# EE 530 Eletrônica Básica I

Física dos Transistores de Efeito de Campo (FET)

Prof. Pedro Xavier

# Resposta exercício-aula passada

- Corrente de dreno

$$I = Q \cdot v$$

$$Q(x) = WC_{ox}\left[V_{GS} - V(x) - V_{TH}\right]$$

μ: mobilidade dos portadores [cm$^2$/(V·s)]

$$v = -\mu_n E$$

$$v = +\mu_n \frac{dV}{dx}$$

$$I_D = WC_{ox}\left[V_{GS} - V(x) - V_{TH}\right]\mu_n \frac{dV(x)}{dx}$$

$$\int_0^L I_D dx = \int_0^{V_{DS}} WC_{ox}\left[V_{GS} - V(x) - V_{TH}\right]\mu_n dV$$

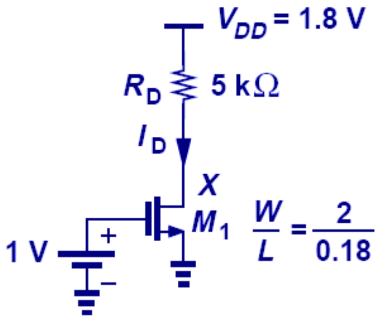
$$I_D L = \mu_n C_{ox} W\left[\int_0^{V_{DS}}\left[V_{GS} - V_{TH}\right]dV - \int_0^{V_{DS}} V(x)dV\right]$$

$$I_D = \mu_n C_{ox}\frac{W}{L}\left[\left[V_{GS} - V_{TH}\right]V_{DS} - \frac{V_{DS}{}^2}{2}\right]$$

$$\boxed{I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}\left[2(V_{GS} - V_{TH})V_{DS} - V_{DS}^2\right]}$$

# Resposta exercício-aula passada

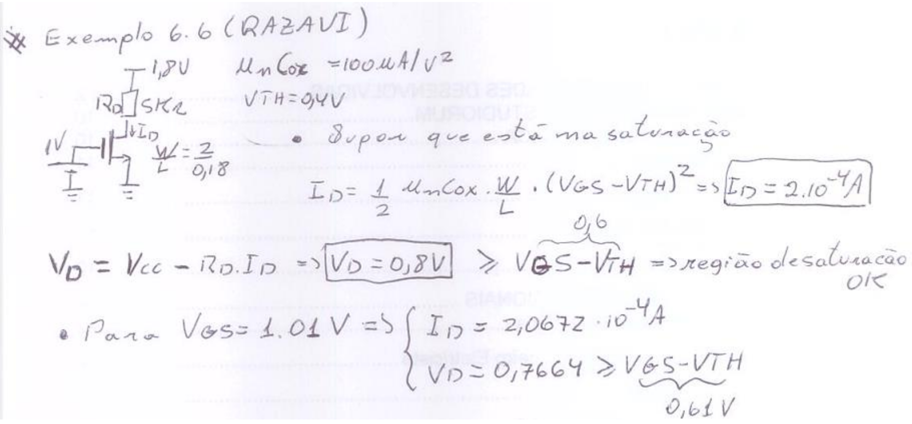
- Exemplo 6.6 - Razavi: Calcule $I_D$ e $V_D$, se $V_G$ aumentar de 10 mV, qual o novo valor de $V_D$?



$\mu_n C_{ox} = 100\ \mu\text{A}/\text{V}^2$ and $V_{TH} = 0.4\ \text{V}$.

# Resposta exercício-aula passada

- Exemplo 6.6 - Razavi: Calcule $I_D$ e $V_D$, se $V_G$ aumentar de 10 mV, qual o novo valor de $V_D$?



