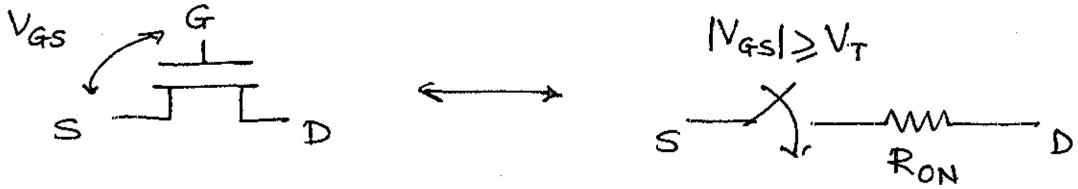
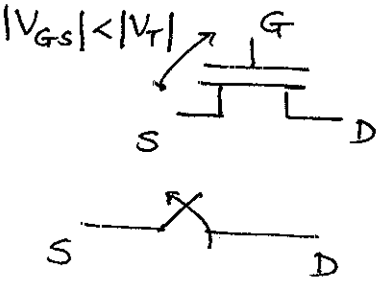
- MOS Transistor (Rabaey Chap 3, H+S chap 4)
  Basic Operation
  Modes of Operation
  Deep Sub-Micron (DSM) MOSFETs

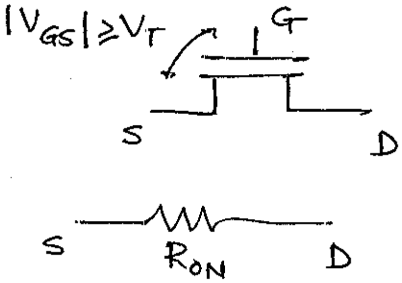
For digital circuits: A MOS transistor ⟷ A switch.



Switch OFF

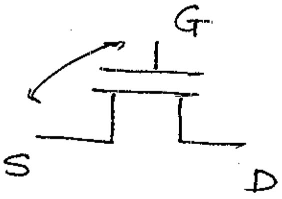


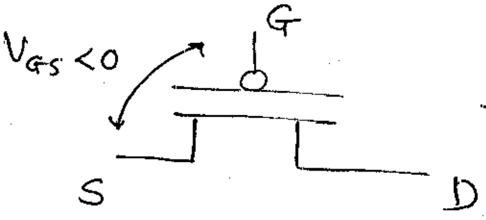
Switch ON



NMOS

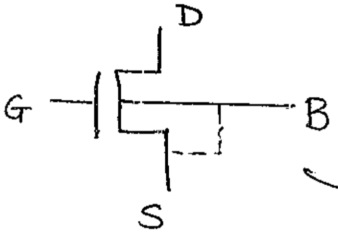
$V_{GS} > 0$



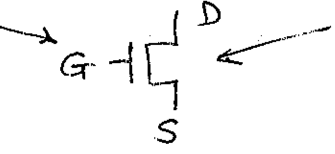


PMOS

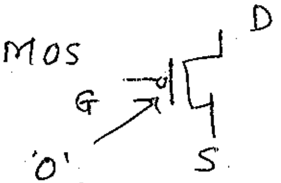
MOSFET is in reality a four terminal device



In most cases in digital design, body is tied to the source

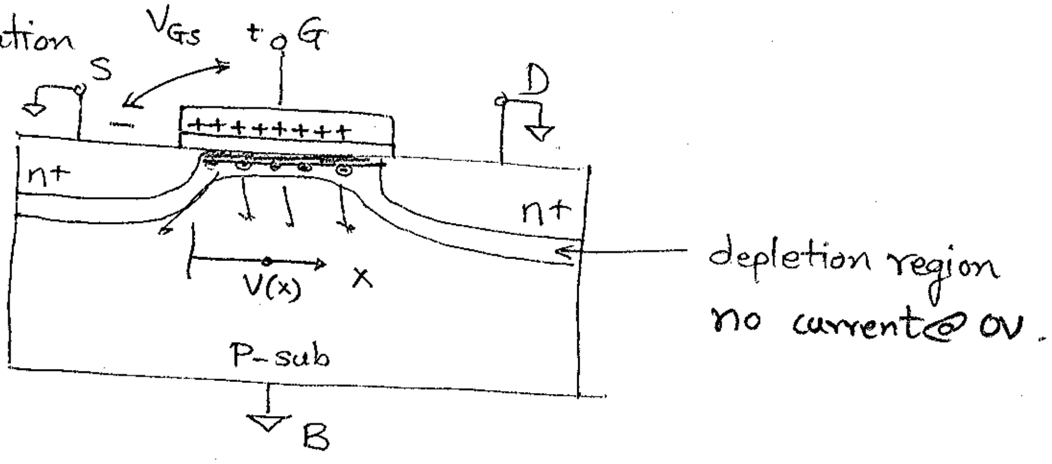


Symbol for PMOS



for inversion.

