ELECTRONICA APLICADA I

Prof. Adj. Ing. Fernando Cagnolo

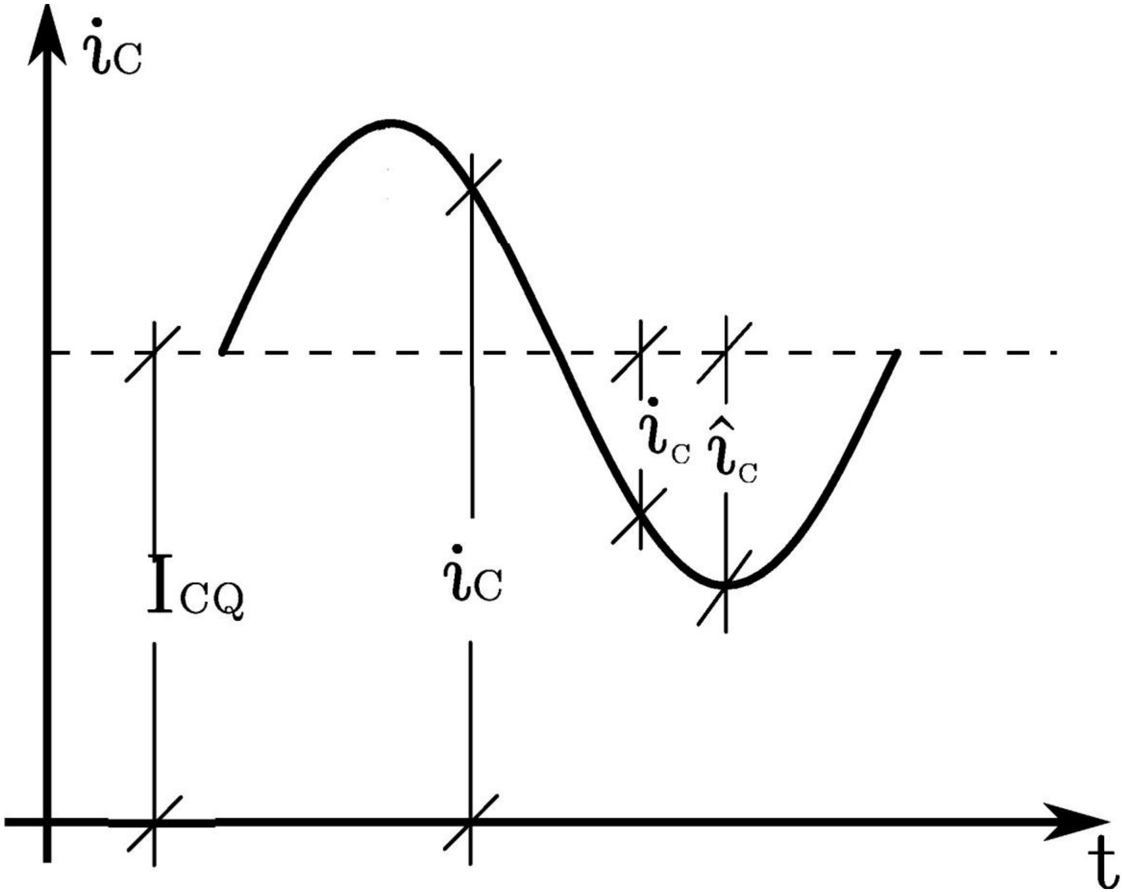
- EL DIODO

Estas diapositivas están basadas en las clases dictadas por el Profesor Ing. Alberto Muhana.

Agradezco el trabajo realizado y facilitado por el Sr. Joaquín Ponce en la generación de los gráficos empleados en el desarrollo de estas diapositivas y al Sr. Mariano Garino por la facilitación del manuscrito tomado en clase.

Por ultimo agradezco la predisposición y colaboración de Ing, Federico Linares en el trabajo de recopilación y armado de estas diapositivas.

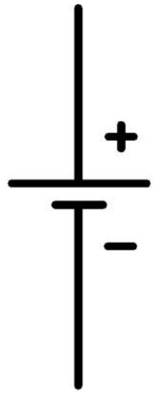
Nomenclatura



$$i_c = \hat{i}_c\, sen(\omega t)$$

$$i_C = I_{CQ} + i_c = I_{CQ} + \hat{i}_c\, sen(\omega t)$$

Fuentes



Fuente de tensión

Fuente de corriente

Símbolos de tensión y corriente

Para el caso de la fuente de tensión:

V_{BB} : Tensión de base.

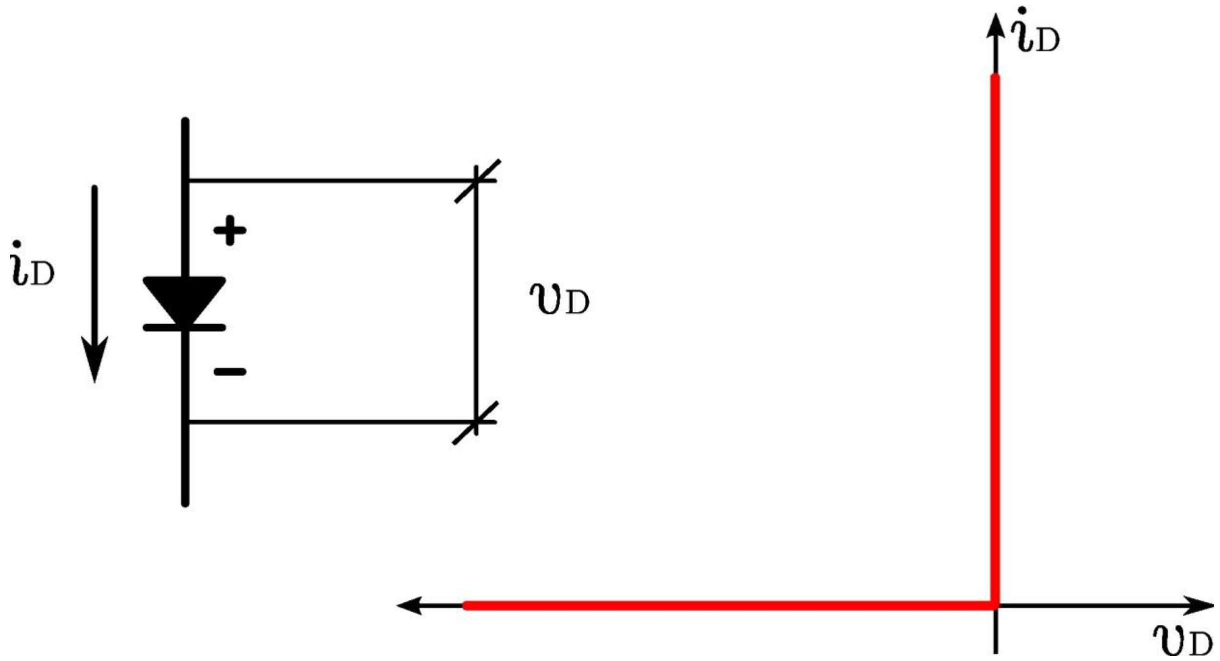
V_{CC} : Tensión de colector.

V_{DD} : Tensión de drenador.

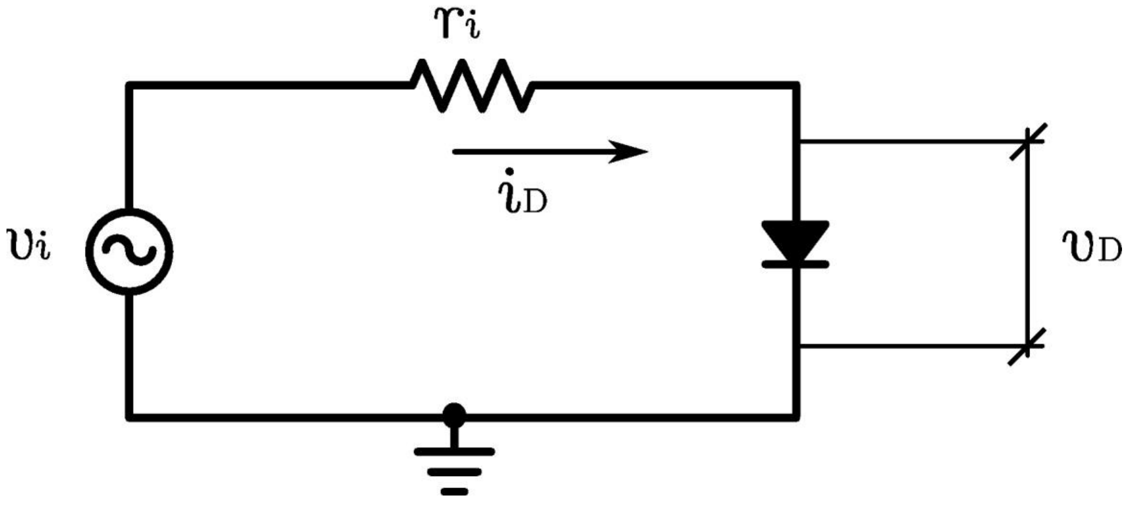
Para el caso de la fuente de corriente:

I_{BB} : Corriente de base.

El diodo ideal



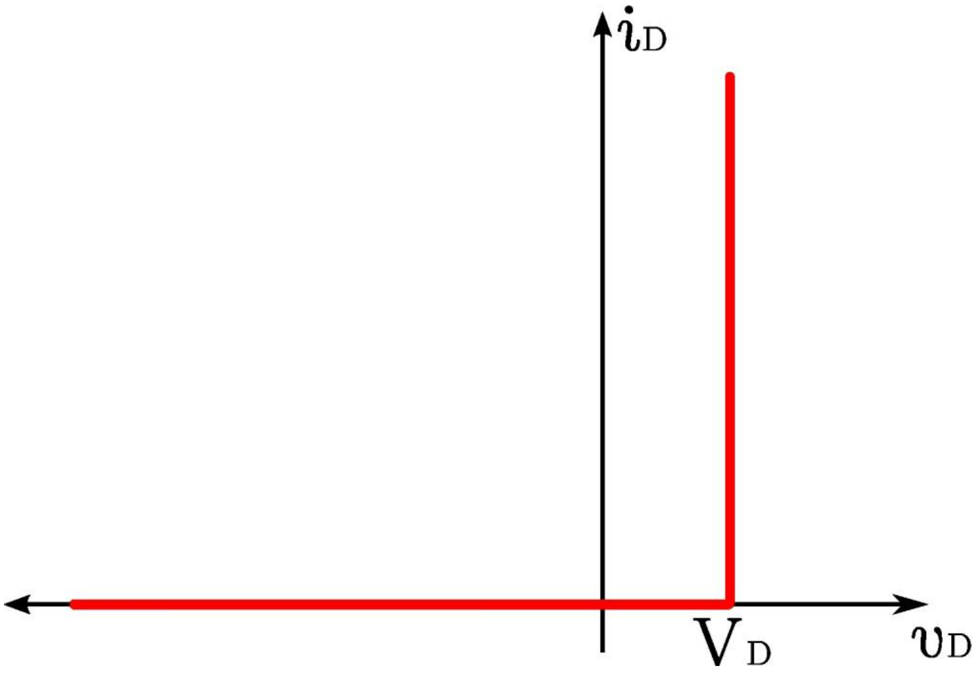
El diodo como llave



$$v_i \leq 0 \Rightarrow i_D = 0 \text{ y } v_D = v_i$$

$$v_i > 0 \Rightarrow i_D \neq 0 \text{ y } v_D = 0$$

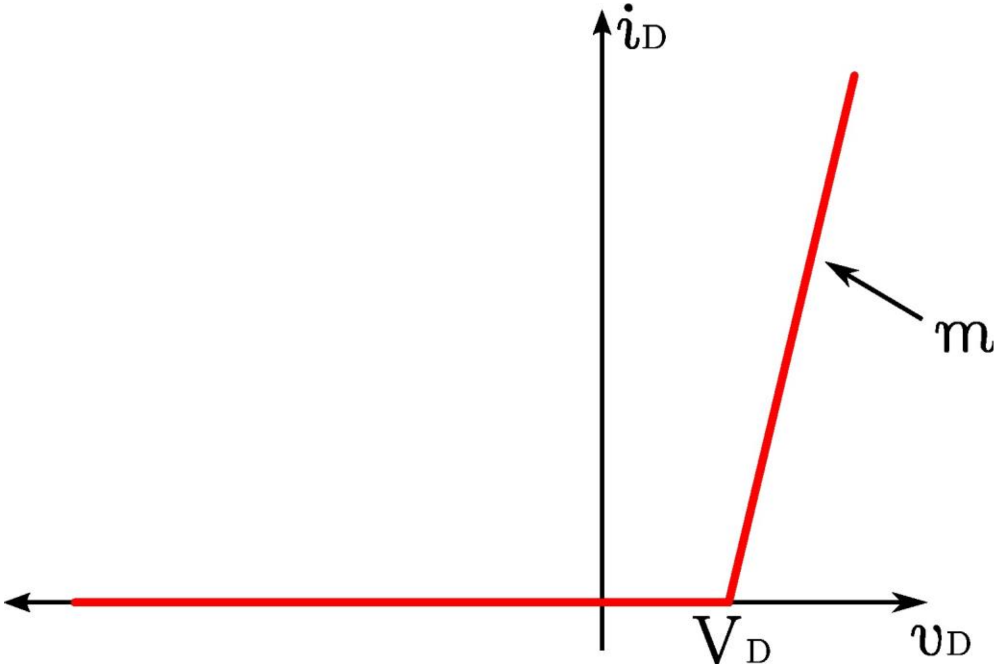
El diodo como llave (cont.)



$$v_D = 0.2(Ge)$$

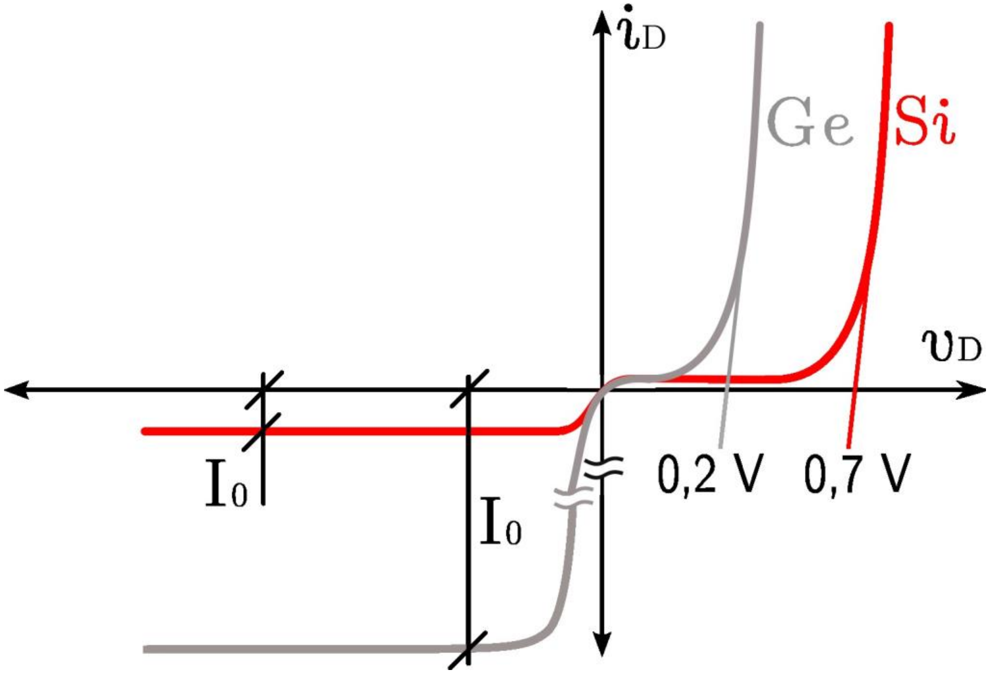
$$v_D = 0.7(Si)$$

El diodo con resistencia interna



$$r_D \neq 0 \text{ donde } m = \frac{1}{r_D}$$

El diodo real



Ecuación del diodo

$$i_D = I_0(e^{\frac{q.v_D}{m.k.T}} - 1)$$

$$i_D = Corriente\ en\ el\ diodo\ [A]$$

$$v_D = Tension\ en\ el\ diodo\ [V]$$

$$I_0 = Corriente\ de\ saturacion\ inversa\ [A]$$

$$q = C\arg a\ del\ electron[C]$$

$$k = Cons\tan te\ de\ Boltzman\ 1.38x10^{-23}\left[\frac{J}{^{\circ}K}\right]$$

$$T = Temperatura\ Absoluta\left[^{\circ}K\right]$$

$$m = Constante\ empirica\ 1 < m < 2$$

Ecuación del diodo (cont.)

- A temperatura ambiente $T = 300^{\circ} K \; y \; m = 1$

donde, $$\frac{m.k.T}{q} = 25mV$$

$$i_D = I_0 (e^{\frac{q.v_D}{m.k.T}} - 1)$$

$$i_D = Corriente \; en \; el \; diodo \; [A]$$

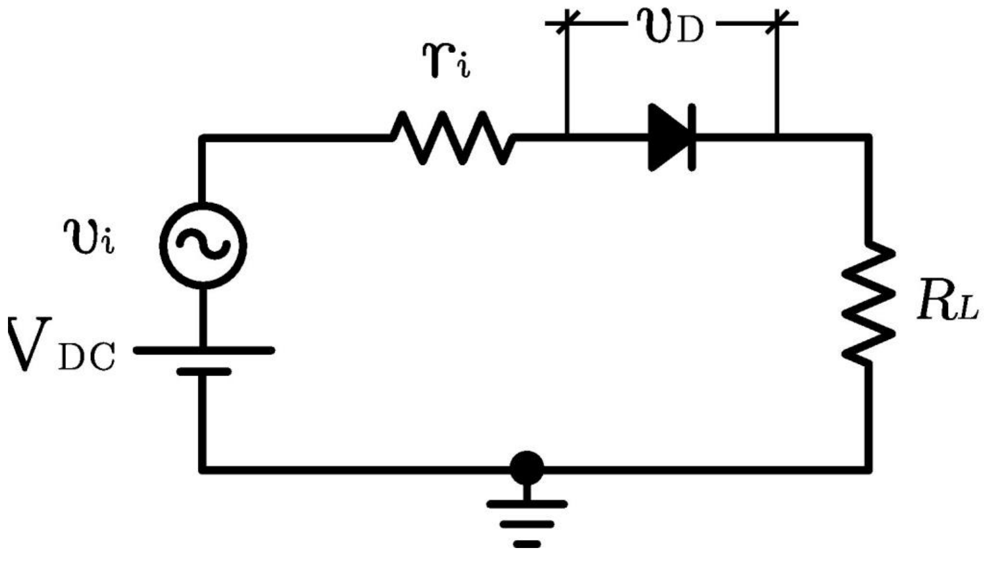
Ecuación del diodo (cont.)

$$Si\ v_D > 0 \qquad |v_D| >> \frac{m.k.T}{q} \Rightarrow i_D = I_O e^{\frac{V_D}{\frac{m.k.T}{q}}}$$

$$Si\ v_D < 0 \qquad |v_D| >> \frac{m.k.T}{q} \Rightarrow i_D = -I_0$$

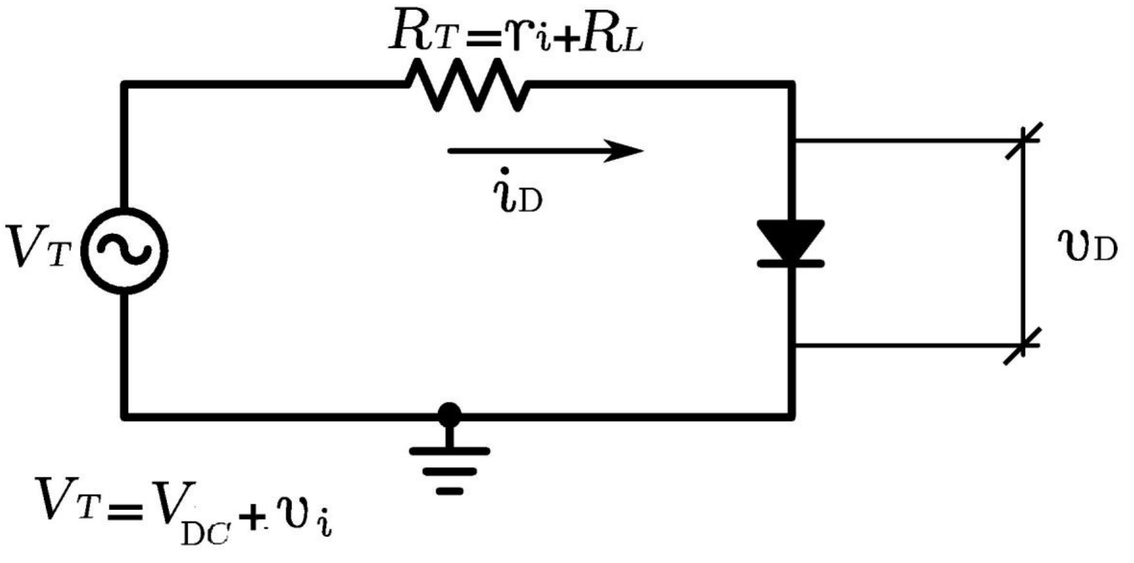
Análisis de los circuitos simples con diodos.

- Recta de Carga



Análisis de los circuitos simples con diodos (Cont.)

Aplicando Thevenin



Análisis grafico

$$Ecuacion\ no\ lineal(Diodo) \Rightarrow i_D = f(v_D)$$

$$Ecuacion\ Lineal\ \ (Thevenin) \Rightarrow v_T = i_D.R_T + v_D$$

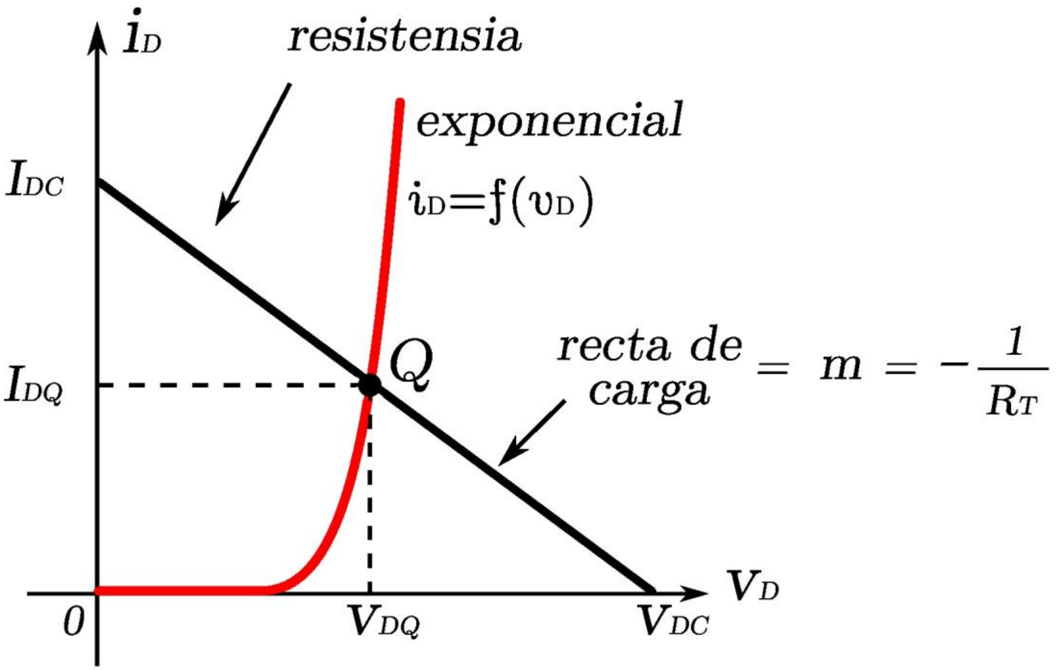
$$i_D = -\frac{v_D}{R_T} + \frac{V_T}{R_T} = -\frac{1}{R_T} v_D + \frac{V_T}{R_T}$$

$$y = \quad m \quad x \ + \ b$$

$$m = -\frac{1}{R_T} \qquad b = \frac{V_T}{R_T}$$

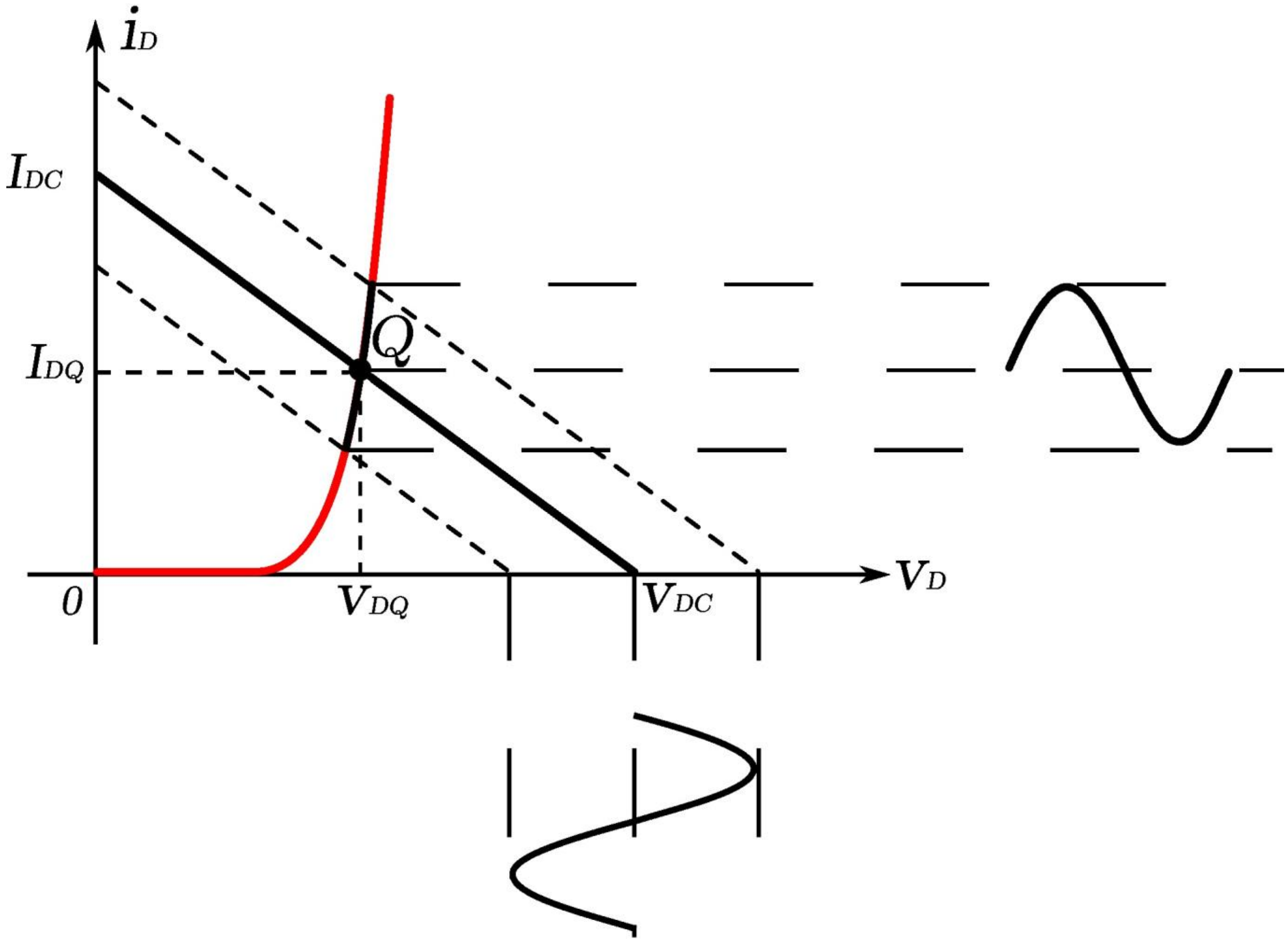
Análisis grafico(Cont.)

- Trazado de recta de carga (sin señal)



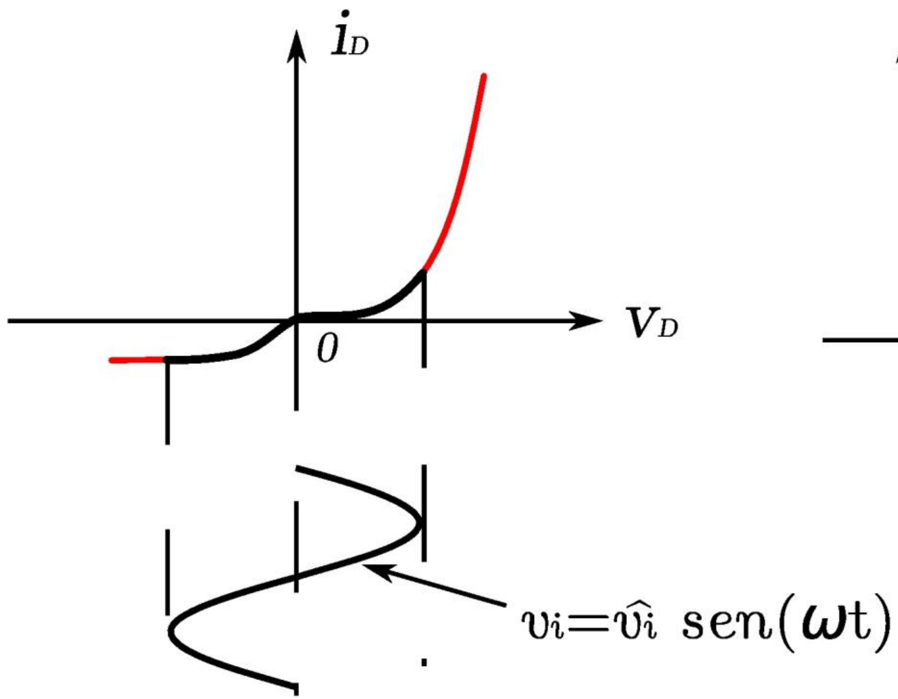
Análisis grafico (Cont.)

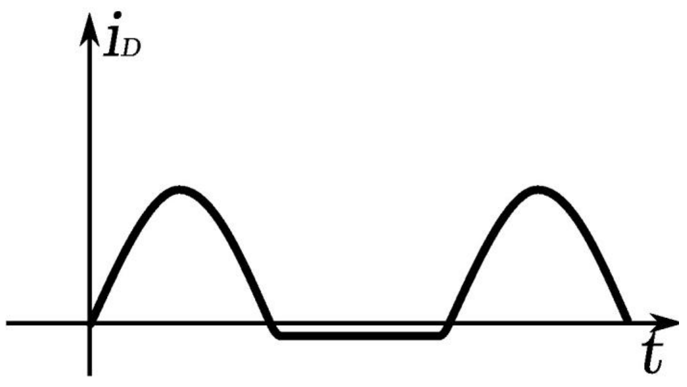
- Trazado de recta de carga (con señal C.C y C.A).



Análisis grafico (Cont.)

