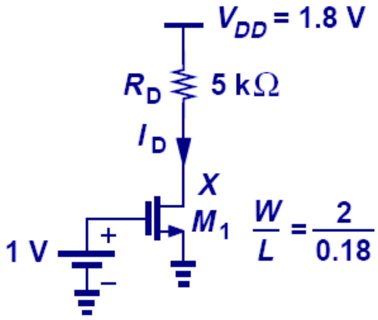
EE 530 Eletrônica Básica I

Física dos Transistores de Efeito de Campo (FET)

Resposta exercício-aula passada

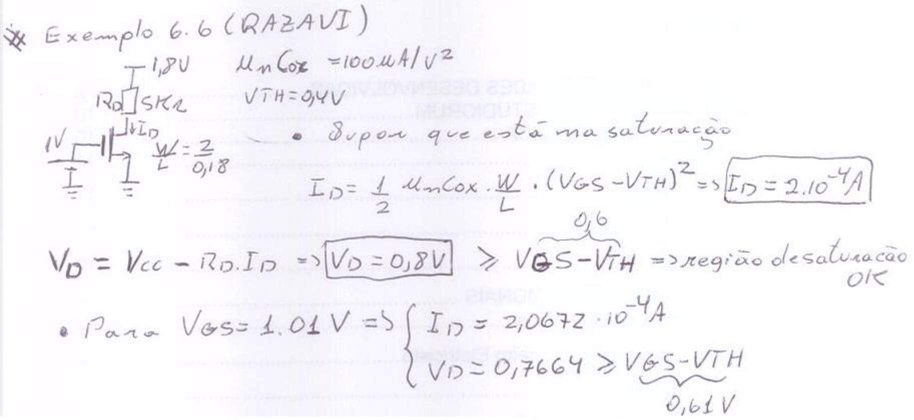
- Exemplo 6.6 - Razavi: Calcule I_D e V_D, se V_G aumentar de 10 mV, qual o novo valor de V_D?



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

R_D 5kΩ

I_D

1V

$\frac{W}{L} = \frac{2}{0,18}$

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

$V_{TH} = 0,4V$

- Supor que está na saturação

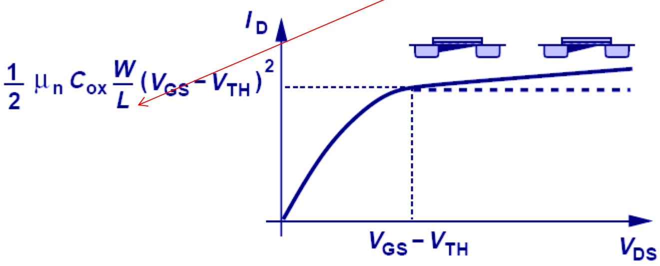
$I_D = \frac{1}{2} \mu_n C_{ox} \cdot \frac{W}{L} \cdot (V_{GS} - V_{TH})^2 \Rightarrow \boxed{I_D = 2 \cdot 10^{-4} A}$

$V_D = V_{cc} - R_D \cdot I_D \Rightarrow \boxed{V_D = 0,8V} \geqslant \underbrace{V_{GS} - V_{TH}}^{0,6} \Rightarrow$ região de saturação OK

