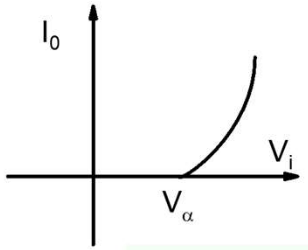
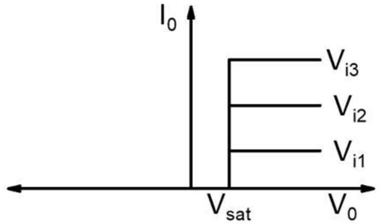
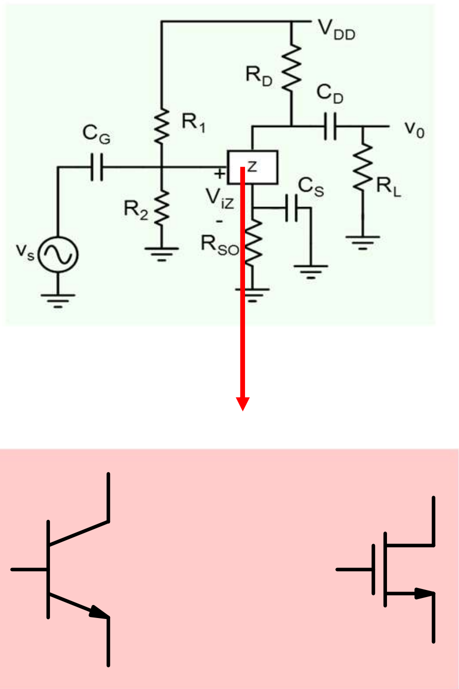
ESC201T: Introduction to Electronics