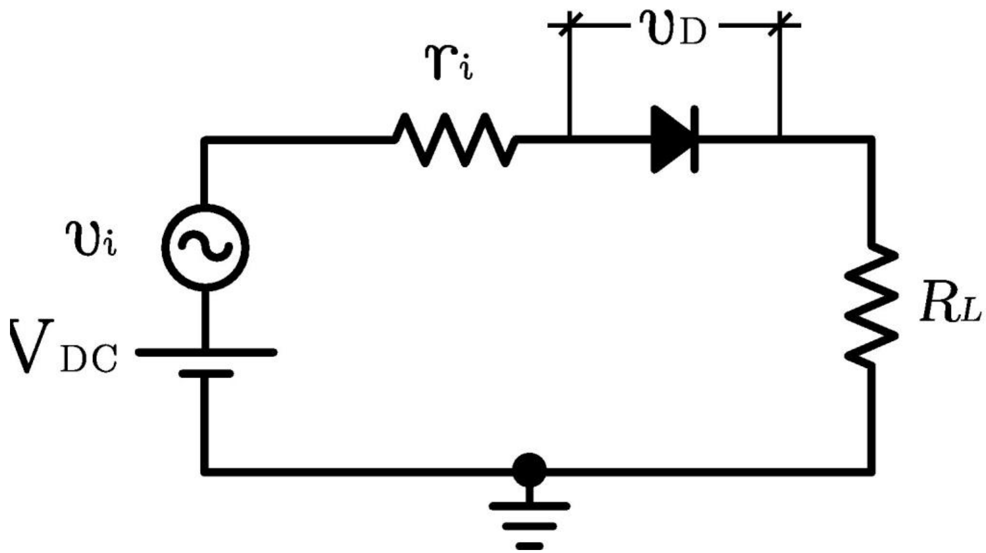
Trazado de recta de carga (con señal C.A solamente).





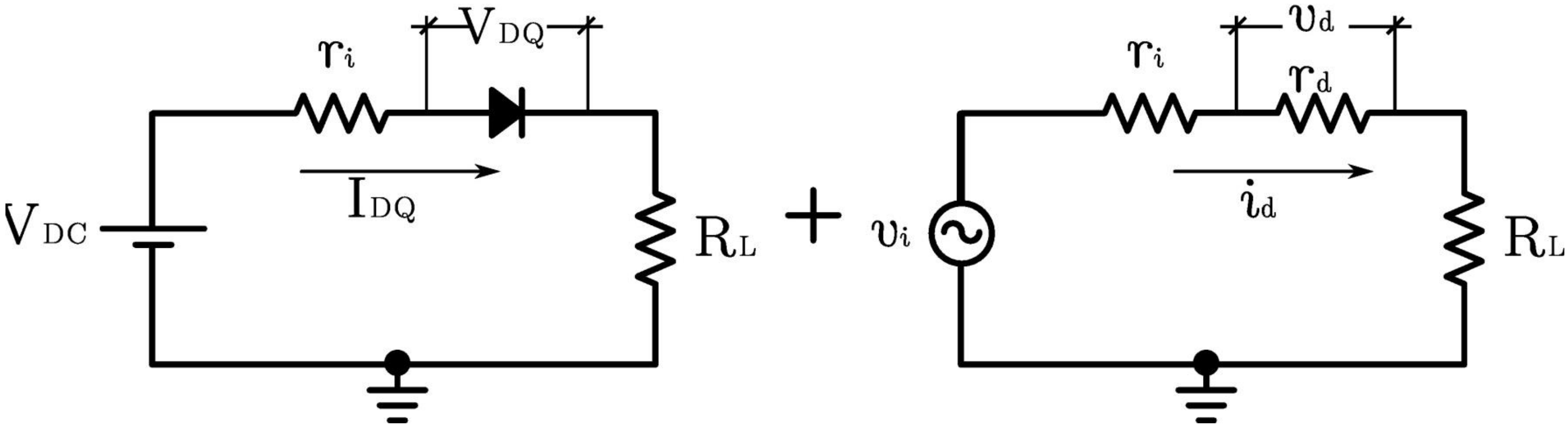
Análisis de señal Débil

- Concepto de Resistencia Dinámica



Análisis de señal Débil

- Desdoblamiento en dos circuitos.



$$I_{DQ} = \frac{V_{DC} - V_{DQ}}{r_i + R_L}$$

$$v_i = V_{i\mathrm{m}} sen(\omega t)$$

$$i_d = \frac{V_{im}}{r_i + R_L + r_d} sen(\omega t)$$

Análisis de señal Débil (Cont.)

$$i_D = I_{DQ} + i_d = \frac{V_{DC} - V_{DQ}}{r_i + R_L} + \frac{V_{im}}{r_i + R_L + r_d} sen(\omega t)$$

Desarrollo en Serie de Taylor

$$i_D = I_{DQ} + i_d = f(v_D) \qquad\qquad v_D = V_{DQ} + v_d$$

$$\left.\begin{array}{l} |i_d| << I_{DQ} \\ \\ |v_d| << V_{DQ} \end{array}\right\} Señal\ Debil$$

$$f(x+\Delta x) = f(x) + \Delta x. f'(x)$$

$$x = V_{DQ} \qquad\qquad \Delta x = v_d$$

Desarrollo en Serie de Taylor (Cont.)

$$i_D = I_{DQ} + i_d = f(V_{DQ} + v_d) = f(V_{DQ}) + v_d \frac{di_D}{dv_D}$$

$$I_{DQ} = f(V_{DQ})$$

$$i_d = v_d \left. \frac{di_D}{dv_D} \right|_Q$$

$$r_d = \frac{1}{m} = \frac{1}{\dfrac{di_D}{dv_D}} = \frac{v_d}{i_d} \qquad v_d = i_d r_d$$

Calculo de la resistencia dinámica

$$i_D = I_0 (e^{\frac{v_D}{\frac{m.k.T}{q}}} - 1)$$

$$Pero\ si\ \left| v_D \right| >> \frac{m.k.T}{q}$$

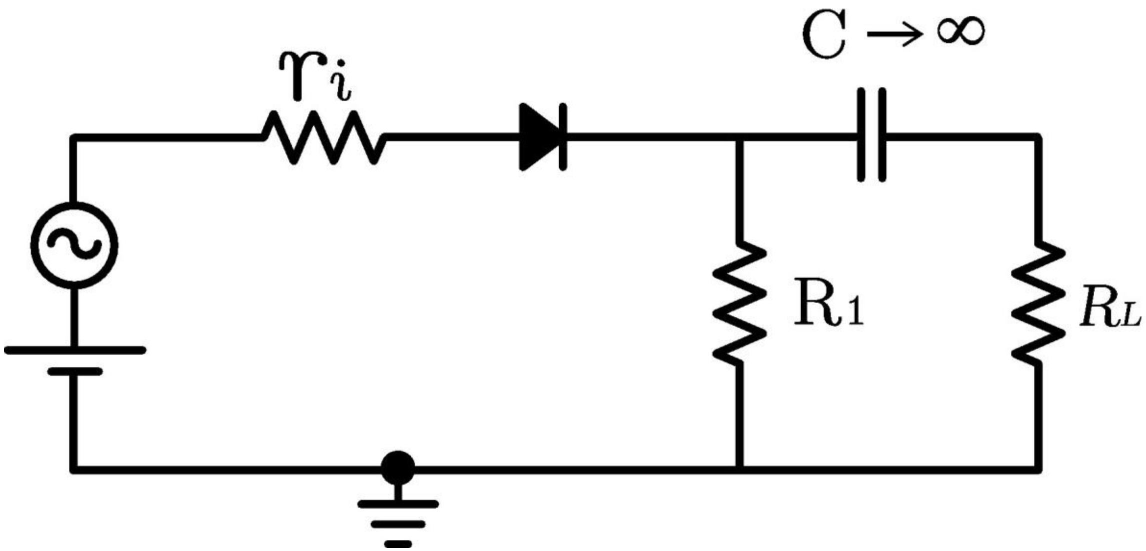
$$i_D = I_0 . e^{\frac{v_D}{\frac{m.k.T}{q}}}$$

$$\left. \frac{di_D}{dv_D} \right|_Q = \underbrace{I_0 . e^{\frac{v_D}{\frac{m.k.T}{q}}}}_{I_{DQ}} . \frac{q}{m.k.T} = \frac{1}{r_d} = I_{DQ} . \frac{q}{m.k.T}$$

$$r_d = \frac{m.k.T}{q} . \frac{1}{I_{DQ}} = \frac{25mV}{I_{DQ}}$$

$$v_L = i_D . R_L = \frac{V_{DC} - V_{DQ}}{r_i + R_L} . R_L + \frac{V_{im}}{r_i + R_L + r_d} . R_L . sen(\omega t)$$

Circuito con elementos reactivos



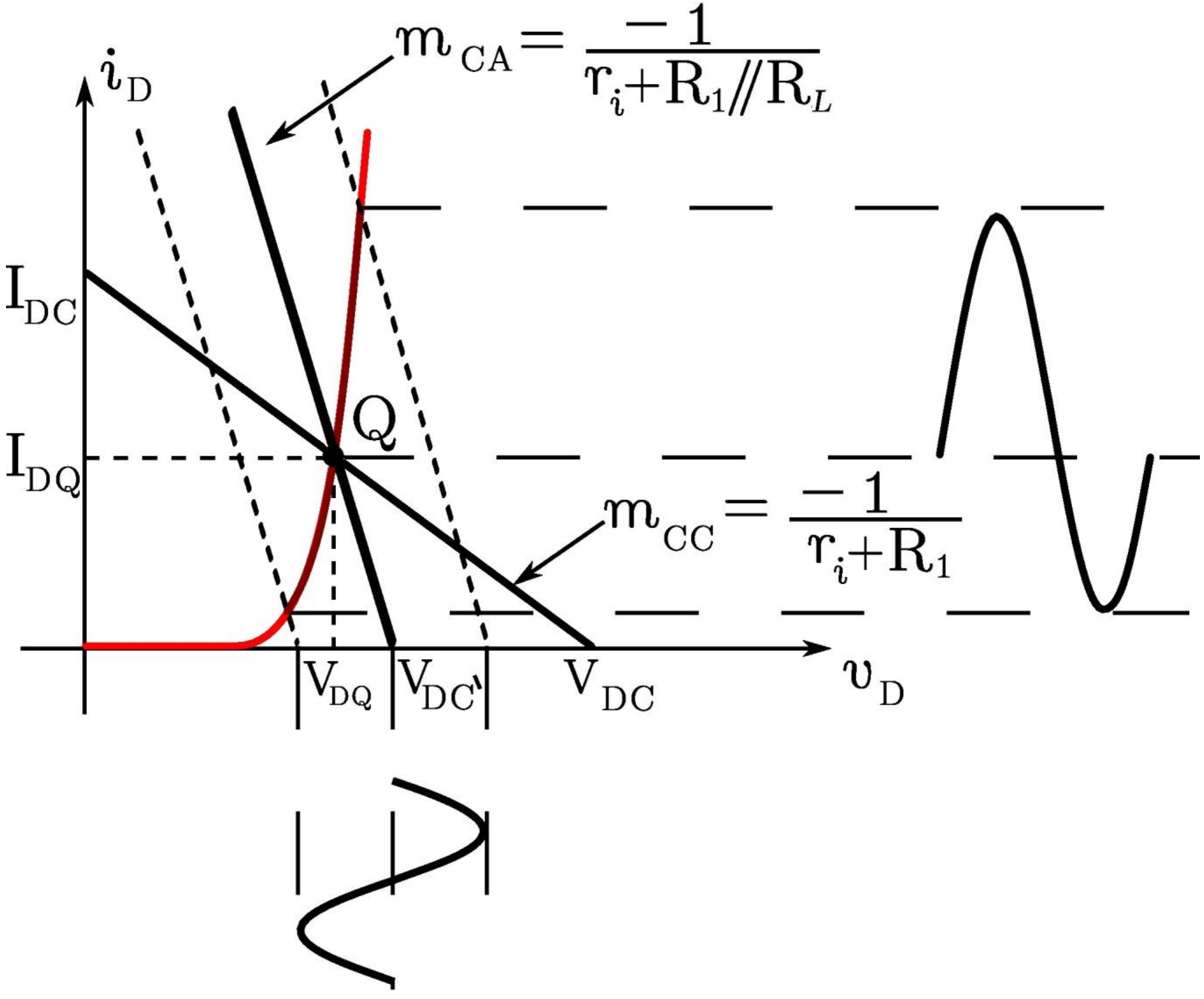
$$R_{T_{CC}} = r_i + R_1$$

$$R_{T_{CA}} = r_i + R_1 // R_L$$

$$R_{T_{CA}} < R_{T_{CC}}$$

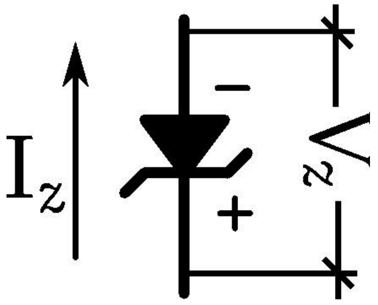
$$m_{CA} > m_{CC}$$

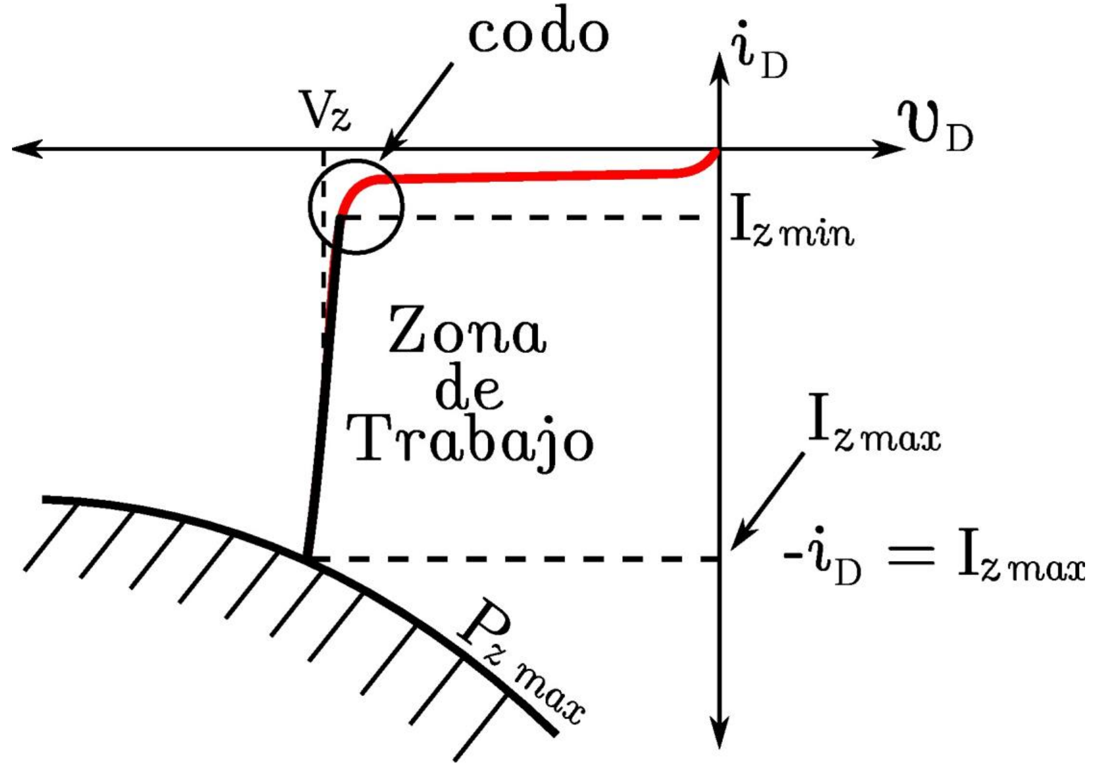
Circuito con elementos reactivos (Cont.)



Diodo Zener

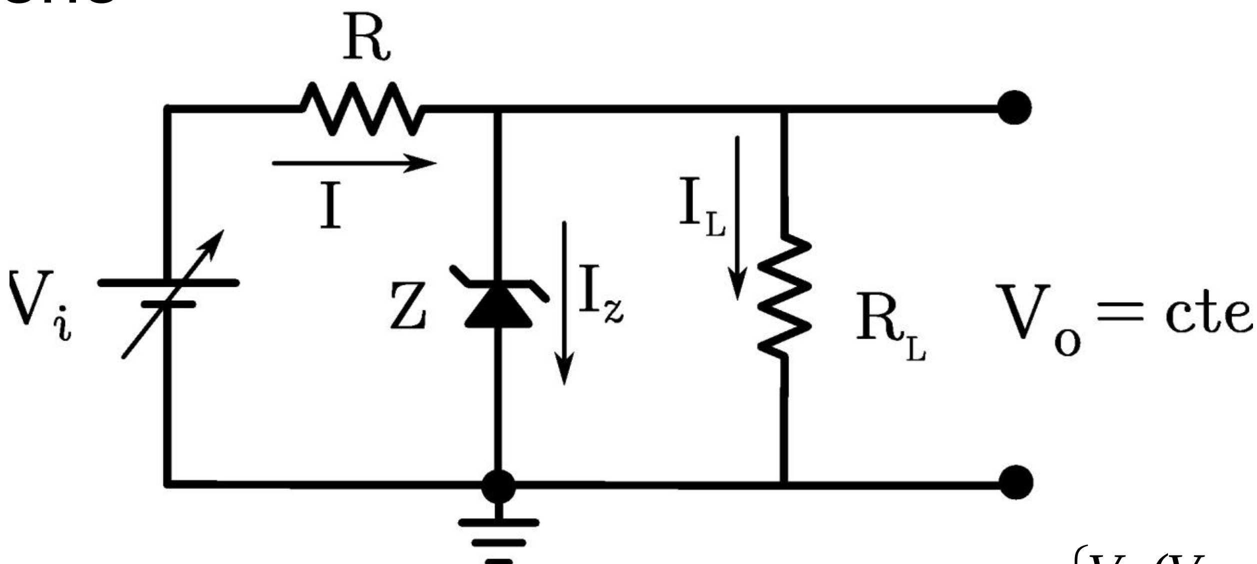
- Símbolo.





Diodo Zener (Cont.)

- Circuito básico estabilizador de tensión
- Diseño



$$Datos \begin{cases} V_Z = V_O = cte \\ P_{Zmax} \\ I_{Z\,min} \;\; si\ no\ esta\ especificado\ I_{Z\,min} = \dfrac{1}{10} I_{Z\,max} \end{cases}$$

$$Puede\ Variar \begin{cases} V_i \;\; (V_{i\,max}; V_{i\,min}) \\ R_L \\ I_L \;\; (I_{L\,max}; I_{L\,min}) \end{cases}$$

Diodo Zener (Cont.)

- Ecuaciones de diseño

$$I = I_Z + I_L$$

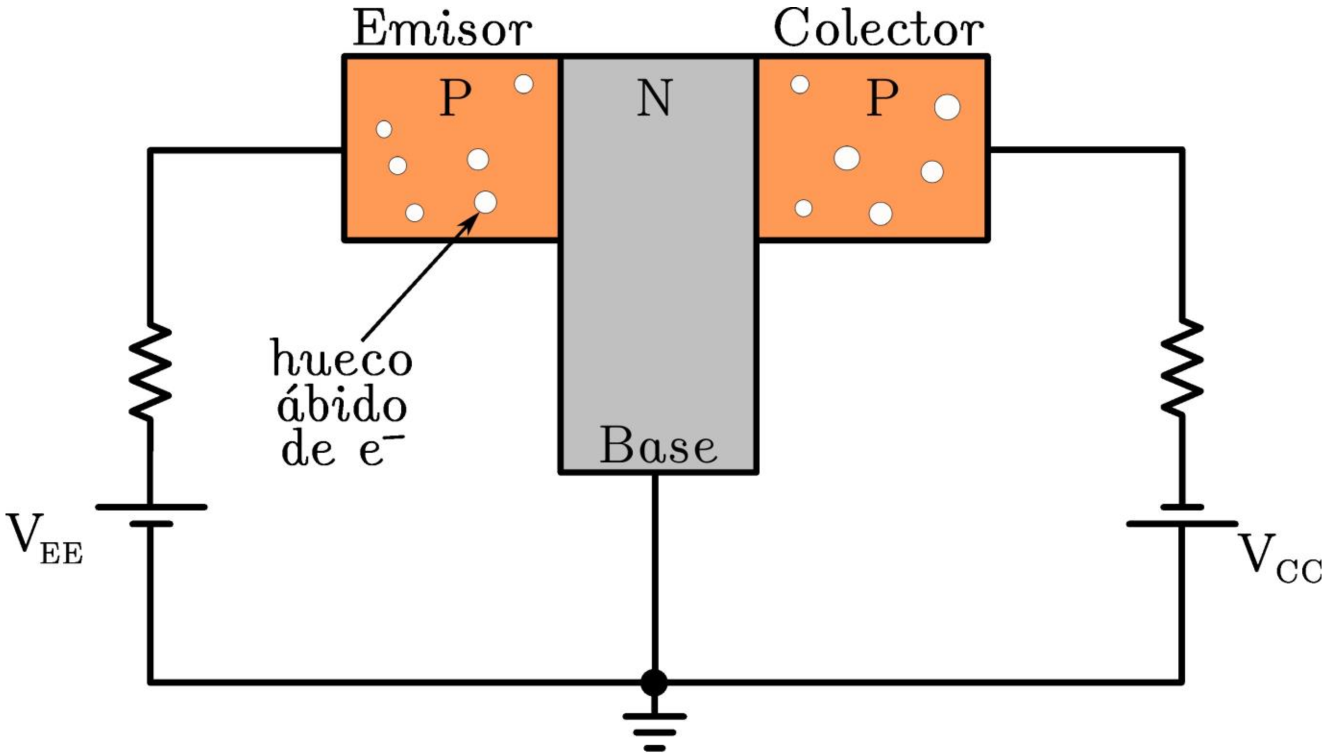
$$I_Z = I - I_L$$

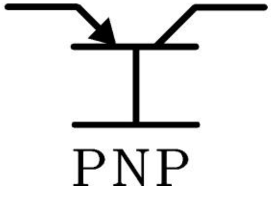
$$I = \frac{V_i - V_Z}{R}$$

$$I_Z = \frac{V_i - V_Z}{R} - I_L$$

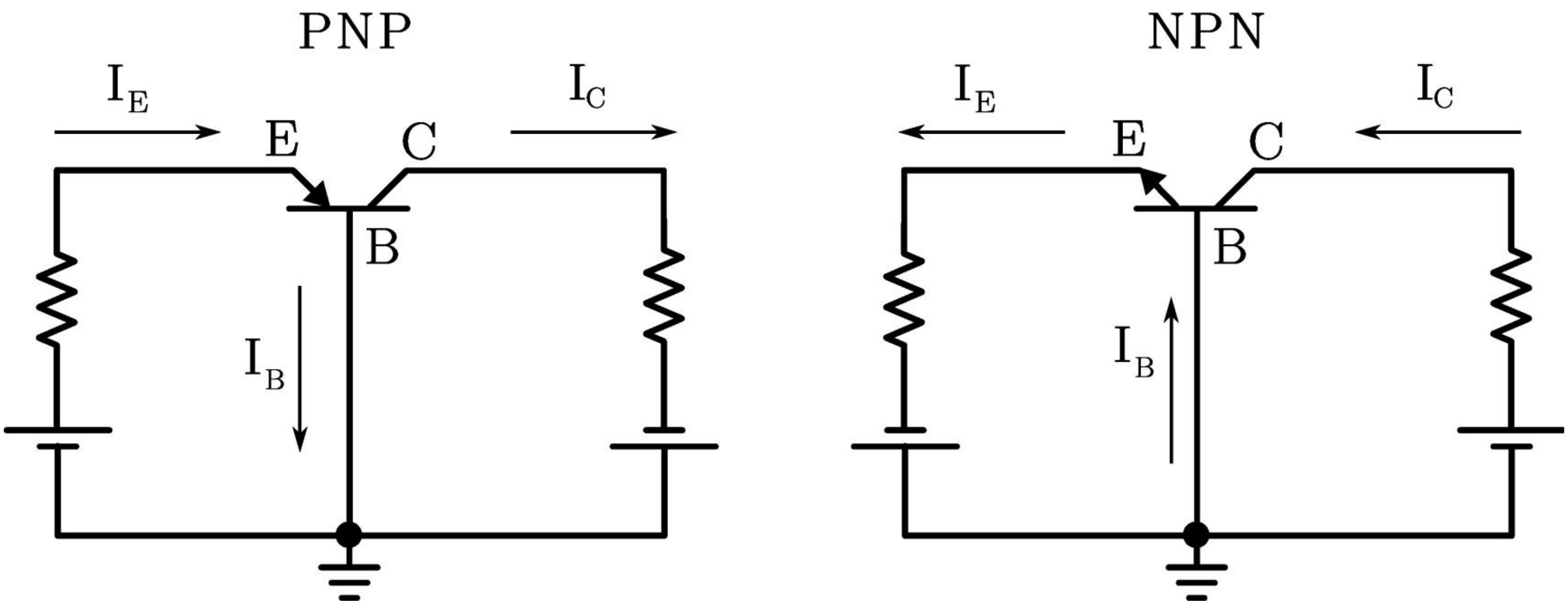
$$\left.\begin{aligned} I_{Z\max} &= \frac{V_{i\max} - V_Z}{R_{\min}} - I_{L\min} \Rightarrow R_{\min} = \frac{V_{i\max} - V_Z}{I_{Z\max} + I_{L\min}} \\ I_{Z\min} &= \frac{V_{i\min} - V_Z}{R_{\max}} - I_{L\max} \Rightarrow R_{\max} = \frac{V_{i\min} - V_Z}{I_{Z\min} + I_{L\max}} \end{aligned}\right\} R = \frac{R_{\max} + R_{\min}}{2}$$

Transistores

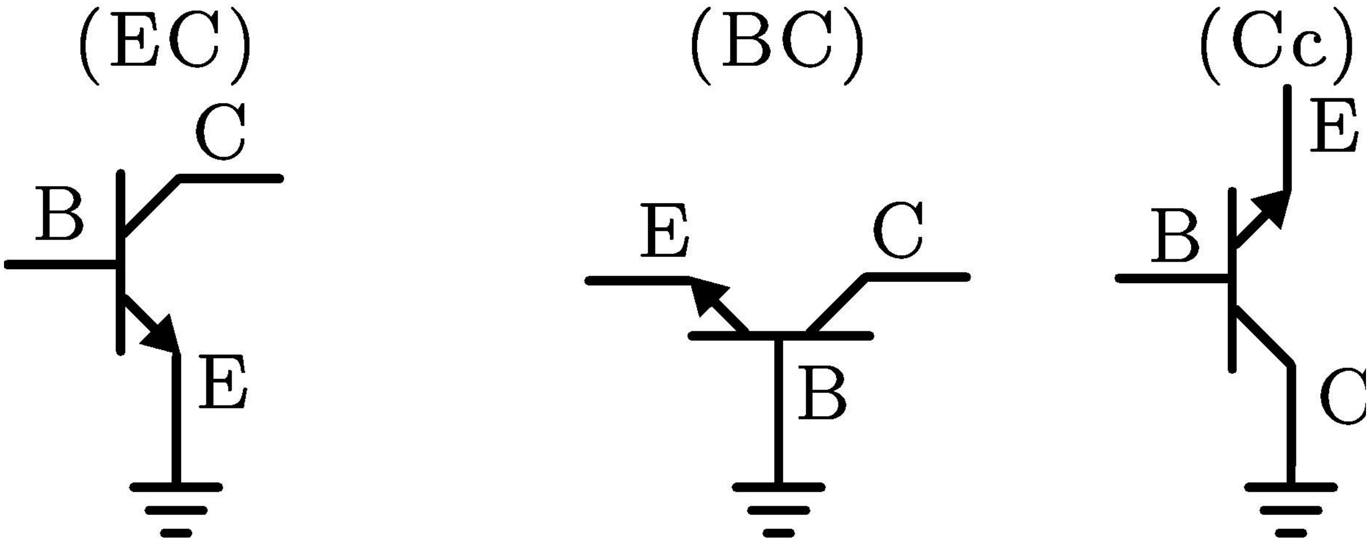




Transistores PNP y NPN



Transistores: Configuraciones



Corrientes en el transistor

$$0{,}9 < \alpha < 0{,}995$$

$$\alpha < 1 \quad siempre$$

$$I_C = \alpha I_E + I_{CB0} \qquad (1)$$

$$\alpha I_E >> I_{CB0}$$

$$\alpha = \left.\frac{I_C}{I_E}\right|_{I_{CB0}=0} \quad Ganancia\ Corriente\ en\ BC\ en\ CC$$

$$I_E = I_C + I_B \qquad (2)$$

$$I_{CB0} = I_C\big|_{I_E=0}$$

$$\beta = \frac{I_C}{I_B} \quad Ganancia\ Corriente\ en\ EC\ en\ CC$$

Corrientes en el transistor (Cont.)

- Relación entre α y β

$$\alpha = \frac{I_C}{I_E} = \frac{I_C}{I_C + I_B} = \frac{I_C / I_B}{I_C / I_B + I_B / I_B} = \frac{\beta}{\beta + 1}$$

$$\beta = \frac{I_C}{I_B} = \frac{I_C}{I_E - I_C} = \frac{I_C / I_E}{I_E / I_E - I_C / I_E} = \frac{\alpha}{1 - \alpha}$$

Corrientes en el transistor (Cont.)

$$de\ (2)\ despejamos\ I_B$$

$$I_B = I_E - I_C$$

$$reemplazo\ (1)\ en\ la\ ecuacion\ anterior$$

$$I_B = I_E - \alpha I_E - I_{CB0} = I_E(1-\alpha) - I_{CB0}$$

$$de\ (1)\ despejamos\ I_E\ y\ la\ reemplazamos\ en\ la\ ecuacion\ anterior$$

$$I_E = \frac{I_C - I_{CB0}}{\alpha}$$

$$I_B = \frac{I_C - I_{CB0}}{\alpha}(1-\alpha) - I_{CB0}$$

Corrientes en el transistor (Cont.)

