Analog IC Design : 2022-23
Lecture 2
MOSFET Single Stage Amplifiers Part-1

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MOSFET Large Signal Equivalent

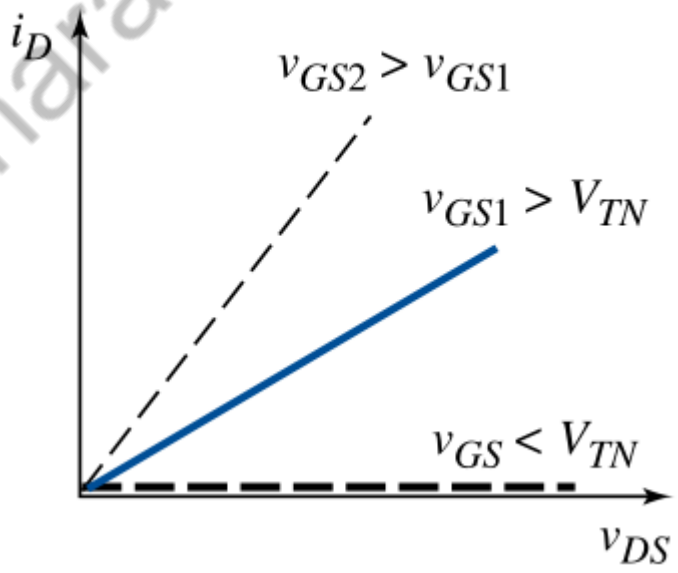
Based on content from
Sedra/Smith “Microelectronic Circuits” - Fifth Edition

MOSFET Large Signal Equivalent

Cut-off Region

$For\ V_{GS} < V_T \qquad I_D = 0$

Linear Region- Small V_{DS}



$$I_D = \frac{\mu_n C_{ox} W (V_{GS} - V_T) V_{DS}}{L}$$

$$Transconductance\ of\ Channel\ g_{DS} = \frac{\mu_n C_{ox} W V_{ov}}{L}$$

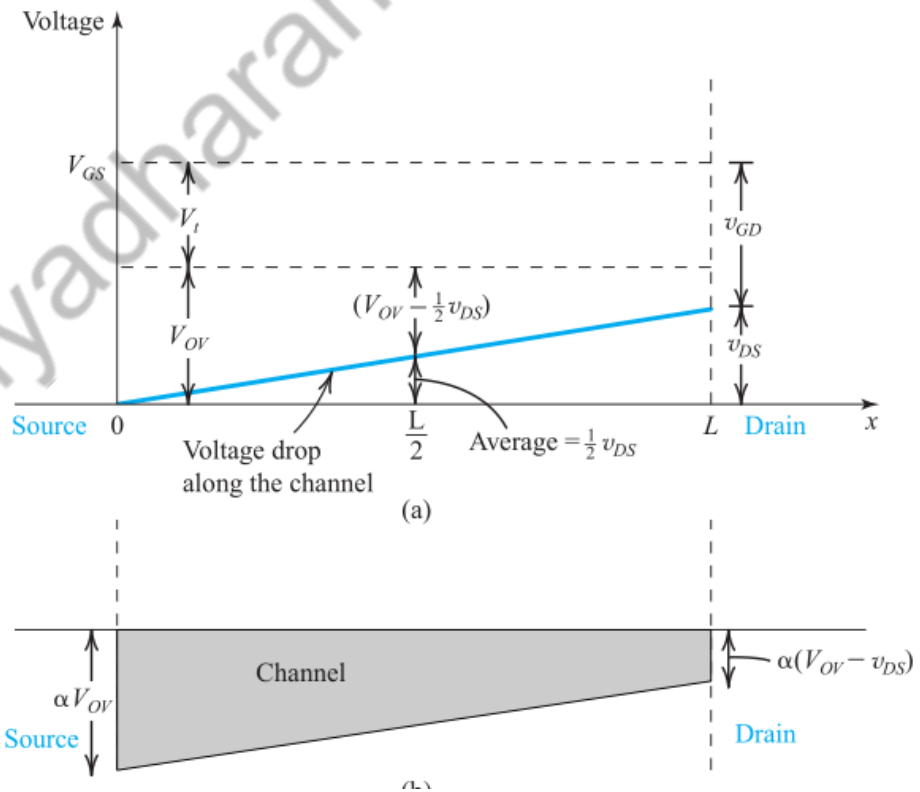
$$Process\ transconductance\ parameter\ k_n' = \mu_n C_{ox}$$

$$I_D = \frac{k_n' W V_{ov} V_{DS}}{L}$$

MOSFET Large Signal Equivalent

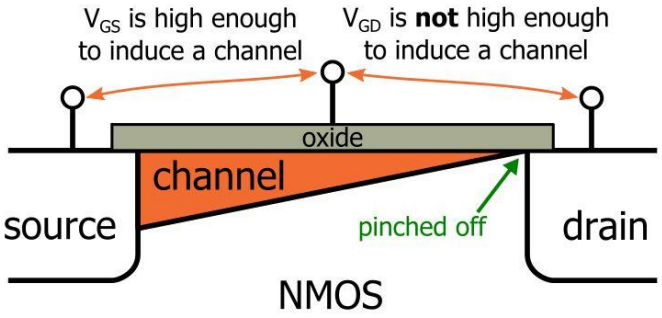
Linear Region as V_{DS} is Increased

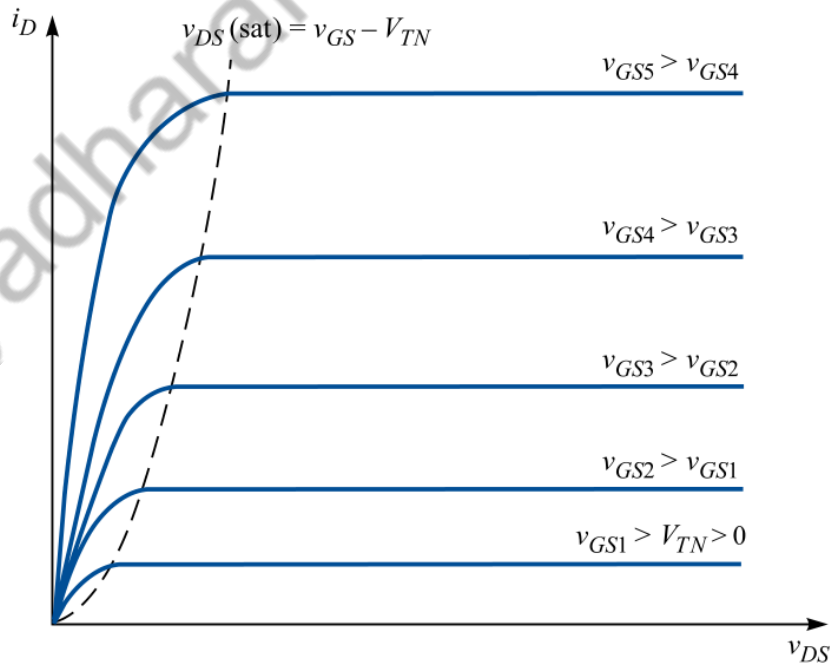
$$I_D = \frac{k_n' W (V_{ov} - \frac{V_{DS}}{2}) V_{DS}}{L}$$



MOSFET Large Signal Equivalent

Saturation Region



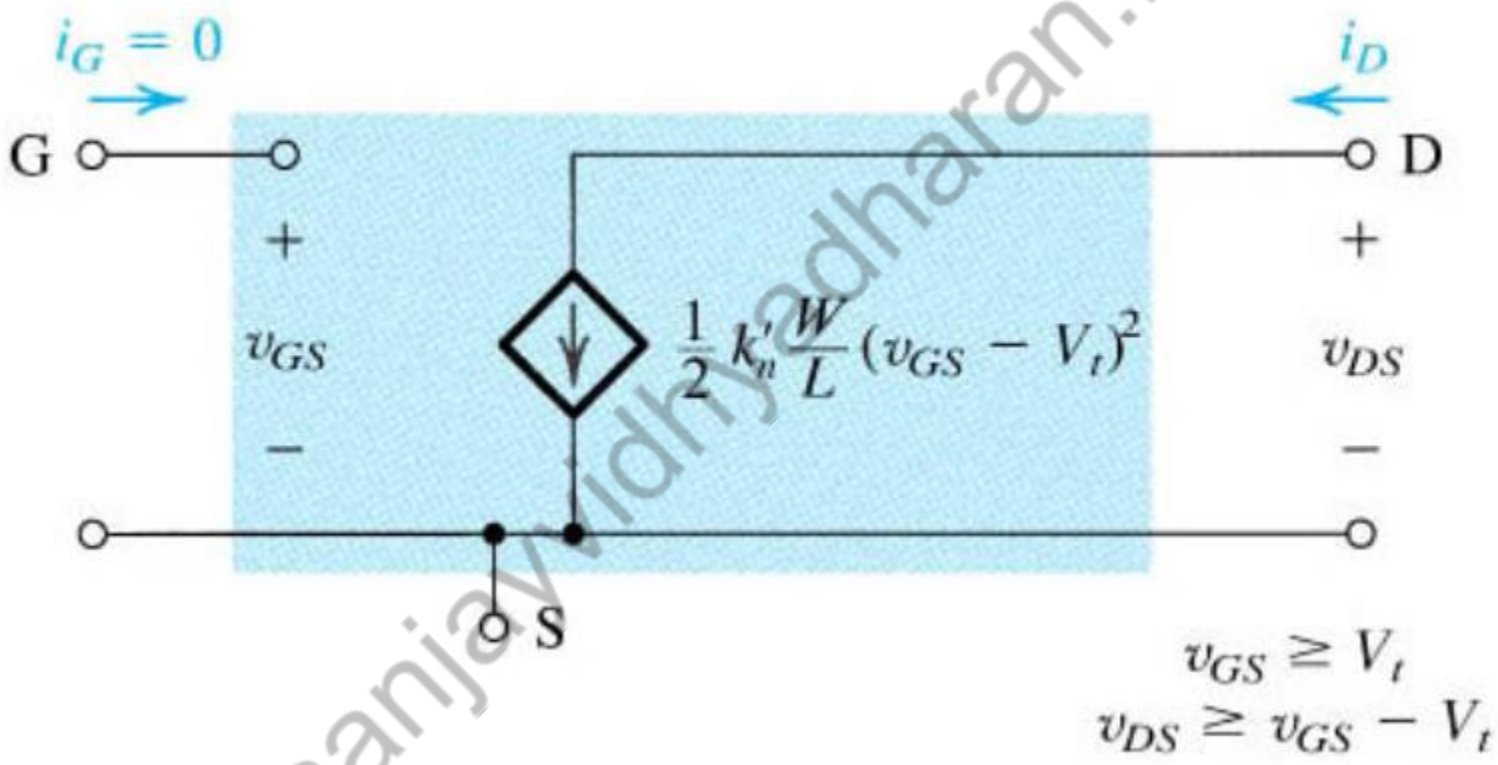


$$V_{DS} = V_{ov} = V_{GS} - V_T$$

$$I_D = \frac{k_n' W (V_{ov} - \frac{V_{DS}}{2}) V_{DS}}{L}$$

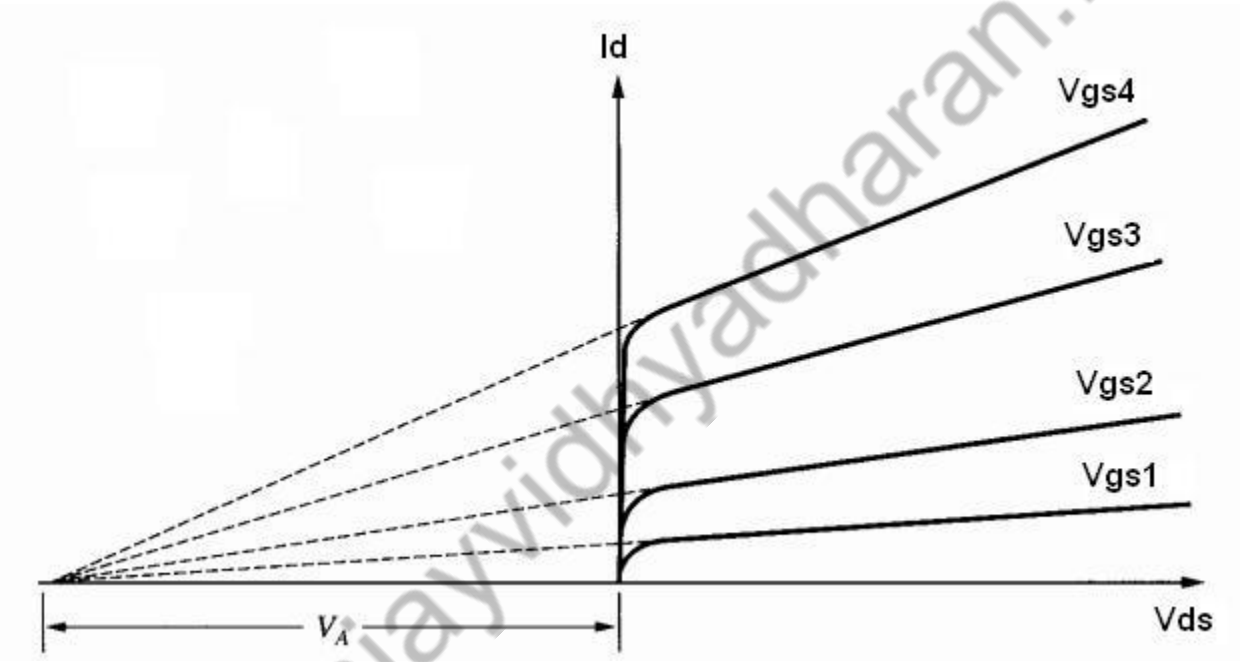
$$I_D = \frac{k_n' W (V_{GS} - V_T)^2}{2L}$$

