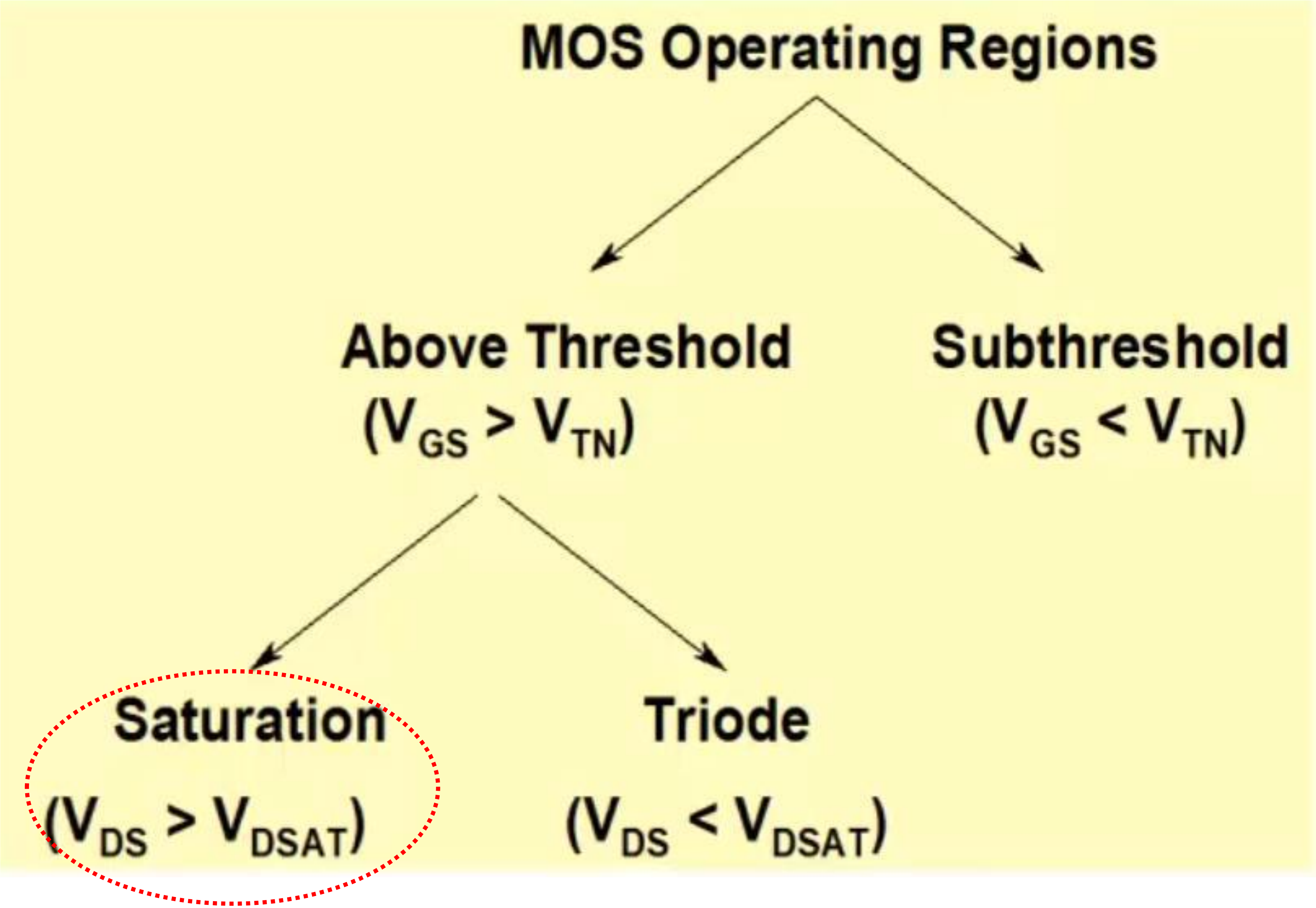
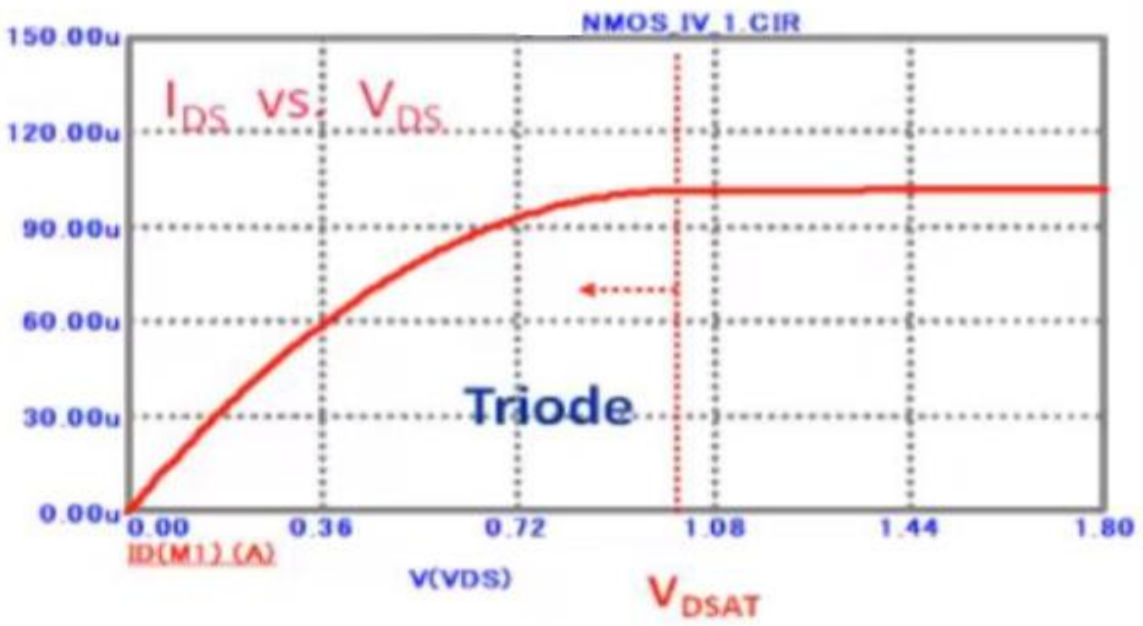
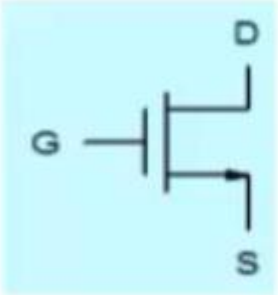

MOS Operating Regions
Above Threshold
($V_{GS} > V_{TN}$)
Subthreshold
($V_{GS} < V_{TN}$)
Saturation
($V_{DS} > V_{DSAT}$)
Triode
($V_{DS} < V_{DSAT}$)

dc Model: Triode (or Linear)