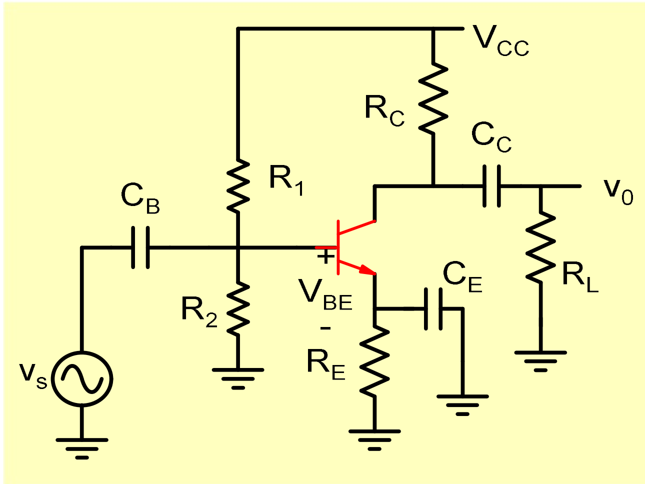
Lecture 28: Transistor Circuits

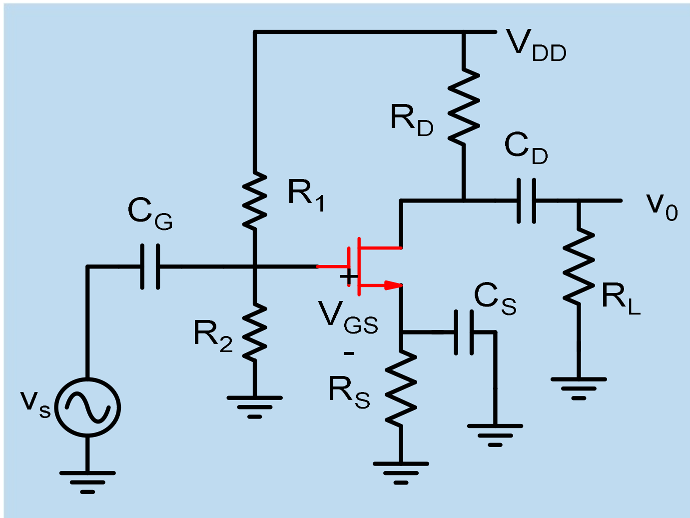
B. Mazhari
Dept. of EE, IIT Kanpur

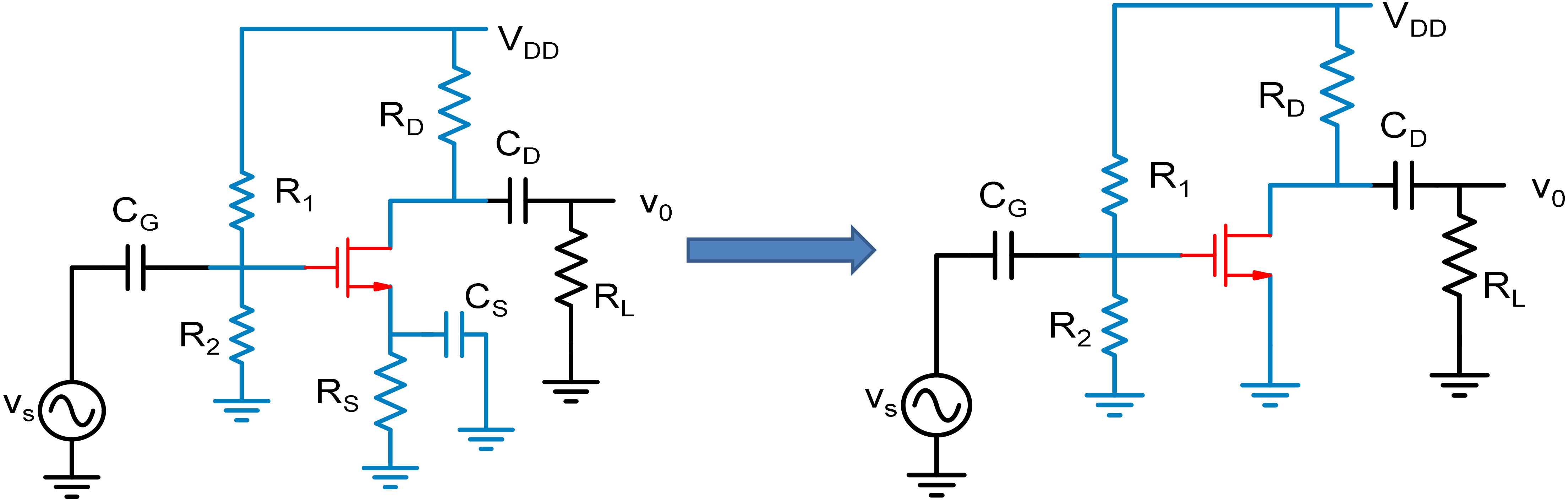

I_0
V_i
V_α


I_0
V_{i3}
V_{i2}
V_{i1}
V_{sat}
V_0

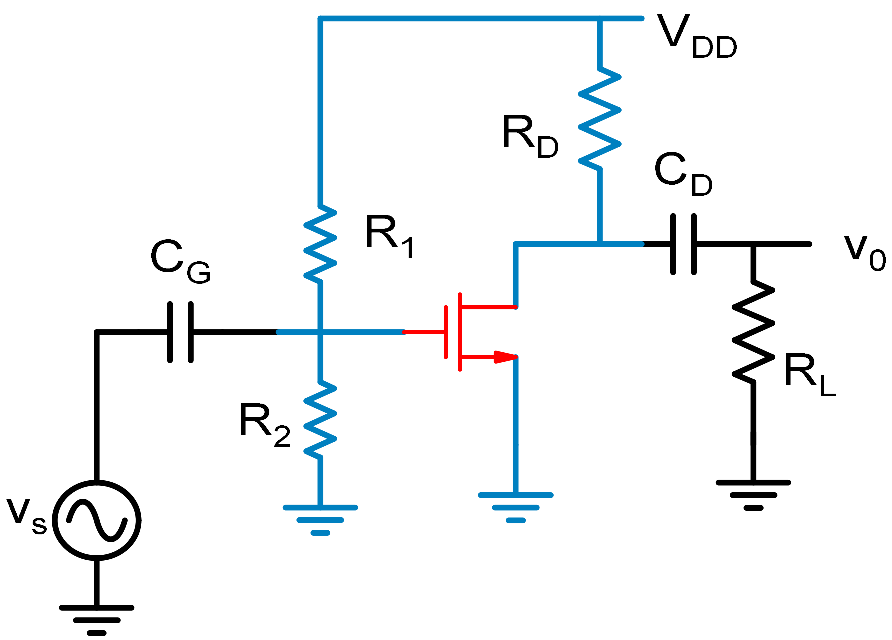

V_{DD}
R_D
C_D
R_1
C_G
v_0
Z
+
V_{iZ}
-
C_S
R_L
R_2
v_s
R_{SO}


V_{CC}
R_C
C_C
R_1
C_B
v_0
+
V_{BE}
-
C_E
R_L
R_2
R_E
v_s

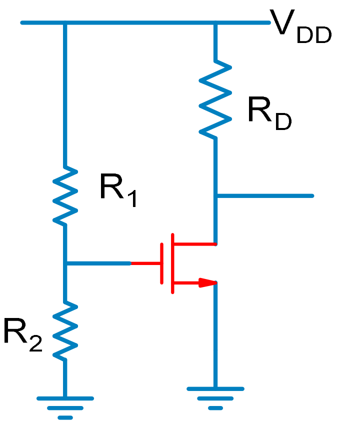

V_{DD}
R_D
C_D
R_1
C_G
v_0
+
V_{GS}
-
C_S
R_L
R_2
R_S
v_s



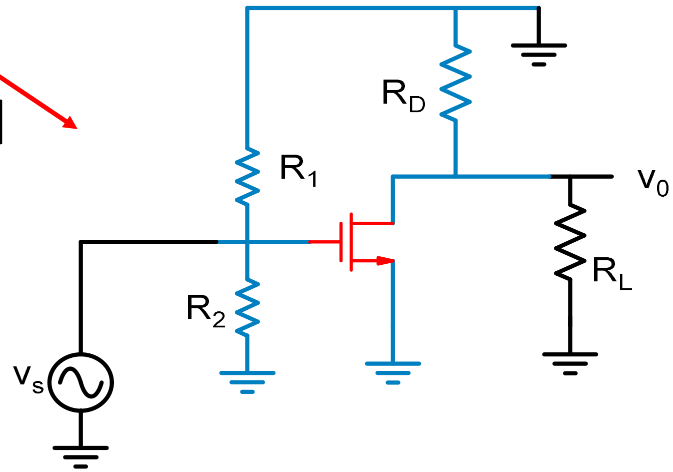
V_DD
R_D
C_D
R_1
C_G
v_0
R_L
R_2
C_S
R_S
v_s
V_DD
R_D
C_D
R_1
C_G
v_0
R_L
R_2
v_s



