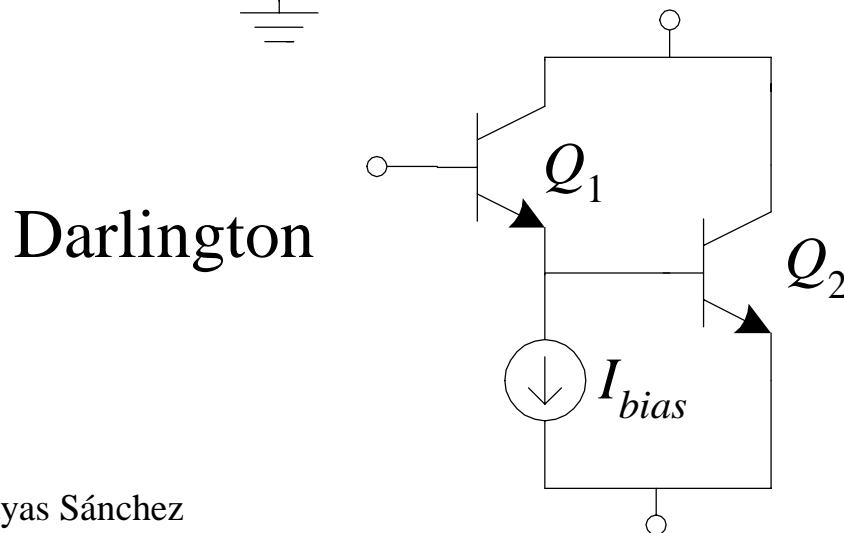
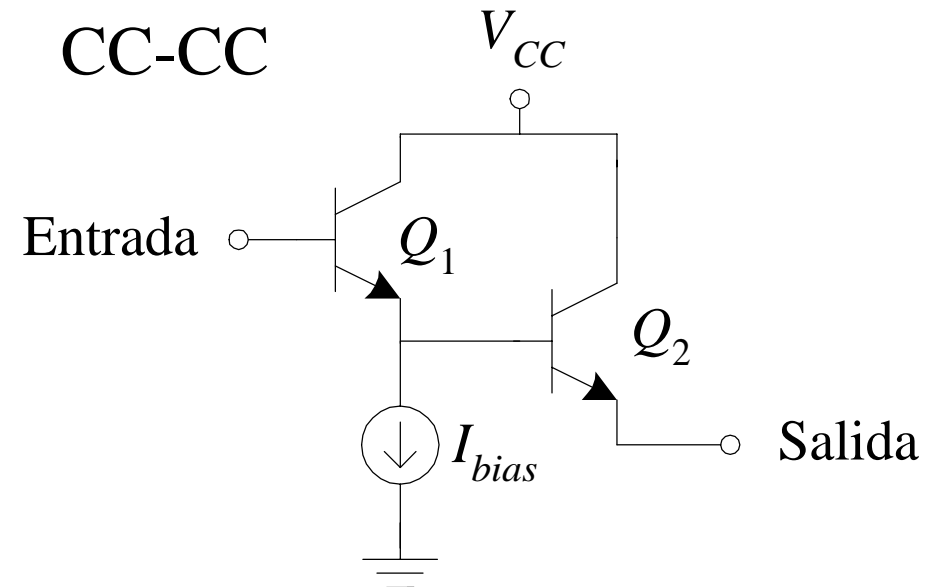
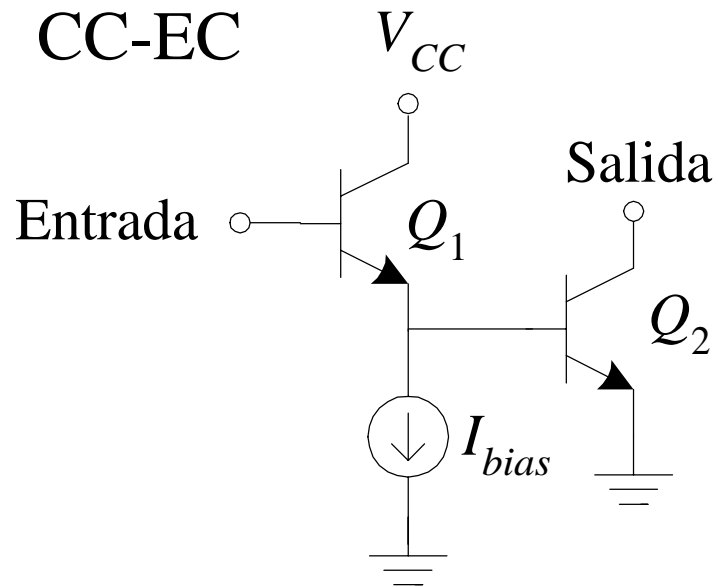

Etapas Básicas de Amplificación

(Parte 2)

Etapas Básicas de Amplificación

- Emisor Común (EC) ✓
- Base Común (BC) ✓
- Colector Común (CC, Seguidor de Emisor) ✓
- Degeneración de Emisor (DE) ✓
- Fuente Común (SC) ✓
- Compuerta Común (GC) ✓
- Drenaje Común (DC, Seguidor de Fuente) ✓
- CC-EC, CC-CC y Darlington
- Cascode
- Diferenciales

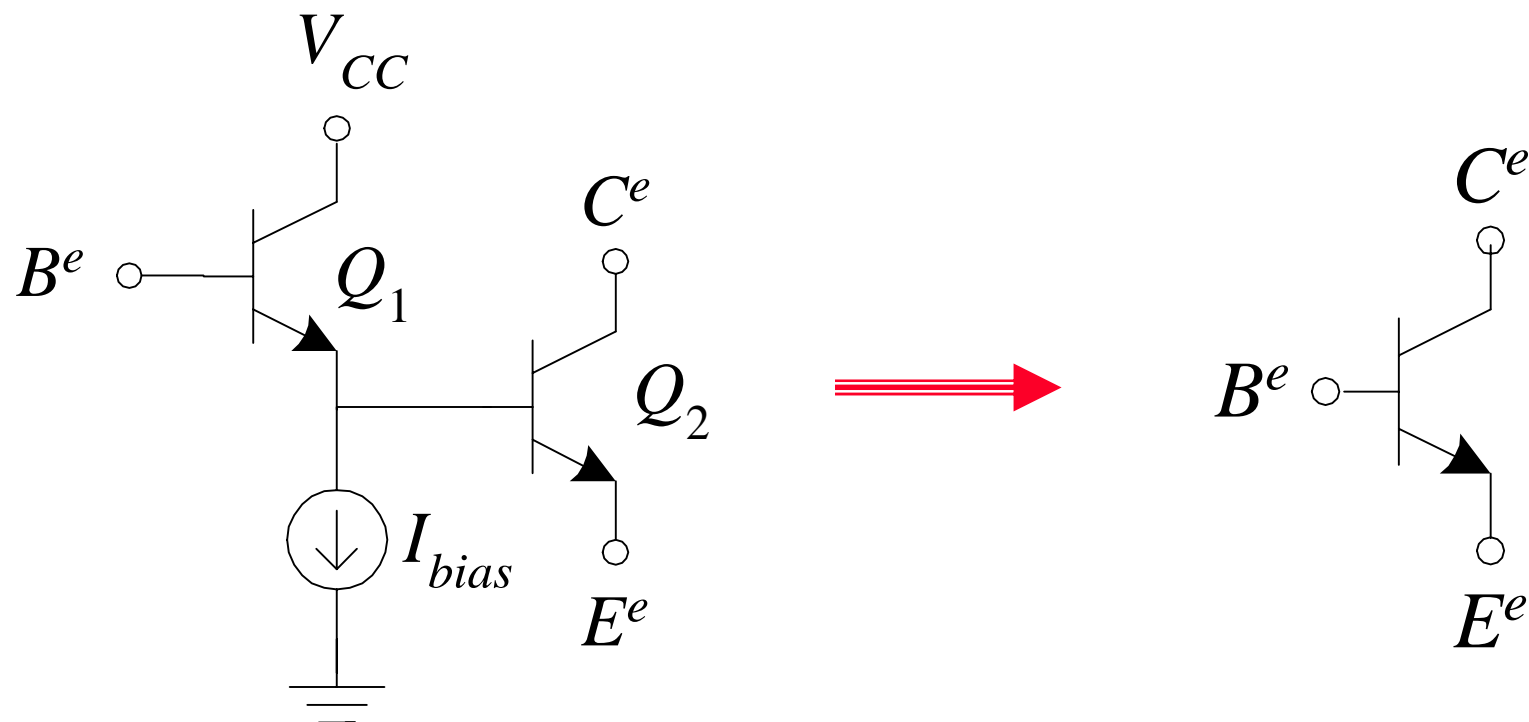
CC-EC, CC-CC y Darlington



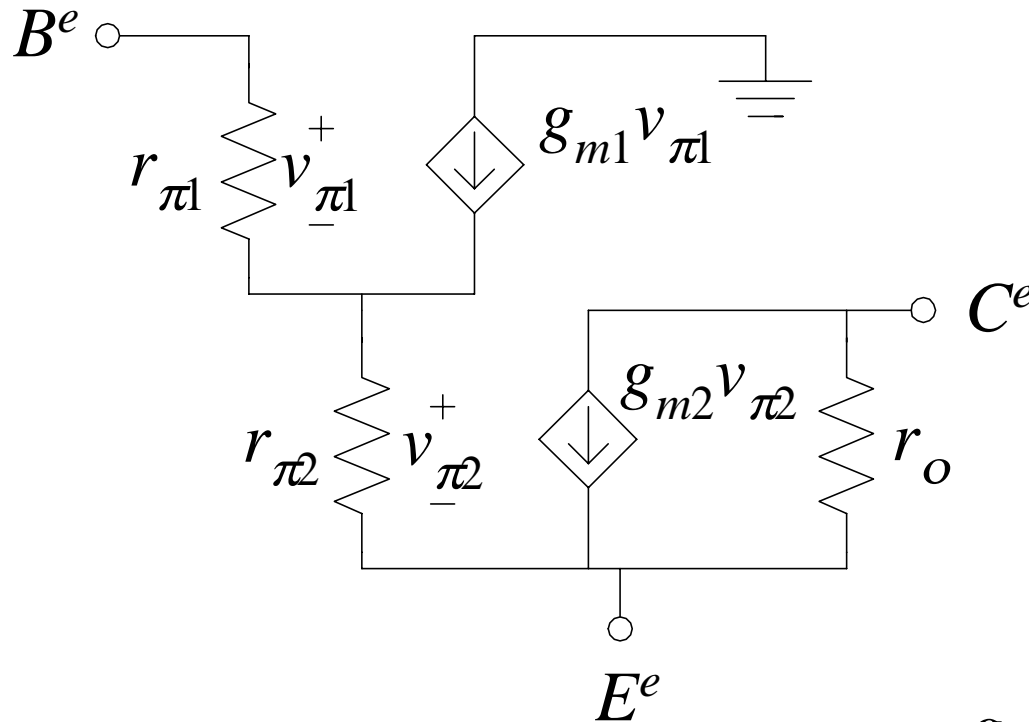
Darlington en CC \equiv CC-CC

Darlington en EC \approx CC-EC

CC-EC, CC-CC y Darlington (cont.)



CC-EC, CC-CC y Darlington - Señal Pequeña



$$r_o^e = r_o \quad *$$

$$r_{\pi}^e = r_{\pi 1} + (\beta_1 + 1)r_{\pi 2}$$

$$g_m^e = \frac{g_{m2} v_{\pi 2}}{v_{\pi 1} + v_{\pi 2}}$$

$$g_m^e = g_{m2} \frac{v_{\pi 2} / v_{\pi 1}}{1 + v_{\pi 2} / v_{\pi 1}}$$

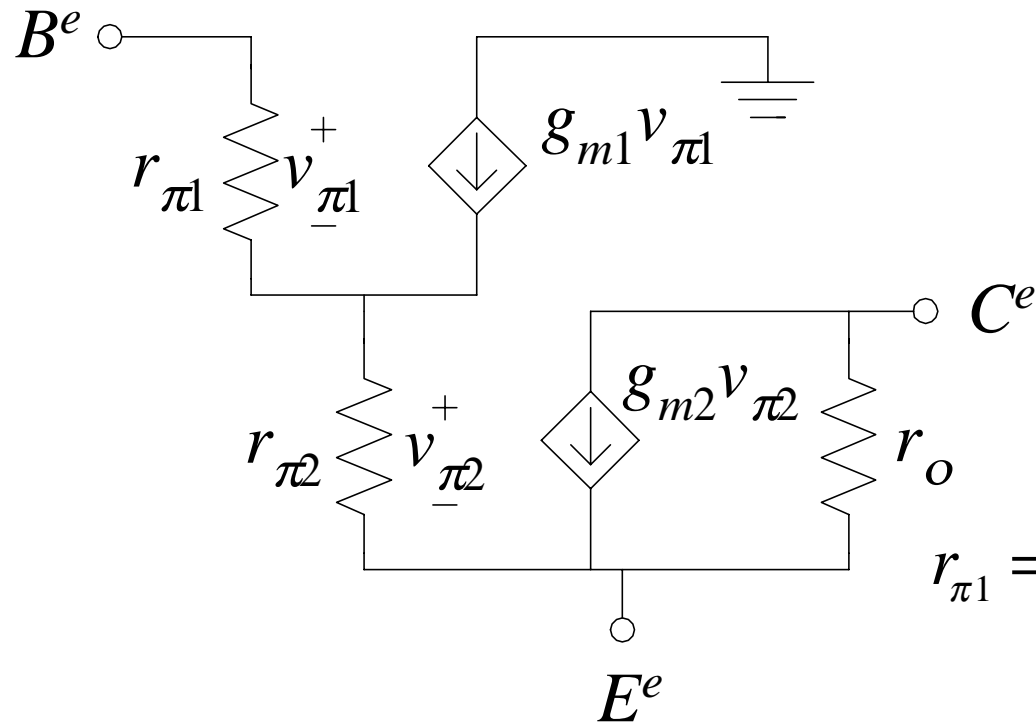
$$g_m^e = g_{m2} r_{\pi 2} \frac{(1 + g_{m1} r_{\pi 1})}{r_{\pi 1} + r_{\pi 2} (1 + g_{m1} r_{\pi 1})}$$

$$v_{\pi 2} = (v_{\pi 1} / r_{\pi 1} + g_{m1} v_{\pi 1}) r_{\pi 2}$$

$$v_{\pi 2} / v_{\pi 1} = r_{\pi 2} (1 / r_{\pi 1} + g_{m1})$$

$$g_m^e = \beta_2 \frac{(1 + \beta_1)}{r_{\pi 1} + r_{\pi 2} (1 + \beta_1)}$$

CC-EC, CC-CC y Darlington – S. P. (cont.)