$$V_{GS} > V_{TN}$$

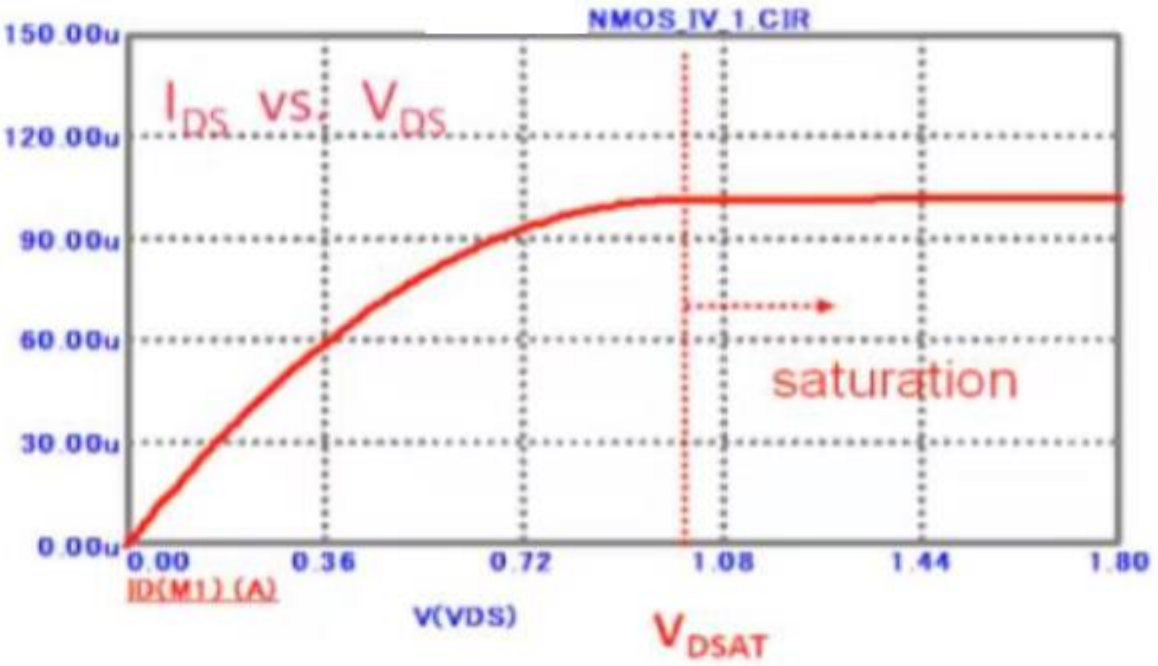
$$V_{DS} < V_{Dsat} = V_{GS} - V_{TN}$$

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

$$\beta_N = kP_N \cdot \frac{W}{L}$$

$$kP_N = \mu_n C_{ox'} \; : (TransConductance\ parameter\ \frac{\mu A}{V^2})$$

DC Model: Saturation Region



$$V_{GS} > V_{THN}$$

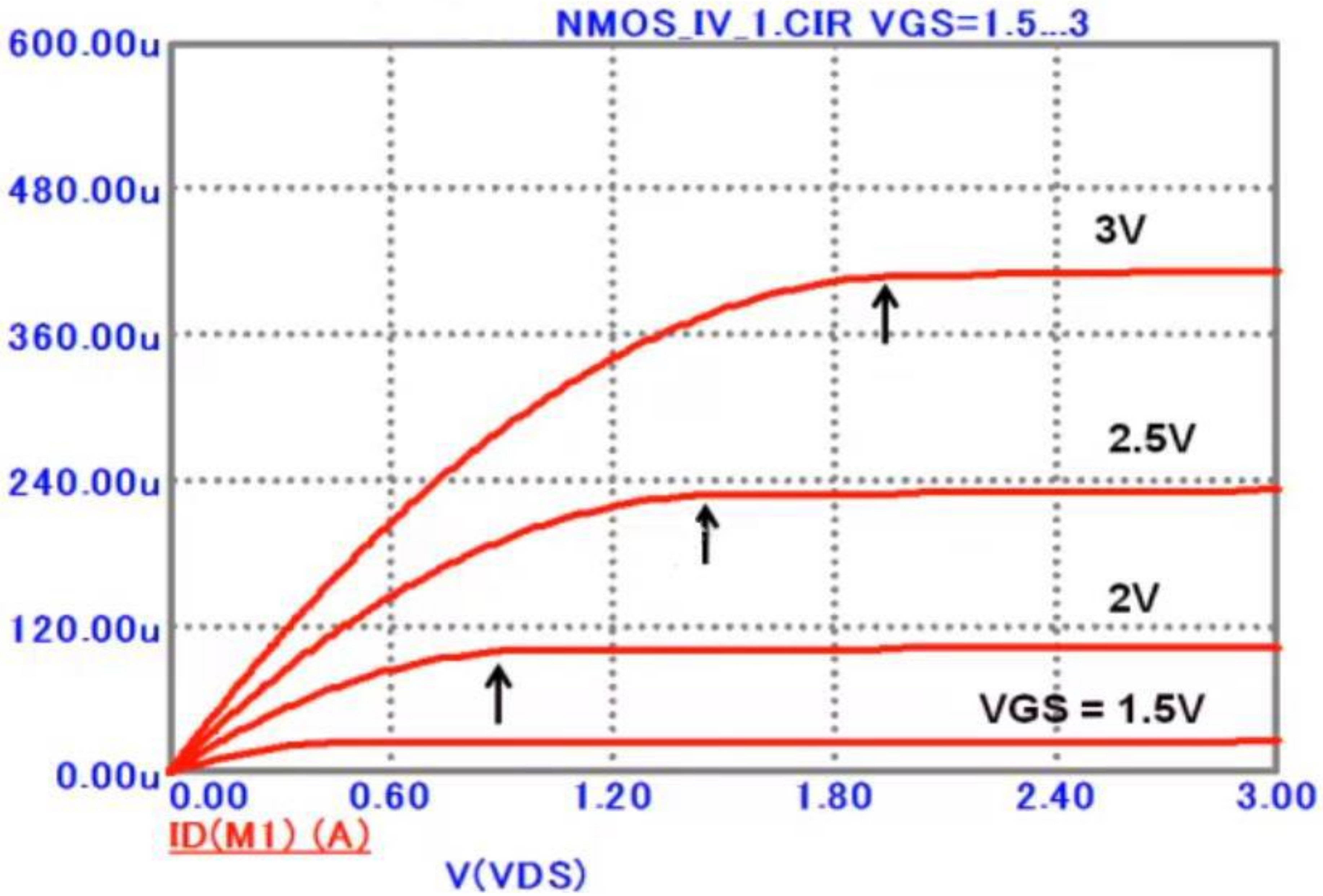
$$V_{DS} \geq V_{GS} - V_{THN}$$

$$I_{DS} = \frac{\beta_N}{2}(V_{GS} - V_{THN})^2[1 + \lambda_n V_{DS}]$$

λ_N is the channel length modulation parameter

Note that unlike BJT, VDSAT is not only larger but also dependent on applied gate-source voltage

Output Characteristics of MOSFET



dc model parameters

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

$$\text{Saturation}: \ I_{DS} = \frac{\beta_N}{2} (V_{GS} - V_{THN})^2 [1 + \lambda_n V_{DS}]$$

$$\beta_N = kP_N \cdot \frac{W}{L}$$

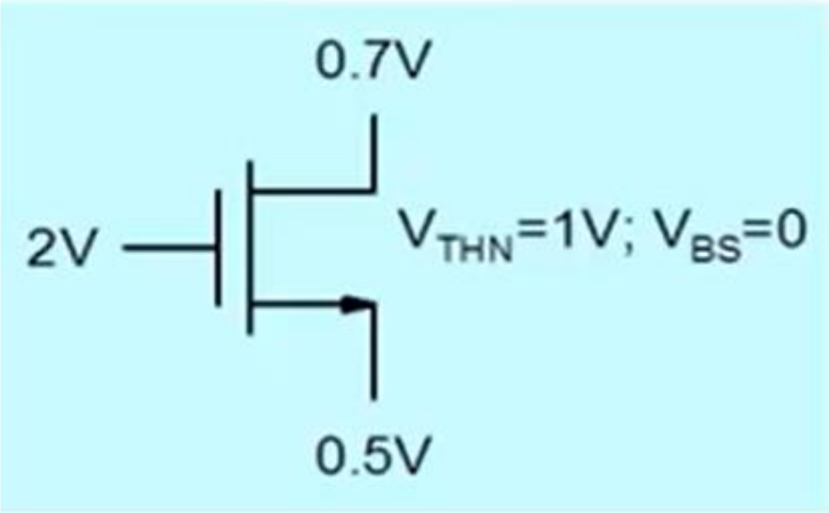
$$\lambda_N$$

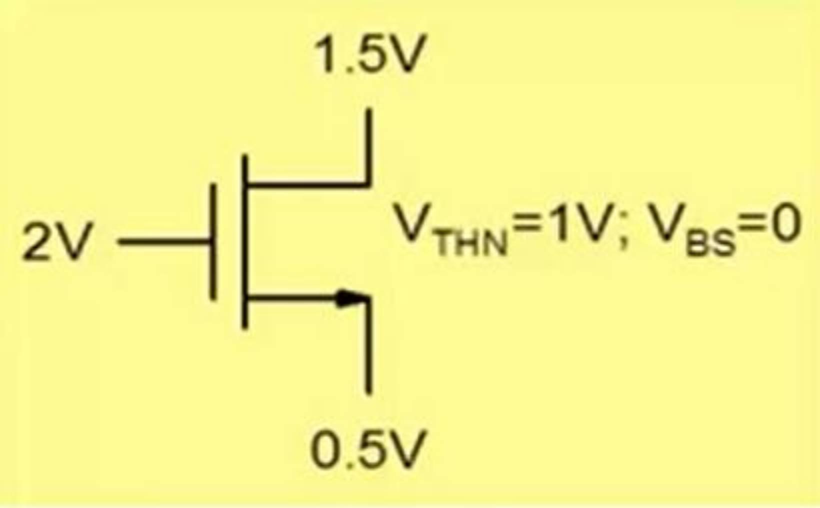
$$V_{THN} = V_{THN0} + \gamma \left(\sqrt{2\phi_F + V_{SB}} - \sqrt{2\phi_F} \right)$$

$$V_{THNO} = 1V; \gamma = 0.7\ V^{1/2}; 2\phi_F = 0.7V;$$
$$KP_N = 100\mu A / V^2; L = 1\mu m; \lambda = 0.01V^{-1}$$

L is usually fixed, W is determined by designer

Which mode is the transistor operating in ?