Basic Operation



+ve charge on gate → repels ~~ner~~ mobile holes leaving +ve acceptor ions

as keep increasing gate voltage, reaches a critical value.

surface 'inverts' n-type material → onset of "strong inversion"

$(2\phi_F)$

$$\phi_F = 60mV \log_{10}\left(\frac{N_A}{n_i}\right)$$

further increase does not change the depletion layer depth, but results in additional electrons being drawn in from the n^+ source → continuous n+ channel is formed between S&D, whose conductivity is modulated by V_{GS}

$$|Q_{B,max}| = \sqrt{2qN_a\varepsilon_{Si}|2\phi_F|} \longleftarrow (2\phi_F + V_{SB})$$

$$\& \ V_{Tn} = V_{FB} - 2\phi_F + \frac{1}{C_{ox}}|Q_{B,max}|$$

If we bias the bulk more negative than the source $V_{SB} > 0$

$$V_T = V_{T_0} + \gamma\left(\sqrt{2\phi_F + V_{SB}} - \sqrt{2\phi_F}\right) \qquad \gamma \approx 0.4\sqrt{V}$$

V_T is positive for NMOS & negative for PMOS.

Resistive Operation (linear region)

$$Q_B = -C_{ox}(V_{GB} - V_T) \qquad \text{MOS capacitor}$$

$$Q(x) = -C_{ox}(V_{GS} - V_T - V(x)) \qquad C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} \quad \frac{\text{Capacitance}}{\text{Area}}$$

$$I_D = V_n(x) \cdot Q(x) \cdot W \qquad V_n(x) = \mu_N E = \mu_N \cdot \frac{\partial V}{\gamma x}$$

$$I_D = \mu_n C_{ox}(V_{gs} - V_T - V(x)) \frac{\partial V(x)}{\partial x} \cdot W$$

$$\int I\,dx = \int \mu_n C_{ox}\left(V_{gs} - V_T - V(x)\right) dV \quad W$$

$$I_D\ L = \mu_N C_{ox}\ W\left((V_{gs}-V_T)(V_{DS}) - \frac{V_{DS}^2}{2}\right)$$

linear or resistive region $V_{GS} > V_T$ V_{DS} very small

$$Q_B(x=0) = C_{ox}(V_{gs} - V_T)$$

$$Q_B(X=L) = C_{ox}(V_{gs} - V_T - V_{DS}) \qquad [V_{GD} > V_{Tn}]$$

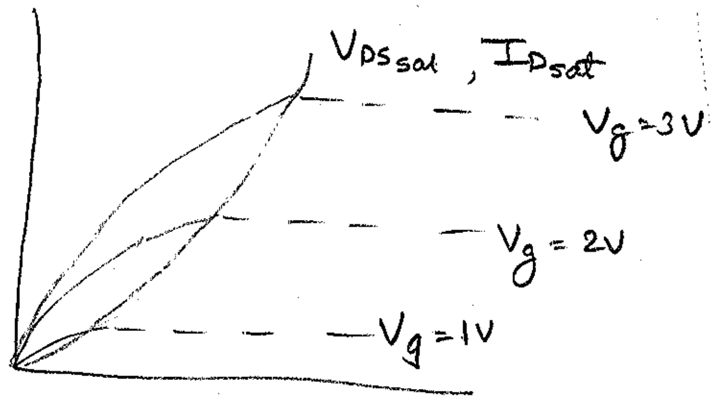
$$Q_{avg} = C_{ox}\left(V_{gs} - V_T - \frac{V_{DS}}{2}\right) \qquad V_{GS} - V_{DS} > V_{Tn}$$

Velocity $V = \mu_N E_{DS} = \mu_N \cdot \frac{V_{DS}}{L}$ or. $V_{DS} < (V_{GS} - V_T)$

$$I_D = V\cdot Q_{avg}\cdot W = \mu_n \cdot \frac{V_{DS}}{L}\cdot W\ C_{ox}\left(V_{gs} - V_T - \frac{V_{DS}}{2}\right)$$

$$= \mu_n C_{ox}\frac{W}{L}\left[(V_{gs}-V_T)V_{DS} - \frac{V_{DS}^2}{2}\right] \qquad V_{DS} < \underbrace{V_{GS}-V_T}_{V_{DS}\text{'sat'}}$$

$$I_{Dsat} = \frac{1}{2}\mu_N C_{ox}\frac{W}{L}(V_{gs}-V_T)^2 \longleftarrow \text{Substitute } V_{DS_{sat}}$$