$$g_m^e = \beta_2 \frac{(1 + \beta_1)}{r_{\pi 1} + r_{\pi 2}(1 + \beta_1)}$$

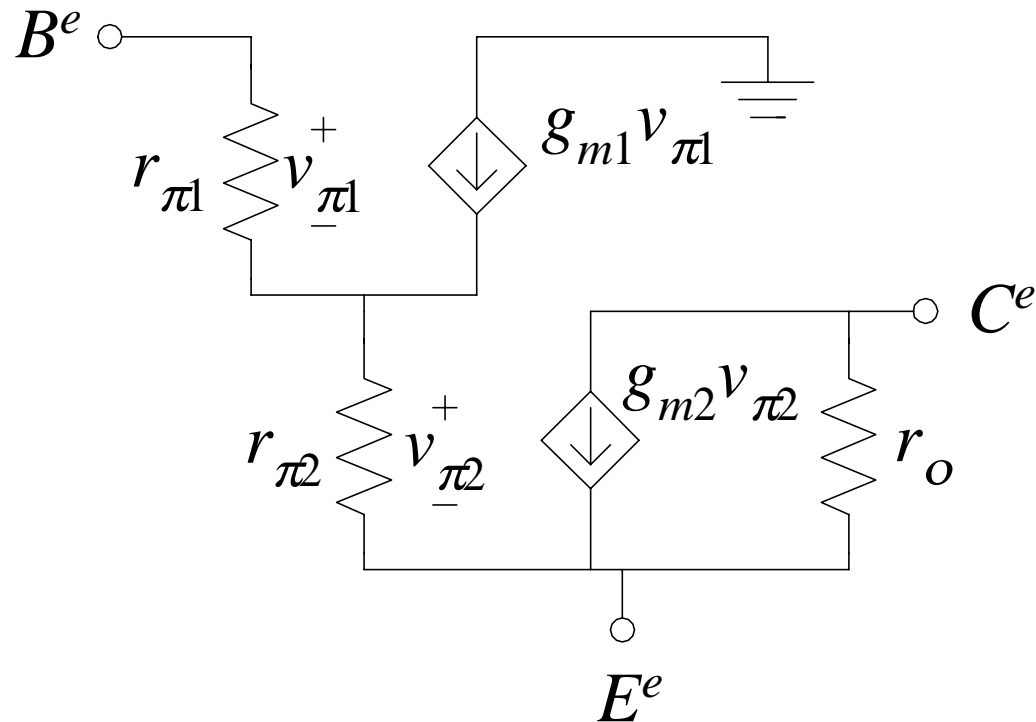
$$r_{\pi 2} = \frac{\beta_2}{g_{m2}} = \frac{\beta_2}{I_{C2}/V_T}$$

$$r_{\pi 1} = \frac{\beta_1}{g_{m1}} = \frac{\beta_1}{I_{C1}/V_T} \approx \frac{\beta_1}{(I_{C2}/\beta_2)/V_T}$$

$$r_{\pi 1} \approx \beta_1 r_{\pi 2}$$

$$g_m^e \approx \frac{\beta_2}{2r_{\pi 2}} = \frac{g_{m2}}{2}$$

CC-EC, CC-CC y Darlington – S. P. (cont.)

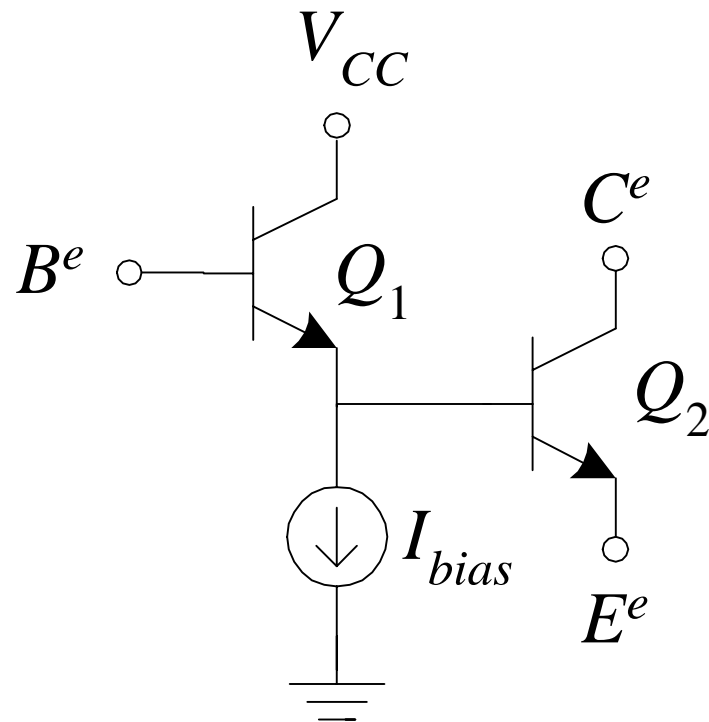


$$i_{b2} = (1 + \beta_1) i_{b1}$$

$$i_{c2} = \beta_2 i_{b2} = \beta_2 (1 + \beta_1) i_{b1}$$

$$\beta^e = \frac{i_{c2}}{i_{b1}} = \beta_2 (1 + \beta_1)$$

CC-EC, CC-CC y Darlington – S. P. (cont.)



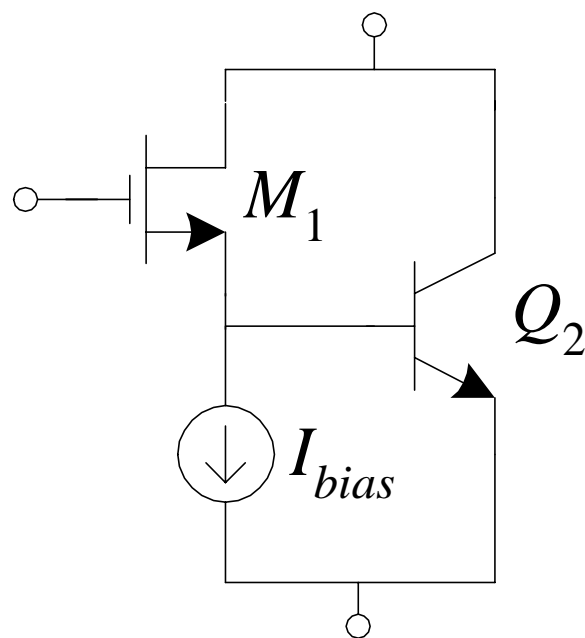
$$r_o^e = r_o \quad *$$

$$r_{\pi}^e = r_{\pi 1} + (\beta_1 + 1)r_{\pi 2}$$

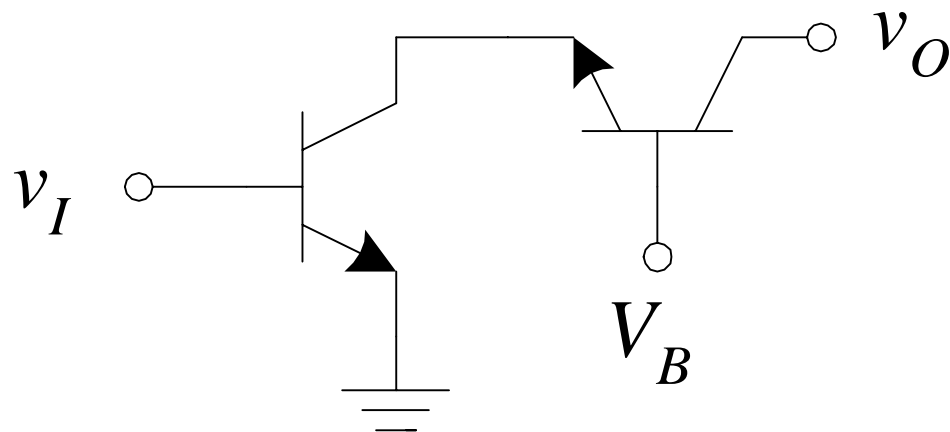
$$g_m^e \approx \frac{\beta_2}{2r_{\pi 2}} = \frac{g_{m2}}{2}$$

$$\beta^e = \frac{i_{c2}}{i_{b1}} = \beta_2(1 + \beta_1)$$

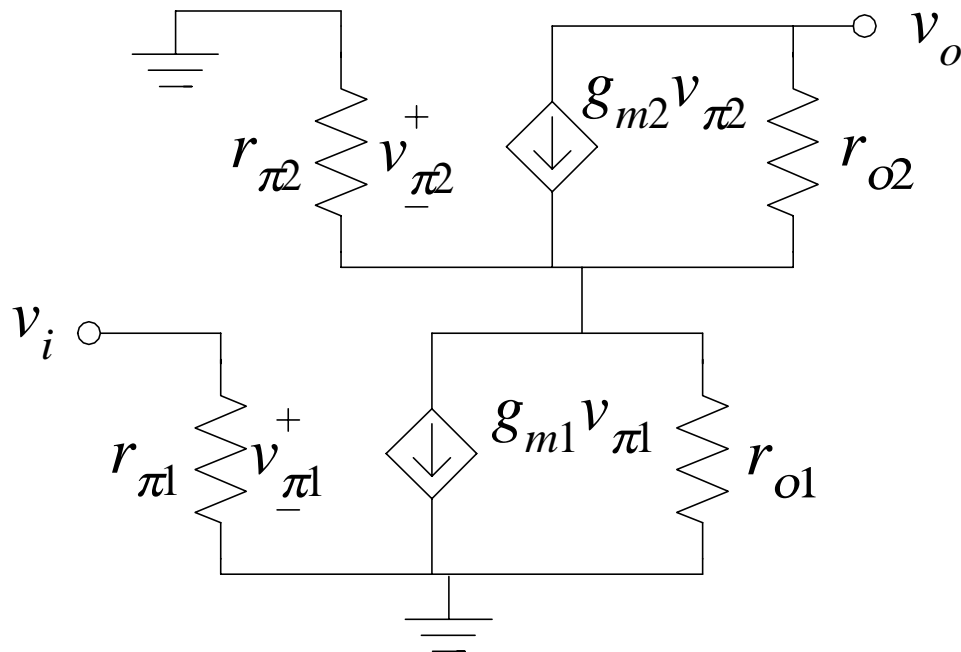
Darlington en Tecnología BiCMOS



Configuración Cascode (EC-BC, SC-GC)



Cascode – Señal Pequeña

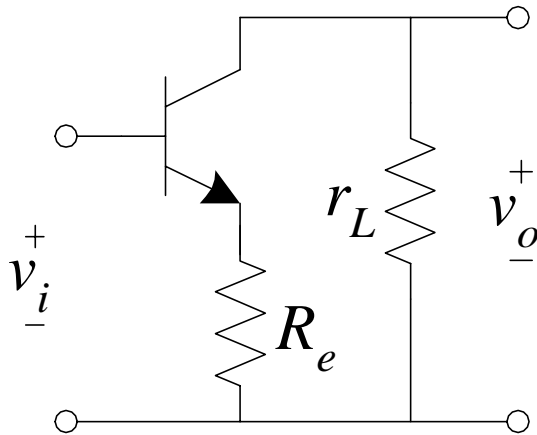


$$r_{\pi}^e = r_{\pi 1}$$

$$g_m^e \approx g_{m1}$$

$$r_o^e = ?$$

Degeneración de Emisor – Señal Peq. (repaso)



