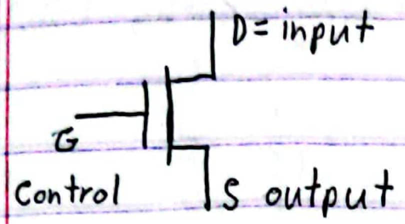
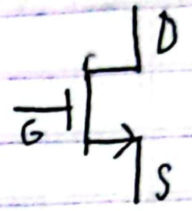
MOSFET Device:



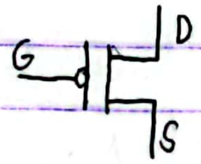
Digital Circuit

G = Gate
D = Drain
S = Source

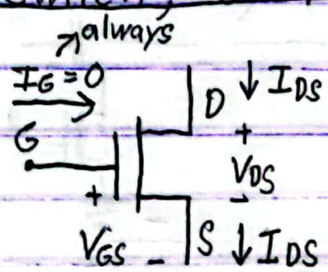


Analog Circuit

* It is a transistor.
* The Above type of MOSFET are called NMOS.
* Another type of MOSFET is PMOS. It's figure,



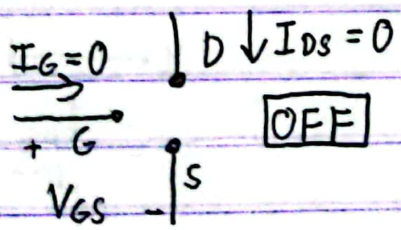
The Switch, S-Model:



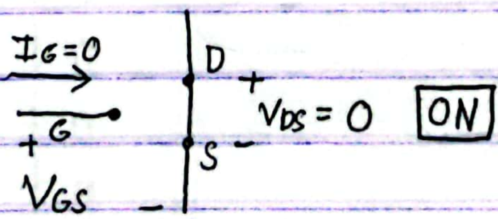
$V_{DS} = V_D - V_S$

$V_{GS} = V_G - V_S$

$V_{GS} < V_T$

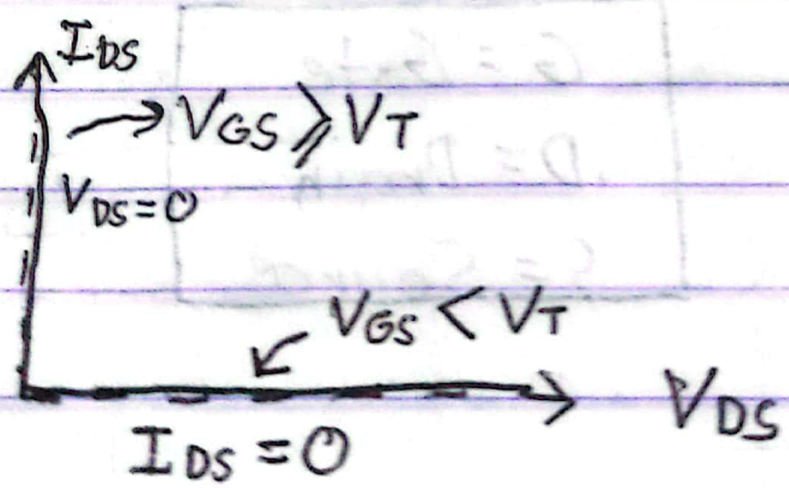


$V_{GS} \geq V_T$



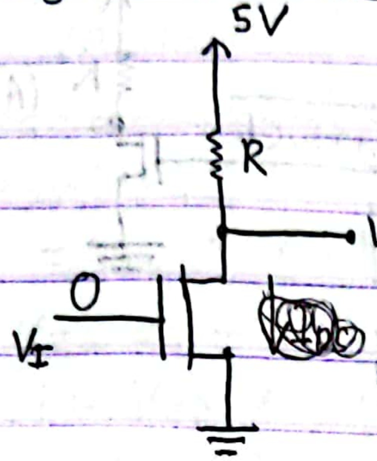
* V_T = Threshold Voltage = 0.5 − 1 V

* If $V_{GS} < V_T$ then $I_{DS} = 0$ (Open Circuit)
* " $V_{GS} \geq V_T$ " $V_{DS} = 0$ (Short ")



MOSFET logic gates [$V_T \sim 1V$]:

① NOT gate / Inverter:

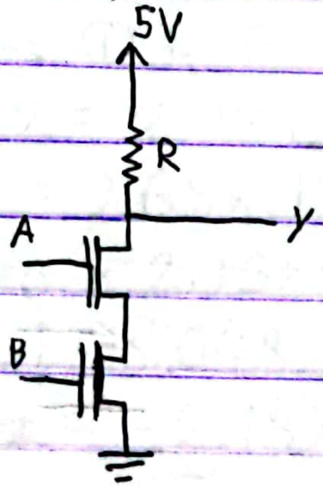


V_I	I	V_o	O
0V	0	5V	1
5V	1	0V	0

$V_{GS} \geq V_T \rightarrow$ S.C

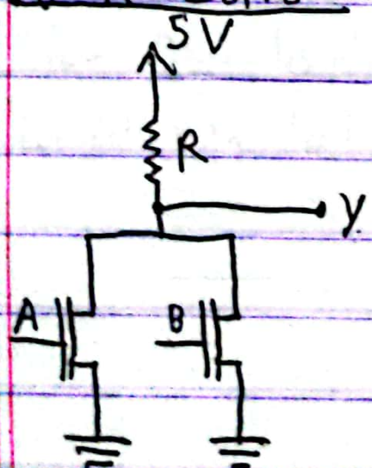
$V_{GS} < V_T \rightarrow$ O.C

② NAND Gate:



A	B	$y = \overline{AB}$
0	0	1
0	1	1
1	0	1
1	1	0

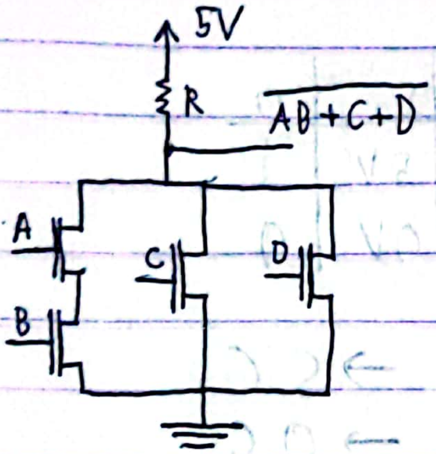
③ NOR Gate:



