

Chapitre 1

Modèles pour les dispositifs bipolaires et MOS

1.1. Relations fondamentales pour le transistor bipolaire

1.1.1. Signal fort, régime actif normal

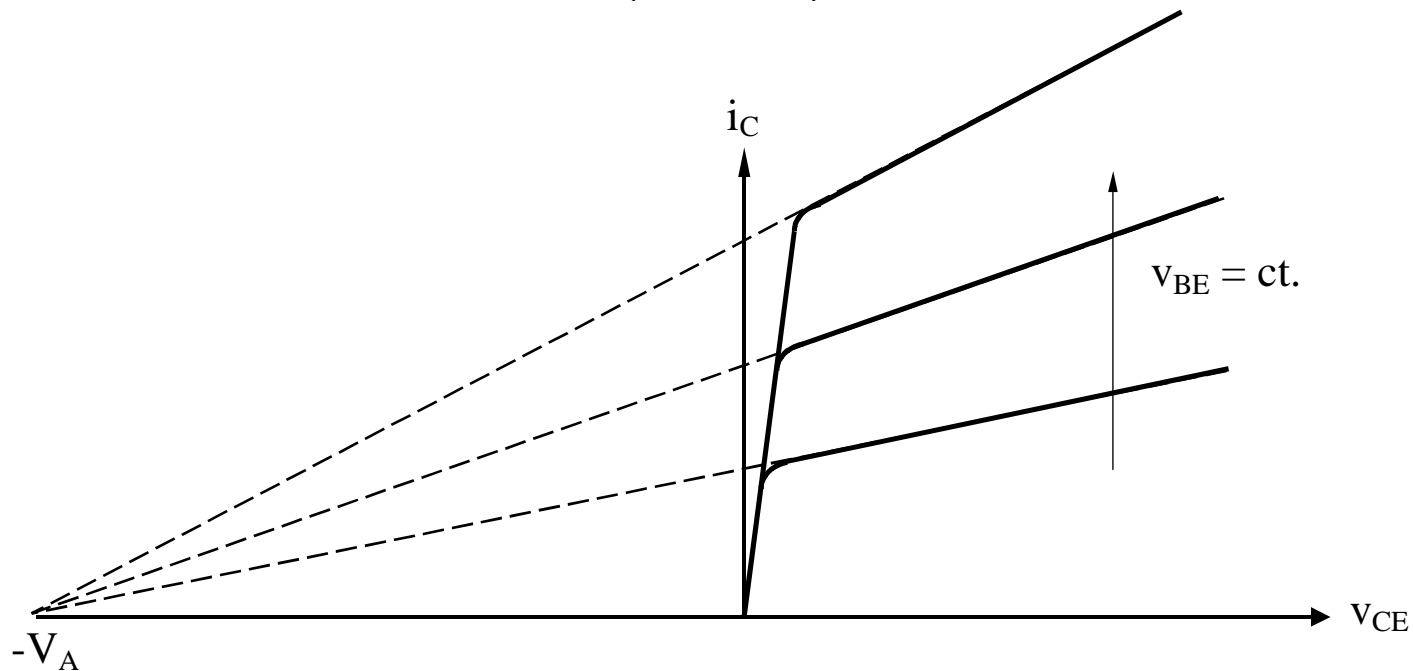
1.1.1. Signal fort, régime actif normal

Le relation entre i_c et v_{BE} :

$$i_c = I_S \left(e^{\frac{v_{BE}}{V_{th}}} - 1 \right) \cong I_S e^{\frac{v_{BE}}{V_{th}}}$$

L'effet Early:

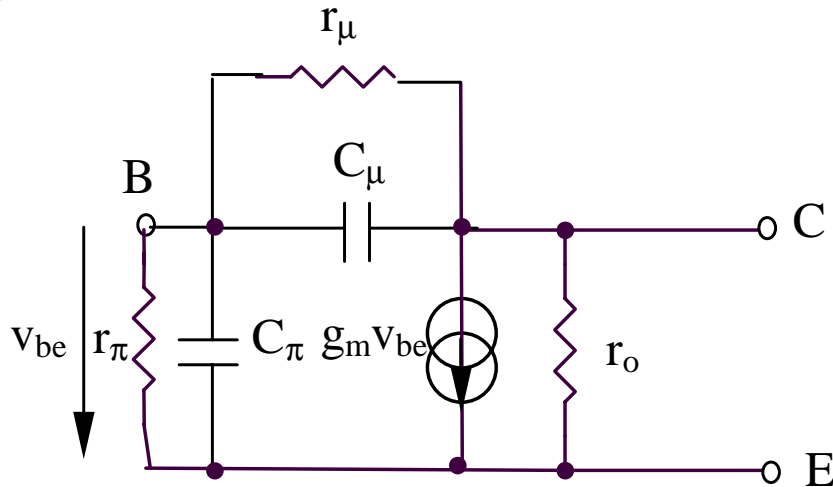
$$i_c = I_S e^{\frac{v_{BE}}{V_{th}}} \left(1 + \frac{v_{CE}}{V_A} \right)$$



