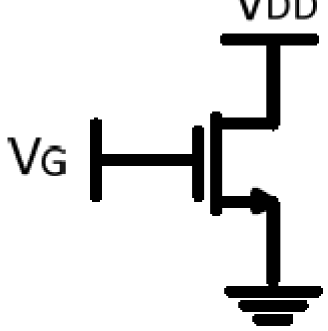
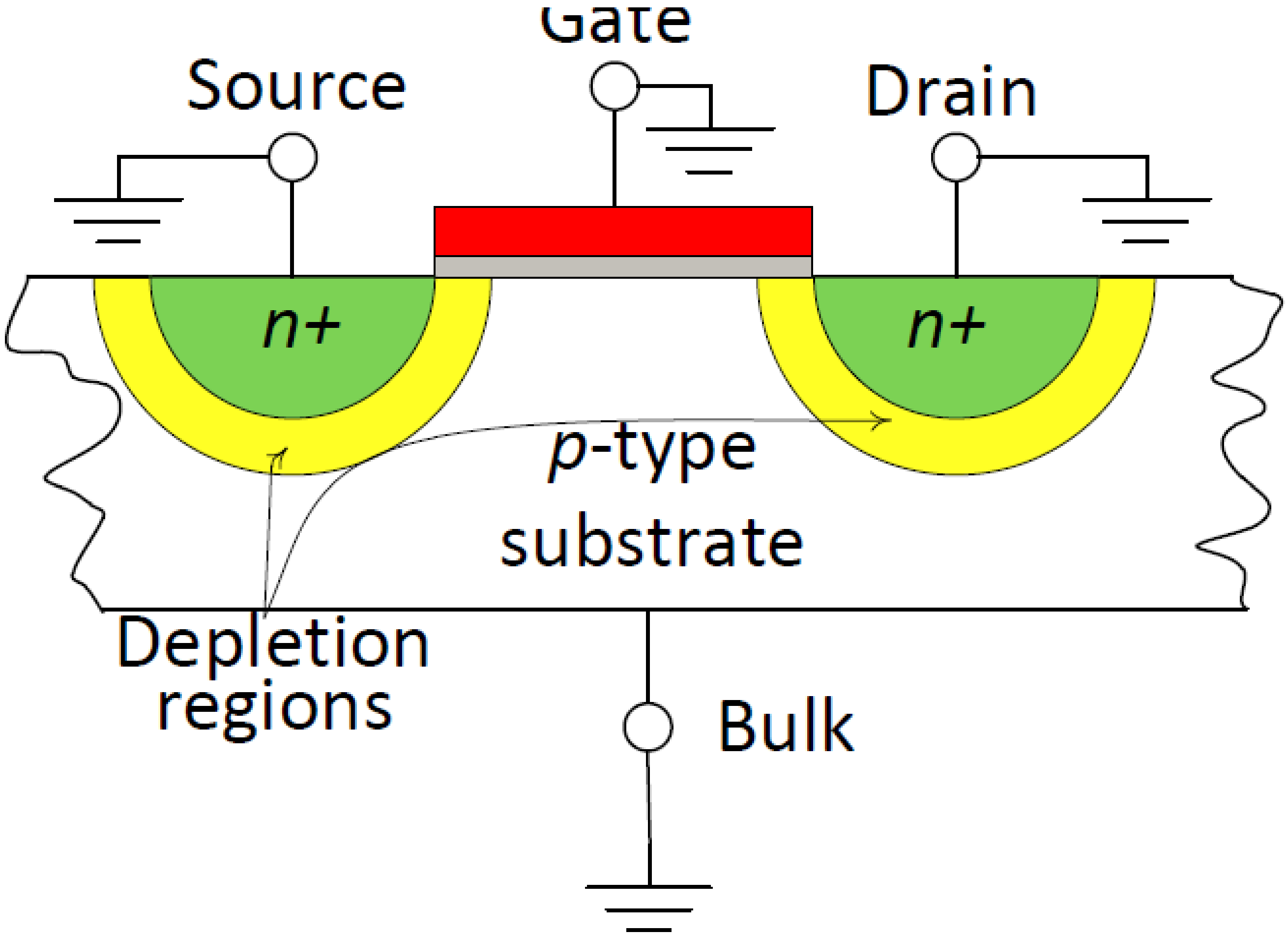
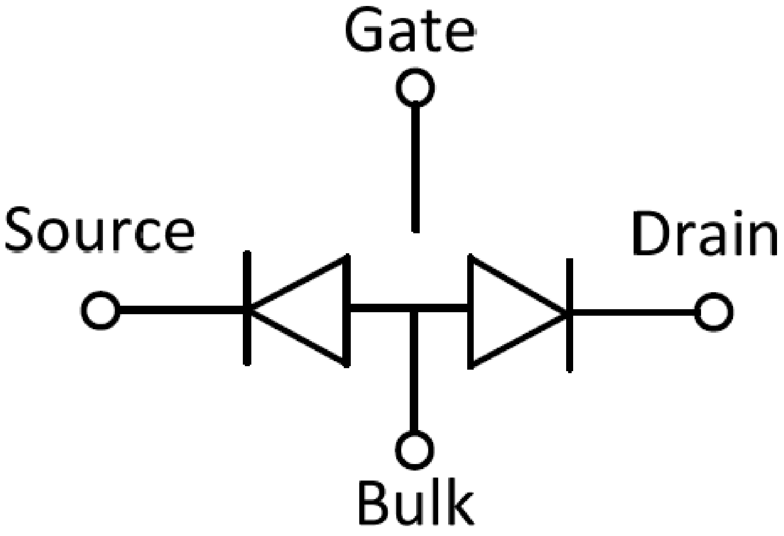
MOS Mode of operation



