# MOSFET

## MOSFET:

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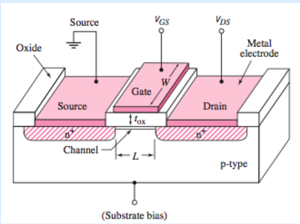
- Noção de Amplificador com MosFet.
  - Modelo para pequenos sinais
  - Amplificador Fonte Comum
  - Amplificador Dreno Comum



# MOSFET

## MOSFET de enriquecimento canal N (NMOS)

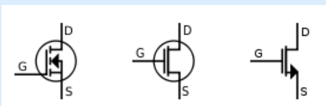
**MOSFET = Metal Oxide Semiconductor Field Effect Transistor**

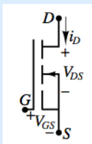



**Drain - dreno Gate - porta Source - fonte**

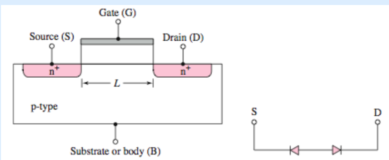
**Substrato / Body** (em geral ligado à Source)

**Canal**




**Região de corte (cut-off)**






# NMOS - funcionamento

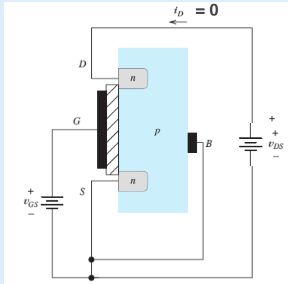
**Tensão de threshold - $V_{to}$ , $V_T$ , $V_{TN}$ , $V_{th}$ , $V_{GSth}$**

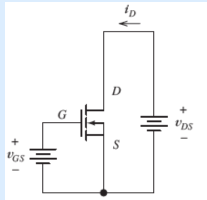
**Região de corte - cut-off**

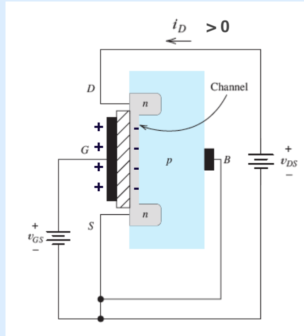
$i_D = 0$ for $v_{GS} \leq V_{to}$

**Região triodo (linear/ohmica)**

$v_{DS} < v_{GS} - V_{to}$ and $v_{GS} \geq V_{to}$



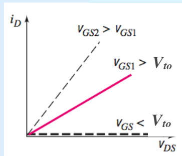






# NMOS - funcionamento (2)

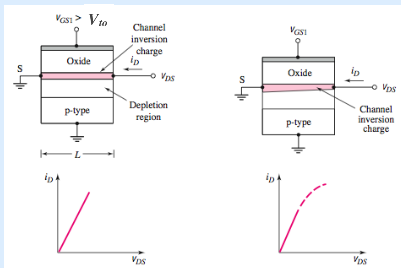
**cut-off** $i_D = 0$ for $v_{GS} \leq V_{to}$   $v_{DS} < v_{GS} - V_{to}$ and $v_{GS} \geq V_{to}$ **Região triodo**

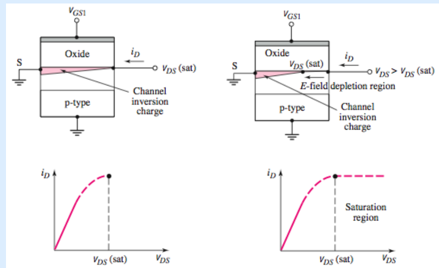



**A largura do canal aumenta com $v_{GS}$**
**- a resistência diminui com $v_{GS}$**
**"Resistência controlada por tensão"**

**$V_{DS}$ (sat) = $v_{GS}$ - $V_{to}$**

**Pinchoff - estrangulamento do canal**



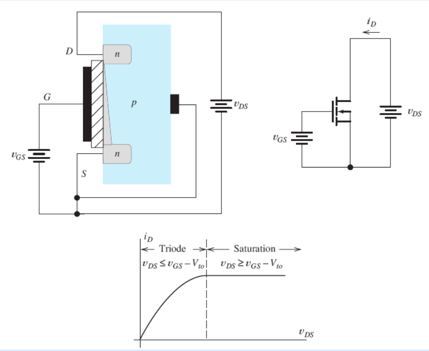
# NMOS - funcionamento (3)

