ECE 65: Components & Circuits Lab

Lecture 13

Metal Oxide Semiconductor Field Effect Transistor (MOSFET) introduction

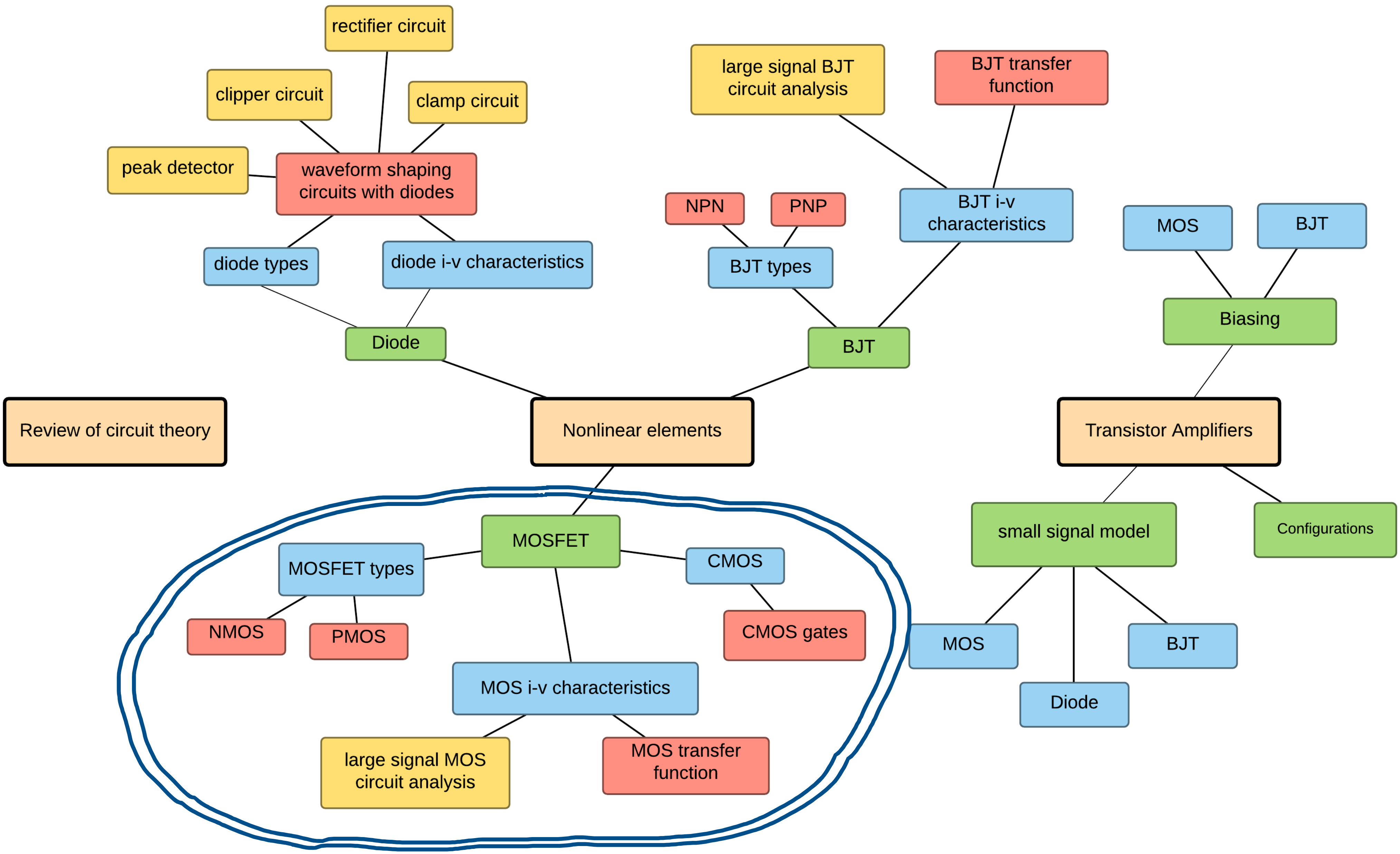
Reference notes: sections 4.1,4.2

Sedra & Smith (7th Ed): sections 5.1-5.3

Saharnaz Baghdadchi

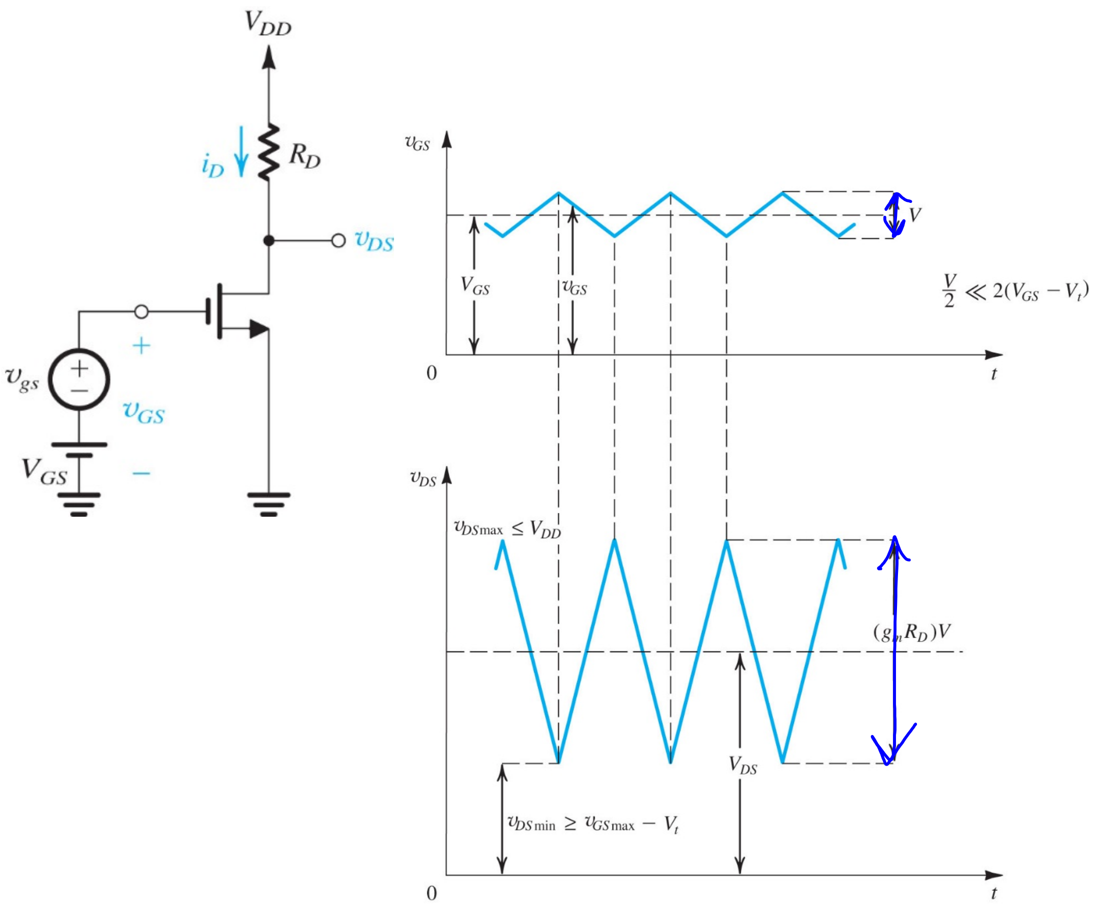
Course map

4. Metal Oxide Semiconductor Field Effect Transistor (MOSFET)

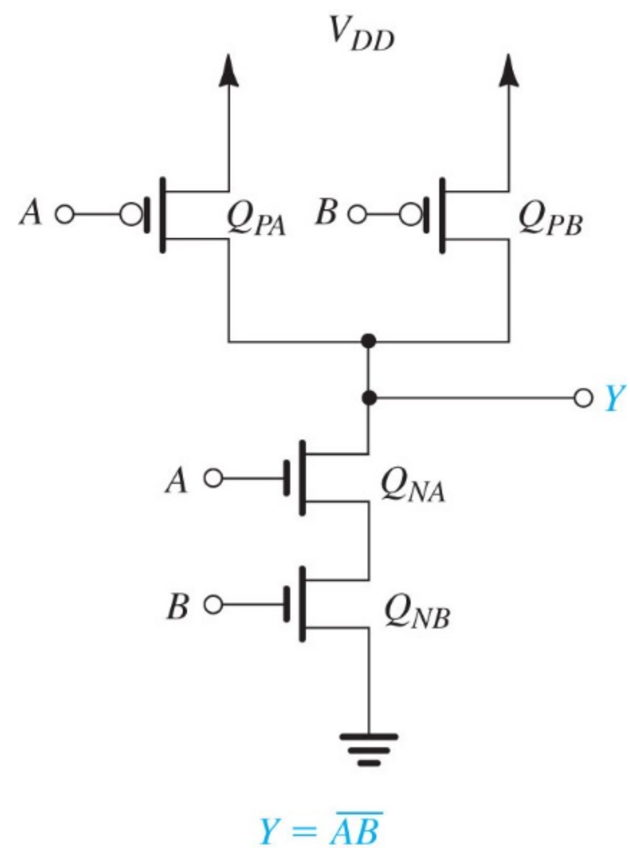


Metal Oxide Semiconductor Field Effect Transistor (MOSFET)