Saturation region

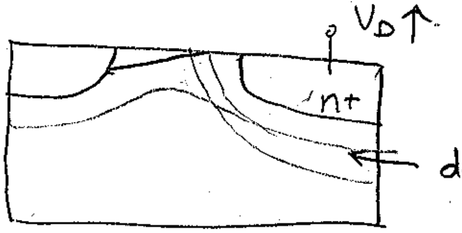
$V_{DS} = V_{DS_{sat}} = V_{gs} - V_T$

$Q_B(x=L) = 0$ vanishes

why do we get current

$$I_D = \underset{\text{very large}}{V}\cdot \underset{\text{very very small}}{Q}\cdot W$$

but has a limit → saturates



$$V_{DS} > V_{DS_{sat}} = V_{gs} - V_T$$

← depletion region widens → reduces 'L'

→ channel length modulation (CLM)

$$I_D = \frac{1}{2}\mu_N C_{ox}\frac{W}{L}(V_{gs}-V_T)^2(1+\lambda V_{DS})$$

Velocity saturation

When high horizontal E-fields reach a critical value $\mathcal{E}_{crit}$ Velocity saturates due to scattering effects. (collisions)

$V_{sat} = 10^5$ m/s $\quad (E_{crit} = 1-5V/\mu m)$

$L_{min} = 0.25\mu m$. $\cancel{F}$ $V_{crit} = 2V$!

$$v_{el} = \frac{\mu_n E_{crit}}{1+E/E_{crit}} = \cancel{\mu_n} \qquad E \leqslant E_{crit}$$

$$= V_{sat} \qquad E \geqslant E_{crit}$$

$$I_D = \frac{\mu_N}{1+\frac{V_{DS}}{E_{crit}\cdot L}}\cdot\frac{V_{DS}}{L}\cdot W\cdot C_{ox}\left(V_{gs}-V_T-\frac{V_{DS}}{2}\right)$$

$$= K(V_{DS})\ \mu_n C_{ox}\frac{W}{L}\left[(V_{gs}-V_T)V_{DS}-\frac{V_{DS}^2}{2}\right]$$

$$K = \frac{1}{1+\frac{V_{DS}}{E_c\cdot L}}$$

Now current at drain @ saturation $I_{Dsat} = V_{sat}\cdot C_{ox}W(V_{gs}-V_T-V_{DSAT})$

$$= K(V_{DS})\cdot C_{ox}\mu_N\frac{W}{L}V_{DS}(V_{gs}-V_T-V_{Dsat})$$

$V_{Dsat} = K(V_{GT})\cdot V_{GT} \qquad V_{gt} = V_{gs}-V_T \qquad$ not intuitive

$$V_{DSAT} = L\cdot E_{crit} = \frac{L\cdot V_{sat}}{\mu_N}$$

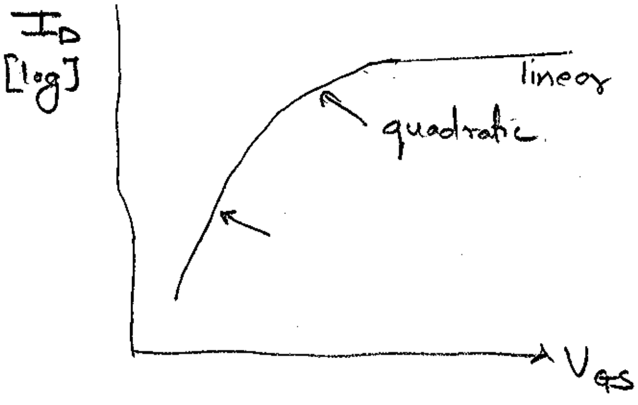
In resistive region equation remains unchanged $V_{DS} < V_{gs}-V_T$

$$I_{Dsat} = \mu_n C_{ox}\frac{W}{L}\left[(V_{gs}-V_T)V_{Dsat}-\frac{V_{Dsat}^2}{2}\right]$$

current saturates before any "pinch-off" occurs.

Sub-threshold Conduction

onset of strong inversion ⟹ ample carriers.
does not mean no current can flow below V_T



$V_{gs} < V_T$

"parasitic $n^+ - p - n^+$

$$I_{DS} = I_S e^{\frac{V_{gs}}{n \cdot kT/q}}$$

undesirable.
current flowing during OFF!

(inverse) rate of decline of current wrt. V_{gs} below V_T → quality of device

$$S = n\left(\frac{KT}{q}\right)\ln(10) \qquad n=1 \quad S = 60\text{mV/decade}$$