MOSFET Large Signal Equivalent



MOSFET Large Signal Equivalent

Channel Length Modulation



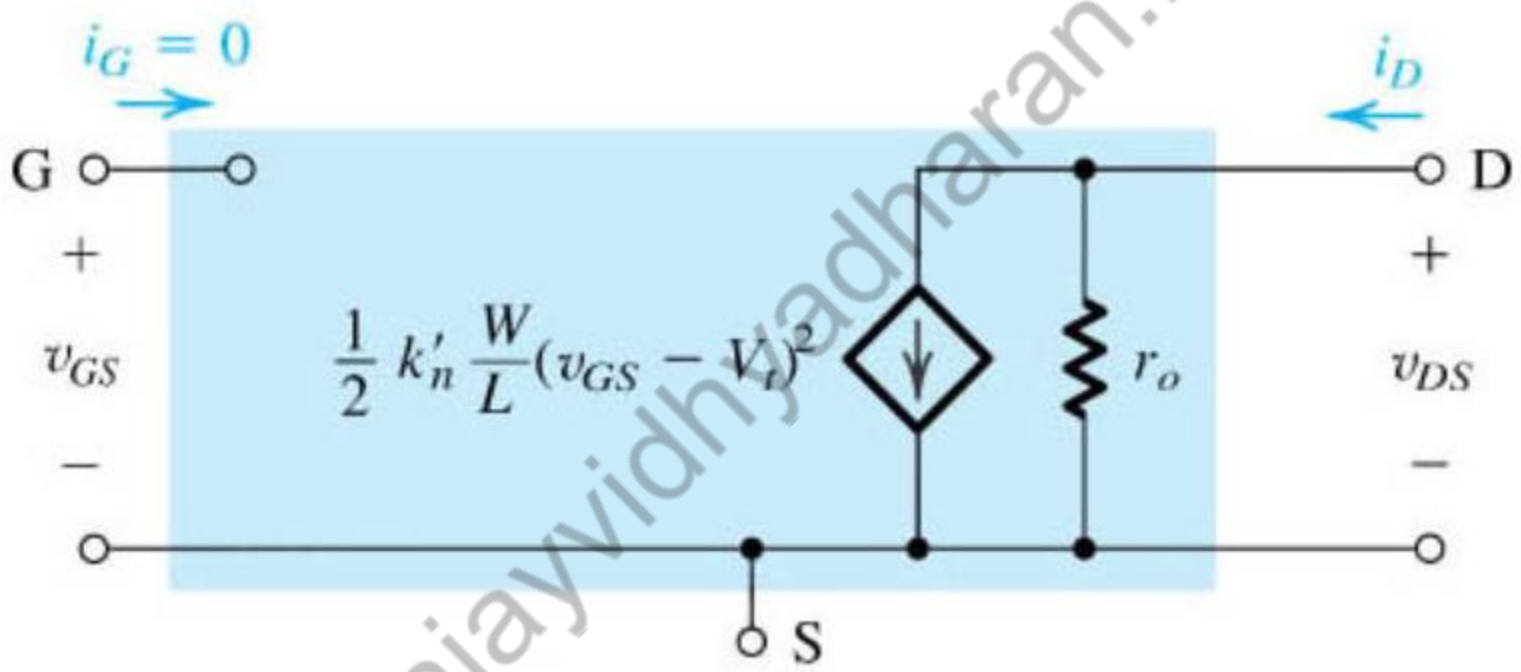
V_A *Early Voltage*

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

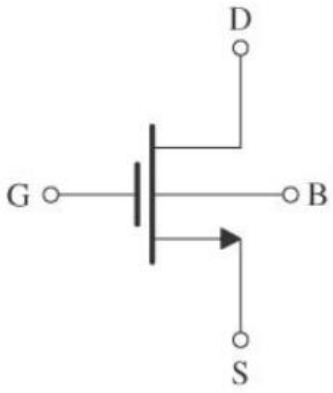
$$r_o \approx \frac{1}{\lambda I_D}$$

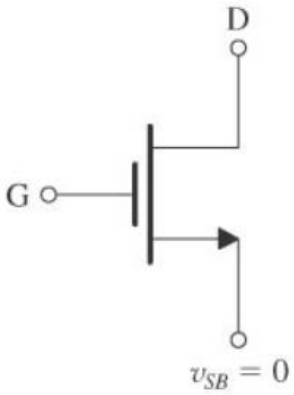
$\lambda \propto 1/L$

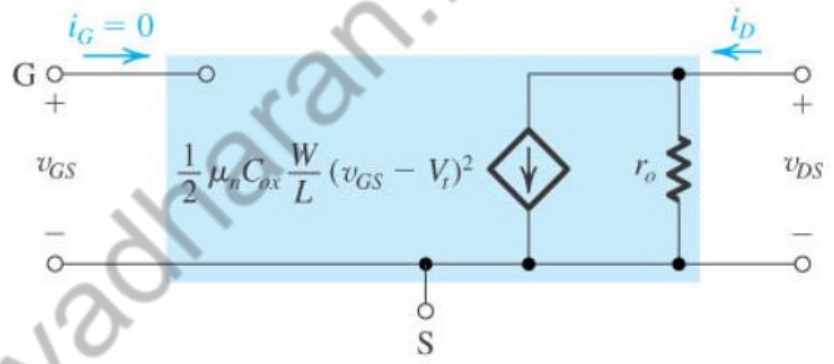
MOSFET Large Signal Equivalent

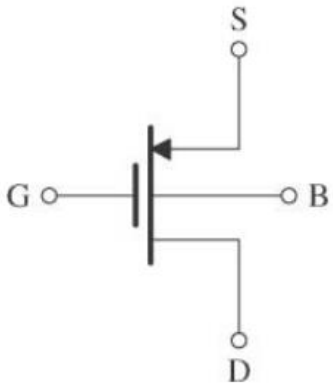


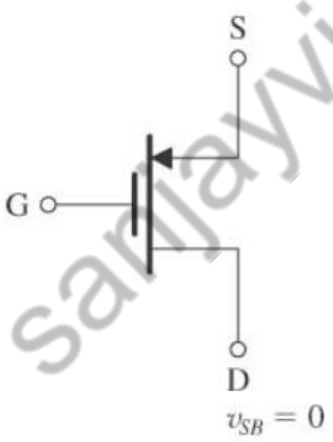
MOSFET Large Signal Equivalent

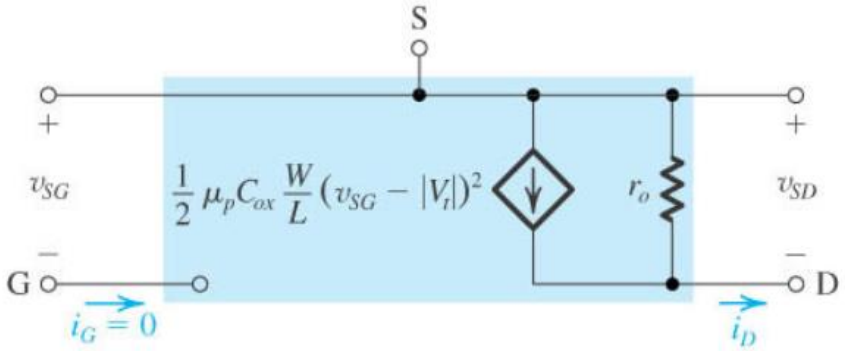




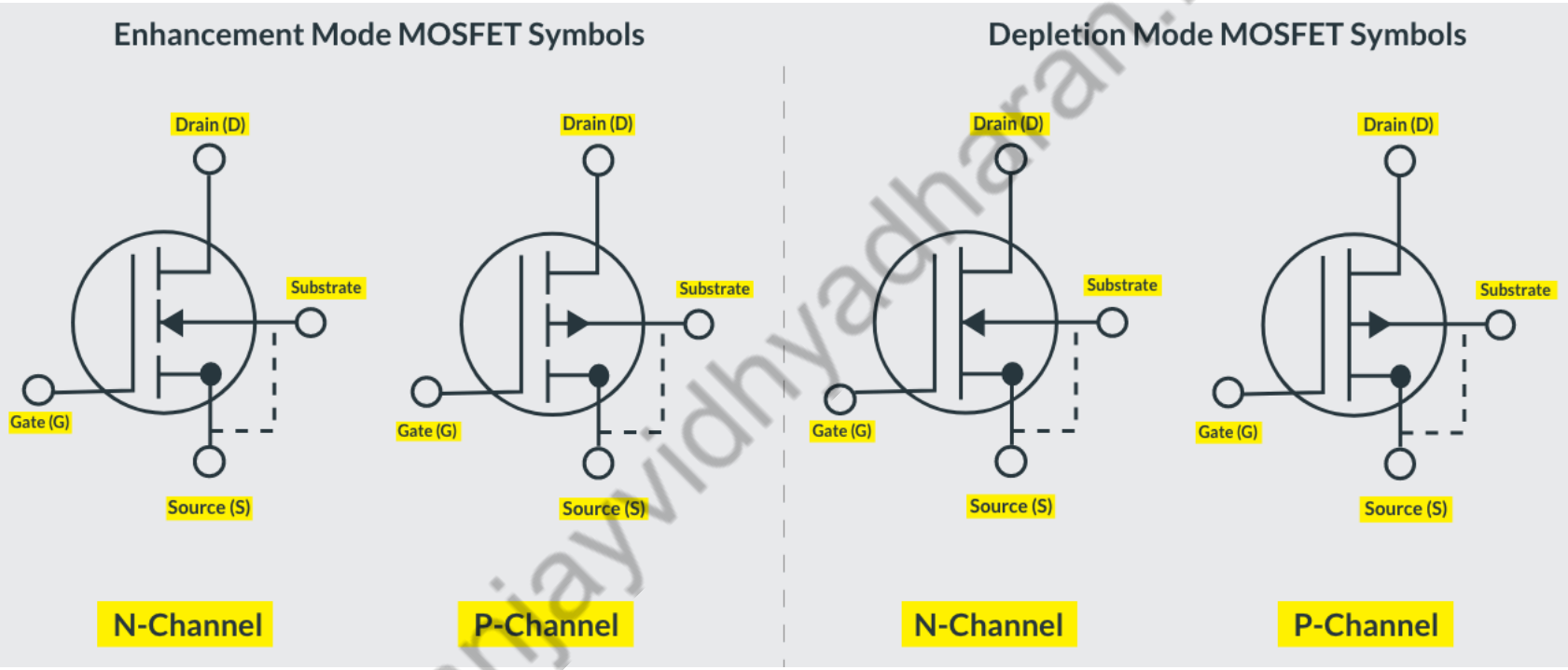




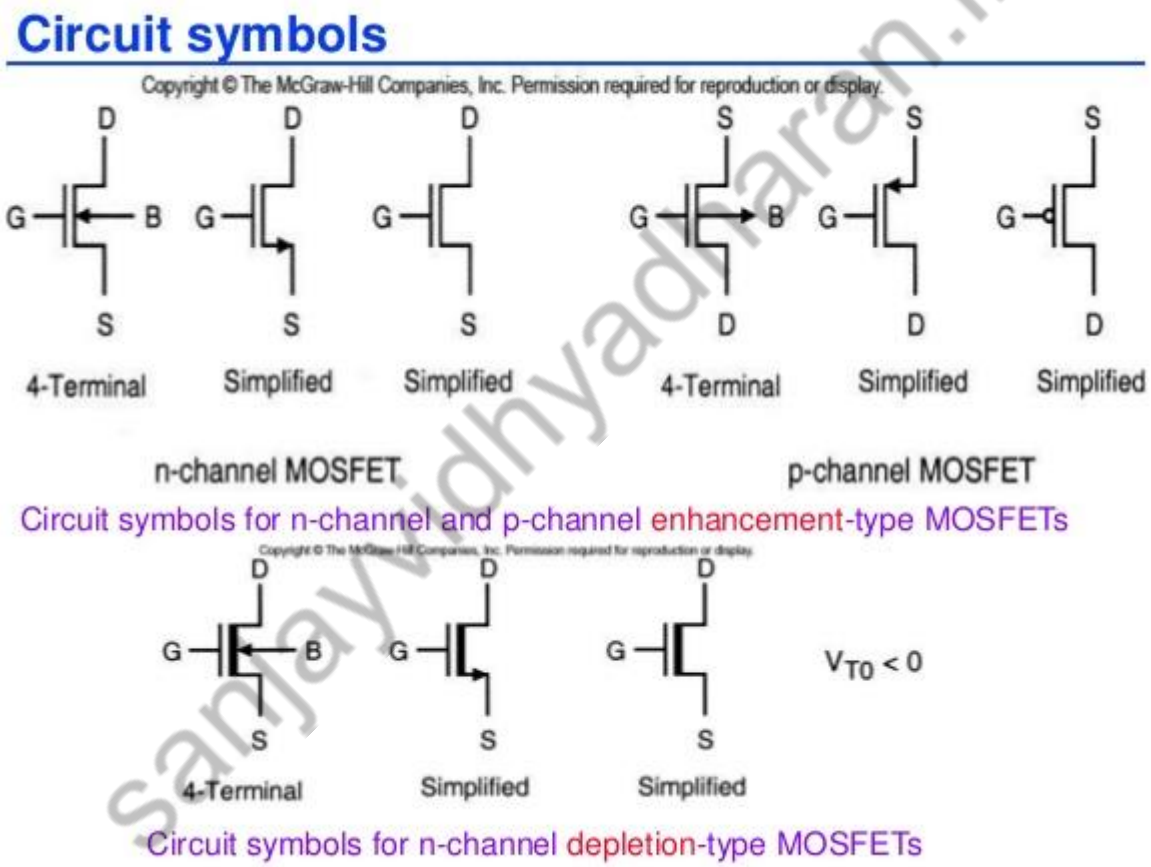




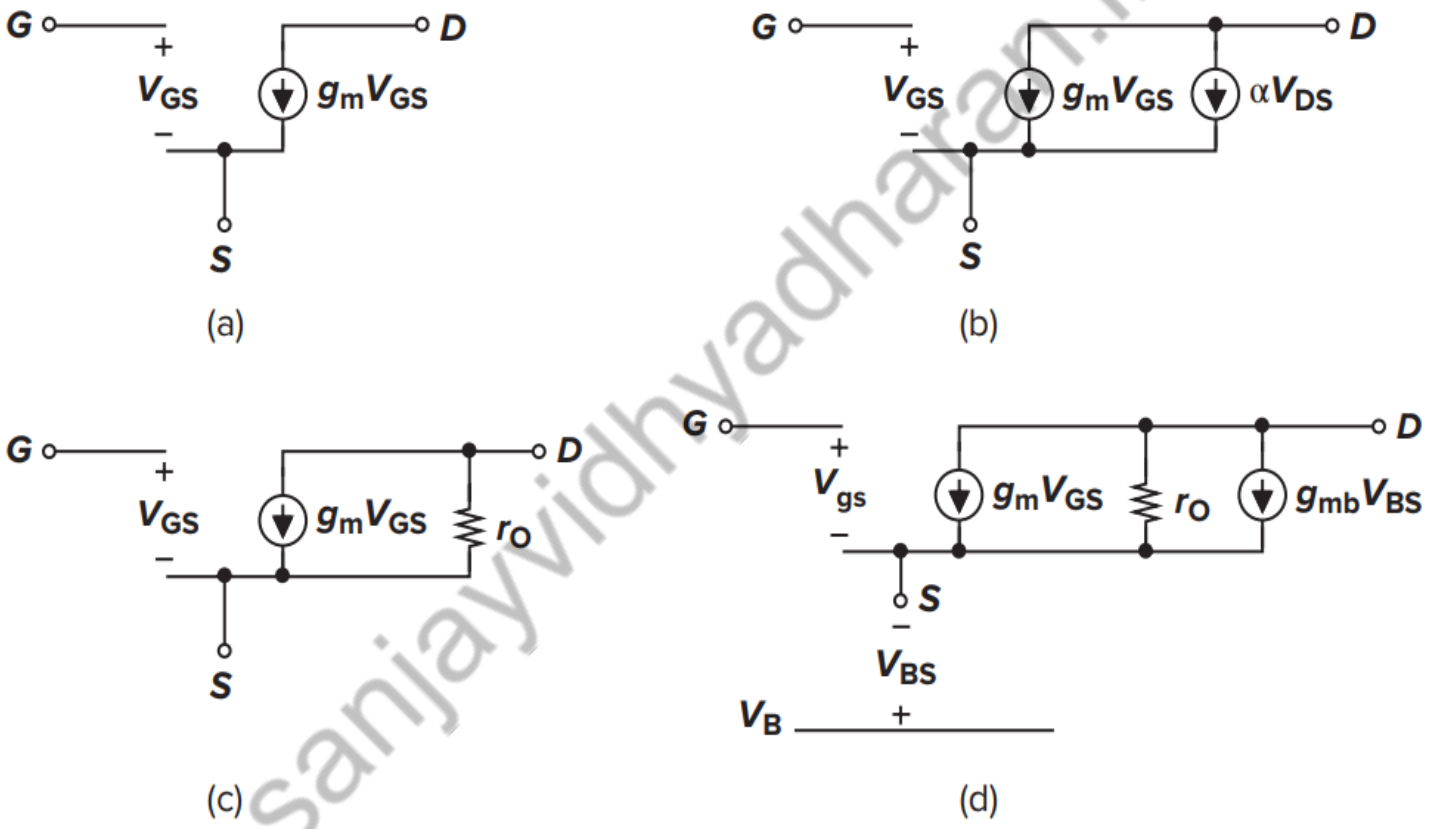
Circuit Symbols



Circuit Symbols



MOSFET Small Signal Equivalent



MOSFET Small Signal Equivalent

Small Signal Modelling

Find an equivalent circuit which relates the incremental changes in *iD*, *vGS*, *vDS*, etc.