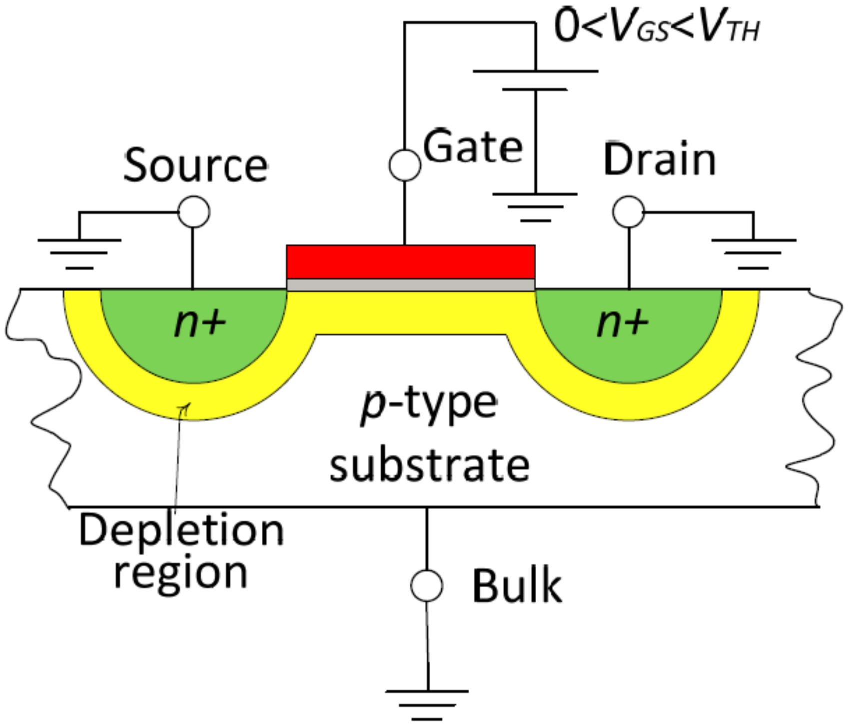
Equivalent circuit of an NMOS transistor with all terminals biased to ground





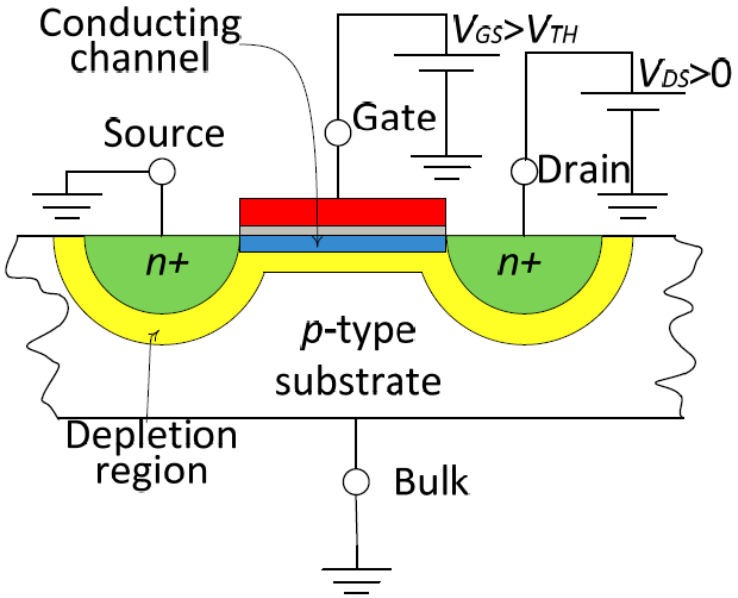
NMOS transistor with a $0<VGS<VTH$.

- current cannot flows between Source and
- Drain, and the device is still in cut-off region.



Linear or triode region

- When *VGS>VTH*, the NMOS transistor is on, i.e. the conducting channel is formed, then a current flow
- between Source and Drain can exist.



$$I_{DS} = \frac{N \cdot q}{t_d} = \frac{Q_{ch}}{t_d}$$

$$Q_{ch} = C_{ox} \cdot L \cdot W \cdot (V_{GS} - V_{TH}) = C_{ox} \cdot L \cdot W \cdot V_{ov}$$

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}$$

$$t_{ox} = \frac{L_{min}}{50}$$

In standard CMOS technologies of the last twenty years t_{ox} is about fifty times lower than the minimum channel length L_{min}

$$t_d = \frac{L}{v_d}$$

Drift time, t_d, is directly proportional to the channel length L, and inversely proportional to the drift velocity of electrons, v_d,

Linear or triode region

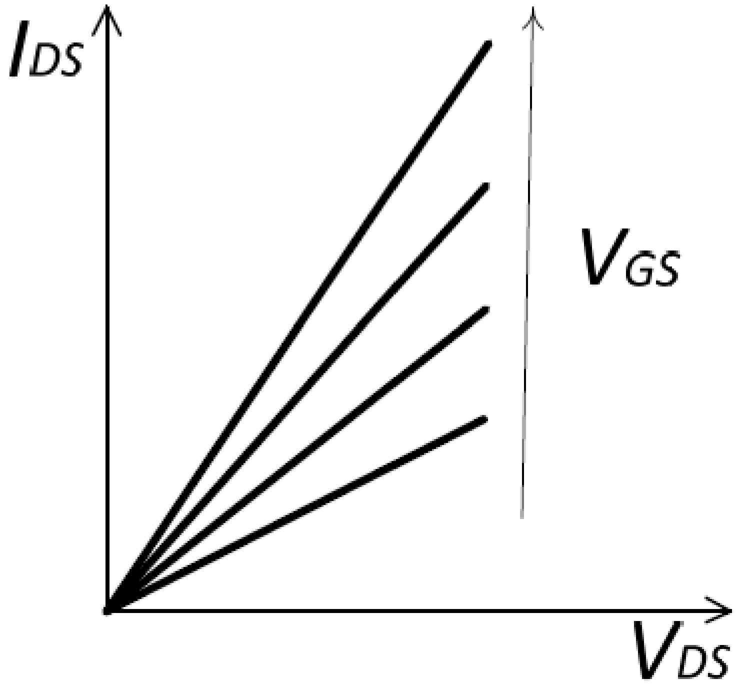
$v_d = \mu_n \cdot \varepsilon_y$

- Drift velocity, *vd*, is proportional to the horizontal electric field, εy,

$\varepsilon_y = \frac{V_{DS}}{L}$

- where *μn* is the electron mobility in the channel. The value of the horizontal electric field, εy

$$I_{DS} = \mu_n \cdot C_{ox} \cdot \frac{W}{L} \cdot (V_{GS} - V_{TH}) \cdot V_{DS} = 2 \cdot k_n \cdot V_{ov} \cdot V_{DS}$$



$$k_n = \frac{1}{2} \cdot \mu_n \cdot C_{ox} \cdot \frac{W}{L}$$

the NMOS transistor acts
like a variable resistance, *R*$_{on}$, whose value depends on *V*$_{ov}$

$$R_{on} = \frac{1}{2 \cdot k_n \cdot (V_{GS} - V_{TH})} = \frac{1}{2 \cdot k_n \cdot V_{ov}}$$