1.1.2. Les modèles du transistor bipolaire en petit signal dans la régime actif normale

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Le modèle d'un transistor bipolaire en petit signal est présenté dans la figure suivante:



Conductance de transfert:

$$\left. \begin{aligned} g_m &= \frac{\partial I_C}{\partial V_{BE}} \\ I_C &\cong I_S \exp\left(\frac{V_{BE}}{V_{th}}\right) \end{aligned} \right\} \Rightarrow g_m = I_S \exp\left(\frac{V_{BE}}{V_{th}}\right) \frac{1}{V_{th}} = \frac{I_C}{V_{th}} \cong 40 I_C$$

Résistance de sortie:

$$r_o = \frac{1}{g_o} = \frac{1}{\frac{\partial I_C}{\partial V_{CE}}} \left. \vphantom{\frac{1}{g_o}} \right\} \Rightarrow r_o = \frac{1}{I_S \exp\left(\frac{V_{BE}}{V_{th}}\right) \frac{1}{V_A}} \cong \frac{V_A}{I_C}$$
$$I_C = I_S \exp\left(\frac{V_{BE}}{V_{th}}\right) \left(1 + \frac{V_{CE}}{V_A}\right)$$

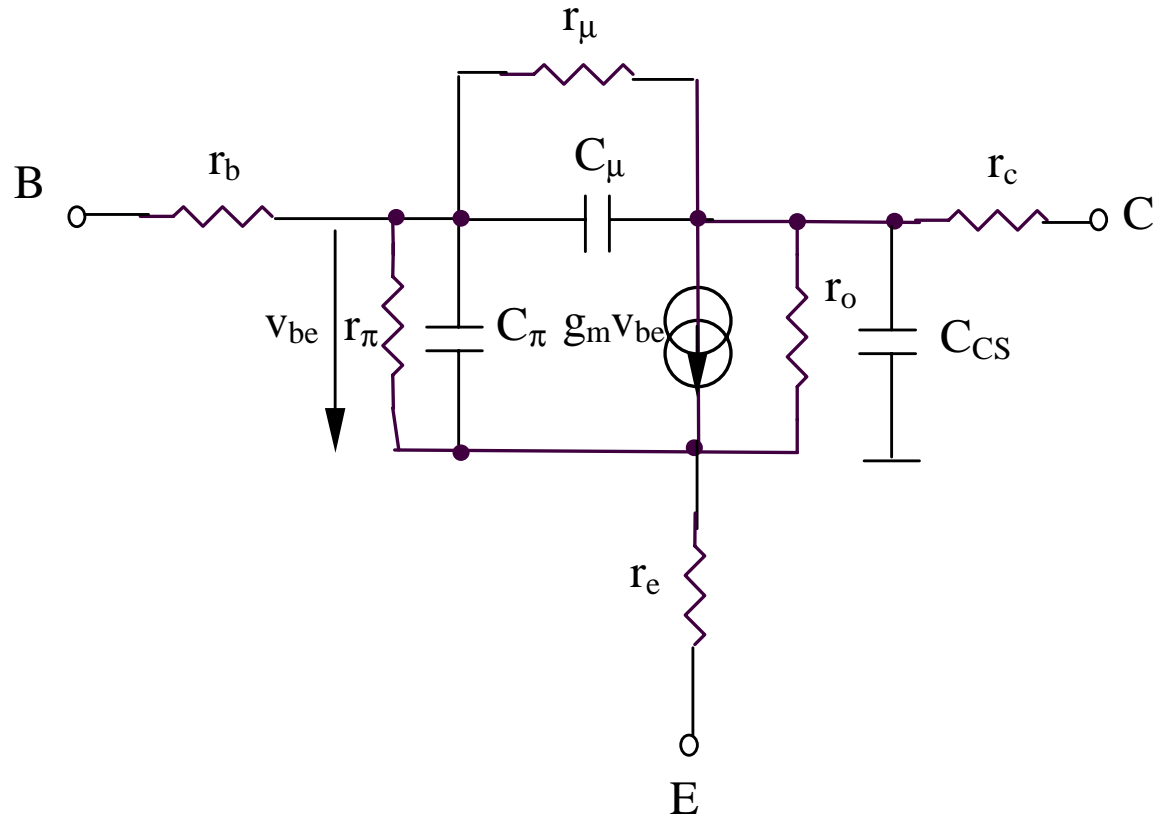
Résistance r_π :

$$r_\pi = \frac{\partial v_{BE}}{\partial i_B} = \frac{\beta}{g_m}$$

Résistance r_μ :

$$r_\mu = \frac{\partial v_{CE}}{\partial i_C} = K\beta_O r_o$$

Un schéma équivalent plus complet:



Exemple:

$$I_C = 1\text{mA}, \beta = 100, V_A = 100\text{V}$$

$$\Rightarrow g_m = 40I_C = 40\text{mA/V}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{40\text{mA/V}} = 2.5\text{k}\Omega$$

$$r_o = \frac{V_A}{I_C} = \frac{100\text{V}}{1\text{mA}} = 100\text{k}\Omega$$

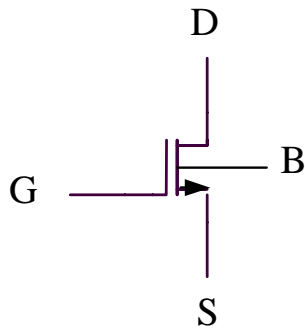
1.2. Relations fondamentales pour le transistor MOS

1.2.1. Signal fort

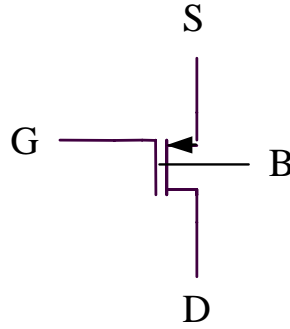
1.2.1. Signal fort

Symboles:

NMOS



PMOS



Notations:

G = porte

D = drain

S = source

B = substrat

W = largeur de canal

L = longueur de canal

(ou W/L = facteur d'aspect)

K' = paramètre de transconductance

V_T = tension de seuil

V_{GS} = tension de porte-source

V_{DS} = tension de drain-source

I. Région du fort inversion

$$V_{GS} > V_T$$

a. Saturation

$$V_{DS} \geq V_{DSsat} = V_{GS} - V_T$$

$$I_D = \frac{K}{2} (V_{GS} - V_T)^2 \qquad K = K' \frac{W}{L} = \mu_n C_{ox} \frac{W}{L}$$

b. Région linéaire

$$V_{DS} < V_{DSsat}$$

$$I_D = K \left[(V_{GS} - V_T) - \frac{V_{DS}}{2} \right] V_{DS}$$

II. Région du faible inversion

$$V_{GS} < V_T$$

$$I_D = I_{D0} \frac{W}{L} \exp\left(\frac{V_{GS} - V_T}{nV_{th}}\right)$$

$$I_D|_{sat} = I_D|_{f.i.}$$

$$\left. \frac{\partial I_D}{\partial V_{GS}} \right|_{sat} = \left. \frac{\partial I_D}{\partial V_{GS}} \right|_{f.i.}$$

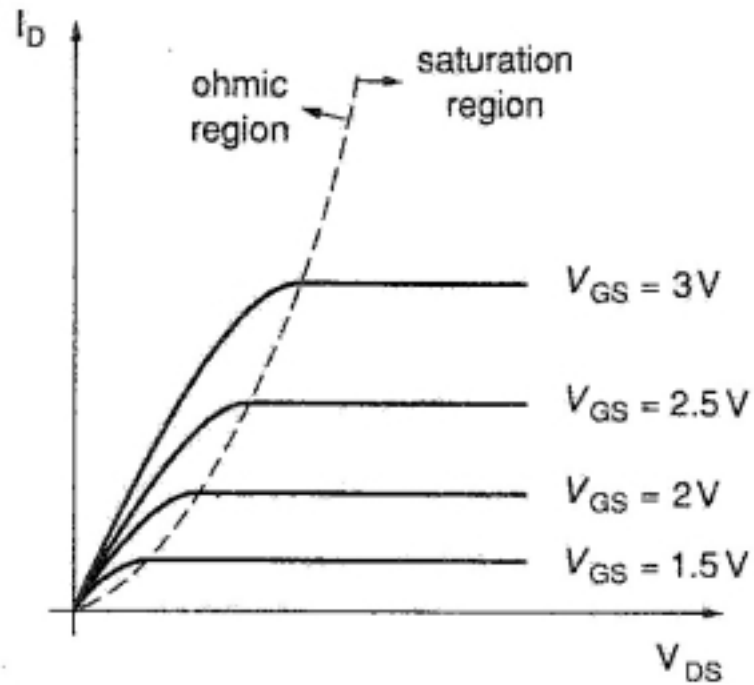
$$\frac{K}{2} (V_{GS} - V_T)^2 = I_{D0} \frac{W}{L} \exp\left(\frac{V_{GS} - V_T}{nV_{th}}\right)$$

$$K(V_{GS} - V_T) = I_{D0} \frac{W}{L} \frac{1}{nV_{th}} \exp\left(\frac{V_{GS} - V_T}{nV_{th}}\right)$$

$$\Rightarrow \begin{cases} \frac{V_{GS} - V_T}{2} = nV_{th} \\ \frac{K}{2} (2nV_{th})^2 = I_{D0} \frac{W}{L} e^2 \end{cases}$$

$$\Rightarrow \begin{cases} V_{GS} = V_T + nV_{th} \\ I_{D0} = \frac{K'2(nV_{th})^2}{e^2} \end{cases}$$