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

Modulação do comprimento do canal

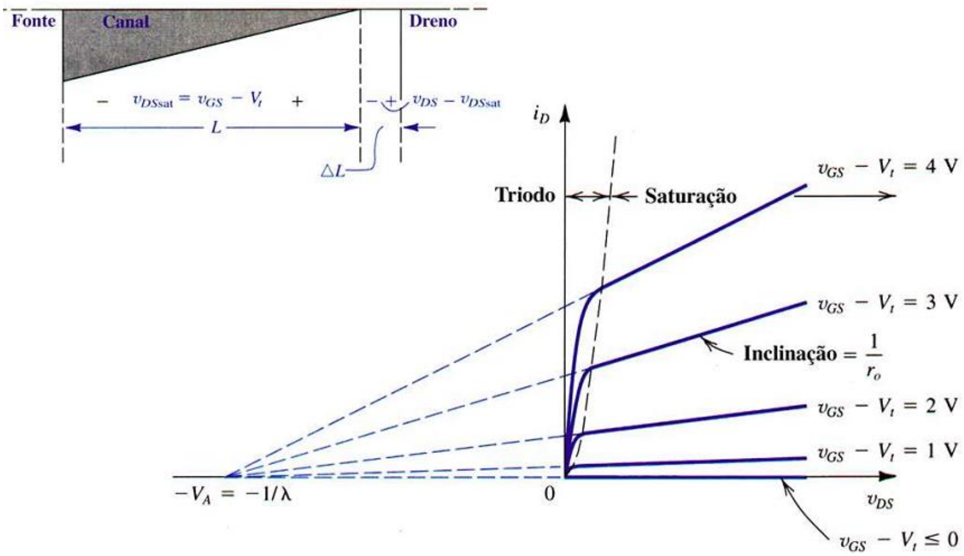
- O aumento de VDS, causa um aumento do estrangulamento do canal, diminuindo seu comprimento efetivo (L).
- I_D aumenta com V_{DS}



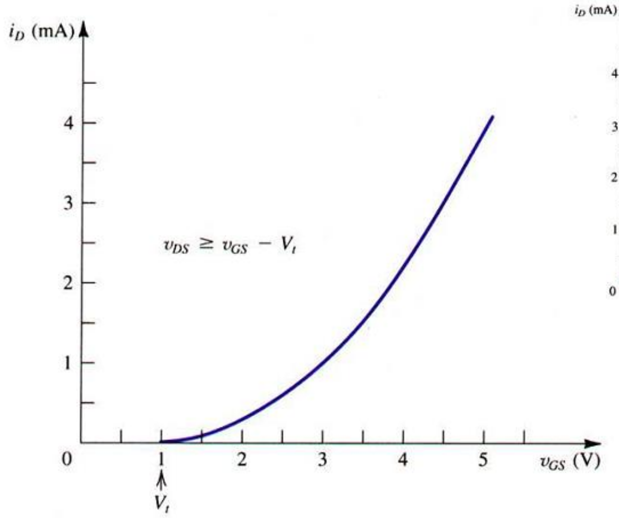
$$\boxed{I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2(1+\lambda V_{DS})}$$

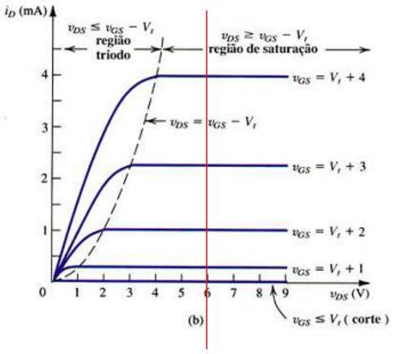
λ: coeficiente de modulação do comprimento do canal

Modulação do comprimento do canal



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



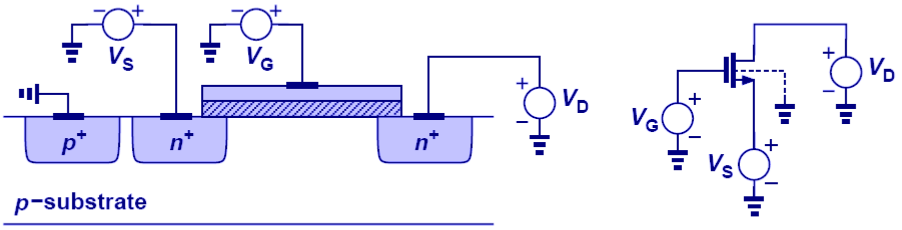


$V_t = 1$ V e $k'_n(W/L) = 0.5$ mA/V^2

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

Efeito de Corpo

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

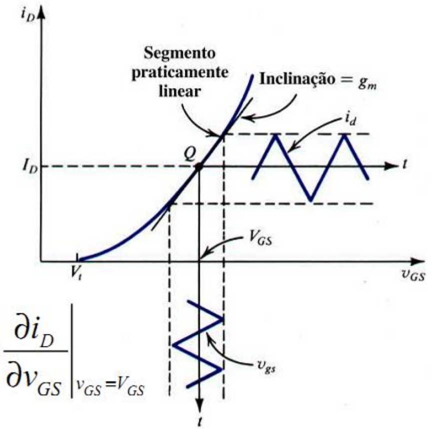


$$V_{TH} = V_{TH0} + \gamma\left(\sqrt{2\phi_F + V_{SB}} - \sqrt{2\phi_F}\right)$$