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

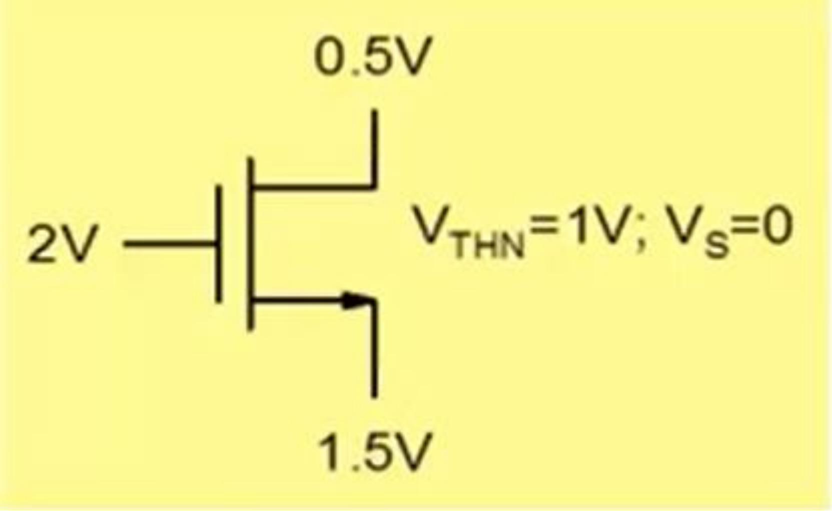
$$V_{DSAT} = V_{GS} - V_{THN} = 0.5$$

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

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

Saturation

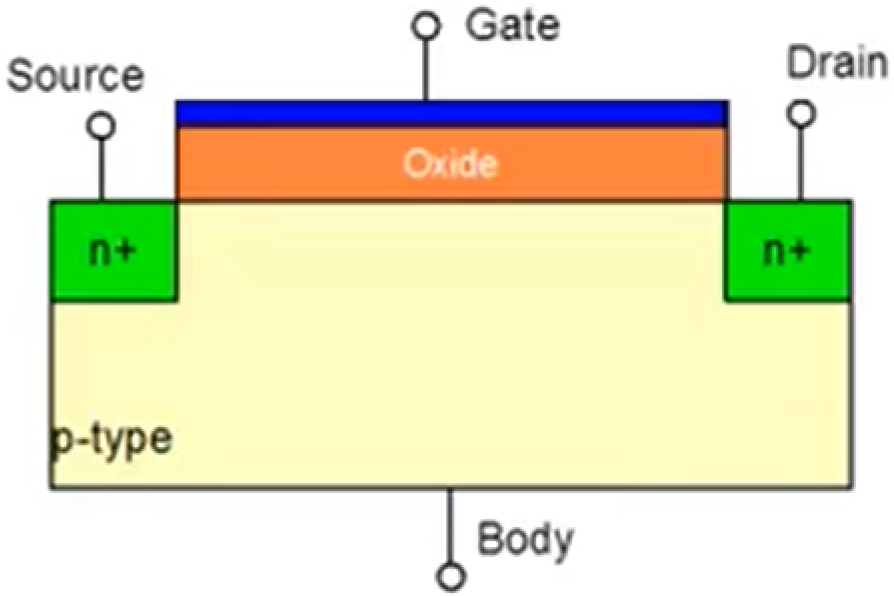
Which mode is the transistor operating in ?



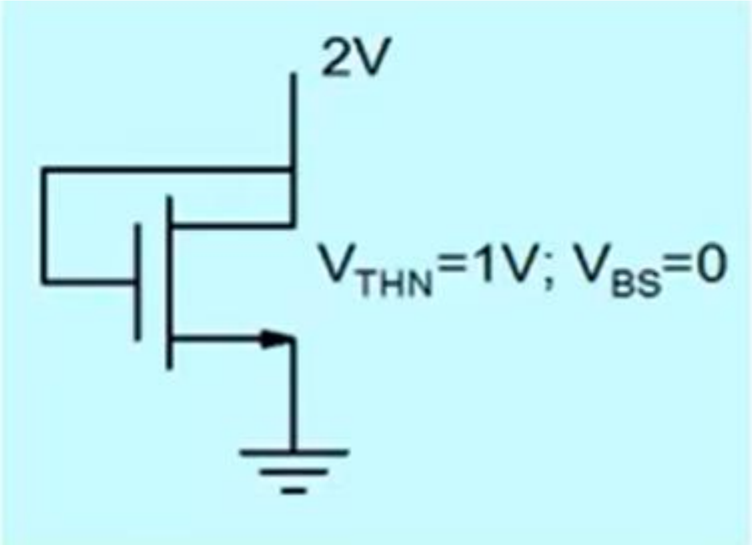
$$V_{GS} = 0.5\,;\, V_{DS} = -1V$$

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

$$V_{DS} > V_{DSAT} \Rightarrow saturation$$



$$V_{GS} = 1.5\,;\, V_{DS} = 1V$$



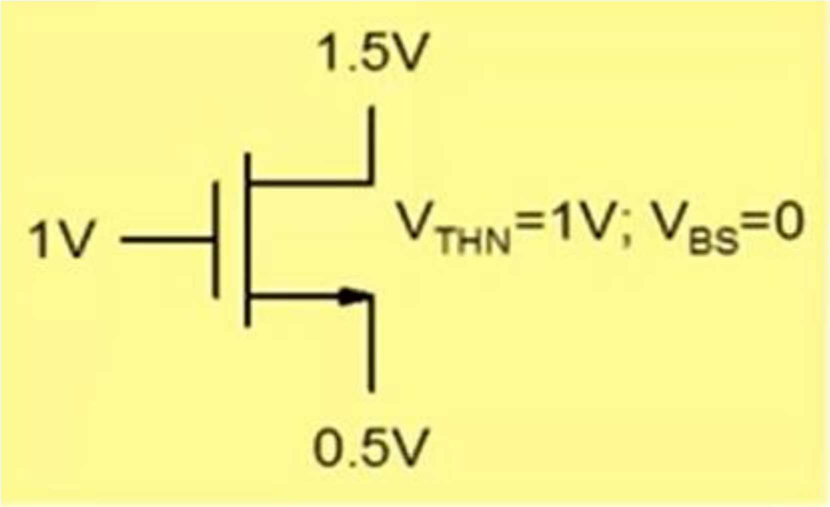
$$V_{GS} = 2\ ;\ V_{DS} = 2$$

Saturation

$$I_{DS} = \frac{\beta_N}{2}(V_{GS} - V_{THN})^2[1 + \lambda_n V_{DS}]$$

$$I_X \cong \frac{\beta_N}{2}(V_X - V_{THN})^2$$

Diode with a turn-on voltage of V_{THN}



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

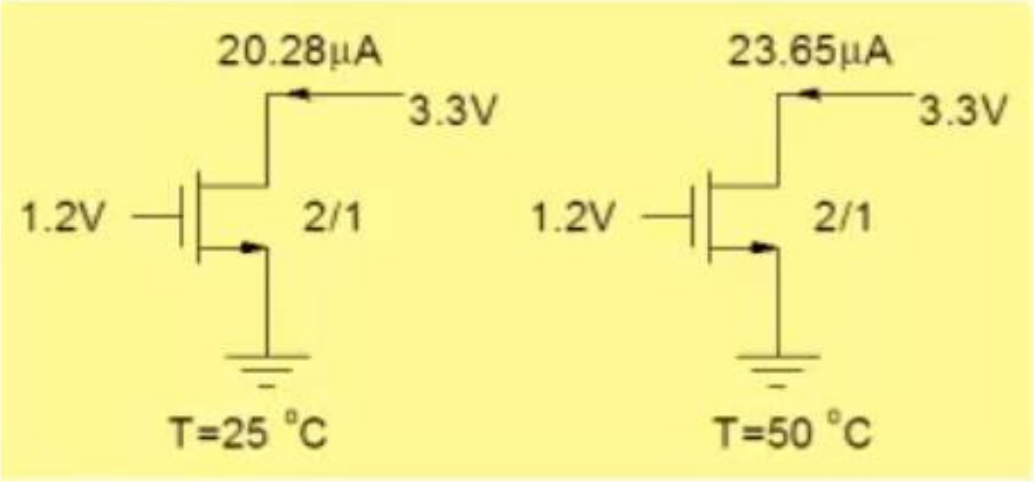
Transistor is in sub-threshold mode of operation