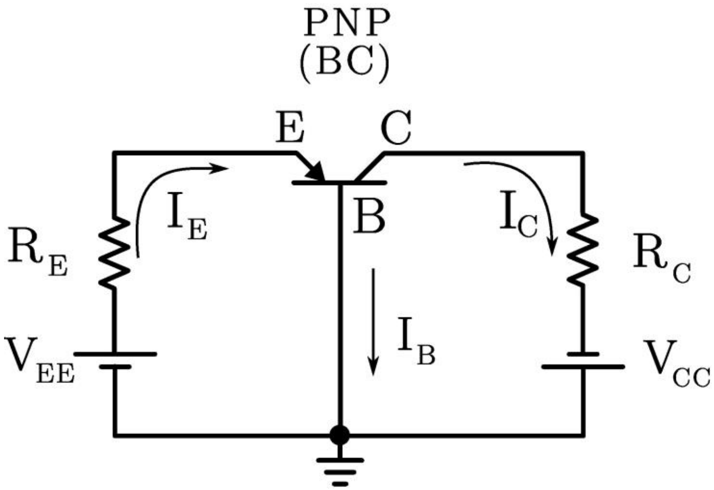
$$I_B = \frac{1-\alpha}{\alpha} I_C - \frac{1-\alpha}{\alpha} I_{CB0} - I_{CB0}$$

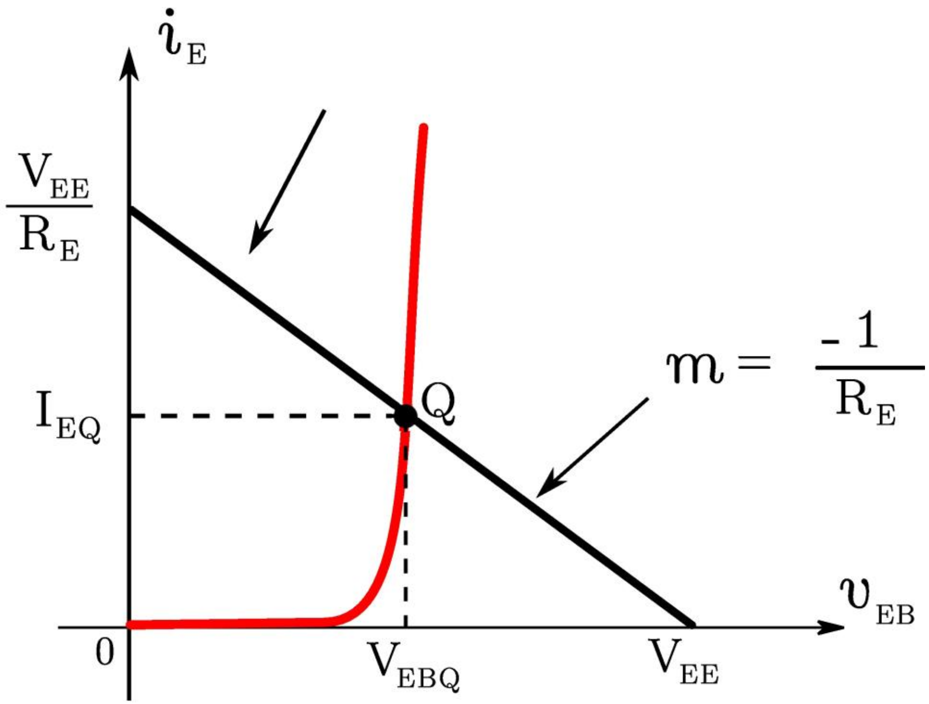
$$I_B = \frac{1-\alpha}{\alpha} I_C - I_{CB0}\left(\frac{1-\alpha}{\alpha} + 1\right)$$

$$I_B = \frac{1-\alpha}{\alpha} I_C - \frac{I_{CB0}}{\alpha} \qquad pero \quad \frac{1-\alpha}{\alpha} = \frac{1}{\beta}$$

$$I_B = \frac{I_C}{\beta} - \frac{I_{CB0}}{\alpha} \qquad (3)$$

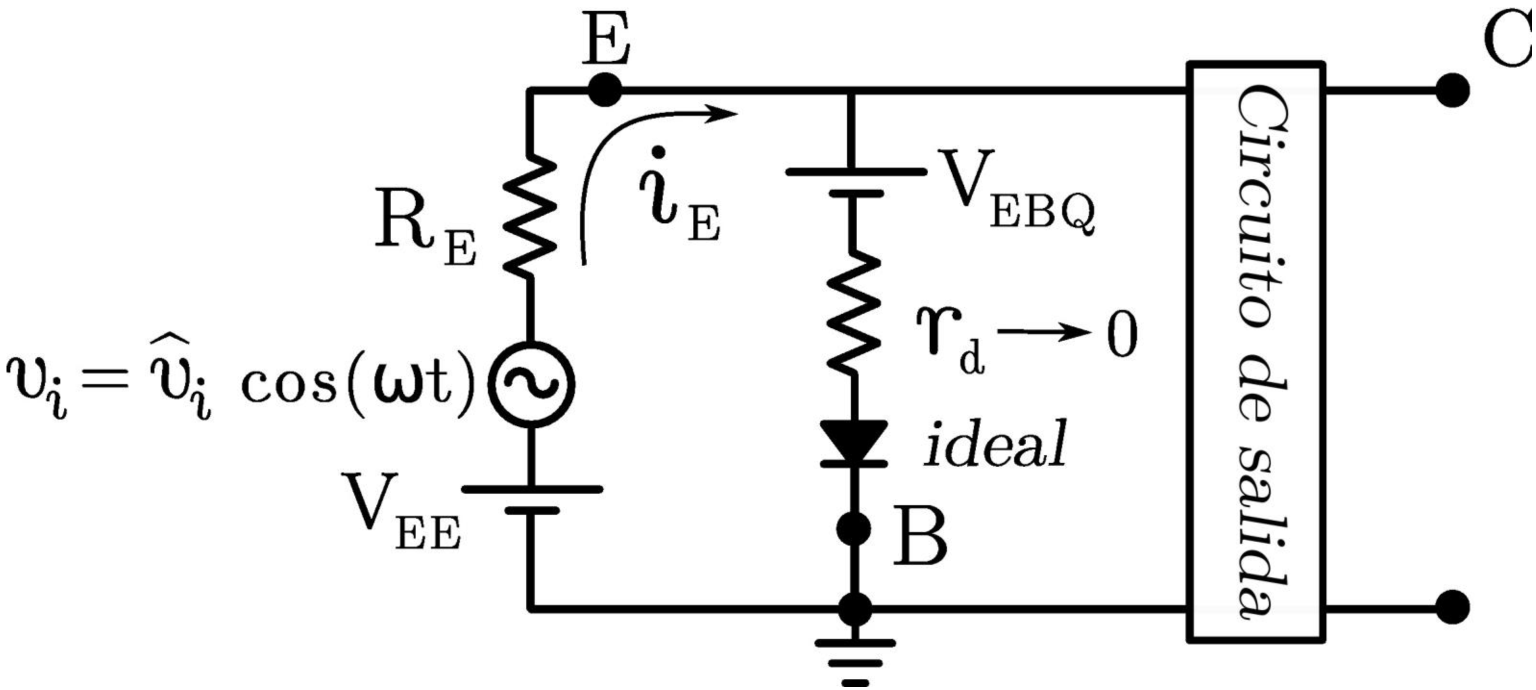
La juntura de entrada (juntura E-B)





$$I_{EQ} = \frac{V_{EE} - V_{EBQ}}{R_E}$$

La juntura de entrada (juntura E-B)(Cont.)

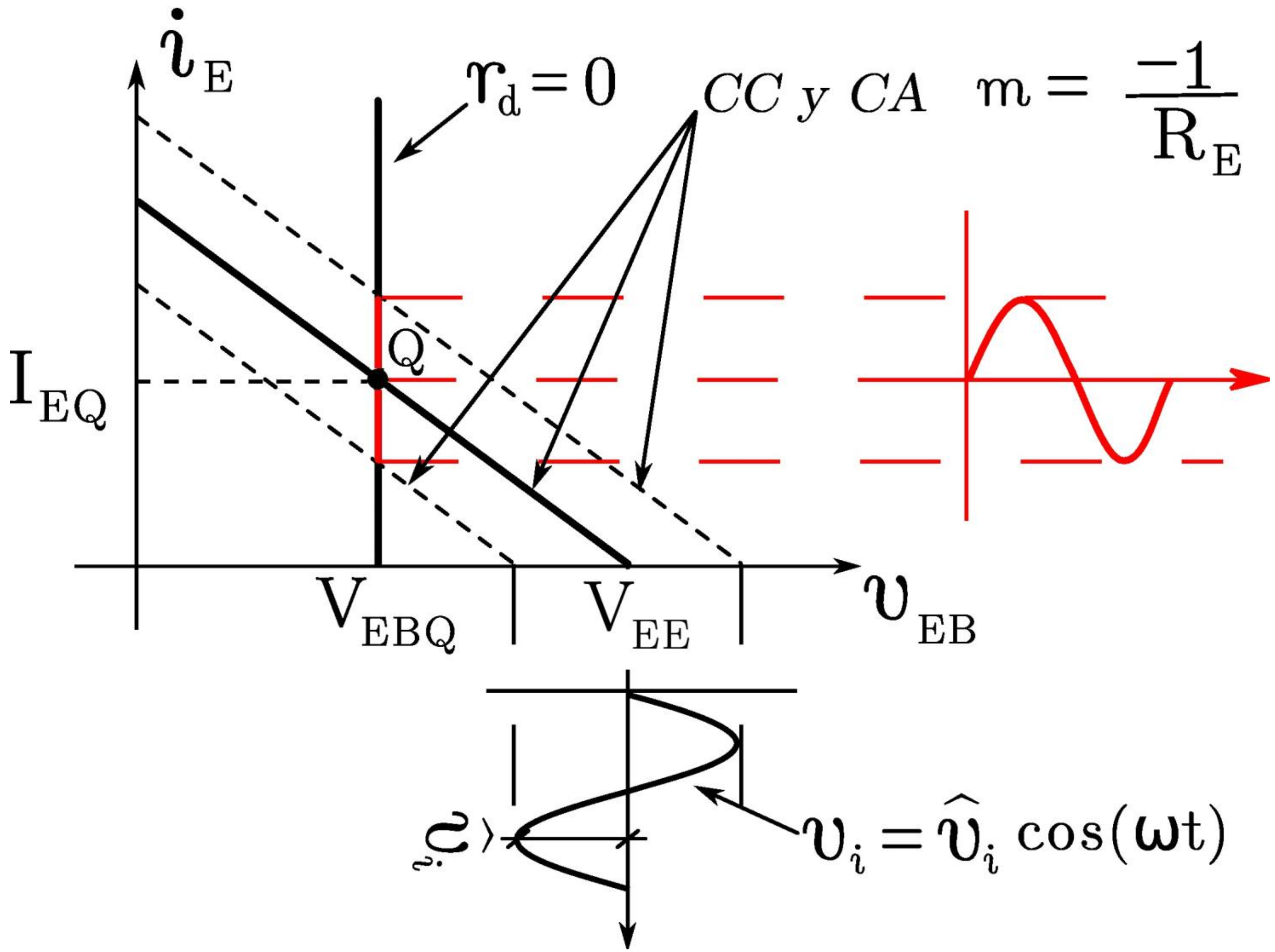


$$i_E = I_{EQ} + i_e$$

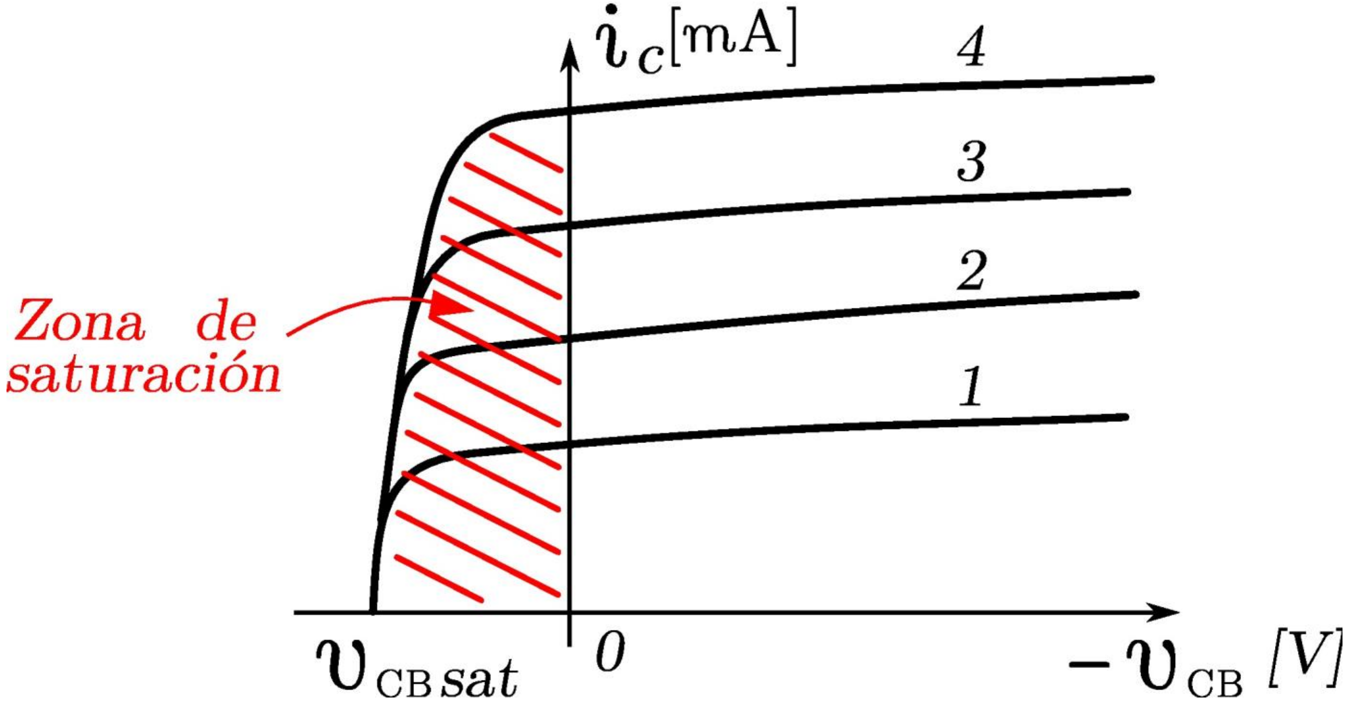
$$i_E = \frac{V_{EE} - V_{EBQ}}{R_E} + \frac{V_{im} sen\omega t}{R_E}$$

$$(V_{EE} - V_{im}) \geq V_{EBQ}$$

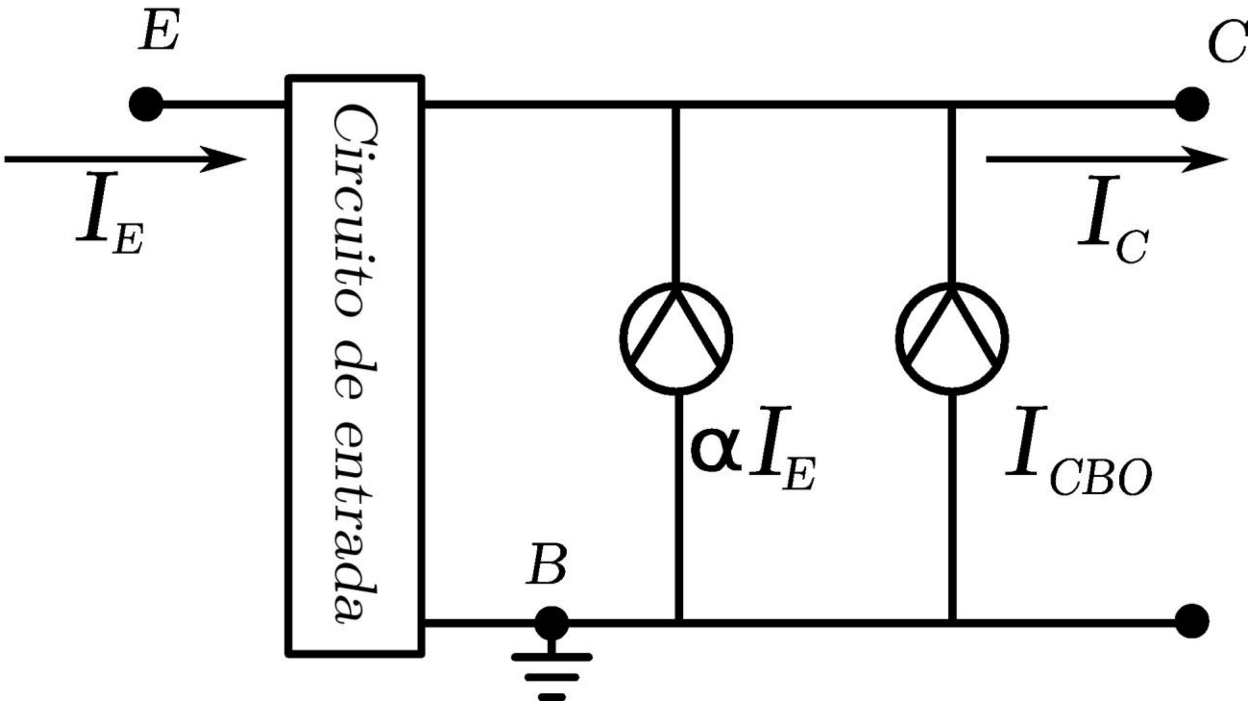
La juntura de entrada (juntura E-B)(Cont.)



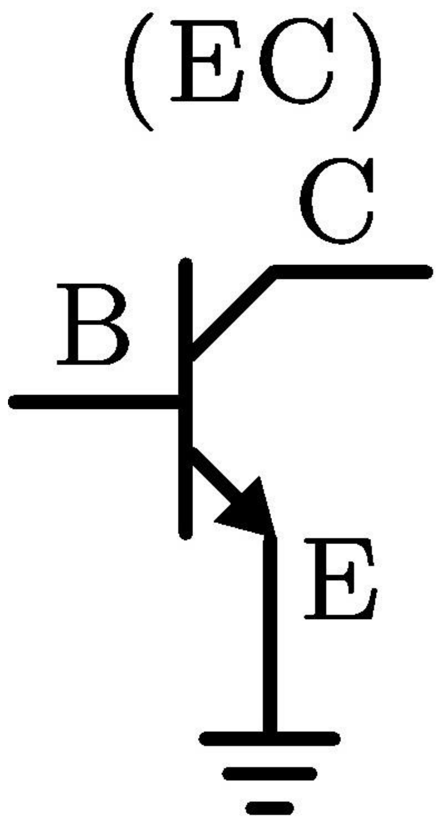
La juntura salida (juntura C-B)



La juntura salida (juntura C-B) (Cont.)



Ganancia de corriente en Continua y Alterna para emisor común



$$\beta = \frac{I_{CQ}}{I_{BQ}} = h_{FE} \ \ (de \ \ continua)$$

$$h_{fe} = \frac{i_c}{i_b} \ \ (en \ alterna)$$

$$i_C = f(\beta, i_B) = \beta i_B$$

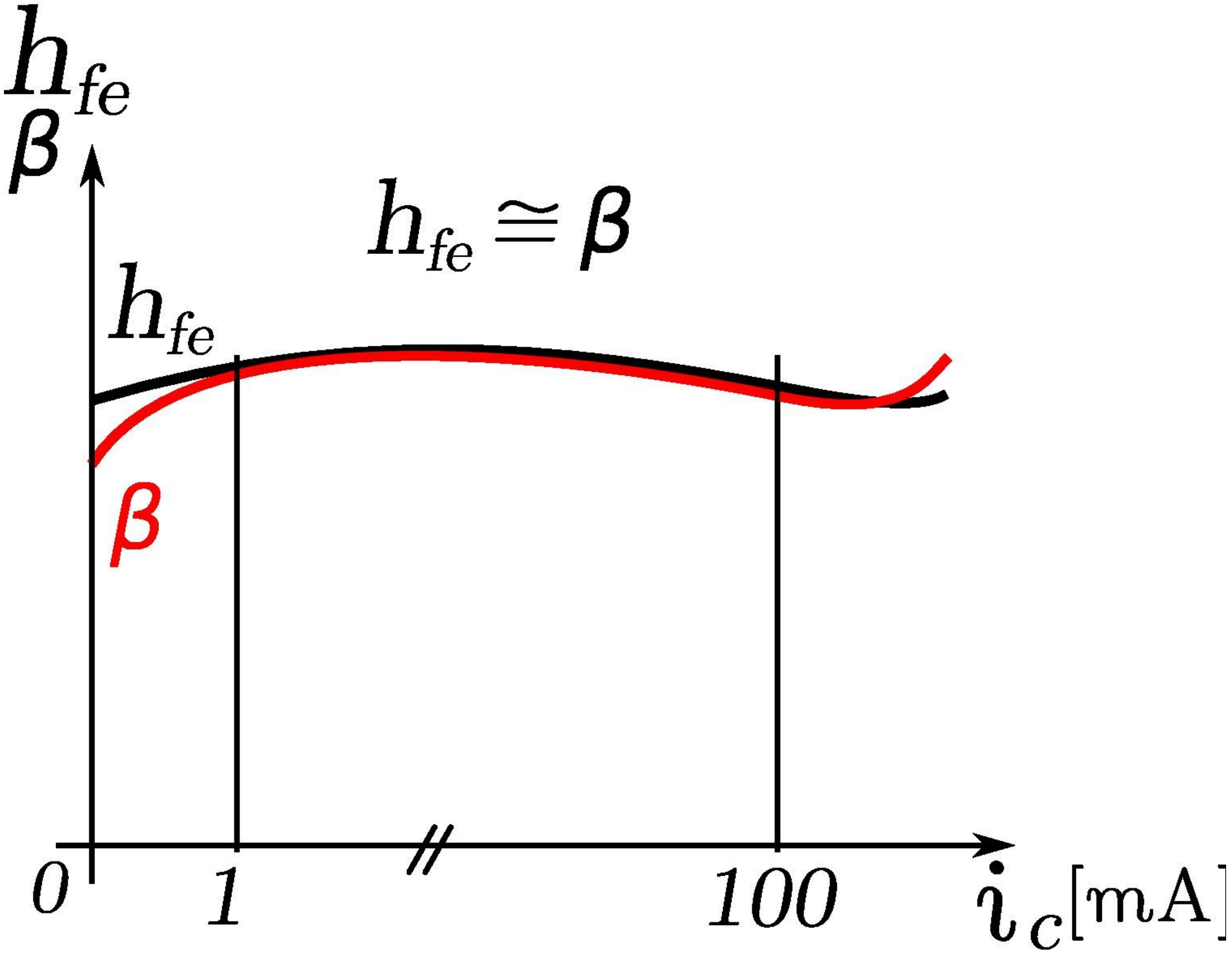
$$h_{fe} = \frac{i_c}{i_b} = \frac{\Delta i_C}{\Delta i_B} = \beta \frac{\Delta i_B}{\Delta i_B} + \frac{\Delta \beta}{\Delta i_B} i_B$$

$$= \beta + \frac{\Delta \beta}{\Delta i_B} i_B$$

$$Si \ \ \frac{\Delta \beta}{\Delta i_B} i_B \ \ es \ pequeña \ compardo \ con \ \beta, se \ tendra$$

$$h_{fe} \approx \beta \equiv h_{FE}$$

Ganancia de corriente en Continua y Alterna para emisor común (Cont.)



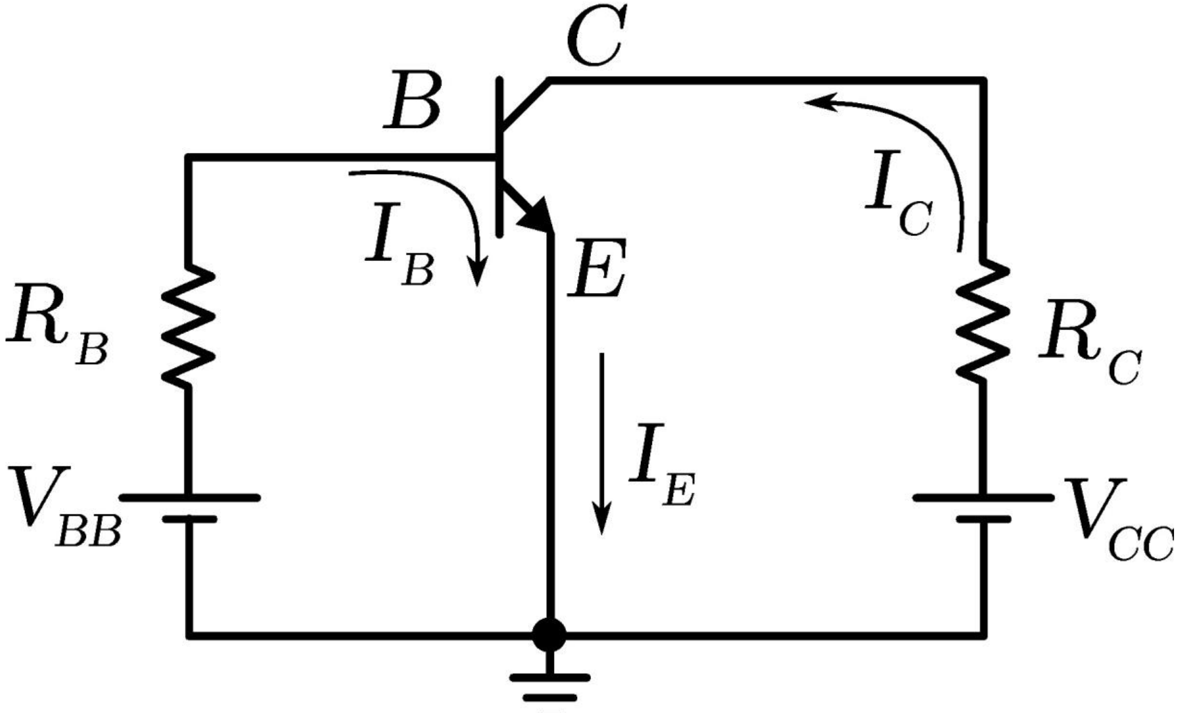
Polarización- El amplificador básico (para E-C)

- Definiciones

”Polarizar es energizar con CC la salida y la entrada”.

Para transistores en CC, ***análisis*** es hallar el punto Q teniendo todos los valores de los elementos como datos; ***diseño***, es hallar todos los valores del circuito teniendo como dato el punto Q.

Polarización- El amplificador básico (para E-C) (Cont.)



Polarización- El amplificador básico (para E-C) (Cont.)

$Analisis:$

$Ecuacion\ de\ entrada\ (por\ Kirchoff):$

$$V_{BB} = I_{BQ}R_B + V_{BEQ} \qquad\qquad Donde\begin{cases} 0,7(Si) \\ 0,2(Ge) \end{cases}$$

$$I_{BQ} = \frac{V_{BB} - V_{BEQ}}{R_B} \qquad (1)$$

$$\beta = \frac{I_{CQ}}{I_{BQ}} \Rightarrow I_{CQ} = \beta I_{BQ} \qquad (2)$$

$Ecuacion\ de\ salida:$

$$V_{CC} = I_{CQ}R_C + V_{CEQ}$$

$$V_{CEQ} = V_{CC} - I_{CQ}R_C = V_{CC} - \beta I_{BQ}R_C \qquad (3)$$

Polarización- El amplificador básico (para E-C) (Cont.)

Diseño :

dado el punto Q, hay que hallar los Resistores

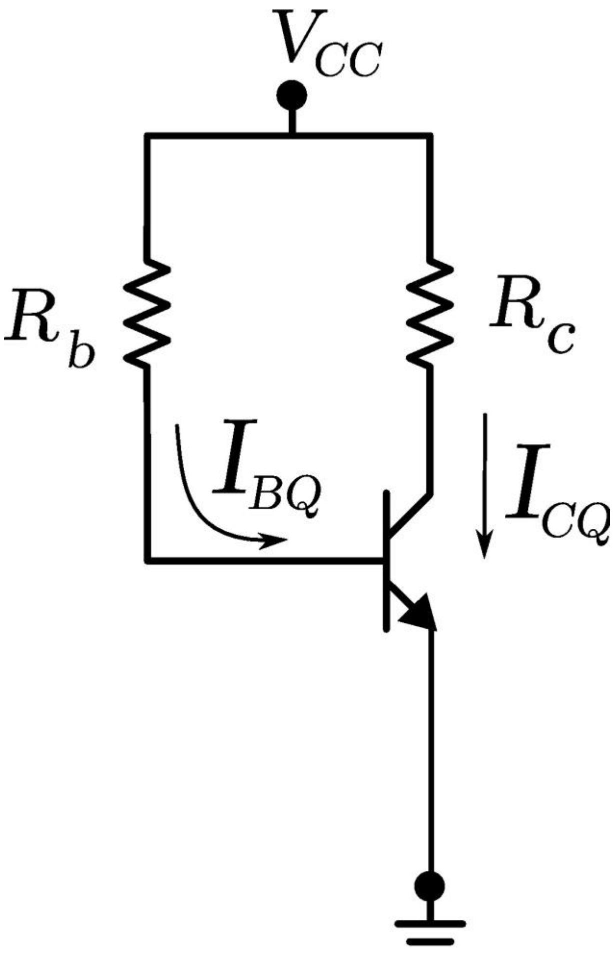
de (1):

$$R_B = \frac{V_{BB} - V_{BEQ}}{I_{BQ}}$$

de (3):

$$R_C = \frac{V_{CC} - V_{CEQ}}{I_{CQ}}$$

Circuito con una fuente y dos resistencias



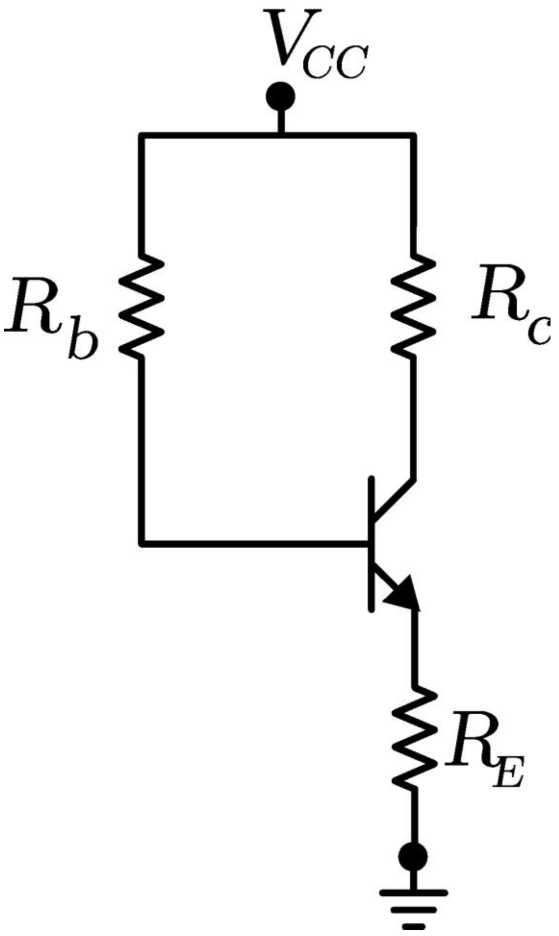
$$I_{BQ} = \frac{V_{CC} - V_{BEQ}}{R_b}$$

$$I_{CQ} = \beta I_{BQ}$$

$$V_{CEQ} = V_{CC} - I_{CQ} R_C$$

$$\boxed{R_C = \frac{V_{CC} - V_{CEQ}}{I_{CQ}}} \qquad \boxed{R_b = \frac{V_{CC} - V_{BEQ}}{I_{BQ}}}$$

Circuito con una fuente y tres resistencias



R_E *estabiliza el punto Q ante variaciones de* β

Analisis

Entrada:

$$V_{CC} = \frac{I_{CQ}}{\beta} R_b + V_{BE} + I_{CQ} R_E$$

$$I_{CQ} = \frac{V_{CC} - V_{BE}}{R_E + \frac{R_b}{\beta}}$$

$$Si,\ R_E >> \frac{R_b}{\beta} \quad \Rightarrow \quad \text{si varia } \beta \text{ no influye mucho.}$$

Si hacemos

$$R_E = 10 \frac{R_b}{\beta} \quad \text{Criterio de estabilidad}$$

$$R_b = \frac{\beta}{10} R_E$$

Salida:

$$V_{CEQ} = V_{CC} - I_{CQ}(R_C + R_E)$$

Circuito con una fuente y tres resistencias (Cont.)