Linear or triode region

- a more accurate calculation of the channel charge is get by adding $V_{DS}/2$

$$Q_{ch} = C_{ox} \cdot L \cdot W \cdot \left(V_{GS} - V_{TH} - \frac{V_{DS}}{2}\right)$$

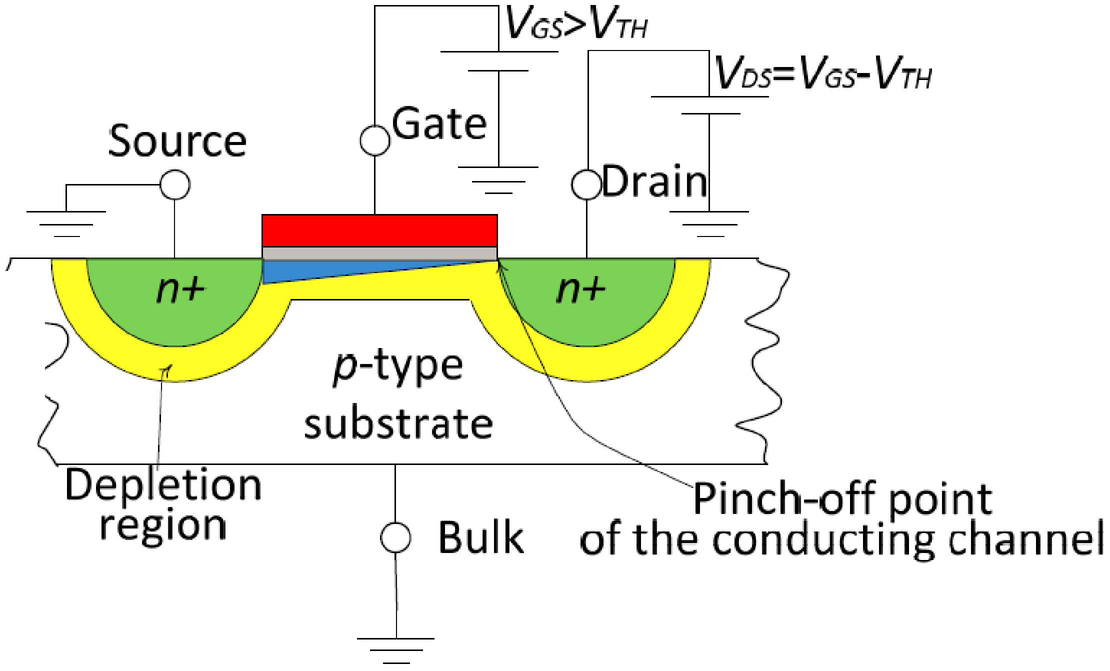
$$I_{DS} = \mu_n \cdot C_{ox} \cdot \frac{W}{L} \cdot \left(V_{GS} - V_{TH} - \frac{V_{DS}}{2}\right) \cdot V_{DS} = 2 \cdot k_n \cdot \left(V_{ov} - \frac{V_{DS}}{2}\right) \cdot V_{DS}$$

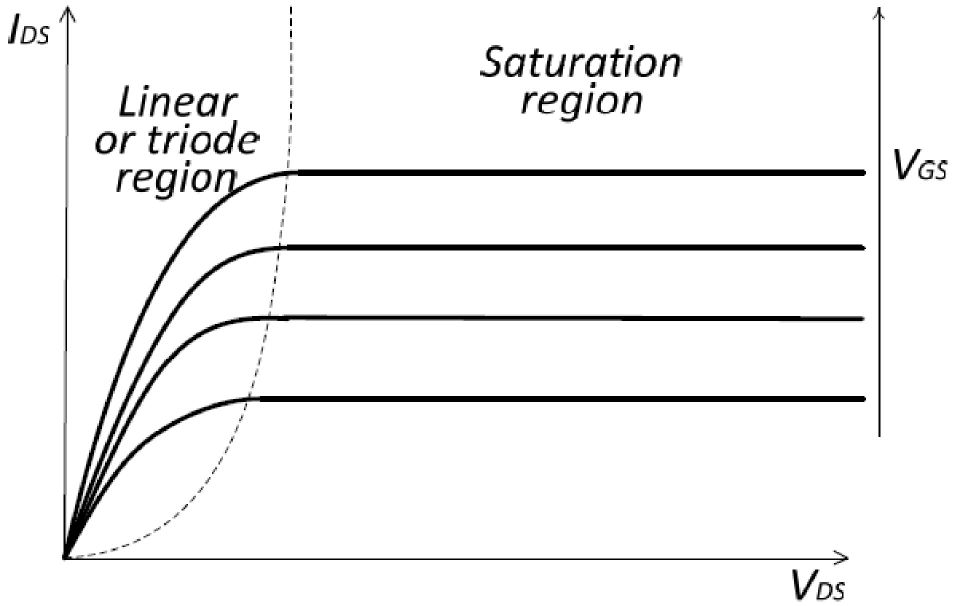
Saturation region

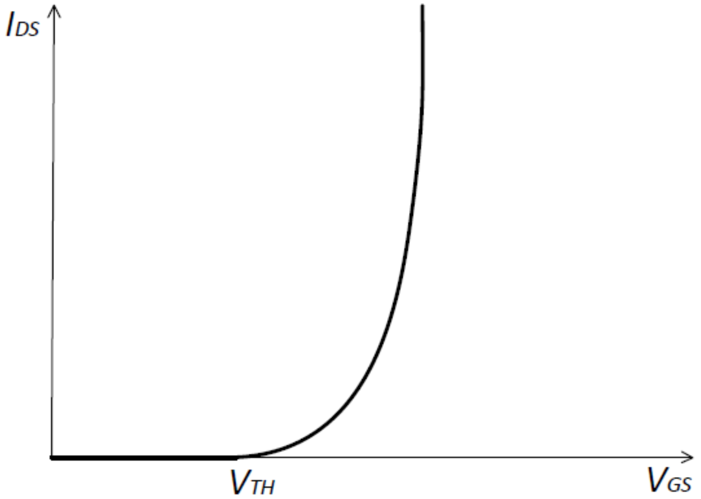
$$V_{GD} = V_{GS} - V_{DS} = V_{GS} - (V_{GS} - V_{\mathrm{TH}}) = V_{\mathrm{TH}}$$