Exemplo 6.6 (RAZAVI)

1,8V
Rd 5KΩ
$I_D$
1V
$\frac{W}{L} = \frac{2}{0,18}$

$\mu_n C_{ox} = 100 \mu A/V^2$

$VTH = 0,4V$

- Supor que está na saturação

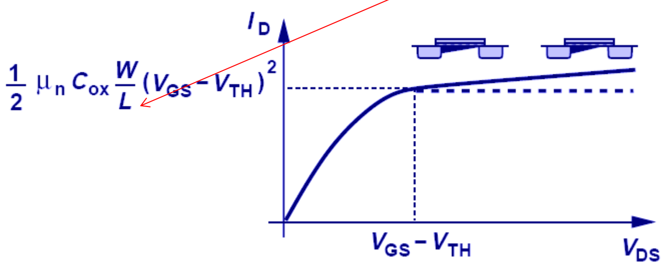
$I_D = \frac{1}{2} \mu_n Cox . \frac{W}{L} . (VGS - VTH)^2 \Rightarrow \boxed{I_D = 2.10^{-4} A}$

$V_D = Vcc - R_D . I_D \Rightarrow \boxed{V_D = 0,8V} \geq \underbrace{VGS - VTH}_{}^{0,6} \Rightarrow$ região de saturação OK

- Para $VGS = 1.01 V \Rightarrow \begin{cases} I_D = 2,0672 \cdot 10^{-4} A \\ V_D = 0,7664 \geq \underbrace{VGS - VTH}_{0,61 V} \end{cases}$

# Modulação do comprimento do canal

- O aumento de VDS, causa um aumento do estrangulamento do canal, diminuindo seu comprimento efetivo (L).
- $I_D$ aumenta com $V_{DS}$



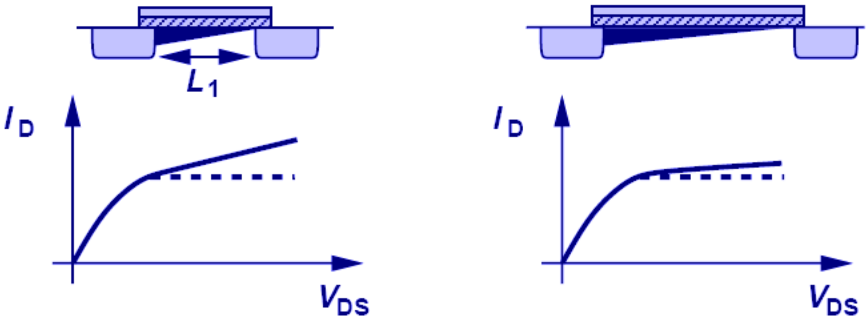
$$\boxed{I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2(1+\lambda V_{DS})}$$

$\lambda$: coeficiente de modulação do comprimento do canal

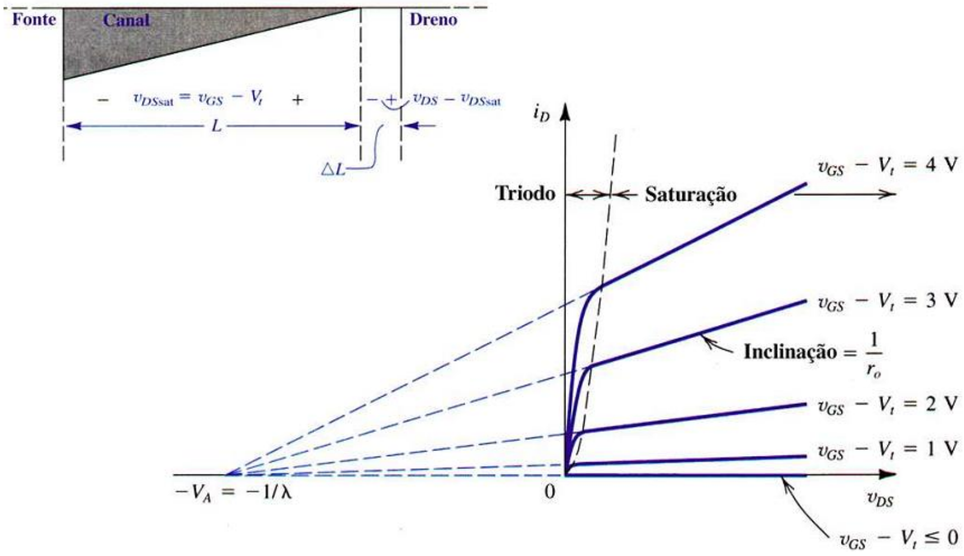
---

# Modulação do comprimento do canal

- Relação $\lambda$ - L
  - O efeito da modulação do comprimento do canal é menor, quanto maior o L.
  - $\lambda \alpha 1/L$