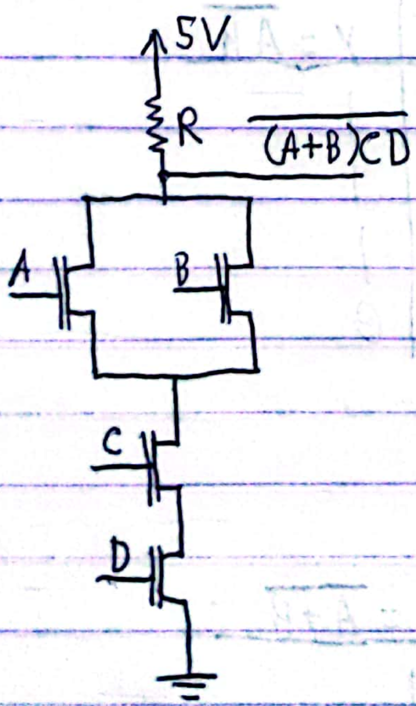
A	B	$y = \overline{A+B}$
0	0	1
0	1	0
1	0	0
1	1	0

Example:

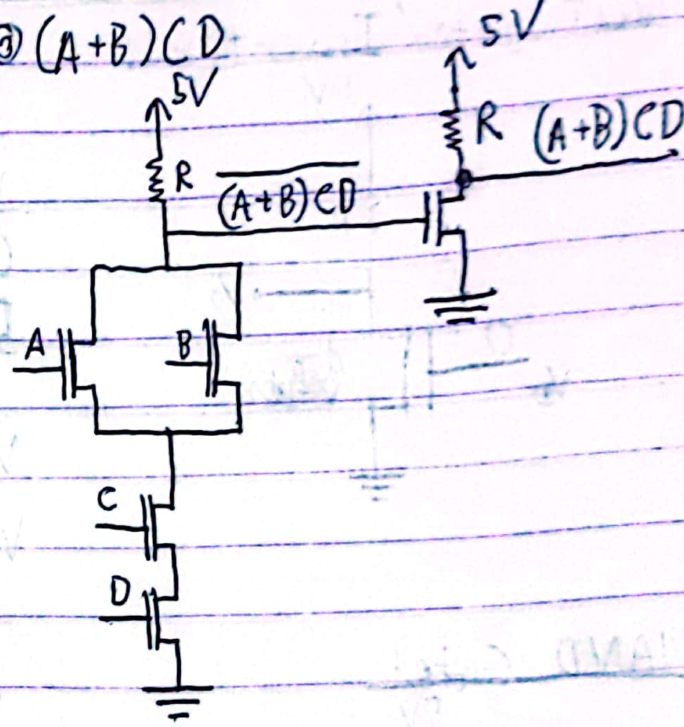
① $\overline{AB + C + D}$



② ~~AB + C~~ $\overline{(A+B)CD}$

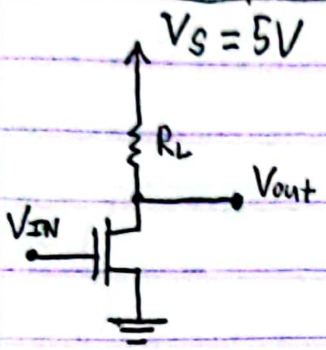


③ $(A+B)CD$



Static analysis:

* MOSFET Inverter (S-model):

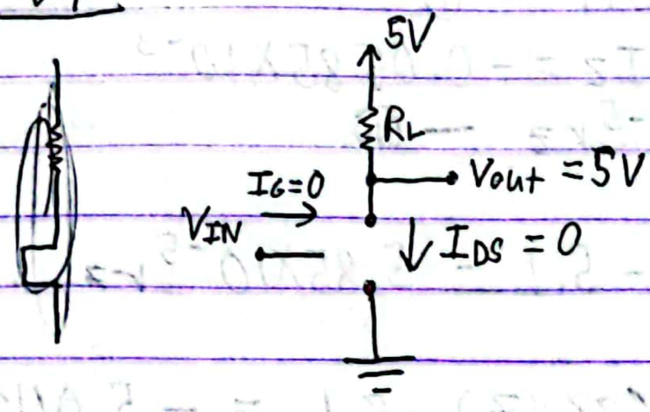


here $V_{IN} = V_{GS}$

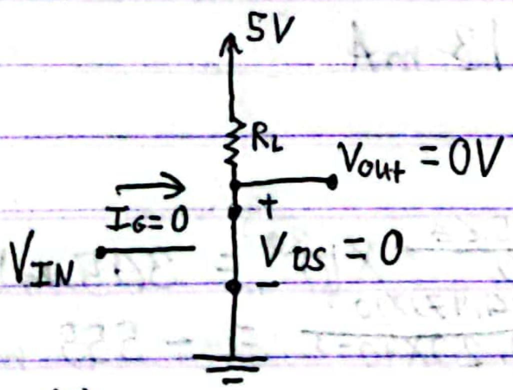
assume $V_T = 1V$ and $V_S = 5V$

$V_{GS} = V_G - V_S = V_G$

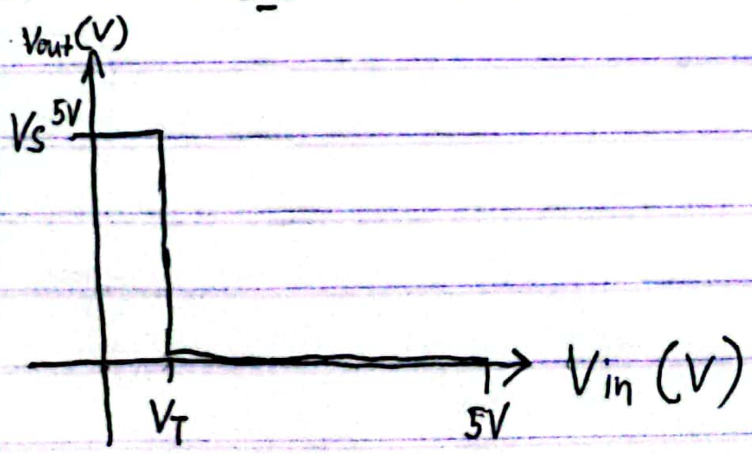
* $V_{IN} < V_T$:



* $V_{IN} \geq V_T$:



*



* **Specification - 1:**

$V_{OH} = 4.5\,V$, $V_{OL} = 0.5\,V$, $V_{IH} = 4\,V$, $V_{IL} = 0.9\,V$

a) Is $V_{OL} < V_{IL}$, $V_{OH} > V_{IH}$
b) Valid input $\longrightarrow$ Valid output

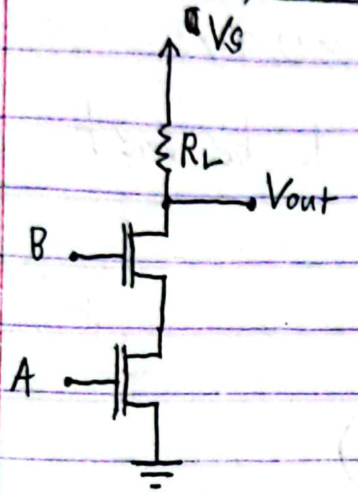
} Conditions to be met

For an inverter,

Input		Output
Valid 0 $(V_i \leq V_{IL})$	$\longrightarrow$	Valid 1 $(V_o \geq V_{OH})$
" 1 $(V_i \geq V_{IH})$	$\longrightarrow$	" 0 $(V_o \leq V_{OL})$

* This specification follows static discipline.
* We cannot change the MOSFET Inverter, we are stuck with what we are given.

Static Analysis of ~~Mo~~ MOSFET NAND (S-model):



A	B	Out
0	0	1
0	1	1
1	0	1
1	1	0

* We can draw the transfer Characteristics graph by considering one input as constant, Like when $A = 0$ or $A = 1$.

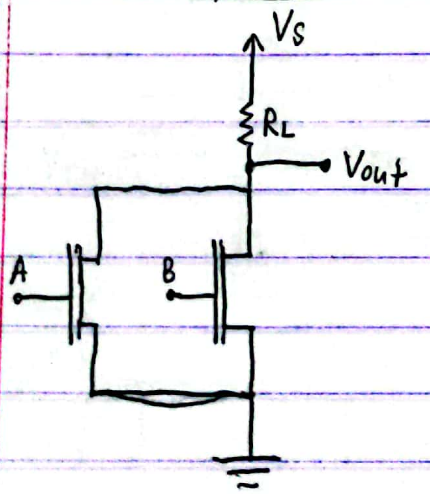
* When $A = 0$,

B	Out
0	1
1	1

When $A = 1$,

B	Out
0	1
1	0

State Analysis of ~~Mos~~ MOSFET NOR (S-model):



A	B	Out
0	0	1
0	1	0
1	0	0
1	1	0

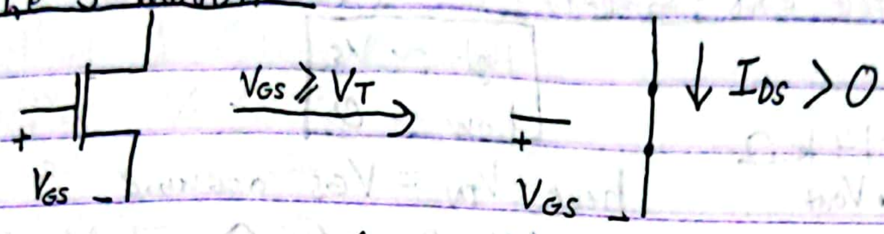
When $A = 0$,

B	Out
0	1
1	0

When $A = 1$,

B	Out
0	0
1	0

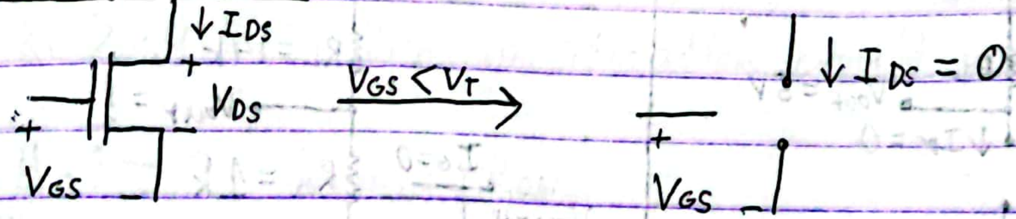
The S-model:

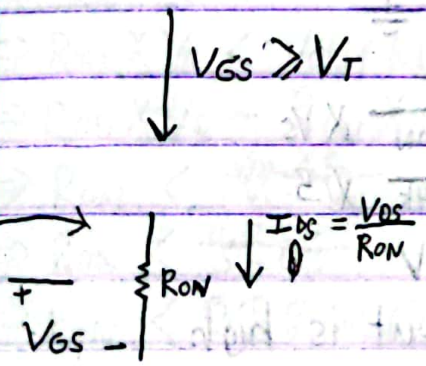


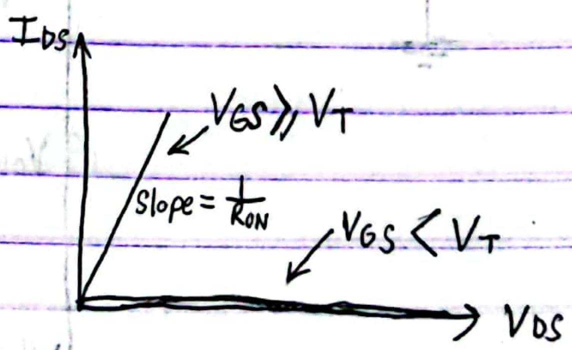
S-Model, ON mode

* But Material (Si) has non-zero resistance.