Caractéristiques de sortie du transistor MOS



Effets secondaires:

a. Modulation de longueur du canal

$$I_D = \frac{K}{2} (V_{GS} - V_T)^2 (1 + \lambda V_{DS})$$

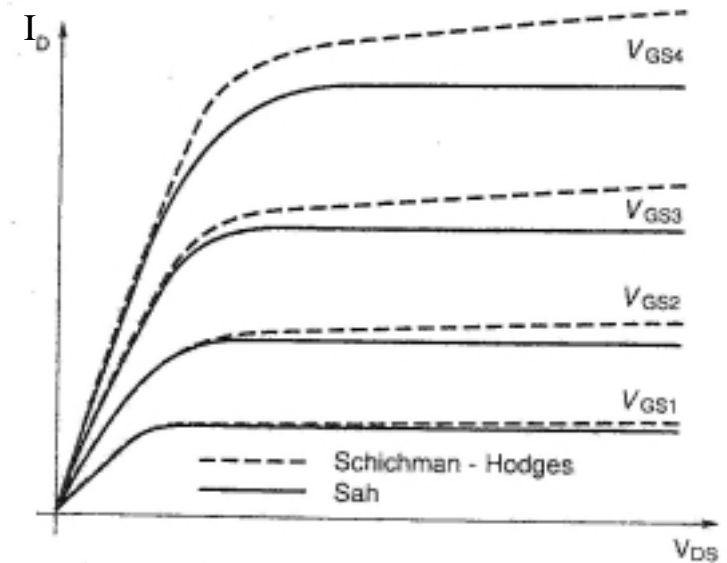
b. Dégradation de mobilité

$$K = \frac{K_0}{[1 + \theta_G (V_{GS} - V_T)](1 + \theta_D V_{DS})}$$

c. Effet de substrate

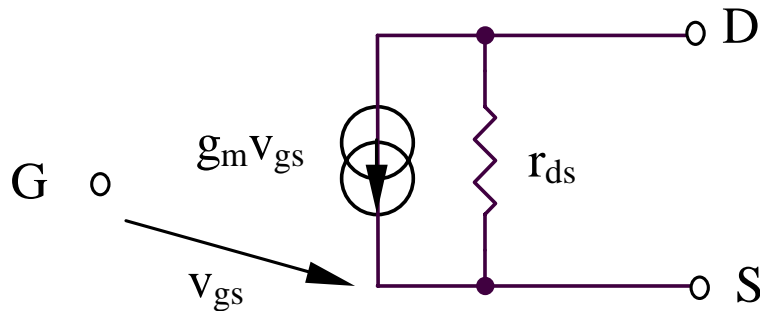
$$V_T = V_{T0} + \gamma(\sqrt{\Phi - V_{BS}} - \sqrt{\Phi})$$

Modulation de longueur du canal



1.2.2. Modèle du transistor MOS en petit signal

1.2.2. Modèle du transistor MOS en petit signal



$$g_m = \frac{\partial I_D}{\partial V_{GS}}$$

$$r_{ds} = \frac{1}{g_{ds}} = \frac{1}{\frac{\partial I_D}{\partial V_{DS}}}$$

$$g_m = \frac{\partial I_D}{\partial V_{GS}} \cong K(V_{GS} - V_T)$$

$$I_D = \frac{K}{2}(V_{GS} - V_T)^2 \Rightarrow V_{GS} - V_T = \sqrt{\frac{2I_D}{K}}$$

$$\left. \begin{array}{l} g_m = \frac{\partial I_D}{\partial V_{GS}} \cong K(V_{GS} - V_T) \\ I_D = \frac{K}{2}(V_{GS} - V_T)^2 \Rightarrow V_{GS} - V_T = \sqrt{\frac{2I_D}{K}} \end{array} \right\} \Rightarrow g_m = \sqrt{2KI_D}$$

$$r_{ds} = \frac{1}{\frac{\partial I_D}{\partial V_{DS}}} = \frac{1}{\frac{K}{2}(V_{GS} - V_T)^2 \lambda} \cong \frac{1}{\lambda I_D}$$