**Região de saturação** $V_{DS}$ *(sat)* = $v_{GS} - V_{to}$

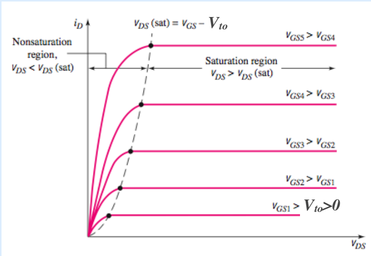
$$v_{DS} \geq v_{GS} - V_{to}$$

se $v_{GS}$ = constante , $i_D$ = constante (fonte de corrente controlada por $v_{GS}$)

$$r_0 = \Delta v_{DS} / \Delta i_D |_{v_{GS}=\text{const.}} = \infty$$




**MosFet ideal**

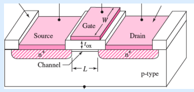





# NMOS - funcionamento (4)

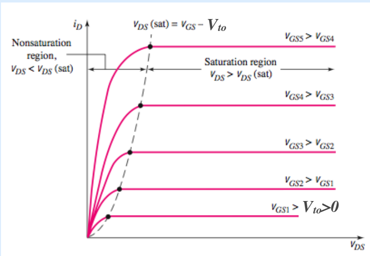
**Parâmetro de condução (A/V²)**

$$K = \left(\frac{W}{L}\right)\frac{KP}{2}$$



$KP = \mu_n C_{ox}$

**MosFet ideal**




**Região de corte - cut-off**

$$i_D = 0 \text{ for } v_{GS} \leq V_{to}$$

**Região triodo (linear/ohmica)**

$v_{DS} < v_{GS} - V_{to}$ and $v_{GS} \geq V_{to}$

$$\boxed{i_D = K\left[2(v_{GS} - V_{to})v_{DS} - v_{DS}^2\right]}$$

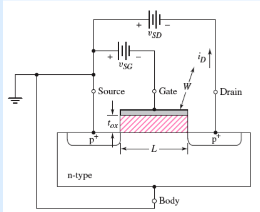
**Região de saturação**

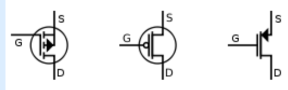
$$v_{DS} \geq v_{GS} - V_{to}$$

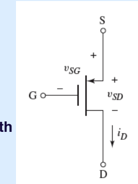
$$\boxed{i_D = K(v_{GS} - V_{to})^2}$$



# PMOS (enriquecimento)







Tensão de threshold - $V_{to}$ , $V_T$ , $\underline{V_{TP}}$ , $V_{th}$ , $V_{GSth}$

$\boxed{V_{TP} < 0}$ $V_{SD}$ *(sat)* = $v_{SG} + V_{TP}$

**Região de corte - cut-off**

$v_{SG} \leq |V_{TP}|$ $i_D = 0$

**Região triodo (linear/ohmica)**

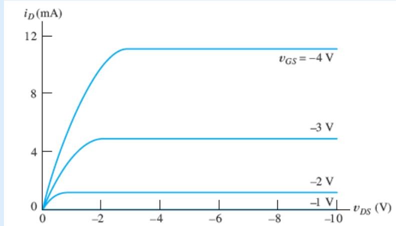
$v_{SG} \geq |V_{TP}|$ $v_{SD} < v_{SG} + V_{TP}$

$$i_D = K_p\left[2(v_{SG} + V_{TP})v_{SD} - v_{SD}^2\right]$$

**Região de saturação**

$v_{SG} \geq |V_{TP}|$ $v_{SD} \geq v_{SG} + V_{TP}$

$$i_D = K_p(v_{SG} + V_{TP})^2$$





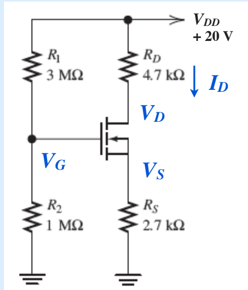

# Exercício

**Calcular o ponto de funcionamento Q ($I_D$,$V_{DS}$,$V_{GS}$) do NMOS**

**NMOS:** $V_{to}$ = 2V ; K = 1 mA/V²

$$V_G = V_{DD}\frac{R_2}{R_1 + R_2} = 20\frac{1}{(3+1)} = 5 \text{ V}$$

$I_G = 0$ **!!!**




**Hipótese tentativa: NMOS está na saturação**

$$V_G = V_{GSQ} + R_S I_{DQ}$$
$$I_{DQ} = K(V_{GSQ} - V_{to})^2$$

$$V_G = V_{GSQ} + R_S K (V_{GSQ} - V_{to})^2$$

$$V_{GSQ}^2 + \left(\frac{1}{R_S K} - 2V_{to}\right)V_{GSQ} + V_{to}^2 - \frac{V_G}{R_S K} = 0$$