dc analysis

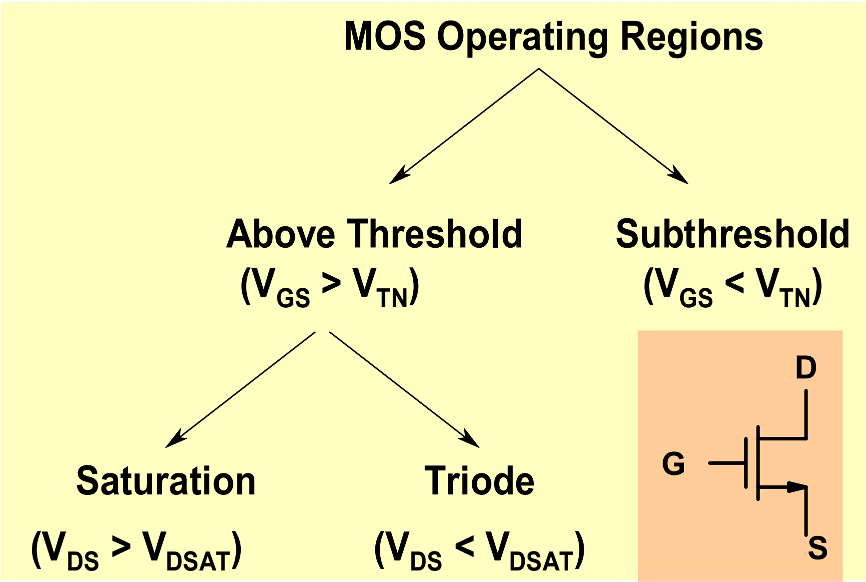


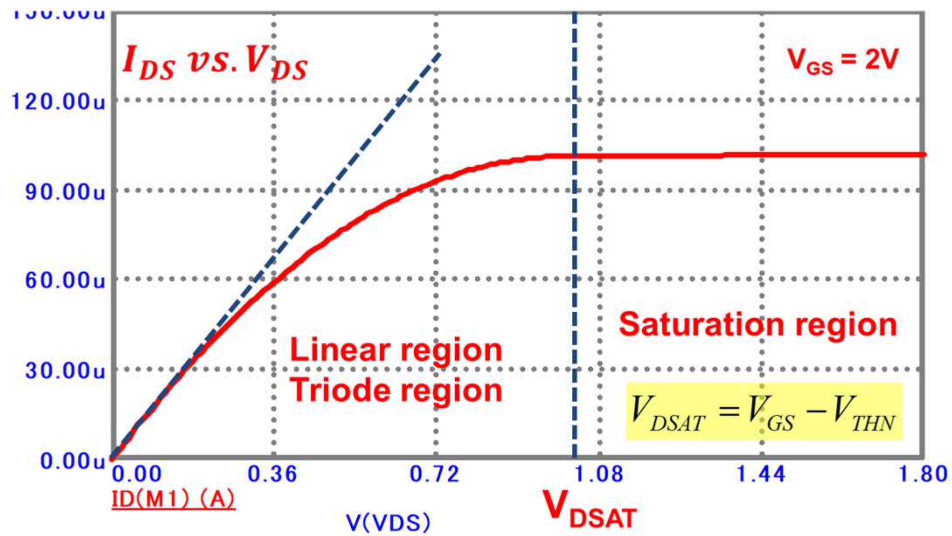
ac or small signal analysis

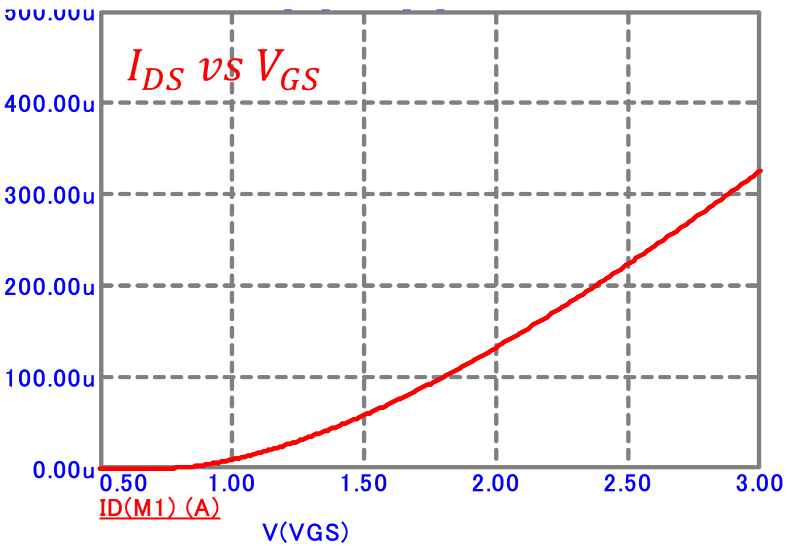


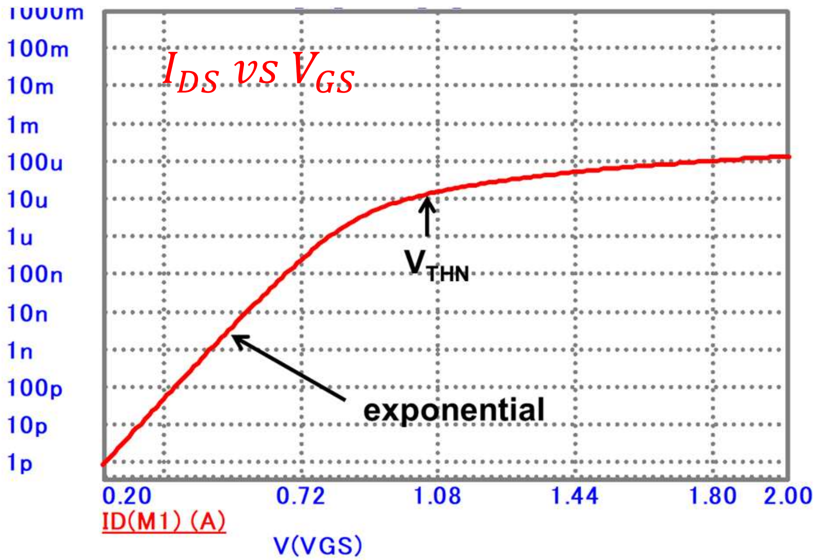
$$A_V = \frac{v_O}{v_S}$$

Need dc and ac (or small signal incremental) model of the transistors

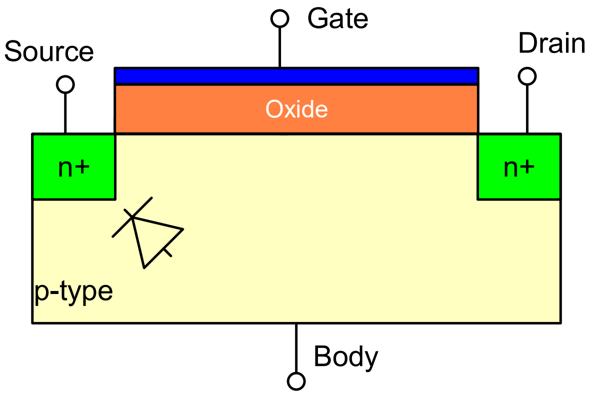

MOS Operating Regions
Above Threshold
($V_{GS} > V_{TN}$)
Subthreshold
($V_{GS} < V_{TN}$)
Saturation
($V_{DS} > V_{DSAT}$)
Triode
($V_{DS} < V_{DSAT}$)
D
G
S