Since the changes are small, the small-signal equivalent circuit has **linear** elements only (e.g., capacitors, resistors, controlled sources)

$$v_{GS} = V_{GS} + v_{gs}\ ,\ i_D = I_D + i_d$$

$$i_D = (1/2)\,\mu_n\, C_{ox}\,(W/L)\,(v_{GS} - V_{Tn})^2\,(1 + \lambda_n v_{DS}) = i_D(v_{GS},\, v_{DS},\, v_{BS})$$

$$(V_{GS} - VTn)^2 + 2(V_{GS} - VTn)\, v_{gs} + v_{gs}^{\,2}$$

$$g_m = \mu_n C_{ox}\left(\frac{W}{L}\right)(V_{GS} - V_{Tn})\,(1 + \lambda_n V_{DS})$$

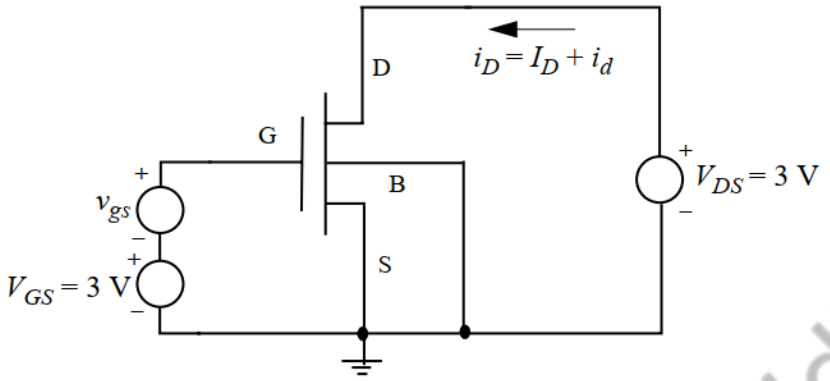
$$g_m = \mu_n C_{ox}\left(\frac{W}{L}\right)(V_{GS} - V_{Tn}) \quad \text{Neglecting CLM}$$

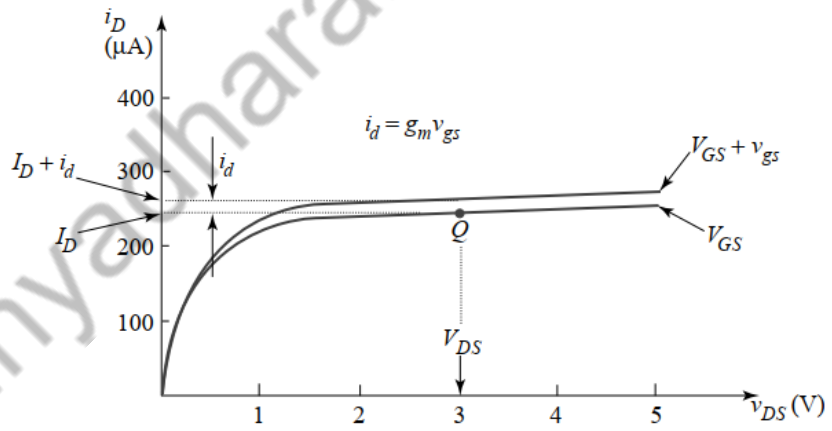
$$g_m = \sqrt{2\mu_n C_{ox}\left(\frac{W}{L}\right) I_D}$$

MOSFET Small Signal Equivalent

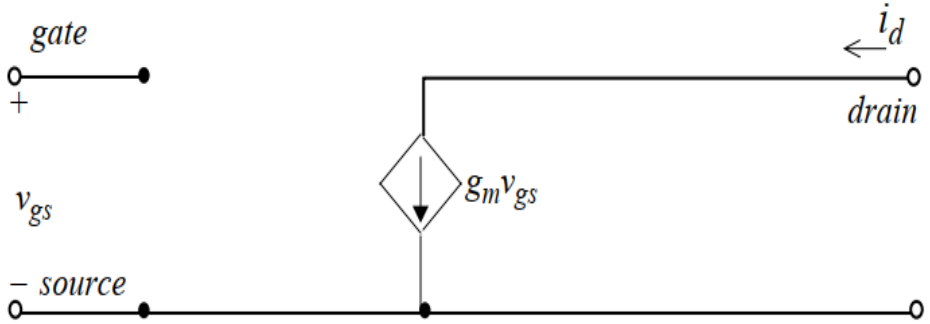
Transconductance

The small-signal drain current due to v_{gs} is given by $i_d = g_m v_{gs}$.



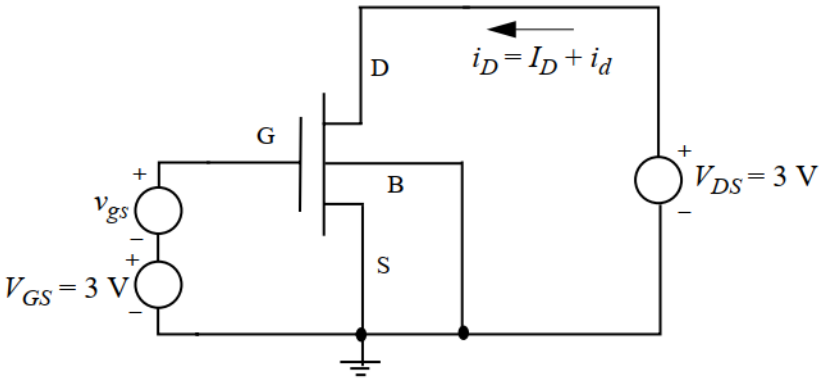


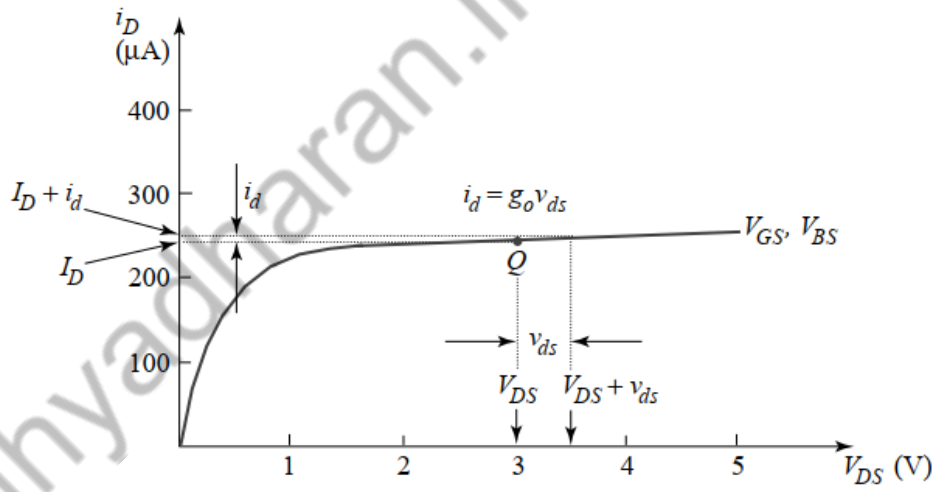
$$g_m = \sqrt{2\mu_n C_{ox}\left(\frac{W}{L}\right) I_D}$$