Amplifiers

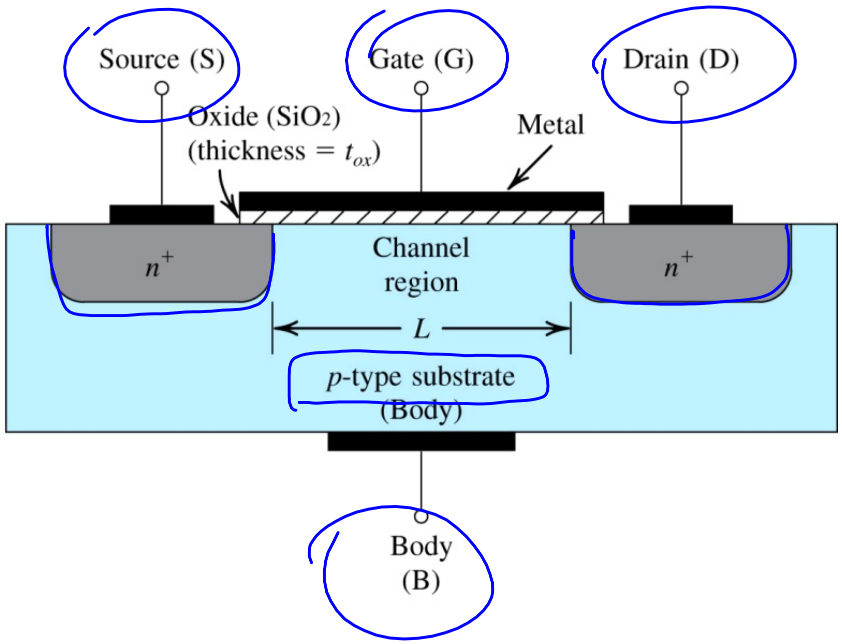


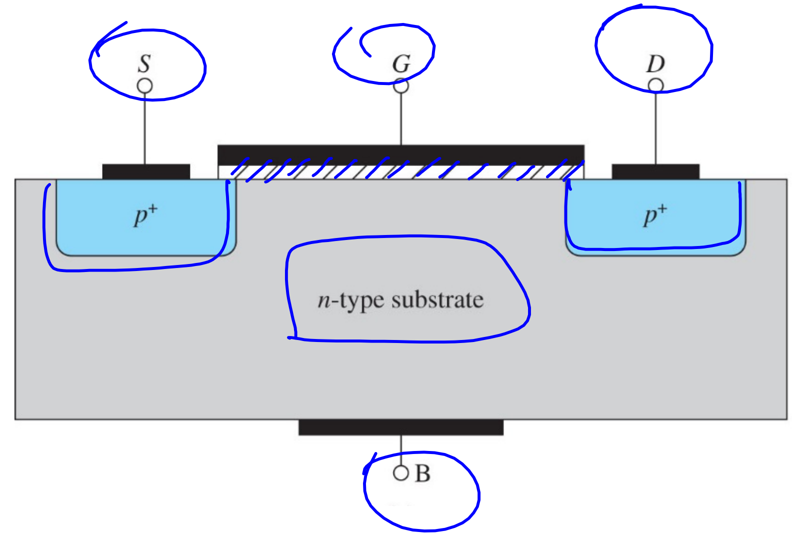
Digital Gates

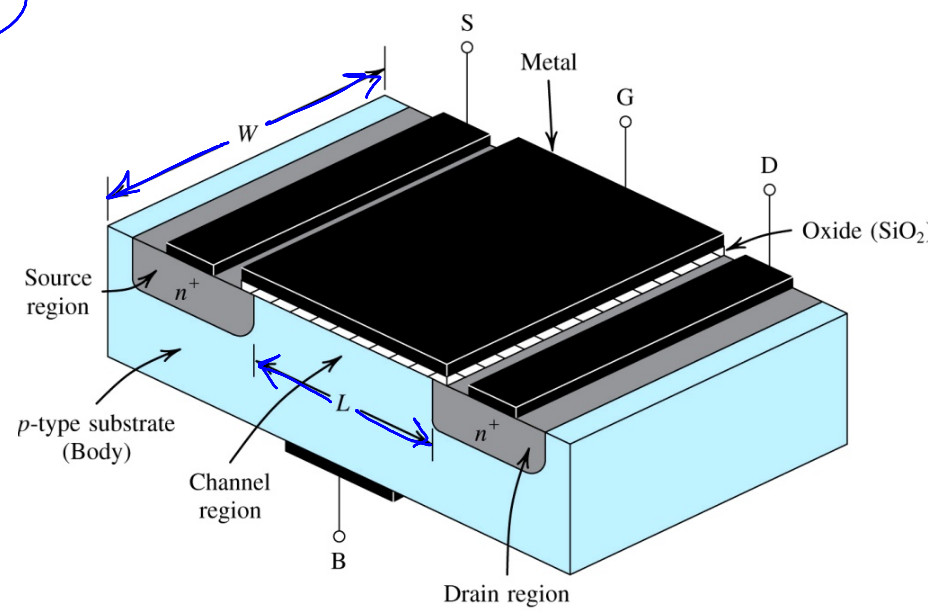


The structure of NMOS and PMOS

The thickness and capacitance of the oxide layer : t_{ox} , C_{ox}







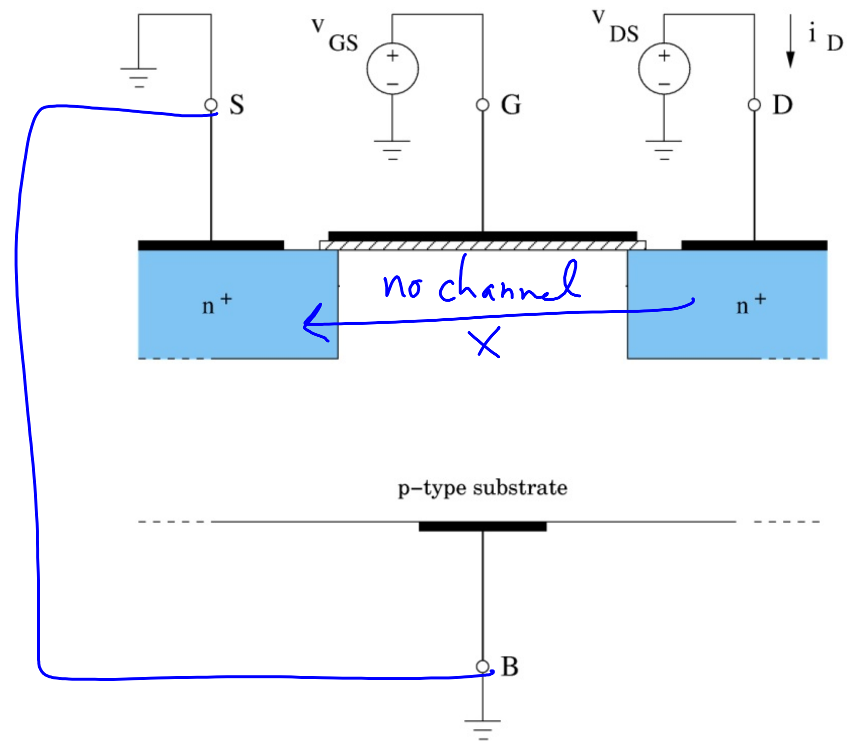
NMOS i-v Characteristics

Cut-off region

<u>No inversion layer</u> $(v_{GS} < V_{tn})$

No current will flow.

In cut-off region, $V_{ov} < 0$.

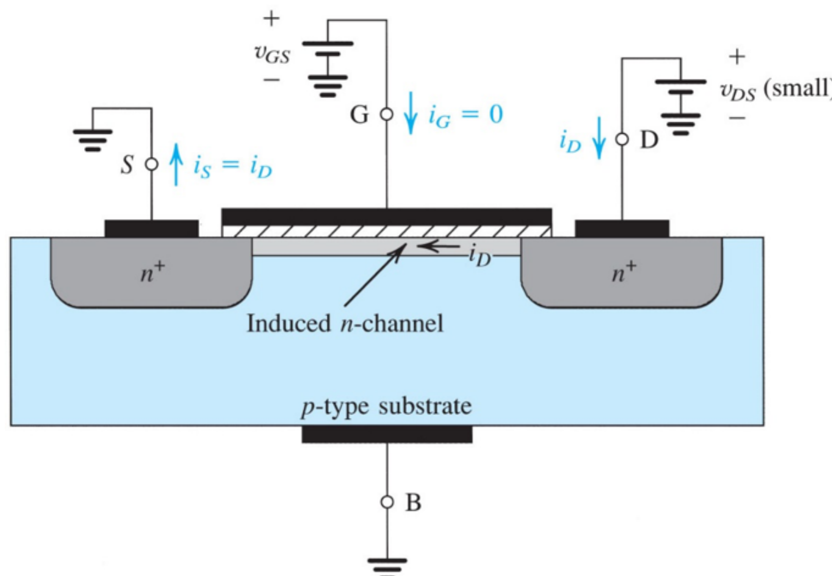


Overdrive Voltage: $V_{OV} = v_{GS} - V_{tn}$

NMOS i-v Characteristics

<u>A channel is formed</u> $(v_{GS} \geq V_{tn})$

If we apply a **<u>small</u>** $\boldsymbol{v_{DS}}$ between drain and source, current will flow in the channel.



$$i_D = \mu_n C_{ox} \frac{W}{L} (v_{GS} - V_{tn})\, v_{DS}$$

$$i_D = \mu_n C_{ox} \frac{W}{L} V_{OV}\, v_{DS}$$

μ_n is the mobility of electrons.

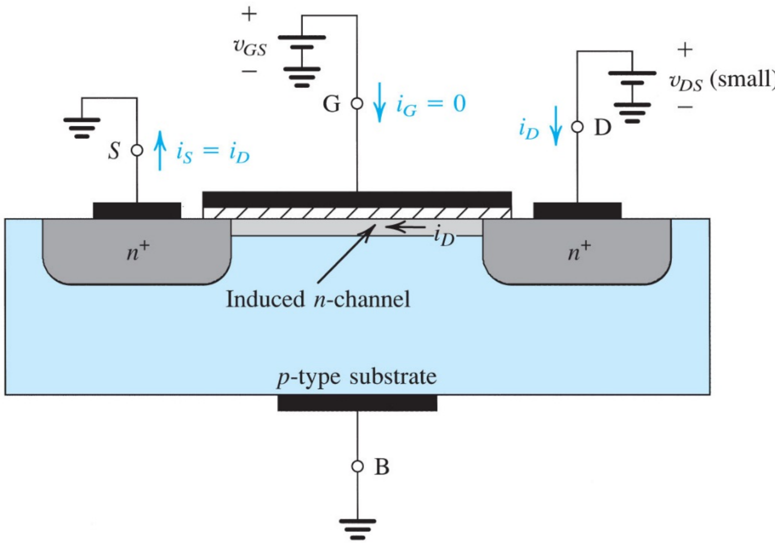
The values of μ_n, C_{ox} , and $\frac{W}{L}$ will be given to you.