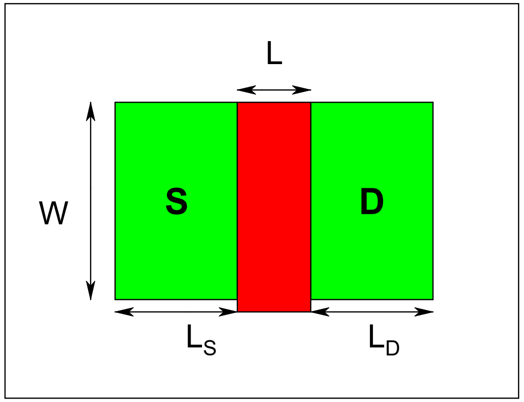

I_{DS} vs. V_{DS}
V_{GS} = 2V
120.00u
90.00u
60.00u
30.00u
0.00u
0.00
0.36
0.72
1.08
1.44
1.80
ID(M1) (A)
V(VDS)
V_{DSAT}
Linear region
Triode region
Saturation region
$V_{DSAT} = V_{GS} - V_{THN}$

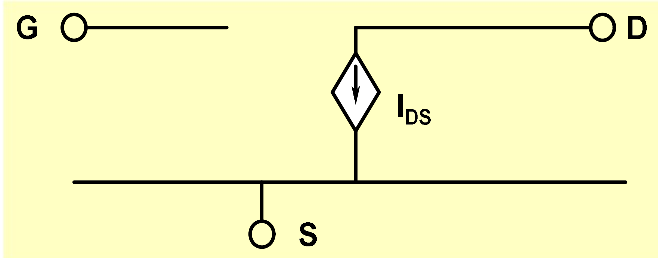

I_{DS} vs V_{GS}
400.00u
300.00u
200.00u
100.00u
0.00u
0.50
1.00
1.50
2.00
2.50
3.00
ID(M1) (A)
V(VGS)


I_{DS} vs V_{GS}
100m
10m
1m
100u
10u
1u
100n
10n
1n
100p
10p
1p
0.20
0.72
1.08
1.44
1.80
2.00
ID(M1) (A)
V(VGS)
V_{THN}
exponential

The dc and ac models of the transistor in saturation region can be represented in the form of an equivalent circuit:

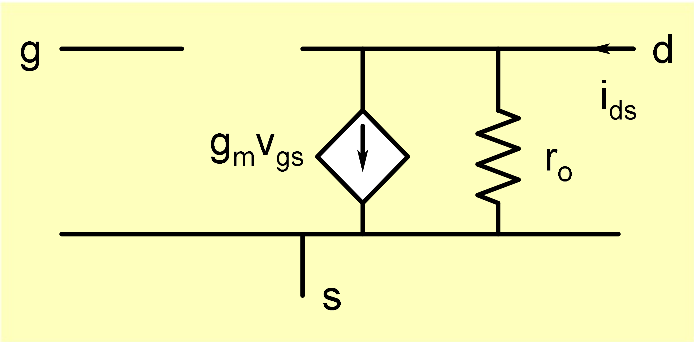






$$I_{DS} = \frac{\beta_N}{2}(V_{GS} - V_{THN})^2 \;\; ; \; \beta_N = KP_N \times \frac{W}{L}$$

kP_N: *Transconductance parameter* $\frac{\mu A}{V^2}$



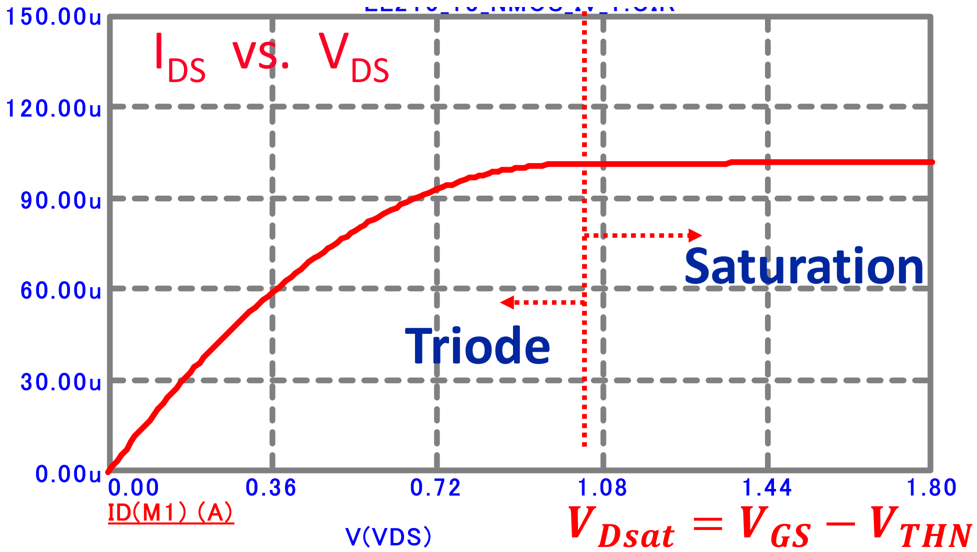
$$g_m = \frac{2I_{DSQ}}{V_{GSQ} - V_{THN}} = \sqrt{2I_{DSQ}\beta}$$

$$r_o = \frac{1}{\lambda_n I_{DSQ}}$$

λ_N *is the channel length modulation parameter*

$$KP_N = 100\mu A/V^2; V_{THN} = 1V; \lambda_n = 0.01V^{-1}$$

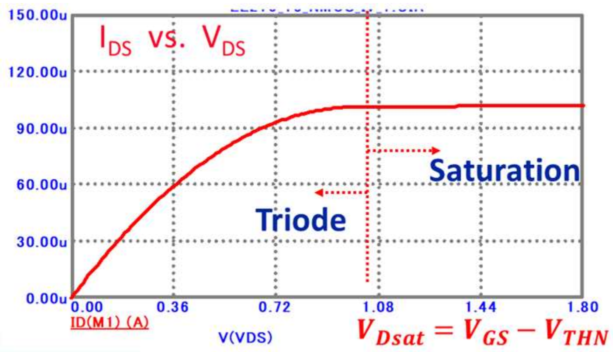
dc Model: Triode (or Linear)

