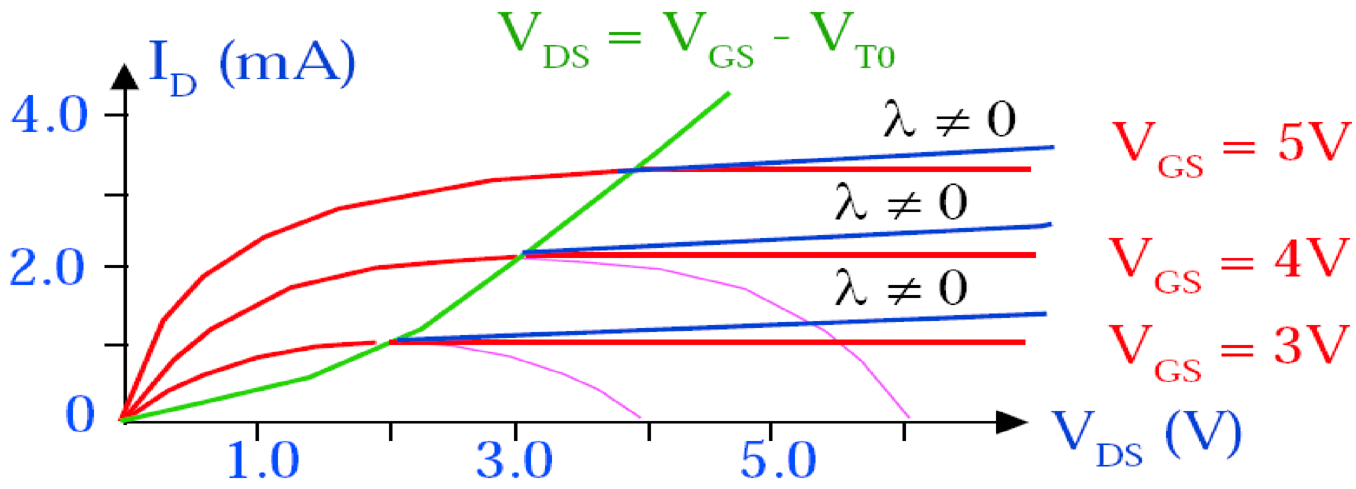
λ = channel length modulation coefficent (V^{-1})

Channel Length Modulation

$$I_D(sat) = \frac{\mu_n C_{ox}}{2}\frac{W}{L'}(V_{GS} - V_{T0})^2 = \frac{\mu_n C_{ox}}{2}\frac{W}{L(1 - \frac{\Delta L}{L})}(V_{GS} - V_{T0})^2$$

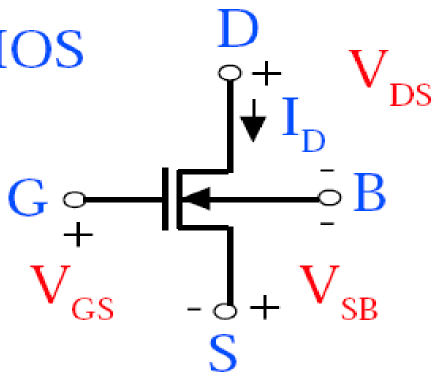
$$\frac{1}{1 - \frac{\Delta L}{L}} = 1 + \lambda V_{DS}$$

$$I_D(sat) = \frac{\mu_n C_{ox}}{2}\frac{W}{L}(V_{GS} - V_{T0})^2(1 + \lambda V_{DS})$$

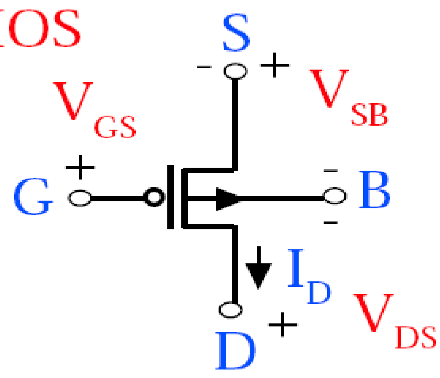


MOS Current-Voltage Characteristics

n-MOS



p-MOS



n-MOS $I_D = 0$ for $V_{GS} \le V_T$

$$I_D(\text{lin}) = \frac{\mu_n C_{ox}}{2}\frac{W}{L}\left[2\left(V_{GS} - V_T(V_{SB})\right)V_{DS} - V_{DS}^2\right] \quad V_{GS} > V_T,\ V_{DS} < V_{GS} - V_T$$