$$V_{GSQ}^2 - 3.630 V_{GSQ} + 2.148 = 0$$

$\boxed{V_{GSQ} = 2.886 \text{ V}}$

$\cancel{V_{GSQ}} = 0.744$ V corte ? $V_{GS} < V_{to}$ ?

$$\boxed{I_{DQ} = K\left(V_{GSQ} - V_{to}\right)^2 = 0.784 \text{ mA}}$$

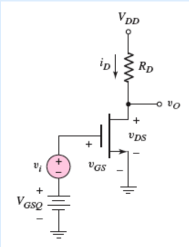
$$\boxed{V_{DSQ} = V_{DD} - (R_D + R_S)\, I_{DQ} = 14.2 \text{ V}}$$

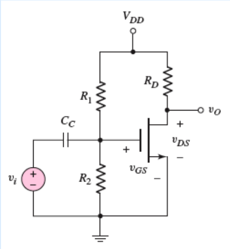
$V_{DS} > V_{GS} - V_{to}$ --> **zona de saturação. OK !!!**

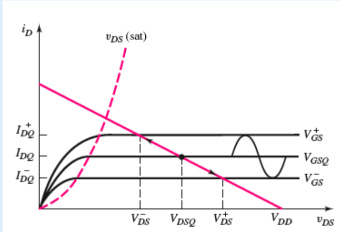
# Noção de Amplificador com MosFet

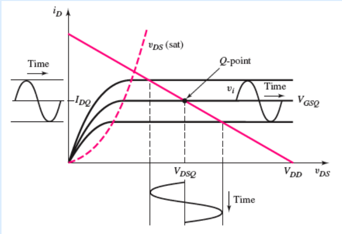
**Recta de Carga (Load Line)** $v_{DS} = V_{DD} - R_D i_D$

$i_D = 0 \rightarrow v_{DS} = V_{DD}$ $\quad$ $v_{DS} = 0 \rightarrow i_D = V_{DD}/R_D$



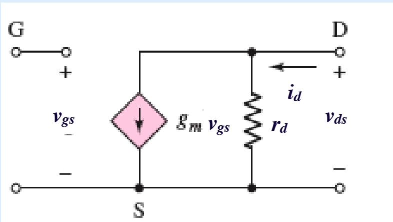




**Amplificador na zona de saturação**

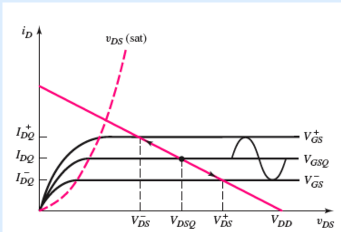
**Nota: $C_C$ (acoplamento) e, eventuais, condensadores de bypass são considerados curto-circuitos à frequência de interesse.**



# Modelo para pequenos sinais




| Variable | Meaning |
|---|---|
| $i_D$, $v_{GS}$ | Total instantaneous values |
| $I_D$, $V_{GS}$ | DC values |
| $i_d$, $v_{gs}$ | Instantaneous ac values |
| $I_d$, $V_{gs}$ | Phasor values |



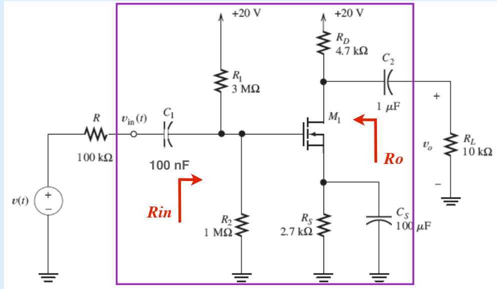

$$g_m = \partial i_D / \partial v_{GS} = \partial K (v_{GS} - V_{to})^2 / \partial v_{GS}$$