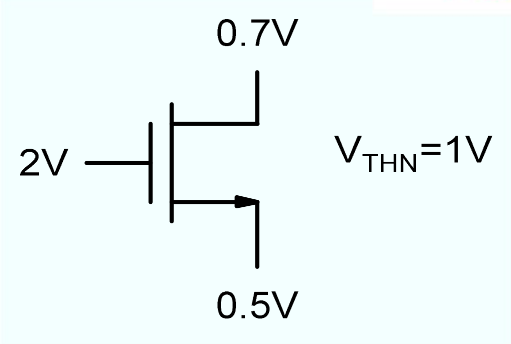


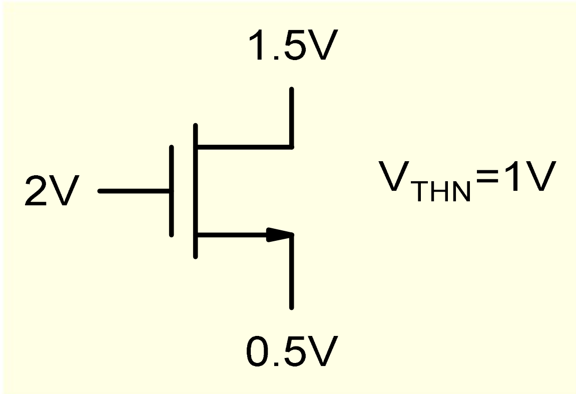
$$I_{DS} = \beta_N \left\{ (V_{GS} - V_{THN}) V_{DS} - \frac{V_{DS}^2}{2} \right\}$$

$$For\ simplicity\ we\ will\ only\ consider\ cases\ where\ I_{DS} \approx KP_N \times \frac{W}{L} \times (V_{GS} - V_{THN}) \times V_{DS}$$

Which mode is the transistor operating in ?







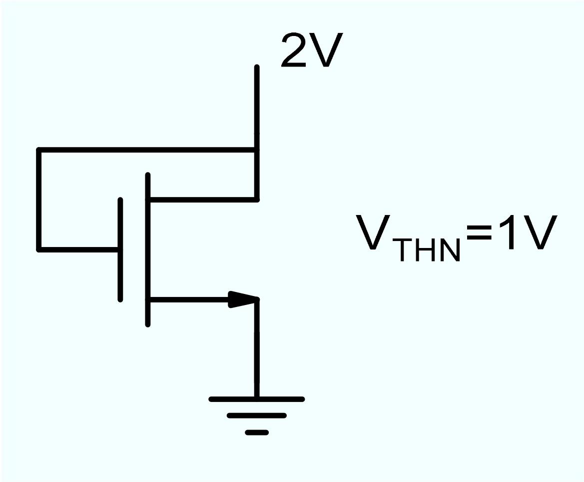
$$V_{GS} = 1.5 \; ; V_{DS} = 0.2$$

$$V_{DSAT} = V_{GS} - V_{THN} = 0.5$$

$$V_{DS} < V_{DSAT} \Rightarrow Linear$$

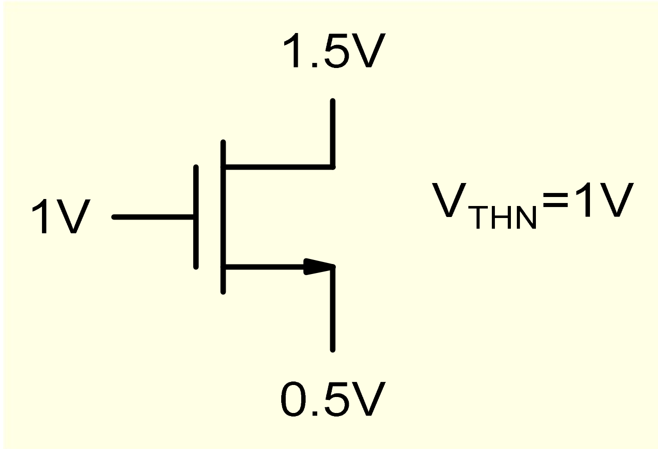
$$V_{DSAT} = 0.5 \; ; V_{DS} = 1V$$

Saturation



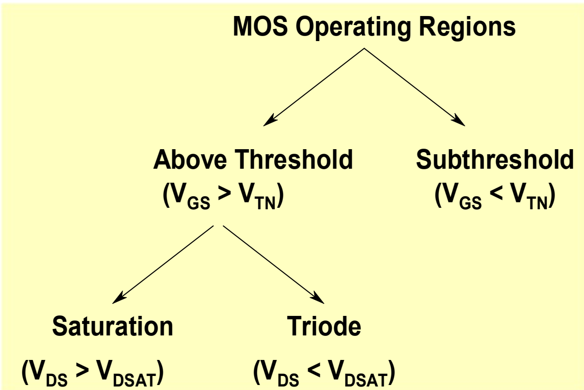
$$V_{GS} = 2\ ;\ V_{DS} = 2$$

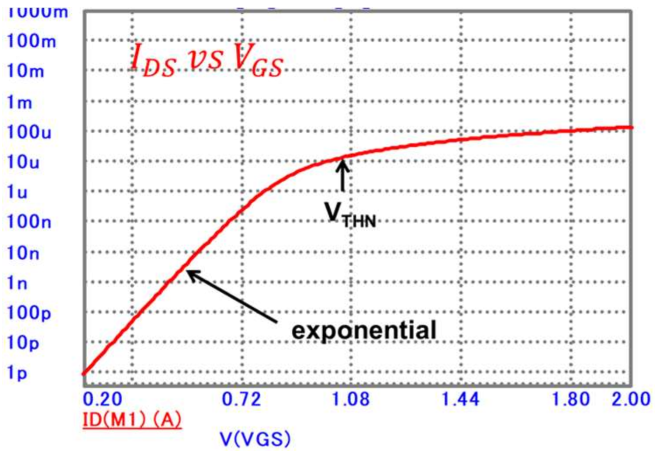
Saturation



$$V_{GS} = 0.5V < V_{THN}$$

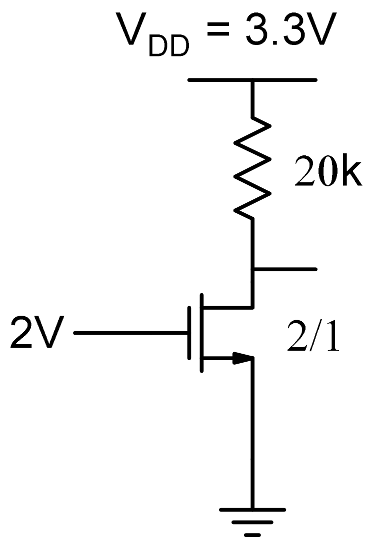
Transistor is in sub-threshold mode of operation