V_{TH0}: Tensão limiar para V_{SB}=0
γ e ϕ_f: parâmetros dependentes da tecnologia

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

Transcondutância MOS (saturação)



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

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

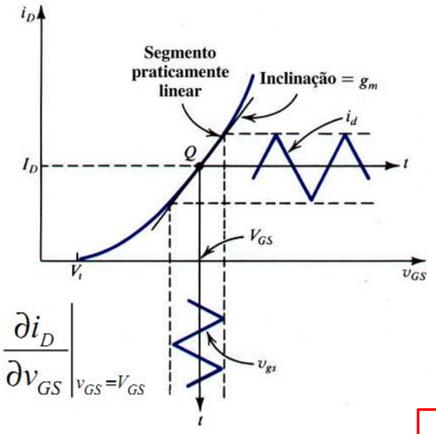
$$g_m = \frac{\partial I_D}{\partial V_{GS}} = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}2(V_{GS} - V_{TH})$$

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

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

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

Transcondutância MOS (saturação)



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

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

$$\left\{\begin{aligned} (V_{GS}-V_{TH}) &= \sqrt{\frac{2I_D}{\mu_n C_{ox}\frac{W}{L}}} \\ g_m &= \mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH}) \end{aligned}\right.$$

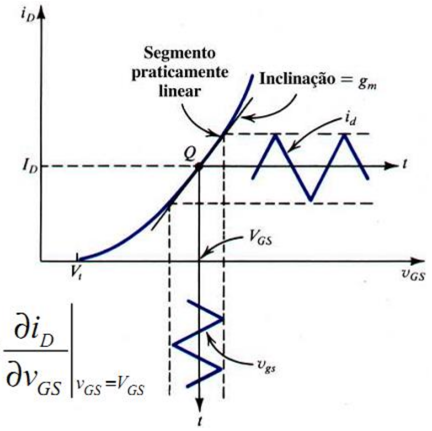
$$g_m = \mu_n C_{ox}\frac{W}{L}\sqrt{\frac{2I_D}{\mu_n C_{ox}\frac{W}{L}}}$$

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

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

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

Transcondutância MOS (saturação)



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

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

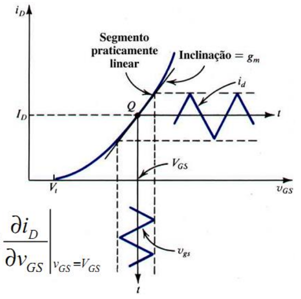
$$\frac{g_m}{I_D} = 2\frac{1}{(V_{GS}-V_{TH})} \Rightarrow \boxed{g_m = \frac{2I_D}{(V_{GS}-V_{TH})}}$$

$$g_m \propto I_D$$

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

Transcondutância MOS (saturação)

- Resumo



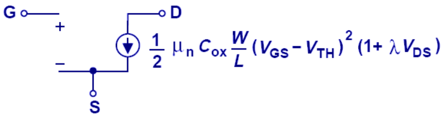
$$g_m \equiv \left.\frac{\partial i_D}{\partial v_{GS}}\right|_{v_{GS}=V_{GS}}$$

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

Modelo de Grandes Sinais

Saturação

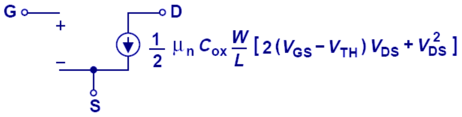
$V_{GS} > V_{TH}$
$V_{DS} > V_{GS} - V_{TH}$



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

(a)

$V_{GS} > V_{TH}$
$V_{DS} < V_{GS} - V_{TH}$

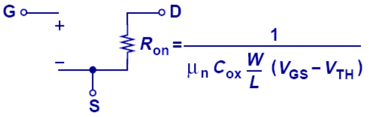


$$\frac{1}{2}\mu_n C_{ox}\frac{W}{L}[2(V_{GS}-V_{TH})V_{DS}+V_{DS}^2]$$

(b)