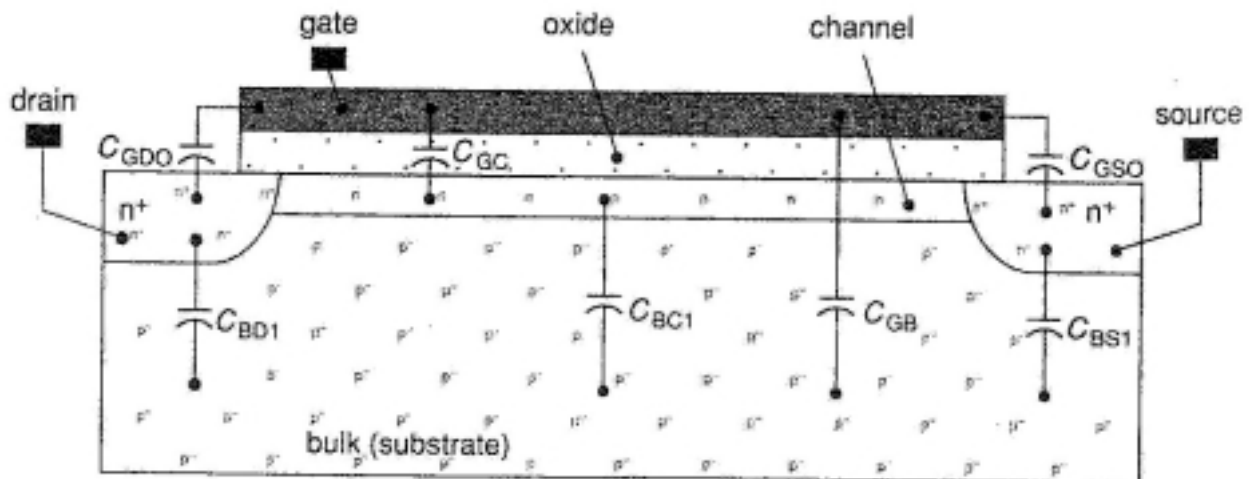
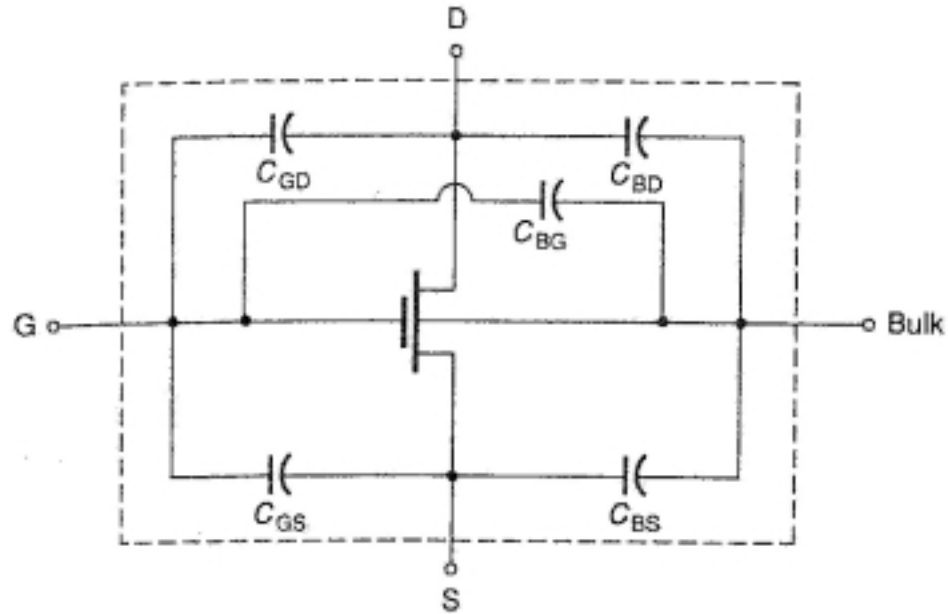
Exemple

$$I_D = 1\text{mA}, \lambda = 10^{-3}\text{V}^{-1}, K = 5 \times 10^{-4}\text{A/V}^2$$