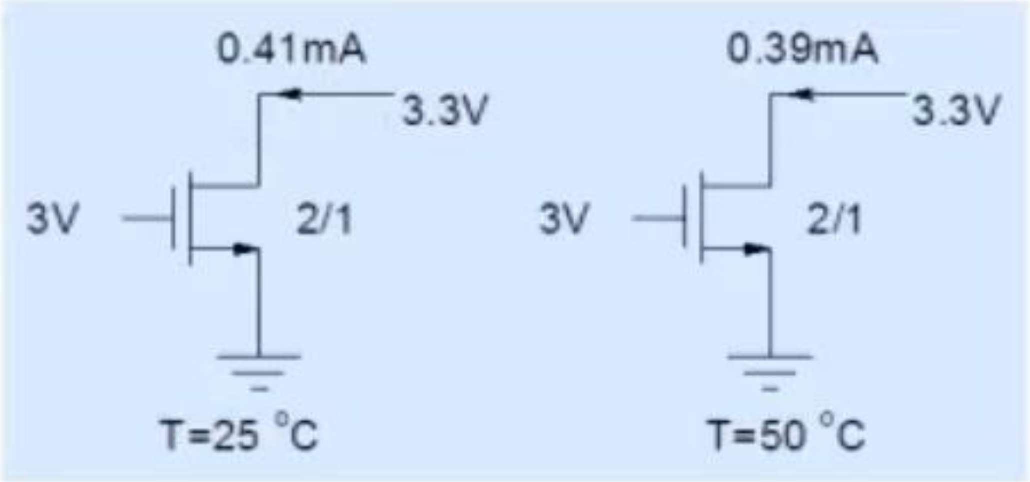
Temperature dependence

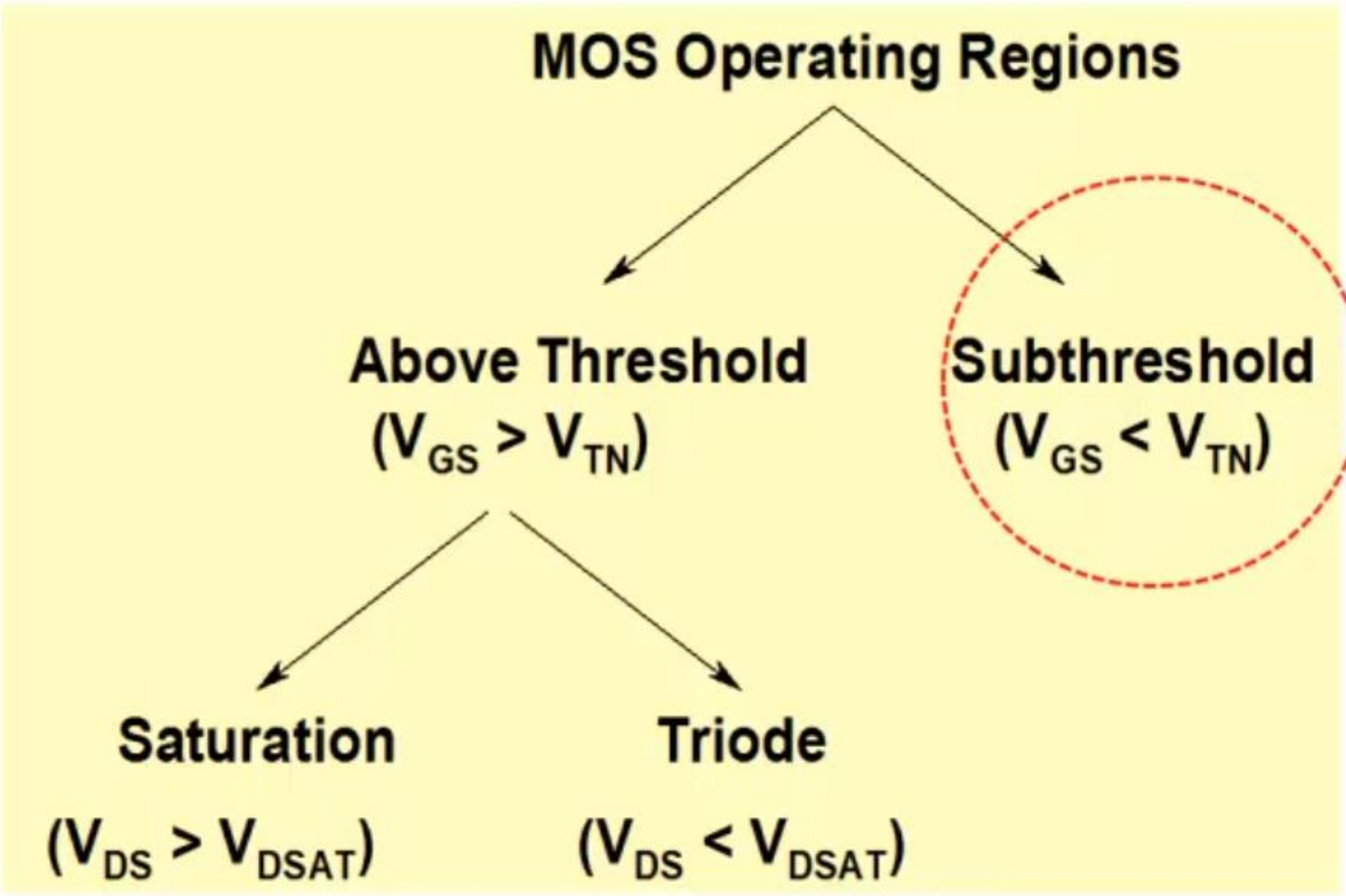
$$I_{DS} = \frac{KP_N}{2} \times \frac{W}{L} \times (V_{GS} - V_{THN})^2$$

Increase in temperature causes both transconductance parameter KP_N and threshold voltage $V_{THN.}$ to decrease

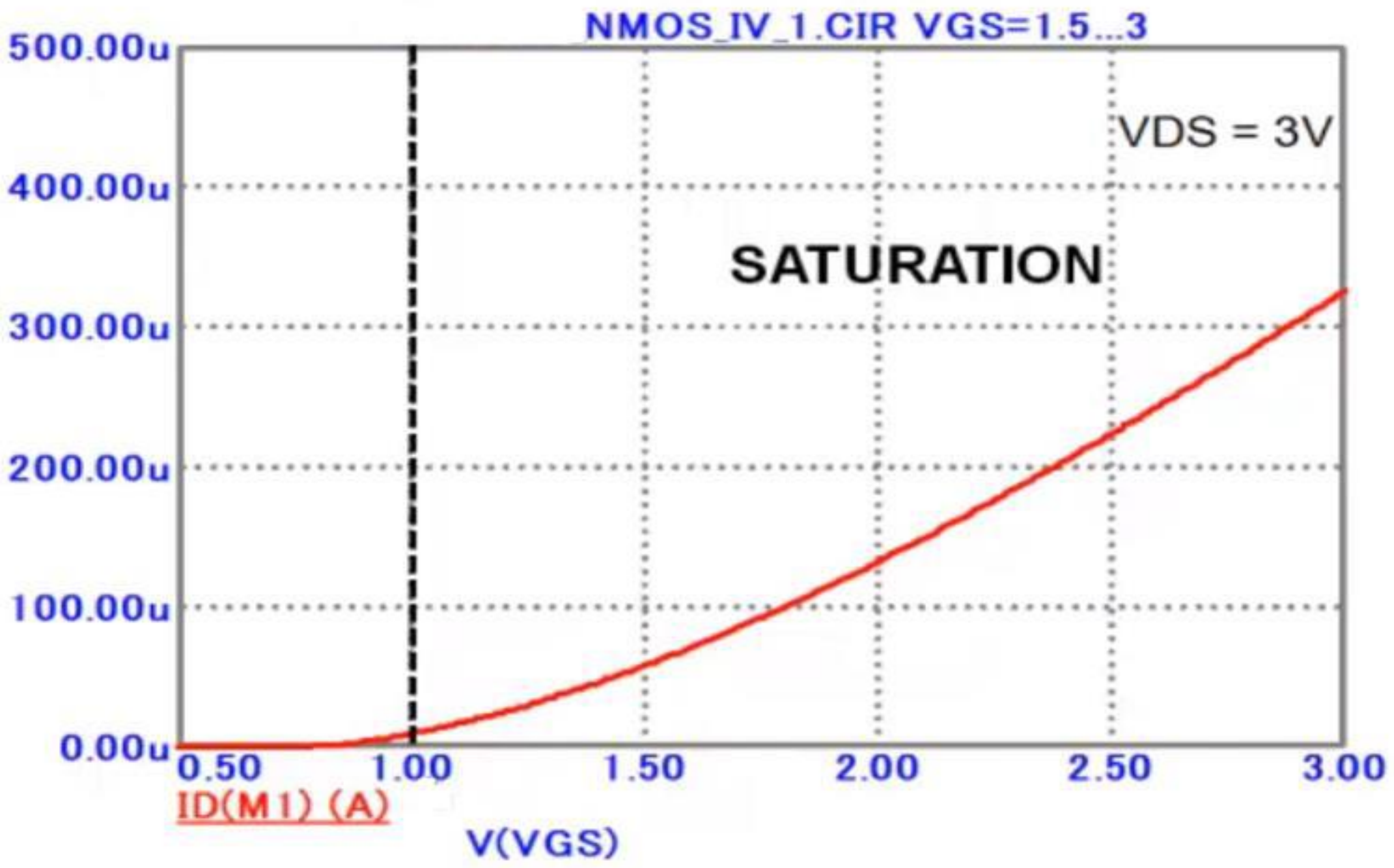
Although both K_{PN} and V_{THN} and decrease with temperature, the former causes a decrease in current while the latter causes an increase in current.m