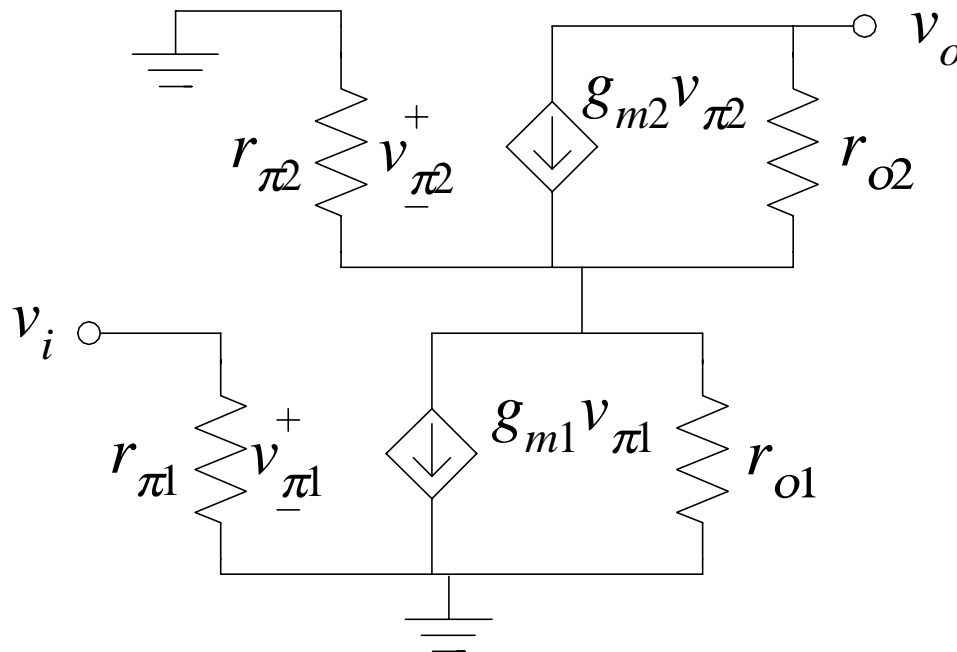
$$A_v = \frac{v_o}{v_i} = \frac{-g_m r_L}{1 + g_m R_e}$$

$$Z_{in} = \frac{v_i}{i_i} = r_\pi + \beta R_e$$

$$A_i = \frac{i_L}{i_i} = -g_m r_\pi = -\beta$$

$$Z_o \approx r_o [1 + g_m (r_\pi \parallel R_e)]$$

Cascode – Señal Pequeña (cont.)



$$r_{\pi}^e = r_{\pi 1}$$

$$g_m^e \approx g_{m1}$$

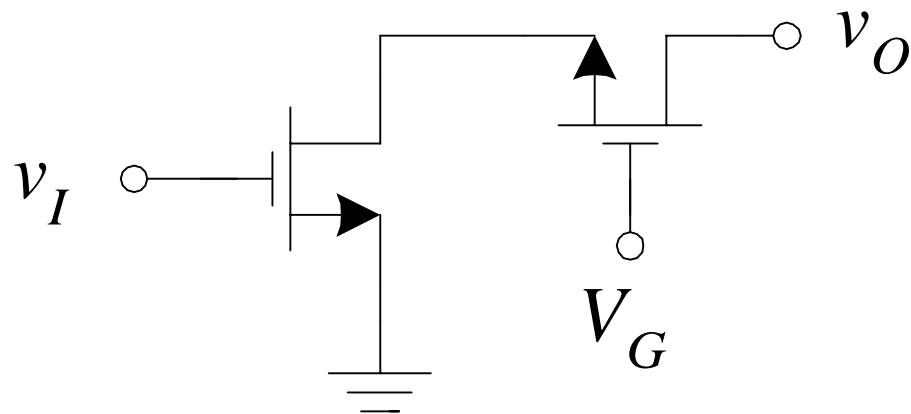
$$r_o^e \approx r_{o2} [1 + g_{m2} (r_{\pi 2} \parallel r_{o1})]$$

$$r_o^e \approx r_{o2} (1 + \beta_2)$$

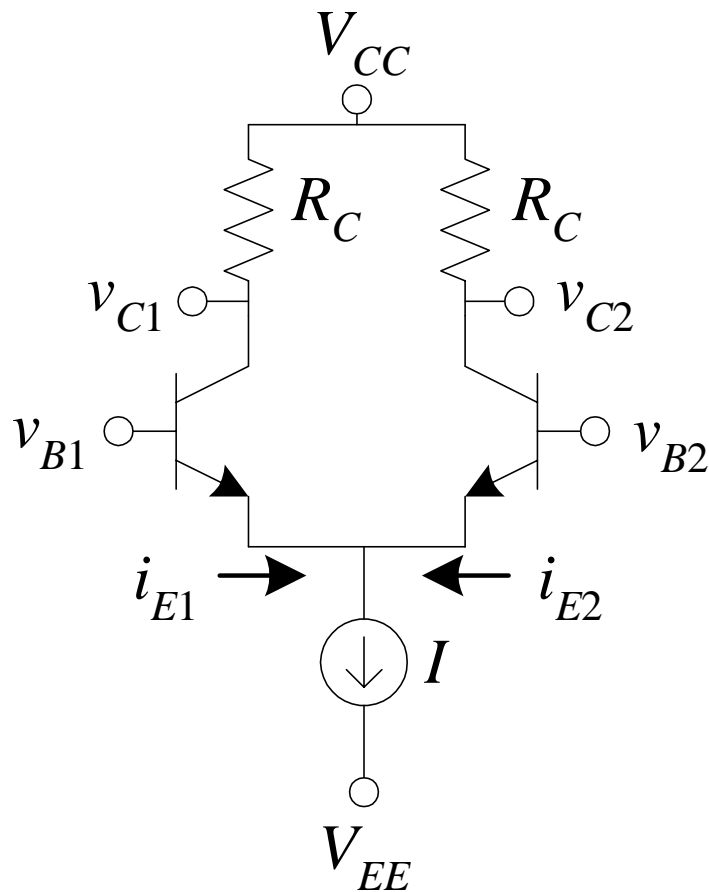
La alta r_o se explota en:

- amplificadores de muy alta ganancia
- referencias de voltaje

Cascode en Tecnología MOS



Amplificador Diferencial – Señal Grande



$$i_{E1} = \frac{I_S}{\alpha} e^{(v_{B1}-v_E)/V_T} \quad i_{E2} = \frac{I_S}{\alpha} e^{(v_{B2}-v_E)/V_T}$$

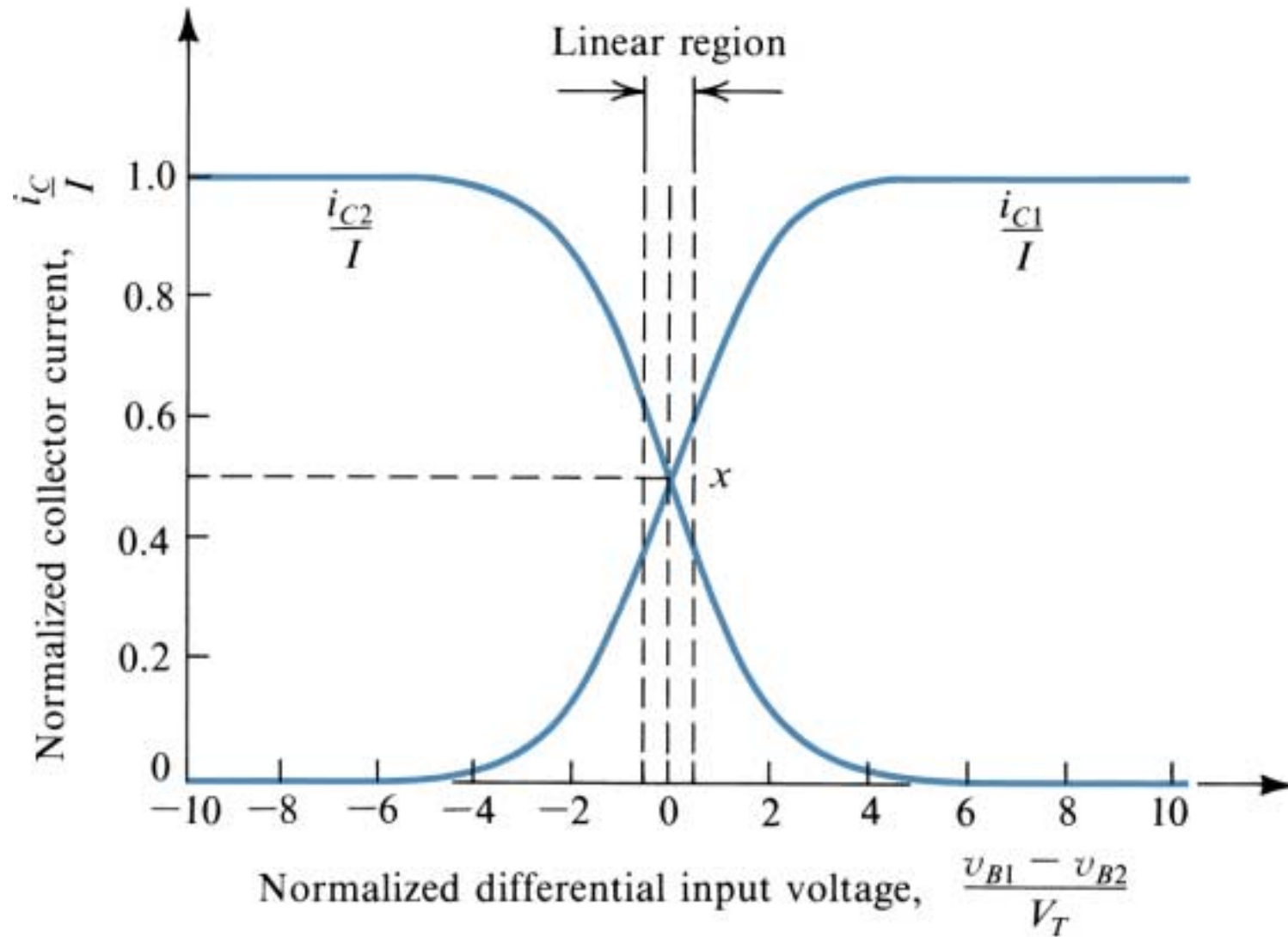
$$\frac{i_{E1}}{i_{E2}} = e^{(v_{B1}-v_{B2})/V_T}$$

$$i_{E1} + i_{E2} = I$$

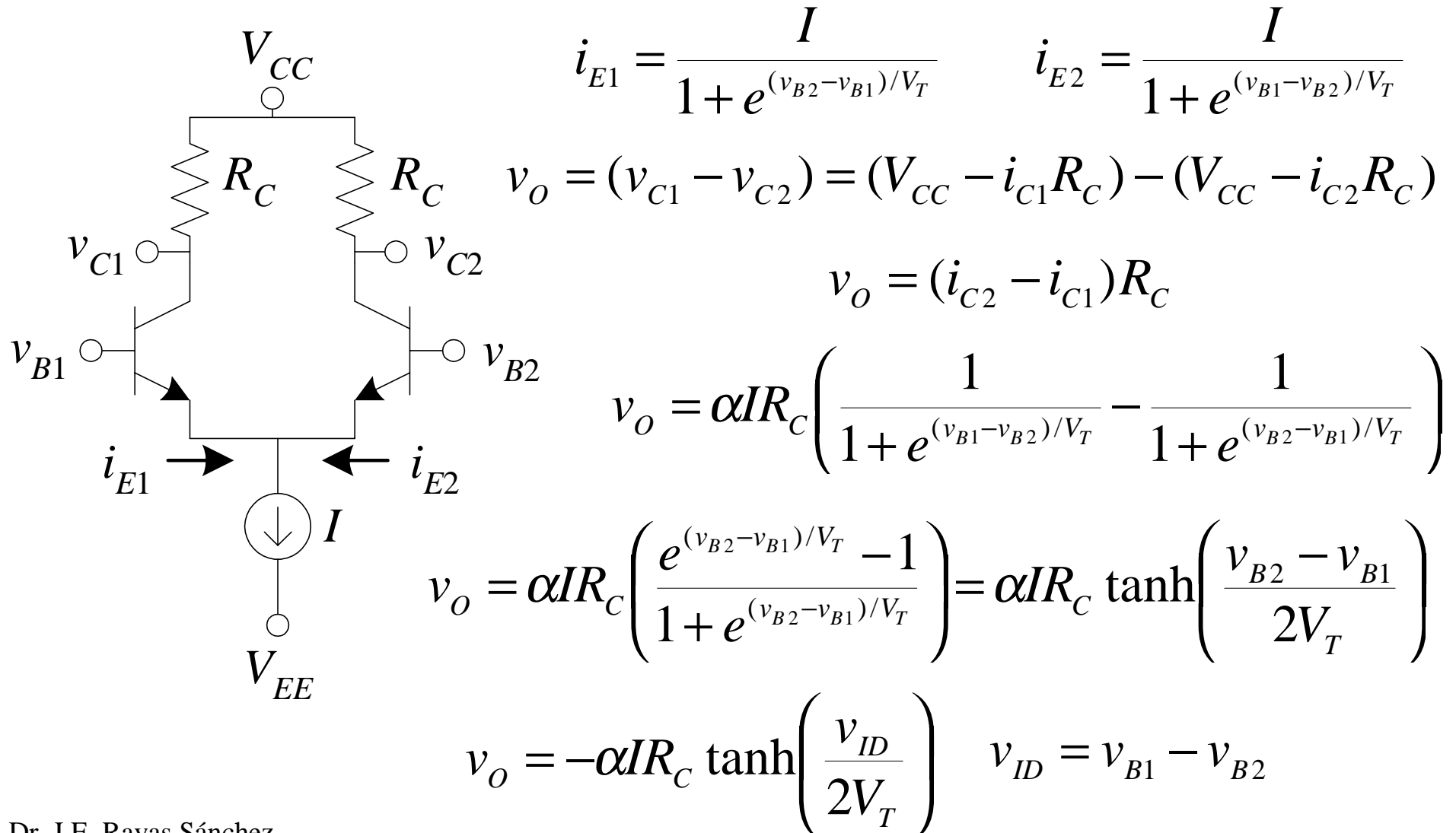
$$i_{E2} = \frac{I}{1 + e^{(v_{B1}-v_{B2})/V_T}}$$

$$i_{E1} = \frac{I}{1 + e^{(v_{B2}-v_{B1})/V_T}}$$

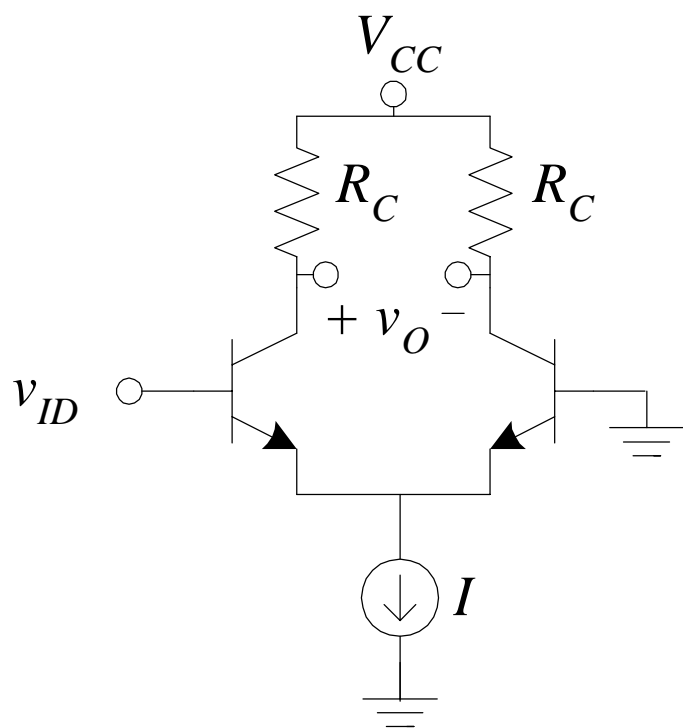
Curva Característica del Par Diferencial