$$\boxed{g_m = 2K(V_{GS} - V_{to})}$$



# Amplificador Fonte Comum

**Exemplo: Amplificador em fonte comum**




**NMOS: $V_{to}$ = 2V ; K = 1 mA/V²**

**$r_d$ = 1 MΩ**

$v(t) = 100\sin(2000\pi t)$ mV

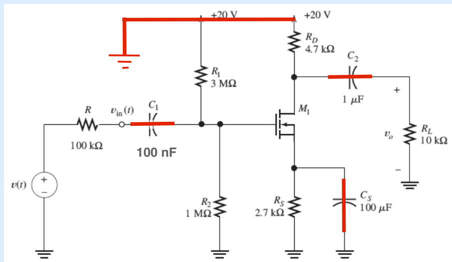
**Calcular:**
**a) polarização**
**b) ganho $v_o/v_{in}$ e $v_o$**
**c) $R_{in}$ e $R_o$**

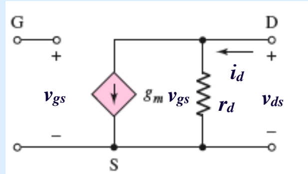
**a) polarização foi calculada no slide 8:**
**$V_{GSQ}$ = 2.886V $V_{DSQ}$ = 14.2V $I_{DQ}$ = 0.78mA**



# Amplificador Fonte Comum (2)

**Análise para pequenos sinais:**

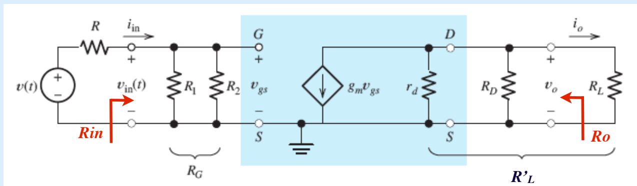



$v(t) = 100\sin(2000\pi t)$ mV

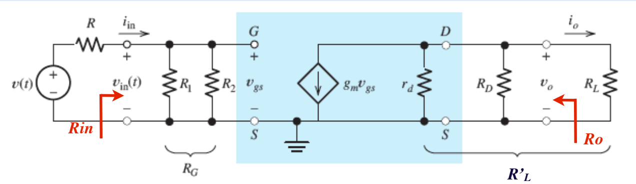
**$|Z_{C1}|$ = 1.6kΩ $|Z_{C2}|$ = 160Ω $|Z_{CS}|$ = 1.6Ω**

**A fonte +20Vdc é um curto-circuito para sinais**




**Calcular:**
**a) polarização**
**b) ganho $v_o/v_{in}$ e $v_o$**
**c) $R_{in}$ e $R_o$**

# Amplificador Fonte Comum (3)




Calcular:
a) polarização
b) ganho $v_o/v_{in}$ e $v_o$
c) $R_{in}$ e $R_o$

$r_d$ = 1 MΩ

$R$ = 100kΩ
$R_1$ = 3 MΩ ; $R_2$ = 1 MΩ
$R_D$ = 4.7kΩ ; $R_L$ = 10kΩ

$v(t) = 100\sin(2000\pi t)$ mV

$R'_L = \dfrac{1}{1/r_d + 1/R_D + 1/R_L} =$ 3.2kΩ

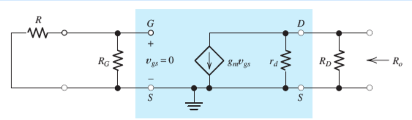
$v_{in} = v_{gs}$

$R_{in} = \dfrac{v_{in}}{i_{in}} = R_G = R_1 || R_2 = 750\ \text{k}\Omega$

$R_o = \dfrac{1}{1/R_D + 1/r_d} = 4.7\ \text{k}\Omega$

$g_m$ = 2 K ($V_{GS}$ - $V_{to}$) = 2 x $10^{-3}$ (2.886 - 2) = 1.77 mA/V

$A_v = \dfrac{v_o}{v_{in}} = -g_m R'_L = -5.66$

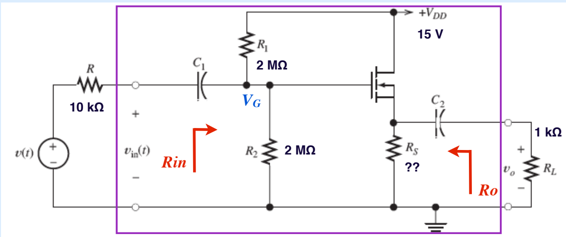


$v_{in} = v(t)\dfrac{R_{in}}{R + R_{in}} = 88.23\sin(2000\pi t)$ mV

$v_o(t) = A_v v_{in}(t) = -500\sin(2000\pi t)$ mV



# Amplificador Dreno Comum (Seguidor de Fonte)




NMOS: $V_{to}$ = 1V ; K = 2 mA/V$^2$
$r_d$ = 1 MΩ

Pretende-se $I_{DQ}$ = 10 mA
Calcular:
a) polarização e $R_S$
b) ganho $v_o/v_{in}$
c) $R_{in}$ e $R_o$