The SR-Model:



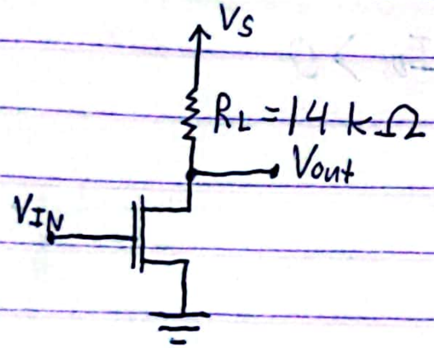




* $R_{ON} = \frac{1}{k_n \frac{W}{L}(V_{GS} - V_T)}$ W, L = Length and Width of the MOSFET
* V_{GS} has 2 values V_{GS} = Low and V_{GS} = High. Use V_{GS} = High for calculating R_{ON}.

This is true only if $V_{DS} \ll V_{GS} - V_T$ (very smaller) and if ~~$V_{GS} > V_T$~~ it is $V_{DS} > V_{GS} - V_T$ then it would act like a current source.

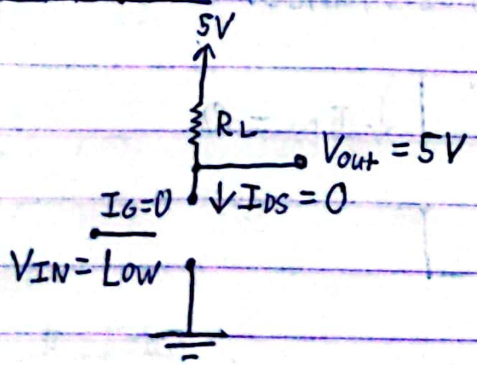
MOSFET Inverter (SR-model):



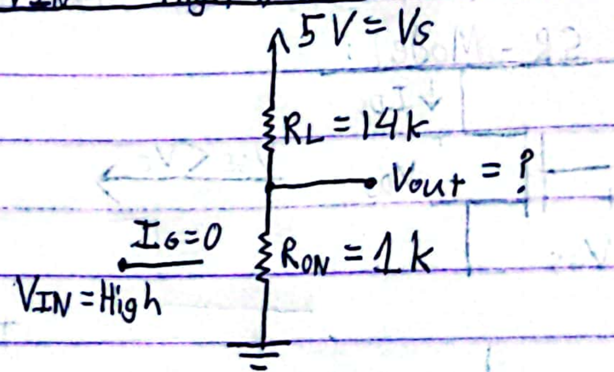
$\boxed{\begin{array}{l} \text{High} \sim V_S \\ \text{Low} \sim 0 \end{array}}$

here $V_{IN} = V_{GS}$ assume
$V_T = 1V$, $R_{ON} = 1\,k\Omega$ and $V_S = 5V$

* $V_{In} \overset{\text{Low}}{=} < V_T$



$V_{IN} = \text{High} > V_T$



$$V_{out} = \frac{R_{ON}}{R_L + R_{ON}} \times V_S$$
$$= \frac{1k}{1k + 14k} \times 5$$
$$= 0.33V$$

When the input is high,
$\underbrace{\frac{R_{ON}}{R_L + R_{ON}} \times V_S}_{V_{out}} < V_T$ must be maintained.

To make a specification work we can : $\frac{R_{ON}}{R_{ON}+R_L} \times V_S < V_{OL}$

* **Method - 1 : Change R_L**

$$\frac{R_{ON}}{R_{ON}+R_L} \times V_S < V_{OL}$$

$$\Rightarrow \frac{R_{ON}}{R_{ON}+R_L} < \frac{V_{OL}}{V_S}$$

$$\Rightarrow \frac{R_L+R_{ON}}{R_{ON}} > \frac{V_S}{V_{OL}}$$

$$\Rightarrow R_L + R_{ON} > \frac{V_S}{V_{OL}} R_{ON}$$

$$\Rightarrow \boxed{R_L > \frac{V_S \times R_{ON}}{V_{OL}} - R_{ON}}$$

$$\Rightarrow R_L > \frac{5 \times 1}{0.2} - 1$$

$\Rightarrow R_L > 24\ k\Omega$ then specification would work.

* **Method - 2 : Change R_{ON}**

$$\frac{R_{ON}}{R_L+R_{ON}} \times V_S < V_{OL}$$

$$\Rightarrow R_{ON} \times V_S < V_{OL}(R_L + R_{ON})$$

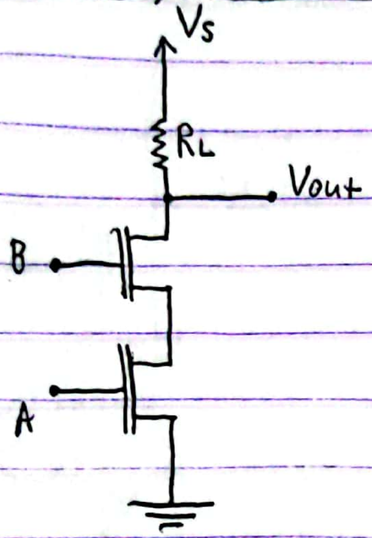
$$\Rightarrow R_{ON} \times V_S - R_{ON} \times V_{OL} < V_{OL} \times R_L$$

$$\Rightarrow R_{ON} < \frac{V_{OL} \times R_L}{V_S - V_{OL}}$$

$$\Rightarrow R_{ON} < \frac{0.2 \times 14}{5 - 0.2}$$

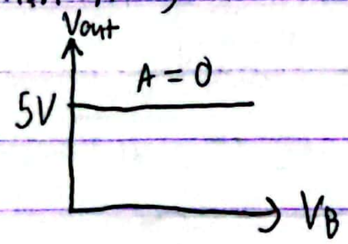
$$\Rightarrow R_{ON} < 0.58\ k\Omega$$

Static Analysis of MOSFET NAND (SR-Model):