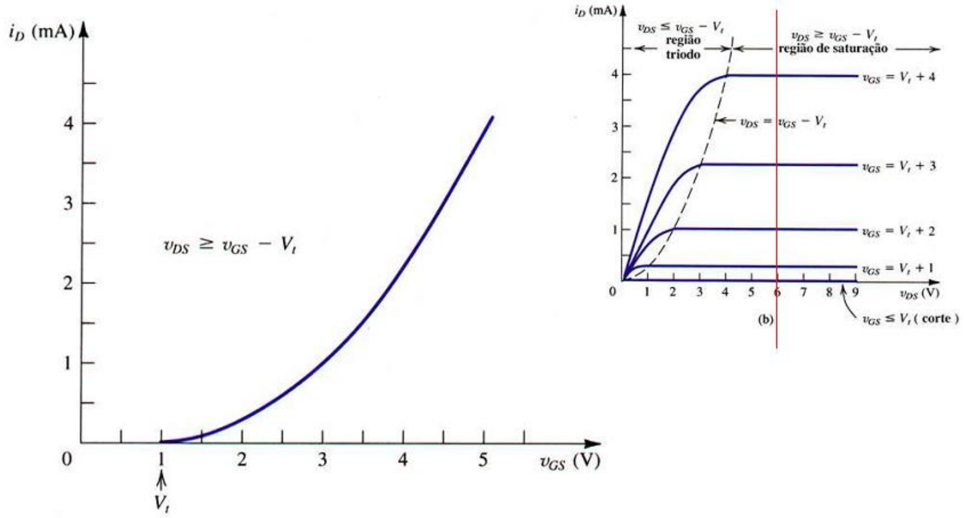
# Modulação do comprimento do canal



# Modulação do comprimento do canal

- Exercício: $I_D$=1mA para $V_{DS}$=.5V ($\lambda$=0,1 $V^{-1}$). Calcule de quanto $I_D$ varia, se $V_{DS}$ for aumentado de 1V. Qual é a impedância de saída?

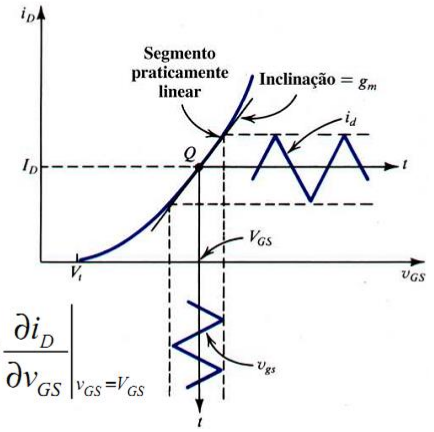
# Característica $i_D - v_{GS}$ do NMOS na saturação



$V_t = 1$ V e $k'_n(W/L) = 0.5$ mA/V²

$$i_D = \frac{1}{2} k_n' \frac{W}{L} (v_{GS} - V_t)^2$$

# Transcondutância MOS (saturação)



$$g_m \equiv \left. \frac{\partial i_D}{\partial v_{GS}} \right|_{v_{GS} = V_{GS}}$$

$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} \left[ (V_{GS} - V_{TH})^2 \right]$$