MOSFET Small Signal Equivalent

Output Conductance



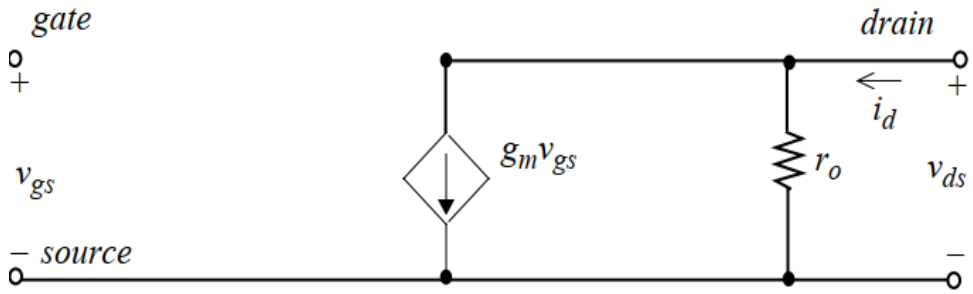


$$i_D = (1/2)\,\mu_n C_{ox}\,(W/L)\,(v_{GS} - V_{Tn})^2\,(1 + \lambda_n v_{DS})$$

$$g_o = \left.\frac{\partial i_D}{\partial v_{DS}}\right|_Q = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)(V_{GS} - V_T)^2\lambda_n \cong \lambda_n I_D$$

$$r_o = \frac{1}{g_o} = \frac{1}{\lambda_n I_D}$$

$$i_d = g_m v_{gs} + (1/r_o)v_{ds}$$



MOSFET Small Signal Equivalent

Backgate Transconductance

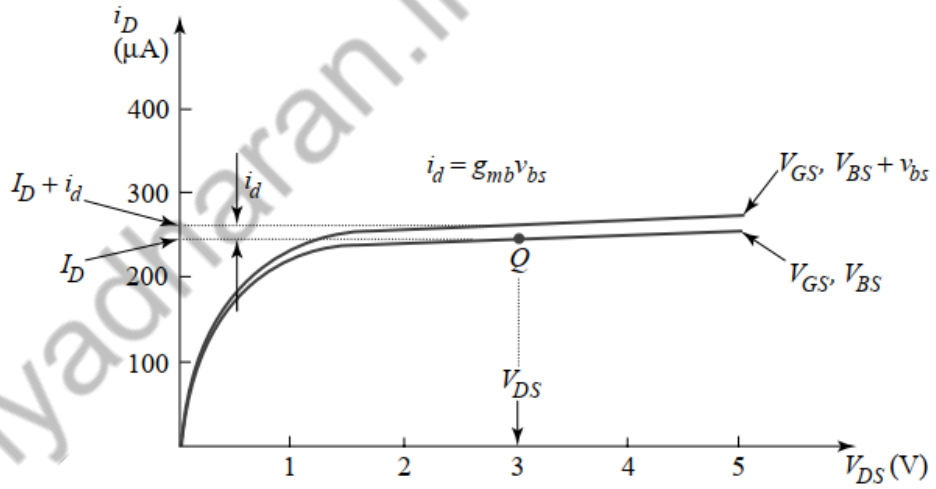
$$i_D = (1/2)\,\mu_n C_{ox}\,(W/L)\,(v_{GS} - V_{Tn})^2\,(1 + \lambda_n v_{DS})$$

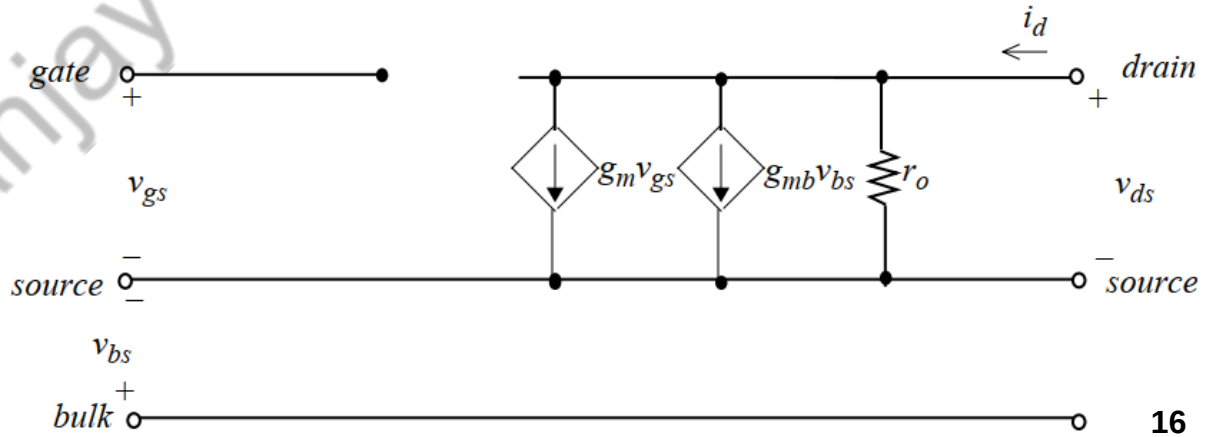
$$g_{mb} = \left.\frac{\partial i_D}{\partial v_{BS}}\right|_Q = \left.\frac{\partial i_D}{\partial V_{Tn}}\right|_Q \left.\frac{\partial V_{Tn}}{\partial v_{BS}}\right|_Q$$

$$\left.\frac{\partial i_D}{\partial V_{Tn}}\right|_Q = -\mu_n C_{ox}\left(\frac{W}{L}\right)(V_{GS} - V_{Tn})\,(1 + \lambda_n V_{DS}) \approx -g_m$$

$$V_{TH} = V_{TH0} + \gamma\left(\sqrt{|2\phi_F| + V_{SB}} - \sqrt{|2\phi_F|}\right)$$

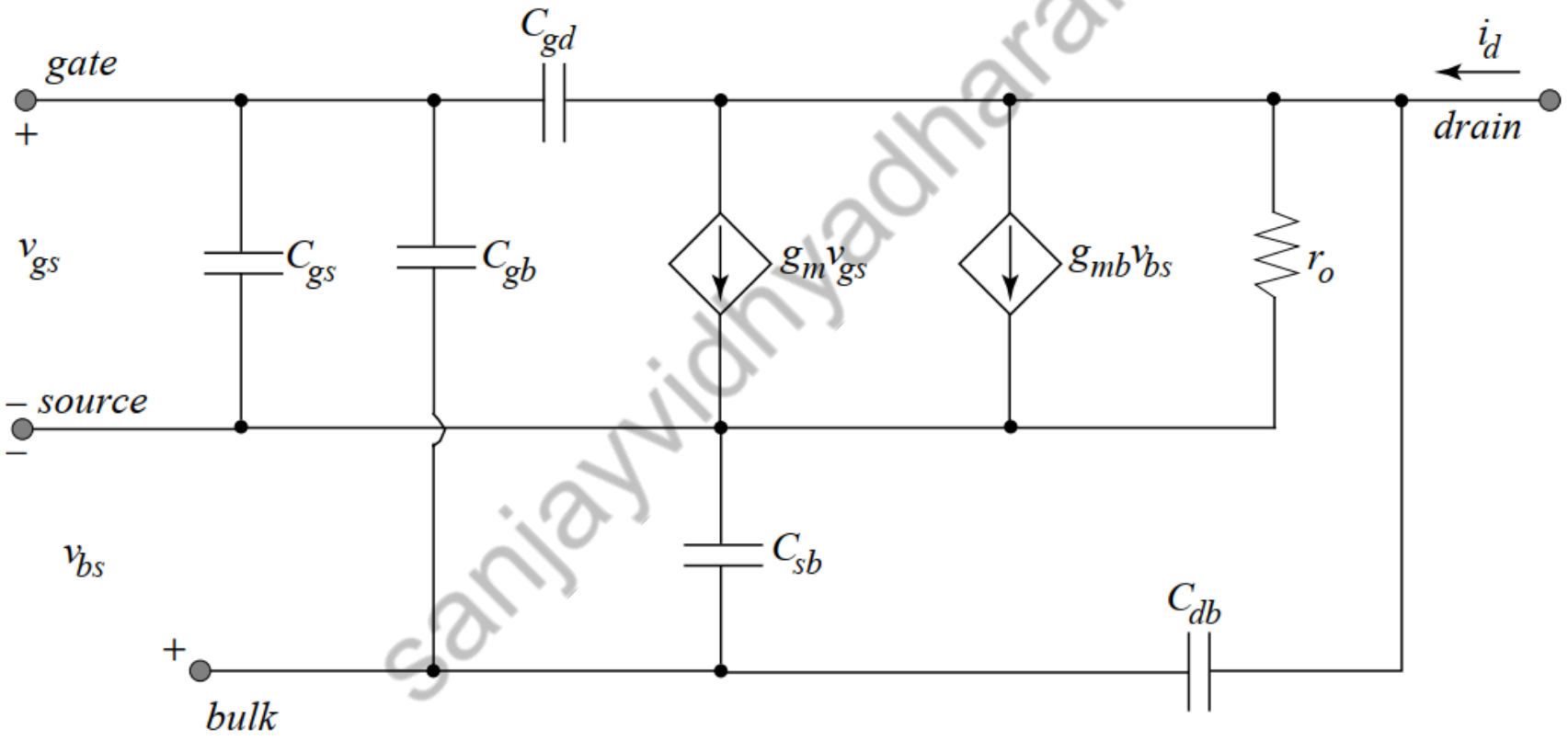
$$g_{mb} = (-g_m)\left.\frac{\partial V_{Tn}}{\partial v_{BS}}\right|_Q = (-g_m)\left(\frac{-\gamma_n}{2\sqrt{-2\phi_p - V_{BS}}}\right) = \frac{\gamma_n g_m}{2\sqrt{-2\phi_p - V_{BS}}}$$