Diseño

Entrada:

$$V_{CC} = \frac{I_{CQ}}{\beta} R_b + V_{BEQ} + I_{CQ}\,\mathrm{R}_E$$

$$= \frac{I_{CQ}}{\cancel{\beta}} \frac{\cancel{\beta} R_E}{10} + V_{BEQ} + I_{CQ}\,\mathrm{R}_E$$

$$= 1{,}1(I_{CQ} R_E) + V_{BEQ} \Rightarrow R_E = \frac{V_{CC} - V_{BEQ}}{1{,}1 I_{CQ}}$$

Salida:

$$V_{CC} = V_{CEQ} + I_{CQ}(R_C + R_E)$$

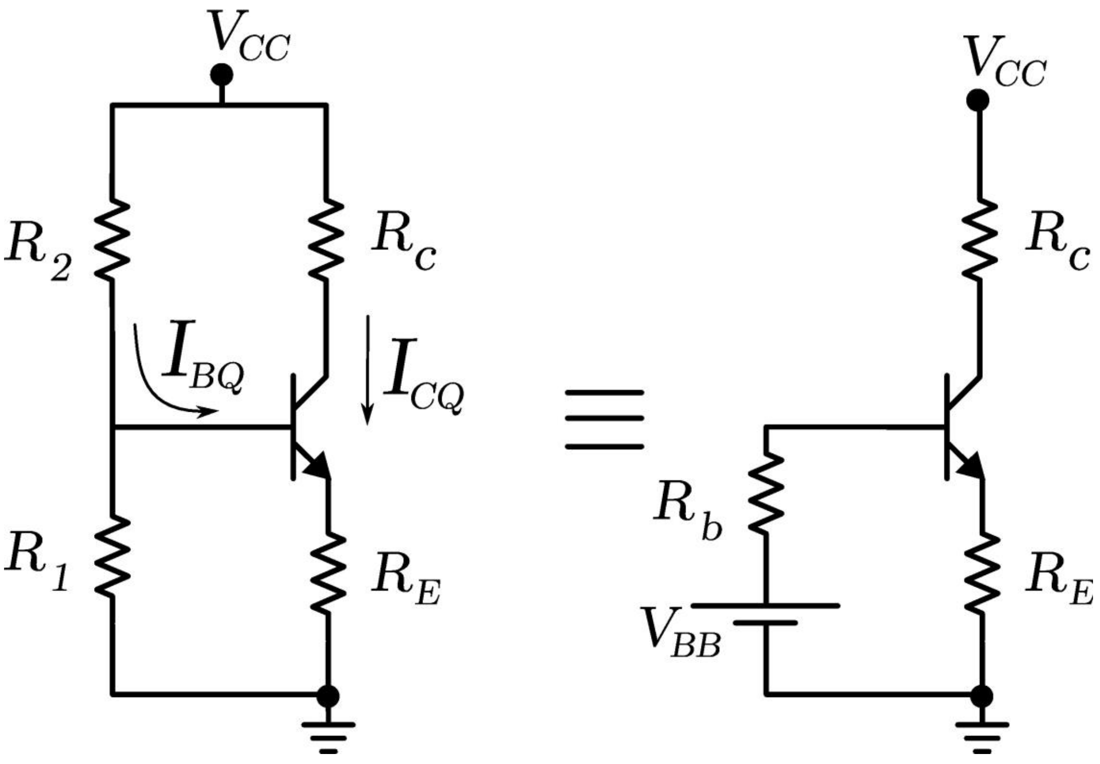
$$R_C = \frac{V_{CC} - V_{CEQ}}{I_{CQ}} - R_E$$

En el Diseño si no importa la estabilidad

se toma $100\Omega < R_E < 2K\Omega$

$$V_{CC} = \frac{I_{CQ}}{\beta} R_b + V_{BEQ} + I_{CQ} R_E \Rightarrow R_b = \beta\left[\frac{V_{CC} - V_{BEQ}}{I_{CQ}} - R_E\right]$$

Circuito fundamental



$$R_b = \frac{R_1 R_2}{R_1 + R_2} \quad (1)$$

$$V_{BB} = \frac{V_{CC}}{R_1 + R_2} R_1 \quad (2)$$

$$V_{BB} = \frac{I_{CQ}}{\beta} R_b + V_{BE} + I_{CQ} R_E$$

$$I_{CQ} = \frac{V_{BB} - V_{BE}}{\frac{R_b}{10} + R_E}$$

$$V_{CEQ} = V_{CC} - I_{CQ}(R_C + R_E)$$

Circuito fundamental (Cont.)

Diseño

$Datos: \ Punto \ Q$

$Transistor \ (i_{C(\max)}; BV_{CE}; \beta; V_{BE})$

$i_{C(\max)} \geq 2I_{CQ} \qquad V_{CC} < BV_{CE}$

$despejando \ (1) \ y \ (2)$

$$\frac{R_1}{R_1+R_2} = \frac{R_b}{R_2} = \frac{V_{BB}}{V_{CC}} = \frac{R_1}{R_1+R_2} \Rightarrow \boxed{R_2 = \frac{V_{CC}}{V_{BB}} R_b}$$

$de \ (2)$

$$R_1 + R_2 = \frac{V_{CC}}{V_{BB}} R_1$$

$$R_1 \left[1 - \frac{V_{CC}}{V_{BB}} \right] = -\frac{V_{CC}}{V_{BB}} R_b$$

$$R_1 = \left(\frac{V_{CC}}{V_{BB}} R_b \right) \Big/ \left(\frac{V_{CC}}{V_{BB}} - \frac{V_{BB}}{V_{BB}} \right) \quad \Rightarrow \quad \boxed{R_1 = \frac{R_b}{1 - \frac{V_{BB}}{V_{CC}}}}$$

Condensadores de acoplamiento y desacoplamiento.

- Recta de Carga C.A y Máxima Excusión Simétrica.

C_1 *acopla la etapa anterior con la etapa en cuestion en C.A.*

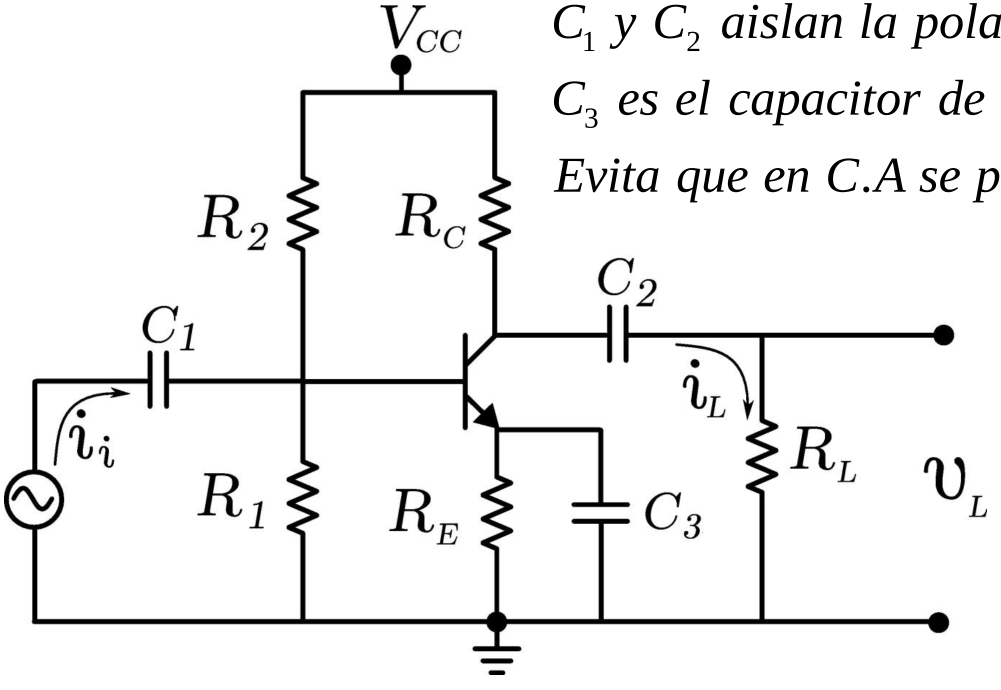
C_2 *acopla la etapa presente con la siguiente, tambien en C.A.*

C_1 *y* C_2 *son como cables para la C.A.*

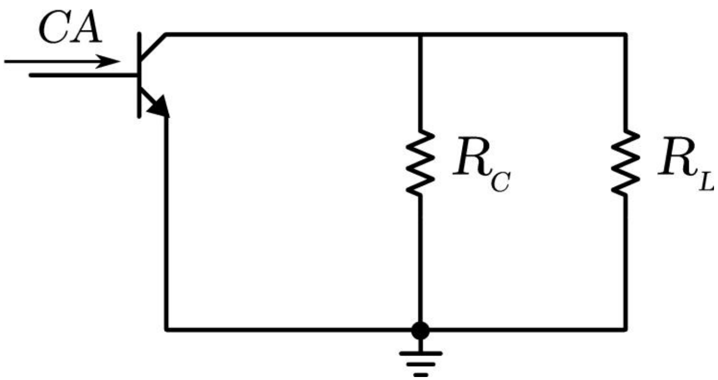
C_1 *y* C_2 *aislan la polarizacion de etapas en C.C.*

C_3 *es el capacitor de desacoplamiento en C.A.*

Evita que en C.A se pierda energia inutilmente en R_E



Recta de carga de C.A



R_{CC} : *Resistencia del circuito de salida a la C.C.*

$R_{CC} = R_C + R_E$

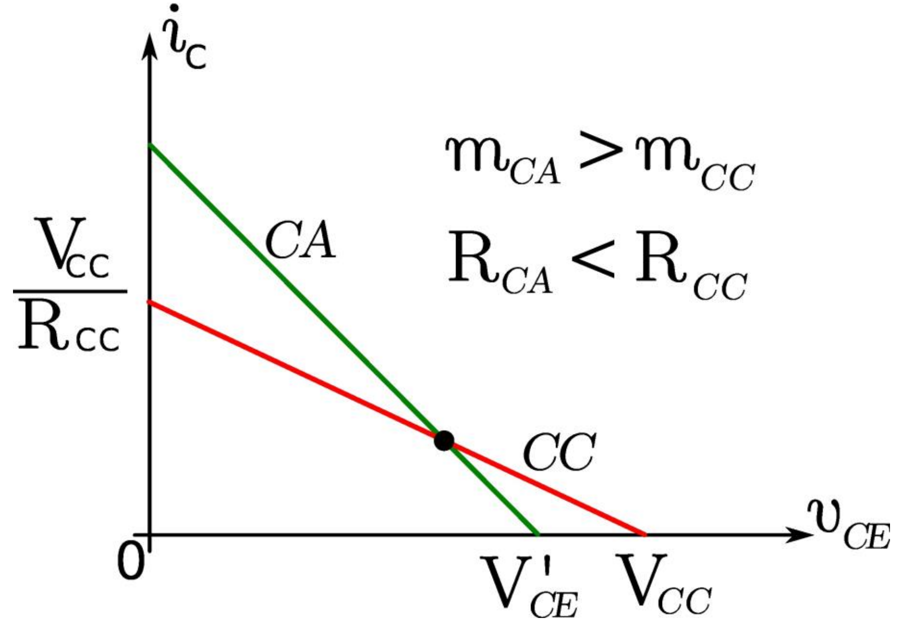
R_{CA} = *Resistencia del circuito de salida a la C.A.*

$R_{CA} = R_C \,//\, R_L$

$$i_c^{'} = I_{CQ} + \frac{V_{CEQ}}{R_{CA}}$$

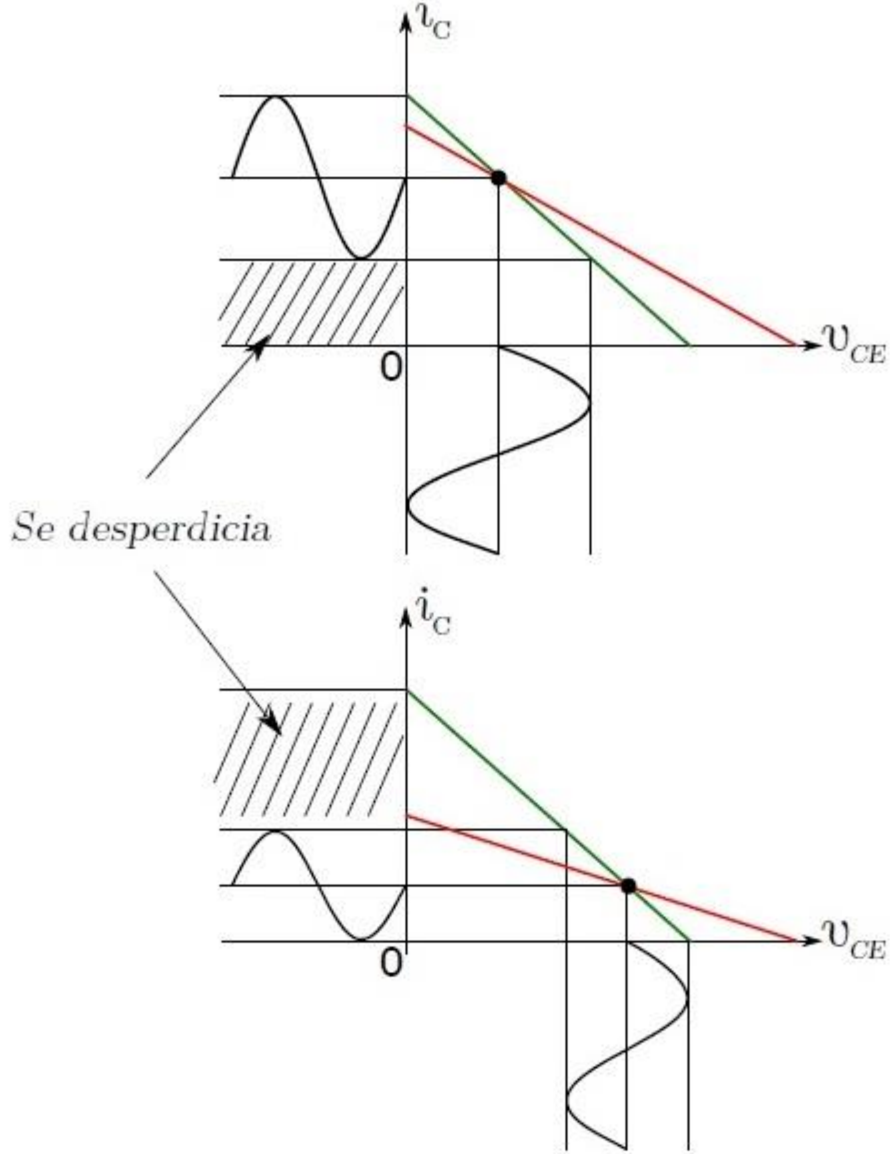
i_c

$$v_{ce}^{'} = V_{CEQ} + \underbrace{I_{CQ} R_{CA}}_{v_{ce}}$$

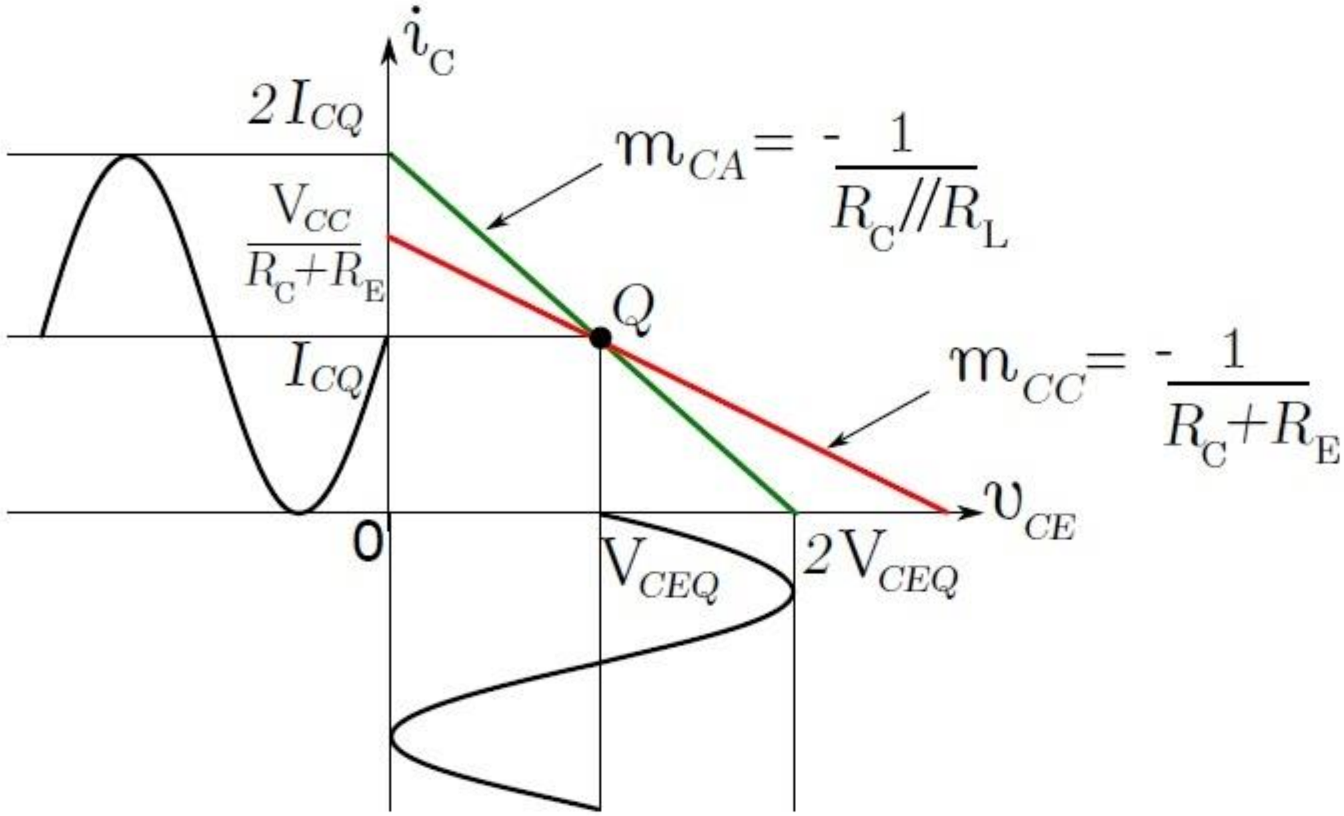


Cuando el punto Q esta en el medio de la recta de C.A, el punto Q esta en maxima excursion simetrica.

Máxima excursión simétrica



Máxima excursión simétrica (Cont.)



Máxima excursión simétrica (Cont.)

La ecuacion de la recta de carga de C.A

$$i_c = -\frac{1}{R_C // R_L} v_{ce}$$

$$i_C - I_{CQ} = -\frac{1}{R_C // R_L}\left(v_{CE} - V_{CEQ}\right)$$

$$Cuando\ v_{CE} = 0 \quad \Rightarrow \quad i_{C,\max} = I_{CQ} + \frac{V_{CEQ}}{R_C // R_L} \ (1)$$

Para obtener MES el pto Q debe estar en el centro de la recta de carga de C.A de modo que:

$$i_{C,\max} = 2I_{CQ} \ (2)$$

Igualando (1) *y* (2)

$$2I_{CQ} = I_{CQ} + \frac{V_{CEQ}}{R_C // R_L}$$

$$I_{CQ} = \frac{V_{CEQ}}{R_C // R_L} \Rightarrow V_{CEQ} = I_{CQ}\left(R_C // R_L\right) \ (3)$$

Máxima excursión simétrica (Cont.)

$$La\ ecuacion\ de\ la\ recta\ de\ carga\ de\ C.C$$

$$V_{CC} = V_{CEQ} + I_{CQ}\left(R_L + R_E\right)$$

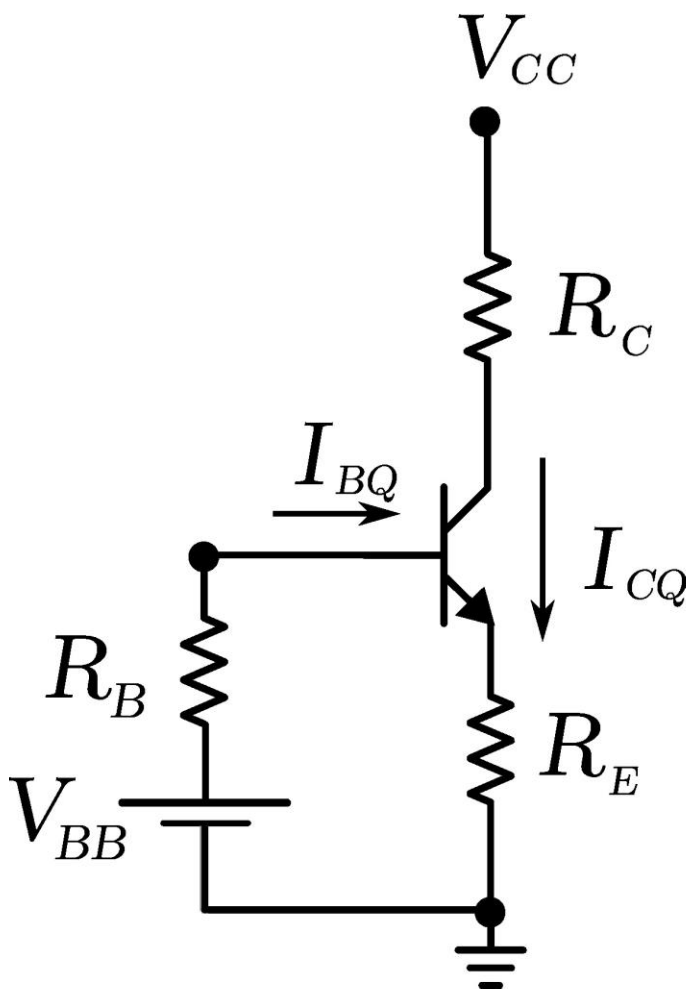
$$Reemplazando\ (3)\ en\ la\ ecuacion\ anterior$$

$$V_{CC} = I_{CQ}\left(R_C\,//\,R_L\right) + I_{CQ}\left(R_E + R_C\right)$$

$$V_{CC} = I_{CQ}\left\{\left(R_E + R_C\right) + \left(R_C\,//\,R_L\right)\right\}$$

$$I_{CQ(MES)} = \frac{V_{CC}}{\left(R_E + R_C\right) + \left(R_C\,//\,R_L\right)}$$

Análisis de Potencia



Potencia Media suministrada por cualquier dispositivo lineal o no.

$$P = \frac{1}{T}\int_0^T V(t) I(t).dt$$

$$V(t) = V_{AV} + v(t)$$

$$I(t) = I_{AV} + i(t)$$

$$Suponemos: \; v(t) \; y \; i(t) \; periodicas \; y \; simetricas$$

$$= \frac{1}{T}\int_0^T \left[V_{AV} + v(t)\right]\left[I_{AV} + i(t)\right]dt$$

$$= \frac{1}{T}\int_0^T V_{AV} I_{AV} dt + \overbrace{\frac{1}{T}\int_0^T V_{AV} i(t) dt}^{=0} + \overbrace{\frac{1}{T}\int_0^T v(t) I_{AV} dt}^{=0} + \frac{1}{T}\int_0^T v(t) i(t) dt$$

$$P = \frac{1}{T}\int_0^T V_{AV} I_{AV} dt + \frac{1}{T}\int_0^T v(t) i(t) dt$$

$$\boxed{P = V_{AV} I_{AV} + \frac{1}{T}\int_0^T v(t) i(t) dt}$$

Potencia Media suministrada por la fuente Pcc:

$$P_{CC} = \frac{1}{T}\int_0^T V_{CC} i_C dt \quad donde \quad \begin{cases} i_C = I_{CQ} + i_c \\ i_c = \hat{i}_c \cos \omega t \end{cases}$$

$$Entonces:$$

$$P_{CC} = V_{CC} I_{CQ} + 0 \Rightarrow I_{CQ} = \frac{P_{CC}}{V_{CC}}$$

$$Se\ tiene\ para\ MES$$

$$I_{CQ} = \frac{V_{CC}}{2(R_L + R_E)},\ igualando\ y\ despejando$$

$$P_{CC(MAX)} = \frac{V_{CC}{}^2}{2(R_L + R_E)}$$

$$Si\ R_E << R_L \Rightarrow \boxed{P_{CC(MAX)} = \frac{V_{CC}{}^2}{2R_L}}$$

Potencia Media disipada en la carga en C.A

$$P_{L(CA)} = \frac{1}{T}\int_0^T {i_c}^2 R_L dt = \frac{1}{T}\int_0^T (\hat{i}_c^{\,2} \cos^2 \omega t) R_L dt$$

$$= \frac{\hat{i}_c^{\,2} R_L}{T}\int_0^T \cos^2 \omega t \; dt$$

$$= \frac{\hat{i}_c^{\,2} R_L}{T}\int_0^T \left(\frac{1+\cos 2\omega t}{2}\right) dt$$

$$P_{L(CA)} = \frac{1}{2}\hat{i}_c^{\,2} R_L$$

$$Para\ MES\ y\ R_E << R_L$$

$$I_{CQ} = \frac{V_{CC}}{2R_L} = \hat{i}_c$$

$$Entonces$$

$$P_{L(MAX)} = \frac{1}{2}\frac{{V_{CC}}^2}{4{R_L}^{\cancel{2}}}\cancel{R}_L = \frac{1}{8}\frac{{V_{CC}}^2}{R_L} \Rightarrow \boxed{P_{L(MAX)} = \frac{{V_{CC}}^2}{8R_L}}$$

Potencia Media disipada en el colector

$$P_C = \frac{1}{T}\int_0^T v_{CE} i_C dt \begin{cases} v_{CE} = V_{CC} - i_C (R_L + R_E) \\ i_C = I_{CQ} + i_c = I_{CQ} + \hat{i}_c \cos \omega t \end{cases}$$

$$= \frac{1}{T}\int_0^T \left[V_{CC} - i_C (R_L + R_E) \right] i_C dt$$

$$= \frac{1}{T}\int_0^T \left[V_{CC} i_C - i_C{}^2 (R_L + R_E) \right] dt$$

$$P_C = \underbrace{\frac{1}{T}\int_0^T V_{CC} i_C dt}_{P_{CC}} - \underbrace{(R_L + R_E)\frac{1}{T}\int_0^T i_C{}^2 dt}_{P_L + P_E}$$

Potencia Media disipada en el colector (Cont.)

Tambien

$$\frac{1}{T}\int_0^T i_C{}^2 dt = \frac{1}{T}\int_0^T \left(I_{CQ} + \hat{i}_c \cos\omega t\right)^2 dt = I_{CQ}{}^2 + \frac{\hat{i}_c{}^2}{2}$$

Luego

$$P_C = P_{CC} - (R_L + R_E)I_{CQ}{}^2 - (R_L + R_E)\frac{\hat{i}_c{}^2}{2}$$

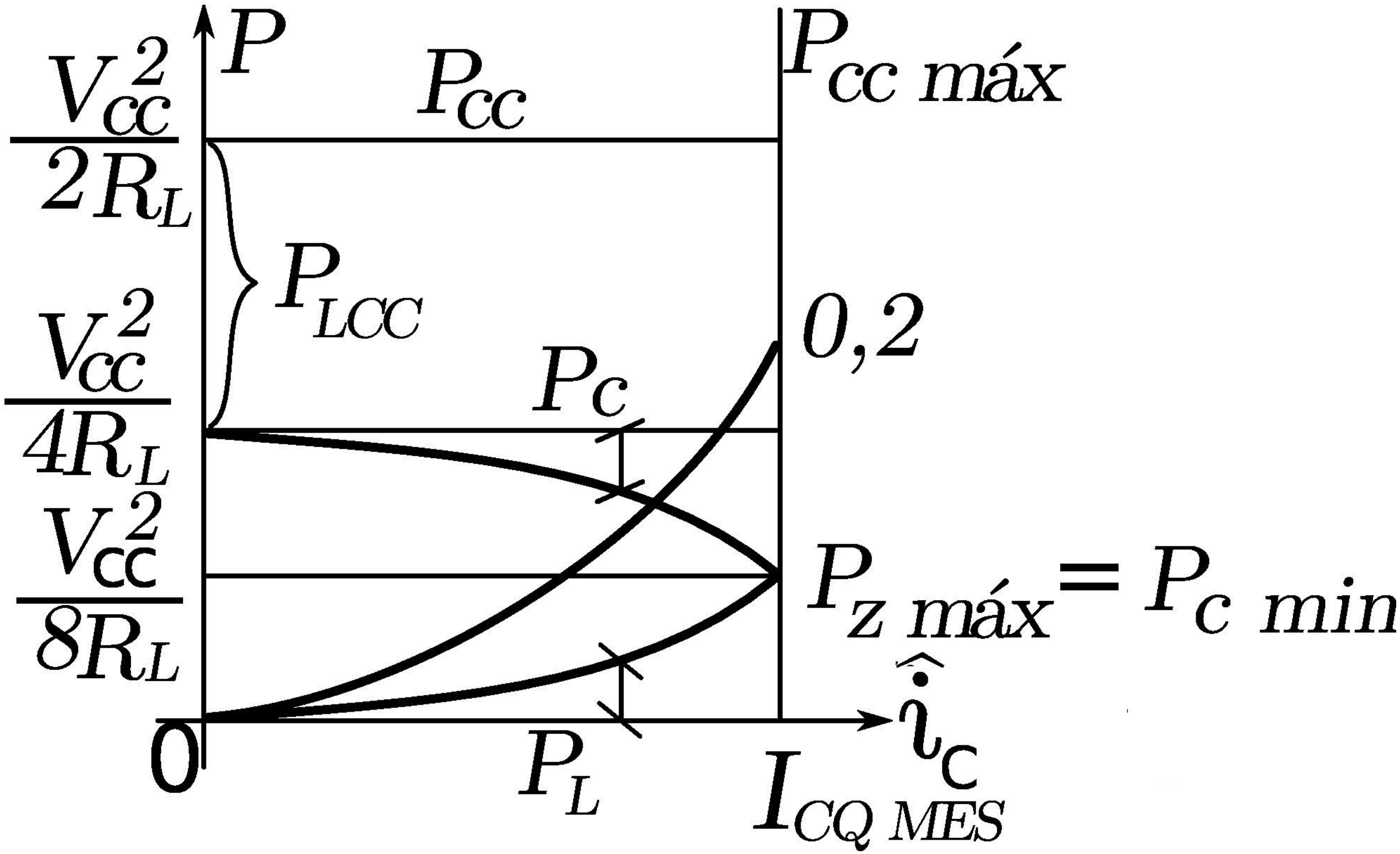
En ausencia de señal :

$$P_{C(\max)} = P_{CC} - (R_L + R_E)I_{CQ}{}^2 \Rightarrow \boxed{P_{C(\max)} = \frac{V_{CC}{}^2}{4(R_L + R_E)} \cong \frac{V_{CC}{}^2}{4R_L}}$$

Con maxima señal :

$$P_{C(\min)} = P_C\Big|_{\hat{i}_c = I_{CQ}} \Rightarrow \boxed{P_{C(\min)} = \frac{V_{CC}{}^2}{8R_L}}$$

Potencia Media disipada en el colector (Cont.)