MOSFET Circuits

Example-1



$$KP_N = 100\mu A/V^2; V_{THN} = 1V; \lambda_n = 0.01V^{-1}$$

Determine I_{DS} and V_{DS}

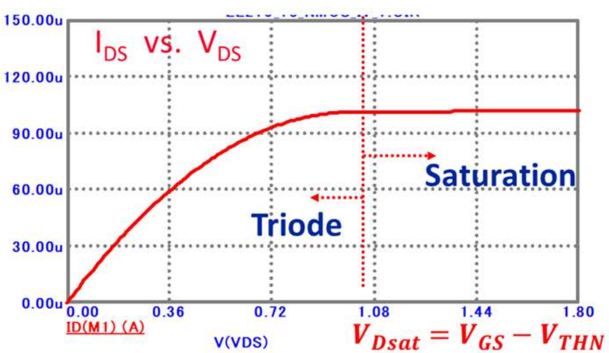
$$\textit{Assume saturation mode of operation}$$

$$I_{DS} = KP_N \times \frac{W}{L} \times \frac{(V_{GS} - V_{THN})^2}{2} = 10^{-4}A$$

$$V_{DS} = V_{DD} - I_{DS} \times R_D = 1.2V$$

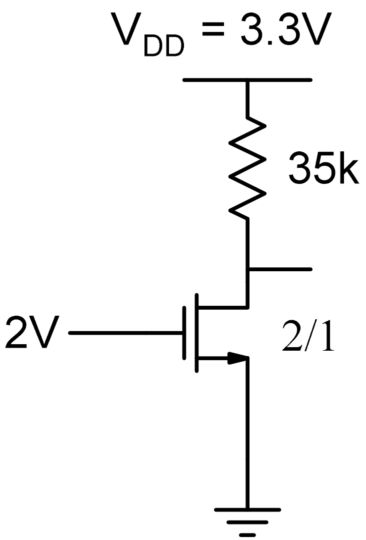
$$V_{Dsat} = V_{GS} - V_{THN} = 1V$$

$$\textit{Since } V_{DS} > V_{Dsat} \textit{ our assumption is correct}$$



MOSFET Circuits

Example-2



$$KP_N = 100\mu A/V^2; V_{THN} = 1V; \lambda_n = 0.01V^{-1}$$

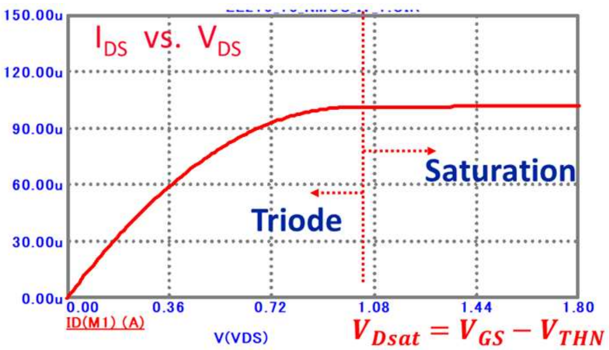
Determine I_{DS} and V_{DS}

Assume saturation mode of operation

$$I_{DS} = KP_N \times \frac{W}{L} \times \frac{(V_{GS} - V_{THN})^2}{2} = 10^{-4}A$$

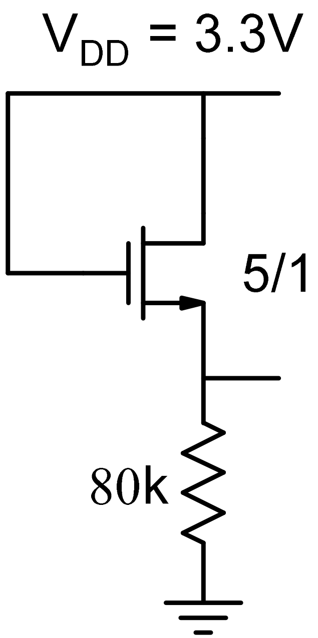
$$V_{DS} = V_{DD} - I_{DS} \times R_D = -0.2V \text{ so assumption incorrect}$$

$$I_{DS} \approx KP_N \times \frac{W}{L} \times (\mathrm{V_{GS}} - \mathrm{V_{THN}}) \times V_{DS}; \mathrm{V_{DS}} = \mathrm{V_{DD}} - \mathrm{I_{DS}} \times R_D$$
$$\Rightarrow I_{DS} = 8.25 \times 10^{-5}A; V_{DS} = 0.412V$$



$$V_{Dsat} = V_{GS} - V_{THN} = 1V$$

Example-3



$$KP_N = 100\mu A/V^2; V_{THN} = 1V; \lambda_n = 0.01V^{-1}$$

Determine I_{DS} and V_{DS}

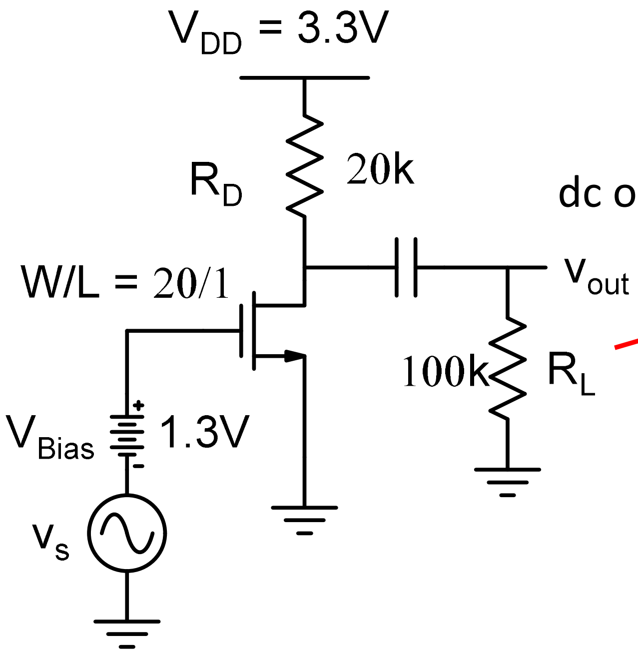
$$V_{DS} = V_{GS}$$
$$\Rightarrow V_{DS} > V_{GS} - V_{THN} = V_{DSAT} \Rightarrow \text{Saturation}$$

$$I_{DS} = KP_N \times \frac{W}{L} \times \frac{(V_{GS} - V_{THN})^2}{2}; V_{GS} = 3.3 - I_{DS} \times 80 \times 10^3$$
$$\Rightarrow I_{DS} = 2.48 \times 10^{-5} A; V_{GS} = 1.315V$$