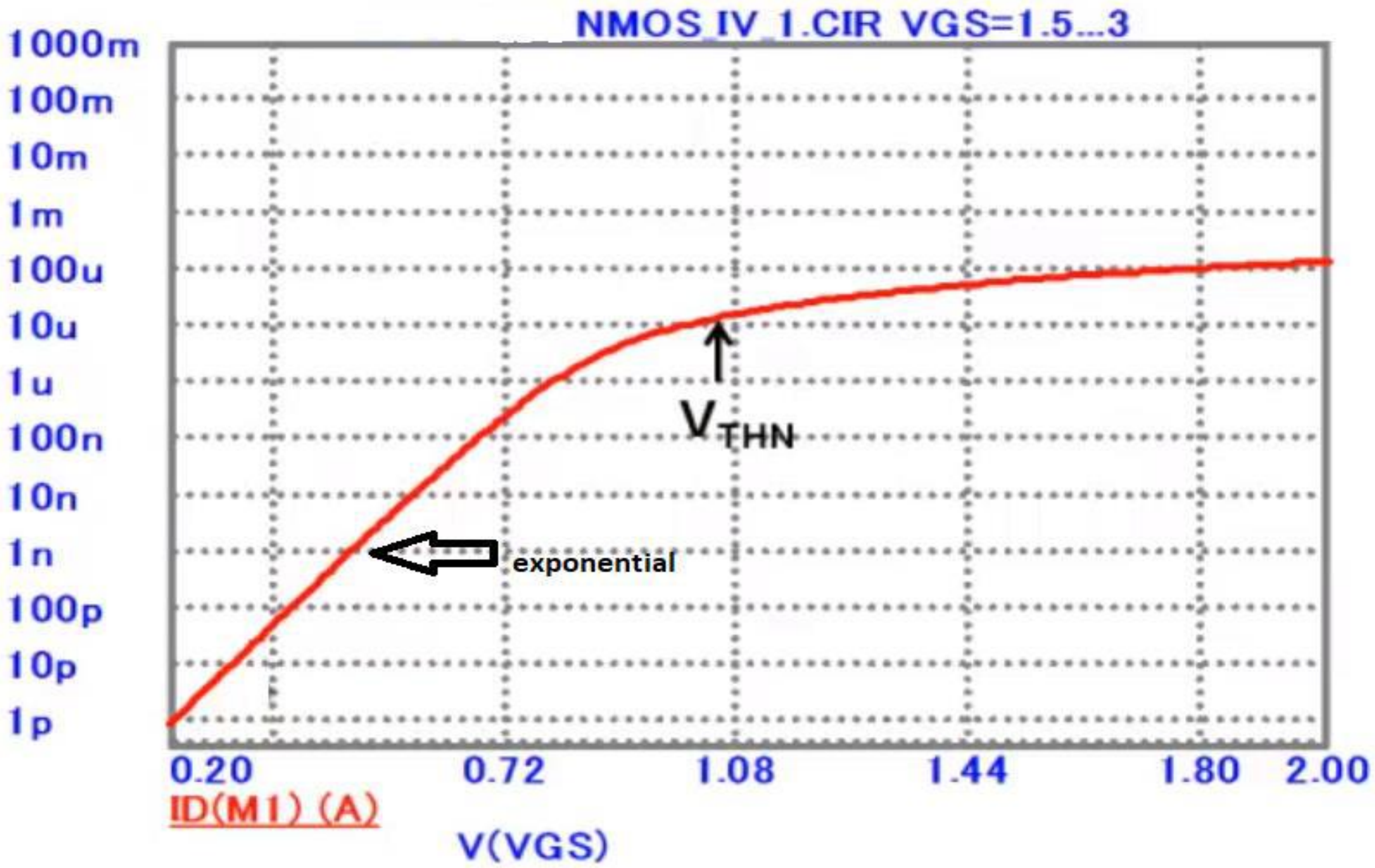



MOS Operating Regions
Above Threshold
($V_{GS} > V_{TN}$)
Subthreshold
($V_{GS} < V_{TN}$)
Saturation
($V_{DS} > V_{DSAT}$)
Triode
($V_{DS} < V_{DSAT}$)

Transfer characteristics of NMOS



Current is very small until gate-source voltage **exceeds threshold voltage V_{THN}**



-Logscale
-Ignoring leakages

$$I_D \propto e^{\frac{qV_{GS}}{N'kT}} \qquad\qquad g_m = \frac{\partial I_{DS}}{\partial Vgs} = \frac{I_{DS}}{nV_T}$$

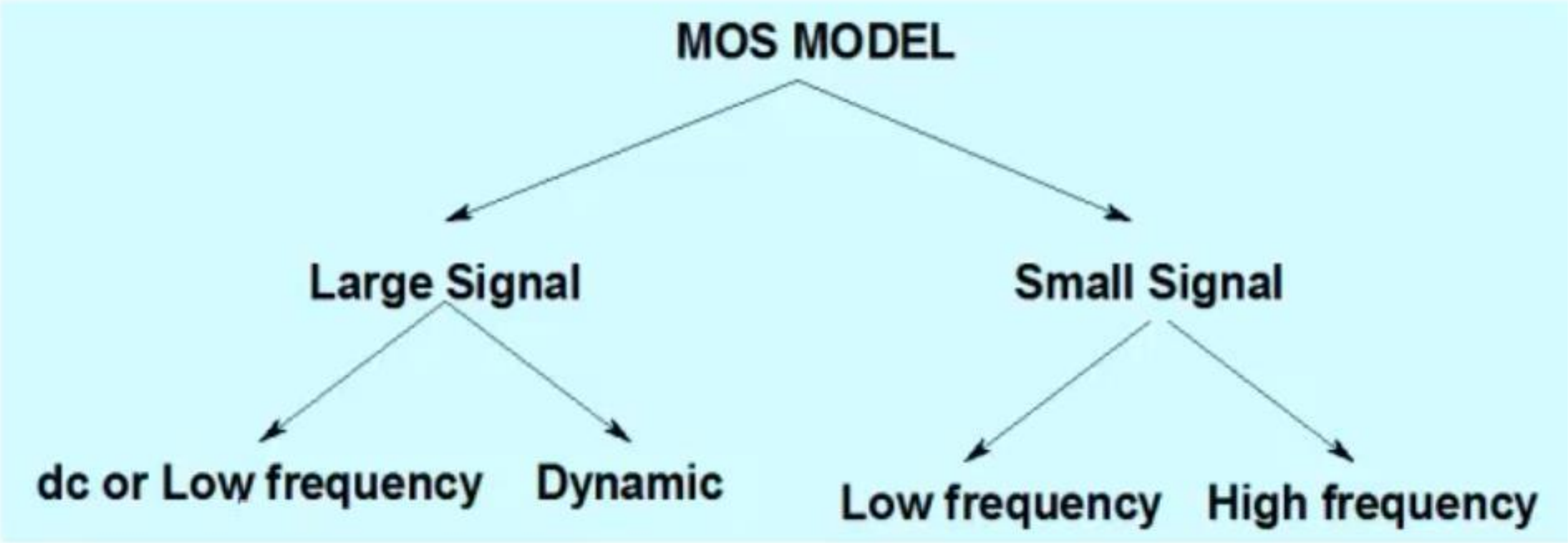
- In subthreshold region, MOS acts like a BJT

$$BJT: \qquad I_C = I_S e^{V_{BE}/V_T}$$

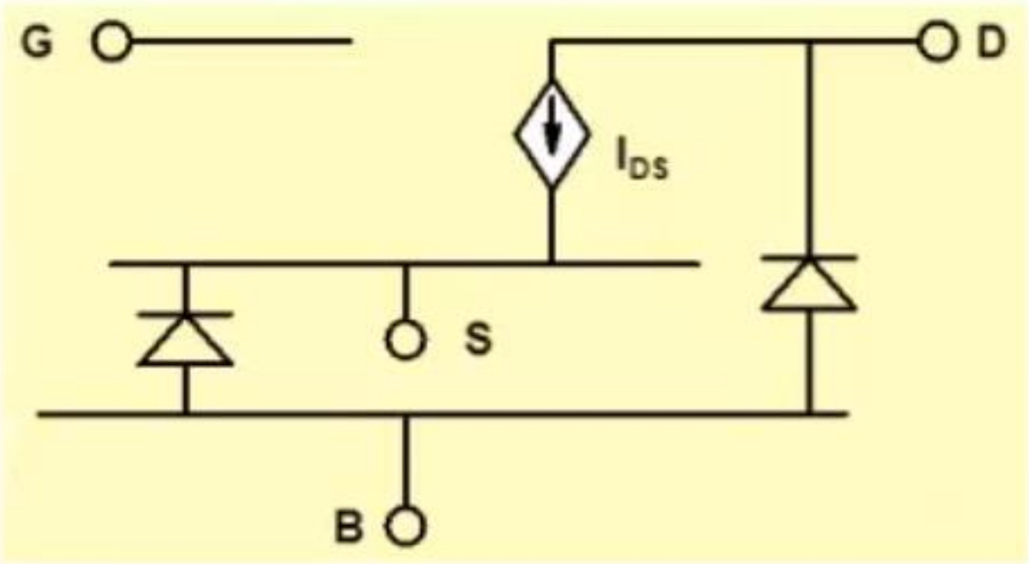
$$MOS: \quad I_{DS} = I_S e^{V_{GS}/\eta V_T}$$