$$\Rightarrow g_m = \sqrt{2KI_D} = 1\text{mA/V}$$

$$r_{ds} = \frac{1}{\lambda I_D} = 1\text{M}\Omega$$

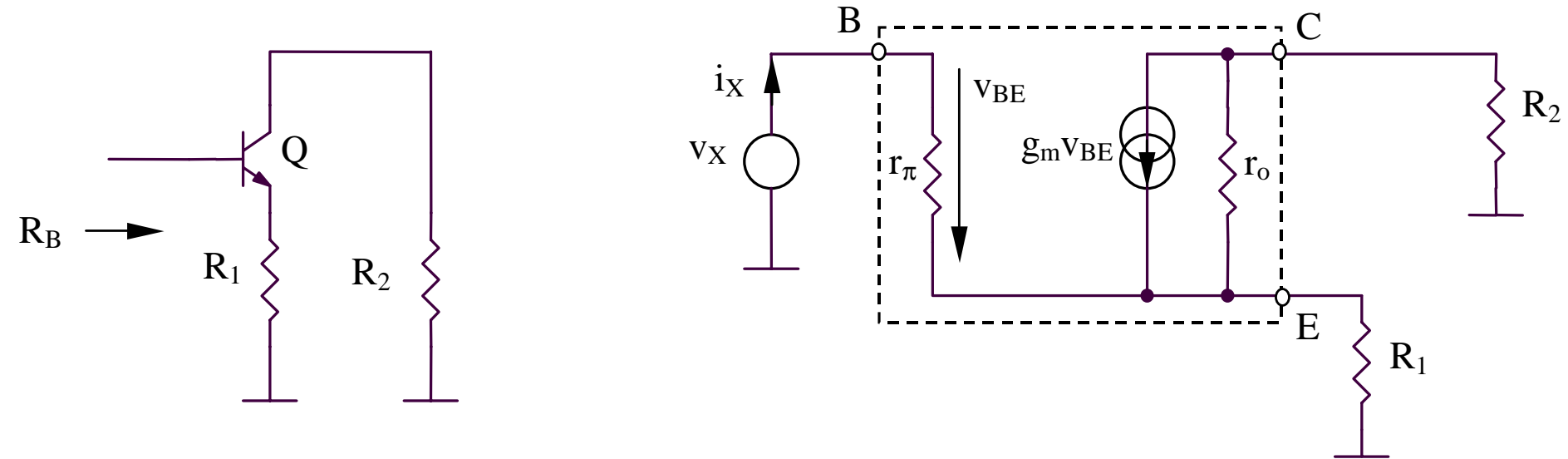
Modèle pour haute fréquence



1.3. Résistances dynamiques

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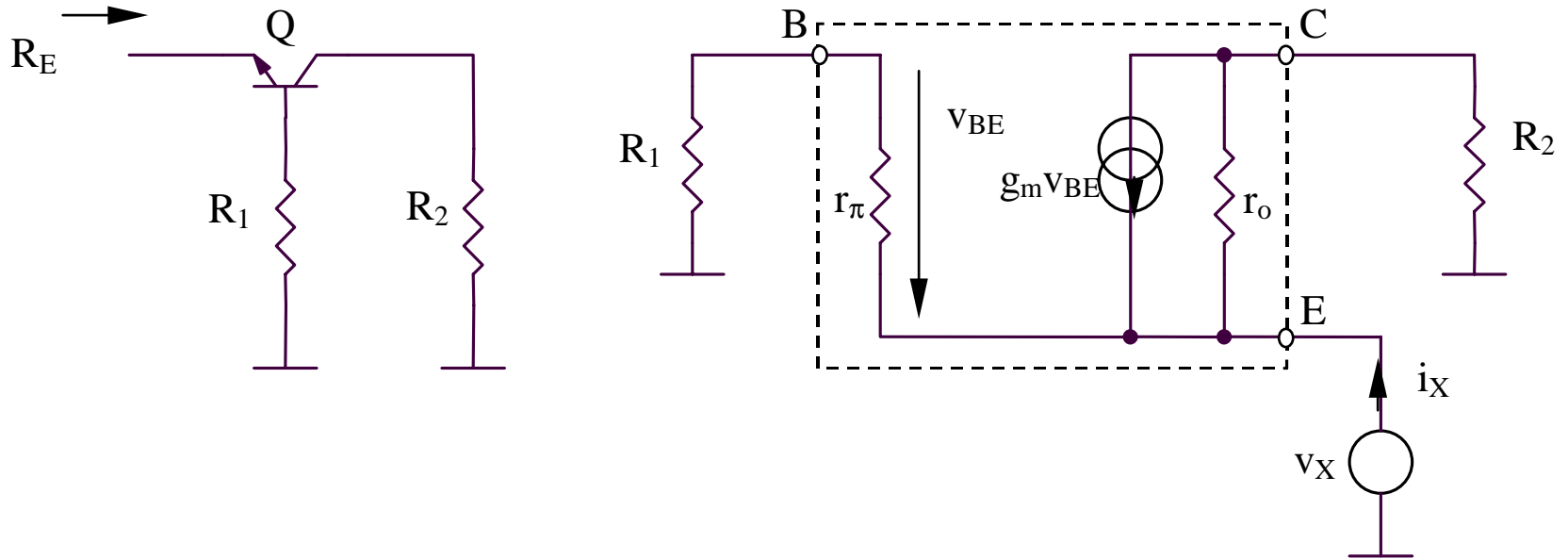
Résistance dans la base