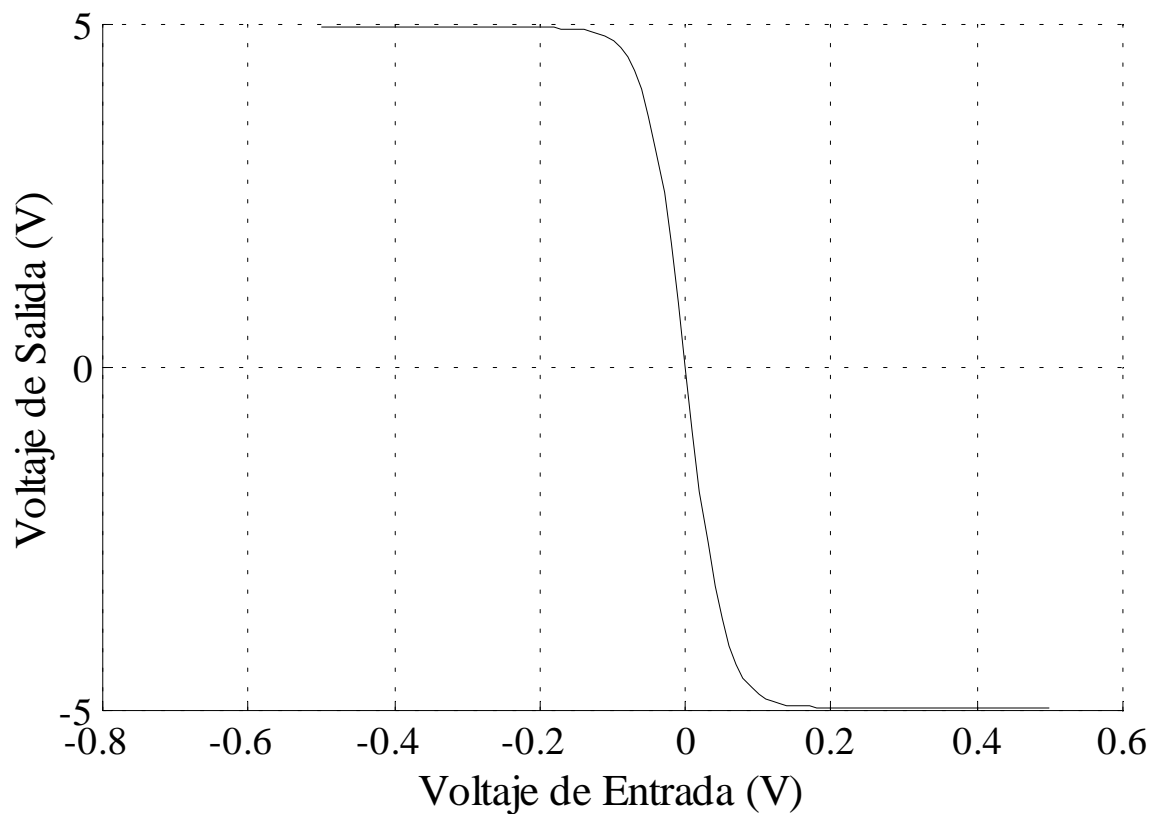
Amp. Diferencial – Señal Grande (cont.)



Amp. Diferencial – Señal Grande (cont.)



$$v_o = -\alpha I R_C \tanh\left(\frac{v_{ID}}{2V_T}\right)$$



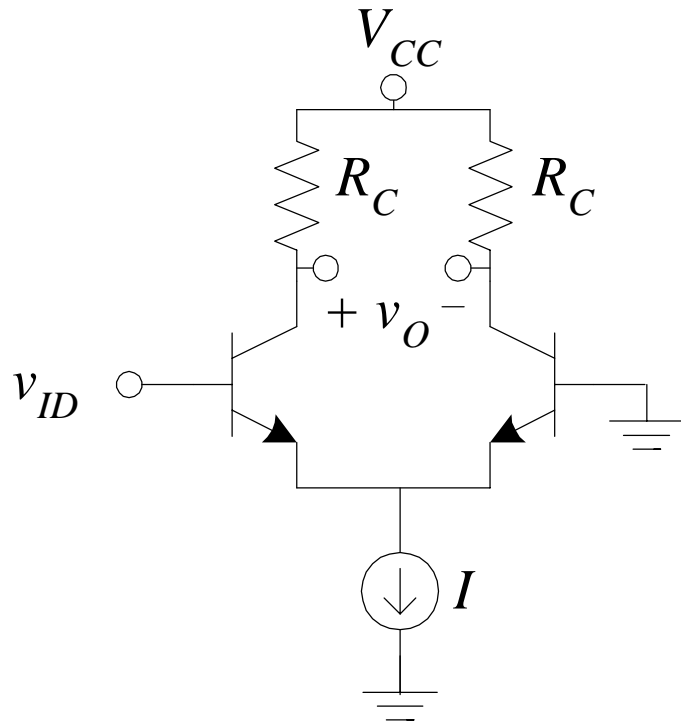
$$R_C = 1\text{K}\Omega$$

$$I = 5\text{ mA}$$

$$V_T = 25\text{mV}$$

$$\alpha = 1$$

Amp. Diferencial – Señal Grande (cont.)



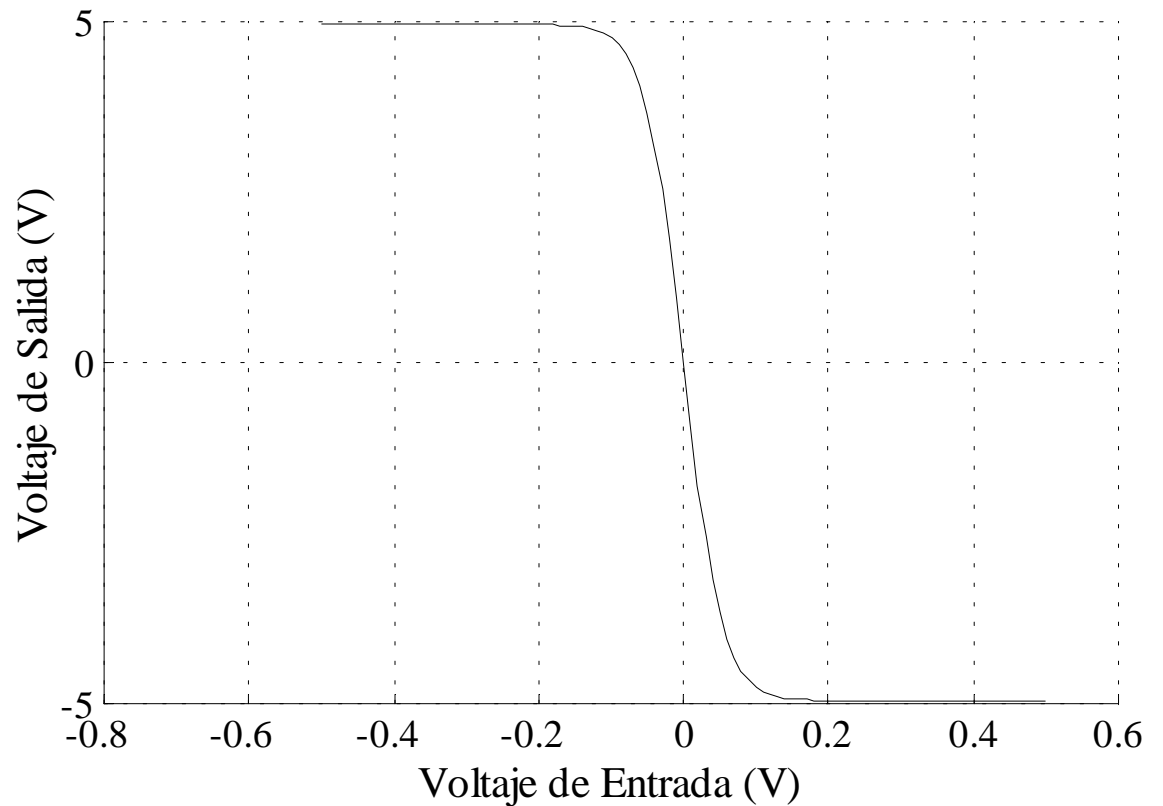
$$V_{CC} = 12\text{V}$$

$$I = 5\text{mA}$$

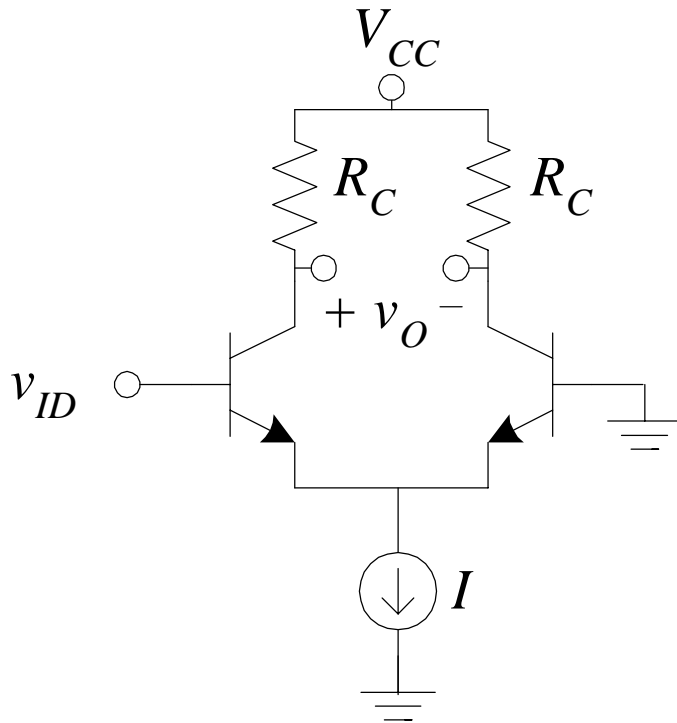
$$R_C = 1\text{k}\Omega$$

$$Q: 2\text{N}2222$$

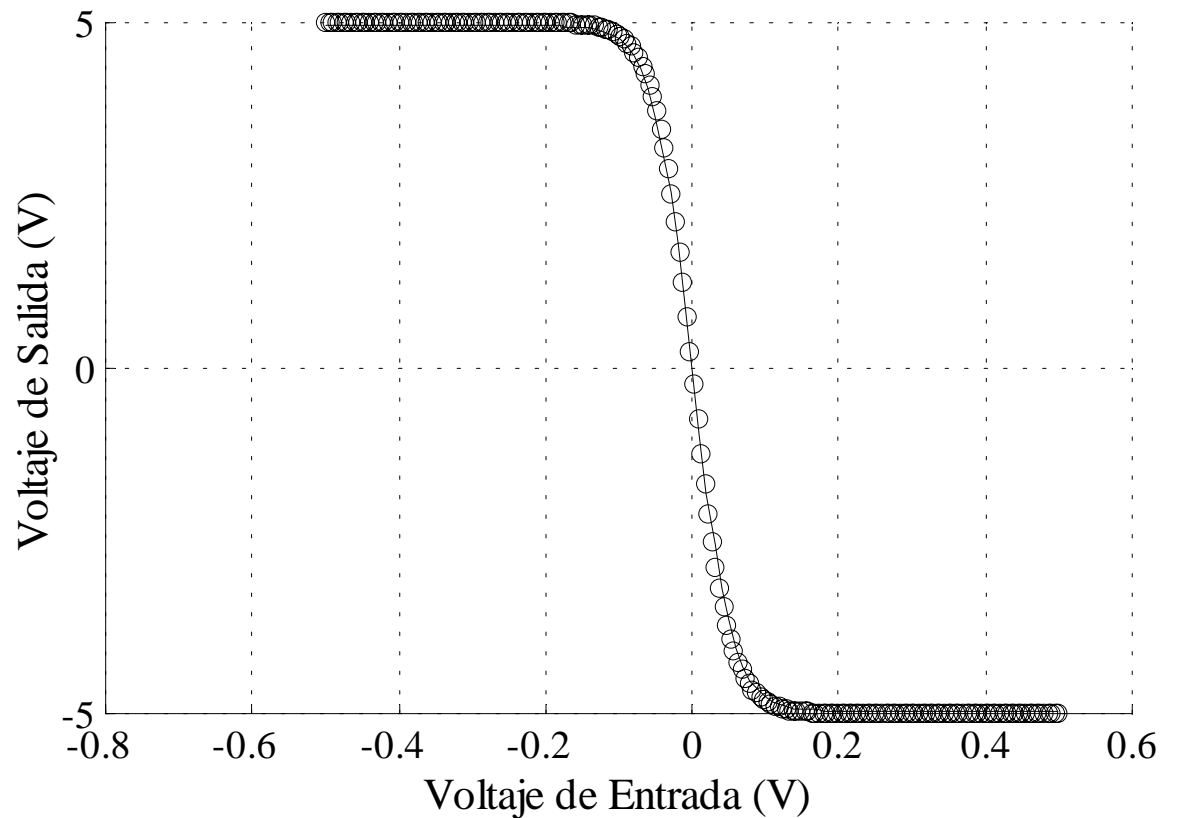
Simulación en Spice:



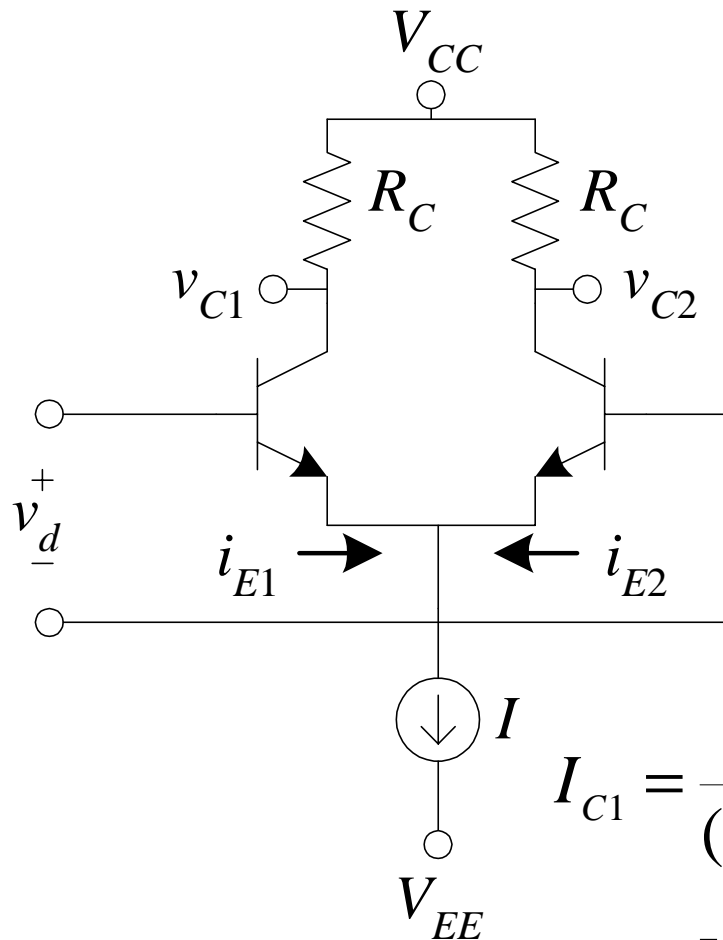
Amp. Diferencial – Señal Grande (cont.)



Spice (—) VS modelo analítico (○):



Amp. Diferencial - Señal Pequeña



$$I_{C1} = \frac{\alpha I}{1 + e^{-v_d/V_T}} \quad I_{C2} = \frac{\alpha I}{1 + e^{v_d/V_T}}$$

$$I_{C1} = \frac{\alpha I e^{(v_d/2V_T)}}{e^{(v_d/2V_T)} + e^{-(v_d/2V_T)}}$$

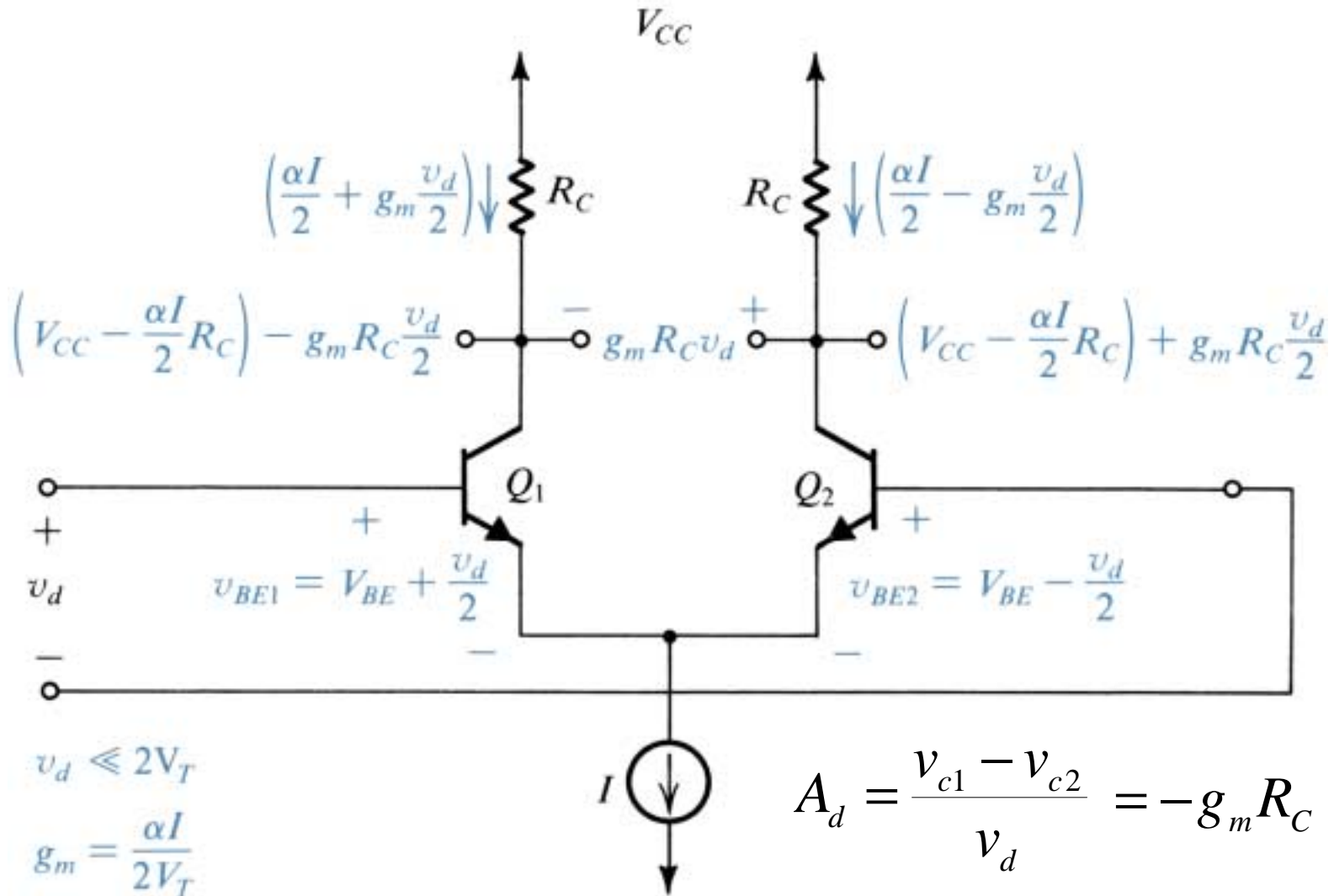
usando $e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \dots$

y suponiendo que $v_d \ll 2V_T$

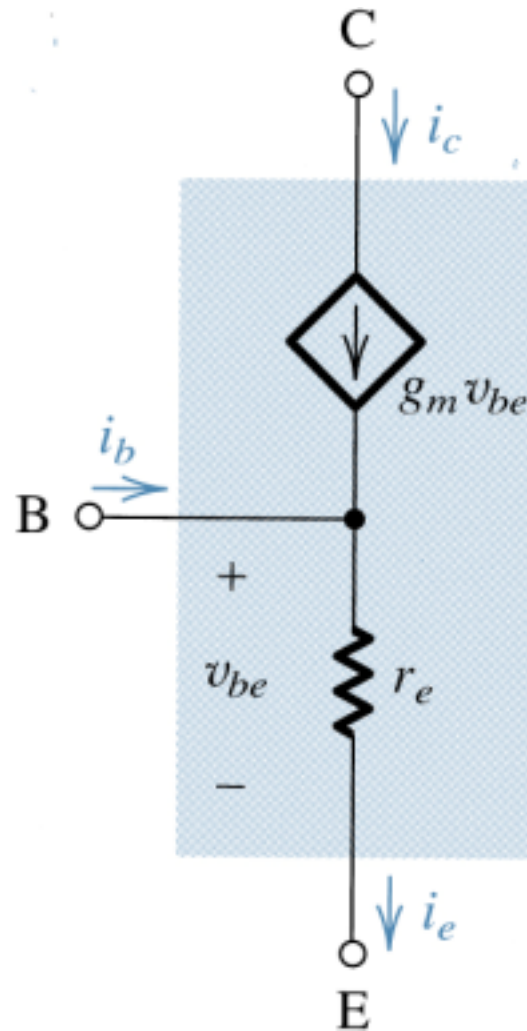
$$I_{C1} = \frac{\alpha I (1 + v_d / 2V_T)}{(1 + v_d / 2V_T) + (1 - v_d / 2V_T)} = \frac{\alpha I}{2} + \frac{\alpha I}{2V_T} \frac{v_d}{2}$$

$$I_{C1} = \frac{\alpha I}{2} + g_m \frac{v_d}{2}, \text{ similarmente } I_{C2} = \frac{\alpha I}{2} - g_m \frac{v_d}{2}$$

Amp. Diferencial - Señal Pequeña (cont.)

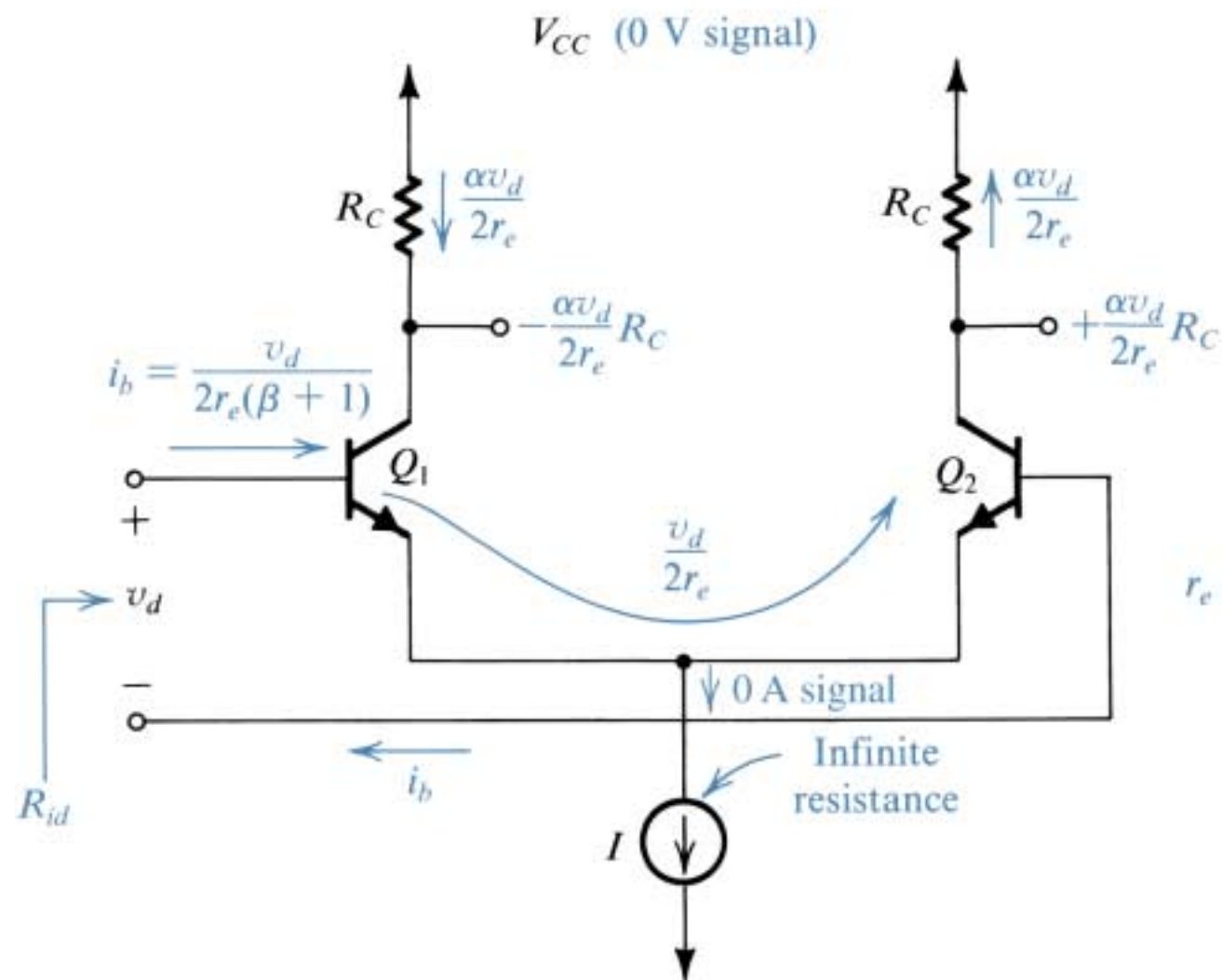


Modelo del BJT en Señal Pequeña (repaso)



$$g_m = I_C / V_T$$
$$r_e = \frac{V_T}{I_E} = \frac{\alpha}{g_m}$$

Análisis en Señal Pequeña (otro punto de vista)