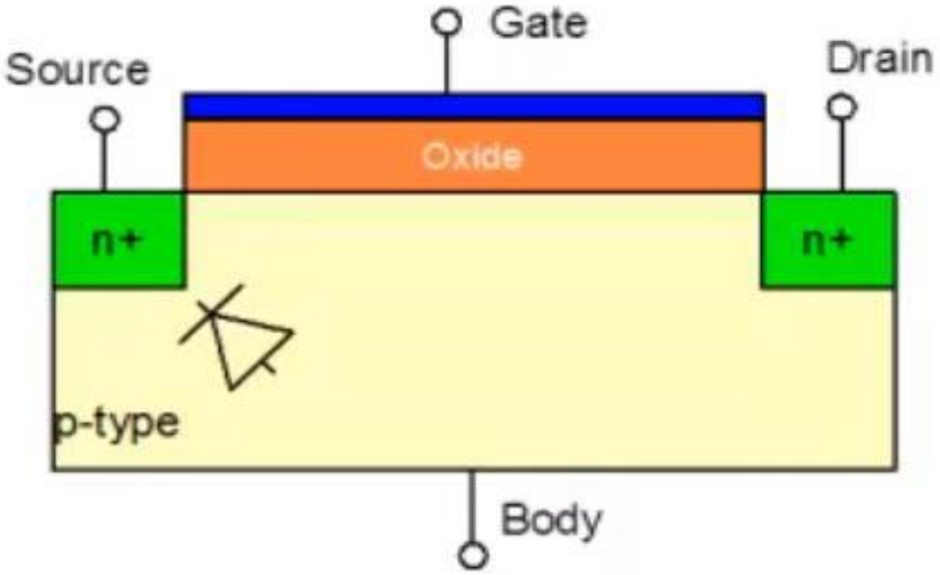
- The advantage of MOS is that it offers almost infinite input impedance. Its disadvantage is that current levels are low.

MOS models : The classification of models can be done on the basis of magnitude and frequency of applied voltages



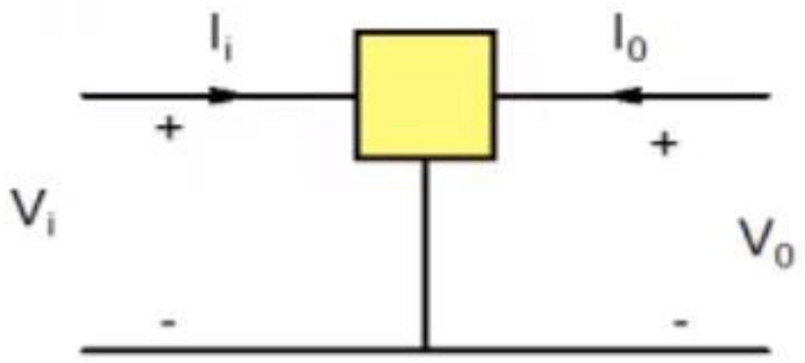
The dc model of the transistor in triode and saturation region can be represented in the form of an equivalent circuit:

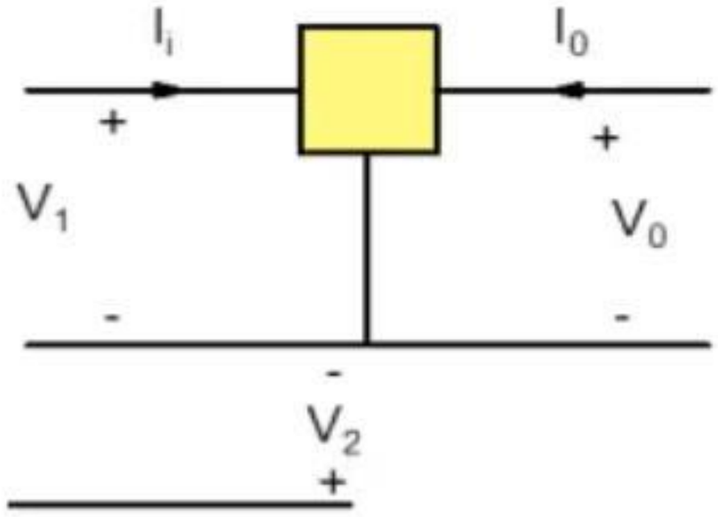


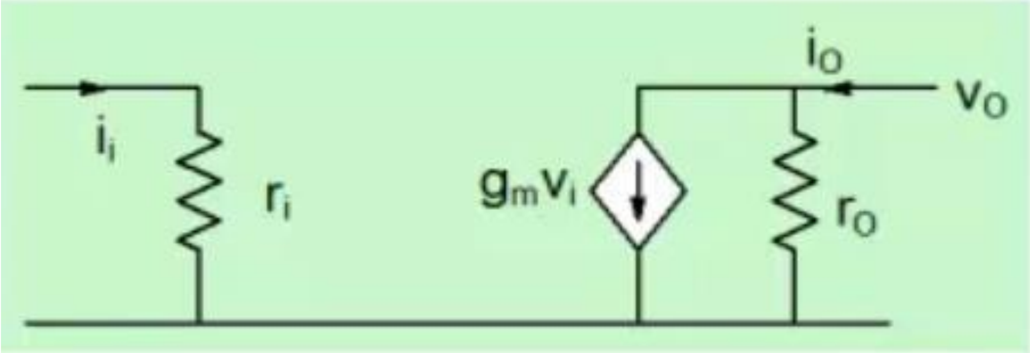


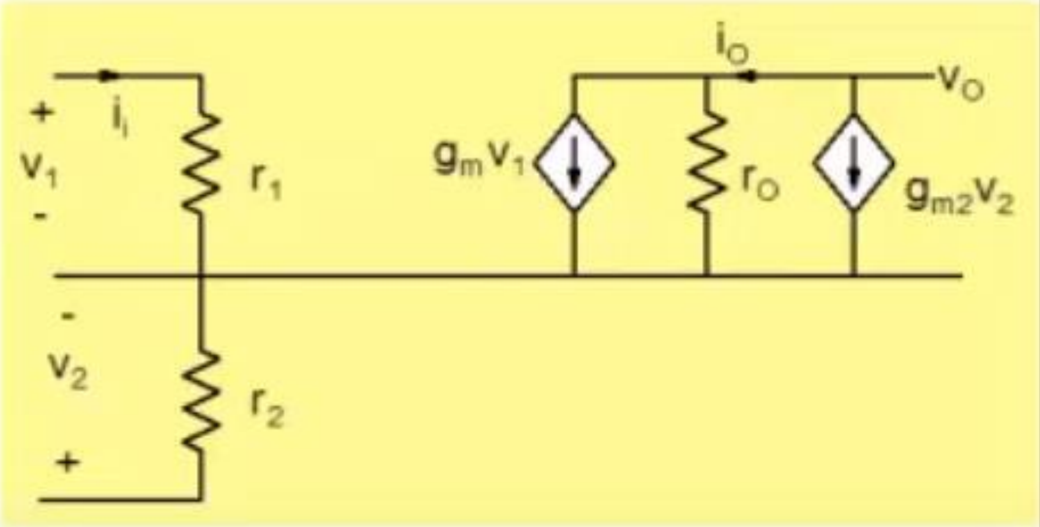
Series resistance associated with gate, source, drain and body terminals is not shown but can play an important role.

Complete small signal model (dc) for a 3-terminal unilateral device.