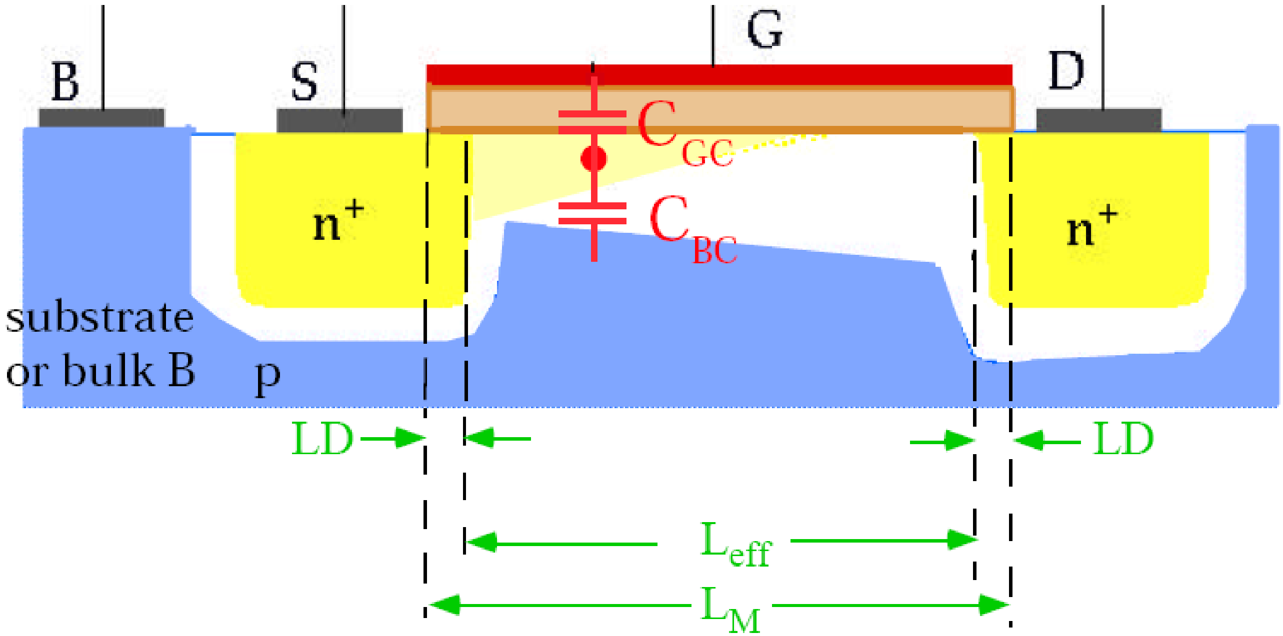
$$I_D(\text{sat}) = \frac{\mu_n C_{ox}}{2}\frac{W}{L}\left(V_{GS} - V_T(V_{SB})\right)^2(1 + \lambda V_{DS}) \quad V_{GS} > V_T,\ V_{DS} \ge V_{GS} - V_T$$

p-MOS $I_D = 0$ for $V_{GS} \ge V_T$

$$I_D(\text{lin}) = \frac{\mu_p C_{ox}}{2}\frac{W}{L}\left[2\left(V_{GS} - V_T(V_{SB})\right)V_{DS} - V_{DS}^2\right] \quad V_{GS} < V_T,\ V_{DS} > V_{GS} - V_T$$

$$I_D(\text{sat}) = \frac{\mu_p C_{ox}}{2}\frac{W}{L}\left(V_{GS} - V_T(V_{SB})\right)^2(1 + \lambda V_{DS}) \quad V_{GS} < V_T,\ V_{DS} \le V_{GS} - V_T$$

Effective Channel Length and Width



SPICE Parameters

$L_{eff} = L_M - 2LD - DL$

$W_{eff} = W_M - DW$

SPICE Parameters

LD -> under diffusion

DL -> error in photolith and etch

DW -> error in photolith and etch