NMOS i-v Characteristics

<ins>A channel is formed</ins> $(v_{GS} \geq V_{tn})$

$$i_D = \mu_n C_{ox} \frac{W}{L} (v_{GS} - V_{tn})\, v_{DS}$$

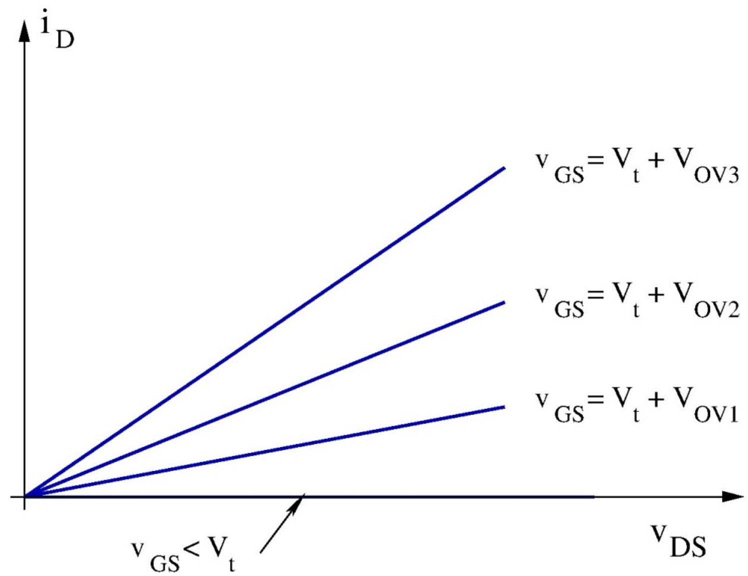
$$i_D = \mu_n C_{ox} \frac{W}{L} V_{OV}\, v_{DS}$$



For **small** v_{DS}, MOSFET acts like a resistor with its conductivity controlled by V_{OV} (or v_{GS}).

$$i_D = g_{DS}\, v_{DS}$$

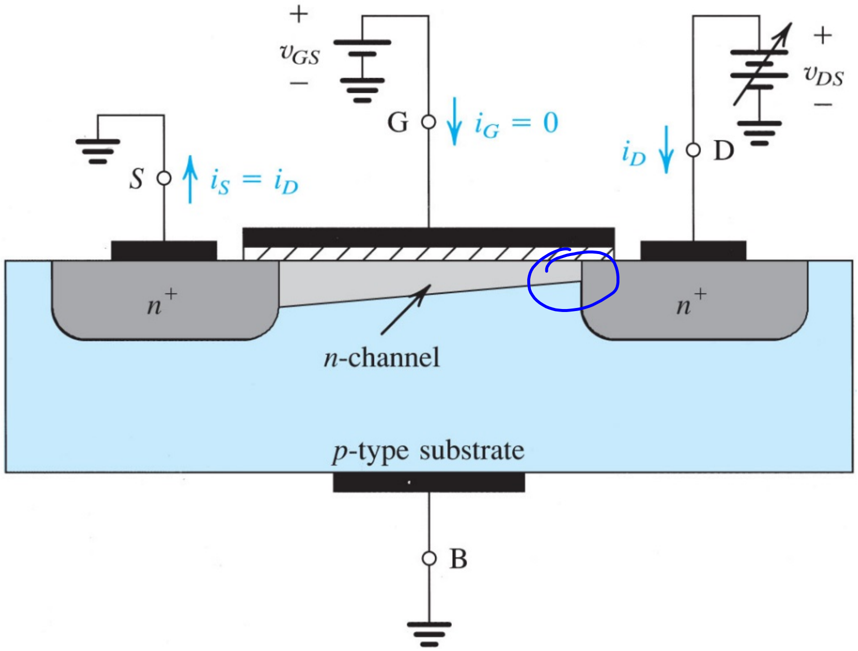
Where $g_{DS} = \mu_n C_{ox} \frac{W}{L} V_{OV}$



NMOS i-v Characteristics

Triode region

As v_{DS} is increased, the channel becomes narrower near the drain.



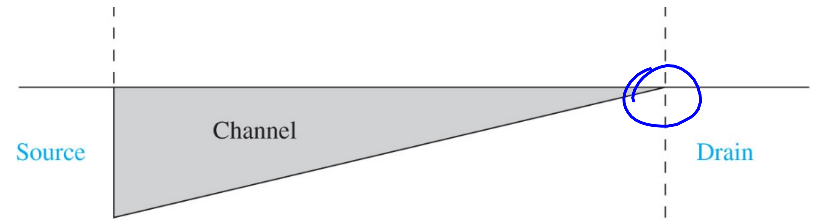
$$\boxed{i_D = \mu_n C_{ox} \frac{W}{L} (V_{OV}\ v_{DS} - 0.5 v_{DS}^2)}$$

For small v_{DS},

$$i_D = \mu_n C_{ox} \frac{W}{L} (V_{OV}\ v_{DS} - 0.5 \cancel{v_{DS}^2}) \approx \underline{\mu_n C_{ox} \frac{W}{L} (v_{GS} - V_{tn})\ v_{DS}}$$