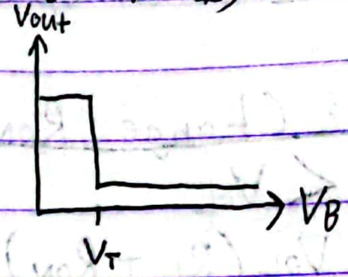


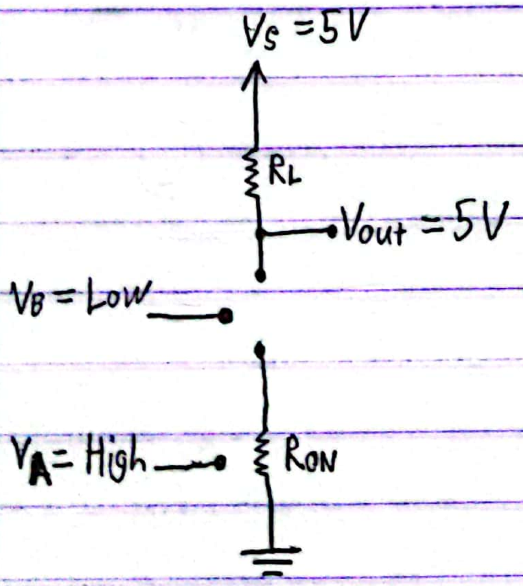
A	B	Out
0	0	1
0	1	1
1	0	1
1	1	0

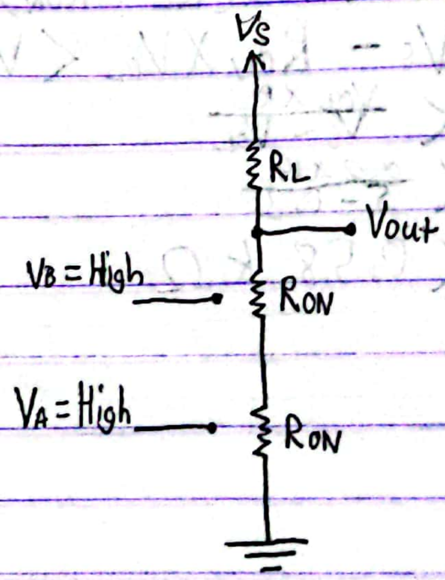
* When $A=0$,



When $A=1$,



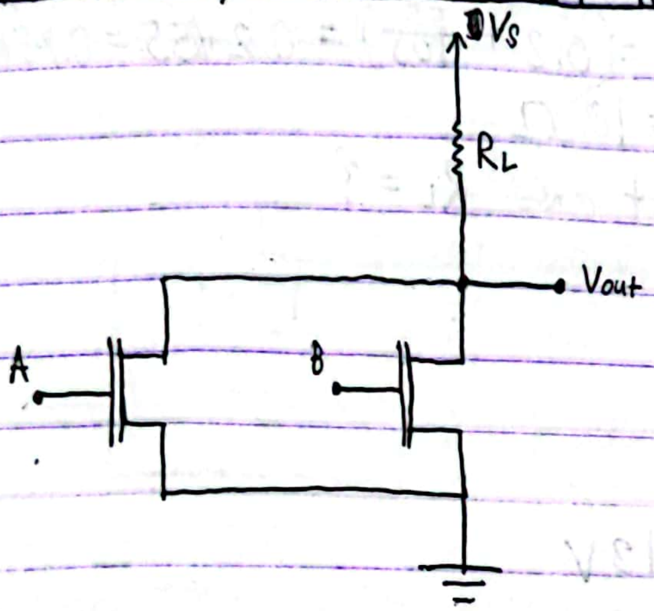




$$R'_{ON} = 2R_{ON}$$

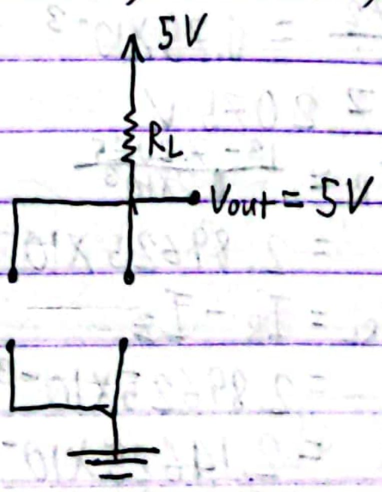
$$V_{out} = \frac{R'_{ON}}{R'_{ON} + R_L} \times V_s$$

Static Analysis of MOSFET NOR (SR-model):



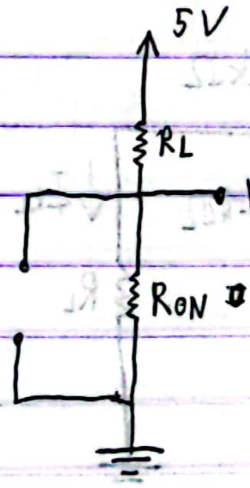
A	B	Out
0	0	1
0	1	0
1	0	0
1	1	0

* When A = Low, B = Low,



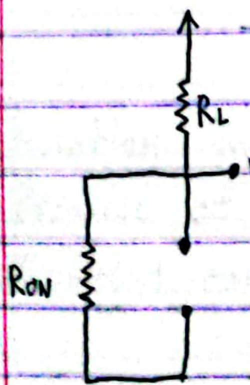
$V_{out} = 5V$

* When A = Low, B = high,



$V_{out} = \frac{R_{ON}}{R_L + R_{ON}} \times V_S$

* When A = High, B = Low



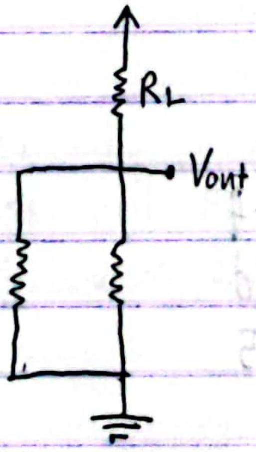
$V_{out} = \frac{R_{ON}}{R_{ON} + R_L} \times V_S$