$$I_{DS} = \frac{1}{2} \cdot \mu_n \cdot C_{ox} \cdot \frac{W}{L} \cdot (V_{GS} - V_{TH})^2 = k_n \cdot (V_{GS} - V_{TH})^2 = k_n \cdot V_{ov}{}^2$$

As *VDS* approaches *VGS-V*TH, the channel charge approaches zero at the Drain end.
In facts, the channel charge is sustained by a Gate-Drain voltage, *VGD*, at the drain side, which is less than *VGS* at the Source side.
When *VDS* compensates for the overdrive voltage *VGS*-*V*TH, *VGD* results to be equal to the threshold voltage
VTH





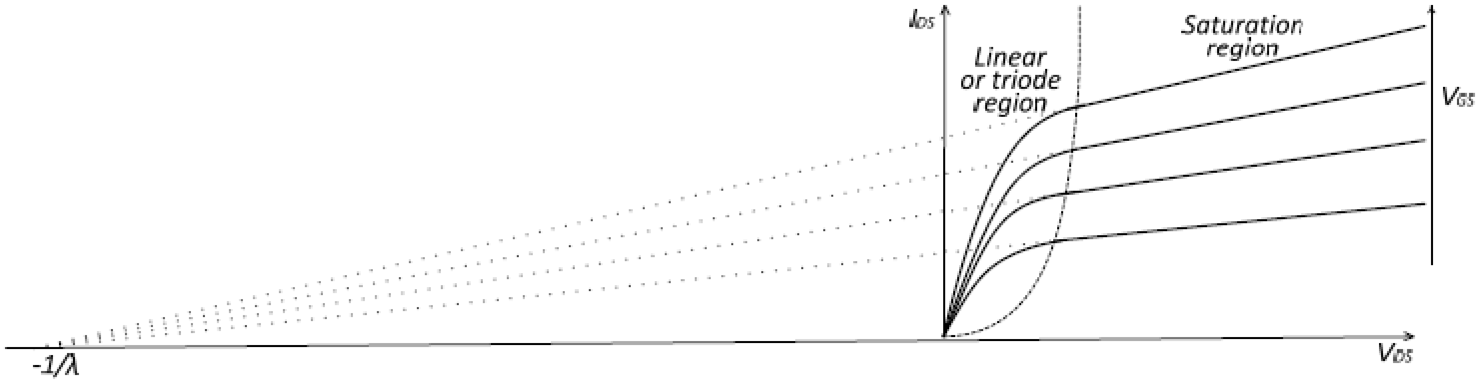


I_{GS}-V_{GS} input characteristic of the NMOS transistor in saturation region

Saturation region

$$L_{eff} = L - \Delta L$$

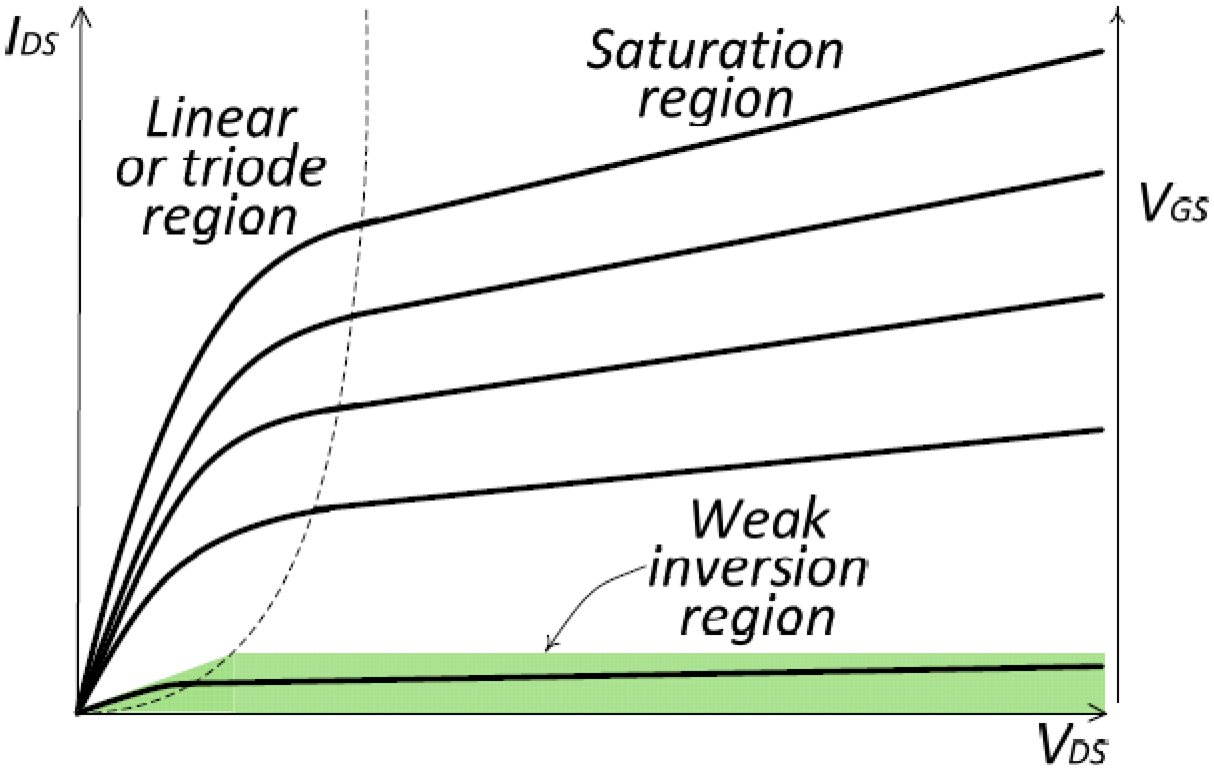
$$I_{DS} = \frac{1}{2} \cdot \mu_n \cdot C_{ox} \cdot \frac{W}{L_{eff}} \cdot (V_{GS} - V_{TH})^2$$