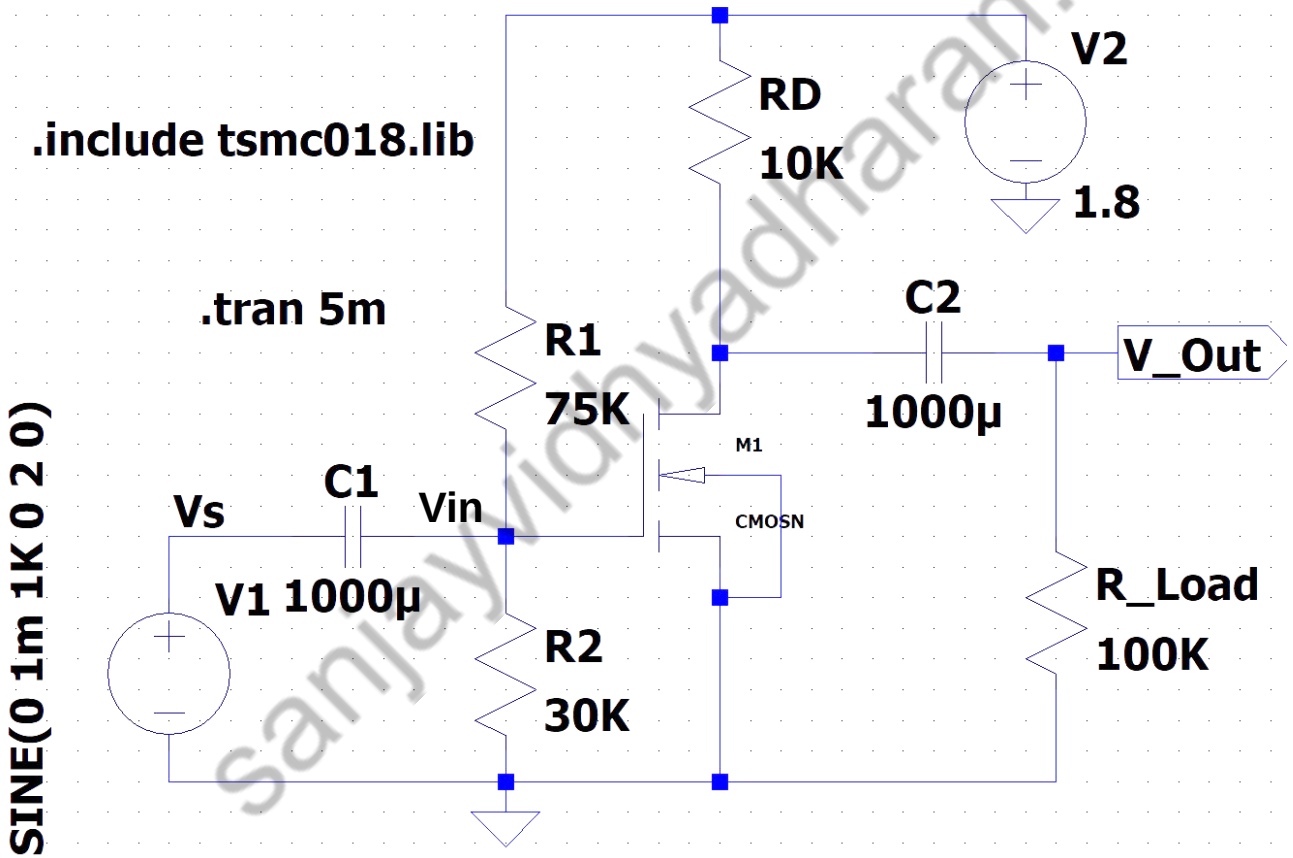


MOSFET Small Signal Equivalent

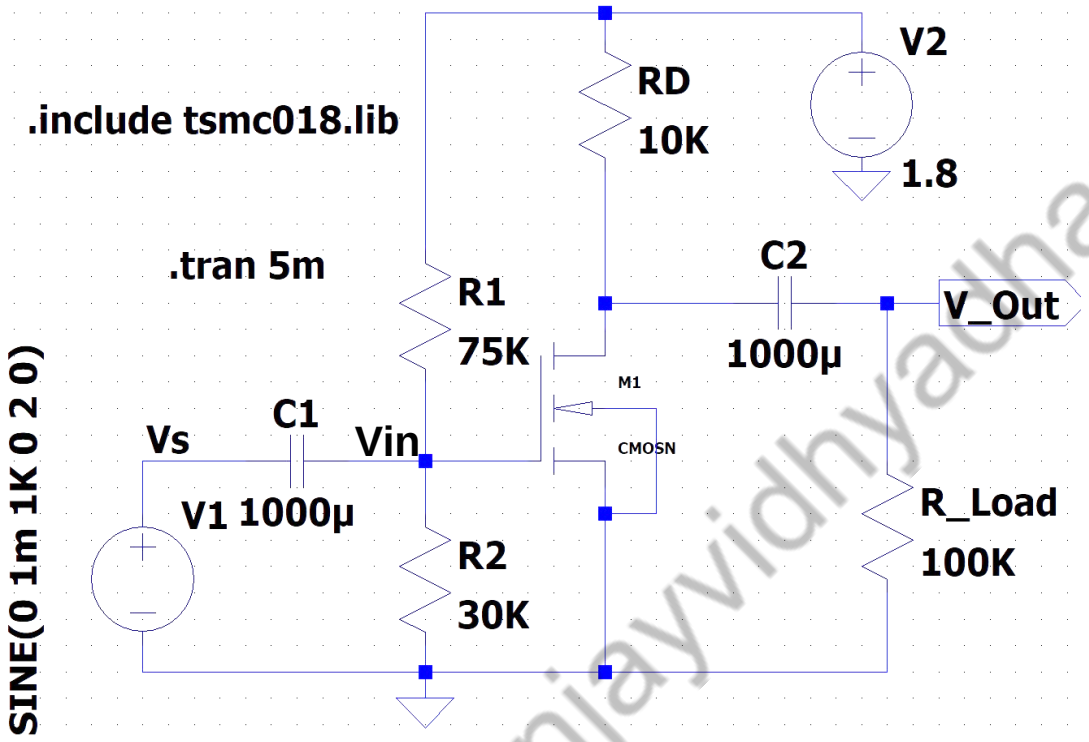
High Frequency Model



CS Amplifier



CS Amplifier



$$V_{Drain} = V_{DD} - I_D * R_D$$

$$V_{Drain} = V_{DD} - (I_{DC} + i_d) * R_D$$

$$V_{Drain} = V_{DQ} - i_d * R_D$$

$$V_{out} = -i_d * R_D$$

$$V_{out} = -g_m V_{in} * R_D$$

$$Gain = -g_m * R_D$$

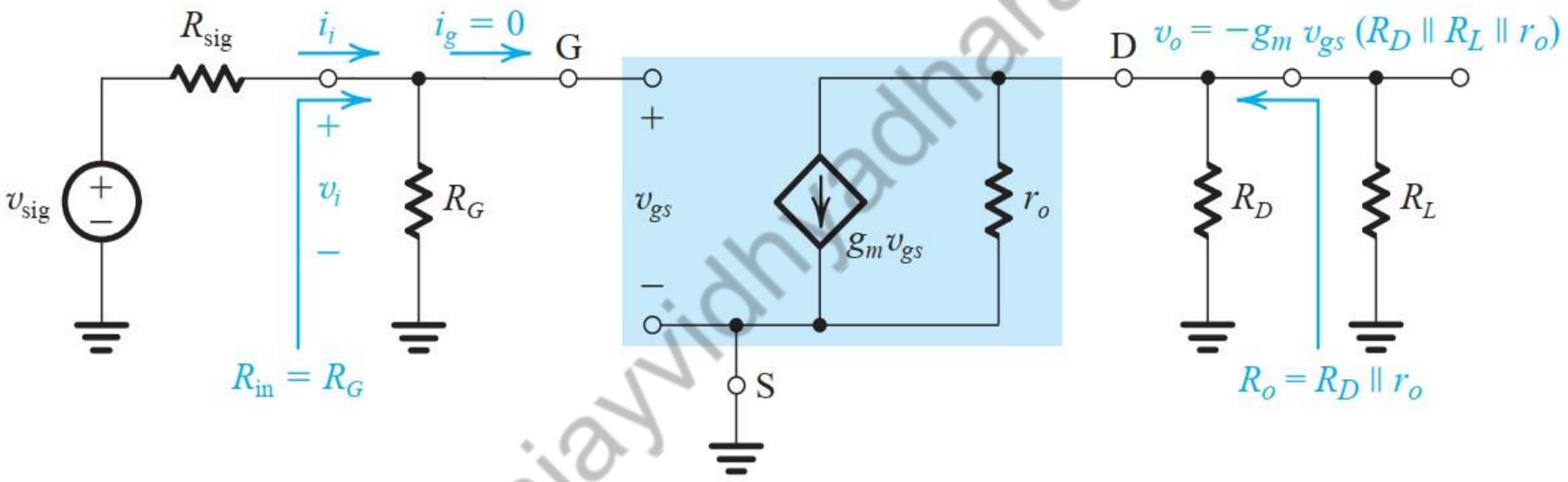
$$g_m = \sqrt{2\mu_n C_{ox}\left(\frac{W}{L}\right) I_D}$$

Example

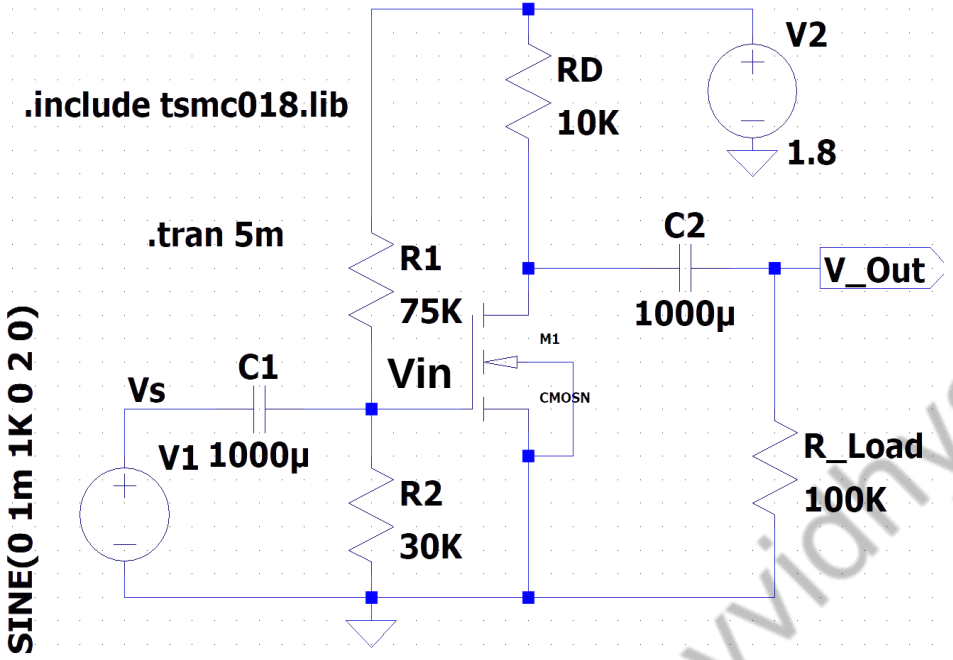
$K_n = 200\mu A/V^2$ $W/L = 50$ $I_D = 100\mu A$ $g_m = 1.4\ m$ $Gain = 14$