$$v_x = i_x r_\pi + (\beta + 1) i_x R_1$$

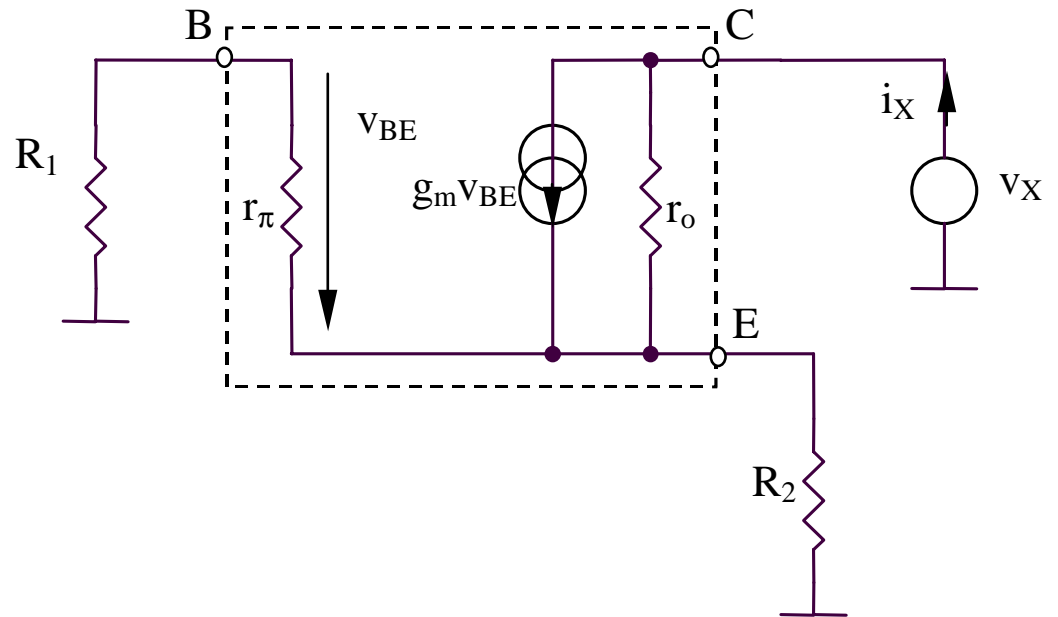
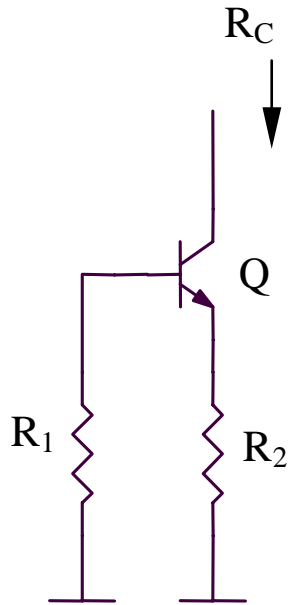
$$R_B = \frac{v_x}{i_x} = r_\pi + (\beta + 1) R_1$$

Résistance dans l'émetteur



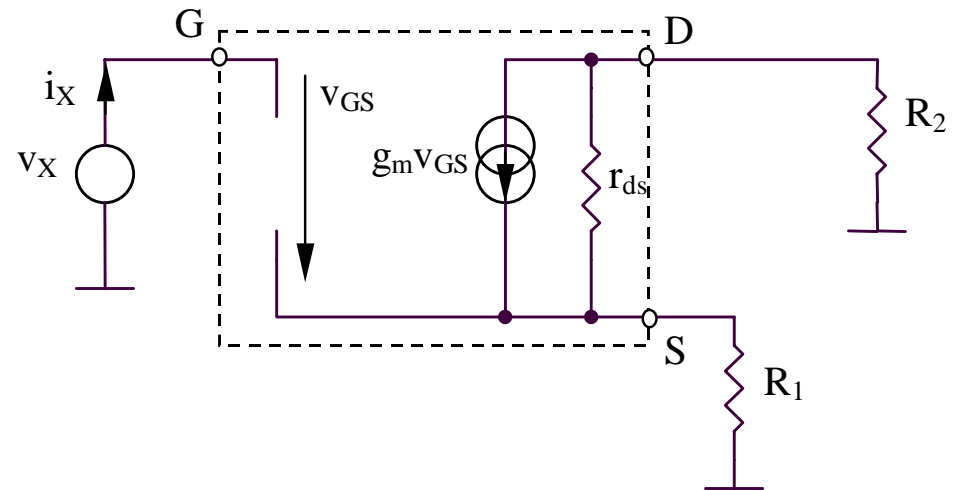
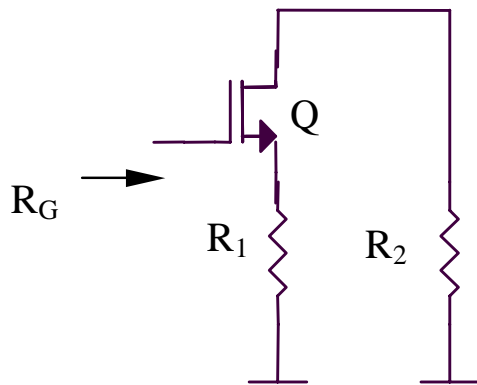
$$R_E = \frac{R_1 + r_{\pi}}{\beta + 1}$$