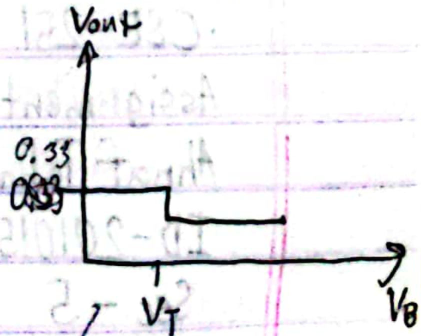
$= 0.33$

When A = high, B = high,

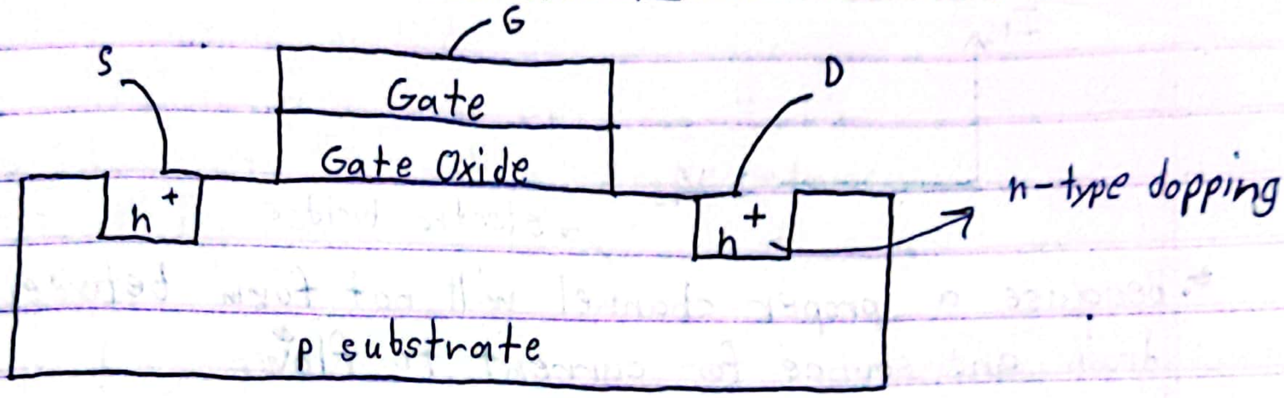
$R'_{ON} = \frac{R_{ON}}{2}$

$V_{out} = \frac{R'_{ON}}{R_L + R'_{ON}} \times V_S$





Internal Structure of MOSFET:

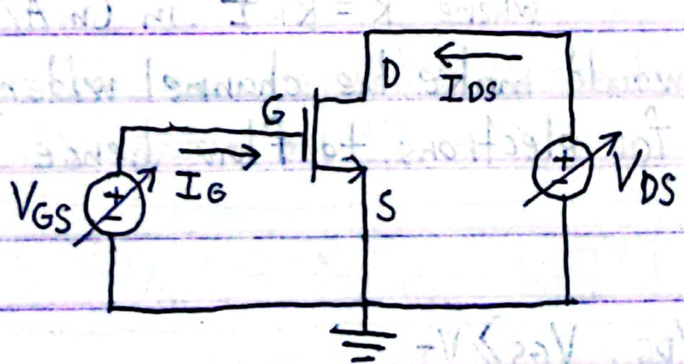


n-type → majority electrons with some holes.
p-type → " holes with " electrons.

* NMOS is made from p-type substrate as a base.

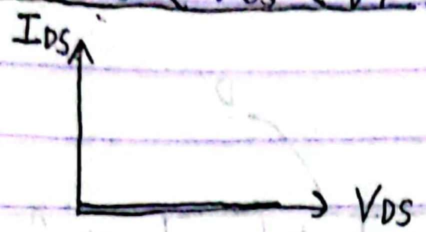
W-10 (L-15) (V-2)

Operation of a MOSFET:



* Relation among V_{GS}, V_{DS} and I_{DS}
* Because of the oxide layer I_{GS} will be always zero.
* Current can never flow from Source to Drain.

* Case-1: $0 < V_{GS} < V_T$



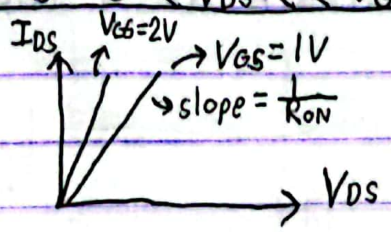
- Because a proper channel will not form between drain and source for current to flow.

electro bridge

* Case-2: $V_{DS} = 0V$, $V_{GS} \geq V_T$

- Channel will be created for current to flow.

* Case-3: $0 < V_{DS} << V_{GS} - V_T$, $V_{GS} \geq V_T$



$$R_{ON} = \left[K_n \frac{W}{L} \times (V_{GS} - V_T)\right]^{-1}$$

$$I_{DS} = \frac{1}{R_{ON}} V_{DS} = K(V_{GS} - V_T)V_{DS}$$

where $K = K_n \frac{W}{L}$ in (mA/V^2)

- Increasing the V_{GS} would make the channel wider, which would make it easier for electrons to flow hence R_{ON} would decrease.

* Case-4: Increased V_{DS}, $V_{GS} \geq V_T$

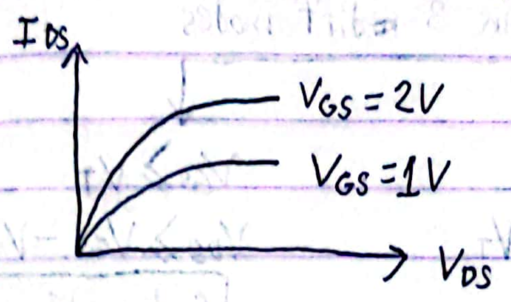
- $V_{GS} - V_{DS} \geq V_T$
- $V_{DS} \leq V_{GS} - V_T$
- $\therefore$, If V_{DS} increase a lot the channel will not remain a flat line hence it will stop current from flowing.
- $V_{GS} = V_T + V_{OV}$ [V_{OV} = Voltage Overdrive]
- higher V_{GS} means higher V_{OV}, and wider the channel will be.