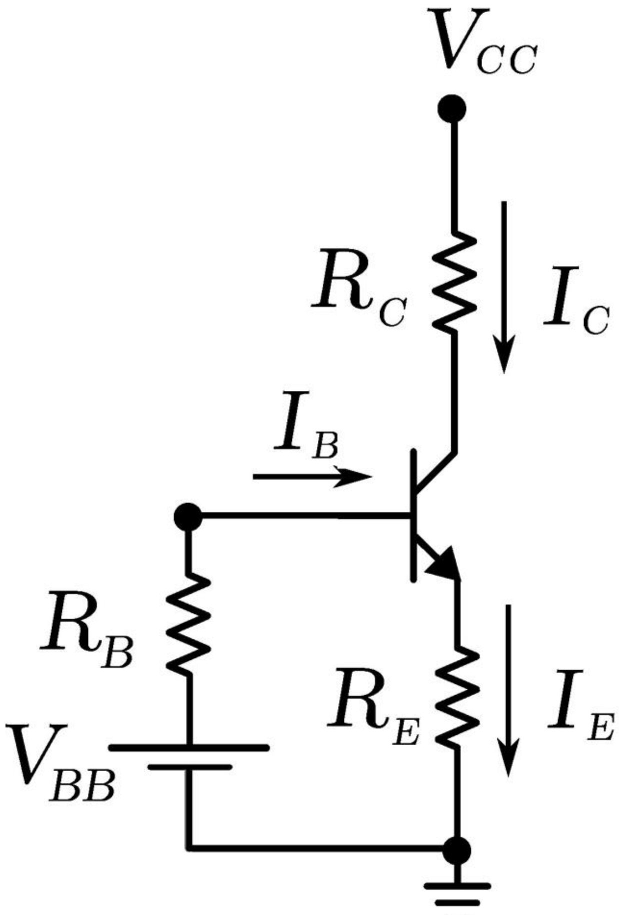
Rendimiento y Factor de Merito

$$\eta = \frac{P_{L(CA)}}{P_{CC}}$$

$$\eta_{(MAX)} = \frac{P_{L(MAX)}}{P_{CC(MAX)}} = \frac{\dfrac{\cancel{V_{CC}}^{2}}{8\cancel{R_L}}}{\dfrac{\cancel{V_{CC}}^{2}}{2\cancel{R_L}}} = \frac{1}{4} \Rightarrow \eta_{(MAX)} = 25\%$$

$$FM = \frac{P_{C(MAX)}}{P_{L(MAX)}} = \frac{V_{CC}^{\ 2} / 4R_L}{V_{CC}^{\ 2} / 8R_L} = 2$$

Estabilidad de la Polarización



$$I_C = \alpha I_E + I_{CBO} \qquad (1)$$

$$I_B = (1-\alpha) I_E - I_{CBO} \qquad (2)$$

$$\beta = \frac{\alpha}{1-\alpha} \qquad \alpha = \frac{\beta}{\beta+1}$$

$$V_{BB} = I_B R_B + V_{BE} + I_E R_E \quad (3)$$

Reemplazamos (2) *en* (3)

$$\begin{aligned} V_{BB} &= \left[(1-\alpha) I_E - I_{CBO}\right] R_B + V_{BE} + I_E R_E \\ &= (1-\alpha) I_E R_B - I_{CBO} R_B + V_{BE} + I_E R_E \\ &= I_E\left[(1-\alpha) R_B + R_E\right] - I_{CBO} R_B + V_{BE} \qquad (4) \end{aligned}$$

Estabilidad de la Polarización (Cont.)

$$De\ (1)$$

$$I_E = \frac{I_C - I_{CBO}}{\alpha} \qquad (5)$$

$$Reemplazamos\ (5)\ en\ (4)\ y\ ordenamos$$

$$V_{BB} - V_{BE} = \left(\frac{I_C - I_{CBO}}{\alpha} \right)\left[(1-\alpha) R_B + R_E \right] - I_{CBO} R_B$$

$$= \left(\frac{I_C}{\alpha} - \frac{I_{CBO}}{\alpha} \right)\left[(1-\alpha) R_B + R_E \right] - I_{CBO} R_B$$

$$= \frac{I_C}{\alpha}\left[(1-\alpha) R_B + R_E \right] - \frac{I_{CBO}}{\alpha}\left[(1-\alpha) R_B + R_E \right] - I_{CBO} R_B$$

$$= \frac{I_C}{\alpha}\left[(1-\alpha) R_B + R_E \right] - \frac{I_{CBO}}{\alpha}\left[(1-\alpha) R_B + R_E + \alpha R_B \right]$$

Estabilidad de la Polarización (Cont.)

$$V_{BB}-V_{BE}=\frac{I_C}{\alpha}\left[(1-\alpha)R_B+R_E\right]-\frac{I_{CBO}}{\alpha}\left[+R_B-\cancel{\alpha}\cancel{R}_B+R_E+\cancel{\alpha}\cancel{R}_B\right]$$

$$=\frac{I_C}{\alpha}\left[(1-\alpha)R_B+R_E\right]-\frac{I_{CBO}}{\alpha}\left[R_E+R_B\right]$$

$$V_{BB}-V_{BE}+\frac{I_{CBO}}{\alpha}\left[R_E+R_B\right]=\frac{I_C}{\alpha}\left[(1-\alpha)R_B+R_E\right]$$

$$\alpha(V_{BB}-V_{BE})+I_{CBO}\left[R_E+R_B\right]=I_C\left[(1-\alpha)R_B+R_E\right]$$

$$I_{CQ}=\frac{\alpha\left[V_{BB}-V_{BE}\right]+I_{CBO}\left[R_E+R_B\right]}{(1-\alpha)R_B+R_E}\quad ecuacion\ general$$

$Si\ \alpha\cong 1$

$$I_{CQ}=\frac{V_{BB}-V_{BE}}{R_E}+I_{CBO}\left(1+\frac{R_B}{R_E}\right)\qquad (6)$$

$Si\ \mathrm{I}_{CBO}\cong 0$

$$I_{CQ}=\frac{V_{BB}-V_{BE}}{R_E}$$

Estabilidad de la Polarización (Cont.)

$$De\ la\ ecuacion\ general\ si\ I_{CBO} \cong 0$$

$$I_{CQ} = \frac{\alpha\left[V_{BB} - V_{BE}\right]}{\left(1-\alpha\right)R_B + R_E}$$

$$I_{CQ} = \frac{V_{BB} - V_{BE}}{\frac{\left(1-\alpha\right)}{\alpha}R_B + \frac{R_E}{\alpha}} = \frac{V_{BB} - V_{BE}}{\frac{R_B}{\beta} + \frac{R_E}{\alpha}}$$

$$I_{CQ} = f(\underbrace{V_{BE}, I_{CBO}, \beta}_{Son\ f(T)}, ...)$$

$$\Delta V_{BE} = V_{BE2} - V_{BE1} = -k\left(T_2 - T_1\right) = -k\Delta T$$

$$donde\ \mathrm{k} = 2{,}5\ {}^{mV}\!/_{^{\circ}C}$$

$$I_{CBO(2)} = I_{CBO(1)} e^{K\Delta T} \qquad donde\ K = 0{,}07\ {}^{1}\!/_{^{\circ}C}$$

$$\Delta I_{CBO} = \Delta I_{CBO(2)} - \Delta I_{CBO(1)} = I_{CBO}(e^{K\Delta T} - 1)$$

Estabilidad de la Polarización (Cont.)

$$\frac{\Delta I_{CQ}}{\Delta T} = \frac{\Delta I_{CQ}}{\Delta V_{BE}} . \frac{\Delta V_{BE}}{\Delta T} + \frac{\Delta I_{CQ}}{\Delta I_{CBO}} . \frac{\Delta I_{CBO}}{\Delta T} + \frac{\Delta I_{CQ}}{\Delta \beta} . \frac{\Delta \beta}{\Delta T}$$

$$\Delta I_{CQ} = \frac{\Delta I_{CQ}}{\Delta V_{BE}} \Delta V_{BE} + \frac{\Delta I_{CQ}}{\Delta I_{CBO}} . \Delta I_{CBO} + \frac{\Delta I_{CQ}}{\Delta \beta} \Delta \beta$$

$Si\ tengo\ \Delta T;\ tengo\ \Delta V_{BE}\ ,\ \Delta I_{CBO}\ y\ \Delta \beta$

$Factores\ de\ estabilidad:$

$$S_V = \frac{\Delta I_{CQ}}{\Delta V_{BE}}$$

$$S_I = \frac{\Delta I_{CQ}}{\Delta I_{CBO}}$$

$$S_\beta = \frac{\Delta I_{CQ}}{\Delta \beta}$$

$Entonces:$

$$\boxed{\Delta I_{CQ} = S_V \Delta V_{BE} + S_I \Delta I_{CBO} + S_\beta \Delta \beta}$$

Estabilidad de la Polarización (Cont.)

$$Partiendo\ de\ (6):\ I_{CQ} = \frac{V_{BB} - V_{BE}}{R_E} + I_{CBO}\left(1 + \frac{R_B}{R_E}\right)$$

$$S_V = \frac{\Delta I_{CQ}}{\Delta V_{BE}} = -\frac{1}{R_E}$$

$$S_I = \frac{\Delta I_{CQ}}{\Delta I_{CBO}} = 1 + \frac{R_B}{R_E}$$

$$\Delta I_{CQ} = -\frac{1}{R_E}\left(-k\Delta T\right) + \left(1 + \frac{R_B}{R_E}\right) I_{CBO}\left(e^{K\Delta T} - 1\right) + \ldots$$

$$= \frac{k\Delta T}{R_E} + \left(1 + \frac{R_B}{R_E}\right) I_{CBO}\left(e^{K\Delta T} - 1\right) + \ldots$$

$$S_\beta = \frac{\Delta I_{CQ}}{\Delta \beta}$$

Estabilidad de la Polarización (Cont.)

$$I_{CQ} = \frac{\alpha\left[V_{BB} - V_{BE}\right]}{\left(1-\alpha\right)R_B + R_E} =$$

$$Como\ \alpha = \frac{\beta}{\beta+1}$$

$$I_{CQ} = \frac{\beta(V_{BB} - V_{BE})}{(\beta+1)(1-\alpha)R_B + (\beta+1)R_E}$$

$$Como\ \alpha = \frac{\beta}{\beta+1} \Rightarrow \beta+1 = \frac{\beta}{\alpha}$$

$$Como\ \beta = \frac{\alpha}{1-\alpha} \Rightarrow 1-\alpha = \frac{\alpha}{\beta}$$

$$Entonces\ \left(\beta+1\right)\left(1-\alpha\right) = \frac{\cancel{\beta}}{\cancel{\alpha}}\frac{\cancel{\alpha}}{\cancel{\beta}} = 1$$

$$I_{CQ} = \frac{\beta(V_{BB} - V_{BE})}{R_B + (\beta+1)R_E}$$

Estabilidad de la Polarización (Cont.)

$$Si\ \beta_1 = inicial\ y\ \beta_2 = final$$

$$I_{CQ1} = \frac{\beta_1 (V_{BB} - V_{BE})}{R_B + (\beta_1 + 1) R_E} \qquad I_{CQ2} = \frac{\beta_2 (V_{BB} - V_{BE})}{R_B + (\beta_2 + 1) R_E}$$

$$\frac{I_{CQ2}}{I_{CQ1}} = \frac{\beta_2 \left[R_B + (\beta_1 + 1) R_E \right]}{\beta_1 \left[R_B + (\beta_2 + 1) R_E \right]}$$

$$\frac{\Delta I_{CQ}}{I_{CQ1}} = \frac{I_{CQ2} - I_{CQ1}}{I_{CQ1}} = \frac{I_{CQ2}}{I_{CQ1}} - 1$$

Estabilidad de la Polarización (Cont.)

$$\frac{\Delta I_{CQ}}{I_{CQ1}} = \frac{\beta_2}{\beta_1}\frac{\left[R_B + (\beta_1 + 1)R_E\right]}{\left[R_B + (\beta_2 + 1)R_E\right]} - 1$$

$$= \frac{\beta_2\left[R_B + (\beta_1 + 1)R_E\right] - \beta_1\left[R_B + (\beta_2 + 1)R_E\right]}{\beta_1\left[R_B + (\beta_2 + 1)R_E\right]}$$

$$= \frac{\beta_2 R_B + \beta_2\beta_1 R_E + \beta_2 R_E - \beta_1 R_B - \beta_1\beta_2 R_E - \beta_1 R_E}{\beta_1\left[R_B + (\beta_2 + 1)R_E\right]}$$

$$= \frac{R_B(\beta_2 - \beta_1) + R_E(\beta_2 - \beta_1)}{\beta_1\left[R_B + (\beta_2 + 1)R_E\right]}$$

$$= \frac{\Delta\beta(R_B + R_E)}{\beta_1\left[R_B + (\beta_2 + 1)R_E\right]} \Rightarrow$$

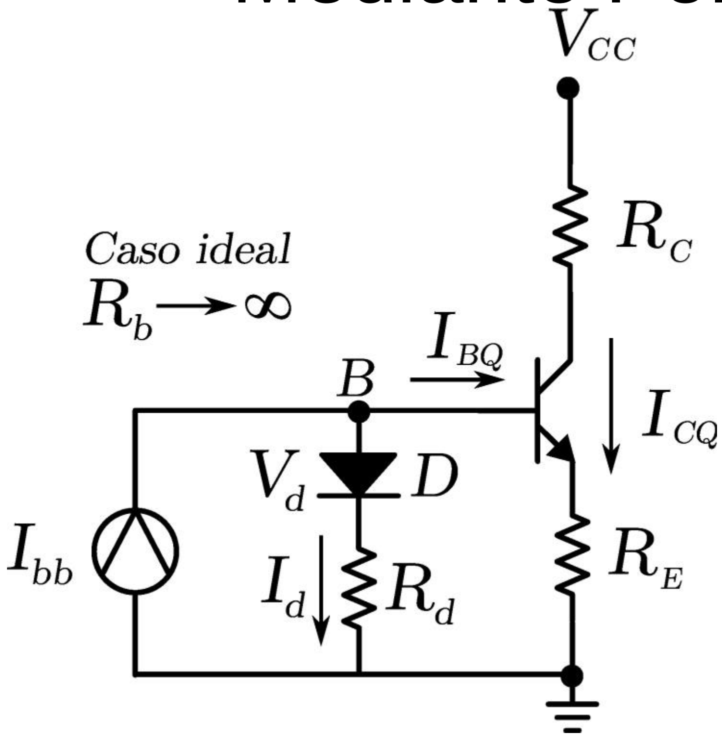
$$S_\beta = \frac{\Delta I_{CQ}}{\Delta\beta} = \frac{I_{CQ1}(R_B + R_E)}{\beta_1\left[R_B + (\beta_2 + 1)R_E\right]}$$

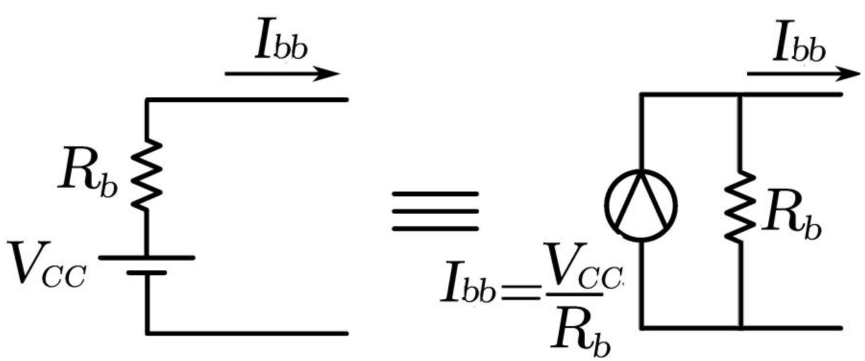
Finalmenete

$$\Delta I_{CQ} = S_V \Delta V_{BE} + S_I \Delta I_{CBO} + S_\beta \Delta\beta + \ldots$$

$$\Delta I_{CQ} = \left(-\frac{1}{R_E}\right)\Delta V_{BE} + \left(1 + \frac{R_B}{R_E}\right)\Delta I_{CBO} + \frac{I_{CQ1}(R_B + R_E)}{\beta_1\left[R_B + (\beta_2 + 1)R_E\right]}\Delta\beta + \ldots$$

Estabilidad Mediante la Compensación ΔT Mediante Polarización por Diodo.





Estabilidad Mediante la Compensación ΔT Mediante Polarización por Diodo.

$$Para\ este\ circuito: \ \frac{\Delta V_D}{\Delta T} = \frac{\Delta V_{BE}}{\Delta T}$$

$$Del\ circuito\ ideal: I_{bb} = I_d + I_{BQ} = I_d + \frac{I_{EQ}}{\beta + 1}$$

$$I_{EQ} = (I_{bb} - I_d)(\beta + 1) \qquad (1)$$

$$V_B = V_d + I_d R_d = V_{BEQ} + I_{EQ} R_E$$

$$I_d = \frac{V_{BEQ} + I_{EQ} R_E - V_d}{R_d} \quad (2)$$

$$reemplazamos\ (2)\ en\ (1)$$

$$I_{EQ} = \left(\frac{I_{bb} R_d}{R_d} + \frac{-V_{BEQ} - I_{EQ} R_E + V_d}{R_d} \right)(\beta + 1)$$

$$I_{EQ} R_d = \left(I_{bb} R_d - V_{BEQ} + V_d \right)(\beta + 1) - I_{EQ} R_E (\beta + 1)$$

$$I_{EQ} \left[\frac{R_d + R_E(\beta + 1)}{(\beta + 1)} \right] = I_{bb} R_d - V_{BEQ} + V_d$$

Estabilidad Mediante la Compensación ΔT Mediante Polarización por Diodo.

$$I_{EQ} = \frac{I_{bb}R_d + V_d - V_{BEQ}}{\frac{R_d}{\beta + 1} + R_e} \cong I_{CQ}$$

$$\frac{\Delta I_{CQ}}{\Delta T} = \frac{\frac{\Delta V_d}{\Delta T} - \frac{\Delta V_{BEQ}}{\Delta T}}{\frac{R_d}{\beta + 1} + R_e} = 0$$

Por lo tanto, la I_{CQ} es insensible a las variaciones de temperatura.

Estabilidad Mediante la Compensación ΔT Mediante Polarización por Diodo o Transistor

$$Ahora\ le\ agregamos\ R_b \neq \infty$$

$$I_{bb} = \frac{V_b}{R_b} + \frac{V_b - V_d}{R_d} + \underbrace{\cancel{I}_{BQ}}_{se\ desprecia}$$

$$Elegimos \begin{cases} R_b \Rightarrow I_{BQ} << V_b / R_b \\ R_d \Rightarrow I_{BQ} << \dfrac{V_b - V_d}{R_d} \end{cases}$$

$$I_{bb} = \frac{V_b}{R_b} + \frac{V_b}{R_d} - \frac{V_d}{R_d} = V_b\left(\frac{1}{R_b} + \frac{1}{R_d}\right) - \frac{V_d}{R_d} = V_b\left(\frac{R_d + R_b}{R_b R_d}\right) - \frac{V_d}{R_d}$$

$$I_{bb} + \frac{V_d}{R_d} = V_b\left(\frac{R_d + R_b}{R_b R_d}\right)$$

$$V_b = \left(I_{bb} + \frac{V_d}{R_d}\right)\left(\frac{R_d R_b}{R_b + R_d}\right) = \frac{\overbrace{I_{bb} R_b\ R_d}^{V_{cc}}}{R_b + R_d} + V_d\ \frac{R_b}{R_b + R_d}$$

$$I_{EQ} = \frac{V_b - V_{BE}}{R_e} = \frac{1}{R_e}\left(\frac{V_{cc} R_d}{R_b + R_d} + V_d\ \frac{R_b}{R_b + R_d} - V_{BE}\right) \cong I_{CQ}$$

Estabilidad Mediante la Compensación ΔT Mediante Polarización por Diodo o Transistor

$$Tenemos\ que:$$

$$\frac{\Delta V_d}{\Delta T} = \frac{\Delta V_{BE}}{\Delta T} = -k$$

$$\frac{\Delta I_{CQ}}{\Delta T} = \frac{1}{R_e}\left(\frac{R_b}{R_d + R_b}\frac{\Delta V_d}{\Delta T} - \frac{\Delta V_{BE}}{\Delta T} \right) = \frac{1}{R_e}\left(k - \frac{R_b}{R_d + R_b}k \right)$$

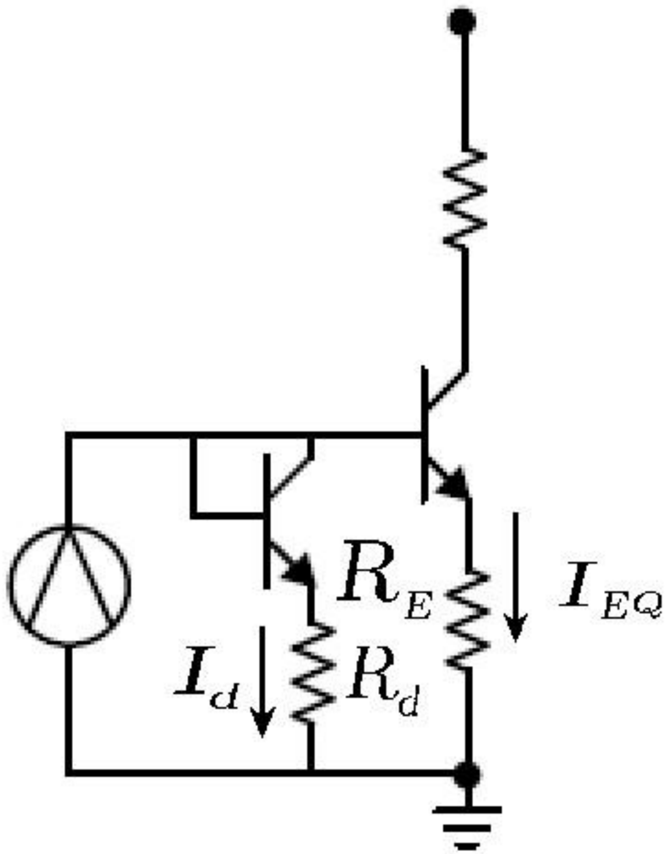
$$= \frac{k}{R_e}\left(\frac{\cancel{R_b} + R_d - \cancel{R_b}}{R_b + R_d} \right)$$

$$\frac{\Delta I_{CQ}}{\Delta T} = \frac{k}{R_e}\left(\frac{1}{1 + \frac{R_b}{R_d}} \right)$$

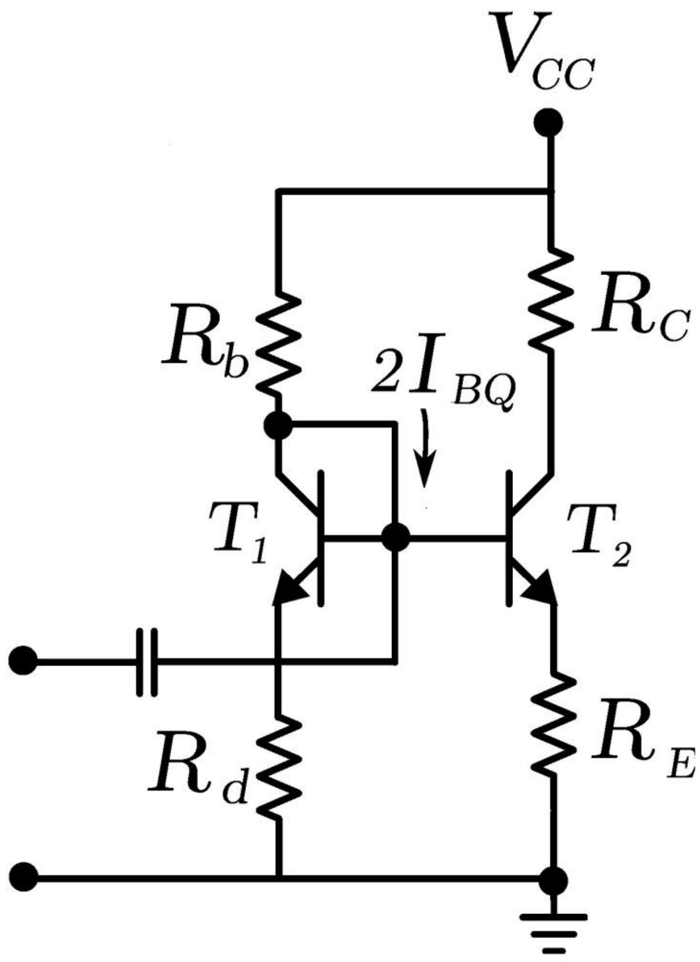
Estabilidad Mediante la Compensación ΔT Mediante Polarización por Diodo o Transistor

Podemos reemplazar el diodo por un transistor.

Se usa en circuitos integrados.



Polarización Balanceada- Polarización por Diodo o Transistor- “Espejo de Corriente”.



Condicion de espejo de corriente:

$$\boxed{R_d = R_E}$$

Iguales transistores, igual β.

Polarización Balanceada- Polarización por Diodo o Transistor- “Espejo de Corriente”.(Cont.)

$$V_{CC} = \left(I_{CQ} + 2\frac{I_{CQ}}{\beta} \right) R_b + V_{BE} + I_{CQ} R_E$$

$$I_{CQ} = \frac{V_{CC} - V_{BE}}{\left(1 + \frac{2}{\beta}\right) R_b + R_E}$$

$$= \frac{V_{CC} - V_{BE}}{\left(\frac{\beta + 2}{\beta}\right) R_b + R_E}$$

Para $\beta >> 2$

$$I_{CQ} = \frac{V_{CC} - V_{BE}}{R_b + R_E}$$

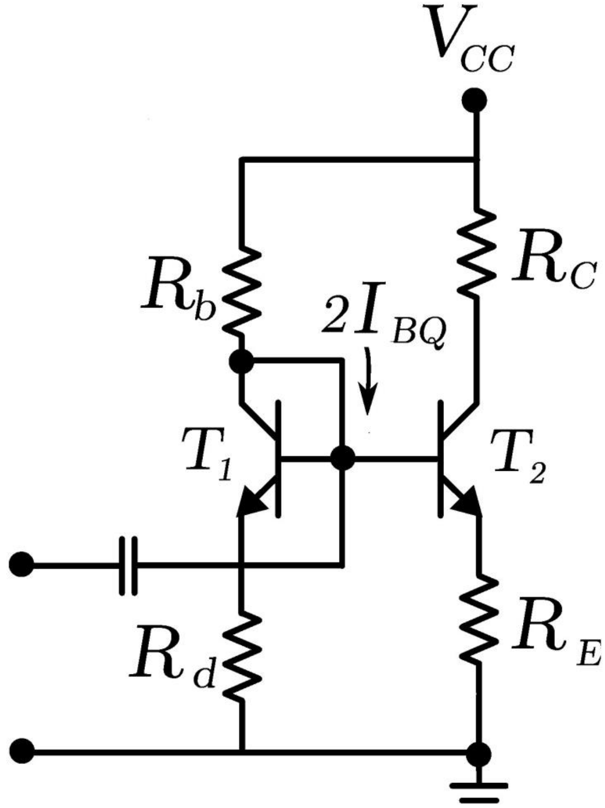
$$\frac{\Delta I_{CQ}}{\Delta T} = \frac{k}{R_b + R_E}$$

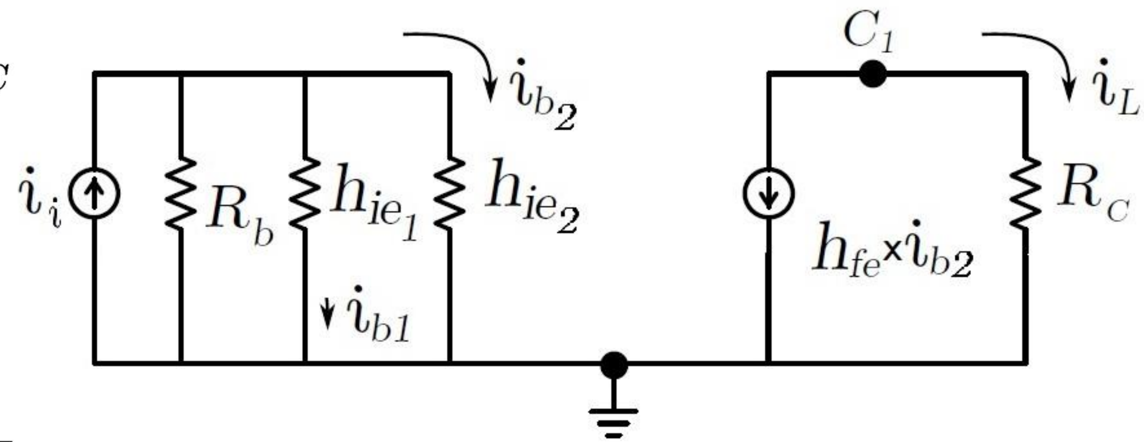
Ahora con $R_d = R_e = 0$ (*es comun para los CI, evita el capacitor de desacople*).

$$I_{CQ} = \frac{V_{CC} - V_{BE}}{R_b} \qquad \frac{\Delta I_{CQ}}{\Delta T} = \frac{k}{R_b}$$

Polarización Balanceada- Polarización por Diodo o Transistor- “Espejo de Corriente”.(Cont.)

$$Para\ alterna\ tenemos:$$





$$R_b >> hie$$

Polarización Balanceada- Polarización por Diodo o Transistor- “Espejo de Corriente”.(Cont.)