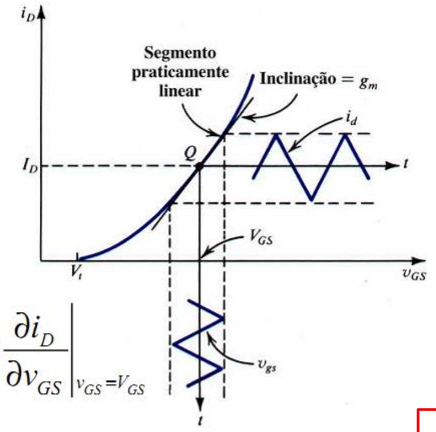
$$g_m = \frac{\partial I_D}{\partial V_{GS}} = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} 2 (V_{GS} - V_{TH})$$

$$\boxed{g_m = \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})}$$

$$g_m \propto V_{GS} - V_{TH}$$

$$g_m \propto \frac{W}{L}$$

# Transcondutância MOS (saturação)



$$g_m \equiv \left.\frac{\partial i_D}{\partial v_{GS}}\right|_{v_{GS}=V_{GS}}$$

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}\left[(V_{GS}-V_{TH})^2\right]$$

$$\begin{cases} (V_{GS}-V_{TH}) = \sqrt{\dfrac{2I_D}{\mu_n C_{ox}\dfrac{W}{L}}} \\ g_m = \mu_n C_{ox}\dfrac{W}{L}(V_{GS}-V_{TH}) \end{cases}$$

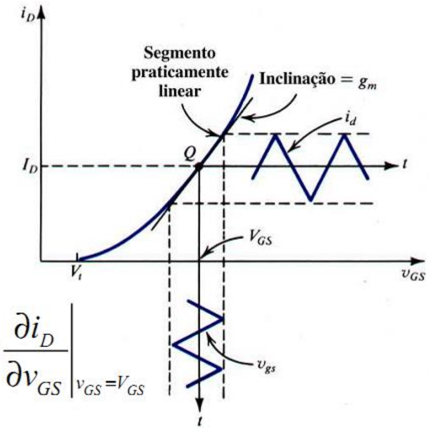
$$g_m = \mu_n C_{ox}\frac{W}{L}\sqrt{\frac{2I_D}{\mu_n C_{ox}\frac{W}{L}}}$$

$$\boxed{g_m = \sqrt{2I_D\mu_n C_{ox}\frac{W}{L}}}$$

$$g_m \propto \sqrt{\frac{W}{L}}$$

$$g_m \propto \sqrt{I_D}$$

# Transcondutância MOS (saturação)



$$g_m \equiv \left.\frac{\partial i_D}{\partial v_{GS}}\right|_{v_{GS}=V_{GS}}$$

$$\begin{cases} g_m = \mu_n C_{ox}\dfrac{W}{L}(V_{GS}-V_{TH}) \\ I_D = \dfrac{1}{2}\mu_n C_{ox}\dfrac{W}{L}\left[(V_{GS}-V_{TH})^2\right] \end{cases}$$

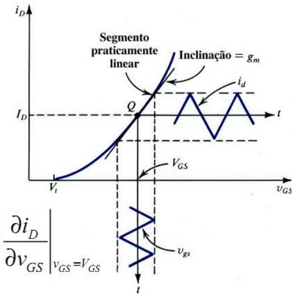
$$\frac{g_m}{I_D} = 2\frac{1}{(V_{GS}-V_{TH})} \Rightarrow \boxed{g_m = \frac{2I_D}{(V_{GS}-V_{TH})}}$$