a) $I_{DQ} = K(V_{GSQ} - V_{to})^2$ $\quad V_{GSQ} = \sqrt{I_{DQ}/K} + V_{to} = 3.236$ V

$V_G = V_{DD} \times \dfrac{R_2}{R_1 + R_2} = 7.5$ V $\quad V_S = V_G - V_{GSQ} = 4.264$ V $\quad R_S = \dfrac{V_S}{I_{DQ}} = 426.4\ \Omega$ $\quad V_{DSQ} = 15 - 4.264 = 10.736$ V

$g_m$ = 2 K ($V_{GS}$ - $V_{to}$) = 2 x 2 x $10^{-3}$ (3.236 - 1) = 8.944 mA/V

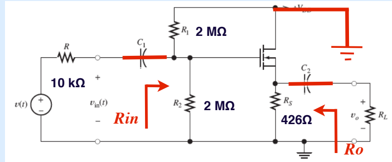
Para a análise de pequenos sinais (com $v(t)$ sinusoidal), considerar C1 e C2 como curto-circuitos e que a fonte $V_{DD}$ é um curto-circuito à massa.

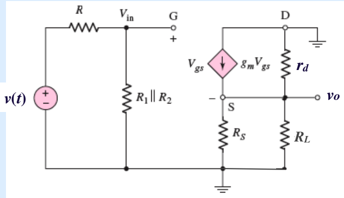


# Amplificador Dreno Comum (2)

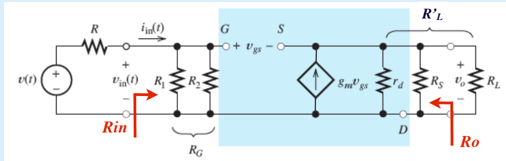
NMOS: $g_m$ = 8.944 mA/V ; $r_d$ = 1 MΩ

Calcular: b) ganho $v_o/v_{in}$ c) $R_{in}$ e $R_o$



$R'_L = \dfrac{1}{1/r_d + 1/R_S + 1/R_L} = 298.9\ \Omega$



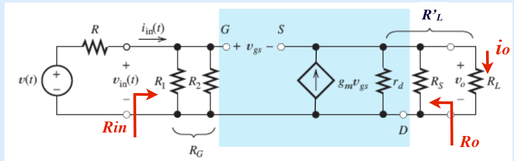

$v_{in} = v_{gs} + v_o$ $\quad v_o = g_m v_{gs} R'_L$

$A_v = \dfrac{v_o}{v_{in}} = \dfrac{g_m R'_L}{1 + g_m R'_L} = 0.7272$

$R_{in} = R_1 || R_2 = 1\ \text{M}\Omega$

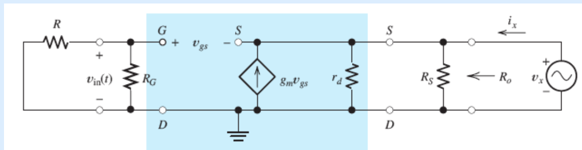


# Amplificador Dreno Comum (3)




NMOS: $g_m$ = 8.944 mA/V ; $r_d$ = 1 MΩ

Calcular: b) ganho $v_o/v_{in}$ c) $R_{in}$ e $R_o$



$R_o = \dfrac{v_x}{i_x}$

$v_{gs} = -v_x$

$R_o = \dfrac{1}{g_m + 1/R_S + 1/r_d} = 88.58\ \Omega$

$A_v = \dfrac{v_o}{v_{in}} = \dfrac{g_m R'_L}{1 + g_m R'_L} = 0.7272$

$R_{in} = R_1 || R_2 = 1\ \text{M}\Omega$

$v_{in} / R_{in} = i_{in}$ $\quad v_o / R_L = i_o$

$\boxed{A_i = i_o / i_{in} = A_v \dfrac{R_{in}}{R_L} = 727.2}$