$I_D = 100\mu A,\ \lambda = 0.12\ V^{-1}$ r_o in few Mega Ohms

CS Amplifier



CS Amplifier



Design Steps

1. Fix I_{DQ} Meeting following conditions

(a) $I_{DQ} * V_{DD} <$ Max Power Constraint

(b) SR= dVo / dt maximum V/µs

SR= I_D / C_{Load}

2. Fix R_D for Max Symmetrical Output swing

$R_D = (V_{DD} - V_{ov})/2I_{DQ}$

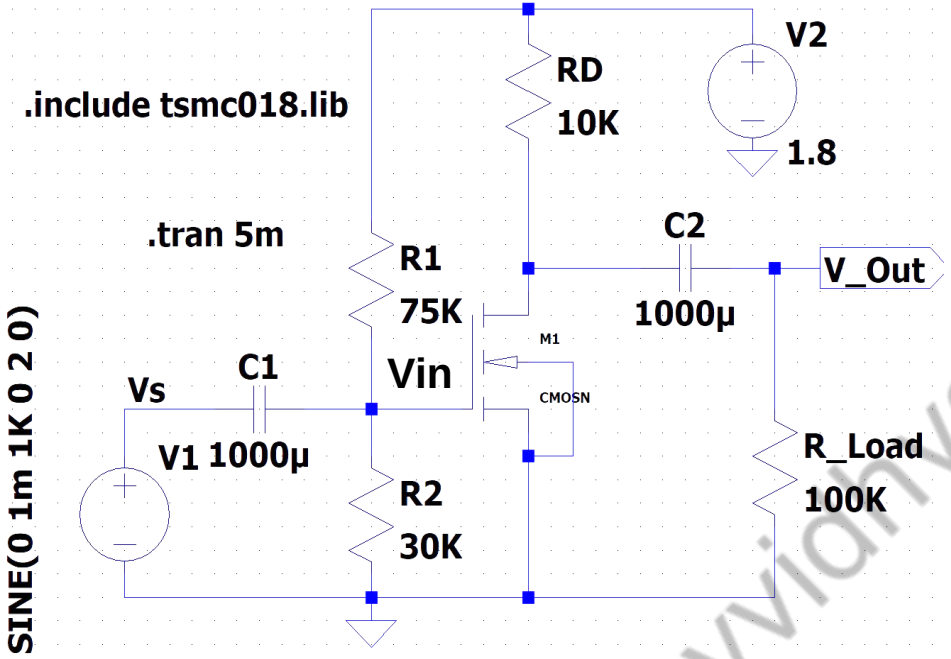
$g_m = 2I_D / V_{ov}$

3. Fix (W/L) for required gain

$$Gain = -g_m * R_D$$

$$g_m = \sqrt{2\mu_n C_{ox}\left(\frac{W}{L}\right) I_D}$$

CS Amplifier



Design Steps

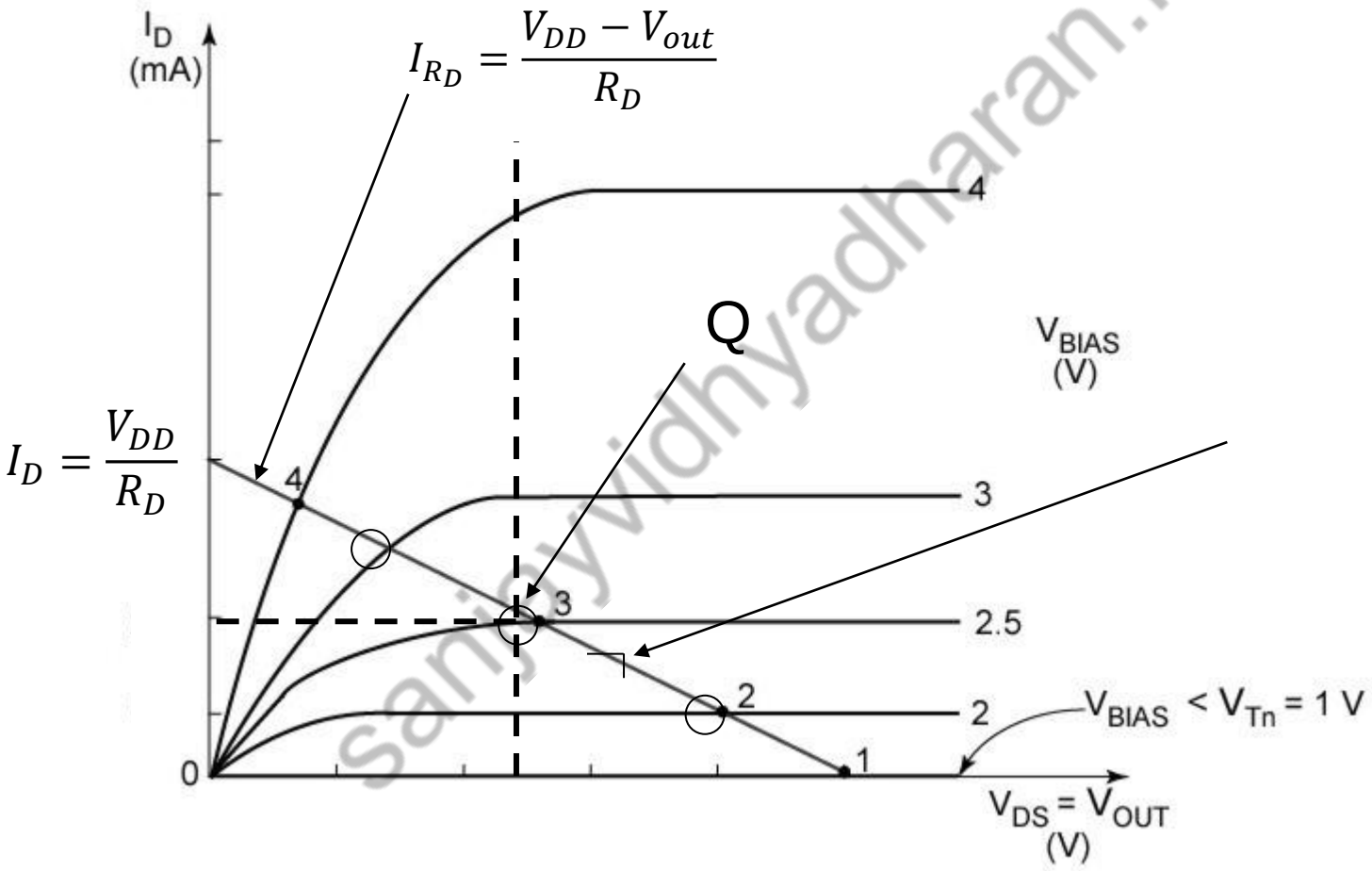
4. Design issues with R1 and R2
   Set for V-overdrive (V_{GS})

5. Values of C1 and C2

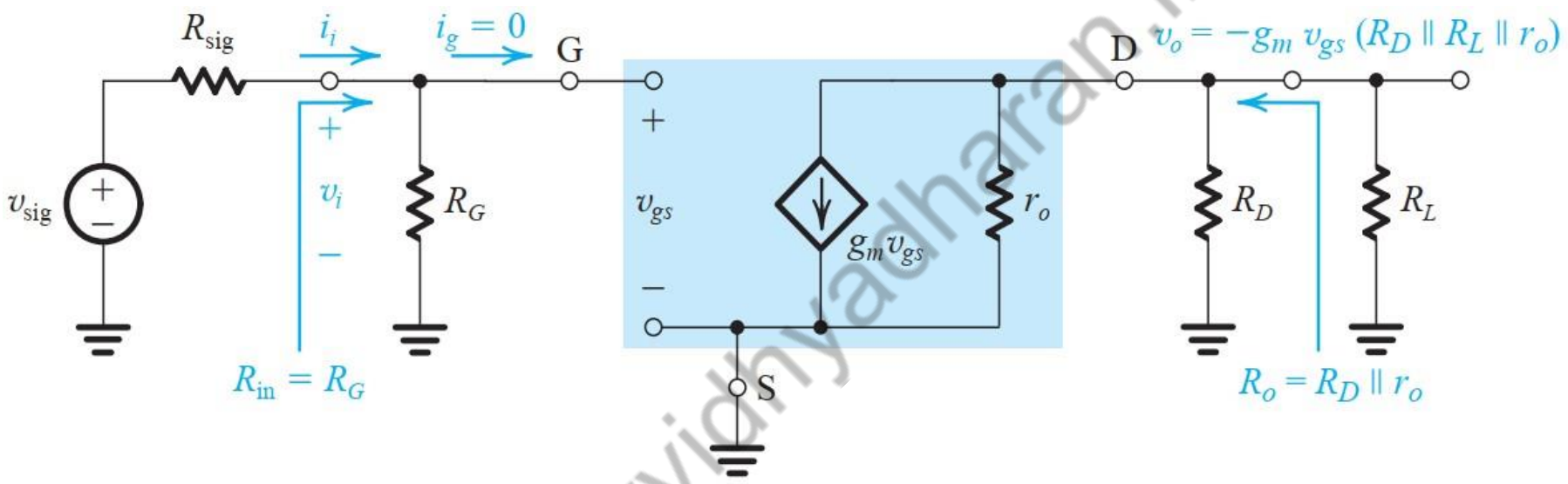
$$Gain = -g_m * R_D$$

$$g_m = \sqrt{2\mu_n C_{ox}\left(\frac{W}{L}\right) I_D}$$

Load-Line Analysis to find Q



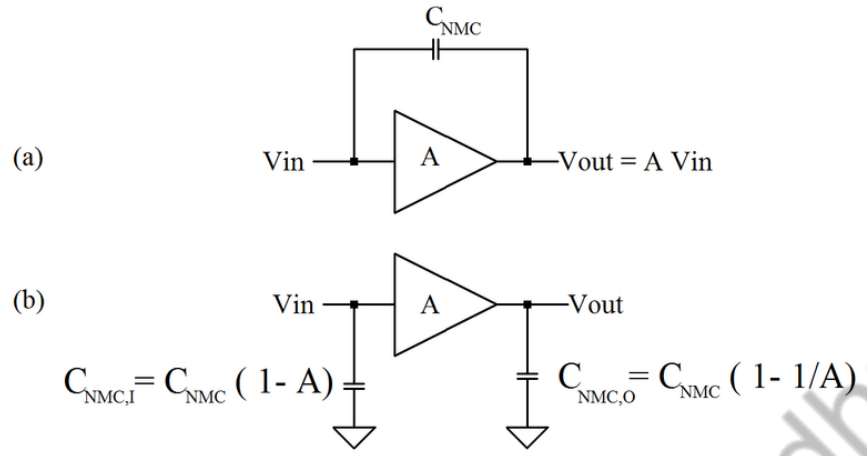
CS Amplifier

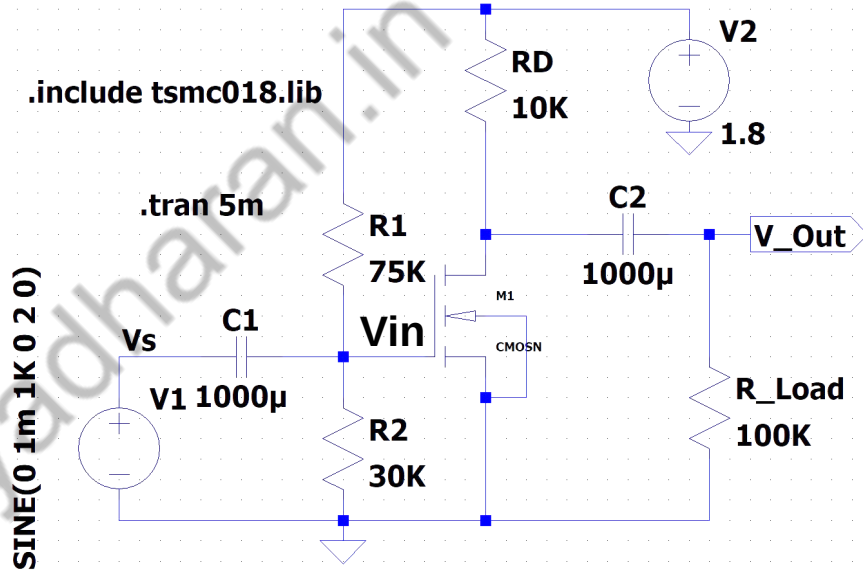


Gain is a function of Load Resistance
High Input Impedence
High Miller Capacitance

CS Amplifier

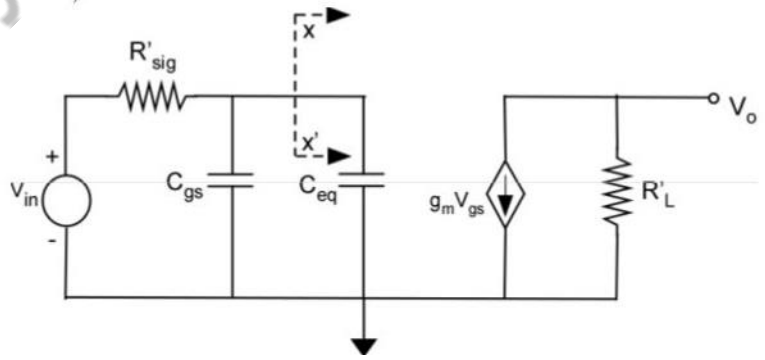
High Miller Capacitance





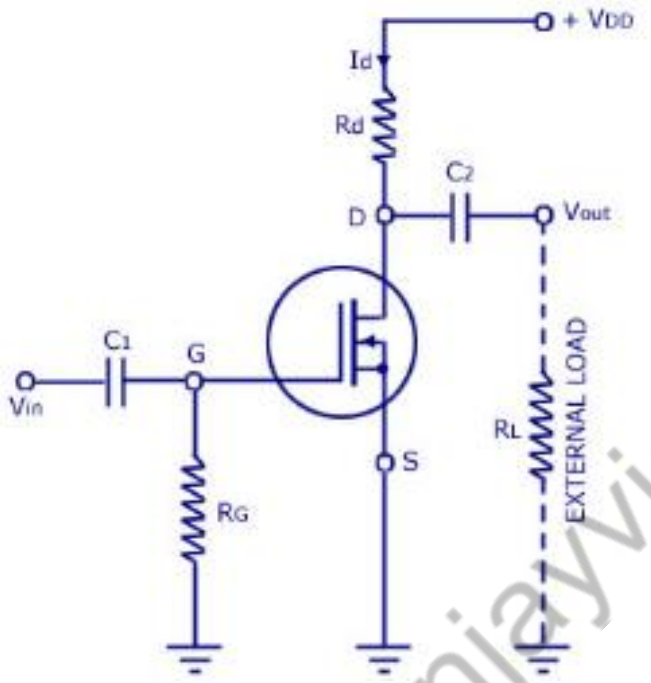
$$C_{eq} = C_{gd}\left(1 + g_m R_L'\right) = \text{Miller Capacitance}$$

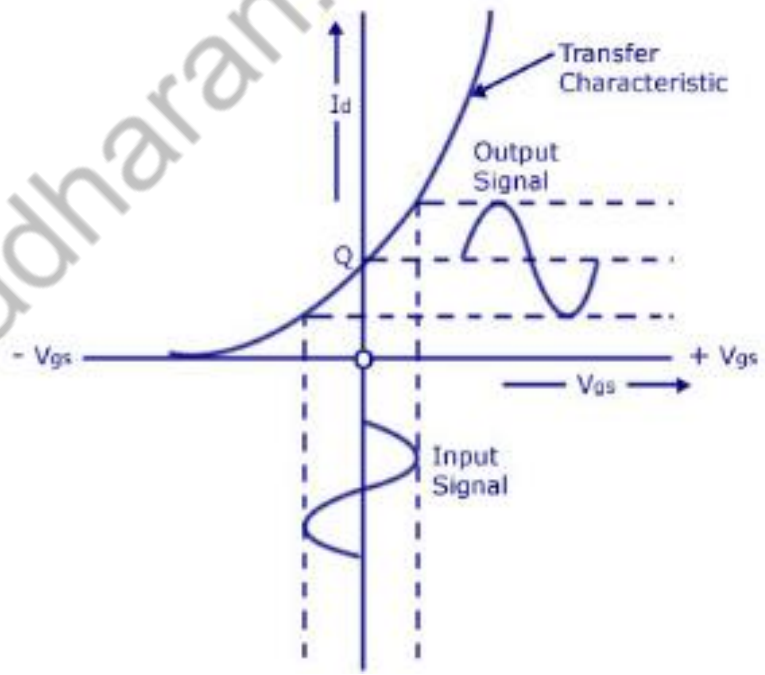
$$v_{in} = \frac{R_g V_{sig}}{R_g + R_{sig}}$$



CS Amplifier

No Q-point Stability

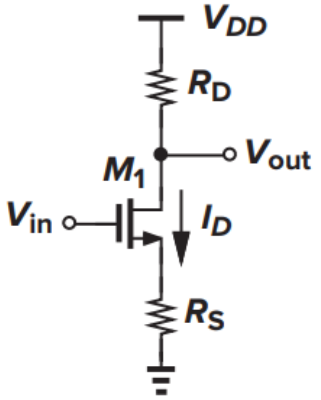




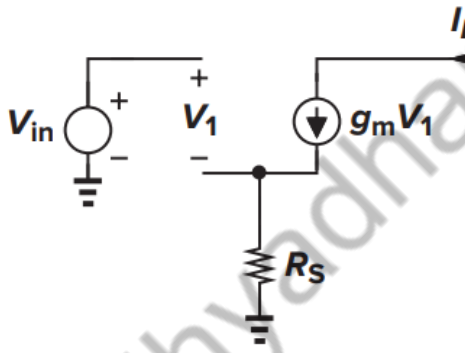
$$i_D = (1/2)\,\mu_n\, C_{ox}\,(W/L)\,(v_{GS} - V_{Tn})^2\,(1 + \lambda_n v_{DS})$$

CS Amplifier

CS stage with source degeneration.