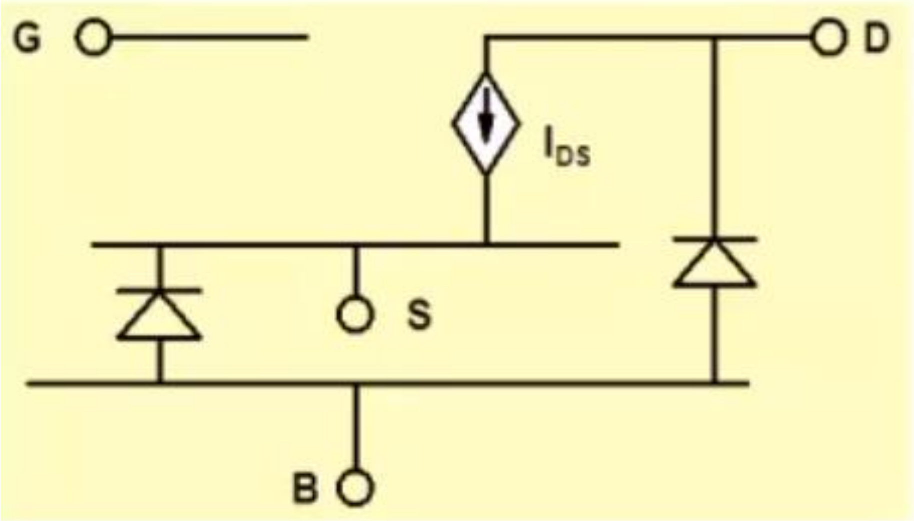








Small Signal Model (dc/low frequency)



$$I_{ds} = \frac{\beta_N}{2}\left(V_{gs} - V_{THN}\right)^2 (1 + \lambda_n V_{ds})$$

$$V_{gs} = V_{GSQ} + v_{gs} \qquad V_{ds} = V_{DSQ} + v_{ds} \qquad V_{sb} = V_{SBQ} + v_{sb}$$

$$I_{ds} = I_{DSQ} + i_{ds}$$

$$I_{DSQ} + i_{ds} = \frac{\beta_N}{2}\left[V_{GSQ} + v_{gs} - V_{THN}\left(V_{BSQ} + v_{bs}\right)\right]^2 \left(1 + \lambda_n V_{DSQ} + \lambda_n v_{ds}\right)$$

not really multiplication, but function

$$i_{ds} \cong I_{DSQ}\left\{\left(\lambda_n v_{ds} + \frac{2v_{gs}}{V_{GSQ} - V_{THN}} + \frac{\gamma \times v_{bs}}{(V_{GSQ} - V_{THN}) \times \sqrt{2\varphi_F - V_{BSQ}}}\right)\right\}$$

$$i_{ds} = \frac{v_{ds}}{r_o} + g_m v_{gs} + g_{mb} v_{bs}$$

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

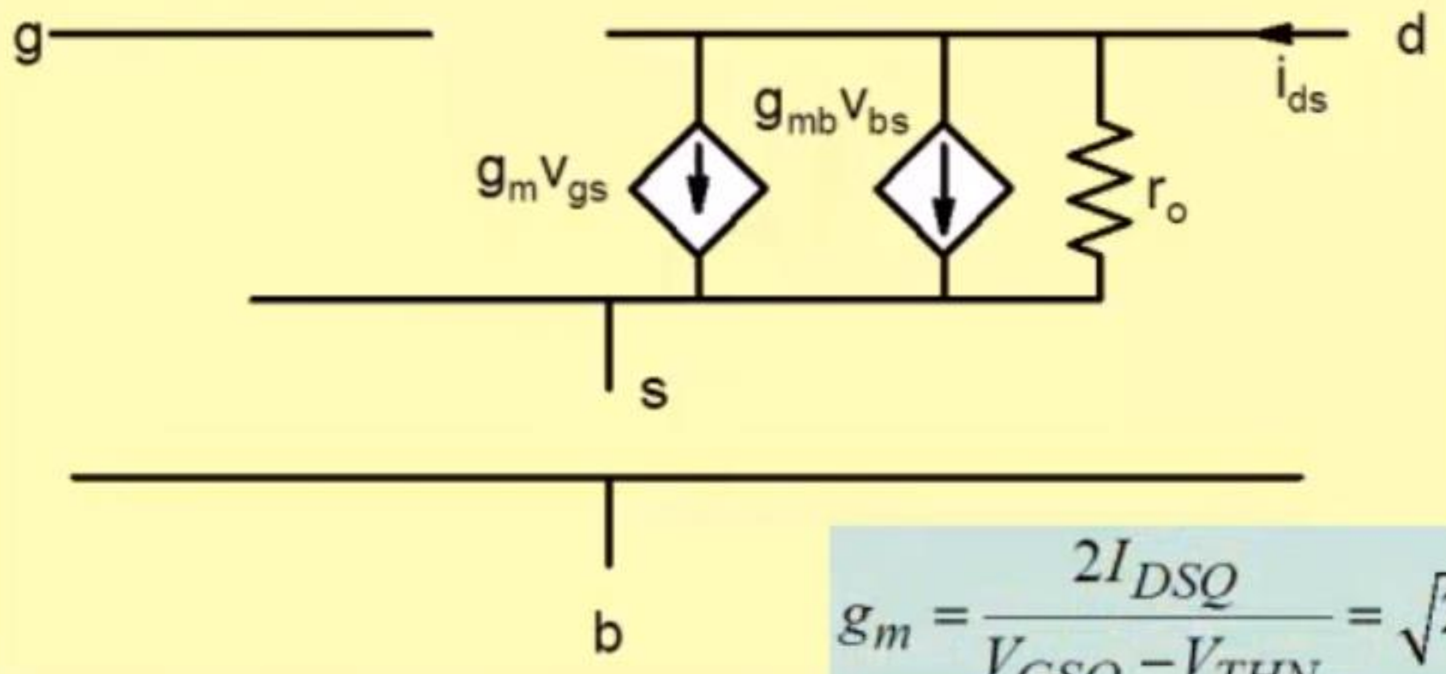
$$g_m = \frac{2I_{DSQ}}{V_{GSQ} - V_{THN}} = \sqrt{2I_{DSQ}\beta}$$