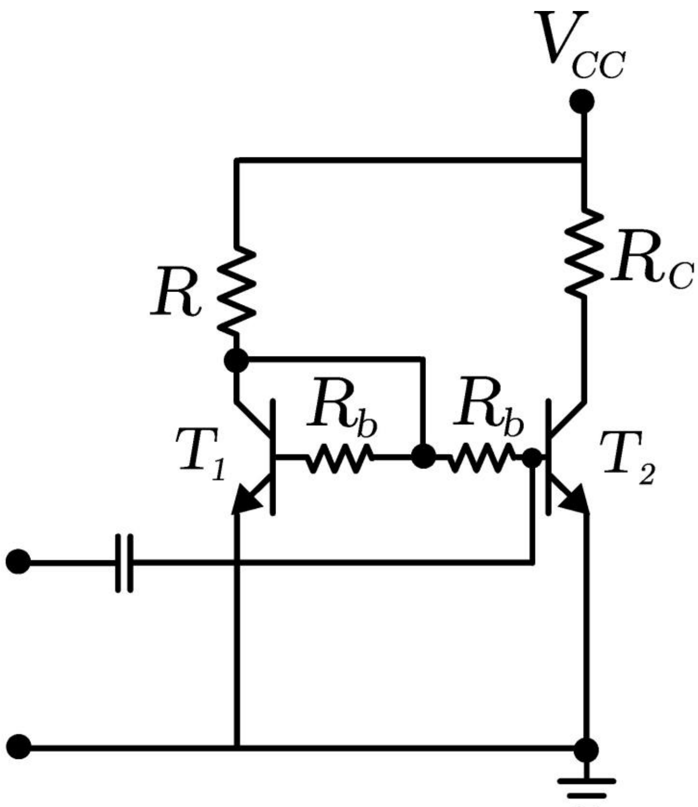
$$i_L = -hfe.i_{b2} \Rightarrow \boxed{\frac{i_L}{i_{b2}} = -hfe}$$

$$i_{b2} = i_i \frac{hie_1 \cancel{hie_2}}{hie_1 + hie_2} \frac{1}{\cancel{hie_2}} \quad Si\ hie_1 = hie_2$$

$$\frac{i_{b2}}{i_i} = \frac{hie}{2hie} \Rightarrow \boxed{\frac{i_{b2}}{i_i} = \frac{1}{2}}$$

$$|A_i| = \frac{i_L}{i_i} = \frac{i_L}{i_{b2}} \frac{i_{b2}}{i_i} = \frac{hfe}{2}$$

Polarización Balanceada- Polarización por Diodo o Transistor- “Espejo de Corriente”.(Cont.)



$$V_{CC} = \left(I_{CQ} + 2\frac{I_{CQ}}{\beta} \right) R + \frac{I_{CQ}}{\beta} R_b + V_{BE}$$

$$V_{CC} - V_{BE} = I_{CQ} R + I_{CQ}\, 2\frac{R}{\beta} + I_{CQ} \frac{R_b}{\beta}$$

$$= I_{CQ} \left(R + R\frac{2}{\beta} + \frac{R_b}{\beta} \right)$$

$$I_{CQ} = \frac{V_{CC} - V_{BE}}{R\left(1 + \frac{2}{\beta}\right) + \frac{R_b}{\beta}} = \frac{V_{CC} - V_{BE}}{\left(\frac{\beta + 2}{\beta}\right) R + \frac{R_b}{\beta}}$$

$si\ \beta >> 2$

$$I_{CQ} = \frac{V_{CC} - V_{BE}}{\frac{R_b}{\beta} + R}$$

Polarización Balanceada- Polarización por Diodo o Transistor- “Espejo de Corriente”.(Cont.)

$$I_{CQ} = \frac{V_{CC} - V_{BE}}{\frac{R_b}{\beta} + R}$$

$$si \quad \frac{R_b}{\beta} << R$$

$$I_{CQ} = \frac{V_{CC} - V_{BE}}{R}$$

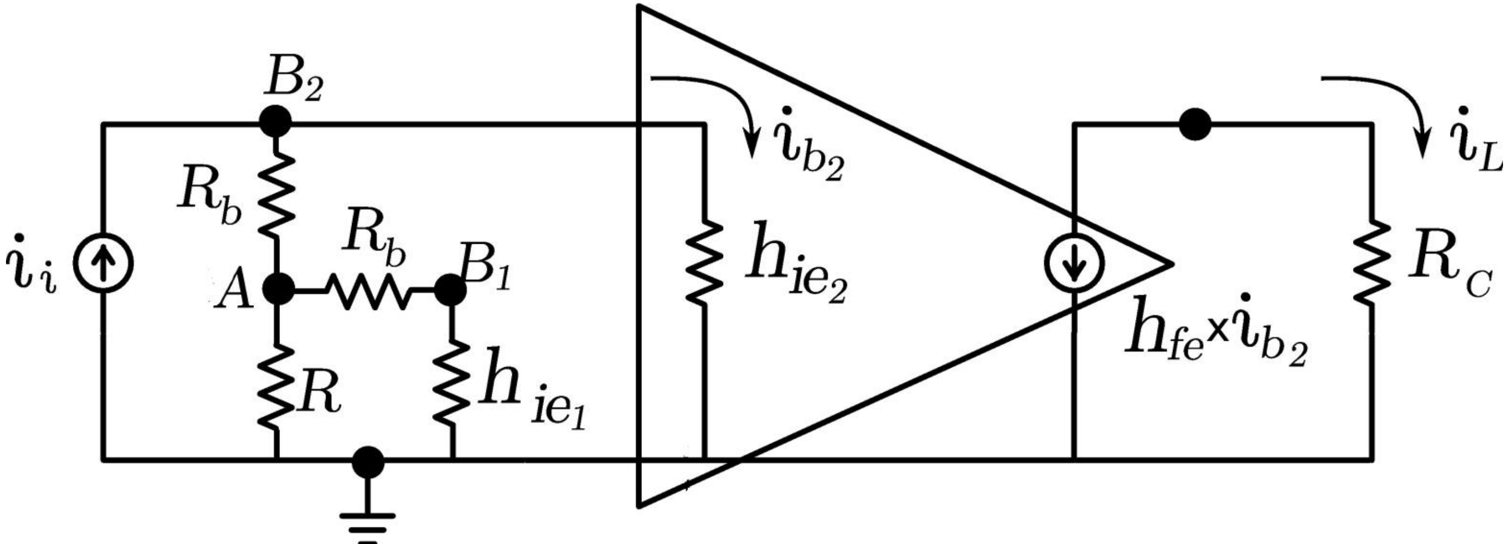
$$\frac{\Delta I_{CQ}}{\Delta T} = -\frac{1}{R}\frac{\Delta V_{BE}}{\Delta T}$$

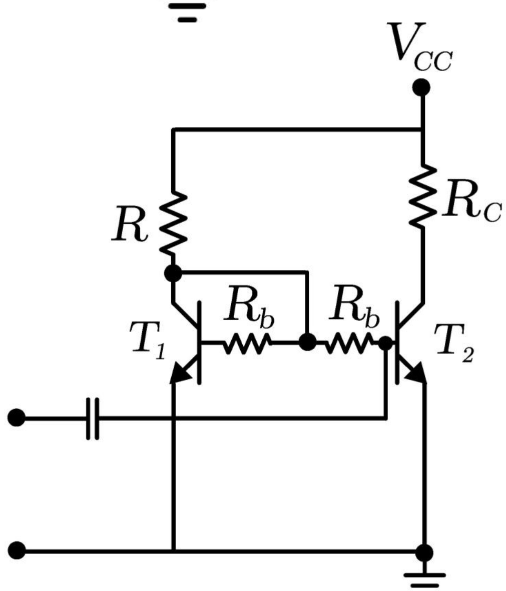
$$Como: \quad \frac{\Delta V_{BE}}{\Delta T} = -k$$

$$\frac{\Delta I_{CQ}}{\Delta T} = -\frac{1}{R} \times (-k) = \frac{k}{R}$$

$$\frac{\Delta I_{CQ}}{\Delta T} = \frac{k}{R}$$

Polarización Balanceada- Polarización por Diodo o Transistor- "Espejo de Corriente".(Cont.)





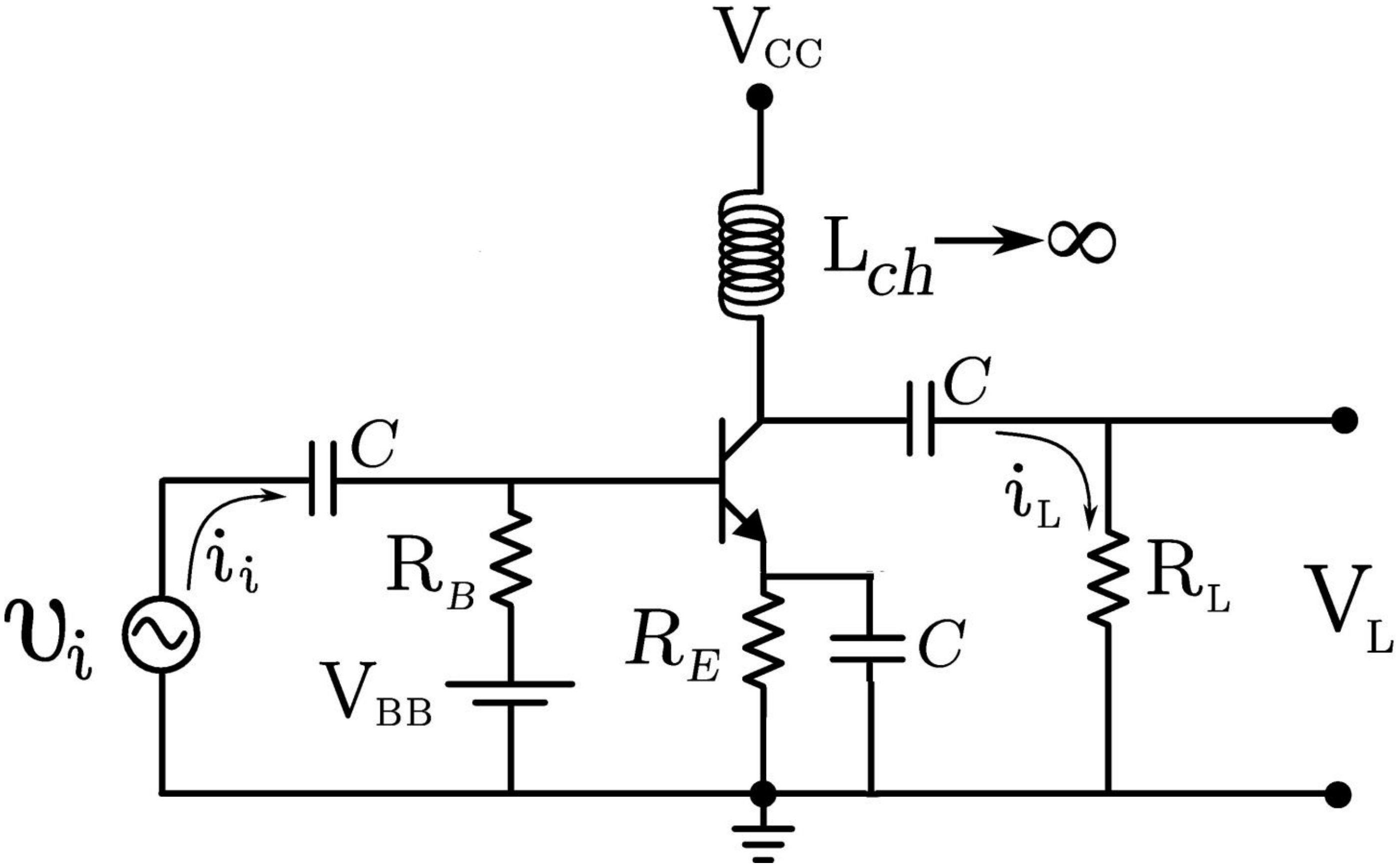
$$Si\ R_b >> hie \Rightarrow i_i \cong i_{b2}$$

$$i_L = -hfe.i_{b2}$$

$$\left|A_i^{`}\right| = \frac{i_L}{i_i} = \frac{hfe.i_{b2}}{i_{b2}} = hfe$$

$$\left|A_i^{`}\right| = 2\left|A_i\right|$$

Amplificador de Potencia Clase A



Amplificador de Potencia Clase A (Cont.)

$$Emisor\ Comun\ con\ acoplamiento\ por\ inductor\ (L-C)$$

$$I_{CQ} = \frac{V_{BB} - V_{BE}}{\frac{R_b}{\beta} + R_E}$$

$$V_{CEQ} = V_{CC} - I_C R_E$$

$$R_{CC} = R_E \qquad\qquad R_{CA} = R_L$$

$$si\ R_E \to 0:\ V_{CEQ} \cong V_{CC} \qquad R_{CC} \cong 0$$

$$I_{CQ_{MES}} = \frac{V_{CC}}{R_{CC} + R_{CA}} = \frac{V_{CC}}{R_L} \cong \frac{V_{CEQ}}{R_L}$$

Amplificador de Potencia Clase A (Cont.)

$$Ecuacion\ de\ la\ recta$$

$$V_{CEQ} = V_{CC} - I_{CQ}R_E$$

$$= V_{CC} - \frac{V_{CC}}{R_L} R_E$$

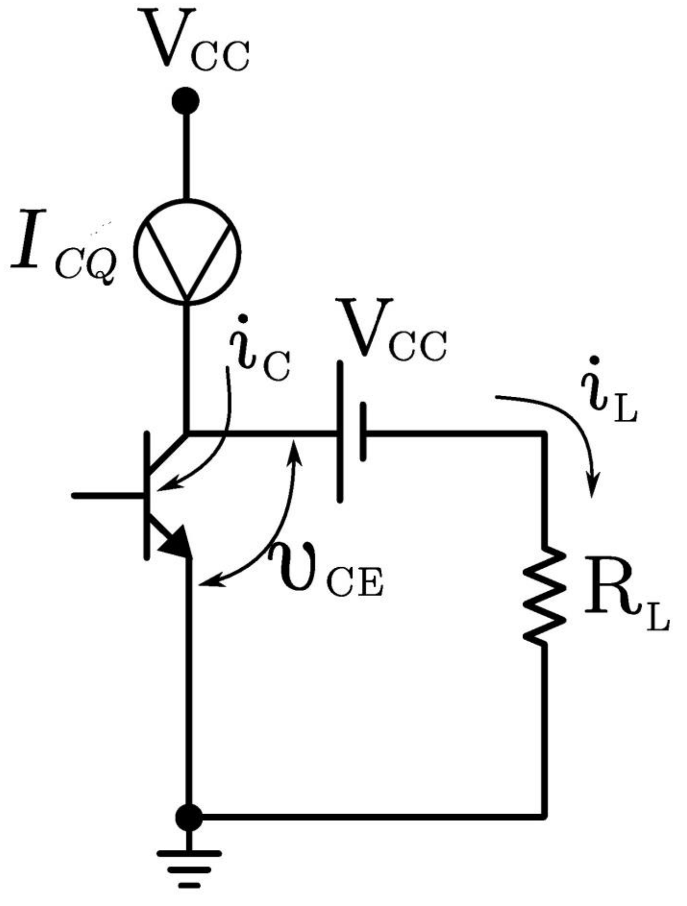
$$= V_{CC}\left(1 - \frac{R_E}{R_L}\right)$$

$$Si\ R_E \cong 0$$

$$V_{CEQ} \cong V_{CC}$$

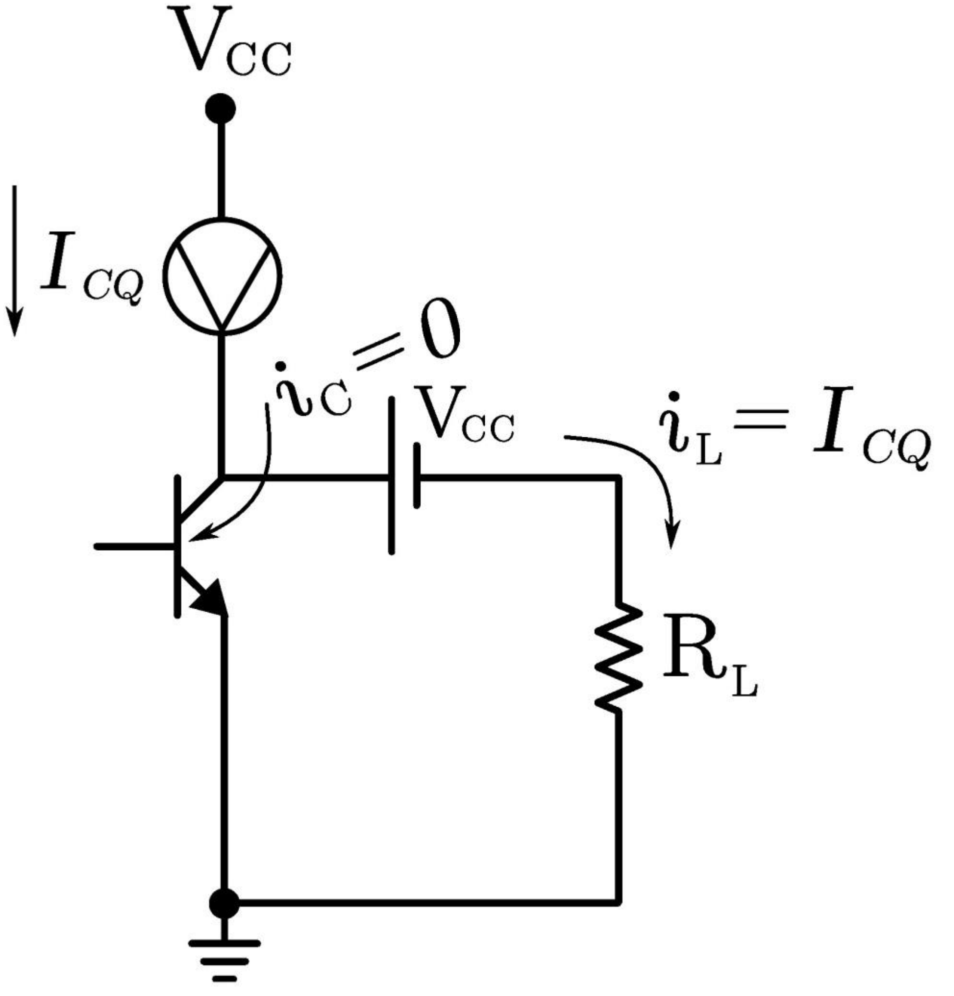
Amplificador de Potencia Clase A (Cont.)

Circuito General



Amplificador de Potencia Clase A (Cont.)

$1^o Caso$



Amplificador de Potencia Clase A (Cont.)

$$v_{CE} = V_{CC} + i_L R_L$$

$$= V_{CC} + I_{CQ} R_L$$

$$= V_{CC} + V_{CC}$$

$$v_{CE} = 2V_{CC}$$

$$Cuando\ i_C = I_{CQ} + i_c = 0$$

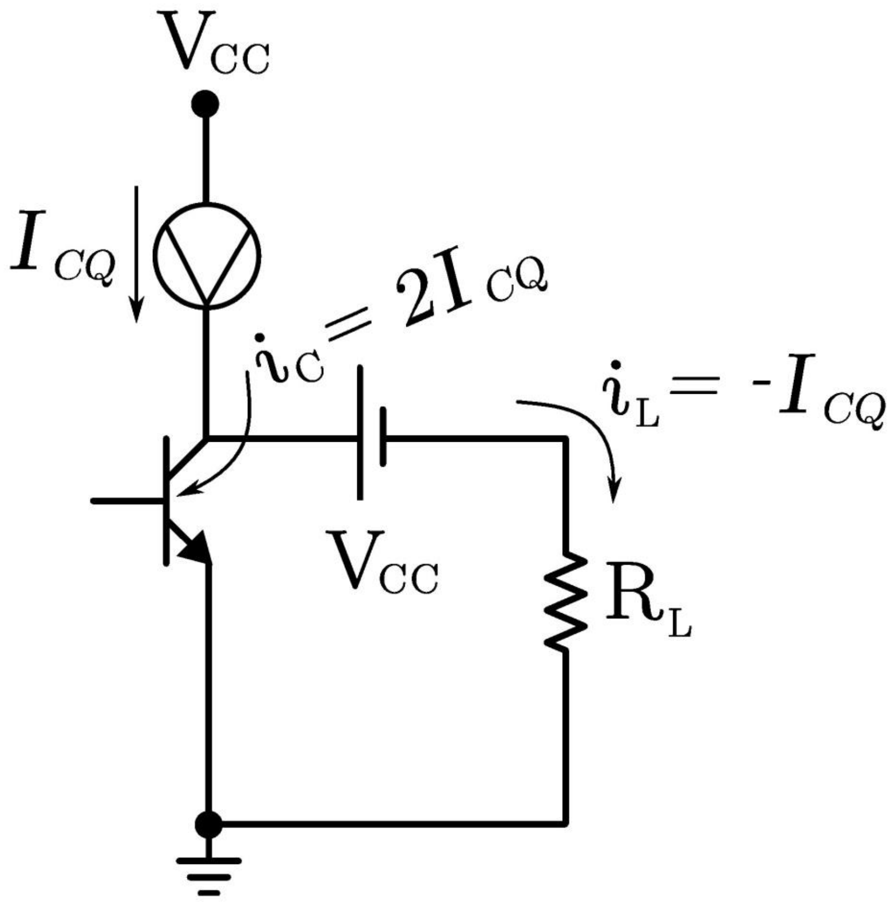
$$el\ T_R\ soporta\ 2V_{CC}$$

$$hay\ que\ tener\ esto\ en\ cuenta\ a\ la\ hora\ de\ elegir\ el\ T_R.$$

$$2V_{CC} \leq BV_{CEO}$$

Amplificador de Potencia Clase A (Cont.)

$2^o\,Caso$



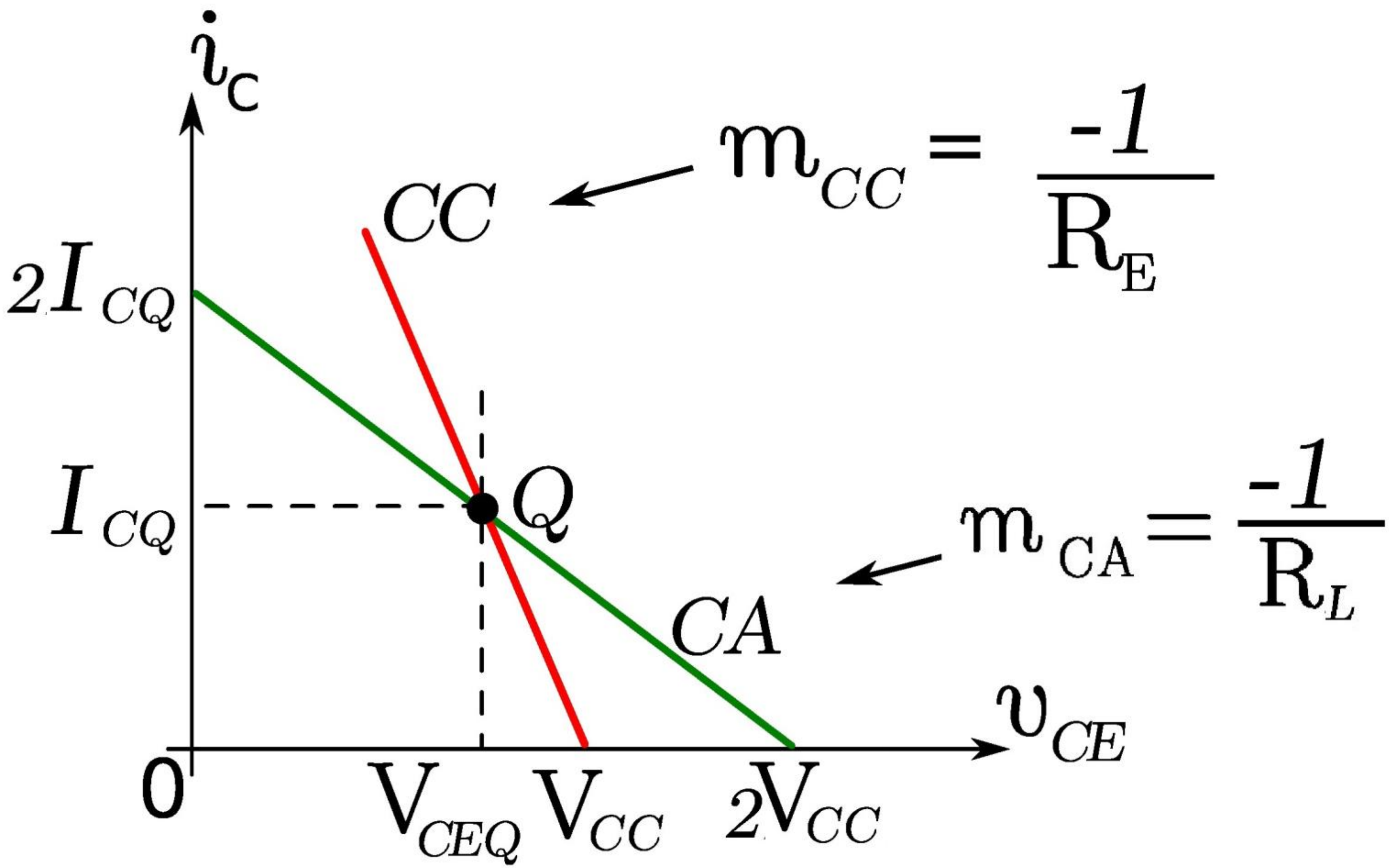
Amplificador de Potencia Clase A (Cont.)

$$v_{CE} = V_{CC} + i_L R_L$$

$$= V_{CC} - I_{CQ} R_L = V_{CC} - V_{CC}$$

$$v_{CE} = 0$$

Amplificador de Potencia Clase A (Cont.)



Análisis de Potencia

$$R_E \to 0 \quad o \quad R_E << R_L$$

$$Sin\ choque:$$

$$P_{CC(\max)} = \frac{V_{CC}{}^2}{2R_L} \qquad P_{L(\max)} = \frac{V_{CC}{}^2}{8R_L}$$

$$P_{C(\max)} = \frac{V_{CC}{}^2}{4R_L} \qquad \eta = \frac{1}{4} \qquad FM = 2$$

$$Con\ choque:$$

$$P_{CC(\max)} = V_{CC} I_{CQ} = V_{CC} \frac{V_{CC}}{R_L} = \frac{V_{CC}{}^2}{R_L}$$

$$P_L = i_L{}^2 R_L = i_c{}^2 R_L \qquad i_L = i_c$$

$$= \left(\frac{\hat{i}_c}{\sqrt{2}} \right)^2 R_L = \frac{\hat{i}_c{}^2}{2} R_L$$

Análisis de Potencia (Cont.)

$$P_{L(\max)} = \frac{1}{2} I_{CQ}{}^{2} R_L = \frac{1}{2} \frac{V_{CC}}{R_L \cancel{2}}^{2} \cancel{R}_L = \frac{V_{CC}{}^{2}}{2R_L}$$

$$P_{C(\max)} = P_{CC} - P_L = P_{CC(\max)} - 0 = \frac{V_{CC}{}^{2}}{R_L}$$

$$P_{C(\min)} = P_{CC(\max)} - P_{L(\max)} = \frac{V_{CC}{}^{2}}{R_L} - \frac{V_{CC}{}^{2}}{2R_L} = \frac{V_{CC}{}^{2}}{2R_L}$$

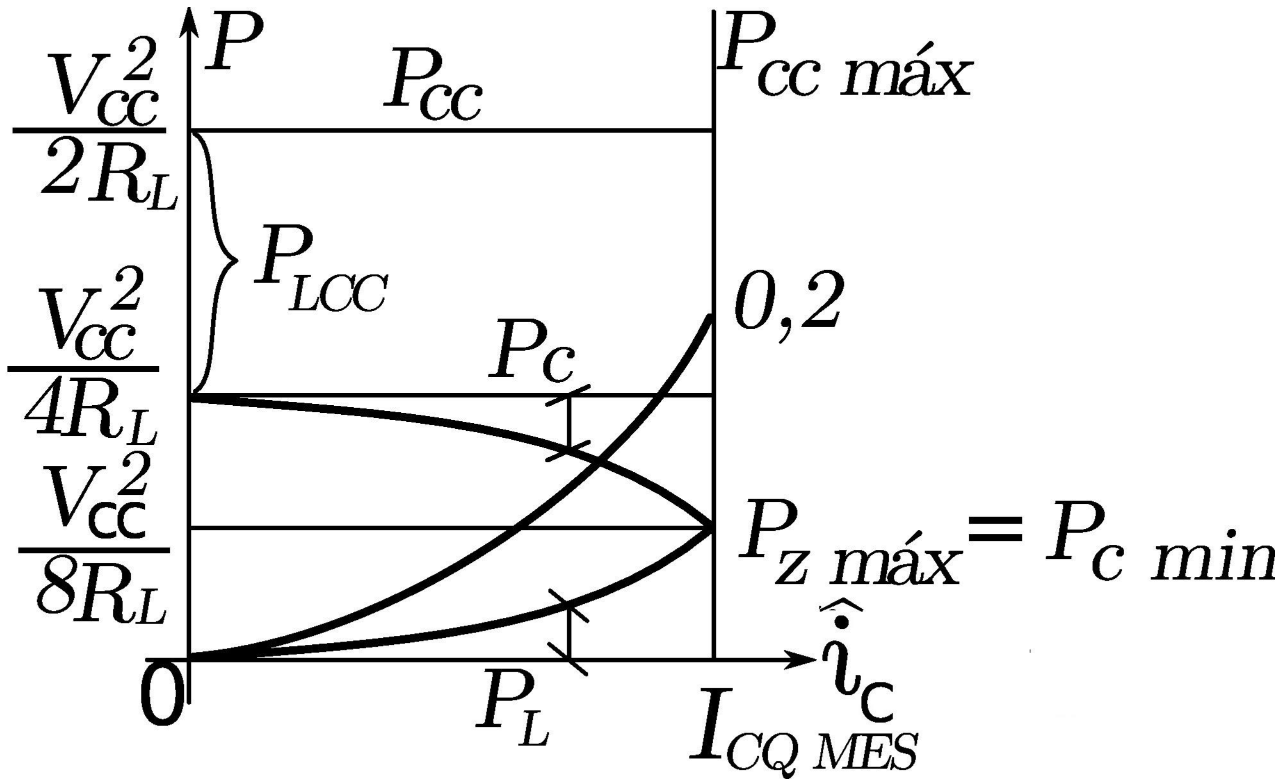
Análisis de Potencia (Cont.)

$$\eta_{(\max)} = \frac{P_{L\max}}{P_{CC\max}} = \frac{\dfrac{V_{CC}{}^2}{2R_L}}{\dfrac{V_{CC}{}^2}{R_L}} = \frac{1}{2} = 50\%$$

$$FM = \frac{P_{C\max}}{P_{L\max}} = \frac{\dfrac{V_{CC}{}^2}{R_L}}{\dfrac{V_{CC}{}^2}{2R_L}} = 2$$

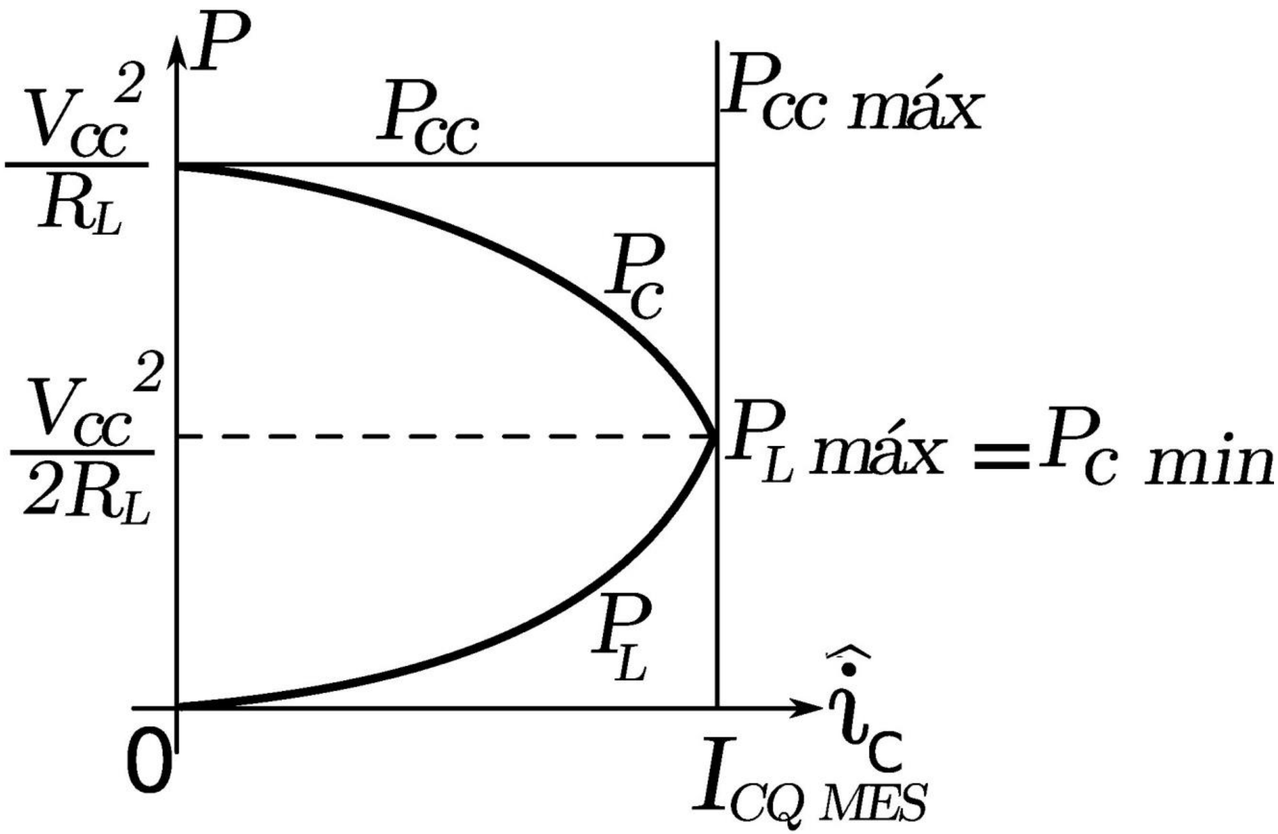
Análisis de Potencia (Cont.)