For the other solution VGS = 0.653V which is not possible since it is less than V_{THN}

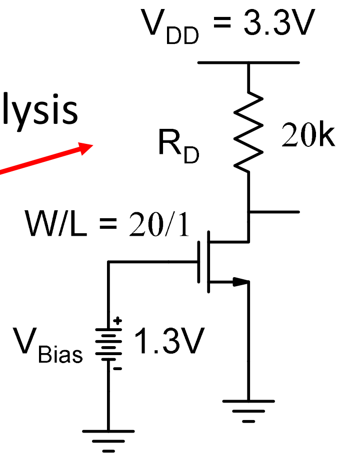
Example-4

Determine the voltage gain of the amplifier $\frac{v_{out}}{v_S}$



$KP_N = 100\mu A/V^2; V_{THN} = 1V; \lambda_n = 0V^{-1}$

dc or Bias point analysis



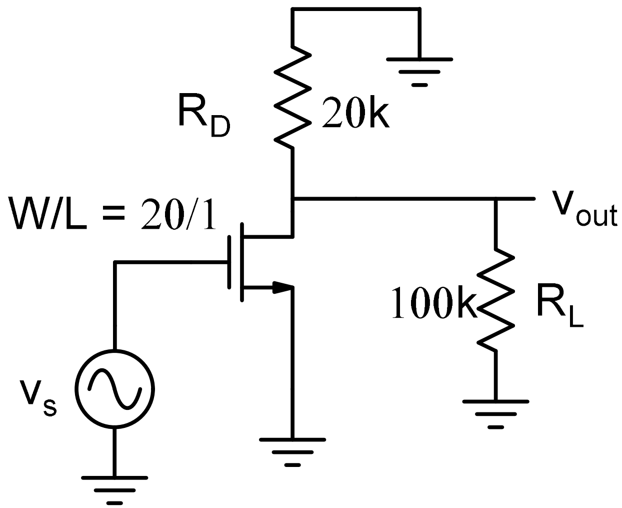
$$I_{DS} = KP_N \times \frac{W}{L} \times \frac{(V_{GS}-V_{THN})^2}{2} = 90\mu A$$

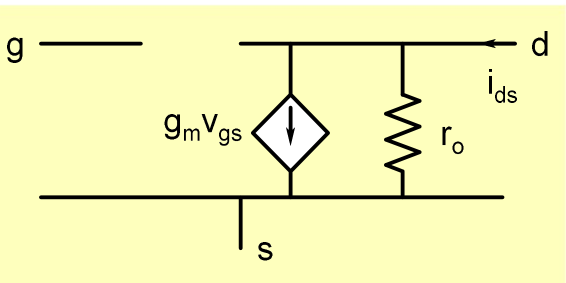
$$V_{DSQ} = V_{DD} - I_{DSQ} \times R_D = 1.5V$$

$$V_{Dsat} = V_{GS} - V_{THN} = 0.3V$$

So Transistor is biased in saturation

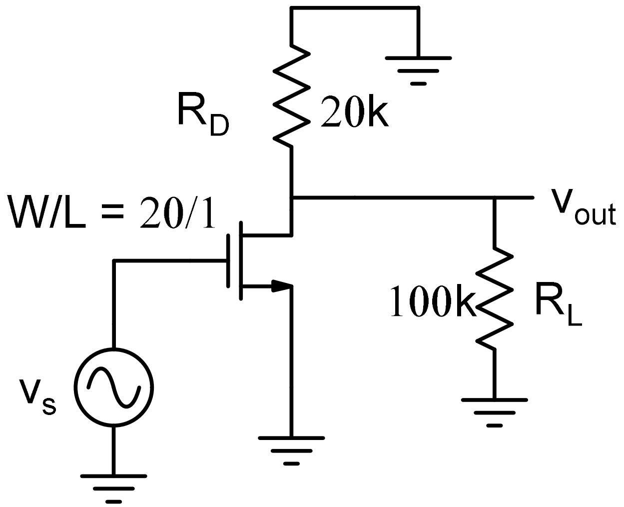
ac or small signal analysis

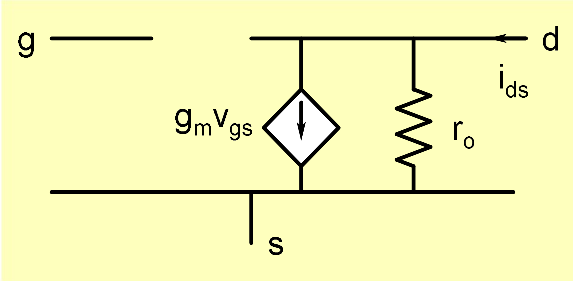




$$g_m = \frac{2I_{DSQ}}{V_{GSQ} - V_{THN}} = \sqrt{2I_{DSQ}\beta} = 6 \times 10^{-4}\Omega^{-1}$$

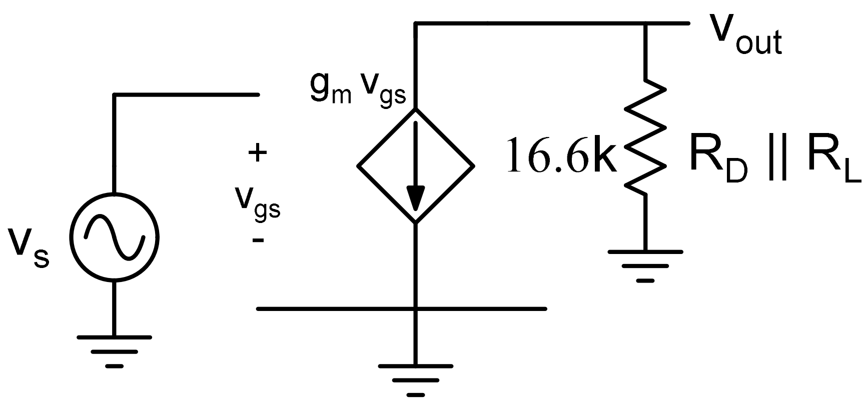
$$r_o = \frac{1}{\lambda_n I_{DSQ}} = \infty$$





$$g_m = \frac{2I_{DSQ}}{V_{GSQ} - V_{THN}} = \sqrt{2I_{DSQ}\beta}$$
$$= 6 \times 10^{-4}\Omega^{-1}$$