Triodo

$V_{GS} > V_{TH}$
$V_{DS} \ll 2(V_{GS} - V_{TH})$

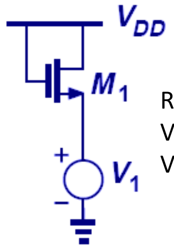


$$R_{on} = \frac{1}{\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})}$$

(c)

Triodo-Região linear

Exemplo

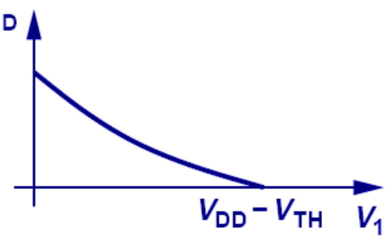


(a)

Região de Saturação:

$V_{DS}=V_{GS}$

$V_{DS}>V_{GS}-V_{TH}$

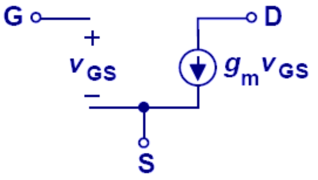


(b)

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

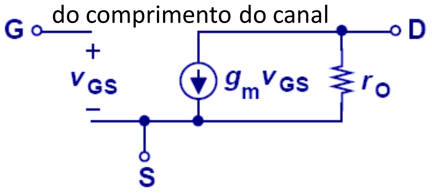
$$I_D=\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{DD}-V_1-V_{TH})^2$$

Modelo de Pequenos Sinais



(a)

Considerando a modulação do comprimento do canal



(b)

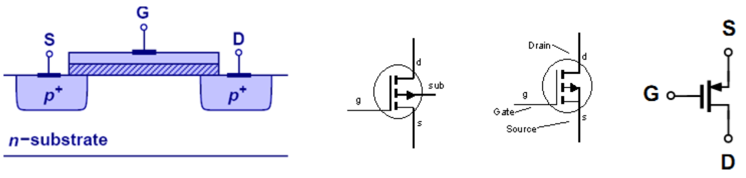
$$I_D=\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2(1+\lambda V_{DS})$$

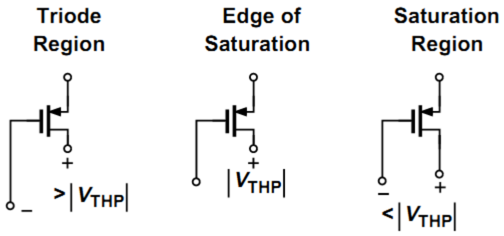
$$r_o=\left(\frac{\partial I_D}{\partial V_{DS}}\right)^{-1}=\frac{1}{\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2\lambda}$$

➡

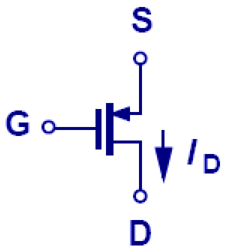
$$\boxed{r_o=\frac{1}{\lambda I_D}}$$

Transistor PMOS





Transistor PMOS - Equações



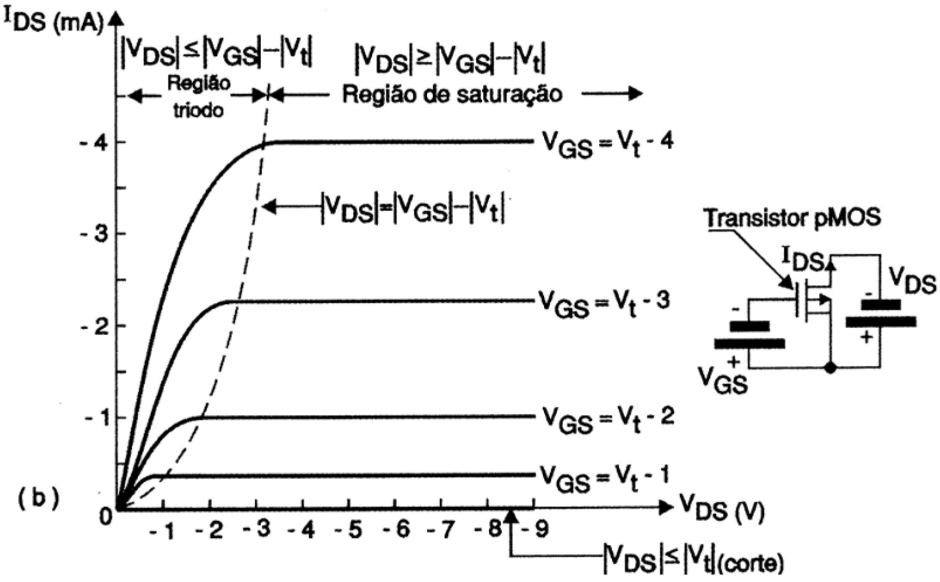
$$I_{D,sat} = \frac{1}{2}\mu_p C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2(1-\lambda V_{DS})$$