$Sin\ choque:$

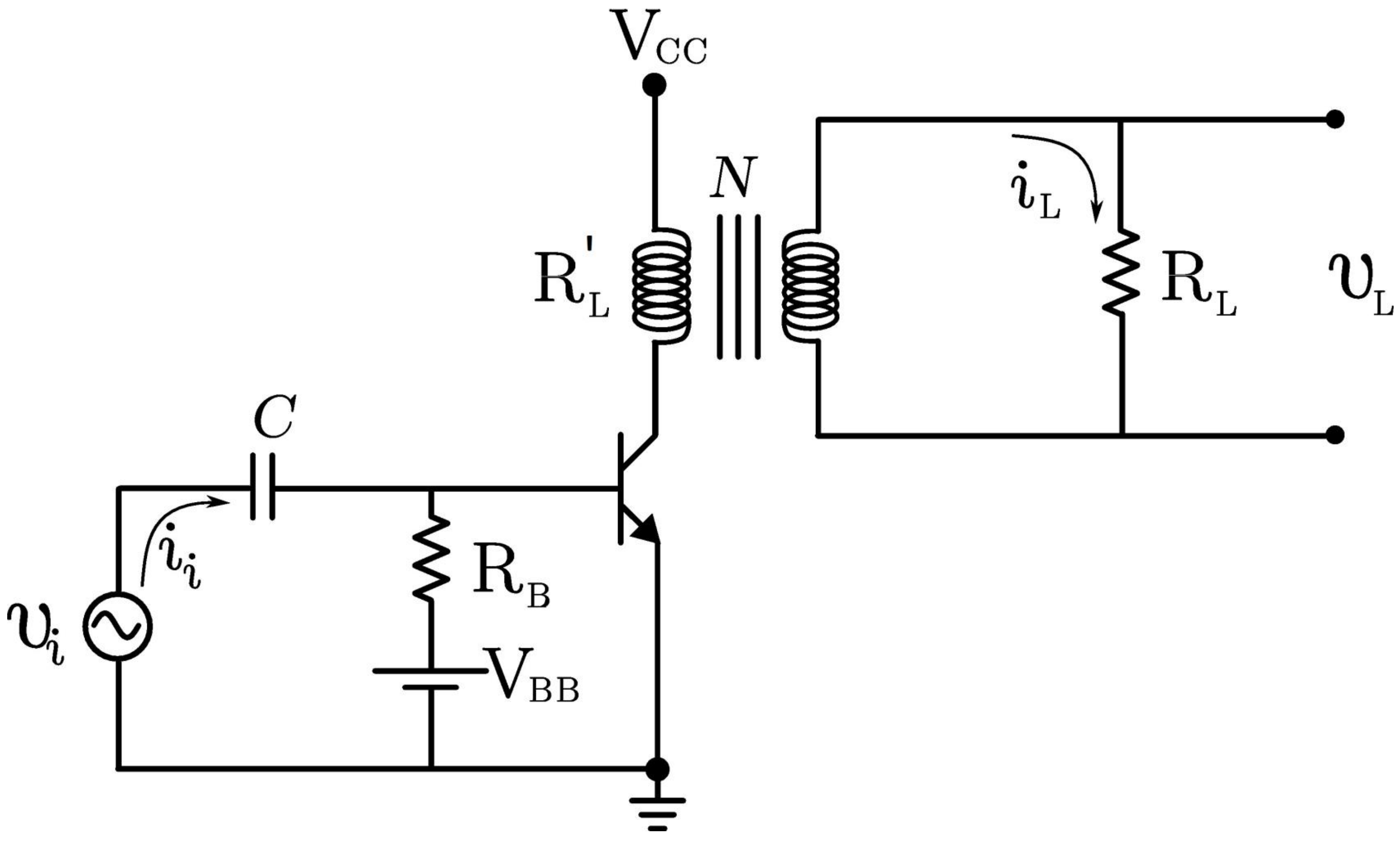


Análisis de Potencia (Cont.)

$Con\ choque:$



Amplificador de Potencia Clase A, con acoplamiento por transformador.



Amplificador de Potencia Clase A, con acoplamiento por transformador (Cont.).

$$R_{CC} = 0 \qquad R_{CA} = R_L^{'}$$

$$N = \frac{N_P}{N_S} = \frac{v_P}{v_S} = \frac{i_S}{i_P} = \sqrt{\frac{Z_P}{Z_S}} \Bigg\} \textit{Propias del transformador.}$$

$$Z_S = R_L \qquad Z_P = R_L^{'}$$

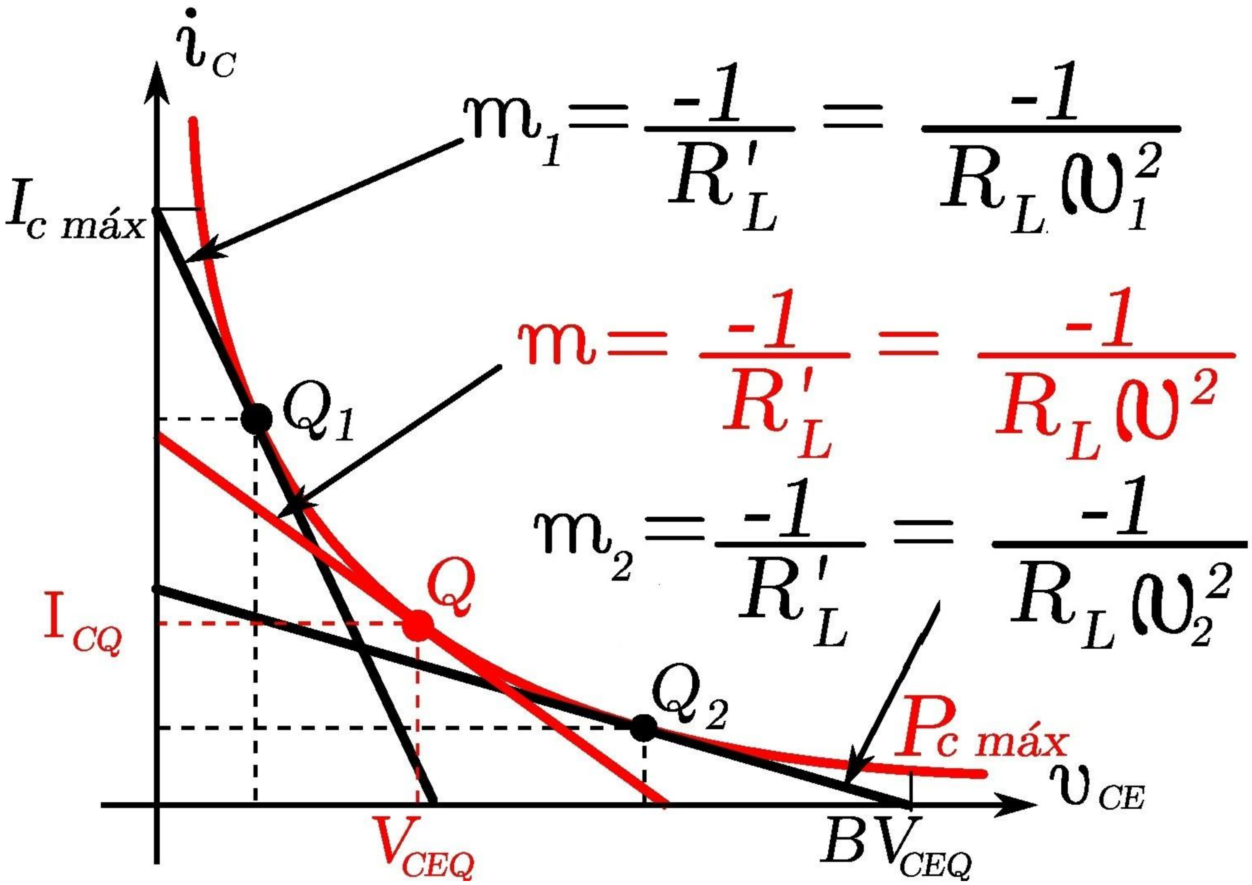
$$N = \sqrt{\frac{R_L^{'}}{R_L}}$$

$$R_L^{'} = N^2 R_L$$

$$I_{CQ} = \frac{V_{CC}}{R_L^{'}} = \frac{V_{CC}}{N^2 R_L} (\textit{vemos que } I_{CQ} = f_{(N)})$$

$$N_{\min} < N < N_{\max}$$

Amplificador de Potencia Clase A, con acoplamiento por transformador (Cont.).



$$N_1 = N_{\min}$$
$$N_2 = N_{\max}$$
$$\left.\begin{matrix} N_1 = N_{\min} \\ N_2 = N_{\max} \end{matrix}\right\} N = \frac{N_{\min} + N_{\max}}{2}$$

Datos:

R_L

$P_{L\max} \rightarrow P_{C\max}$

$$FM = \frac{P_{C\max}}{P_{L\max}}$$

$$P_{C\max} = FM . P_{L\max}$$

Para este circuito

$$FM = 2$$

$$P_{C\max} = 2 P_{L\max}$$

Amplificador de Potencia Clase A, con acoplamiento por transformador (Cont.).

$$2I_{CQ} \leq i_{c(\max)} \qquad 2V_{CEQ} = 2V_{CC} \leq BV_{CEO}$$

$$Clase\ A \begin{cases} Sin\ choque: V_{CC} \leq BV_{CEO} \\ Con\ choque\ o\ trafo: 2V_{CC} \leq BV_{CEO} \end{cases}$$

$$P_C = v_{CE} i_C \qquad i_C = I_{CQ} + \mathrm{i_c}$$

$$P_{C(\max)}\ se\ da\ cuando\ no\ hay\ se\tilde{n}al:\ i_c = 0$$

$$P_{C(\max)} = v_{CEQ} I_{CQ} \qquad \Rightarrow I_{CQ} = \frac{P_{C(\max)}}{v_{CEQ}}$$

$$I_{CQ} = \frac{P_{C(\max)}}{I_{CQ} R_L^{'}} = \frac{P_{C(\max)}}{I_{CQ} N^2 R_L}$$

Amplificador de Potencia Clase A, con acoplamiento por transformador (Cont.).

$$I_{CQ}{}^{2} = \frac{P_{C(\max)}}{N^{2}R_{L}}$$

$$I_{CQ} = \frac{1}{N}\sqrt{\frac{P_{C(\max)}}{R_{L}}} = \frac{1}{N}\sqrt{\frac{2P_{L(\max)}}{R_{L}}} \qquad (1)$$

$$V_{CEQ} = I_{CQ}R_{L}{}' = \frac{1}{\cancel{N}}\sqrt{\frac{2P_{L(\max)}}{R_{L}}}N^{\cancel{2}}R_{L}$$

$$= N\sqrt{\frac{2P_{L(\max)}R_{L}{}^{\cancel{2}}}{\cancel{R_{L}}}}$$

$$V_{CEQ} = N\sqrt{2P_{L(\max)}R_{L}} \qquad (2)$$

Amplificador de Potencia Clase A, con acoplamiento por transformador (Cont.).

$$I_{CQ1} = \frac{1}{N_1}\sqrt{\frac{2P_{L(\max)}}{R_L}}$$

$$N_1 = N_{\min}$$

$$N_{\min} = \frac{1}{I_{CQ1}}\sqrt{\frac{2P_{L(\max)}}{R_L}}$$

$$I_{CQ1} = \frac{i_{C(\max)}}{2}$$

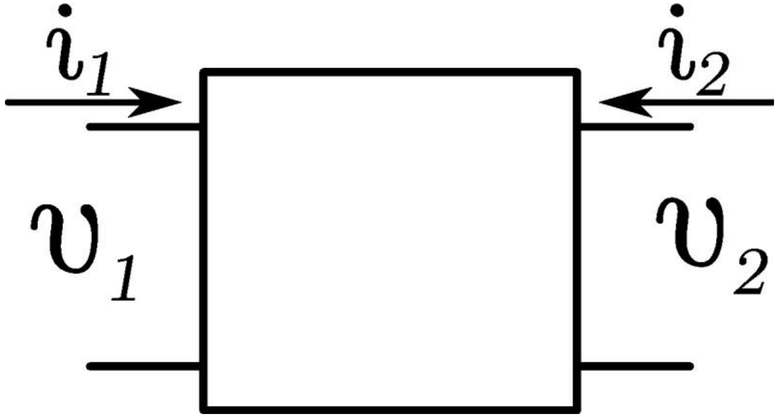
$$N_{\max} = N_2 = \frac{V_{CEQ2}}{\sqrt{2P_{L(\max)}R_L}}$$

$$V_{CEQ2} = \frac{BV_{CEO}}{2}$$

$$N = \frac{N_{\min} + N_{\max}}{2}$$

Parámetros Híbridos

Se parte de la teoria del cuadripolo o redes de dos pares de terminales:



En general:

$$v_1 = h_{11} i_1 + h_{12} v_2$$

$$i_2 = h_{21} i_1 + h_{22} v_2$$

Para transistores:

$$v_1 = h_i i_1 + h_r v_2$$

$$i_2 = h_f i_1 + h_o v_2$$

Parámetros Híbridos (Cont.)

$$i : entrada \qquad r : reverso$$

$$f : directa \qquad o : salida$$

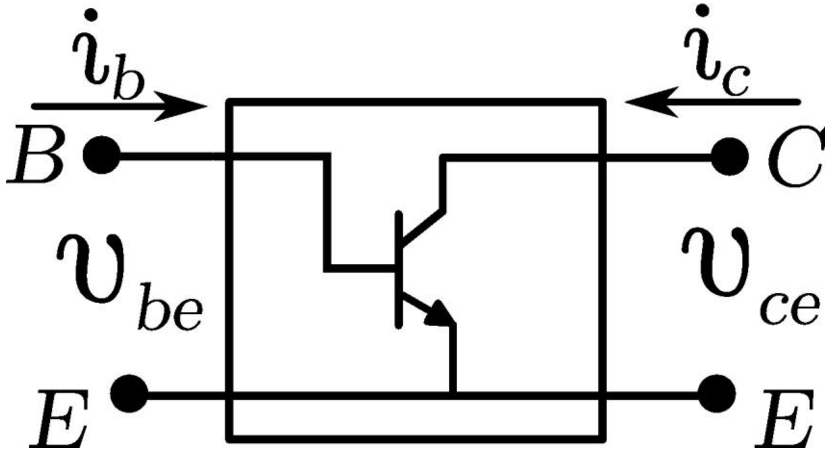
$$h_i : impedancia\ de\ entrada.$$

$$h_r : ganancia\ inversa\ de\ voltaje.$$

$$h_f : ganancia\ directa\ de\ corriente.$$

$$h_o : admitancia\ de\ salida.$$

Parámetros Híbridos. Configuración Emisor Común.



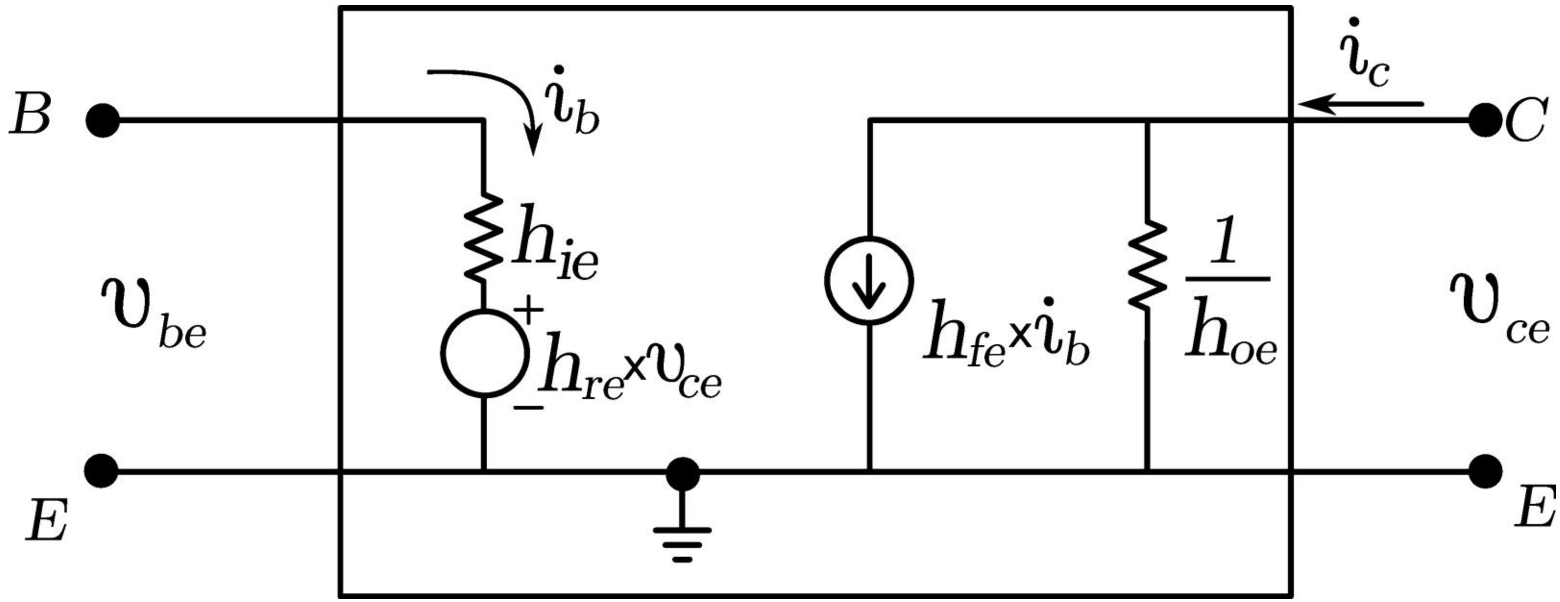
$$i_1 = i_b$$

$$i_2 = i_c \qquad \textit{Ley de Kirchoff de voltaje}: \quad v_{be} = h_{ie} i_b + h_{re} v_{ce}$$

$$v_1 = v_{be} \qquad \textit{Ley de Kirchoff de corriente}: \; i_c = h_{fe} i_b + h_{oe} v_{ce}$$

$$v_2 = v_{ce}$$

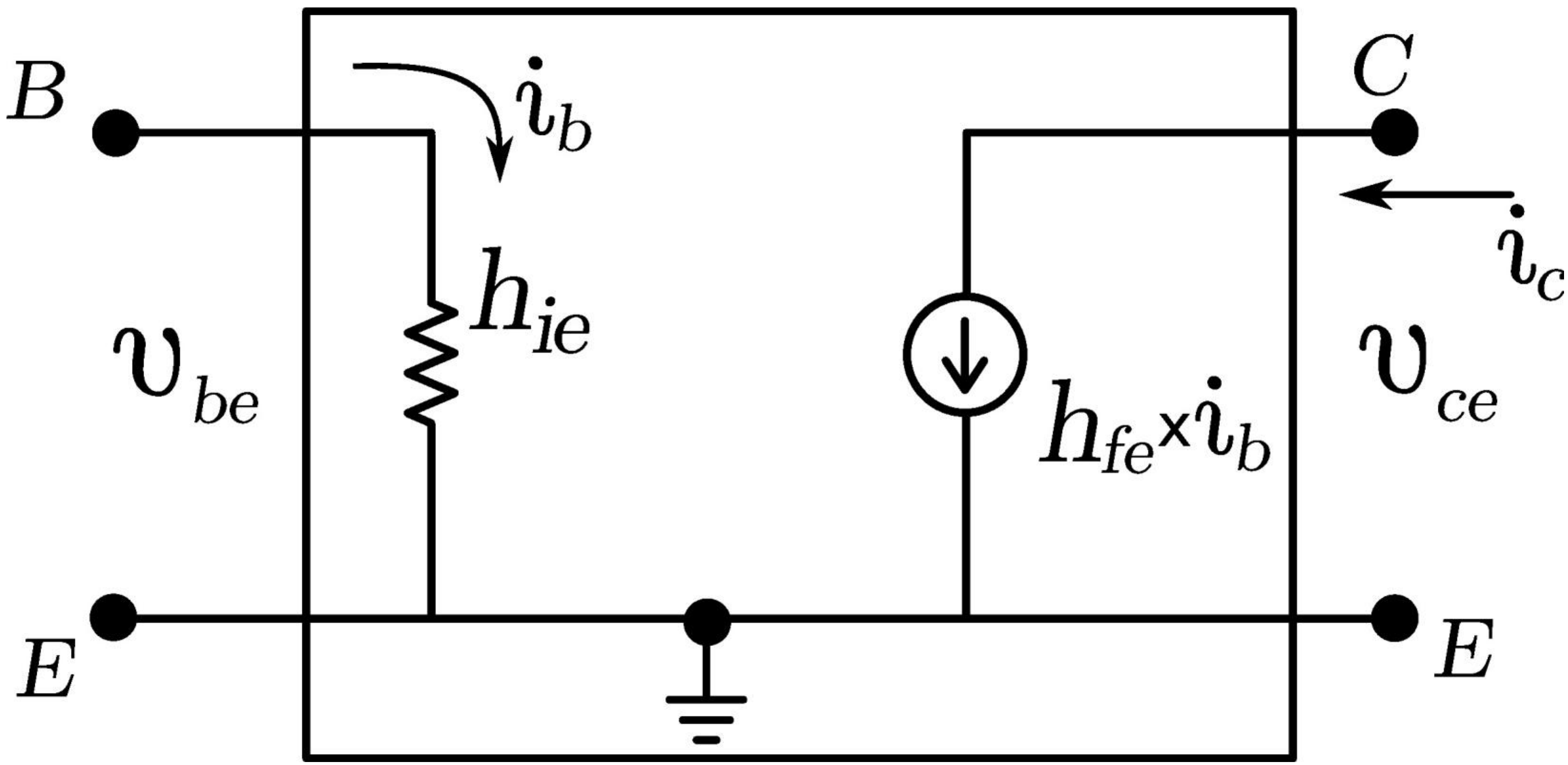
Parámetros Híbridos Modelo Completo



$$h_{oe} \rightarrow 10^{-4} S \ a \ 10^{-6} S$$

$$\frac{1}{h_{oe}} \rightarrow 10^{4} \Omega \ a \ 10^{6} \Omega \rightarrow circuito\ abierto$$

Parámetros Híbridos-Modelo Simplificado



Parámetros Híbridos (Cont.)

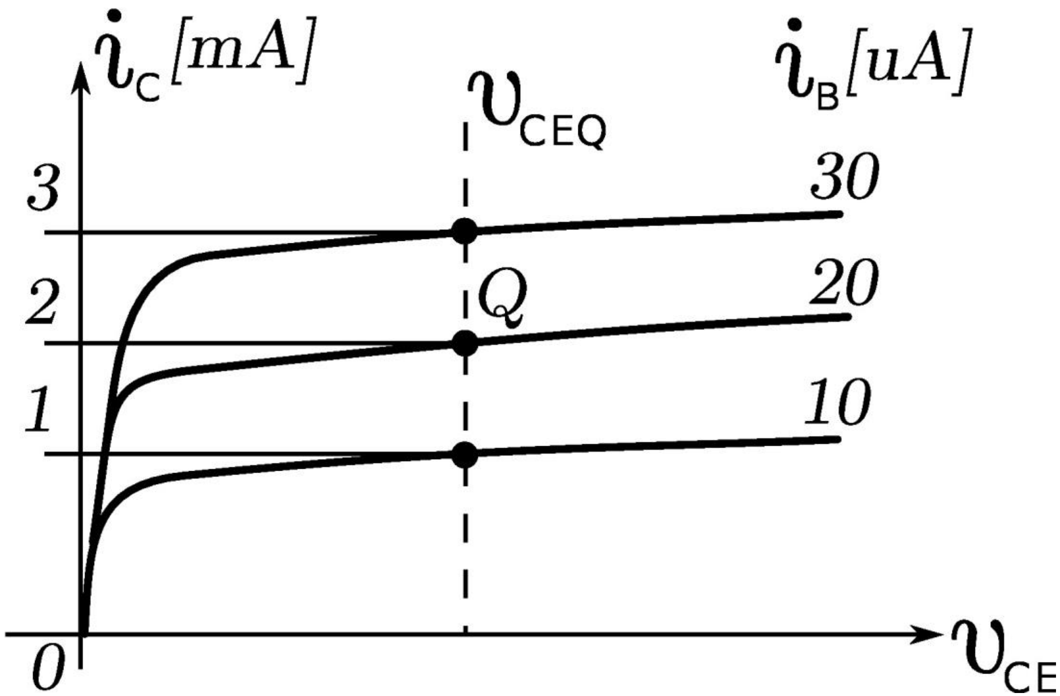
$$h_{ie} = \left.\frac{v_{be}}{i_b}\right|_{\substack{v_{ce}=0 \\ V_{CEQ}=cte}} \begin{cases} \text{impedancia de entrada del TR en E.C} \\ \text{con la salida en cortocircuito.} \end{cases}$$

$$h_{re} = \left.\frac{v_{be}}{v_{ce}}\right|_{\substack{i_b=0 \\ I_{BQ}=cte}} \begin{cases} \text{ganancia inversa de Voltaje con la} \\ \text{entrada abierta en E.C.} \end{cases}$$

$$h_{fe} = \left.\frac{i_c}{i_b}\right|_{\substack{v_{ce}=0 \\ V_{CEQ}=cte}} \begin{cases} \text{ganancia de corriente en E.C con la} \\ \text{salida en cortocircuito para C.A.} \end{cases}$$

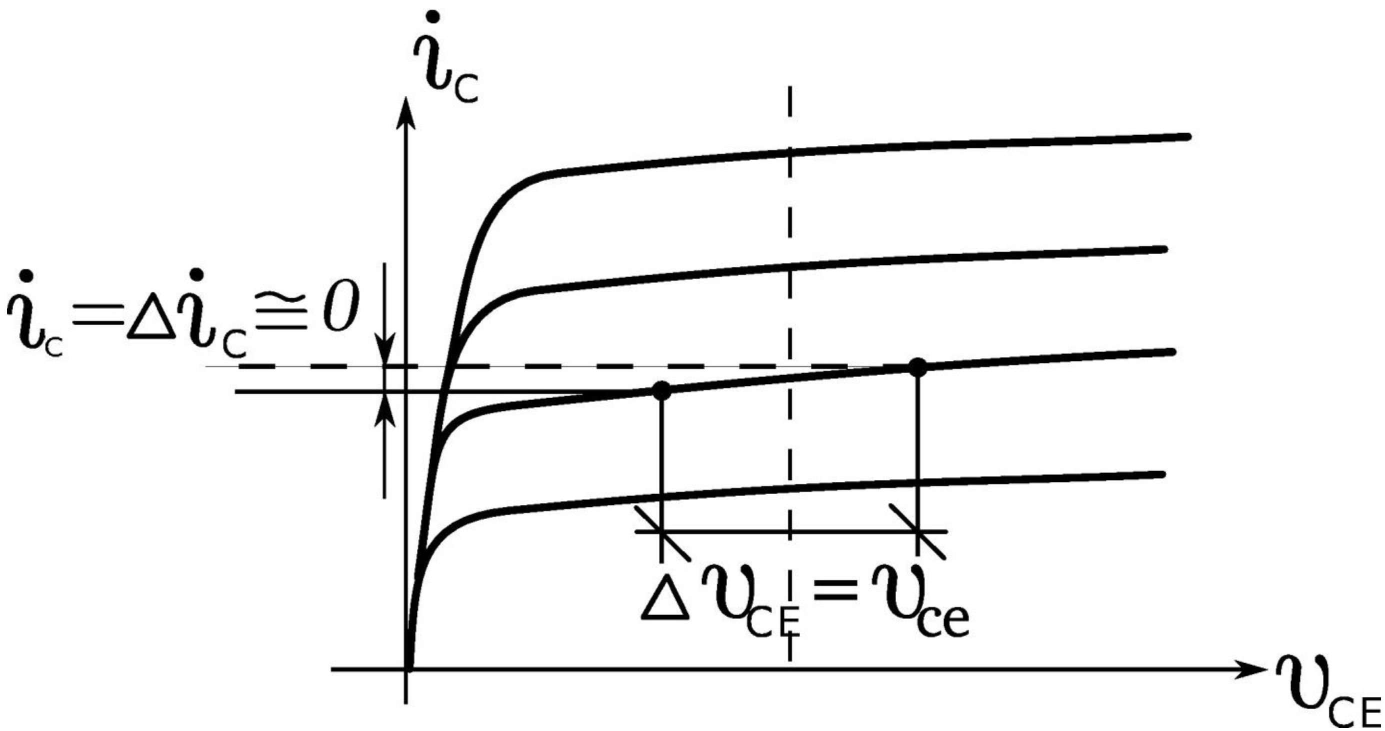
$$h_{oe} = \left.\frac{i_c}{v_{ce}}\right|_{\substack{i_b=0 \\ I_{BQ}=cte}} \begin{cases} \text{admitancia de salida en E.C con la} \\ \text{entrada abierta.} \end{cases}$$