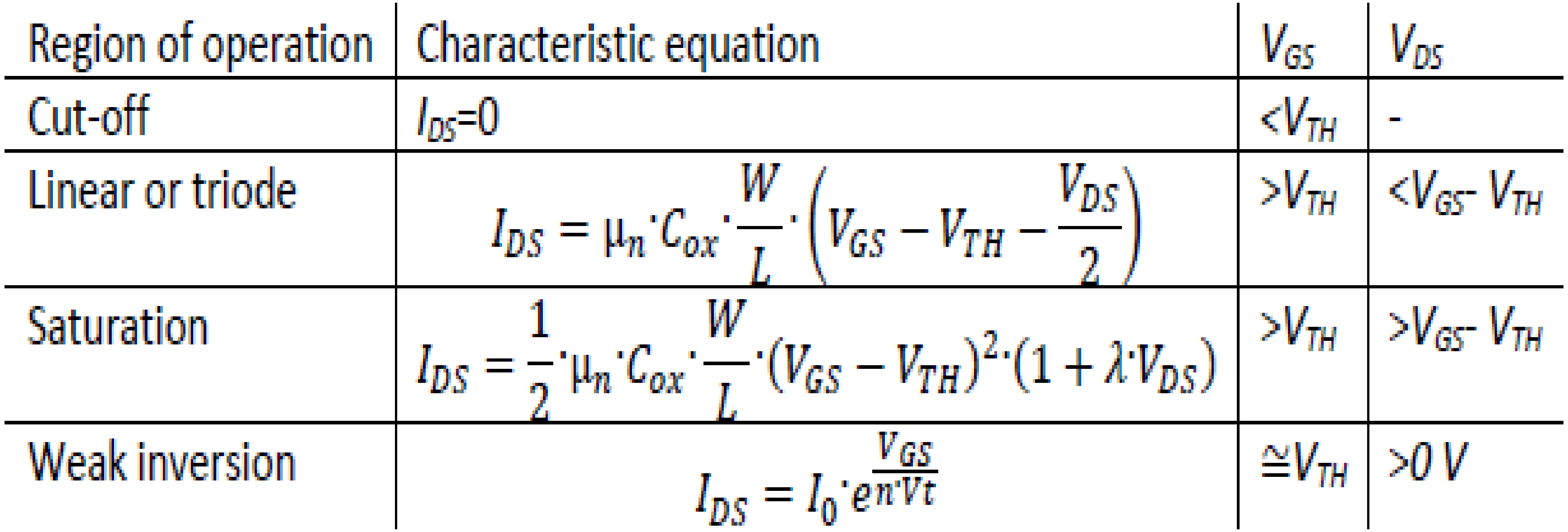
Weak inversion-leakage

$$I_{DS} = I_S \cdot e^{\frac{V_{sur}}{V_t}}$$

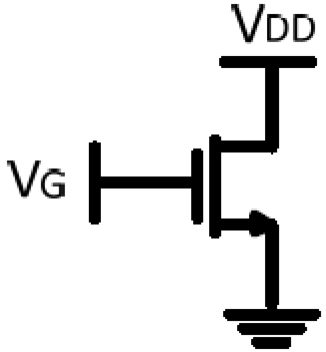
$$I_{DS} = I_0 \cdot e^{\frac{V_{GS}}{n \cdot V_t}}$$



Summary for NMOS

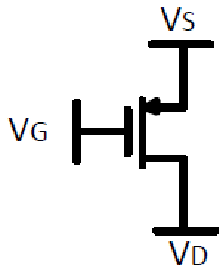


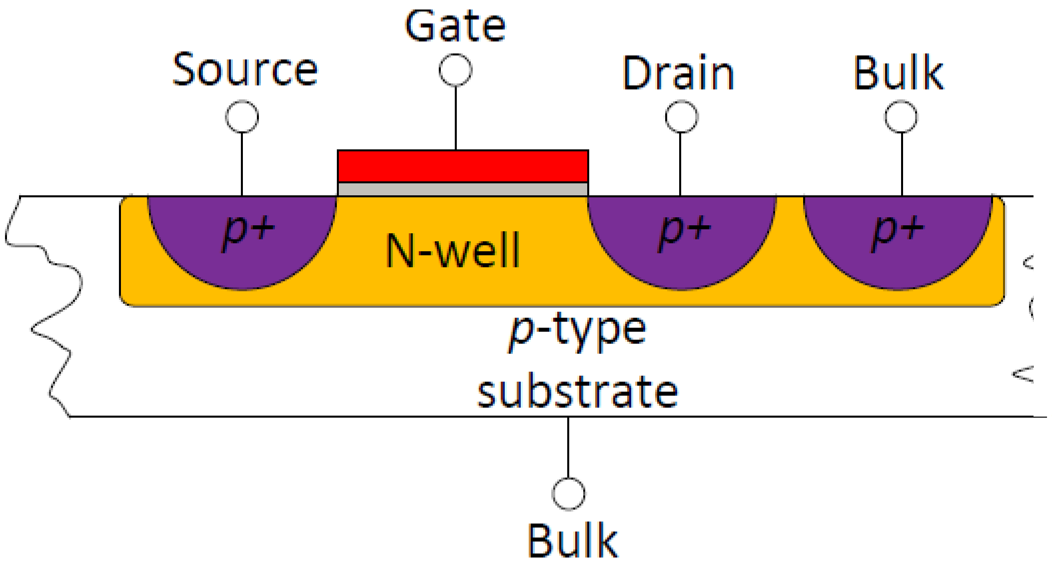
Region of operation	Characteristic equation	V_{GS}	V_{DS}
Cut-off	$I_{DS}=0$	$<V_{TH}$	-
Linear or triode	$I_{DS} = \mu_n \cdot C_{ox} \cdot \frac{W}{L} \cdot \left(V_{GS} - V_{TH} - \frac{V_{DS}}{2}\right)$	$>V_{TH}$	$<V_{GS}- V_{TH}$
Saturation	$I_{DS} = \frac{1}{2} \cdot \mu_n \cdot C_{ox} \cdot \frac{W}{L} \cdot (V_{GS} - V_{TH})^2 \cdot (1 + \lambda \cdot V_{DS})$	$>V_{TH}$	$>V_{GS}- V_{TH}$
Weak inversion	$I_{DS} = I_0 \cdot e^{\frac{V_{GS}}{n \cdot Vt}}$	$\cong V_{TH}$	$>0\ V$