$$g_m \propto I_D$$

$$g_m \propto \frac{1}{V_{GS}-V_{TH}}$$

# Transcondutância MOS (saturação)

- Resumo



$$g_m \equiv \left.\frac{\partial i_D}{\partial v_{GS}}\right|_{v_{GS}=V_{GS}}$$

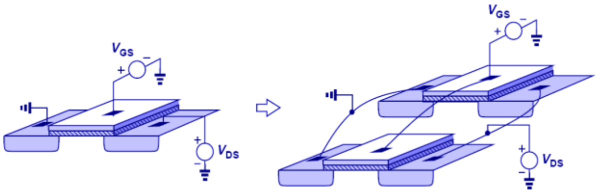
| $\frac{W}{L}$ Constant<br>$V_{GS}-V_{TH}$ Variable | $\frac{W}{L}$ Variable<br>$V_{GS}-V_{TH}$ Constant | $\frac{W}{L}$ Variable<br>$V_{GS}-V_{TH}$ Constant |
|---|---|---|
| $g_m \propto \sqrt{I_D}$<br>$g_m \propto V_{GS}-V_{TH}$ | $g_m \propto I_D$<br>$g_m \propto \frac{W}{L}$ | $g_m \propto \sqrt{\frac{W}{L}}$<br>$g_m \propto \frac{1}{V_{GS}-V_{TH}}$ |

$$g_m = \mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH}) \qquad g_m = \sqrt{2\mu_n C_{ox}\frac{W}{L}I_D} \qquad g_m = \frac{2I_D}{V_{GS}-V_{TH}}$$

---

# Transcondutância MOS (saturação)

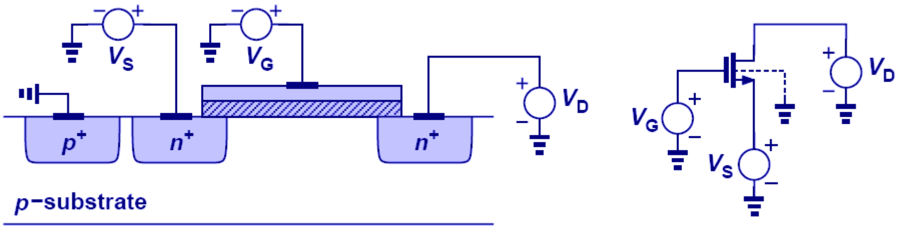
- Ao dobrarmos a largura (W), colocando 2 FETs em paralelo, dobramos $I_D$, portanto $g_m$, também, dobra.



$$g_m = \frac{2I_D}{V_{GS}-V_{TH}}$$

# Efeito de Corpo

Quando $V_S \neq V_B$ (tensão de corpo) , $V_{TH}$ é alterado.



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

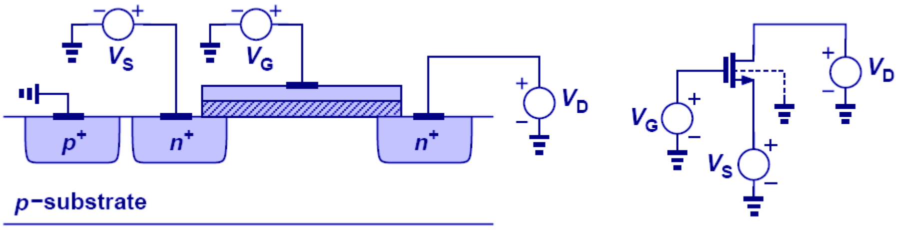
$V_{TH0}$: Tensão limiar para $V_{SB}$=0
$\gamma$ e $\phi_f$: parâmetros dependentes da tecnologia

$$\gamma = \frac{\sqrt{2qN_A\varepsilon_S}}{C_{ox}}$$

---

# Efeito de Corpo

Determine $I_D$. $V_S$=0.5V; $V_G$=$V_D$=1.4V; $\mu_n C_{ox}$=100µA/V$^2$; W/L=50; $V_{TH0}$=0.6V; $\gamma$=0.4; $\phi_F$=0.4; $\lambda$=0.