(a)



(b)

$$V_{IN} = V_{GS} + I_D\ R_S$$

$$\Delta I_D = \Delta(V_{IN} - V_{GS})/R_S$$

$$v_{in} = v_{gs+}\ i_d\ R_s$$

$$v_{in} = v_{gs+}\ g_m\ v_{gs}\ R_s$$

$$v_{in} = v_{gs}\ \ (1 + g_m\ R_s)$$

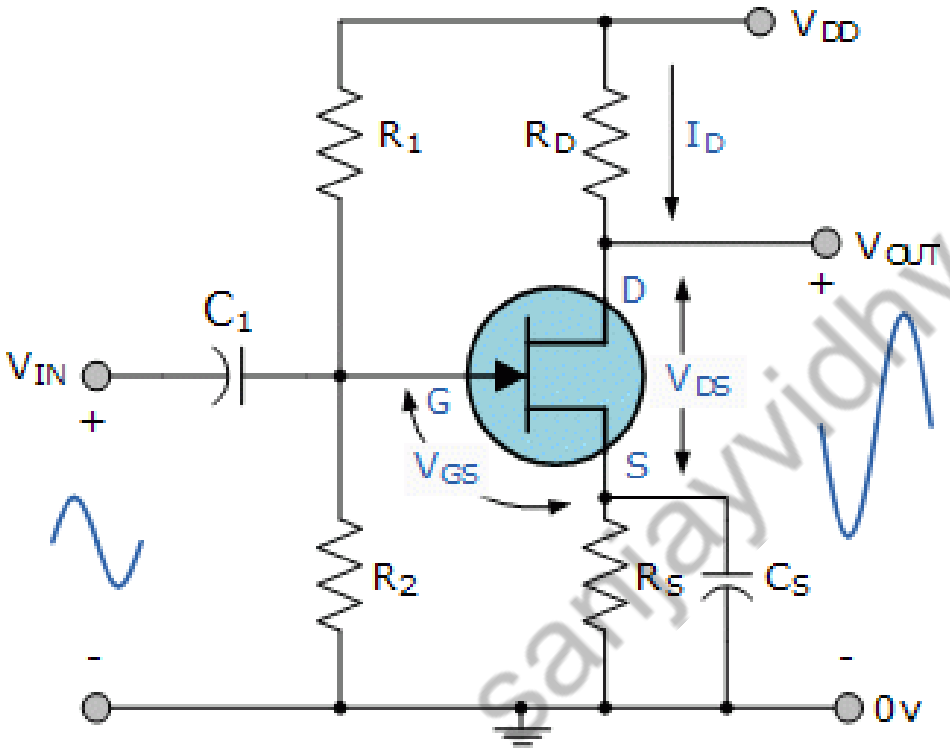
$$v_{out} = i_d\ R_D$$

$$v_{out} = -v_{gs}\ \ g_m\ R_D$$

$$Gain \sim -\frac{R_D}{R_s}$$

CS Amplifier

CS stage with source degeneration and bypass capacitor.



$$Gain \sim -g_m R_D$$

Design Steps

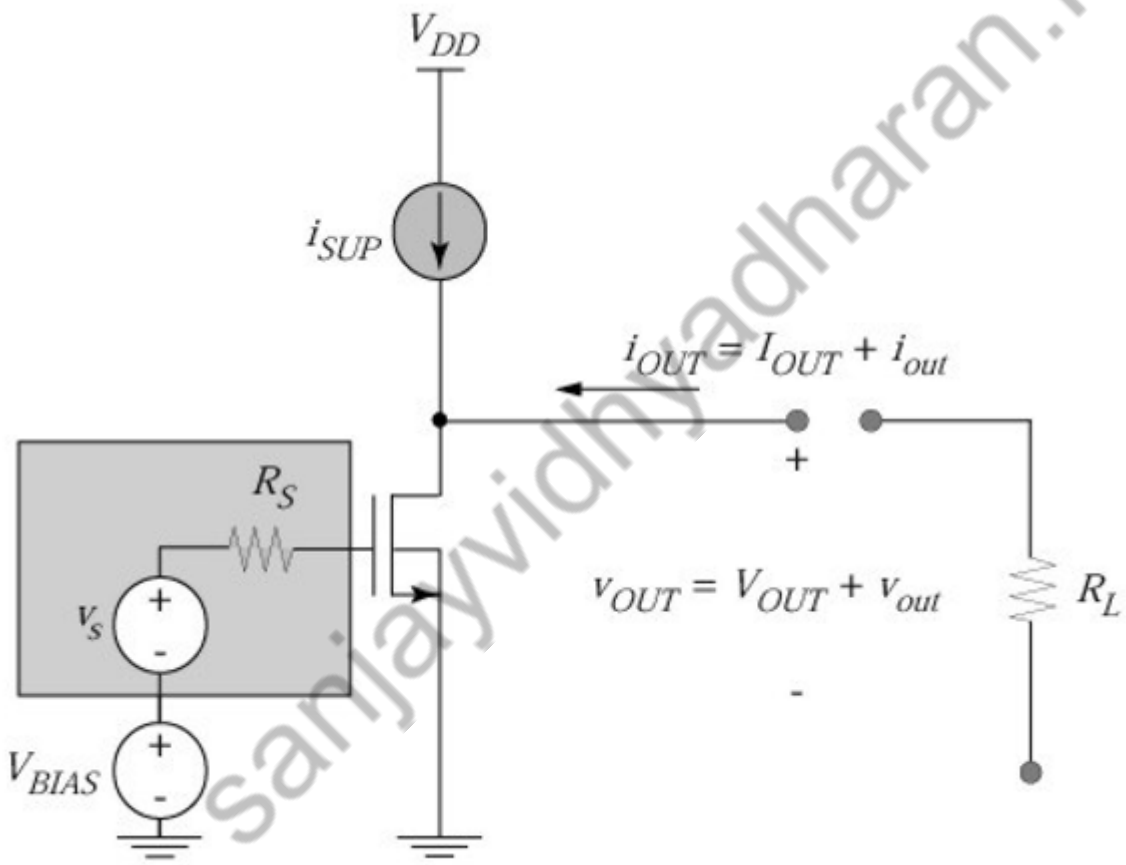
1. Fix I_{DQ} Meeting following conditions
(a) $I_{DQ} * V_{DD} <$ Max Power Constraint

(b) SR= dVo / dt maximum V/µs
SR= I_{DQ} / C_{Load}

2. Fix R_D for Max Symmetrical Output swing
$R_D = (0.9\ V_{DD} - V_{ov}) / 2I_{DQ}$

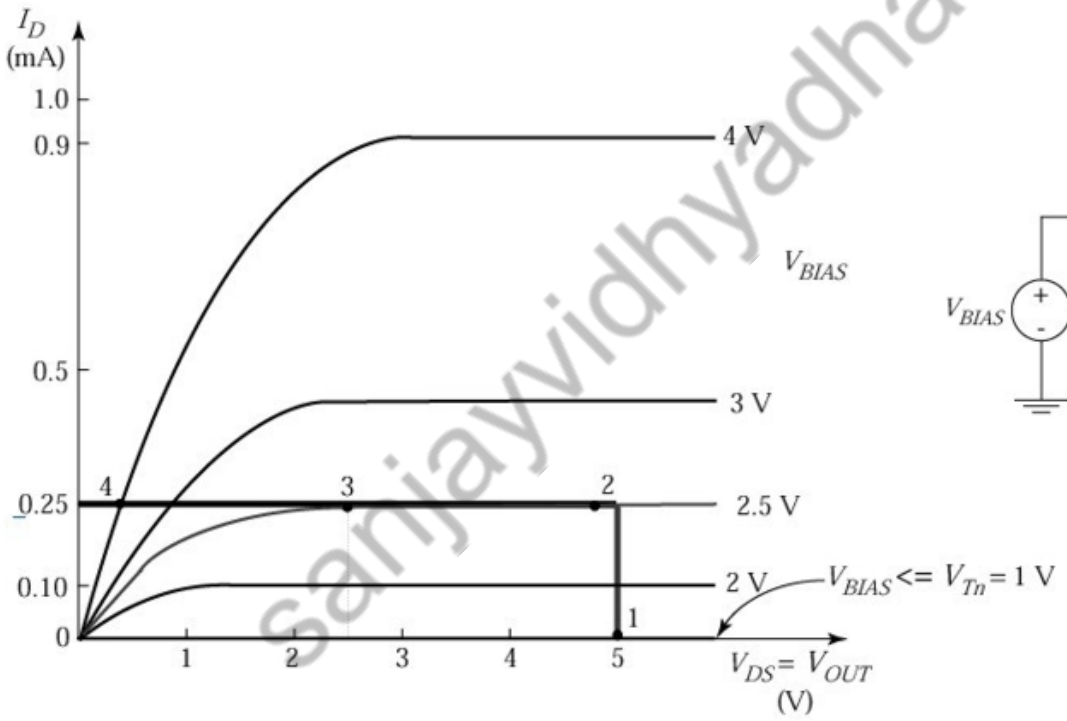
3. $R_S = 0.1\ V_{DD} / I_{DQ}$

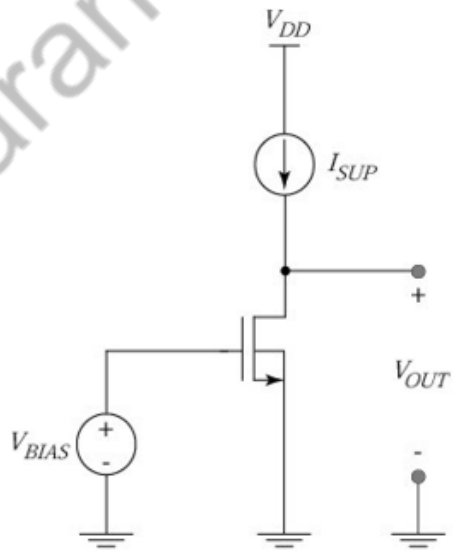
CS Amp with Current Source Supply



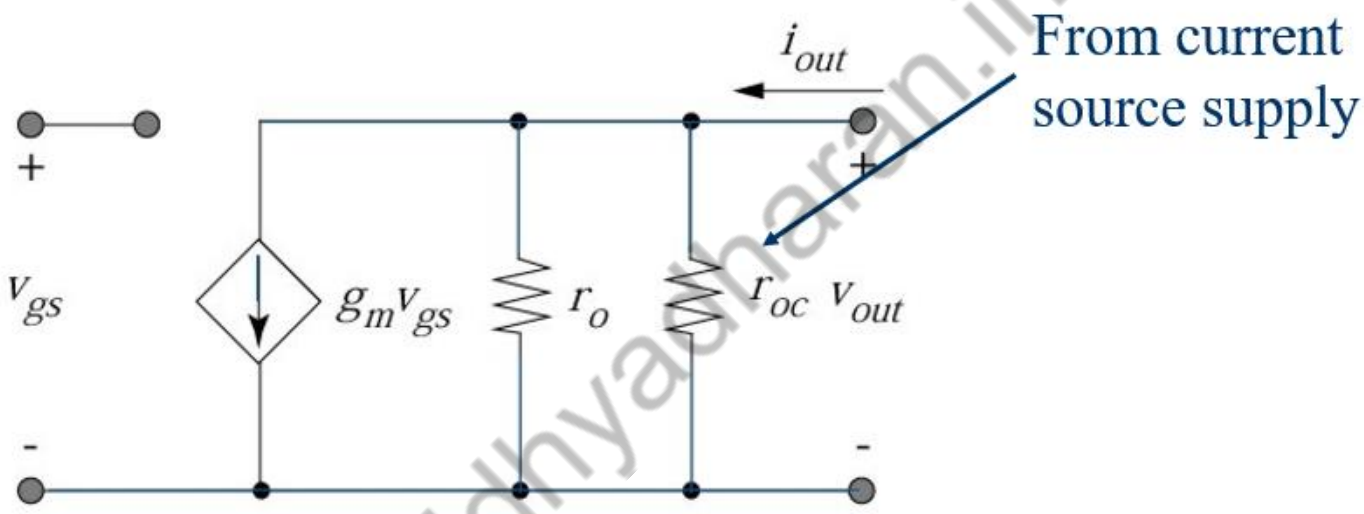
Gain = ?