$$g_{mb} = g_m . \eta$$

$$\eta = \frac{\gamma}{2\sqrt{2\Phi_F + V_{SBQ}}}$$

Low frequency Small Signal model

$$i_{ds} = g_m v_{gs} + g_{mb} v_{bs} + \frac{v_{ds}}{r_o}$$



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

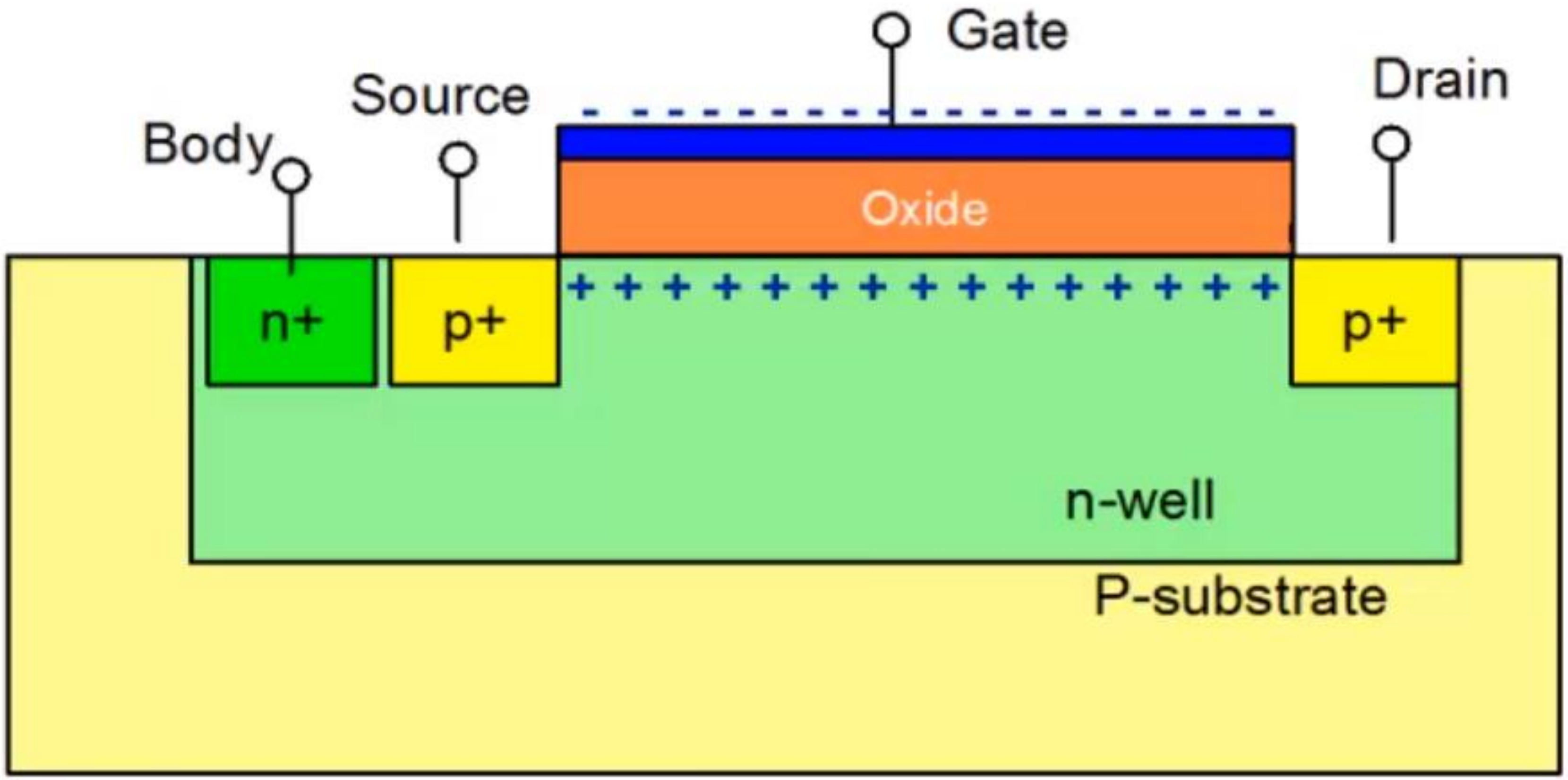
$$r_o = \frac{1}{\lambda_n I_{DSQ}}$$

$$g_{mb} = g_m.\eta$$

$$\eta = \frac{\gamma}{2\sqrt{2\Phi_F + V_{SBQ}}}$$

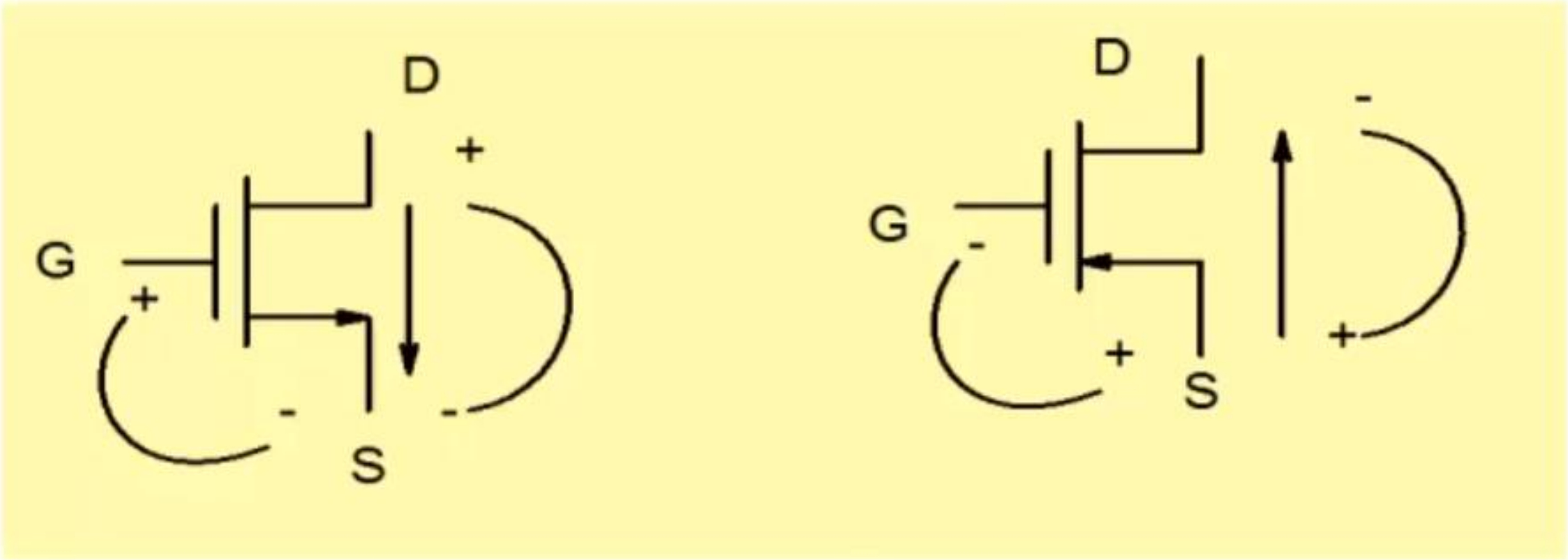
The small signal approximation $i_{ds} = g_m v_{gs}$ is accurate when $v_{gs} << 2(V_{GS} - V_{THN})$

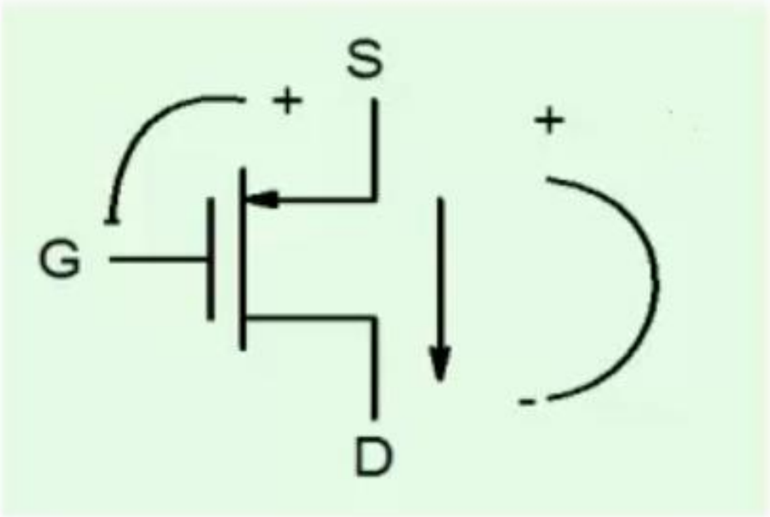
PMOS



V_{GS} is negative ; Threshold voltage V_{TP} is negative

V_{DS} is negative ; I_{DS} is negative





$$V_{GSN} \rightarrow V_{SGP}$$

$$I_{DSN} \rightarrow I_{SDP}$$

$$V_{DSN} \rightarrow V_{SDP}$$

Transformations

$$V_{GSN} \rightarrow V_{SGP} \qquad V_{DSN} \rightarrow V_{SDP} \qquad V_{BSN} \rightarrow V_{SBP}$$

$$V_{THN} \rightarrow -V_{THP} \qquad I_{DSN} \rightarrow I_{SDP}$$

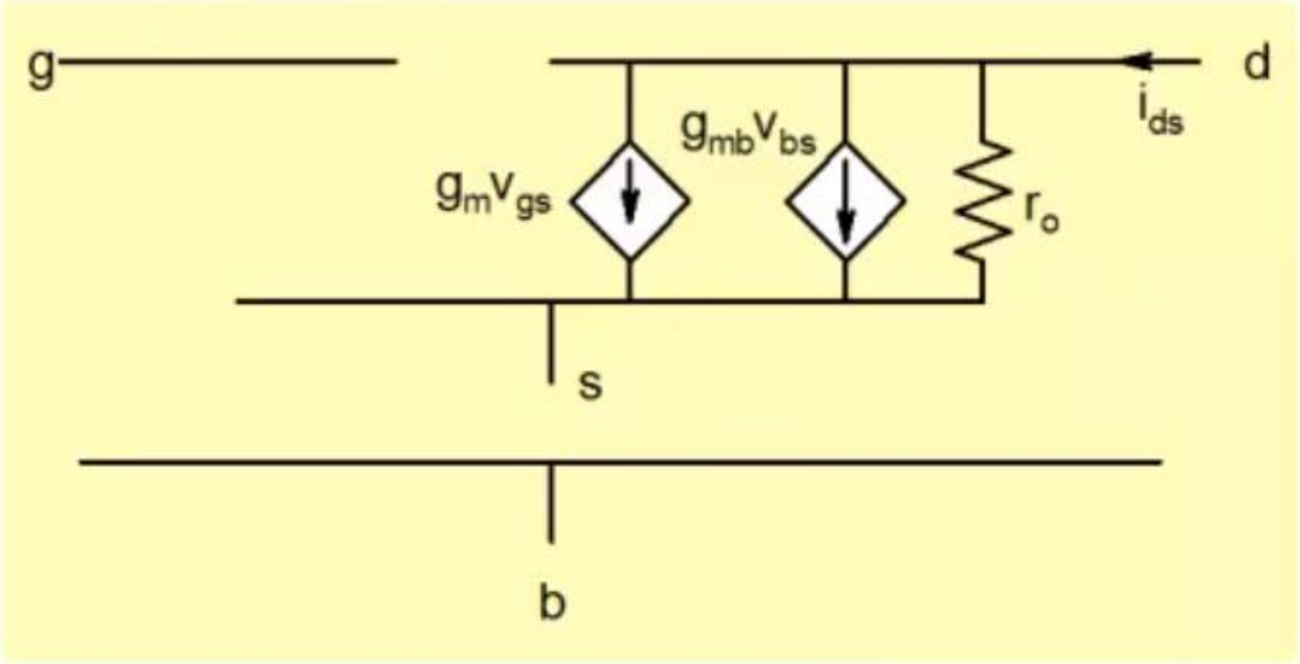
$$I_{DS} = \frac{\beta_N}{2}(V_{GS} - V_{THN})^2[1 + \lambda_n V_{DS}] \rightarrow$$

$$I_{SD} = \frac{\beta_P}{2}(V_{SG} + V_{THP})^2[1 + \lambda_p V_{SD}]$$

$$i_{sd} = g_m v_{sg} + g_{mb} v_{sb} + \frac{v_{sd}}{r_o}$$

$i_{ds} = g_m v_{gs} + g_{mb} v_{bs} + \frac{v_{ds}}{r_o}$ same as NMOS

Small Signal Model



$$g_m = \frac{2I_{SDQ}}{V_{SGQ} + V_{THP}}$$

$$r_o = \frac{1}{\lambda_p I_{SDQ}}$$