NMOS i-v Characteristics

Saturation region

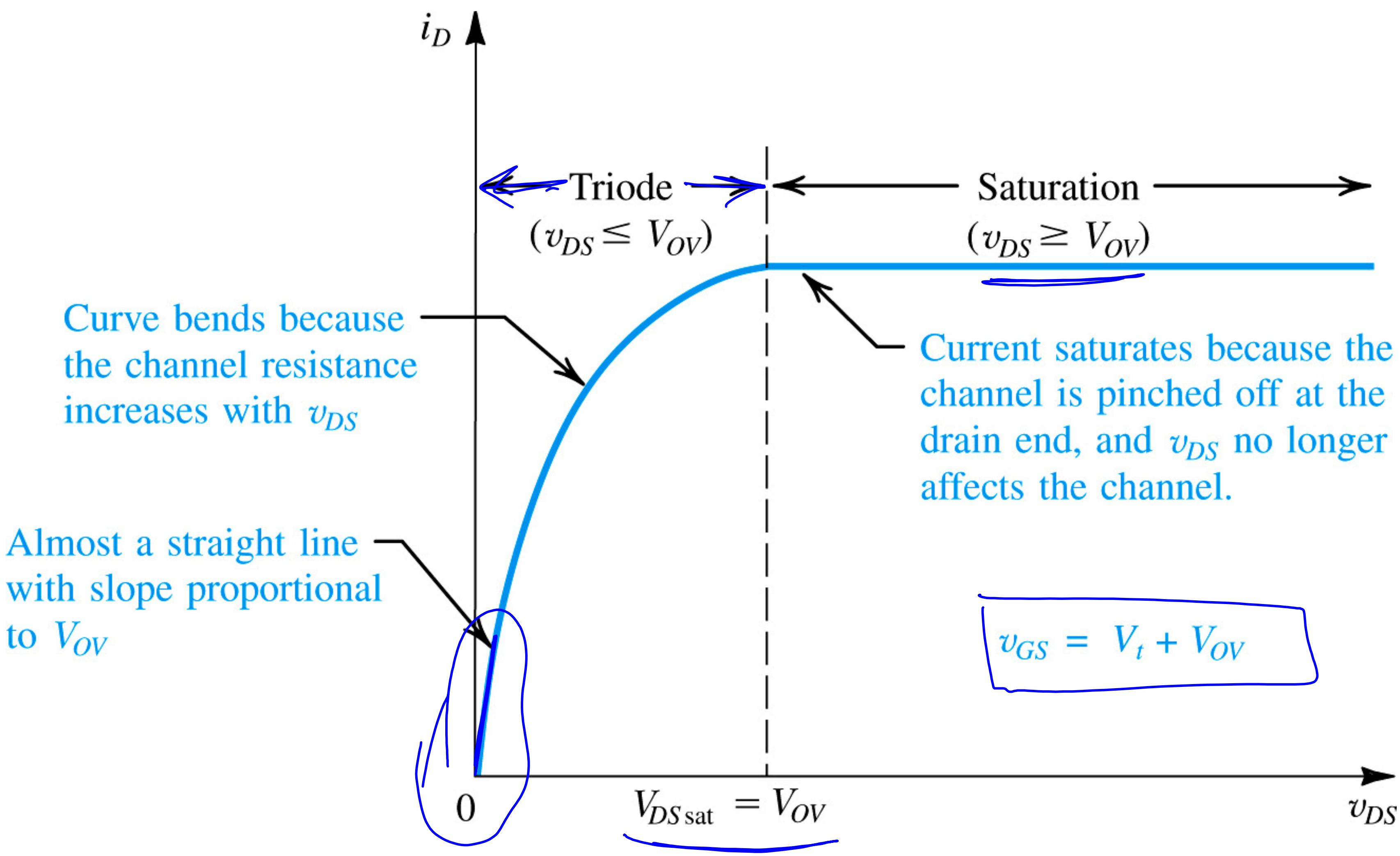


When v_{DS} is increased further such that $v_{DS} = V_{OV}$, the channel depth becomes zero at the drain (Channel “pinched off”).

$$i_D = 0.5\,\mu_n C_{ox} \frac{W}{L} V_{OV}^2$$

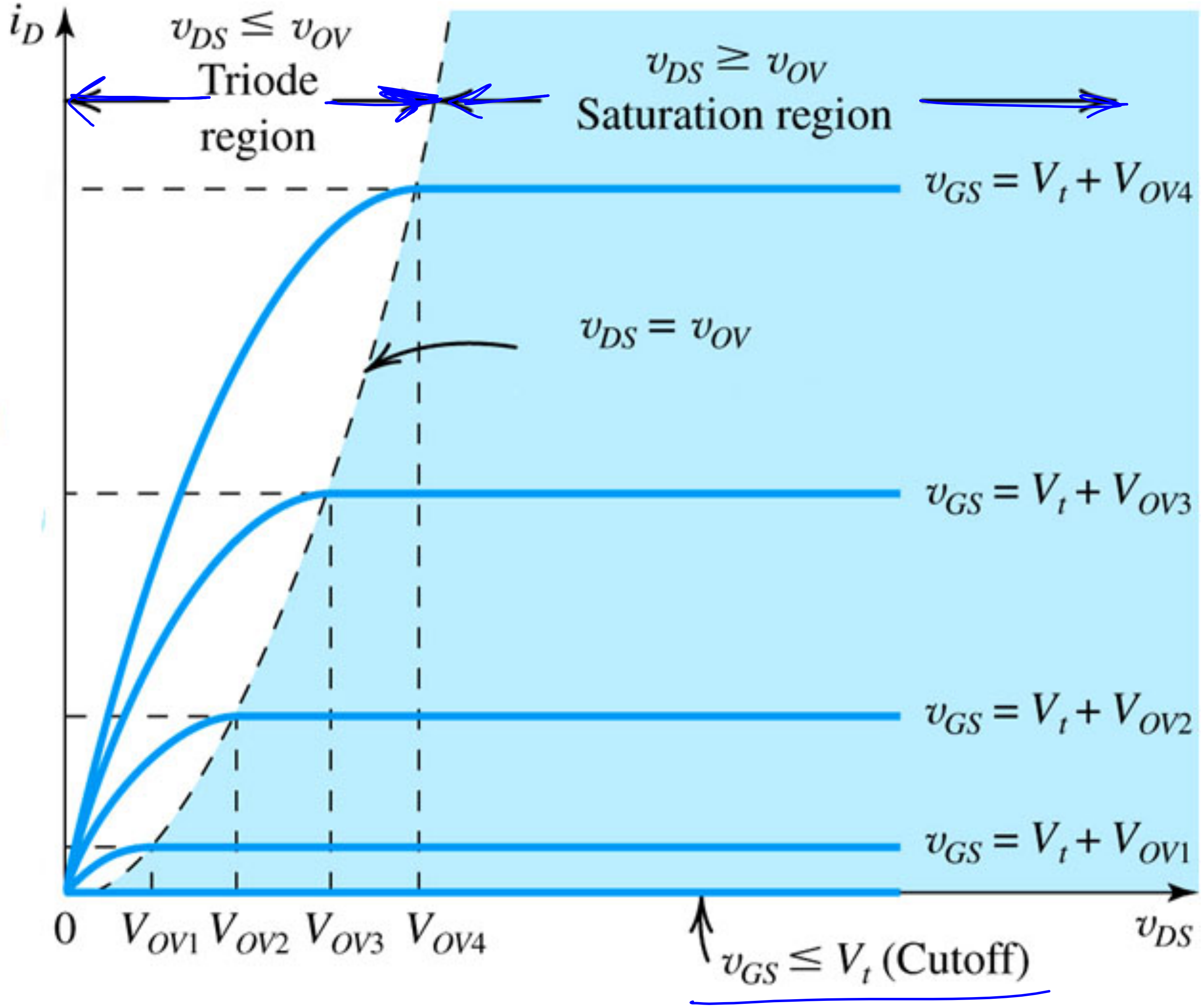
NMOS i–v Characteristics

For a given v_{GS} (or V_{OV})