Résistance dans le collecteur



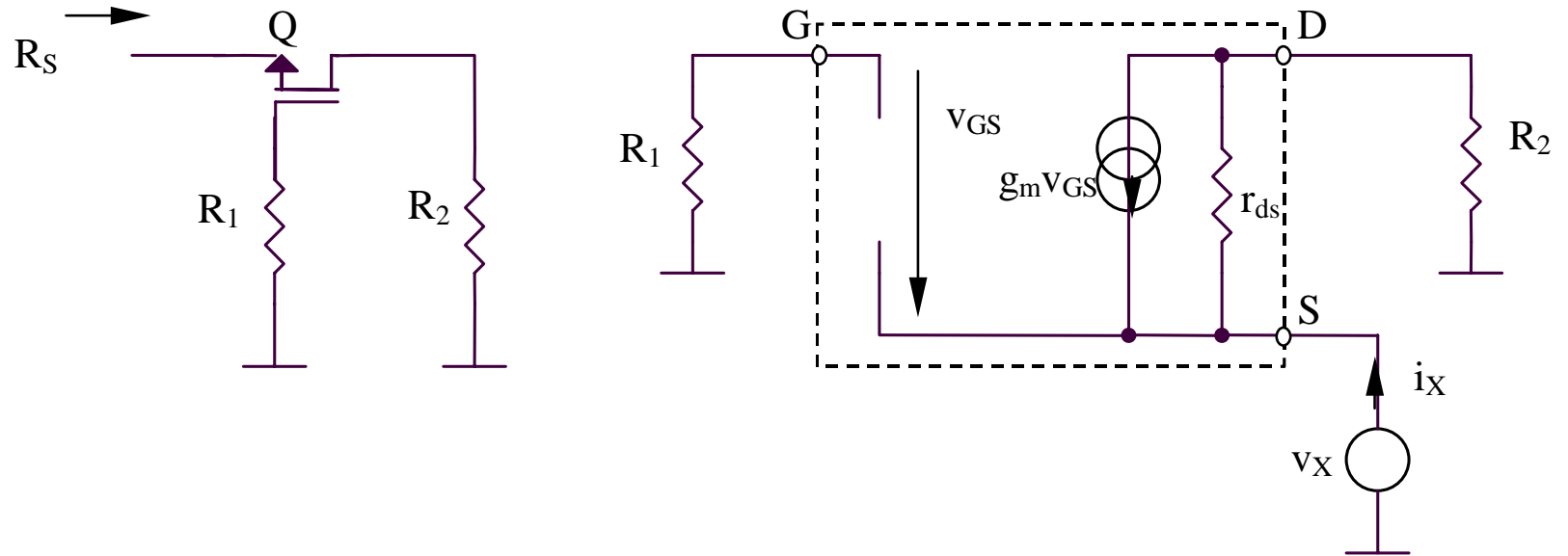
$$R_C = r_o \left(1 + \frac{\beta R_2}{r_\pi + R_1 + R_2} \right)$$

Résistance dans la porte



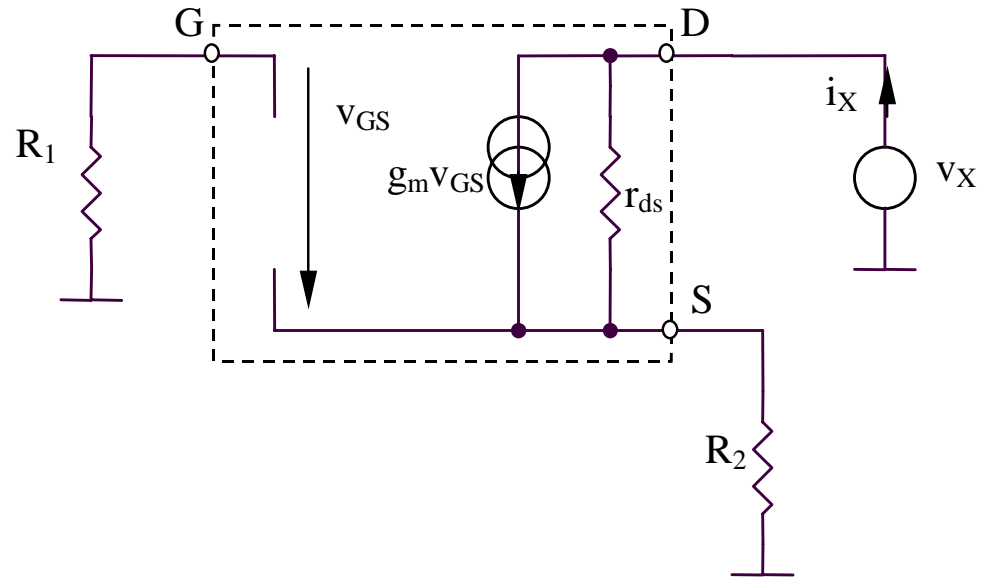
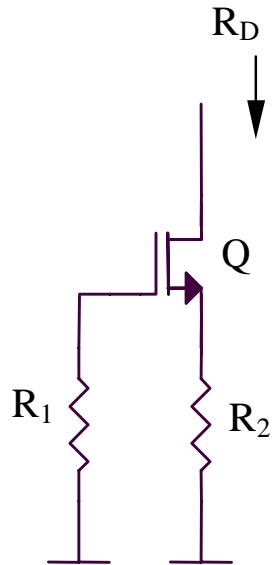
$$R_G = \infty$$

Résistance dans la source



$$i_x \cong -g_m v_{gs} = g_m v_x \Rightarrow R_S = \frac{v_x}{i_x} = \frac{1}{g_m}$$

Résistance dans la drain



$$\left. \begin{aligned} v_x &= (i_x - g_m v_{gs}) r_{ds} + i_x R_2 \\ v_{gs} &= -i_x R_2 \end{aligned} \right\} \Rightarrow R_D = \frac{v_x}{i_x} = r_{ds} (1 + g_m R_2) + R_2 \cong r_{ds} (1 + g_m R_2)$$