$$R_{id} = (\beta + 1)2r_e$$

$$= 2r_\pi$$

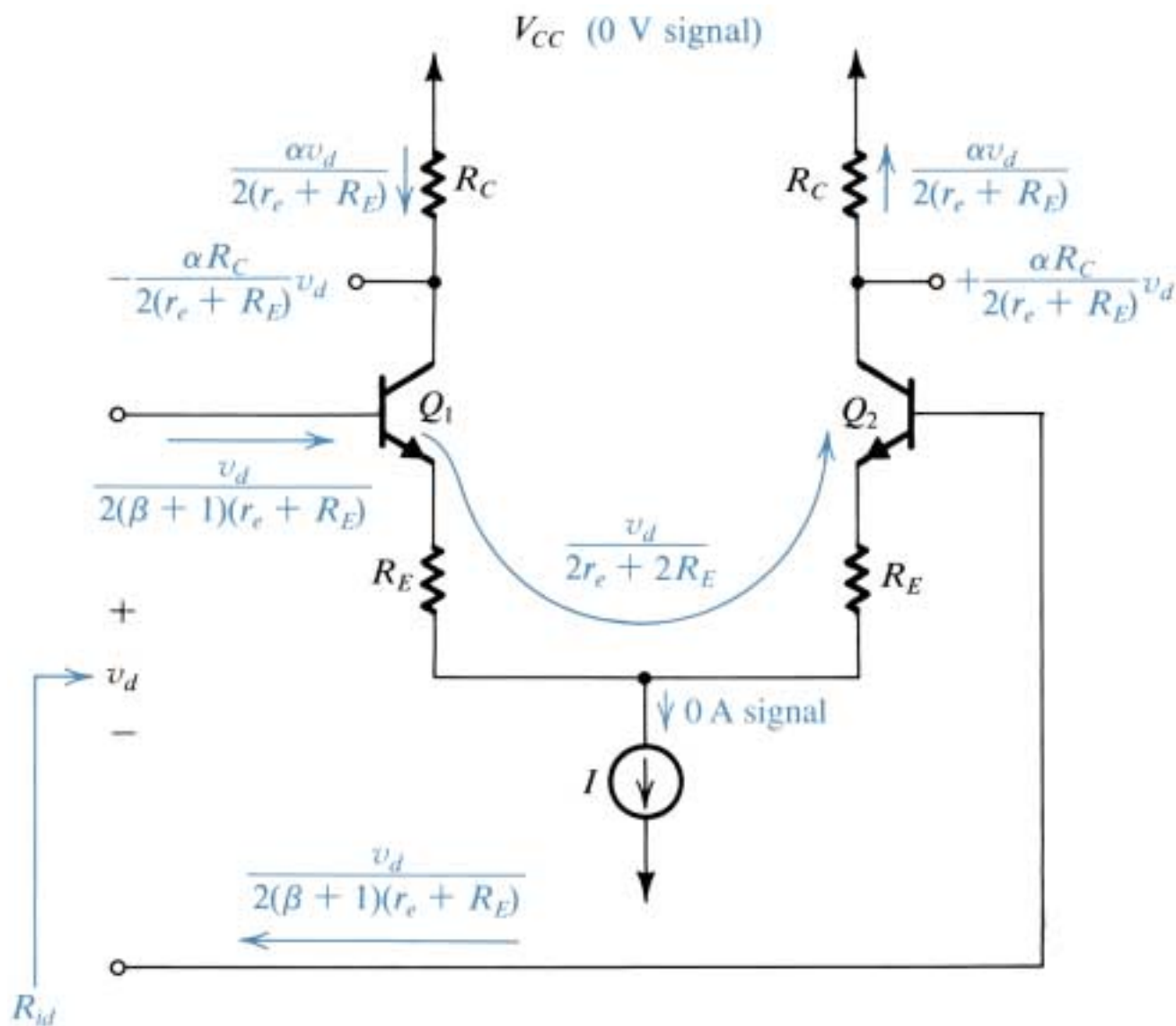
$$A_d = \frac{v_{c1} - v_{c2}}{v_d}$$

$$r_e = \frac{V_T}{I/2}$$

$$A_d = -\frac{\alpha}{r_e} R_C$$

$$= -g_m R_C$$

Amp. Dif. en Degeneración de Emisor



$$R_{id} = (\beta + 1)2(r_e + R_E)$$

$$R_{id} = 2[r_\pi + (\beta + 1)R_E]$$

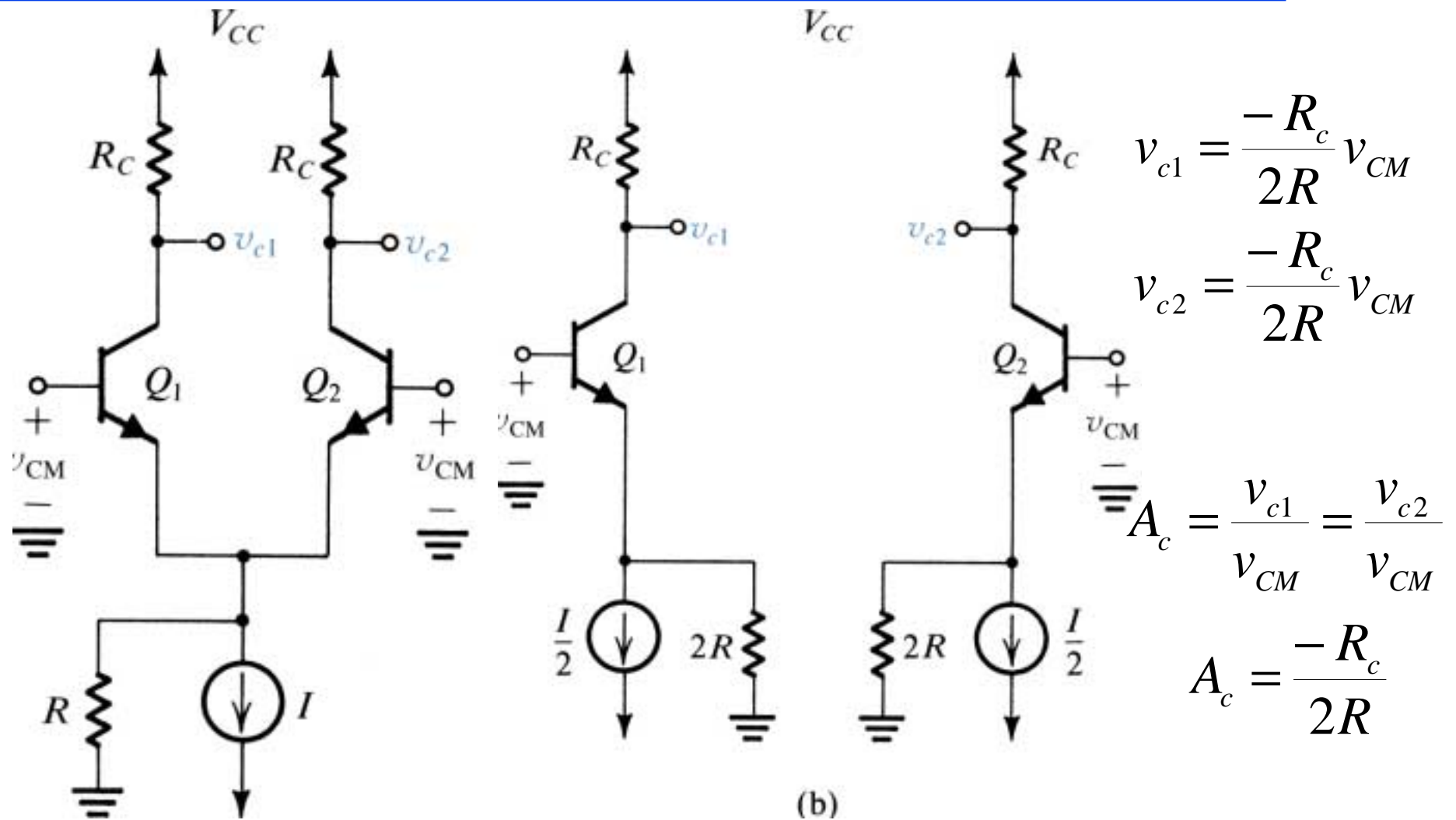
$$A_d = \frac{v_{c1} - v_{c2}}{v_d}$$

$$A_d = -\frac{\alpha R_C}{(r_e + R_E)}$$

si $R_E \gg r_e$ y $\beta \gg 1$

$$A_d = -\frac{R_C}{R_E}$$

Ganancia de Modo Común

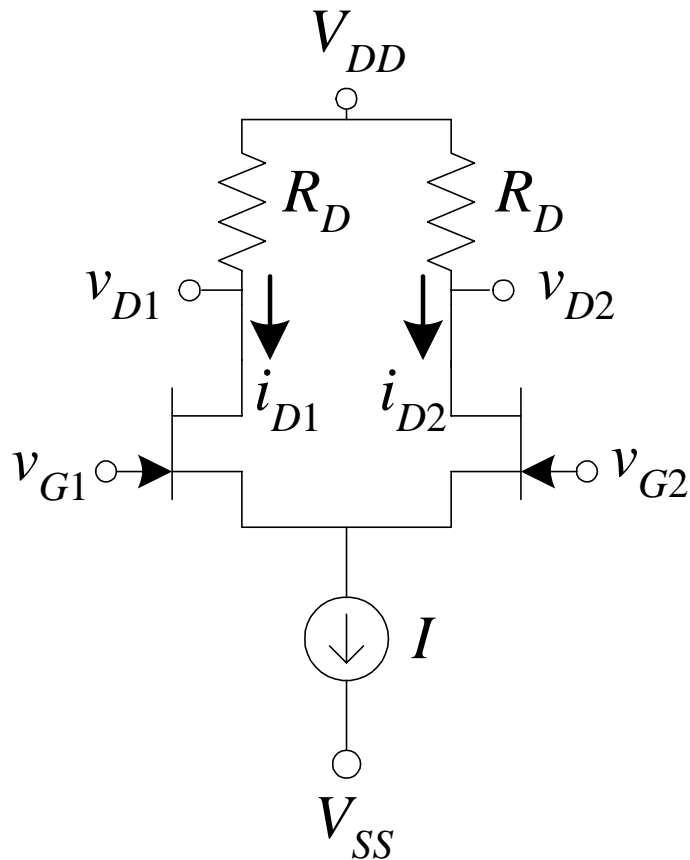


Razón de Rechazo de Modo Común (CMRR)

$$CMRR = \left| \frac{A_d}{A_c} \right| = \left| \frac{-\frac{1}{2} g_m R_c}{-\frac{R_c}{2R}} \right| = g_m R$$

$$CMRR = 20 \log \left| \frac{A_d}{A_c} \right| \quad (\text{dB})$$

Par Diferencial JFET



$$i_{D1} = K(v_{GS1} - V_t)^2 \quad i_{D2} = K(v_{GS2} - V_t)^2$$

$$v_{id} = v_{GS1} - v_{GS2}$$

$$\sqrt{i_{D1}} - \sqrt{i_{D2}} = \sqrt{K} v_{id} \quad i_{D1} + i_{D2} = I$$

resolviendo simultáneamente,

$$i_{D1} = \frac{I}{2} + \sqrt{2KI} \left(\frac{v_{id}}{2} \right) \sqrt{1 - \frac{(v_{id}/2)^2}{(I/2K)}}$$

$$i_{D2} = \frac{I}{2} - \sqrt{2KI} \left(\frac{v_{id}}{2} \right) \sqrt{1 - \frac{(v_{id}/2)^2}{(I/2K)}}$$

Par Diferencial JFET (cont.)