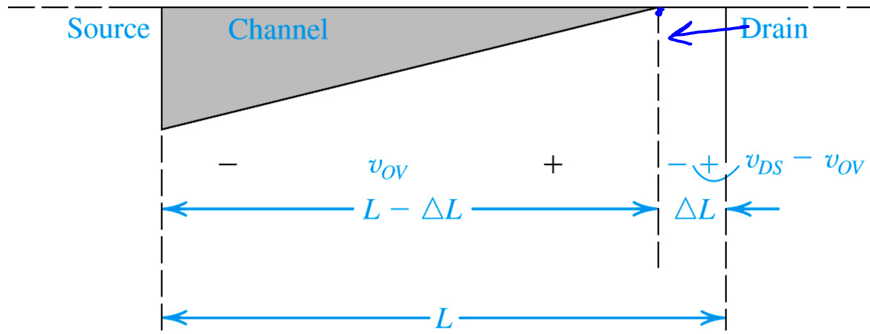
NMOS i-v Characteristics Plot

$v_{DS} = v_{OV}$ the edge of saturation



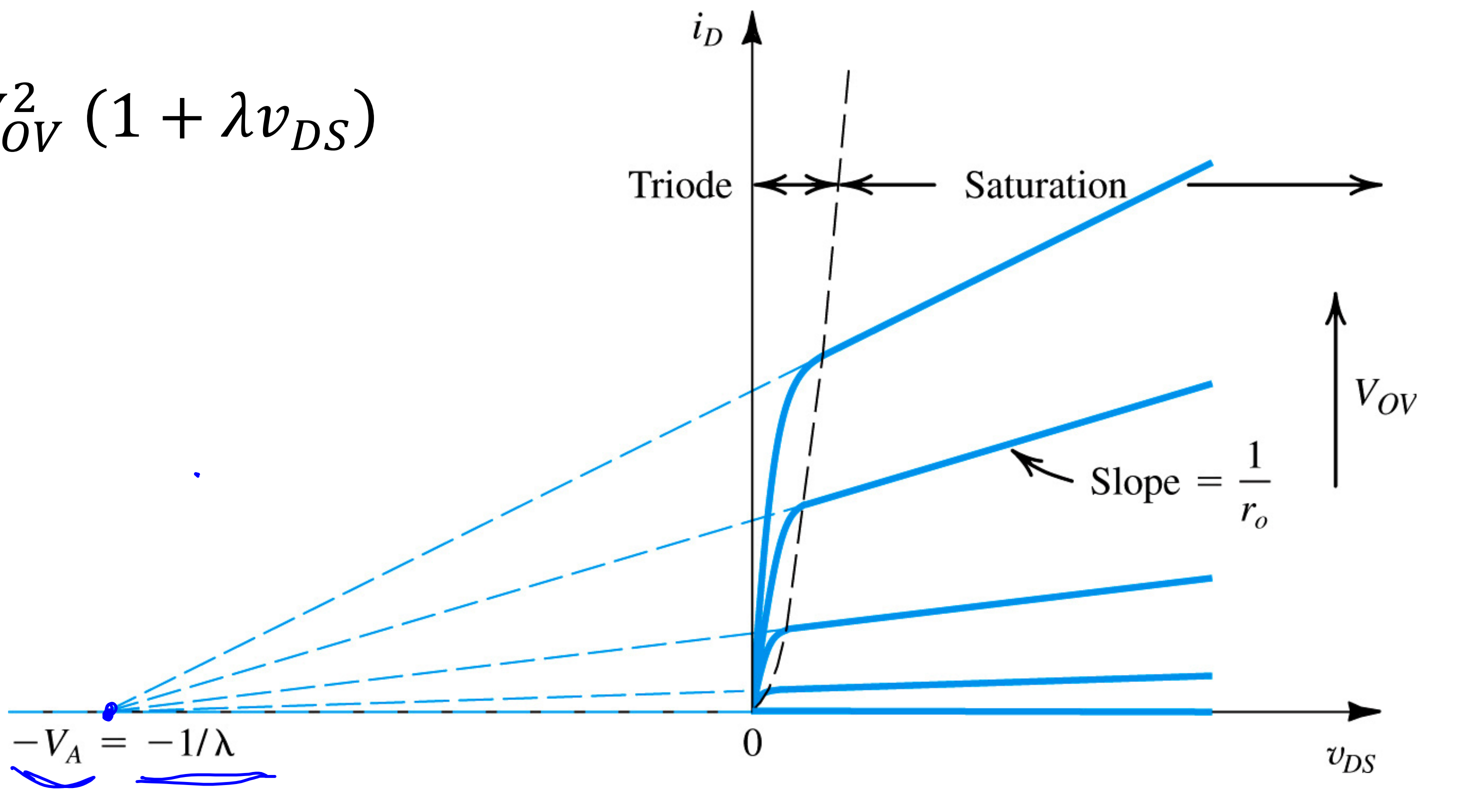
Channel-Length Modulation

As v_{DS} increases beyond V_{OV} , the pinch-off point moves “slightly” away from the drain: <u>Channel- length Modulation</u>