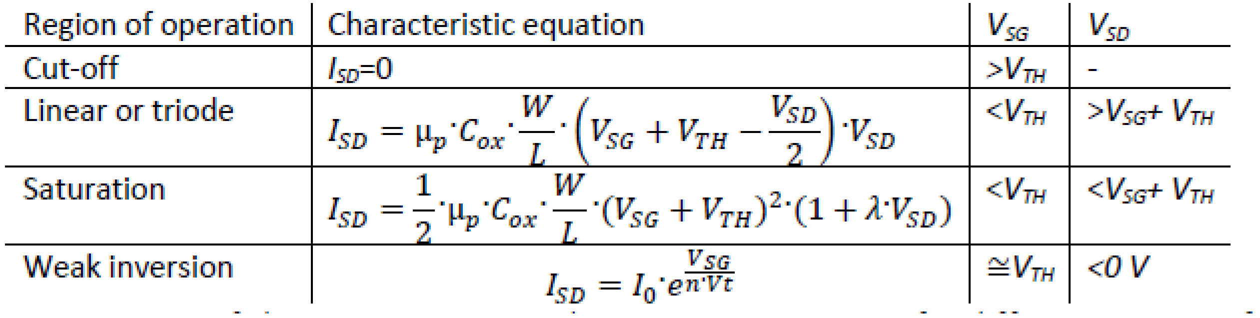


Micrwind video: https://youtu.be/MDARZD9OLNI

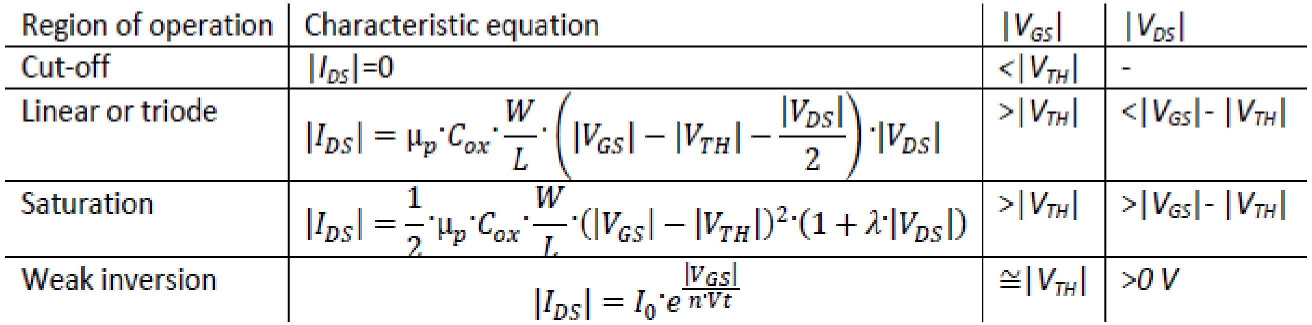
PMOS







Region of operation	Characteristic equation	V_{SG}	V_{SD}
Cut-off	$I_{SD}=0$	$>V_{TH}$	-
Linear or triode	$I_{SD} = \mu_p \cdot C_{ox} \cdot \frac{W}{L} \cdot \left(V_{SG} + V_{TH} - \frac{V_{SD}}{2}\right) \cdot V_{SD}$	$<V_{TH}$	$>V_{SG}+V_{TH}$
Saturation	$I_{SD} = \frac{1}{2} \cdot \mu_p \cdot C_{ox} \cdot \frac{W}{L} \cdot (V_{SG} + V_{TH})^2 \cdot (1 + \lambda \cdot V_{SD})$	$<V_{TH}$	$<V_{SG}+V_{TH}$
Weak inversion	$I_{SD} = I_0 \cdot e^{\frac{V_{SG}}{n \cdot Vt}}$	$\cong V_{TH}$	$<0\ V$



Region of operation	Characteristic equation	$\lvert V_{GS}\rvert$	$\lvert V_{DS}\rvert$
Cut-off	$\lvert I_{DS}\rvert=0$	$<\lvert V_{TH}\rvert$	-
Linear or triode	$\lvert I_{DS}\rvert = \mu_p \cdot C_{ox} \cdot \frac{W}{L} \cdot \left(\lvert V_{GS}\rvert - \lvert V_{TH}\rvert - \frac{\lvert V_{DS}\rvert}{2}\right) \cdot \lvert V_{DS}\rvert$	$>\lvert V_{TH}\rvert$	$<\lvert V_{GS}\rvert - \lvert V_{TH}\rvert$
Saturation	$\lvert I_{DS}\rvert = \frac{1}{2} \cdot \mu_p \cdot C_{ox} \cdot \frac{W}{L} \cdot (\lvert V_{GS}\rvert - \lvert V_{TH}\rvert)^2 \cdot (1 + \lambda \cdot \lvert V_{DS}\rvert)$	$>\lvert V_{TH}\rvert$	$>\lvert V_{GS}\rvert - \lvert V_{TH}\rvert$
Weak inversion	$\lvert I_{DS}\rvert = I_0 \cdot e^{\frac{\lvert V_{GS}\rvert}{n \cdot Vt}}$	$\cong\lvert V_{TH}\rvert$	$>0\ V$

- cut-off;
- linear or triode;
- saturation;
- weak inversion.