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

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

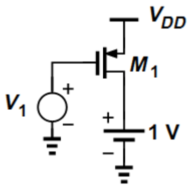
Obs: O modelo de pequenos sinais é o mesmo

Característica i_D - v_{DS} para o PMOS



Exemplo 6.15 - Razavi

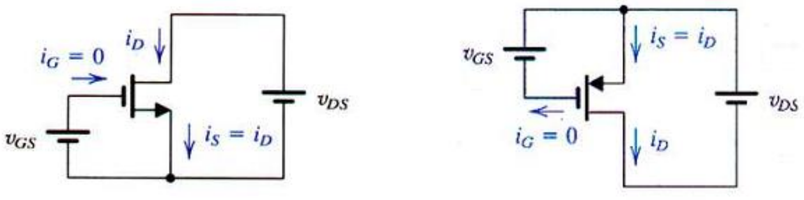
- Determine a região de operação de M1, de acordo com V_1(V_{DD} a 0V).



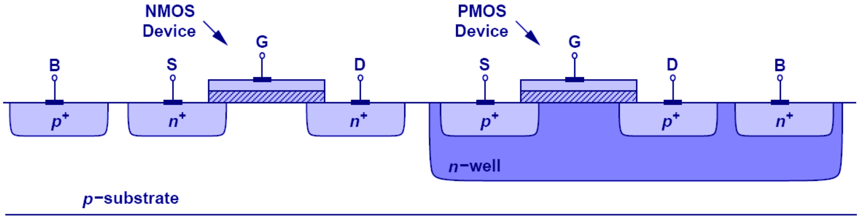
$$V_{DD} = 2.5\text{ V}$$

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

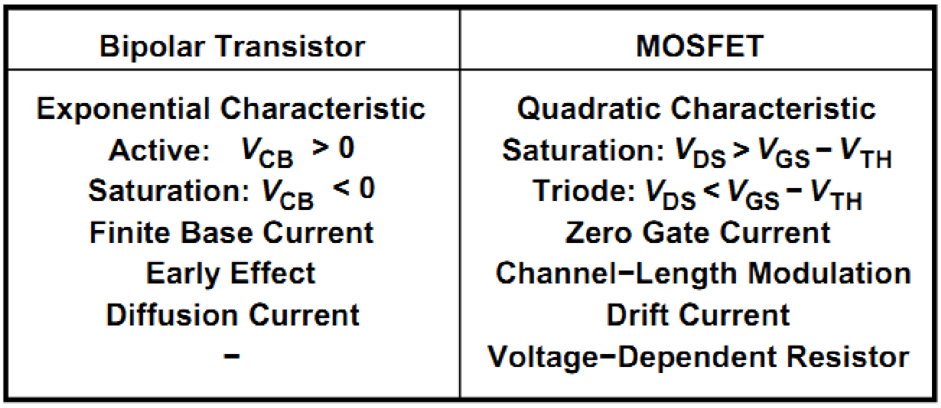
Comparação PMOS - NMOS



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)

Sugestão de estudo

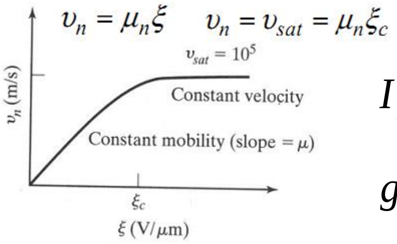
- Razavi, Cap. 6
- Sedra/Smith cap. 5 seções 5.1 até 5.3
  - Exercícios e problemas correspondentes

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



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

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

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