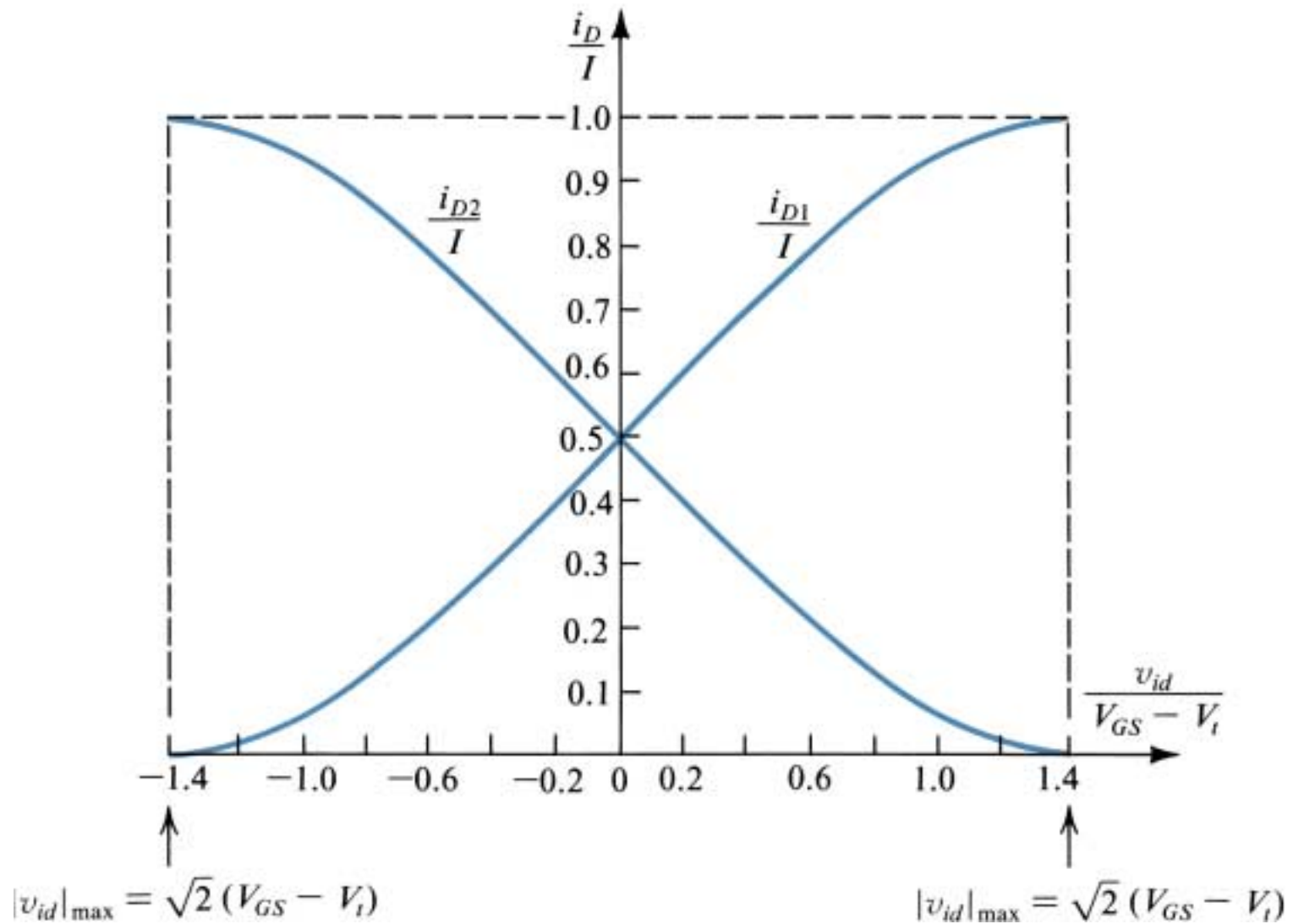
$$i_{D1} = \frac{I}{2} + \sqrt{2KI} \left(\frac{v_{id}}{2} \right) \sqrt{1 - \frac{(v_{id}/2)^2}{(I/2K)}} \quad i_{D2} = \frac{I}{2} - \sqrt{2KI} \left(\frac{v_{id}}{2} \right) \sqrt{1 - \frac{(v_{id}/2)^2}{(I/2K)}}$$

$$\text{como } \frac{I}{2} = K(V_{GS} - V_t)^2, \quad 2K = \frac{I}{(V_{GS} - V_t)^2}, \quad I/2K = (V_{GS} - V_t)^2$$

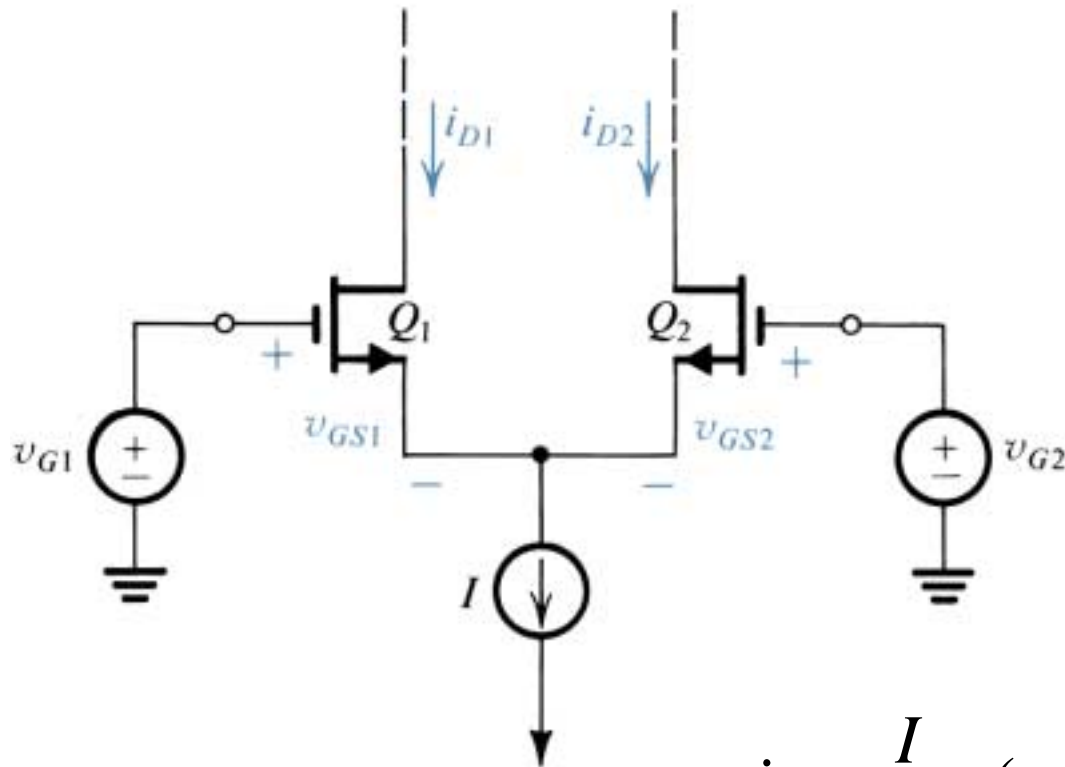
$$i_{D1} = \frac{I}{2} + \left(\frac{I}{V_{GS} - V_t} \right) \left(\frac{v_{id}}{2} \right) \sqrt{1 - \frac{(v_{id}/2)^2}{(V_{GS} - V_t)^2}}$$

$$i_{D2} = \frac{I}{2} - \left(\frac{I}{V_{GS} - V_t} \right) \left(\frac{v_{id}}{2} \right) \sqrt{1 - \frac{(v_{id}/2)^2}{(V_{GS} - V_t)^2}}$$

Curva de Transconductancia



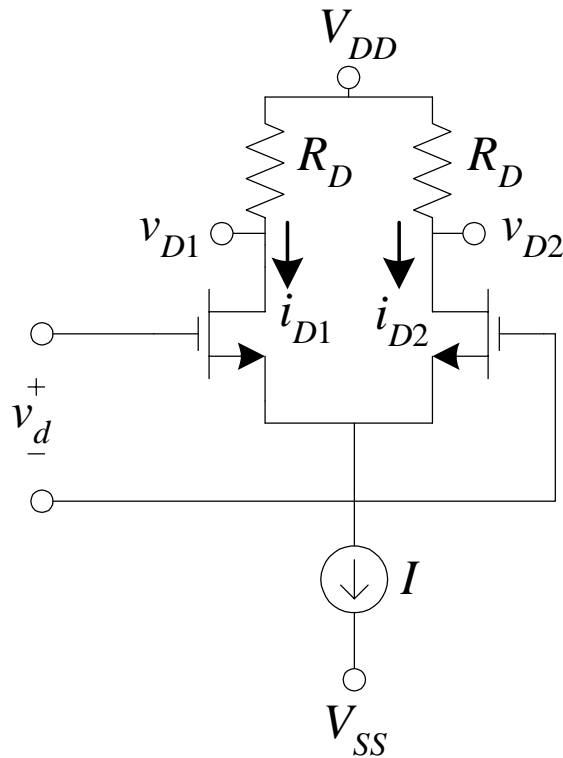
Par Diferencial E-MOS



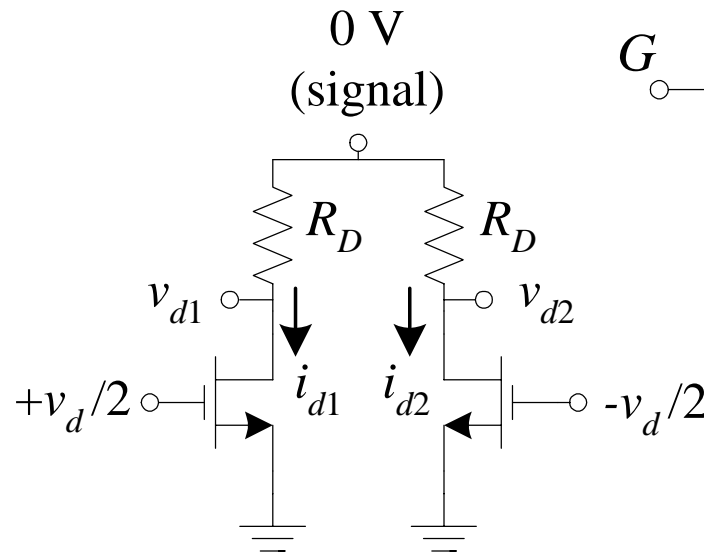
$$i_{D1} = \frac{I}{2} + \left(\frac{I}{V_{GS} - V_t} \right) \left(\frac{v_{id}}{2} \right) \sqrt{1 - \frac{(v_{id}/2)^2}{(V_{GS} - V_t)^2}}$$

$$i_{D2} = \frac{I}{2} - \left(\frac{I}{V_{GS} - V_t} \right) \left(\frac{v_{id}}{2} \right) \sqrt{1 - \frac{(v_{id}/2)^2}{(V_{GS} - V_t)^2}}$$

Análisis en Señal Pequeña (Modo Diferencial)

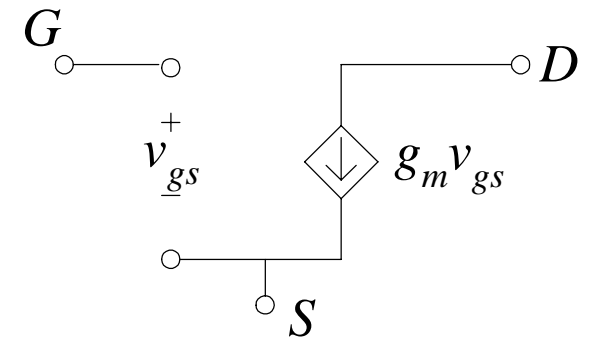


$$I_{D1} = I_{D2} = \frac{I}{2}$$



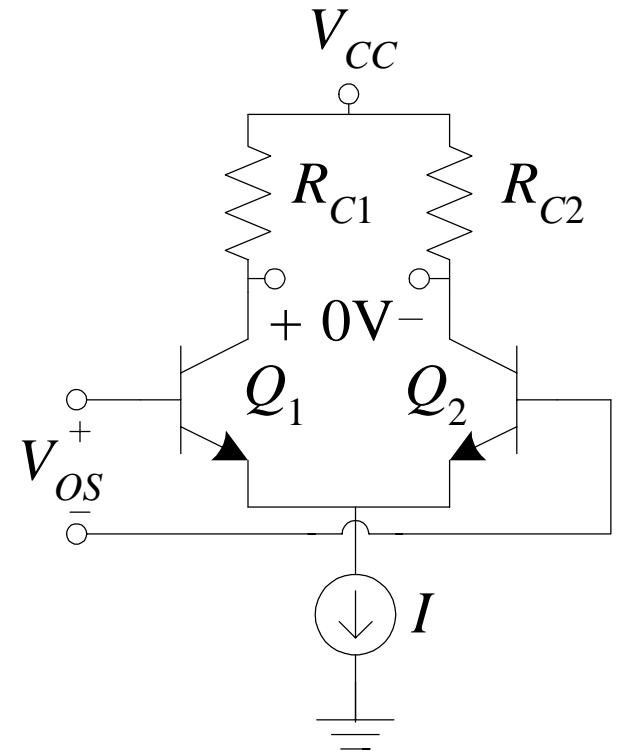
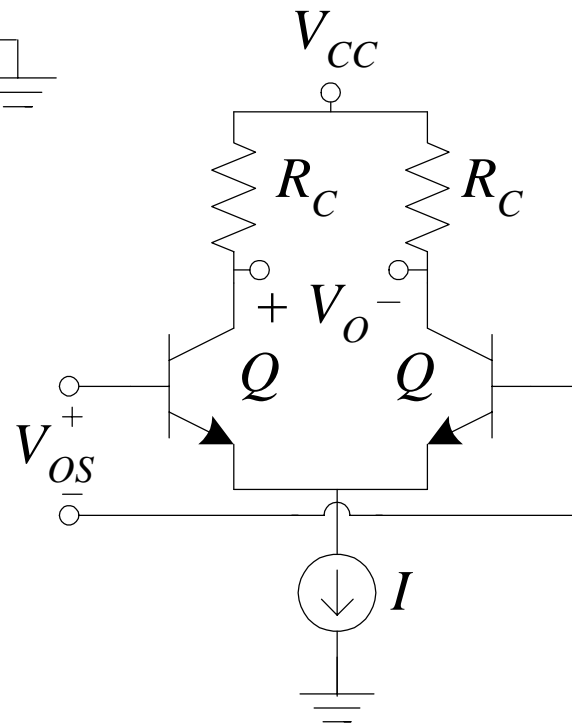
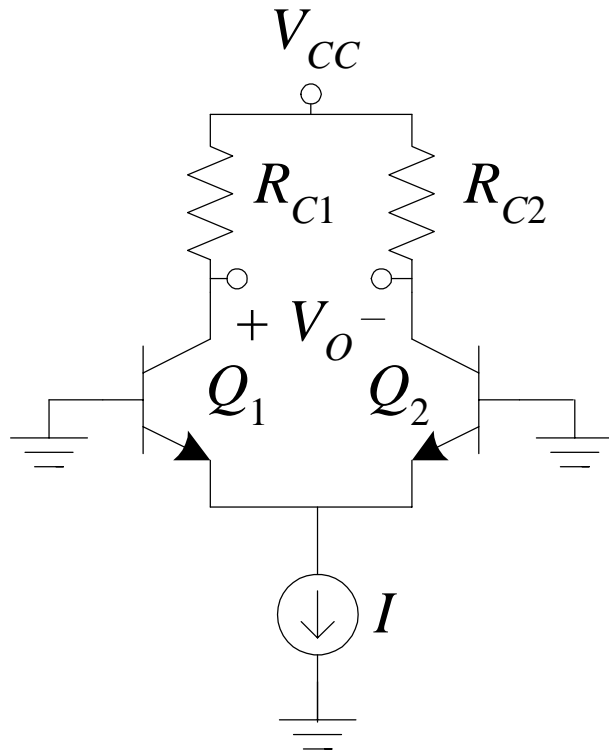
$$v_{d1} = -g_m R_D \frac{v_d}{2}$$