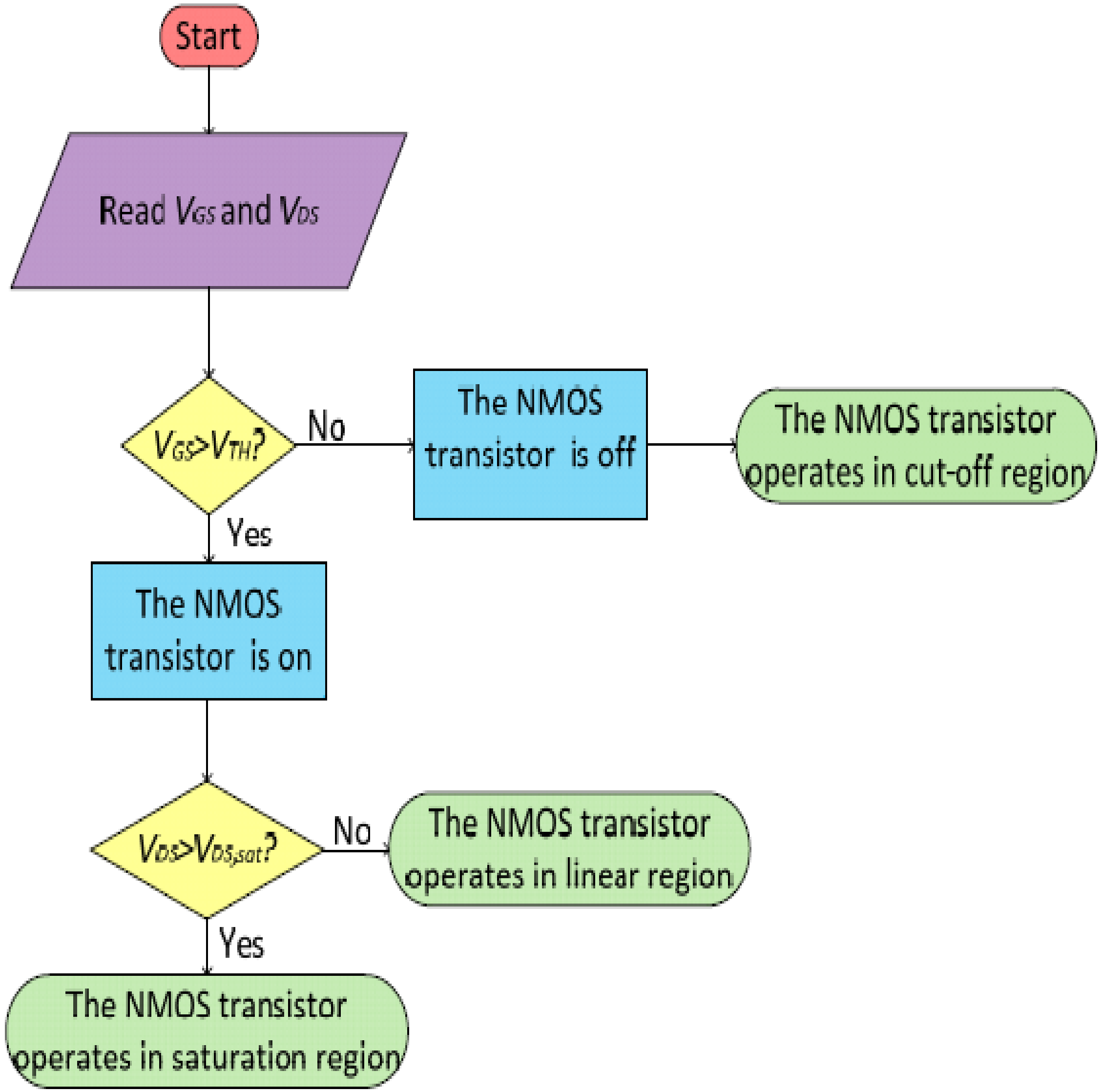
NMOS	PMOS
I_{DS} →	I_{SD}
V_{GS} →	V_{SG}
V_{DS} →	V_{SD}
V_{TH} →	$-V_{TH}$
μ_n →	μ_p

$$\frac{\mu_n}{\mu_p} \cong 2.5$$

As in the PMOS transistor, I_{SD} is due to the drift of holes, the hole mobility, μ_p, has to be considered. The mobility of holes is quite less than electrons,

Therefore, a PMOS transistor has to be larger than a NMOS transistor in the same bias conditions in order to provide the same current.

NMOS transistor



Start

Read V_{GS} and V_{DS}

$V_{GS}>V_{TH}$?

No

The NMOS transistor is off

The NMOS transistor operates in cut-off region

Yes

The NMOS transistor is on

$V_{DS}>V_{DS,sat}$?