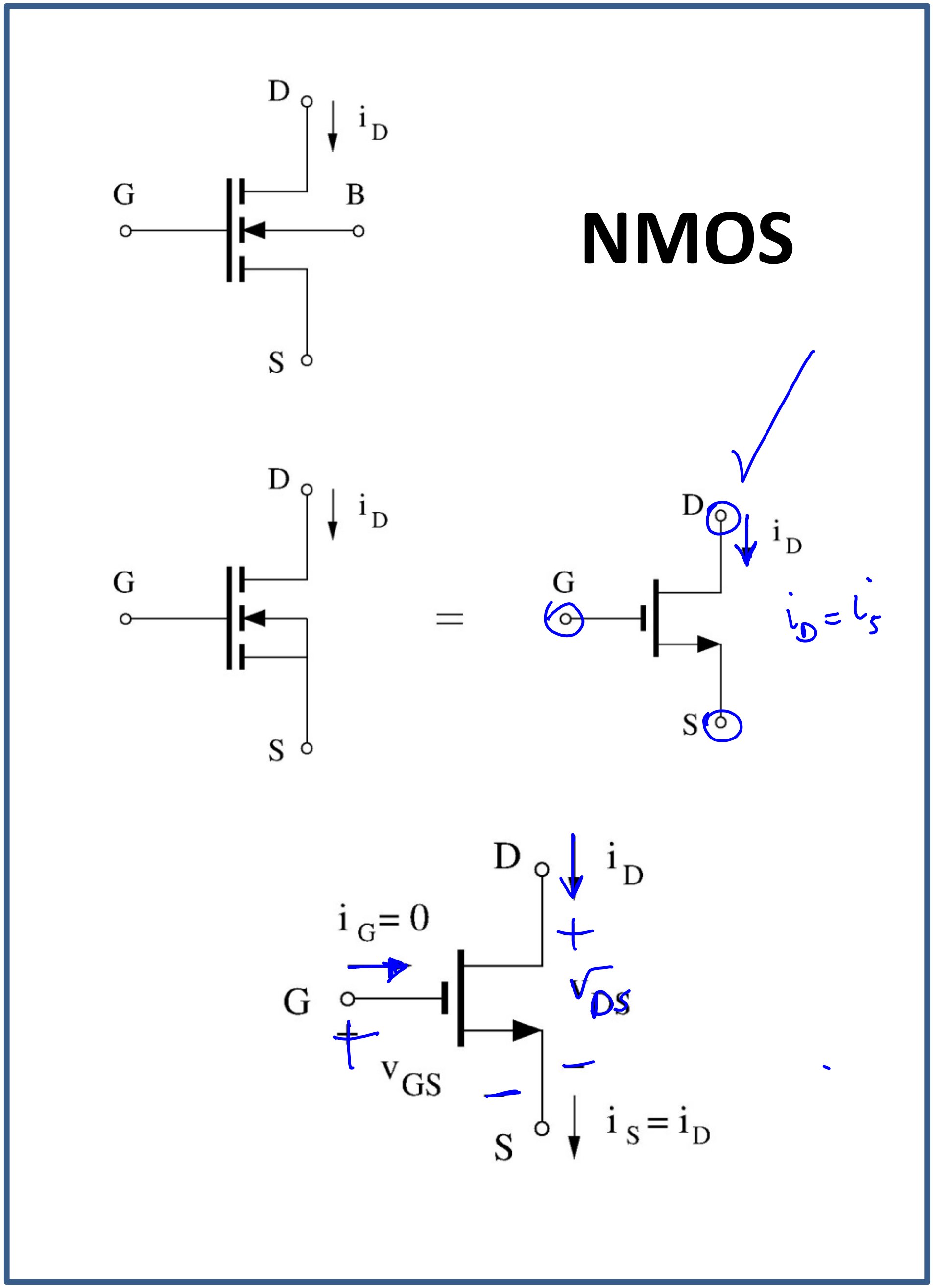


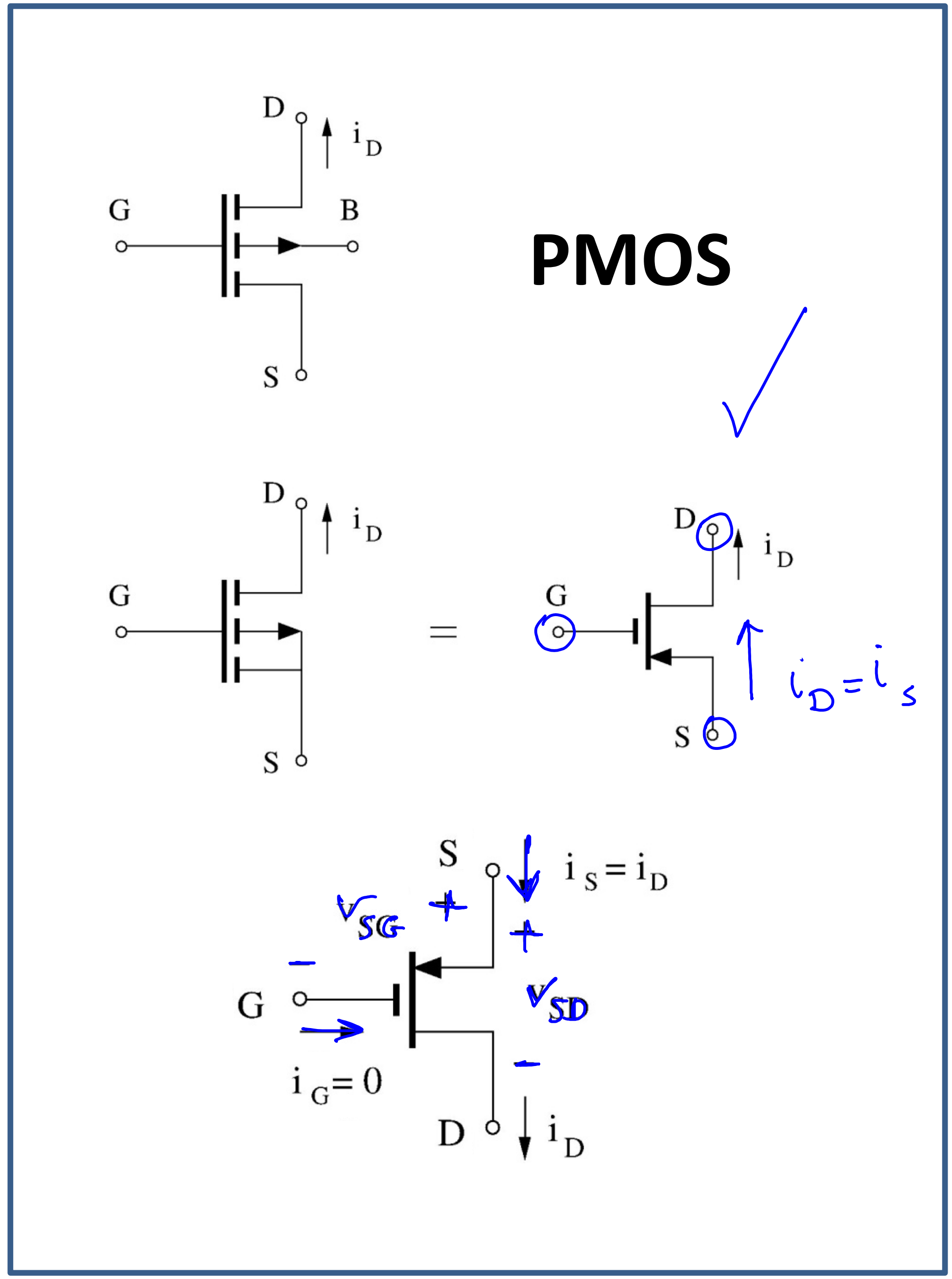
$$i_D = 0.5\,\mu_n C_{ox} \frac{W}{L} V_{OV}^2 \,(1 + \lambda v_{DS})$$

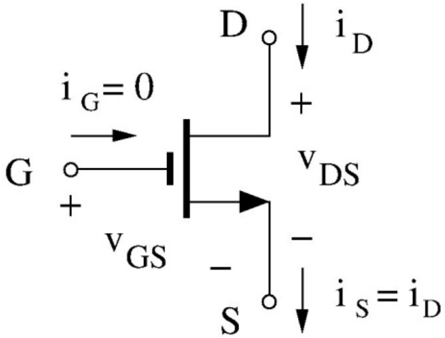
$$\lambda = \frac{1}{V_A}$$



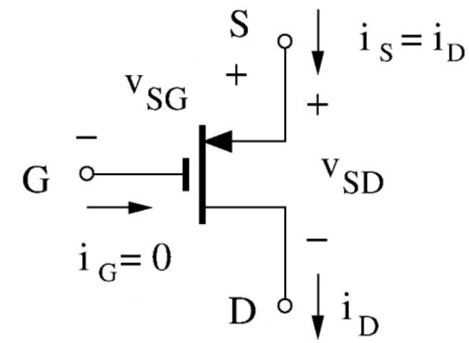
MOS Circuit symbols and conventions







MOS i-v Equations



NMOS $(V_{OV} = v_{GS} - V_{tn})$

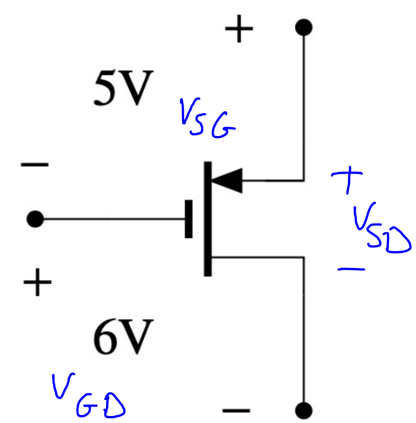
Cut– Off :	$V_{OV} < 0$	$i_D = 0$
Triode :	$V_{OV} \geq 0$ and $v_{DS} \leq V_{OV}$	$i_D = 0.5\, \mu_n C_{ox} \frac{W}{L} (2\, V_{OV} v_{DS} - v_{DS}^2)$
Saturation :	$V_{OV} \geq 0$ and $v_{DS} \geq V_{OV}$	$i_D = 0.5\, \mu_n C_{ox} \frac{W}{L}\, V_{OV}^2\, (1 + \lambda v_{DS})$

PMOS $(V_{OV} = v_{SG} - \lvert V_{tp} \rvert)$

Cut– Off :	$V_{OV} < 0$	$i_D = 0$
Triode :	$V_{OV} \geq 0$ and $v_{SD} \leq V_{OV}$	$i_D = 0.5\, \mu_p C_{ox} \frac{W}{L} (2\, V_{OV} v_{\mathrm{SD}} - v_{SD}^2)$
Saturation :	$V_{OV} \geq 0$ and $v_{SD} \geq V_{OV}$	$i_D = 0.5\, \mu_p C_{ox} \frac{W}{L}\, V_{OV}^2\, (1 + \lambda v_{SD})$

Lecture 13 reading quiz

For the MOSFET below, $v_{SG} = 5V, v_{GD} = 6V,$ $\mu_p C_{ox} \left(\frac{W}{L}\right)_p = 0.7 \frac{mA}{V^2},$ $|V_{tp}| = 2V$. Find the mode of operation of the MOSFET and the drain current i_D.