Continuation of V-2

Because of this

- But since V_{DS} is applied V_{ov} will decrease.
- Voltage diff between V_{GS} and V_D, $= V_{GS} - V_D = V_T + (V_{ov} - V_D)$
- $\therefore V_{DS} \leq V_{GS} - V_T$ [This mode is called the ~~fro~~ triode mode of the MOSFET]

* $I_{DS} = K_n \frac{W}{L} [V_{ov} \cdot V_{DS} - \frac{1}{2} V_{DS}^2]$ (will be used more)



- The relationship between I_{DS} and V_{DS} will non-linear (will be quadratic)

- If V_{DS} is small, we can ignore V_{DS}^2 (mA/V^2)

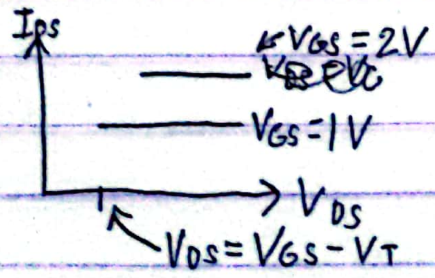
* $\therefore I_{DS} = K[V_{ov}]V_{DS} = K[V_{GS} - V_T]V_{DS}$, where $[K = K_n \frac{W}{L}$ ~~μ~~ in $\wedge]$

* Case-5: $V_{DS} = V_{GS} - V_T = V_{ov}$, $V_{GS} \geq V_T$

- The channel will be pinch offed it will look like a triangle shape.
- Current, I_{DS} can be found by replacing V_{DS} with V_{ov}.
- $I_{DS} = K[V_{ov} \cdot V_{ov} - \frac{1}{2} V_{ov}^2]$

$$\Rightarrow \boxed{I_{DS} = \frac{K}{2} V_{ov}^2 = \frac{K}{2}[V_{GS} - V_T]^2}$$

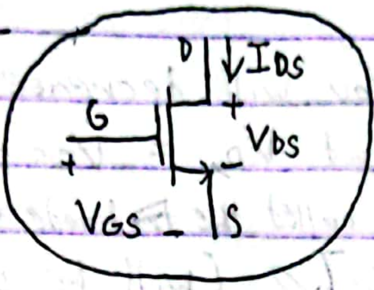
* Case-6: $V_{DS} > V_{GS} - V_T$



$\uparrow I_{DS} = \frac{K}{2}[V_{GS}\uparrow - V_T]^2$

- The current is not increasing due to the saturation phenomenon, due to " pinching off of the channel.

Summary:

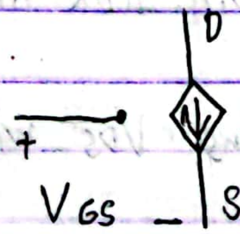


MOSFET

can be in 3 ~~m~~ diff modes

- $V_{GS} < V_T$
  $\boxed{\text{Cut off}}$
  $I_{DS} = 0$
- $V_{GS} \geq V_T$
  $0 < V_{DS} < V_{GS} - V_T$
  $\boxed{\text{Triode}}$
  $I_{DS} = K[(V_{GS} - V_T) - \frac{1}{2} V_{DS}] V_{DS}$
- $V_{GS} \geq V_T$
  $V_{DS} \geq V_{GS} - V_T$
  $\boxed{\text{Saturation}}$
  $I_{DS} = \frac{K}{2}[V_{GS} - V_T]^2$

* In the saturation mode MOSFET will behave like a current source ~~acting like a~~ controlled by V_{GS}.



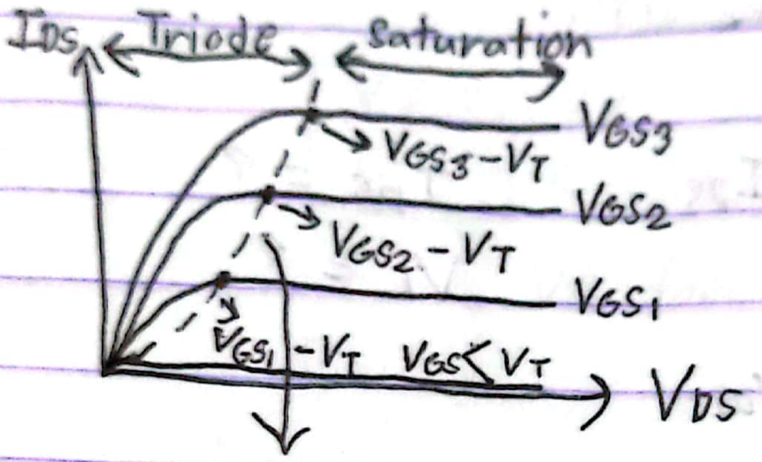
$$I_{DS} = \frac{K}{2}[V_{GS} - V_T]^2$$

- It is not a linear device.

* Another condition the MOSFET can have is:

$V_{DS} \ll V_{GS} - V_T \Rightarrow \boxed{\text{R model}}$

- $I_{DS} = \frac{1}{R_{ON}} \cdot V_{DS}$
- $R_{ON} = \frac{1}{K(V_{GS} - V_T)}$



$V_{GS3} > V_{GS2} > V_{GS1}$

Seperator between triode and saturation region

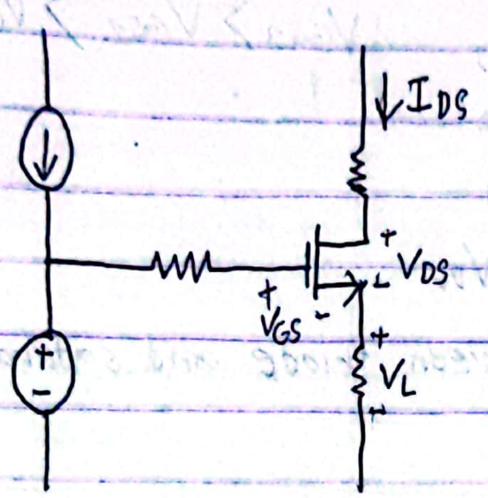
- This threshold is defined as:

$V_{DS} = V_{GS} - V_T$

$I_{DS} = \frac{K}{2} [V_{GS} - V_T]^2$

$I_{DS} = \frac{K}{2} V_{DS}^2 \rightarrow$ eqn of the seperator.