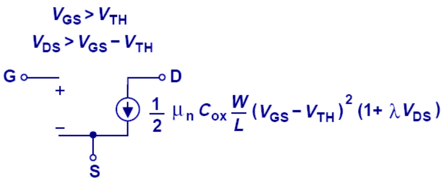
$$V_{TH} = V_{TH0} + \gamma\left(\sqrt{2\phi_F + V_{SB}} - \sqrt{2\phi_F}\right)$$

$V_{TH0}$: Tensão limiar para $V_{SB}$=0
$\gamma$ E $\phi_f$: parâmetros dependentes da tecnologia

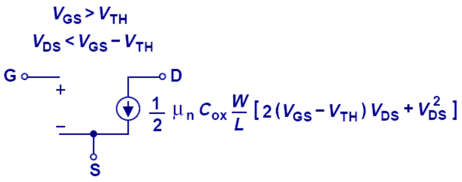
$$\gamma = \frac{\sqrt{2qN_A\varepsilon_S}}{C_{ox}}$$

# Modelo de Grandes Sinais

**Saturação**

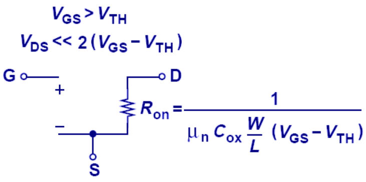


(a)



(b)

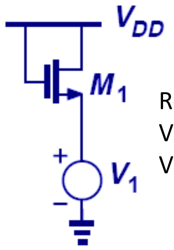
**Triodo**



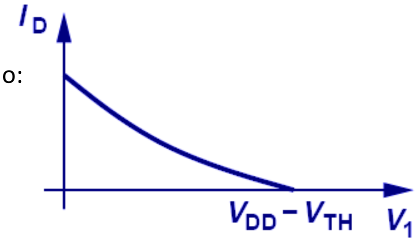
(c)

**Triodo-Região linear**

# Exemplo



Região de Saturação:
$V_{DS}=V_{GS}$
$V_{DS}>V_{GS}-V_{TH}$



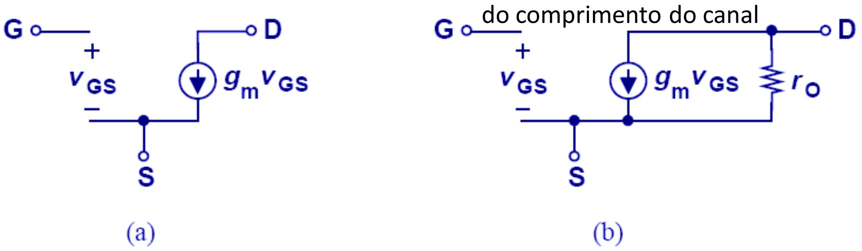
(a)

(b)

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2$$

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{DD}-V_1-V_{TH})^2$$

# Modelo de Pequenos Sinais



Considerando a modulação do comprimento do canal

(a)

(b)

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2(1+\lambda V_{DS})$$

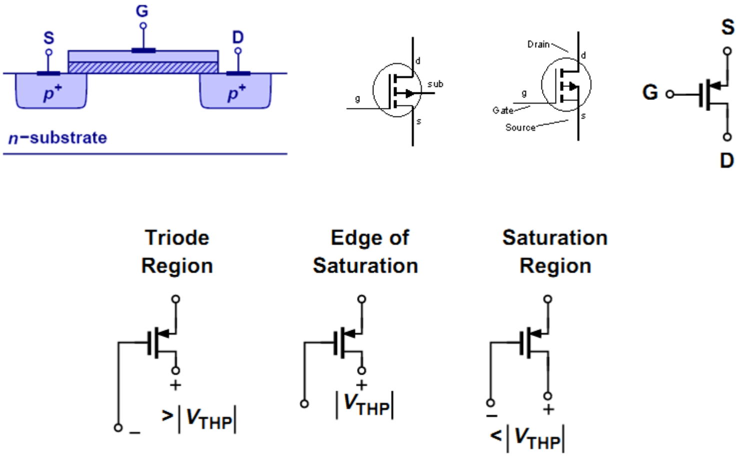
$$r_o = \left(\frac{\partial I_D}{\partial V_{DS}}\right)^{-1} = \frac{1}{\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2\lambda}$$