From the circuit schematic :

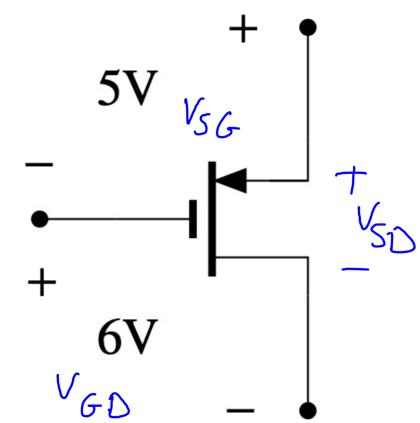
$V_{SG} = 5V$ and $V_{GD} = 6\ V \longrightarrow V_{DG} = -6\ V$

$V_{ov} = V_{SG} - |V_{tp}| = 5 - 2 = 3\ V > 0$

$\Rightarrow$ PMOS is ON

Lecture 13 reading quiz

For the MOSFET below, $v_{SG} = 5V, v_{GD} = 6V,$ $\mu_p C_{ox}\left(\frac{W}{L}\right)_p = 0.7\frac{mA}{V^2},$ $|V_{tp}| = 2V$. Find the mode of operation of the MOSFET and the drain current i_D.



$V_{ov} = 3\ V$

$V_{SD} = V_{SG} - V_{DG}$: $V_S - V_D = (V_S - V_G) - (V_D - V_G)$

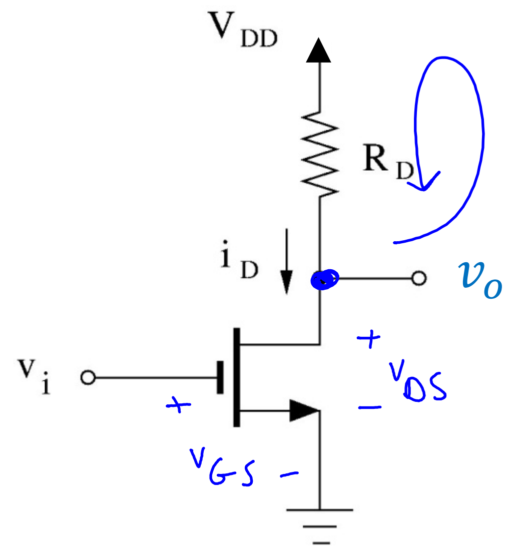
$V_{SD} = 5V - (-6V) = 11V > V_{ov}$

$\Rightarrow$ PMOS is in saturation

$i_D = \frac{1}{2}\mu_p C_{ox}\left(\frac{W}{L}\right)_p V_{ov}^2 = \frac{1}{2} \times 0.7\left(\frac{mA}{V^2}\right) \times 3^2\ (V^2) = 3.15\ mA$

Example.

In the circuit below, $R_D = 1k$, and $V_{DD} = 12\ V$. Find v_o for $v_i = 0$ and $12V$. ($\mu_n C_{ox} \frac{W}{L} = 0.5\ \text{mA}/V^2$, $V_{tn} = 2\ V$, and $\lambda = 0$)



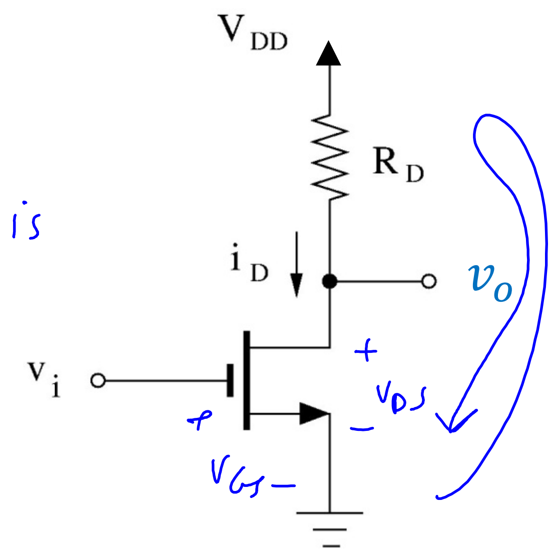
$v_i = 0$

$V_{GS} = 0 \longrightarrow V_{OV} = V_{GS} - V_{tn} = -2V < 0 \longrightarrow$ MOS is in cut-off

$i_D = 0$

$V_D = V_o = V_{DD} - R_D i_D = V_{DD} = 12\ V$

$V_i = 12V$



$V_{GS} = V_i = 12V$

$V_{ov} = V_{GS} - V_{tn} = 12V - 2V = 10V > 0 \longrightarrow$ MOSFET is ON

Assume saturation:

$$i_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} V_{ov}^2 = \frac{1}{2} k_n V_{ov}^2$$

$$i_D = \frac{1}{2} \times 0.5 \left(mA/V^2 \right) \times \left(10 \, (V) \right)^2 = 25 \, mA$$

DS KVL: $V_{DD} = R_D \times i_D + V_{DS} \longrightarrow 12V = 1k\Omega \times 25mA + V_{DS}$

$\longrightarrow V_{DS} = -13V < V_{DD}$

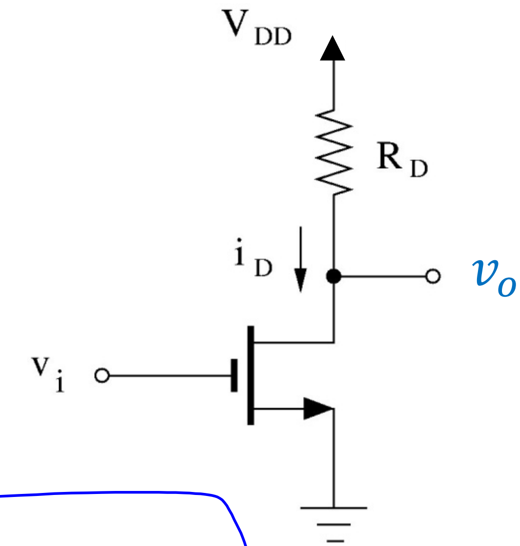
assumption was not correct.

MOSFET is in triode: $V_{DS} < V_{ov}$, $V_{ov} > 0$

$$i_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} \left(2 V_{ov} V_{DS} - V_{DS}^2 \right)$$

$$① \quad i_D\,(mA) = \frac{1}{2} \times 0.5 \times (20\,V_{DS} - V_{DS}^2)$$

$$② \quad i_D\,(mA) = \frac{12V - V_{DS}}{1\,(k\Omega)}$$



$$12(V) - V_{DS} = 5\,V_{DS} - 0.25\,V_{DS}^2$$

$$\rightarrow V_{DS}^2 - 24\,V_{DS} + 48 = 0$$

$$ax^2 + bx + c = 0$$

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$V_{DS} = \begin{cases} 2.2\,(V) \checkmark \\ 21.8\,(V) > V_{DD} \times \end{cases}$$

$$V_{DS} = 2.2\ V < V_{ov}$$

$$V_o = V_{DS} = 2.2\,V \quad , \quad i_D = 9.8\,mA$$