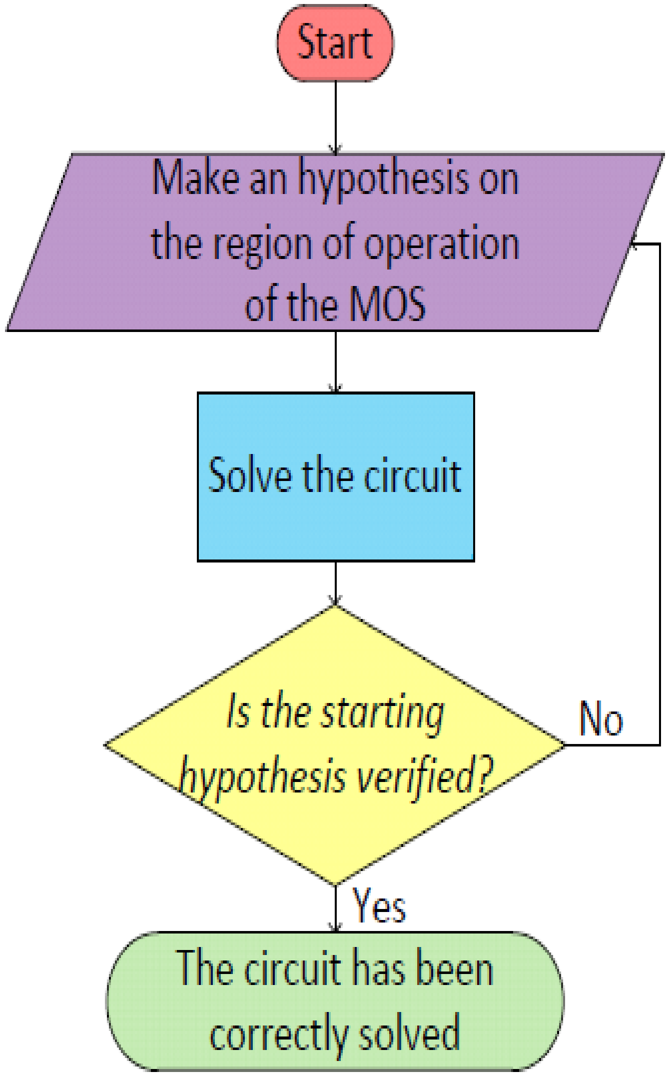
No

The NMOS transistor operates in linear region

Yes

The NMOS transistor operates in saturation region

Algorithm for solving a circuit including a MOS transistor by hand.



Start

Make an hypothesis on the region of operation of the MOS

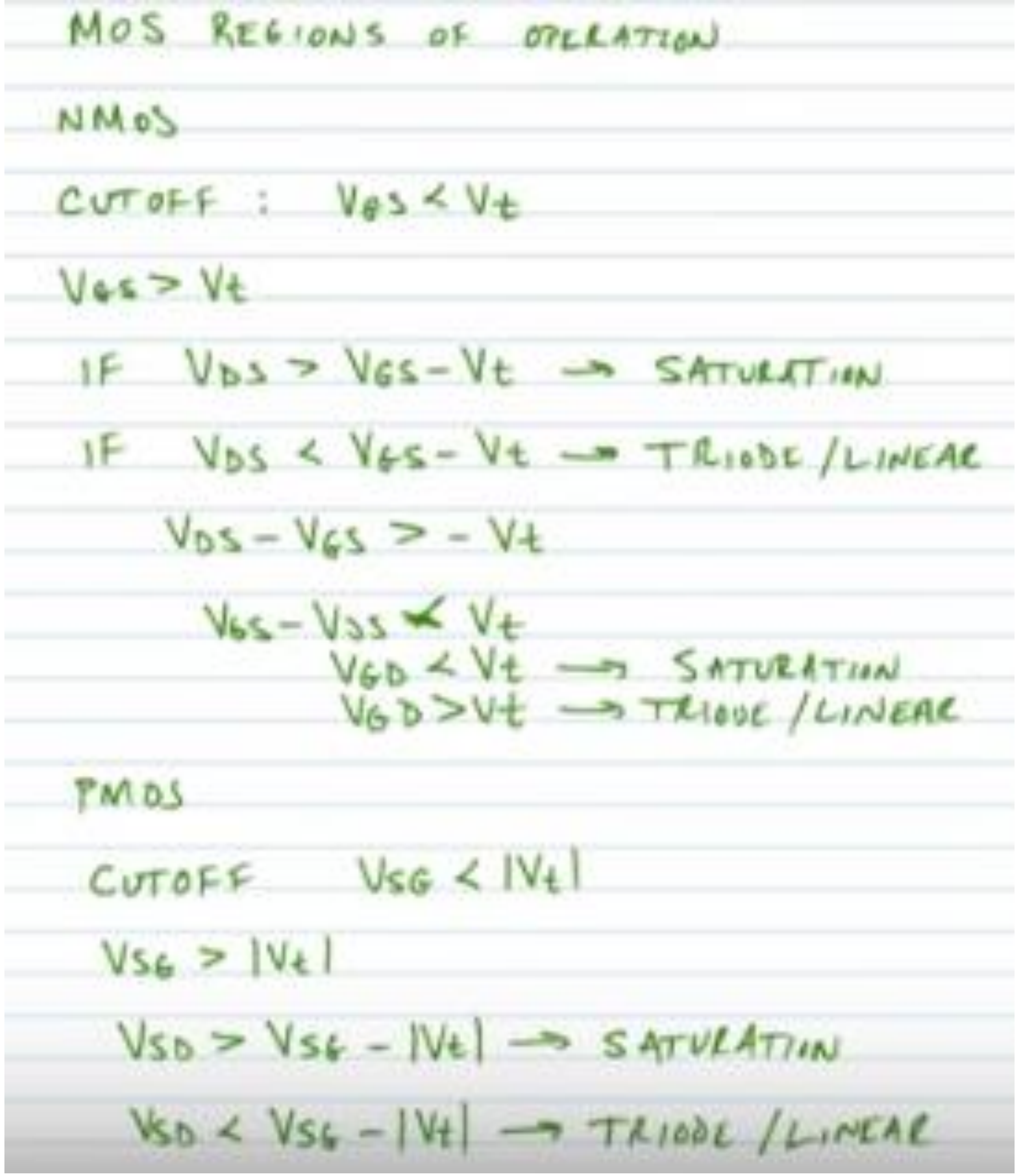
Solve the circuit

Is the starting hypothesis verified?

No

Yes

The circuit has been correctly solved



MOS REGIONS OF OPERATION

NMOS

CUTOFF : $V_{GS} < V_t$

$V_{GS} > V_t$

IF $V_{DS} > V_{GS} - V_t$ → SATURATION

IF $V_{DS} < V_{GS} - V_t$ → TRIODE / LINEAR

$V_{DS} - V_{GS} > - V_t$

$V_{GS} - V_{DS} < V_t$

$V_{GD} < V_t$ → SATURATION

$V_{GD} > V_t$ → TRIODE / LINEAR

PMOS

CUTOFF $V_{SG} < |V_t|$

$V_{SG} > |V_t|$

$V_{SD} > V_{SG} - |V_t|$ → SATURATION

$V_{SD} < V_{SG} - |V_t|$ → TRIODE / LINEAR