CS Amp with Current Source Supply





CS Amp with Current Source Supply

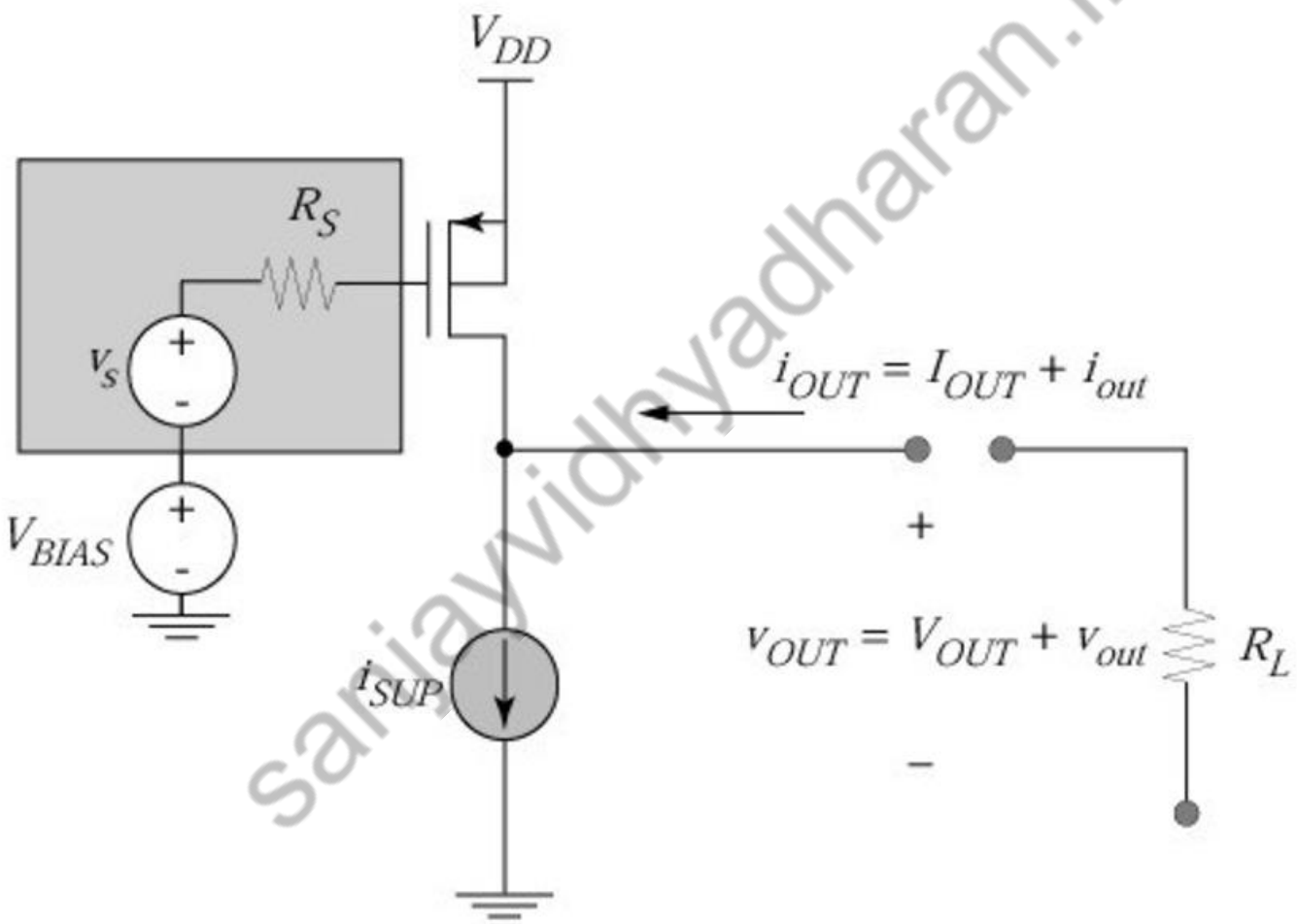


$$R_{in} = \infty$$

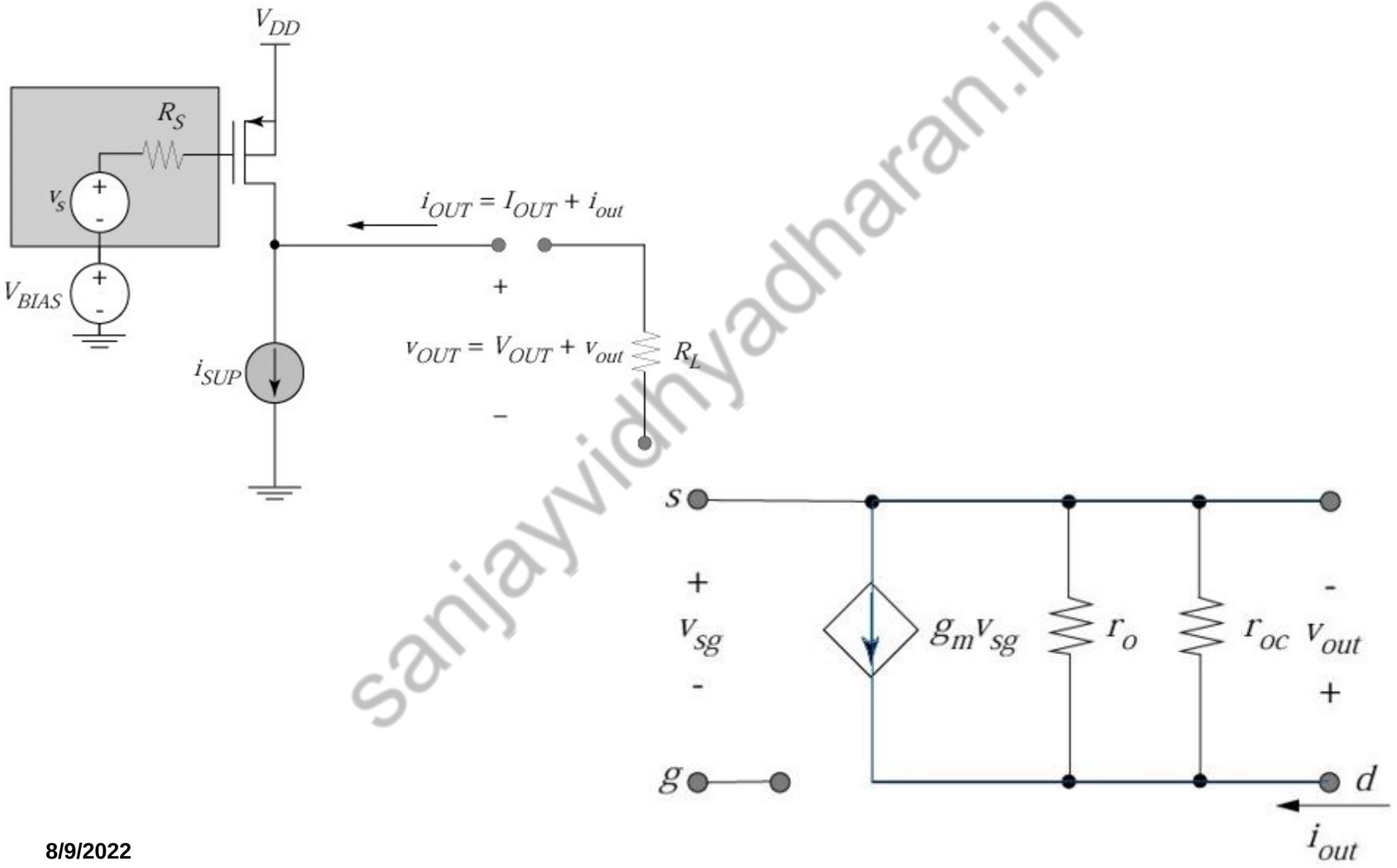
$$G_m = g_m$$

$$R_{out} = r_o \,||\, r_{oc}$$

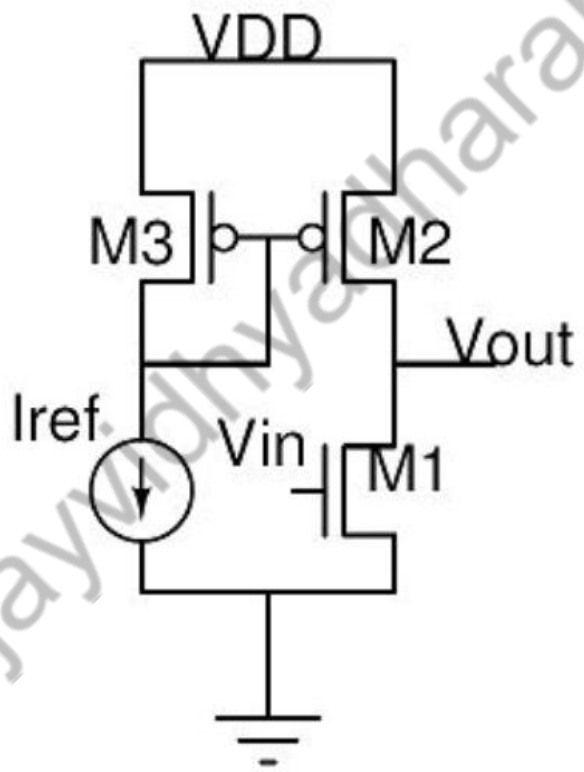
P-Channel CS Amplifier



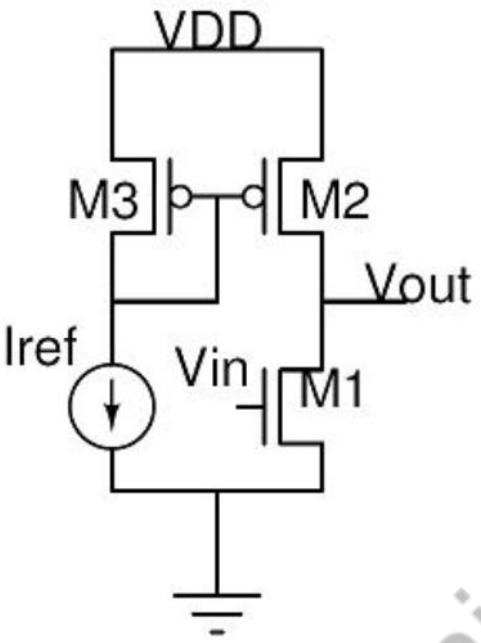
P-Channel CS Amplifier

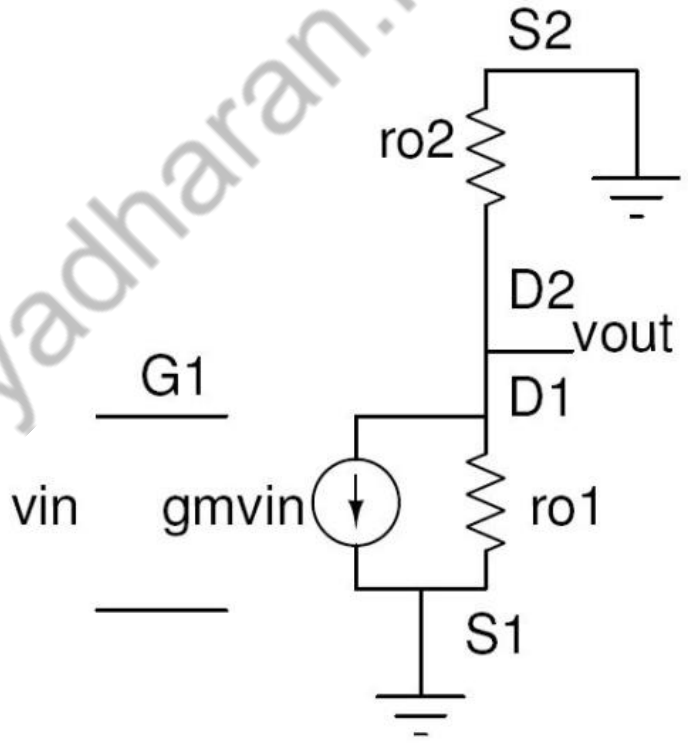


CS Amplifier with Active Load



CS Amplifier with Active Load





$$v_{out} = g_{m1} v_{in} * (r_{01} || r_{o2})$$

Thank you