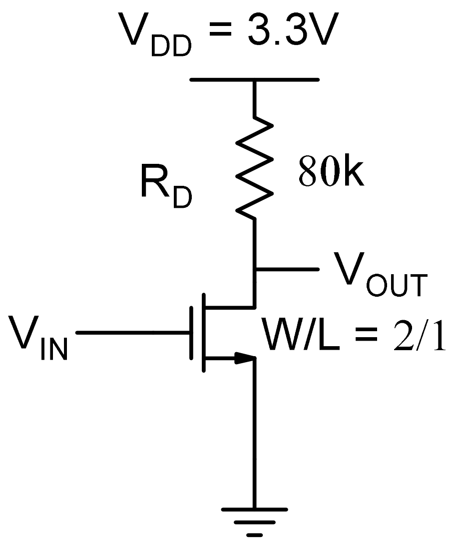
$$r_o = \frac{1}{\lambda_n I_{DSQ}} = \infty$$

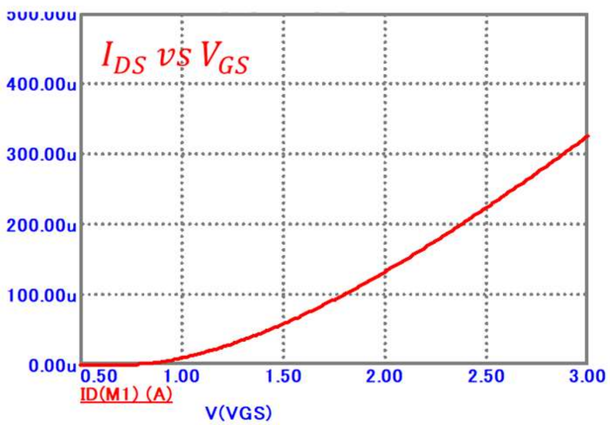


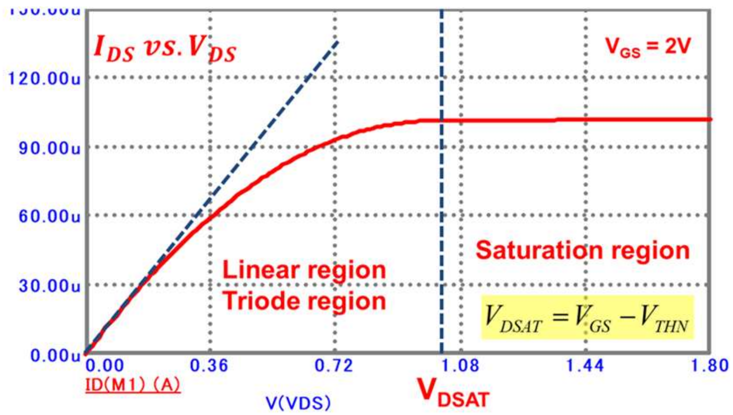
$$\frac{v_{out}}{v_s} = -g_m \times R_D \| R_L = -10$$

Example-5 Plot V_{OUT} vs. V_{IN} curve.

MOS Digital NOT gate

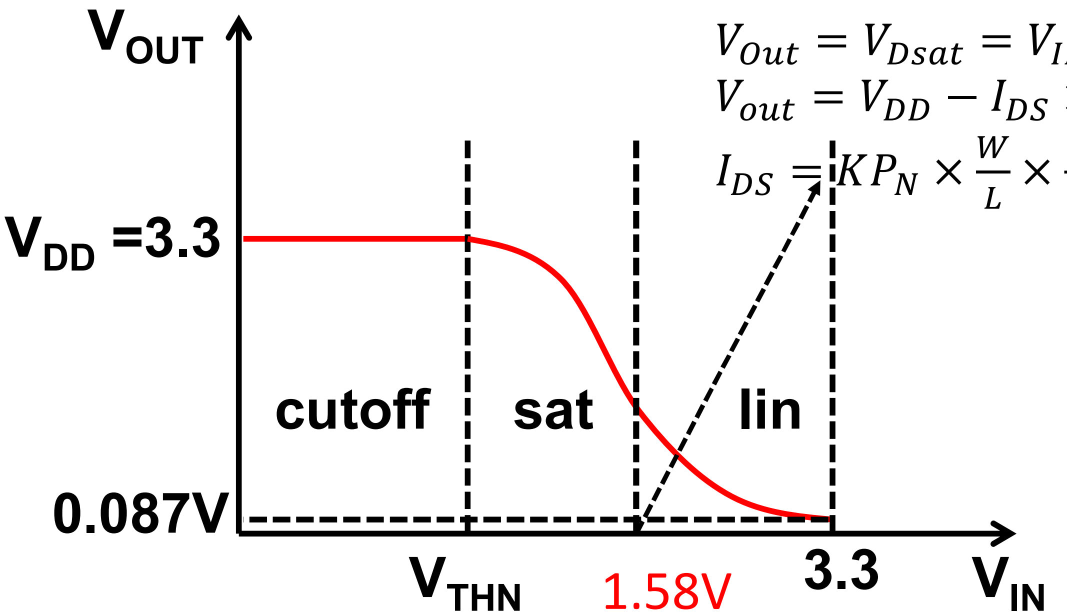






$KP_N = 100\mu A/V^2; V_{THN} = 1V; \lambda_n = 0.01V^{-1}$

$$V_{out} = V_{DD} - I_{DS} \times R_D$$
$$I_{DS} = KP_N \times \frac{W}{L} \times (V_{IN} - V_{THN}) \times V_{out}$$



$$V_{Out} = V_{Dsat} = V_{IN} - V_{THN}$$
$$V_{out} = V_{DD} - I_{DS} \times R_D$$
$$I_{DS} = KP_N \times \frac{W}{L} \times \frac{(V_{GS}-V_{THN})^2}{2}$$