⇨

$$\boxed{r_o = \frac{1}{\lambda I_D}}$$

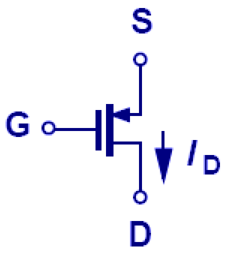
Prof. Pedro Xavier

# Transistor PMOS



Prof. Pedro Xavier

# Transistor PMOS - Equações



$$I_{D,sat}=\frac{1}{2}\mu_p C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2(1-\lambda V_{DS})$$

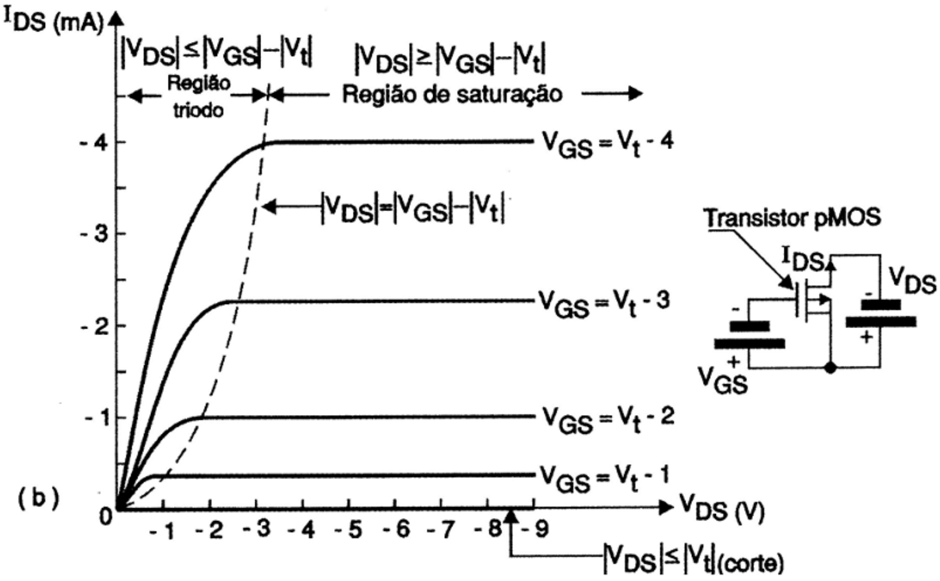
$$I_{D,tri}=\frac{1}{2}\mu_p C_{ox}\frac{W}{L}\left[2(V_{GS}-V_{TH})V_{DS}-V_{DS}^2\right]$$

$$\boxed{\begin{aligned}I_{D,sat}&=\frac{1}{2}\mu_p C_{ox}\frac{W}{L}\left(|V_{GS}|-|V_{TH}|\right)^2\left(1+\lambda|V_{DS}|\right)\\ I_{D,tri}&=\frac{1}{2}\mu_p C_{ox}\frac{W}{L}\left[2\left(|V_{GS}|-|V_{TH}|\right)|V_{DS}|-V_{DS}^2\right]\end{aligned}}$$

**Obs: O modelo de pequenos sinais é o mesmo**

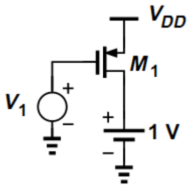
Prof. Pedro Xavier

# Característica $i_D$ - $v_{DS}$ para o PMOS



# Exemplo 6.15 - Razavi

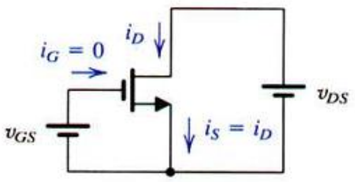
- Determine a região de operação de M1, de acordo com $V_1$($V_{DD}$ a 0V).