$$v_{d2} = g_m R_D \frac{v_d}{2}$$



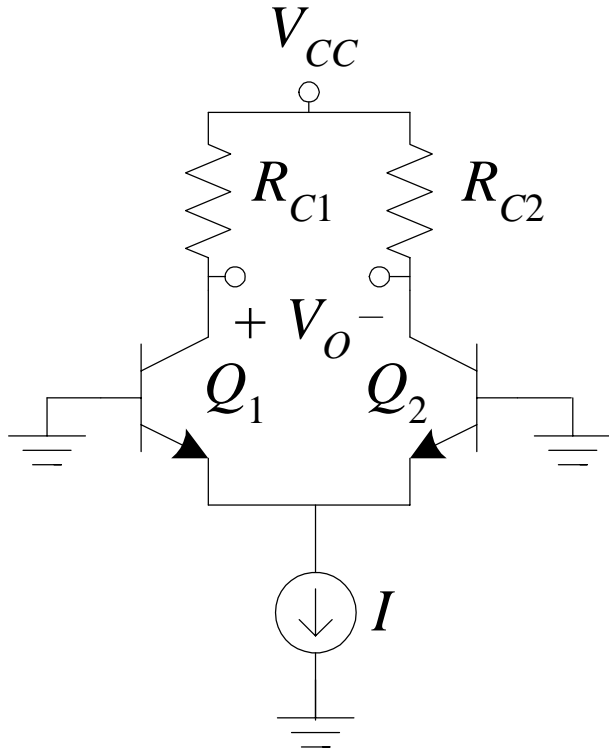
$$A_d = \frac{v_{d1} - v_{d2}}{v_d} = -g_m R_D$$

Asimetría en el Amplificador Diferencial



V_{os} Input offset voltage

V_{OS} en Función de la Asimetría en R_C



$$R_{C1} = R_C + \frac{\Delta R_C}{2} \qquad R_{C2} = R_C - \frac{\Delta R_C}{2}$$

$$v_{C1} = V_{CC} - \frac{\alpha I}{2} \left(R_C + \frac{\Delta R_C}{2} \right)$$

$$v_{C2} = V_{CC} - \frac{\alpha I}{2} \left(R_C - \frac{\Delta R_C}{2} \right)$$

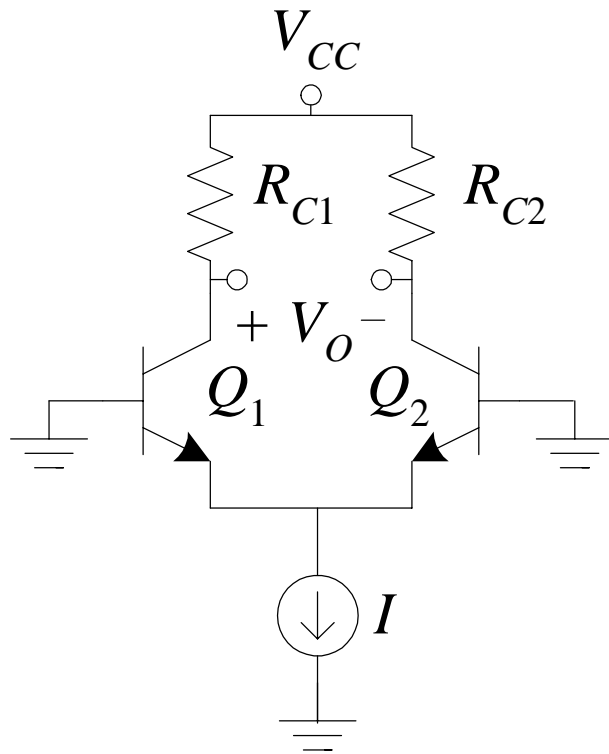
$$V_O = \frac{-\alpha I}{2} \Delta R_C \qquad V_{OS} = \frac{-\alpha I}{2} \Delta R_C / A_d$$

$$A_d = -g_m R_C = -\frac{\alpha I / 2}{V_T} R_C$$

$$V_{OS} = V_T \frac{\Delta R_C}{R_C}$$

$$V_{OS} = V_T 2(\text{Tol}_{R_C})$$

V_{OS} en Función de la Asimetría en I_S



$$I_{S1} = I_S + \frac{\Delta I_S}{2}$$

$$I_{S2} = I_S - \frac{\Delta I_S}{2}$$

$$I_{C1} = I_{S1} e^{V_{BE}/V_T}$$

$$I_{C2} = I_{S2} e^{V_{BE}/V_T}$$

$$\frac{I_{C1}}{I_{C2}} = \frac{I_{S1}}{I_{S2}}$$

$$\alpha I = I_{C1} + I_{C2}$$

Resolviendo simultáneamente:

$$I_{C1} = \frac{\alpha I}{2} \left(1 + \frac{\Delta I_S}{2I_S} \right)$$

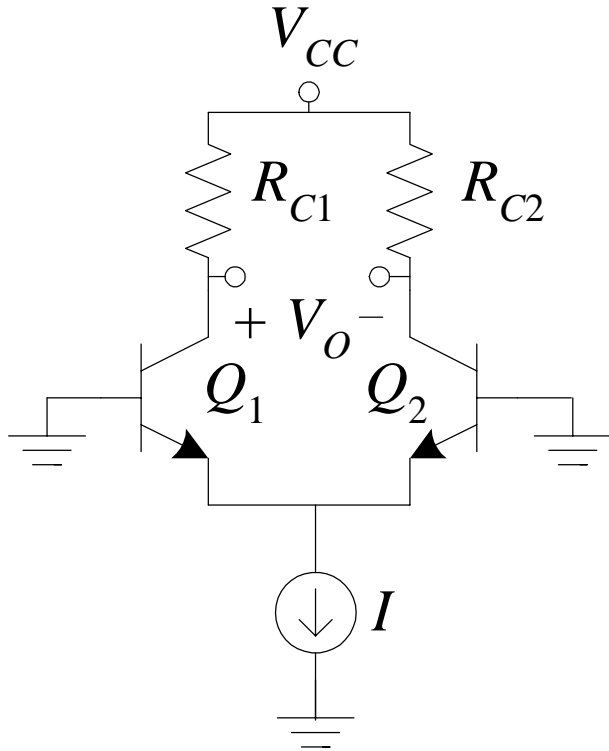
$$I_{C2} = \frac{\alpha I}{2} \left(1 - \frac{\Delta I_S}{2I_S} \right)$$

$$V_O = (V_{CC} - I_{C1}R_C) - (V_{CC} - I_{C2}R_C)$$

$$V_O = -\frac{\alpha I}{2} \left(\frac{\Delta I_S}{I_S} \right) R_C$$

$$V_{OS} = V_T \frac{\Delta I_S}{I_S}$$

V_{OS} en Función de la Asimetría en R_C y en I_S



$$V_{OS} = V_T \frac{\Delta R_C}{R_C}$$

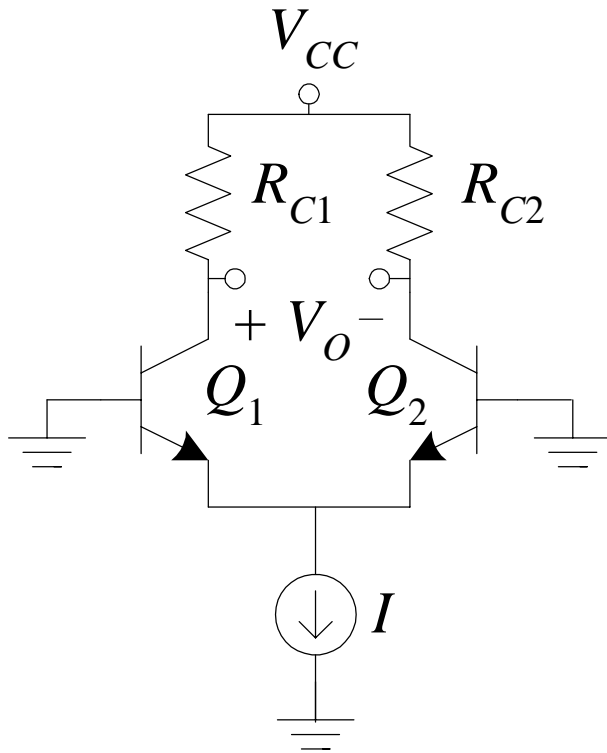
$$V_{OS} = V_T \frac{\Delta I_S}{I_S}$$

$$V_{OS} = V_T \left(\frac{\Delta R_C}{R_C} + \frac{\Delta I_S}{I_S} \right)$$

$$\frac{\partial V_{OS}}{\partial T} = \frac{V_{OS}}{T}$$

Ej.: Si $V_{OS} = 3\text{mV}$ a temperatura ambiente, la deriva en V_{OS} con la temperatura es de $10\mu\text{V}/^\circ\text{C}$

Efectos de la Asimetría en β



$$\text{si } \beta_1 = \beta_2 = \beta \quad I_{B1} = I_{B2} = \frac{I/2}{\beta + 1}$$

I_{OS} Input offset current

$$I_{OS} \equiv |I_{B1} - I_{B2}|$$

$$\beta_1 = \beta + \frac{\Delta\beta}{2}$$

$$\beta_2 = \beta - \frac{\Delta\beta}{2}$$

$$I_{B1} = \frac{I/2}{\beta_1 + 1} = \frac{I}{2} \frac{1}{\beta + 1 + \Delta\beta/2}$$

$$I_{B2} = \frac{I/2}{\beta_2 + 1} = \frac{I}{2} \frac{1}{\beta + 1 - \Delta\beta/2}$$

Efectos de la Asimetría en β (cont.)

$$I_{B1} = \frac{I/2}{\beta_1 + 1} = \frac{I}{2} \frac{1}{\beta + 1 + \Delta\beta/2} = \frac{I}{2} \left(\frac{1}{\beta + 1} \right) \frac{1}{1 + \frac{\Delta\beta}{2(\beta + 1)}}$$

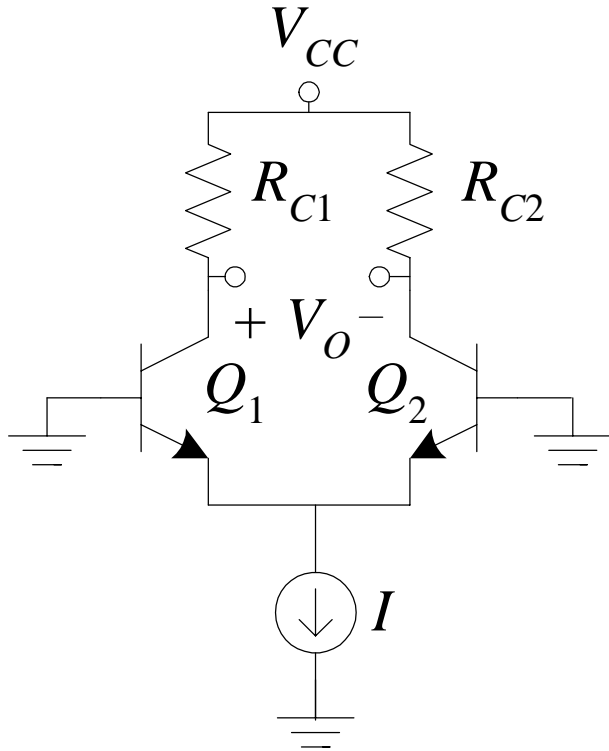
$$I_{B1} = \frac{I}{2} \left(\frac{1}{\beta + 1} \right) \left(\frac{2(\beta + 1)}{2(\beta + 1) + \Delta\beta} \right) = \frac{I}{2} \left(\frac{1}{\beta + 1} \right) \left(1 - \frac{\Delta\beta}{2(\beta + 1) + \Delta\beta} \right)$$

Si $2(\beta + 1) \gg \Delta\beta$,

$$I_{B1} = \frac{I}{2} \left(\frac{1}{\beta + 1} \right) \left(1 - \frac{\Delta\beta}{2(\beta + 1)} \right)$$

Similarmente $I_{B2} = \frac{I}{2} \left(\frac{1}{\beta + 1} \right) \left(1 + \frac{\Delta\beta}{2(\beta + 1)} \right)$

Efectos de la Asimetría en β (cont.)



$$I_{OS} \equiv |I_{B1} - I_{B2}|$$

$$I_{B1} = \frac{I}{2} \left(\frac{1}{\beta + 1} \right) \left(1 - \frac{\Delta\beta}{2(\beta + 1)} \right)$$

$$I_{B2} = \frac{I}{2} \left(\frac{1}{\beta + 1} \right) \left(1 + \frac{\Delta\beta}{2(\beta + 1)} \right)$$

$$I_B \text{ Input bias current} \quad I_B \equiv \frac{I_{B1} + I_{B2}}{2}$$

$$I_B = \frac{I}{2} \frac{1}{\beta + 1}$$

$$I_{OS} = I_B \frac{\Delta\beta}{(\beta + 1)} \text{ siempre que } 2(\beta + 1) \gg \Delta\beta$$