MOSFET in a DC circuit:



$I_{DS} = ?$

$V_L = ?$

* We need to use Method of Assumed state to solve it:

① Assume:

Cutoff: $I_{DS} = 0$

Triode: $I_{DS} = K[V_{ov} - \frac{1}{2}V_{DS}]V_{DS}$, where, $[V_{ov} = V_{GS} - V_T]$

Saturation: $I_{DS} = \frac{K}{2}[V_{GS} - V_T]^2$

- Start with saturation then triode then Cutoff.

② Solve:

KCL

KVL

③ Verify:

Cutoff: $V_{GS} < V_T$

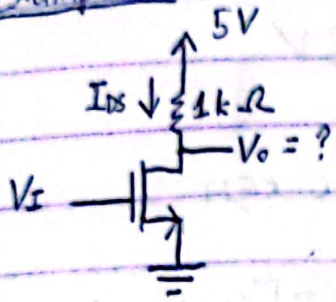
Triode: $V_{GS} \geq V_T$, $V_{DS} < V_{GS} - V_T$

Saturation: $V_{GS} \geq V_T$, $V_{DS} \geq V_{GS} - V_T$

* $I_G = 0$ always for MOSFET

Examples:

①



$V_T = 0.8V$
$K = 0.5\ mA/V^2$

Find V_o for ⓐ $V_I = 2.5V$, ⓑ $V_I = 5V$

ⓐ MOSFET in Saturation mode (assumed).

$V_S = 0$, $V_G = V_I = 2.5V$, $V_{GS} = V_G - V_S = 2.5V$

$\therefore I_{DS} = \frac{k[V_{GS} - V_T]^2}{2} = \frac{0.5[2.5-0.8]^2}{2} = 0.7725\ mA$

$I_{DS} = \frac{5 - V_o}{R}$

$V_o = 5 - I_{DS} \times R = 5 - 0.7725 \times 1 = 4.2275\ V$

$V_{DS} = V_o - V_S = V_o - 0 = V_o = 4.22275V$

Check:

- $V_{GS} \geqslant V_T$
  $2.5 \geqslant 0.8$ (True)
- $V_{DS} \geqslant V_{GS} - V_T$
  $\Rightarrow V_o \geqslant V_{GS} - V_T$
  $\Rightarrow 4.2275 \geqslant 2.5 - 0.8$
  $\Rightarrow 4.2275 \geqslant 1.7$ (True)

Since both conditions are fulfilled so the assumption is correct.

ⓑ $V_I = 5V$, $V_{GS} = V_I - V_S = 5V$, Assume Saturation mode:

$I_{DS} = \frac{k}{2}[V_{GS} - V_T]^2 = \frac{0.5}{2}[5 - 0.8]^2 = 4.41\ mA$

$V_o = 5 - I_{DS} \times R = 5 - 4.41 \times 1 = 0.59V$

Checking:

- $V_{GS} \geqslant V_T$
  $5 \geqslant 0.8$ (True)
- $V_{DS} \geqslant V_{GS} - V_T$
  $\Rightarrow V_o \geqslant V_{GS} - V_T$
  $\Rightarrow 0.59 \geqslant 5 - 0.8$ (False)

$\therefore$ Assumption is not true.

* Assume Triode Mode:

$V_{GS} = 5V$, $V_{ov} = 5 - V_T = 5 - 0.8 = 4.2V$

$I_{DS} = K[V_{ov} - \frac{1}{2}V_{DS}]V_{DS}$

$\Rightarrow \boxed{I_{DS} = 0.5[4.2 - 0.5V_o]V_o}$ quadratic eqn

$\frac{5 - V_o}{R} = I_{DS} \Rightarrow V_o = 5 - I_{DS} \times R = 5 - 0.5[4.2V_{DS} - 0.5V_{DS}^2]$

$\Rightarrow V_o = 5 - 2.1V_{DS} + 0.25V_{DS}^2$

$\Rightarrow \boxed{0.25V_{DS}^2 - 3.1V_{DS} + 5 = 0}$ $[V_{DS} = V_o]$

$\Rightarrow 0.25x^2 - 3.1x + 5 = 0$

$\Rightarrow x = 1.9V, x = 10.492$

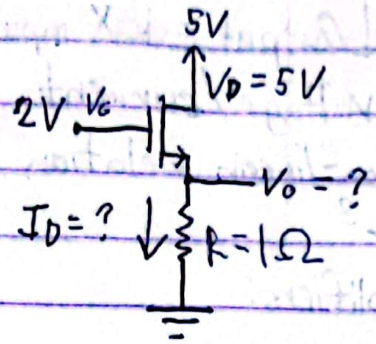
$\therefore V_o = 1.9V$

* Check:

$V_{GS} \geq V_T$	$V_{DS} < V_{GS} - V_T$
$5 \geq 0.8$ (True)	$1.9 < 5 - 0.8$ (True)

* $\therefore$ Assumption is correct.

#1 Example:



$K = 2\ mA/V^2$

$V_T = 1\ V$

* Assume Saturation mode:

$V_{GS} = V_G - V_S$

$\Rightarrow V_{GS} = 2 - V_o$

$I_{DS} = \frac{K}{2}[V_{GS} - V_T]^2$

$\Rightarrow I_{DS} = \frac{2}{2}[2 - V_o - 1]^2$

$\Rightarrow I_{DS} = [1 - 2V_o + V_o^2]$

$I_D = \frac{V_o - 0}{R} \Rightarrow V_o = I_D R$

$V_o = I_{DS} \times R = I_{DS} \times 1 = 1 - 2V_o + V_o^2$

$\Rightarrow V_o^2 - 3V_o + 1 = 0$

$\therefore V_o = 2.6\ V$ and $V_o = 0.4\ V$ ✓

$2 - V_o \geq 1V \Rightarrow V_o \leq 1V$, $\therefore V_o = 0.4V$

$\therefore I_{DS} = 0.4\ mA$

* Check:

- $V_{GS} \geq V_T$

  $1.6 \geq 1$ (True)

- $V_{DS} \geq V_{GS} - V_T$

  $\Rightarrow V_D - V_S \geq V_{GS} - V_T$

  $\Rightarrow 5 - 0.4 \geq 1.6 - 1$

  $\Rightarrow 4.6V \geq 0.6V$ (True)

$\therefore$ The assumption is ~~true~~ correct.