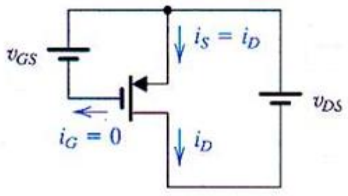


$$V_{DD} = 2.5\ \text{V}$$

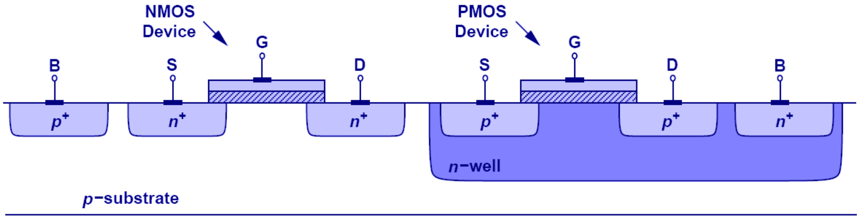
$$|V_{TH}| = 0.5\ \text{V}$$

# Comparação PMOS - NMOS

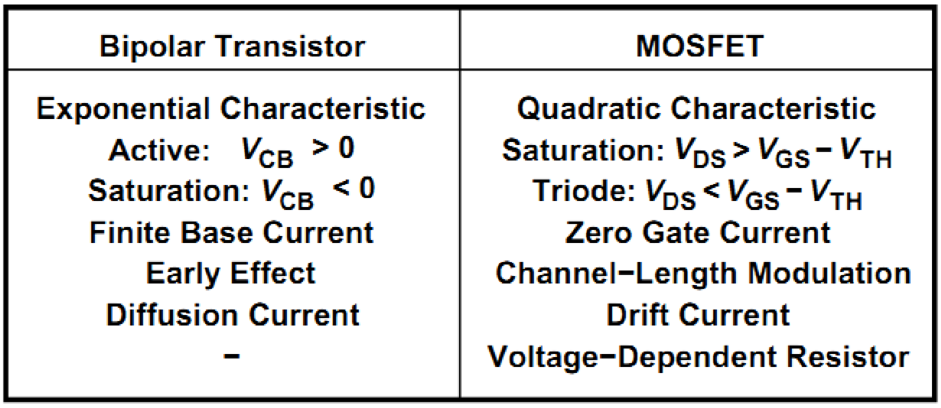




# CMOS (MOS COMPLEMENTAR)



# Comparação MOSFET - TBJ



| Bipolar Transistor | MOSFET |
|---|---|
| Exponential Characteristic | Quadratic Characteristic |
| Active: $V_{CB} > 0$ | Saturation: $V_{DS} > V_{GS} - V_{TH}$ |
| Saturation: $V_{CB} < 0$ | Triode: $V_{DS} < V_{GS} - V_{TH}$ |
| Finite Base Current | Zero Gate Current |
| Early Effect | Channel−Length Modulation |
| Diffusion Current | Drift Current |
| − | Voltage−Dependent Resistor |

# Fontes de figuras da aula

- Aula do prof. Fabiano Fruett
- Fundamentos de Microeletrônica (Razavi)
- Microeletrônica (Sedra)

Prof. Pedro Xavier

# Sugestão de estudo

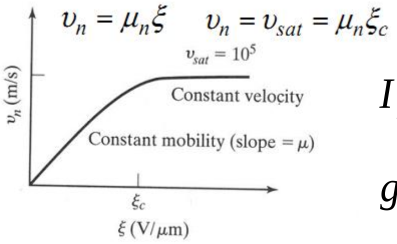
- Razavi, Cap. 6
- Sedra/Smith cap. 5 seções 5.1 até 5.3
  - Exercícios e problemas correspondentes

Para saber mais:

Paul R. Gray e Robert G. Meyer, Analysis and Design of Analog integrated Circuits, John Wiley & Sons

T. Tsividis, Design considerations in single-chanel MOS analog integrated circuits – A tutorial”, IEEE JSSC SC 13, pp 383-391, junho de 1978

# Efeito da Velocidade de Saturação em Transistores com o Canal Curto



$$Q = WC_{ox}(V_{GS} - V_{TH})$$

$$I_D = v_{sat} \cdot Q = v_{sat} \cdot WC_{ox}\left(V_{GS} - V_{TH}\right)$$

$$g_m = \frac{\partial I_D}{\partial V_{GS}} = v_{sat} WC_{ox}$$