Parámetros Híbridos. Valor de hfe a partir de las características i-v



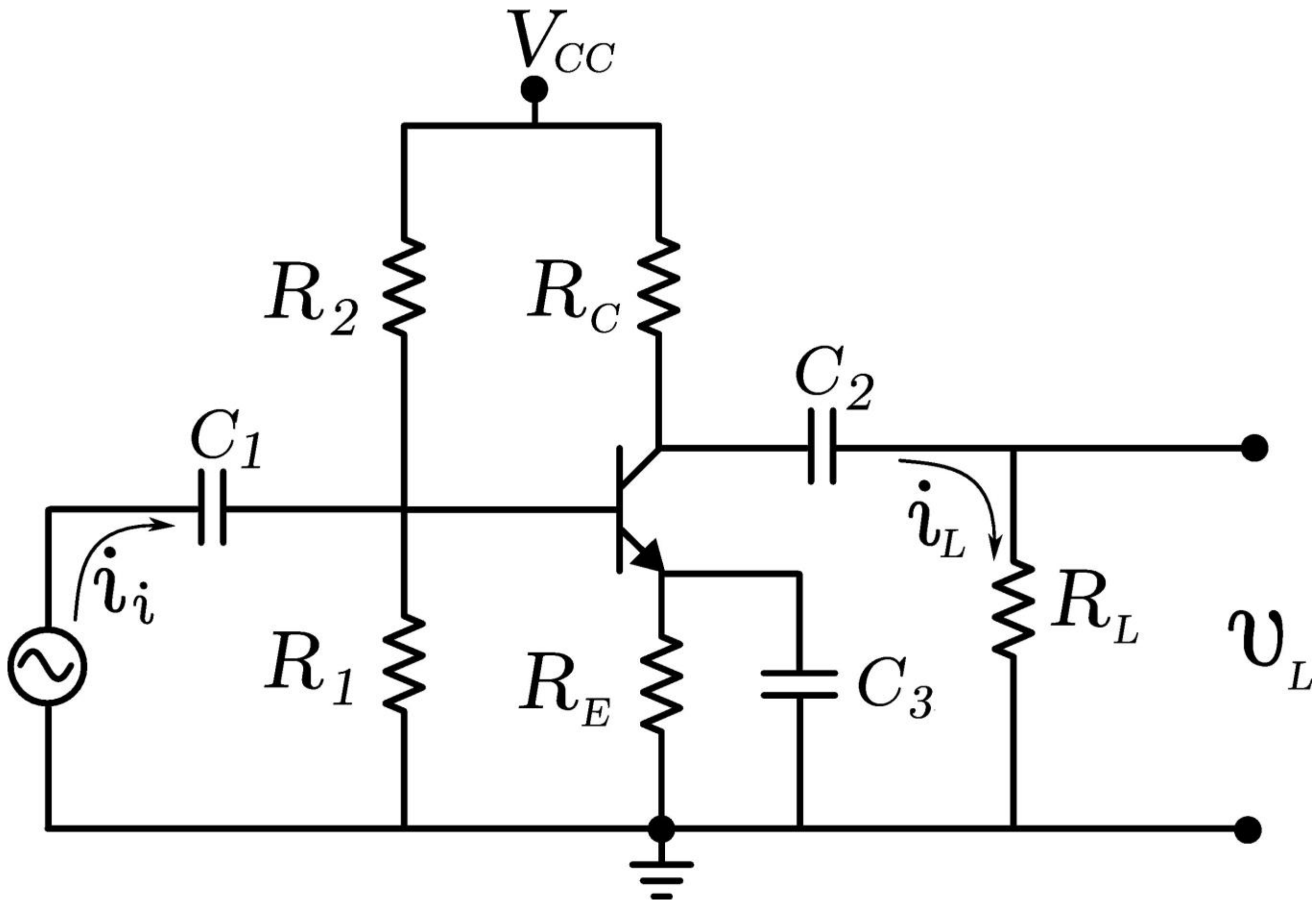
$$h_{fe} = \left.\frac{\Delta i_C}{\Delta i_B}\right|_Q = \frac{3mA - 1mA}{30uA - 10uA} = 100$$

Parámetros Híbridos- Valor de hoe a partir de las características i-v

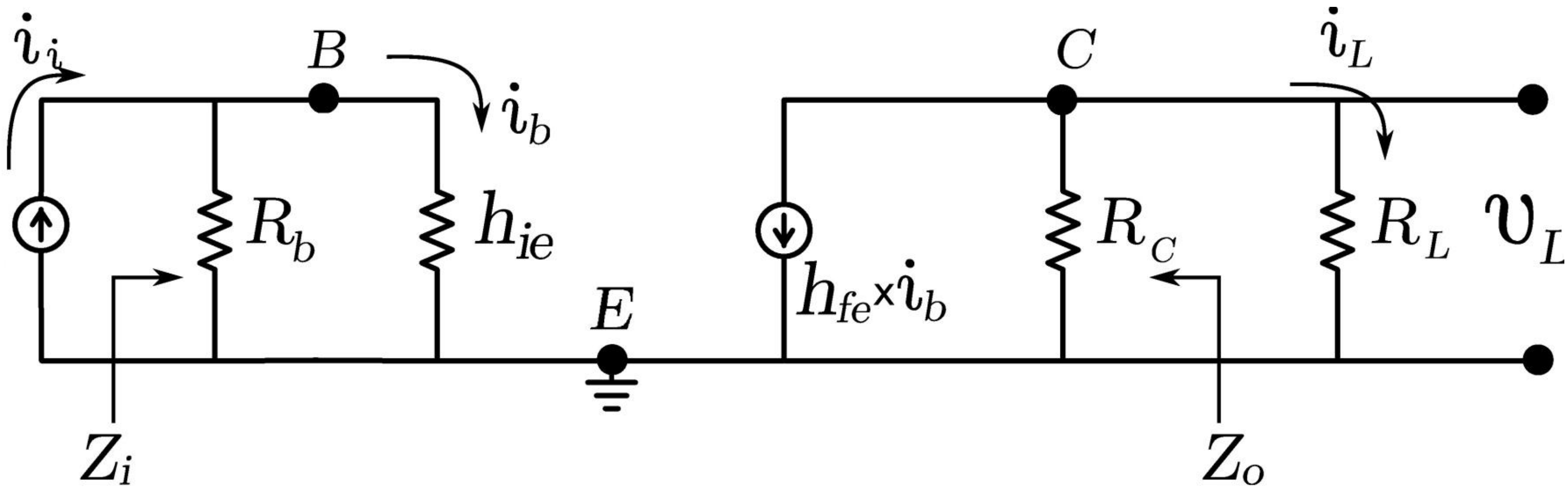


$$h_{oe} = \left.\frac{\Delta i_C}{\Delta v_{CE}}\right|_Q \qquad h_{ie} = \frac{25\ mV}{I_{BQ}} = \frac{25\ mV}{\dfrac{I_{CQ}}{h_{fe}}} = h_{fe}\,\frac{25\ mV}{I_{CQ}}$$

Etapa Amplificadora Emisor Común



Etapa Amplificadora Emisor Común. Circuito Equivalente.



$$Z_i = R_b // h_{ie} \qquad Z_o = R_c$$

Etapa Amplificadora Emisor Común. Ganancia de Corriente.

$$A_i = \frac{i_L}{i_i} = \frac{i_L}{i_b} \times \frac{i_b}{i_i}$$

$$i_L = \frac{v_L}{R_L} = \frac{-h_{fe} i_b R_C // R_L}{R_L} = -h_{fe} i_b \frac{R_C \cancel{R_L}}{R_C + R_L} \frac{1}{\cancel{R_L}}$$

$$\frac{i_L}{i_b} = -h_{fe} \frac{R_C}{R_C + R_L}$$

$$i_b = \frac{v_i}{h_{ie}} = i_i \frac{R_b \cancel{h_{ie}}}{R_b + h_{ie}} \frac{1}{\cancel{h_{ie}}} = i_i \frac{R_b}{R_b + h_{ie}}$$

$$\frac{i_b}{i_i} = \frac{R_b}{R_b + h_{ie}}$$

$$A_i = -h_{fe} \frac{R_C}{R_C + R_L} \frac{R_b}{R_b + h_{ie}}$$

$$Si \left\{ \begin{matrix} R_L << R_C \\ h_{ie} << R_b \end{matrix} \right\} \Rightarrow A_i = -h_{fe} \frac{\cancel{R_C}}{\cancel{R_C}} \frac{\cancel{R_b}}{\cancel{R_b}} \cong -h_{fe}$$

Etapa Amplificadora Emisor Común. Ganancia de tensión.

$$A_V = \frac{v_L}{v_i} = \frac{i_L}{i_i}\frac{R_L}{Z_i}$$

$$A_V = A_i \frac{R_L}{Z_i} = -h_{fe}\frac{R_C}{R_C + R_L}\frac{R_b}{R_b + h_{ie}}\frac{R_L}{\dfrac{R_b \times h_{ie}}{R_b + h_{ie}}} = -h_{fe}\frac{R_C \times R_L}{R_C + R_L}\frac{1}{h_{ie}}$$

$$A_V = -h_{fe}\frac{R_C\,//\,R_L}{h_{ie}}$$

$Si\ R_L << R_C:$

$$A_V \cong -h_{fe}\frac{\cancel{R_C} \times R_L}{\cancel{R_C}}\frac{1}{h_{ie}} \cong -h_{fe}\frac{R_L}{h_{ie}} = -\frac{R_L}{h_{ie}/h_{fe}} = -\frac{R_L}{h_{ib}}$$

$$A_V = -\frac{1}{h_{ib}}R_L$$

Etapa Amplificadora Emisor Común. Ganancia de Potencia.

$$A_P = \frac{P_L}{P_i} = \frac{v_L}{v_i} \times \frac{i_L}{i_i} = A_V \times A_i$$

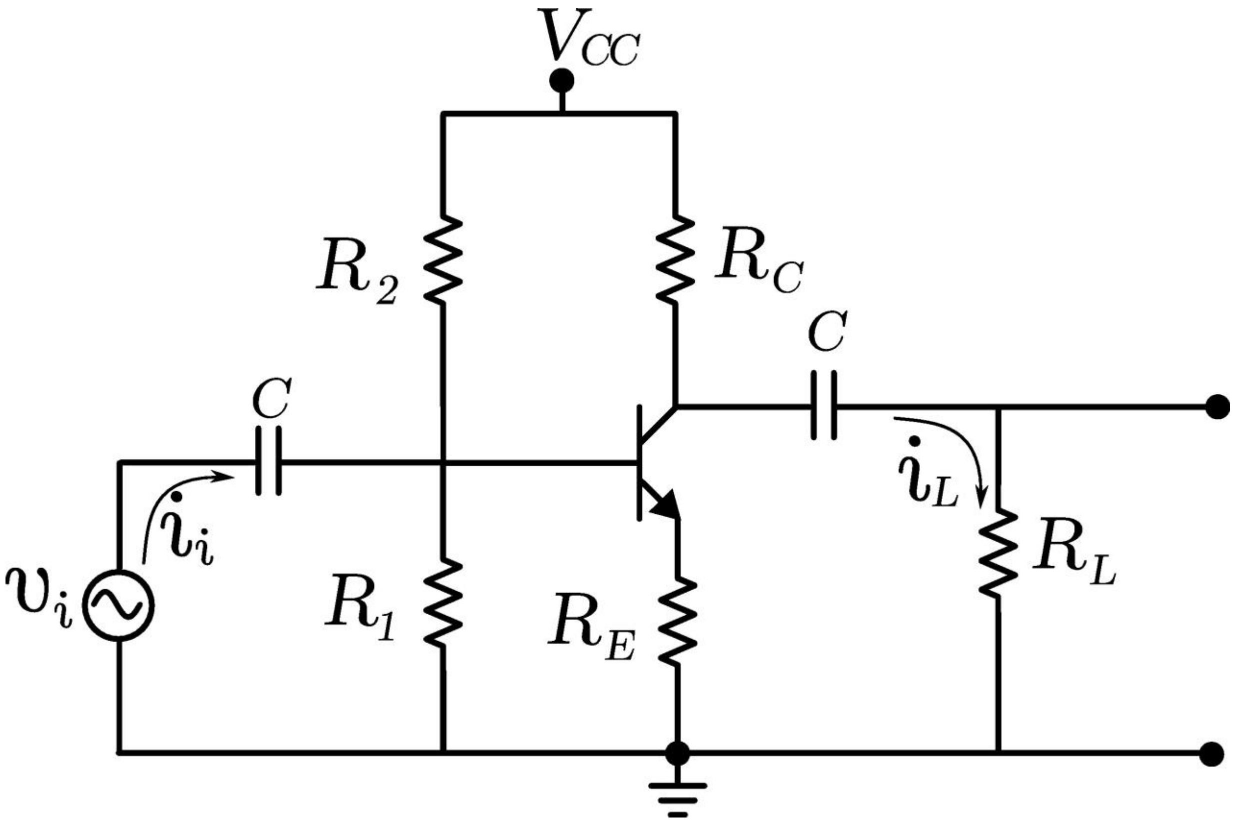
$$Como: \; A_V = A_i \frac{R_L}{Z_i}$$

$$A_P = A_i \frac{R_L}{Z_i} A_i = A_i^{\,2} \frac{R_L}{Z_i}$$

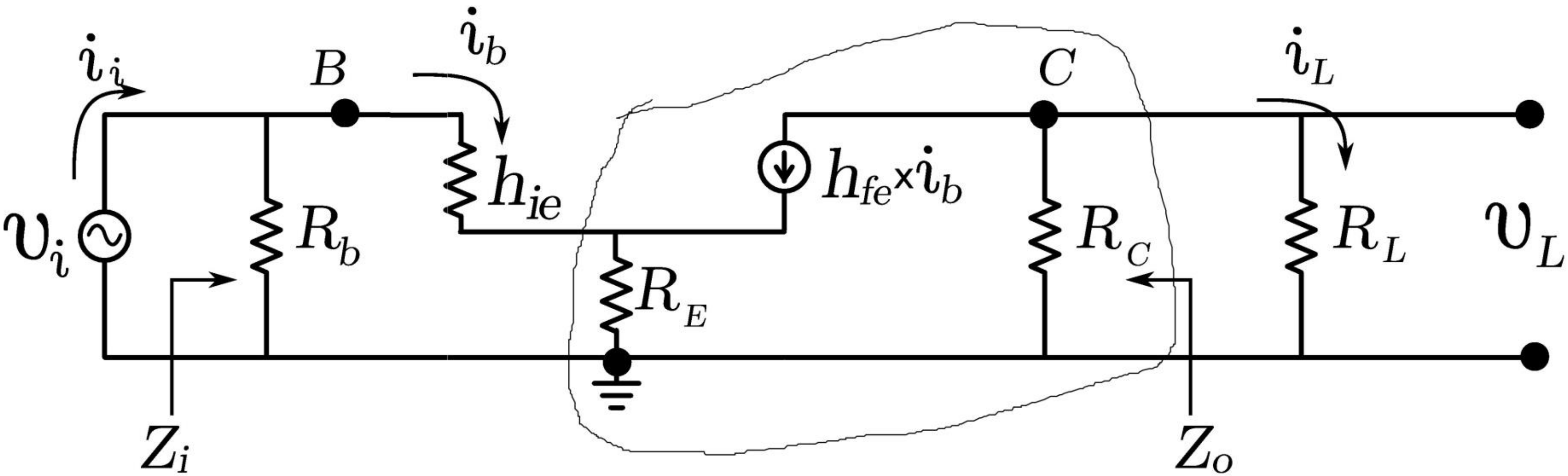
$$Como: \; A_i = A_V \frac{Z_i}{R_L}$$

$$A_P = A_V A_V \frac{Z_i}{R_L} = A_V^{\,2} \frac{Z_i}{R_L}$$

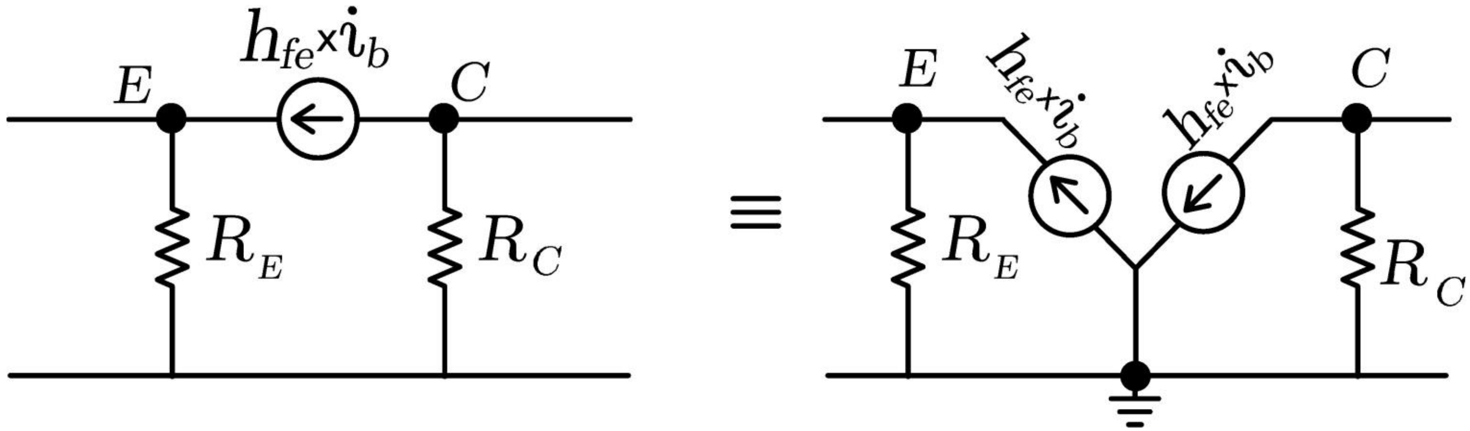
Etapa Amplificadora E.C sin capacitor de desacople. Reflexión de impedancia.

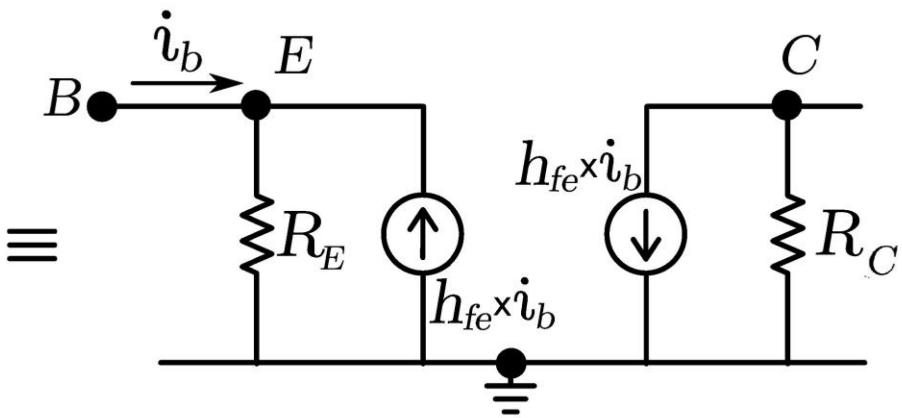


Circuito equivalente para señal débil.



Desdoblamos la fuente de corriente



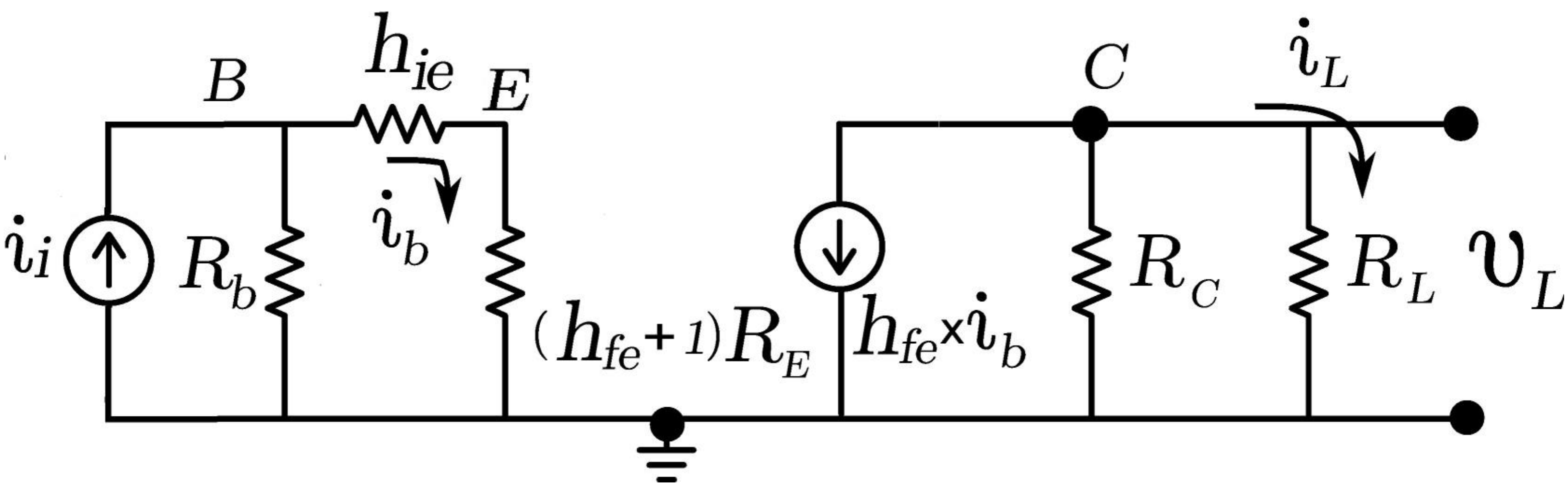


$$
\begin{aligned}
v_e &= \left(i_b + h_{fe} i_b\right) R_E \\
&= i_b \left(h_{fe} + 1\right) R_E \\
&= i_b \left[R_E \left(h_{fe} + 1\right) \right]
\end{aligned}
$$

Circuito equivalente para señal debil con Re reflejada a la base

La combinacion de R_E *en* $//$ *con* $h_{fe} i_b$ *es reemplazada por la resistencia reflejada* $\left(h_{fe}+1\right)R_E$

$$\begin{aligned} v_e &= \left(i_b + h_{fe} i_b\right) R_E \\ &= i_b \left(h_{fe}+1\right) R_E \\ &= i_b \left[R_E \left(h_{fe}+1\right)\right] \end{aligned}$$



Calculo de impedancias y ganancias

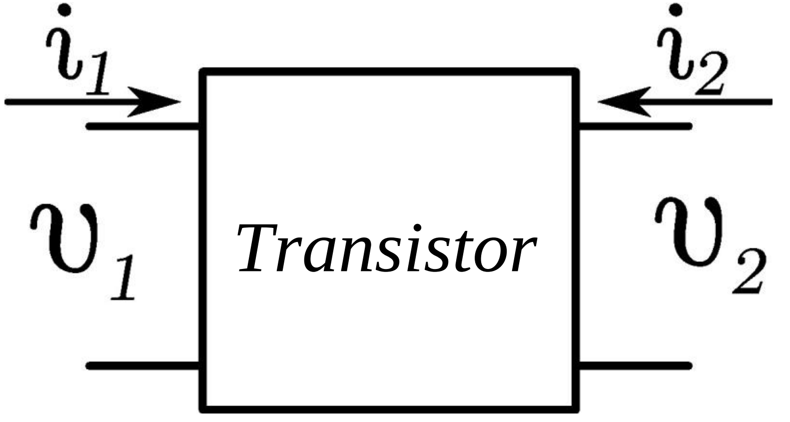
$$Z_i = R_b // \left[h_{ie} + R_e (h_{fe} + 1) \right] \qquad \uparrow$$

$$Z_o = R_C \qquad =$$

$$A_i = -h_{fe} \frac{R_C}{R_C + R_L} \frac{R_b}{R_b + h_{ie} + R_e (h_{fe} + 1)} \qquad \downarrow$$

$$A_V = A_i \frac{R_L}{Z_i} \qquad \downarrow\downarrow$$

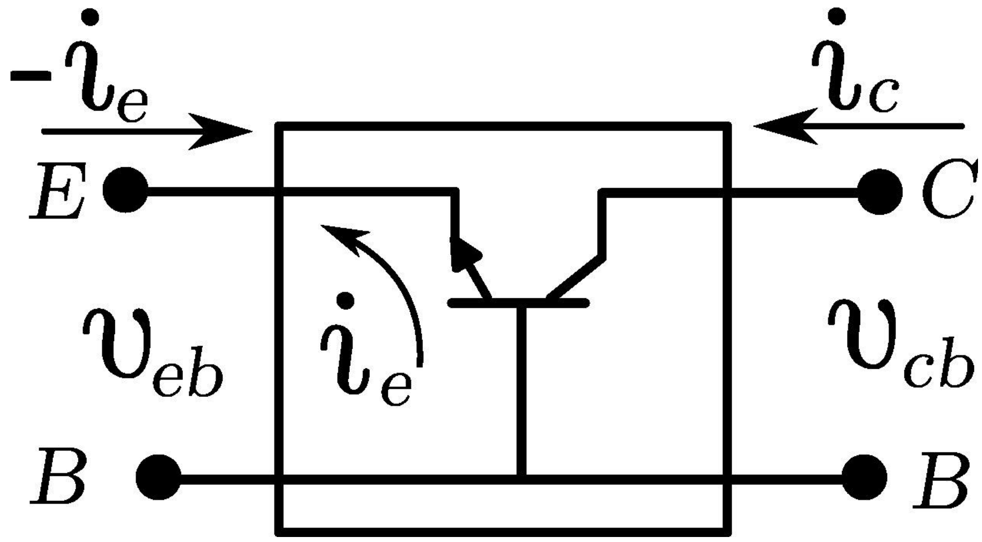
Parámetros Internos para Base Común.



$$v_i = h_i i_1 + h_r v_2$$

$$i_2 = h_f i_1 + h_o v_2$$

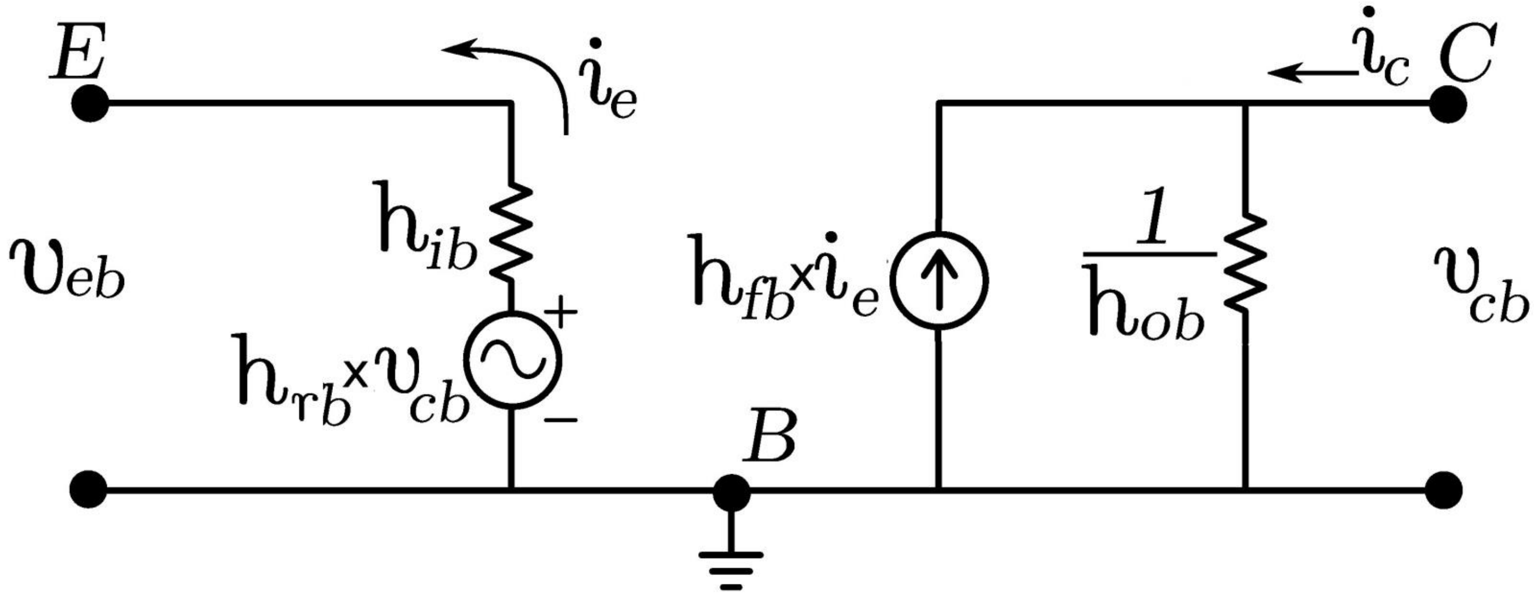
Parámetros Internos para Base Común (Cont.)



$$v_{eb} = h_{ib}(-i_e) + h_{rb}v_{cb}$$

$$i_c = h_{fb}(-i_e) + h_{ob}v_{cb}$$

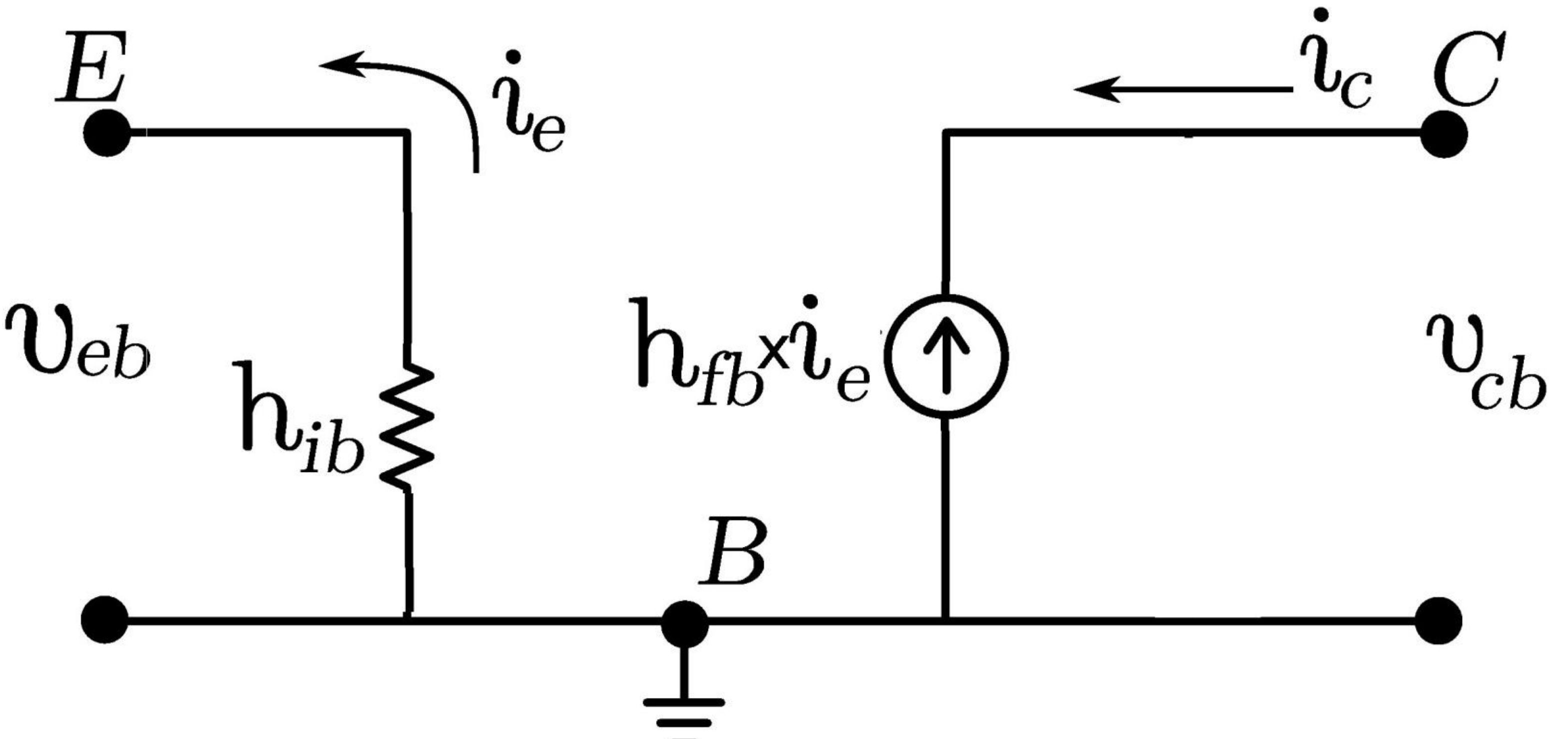
Circuito equivalente completo.



$$h_{rb} \rightarrow 0 \Rightarrow h_{rb} v_{cb} \rightarrow 0$$

$$h_{ob} \rightarrow 0 \Rightarrow \frac{1}{h_{ob}} \begin{pmatrix} da\ un\ valor\ muy\ alto \\ se\ puede\ despreciar. \end{pmatrix}$$

Circuito equivalente simplificado.



Definición de los parámetros híbridos.

$$v_{eb} = h_{ib}(-i_e) + h_{rb}v_{cb}$$

$$i_c = h_{fb}(-i_e) + h_{ob}v_{cb}$$

$$h_{ib} = \left.\frac{v_{eb}}{-i_e}\right|_{v_{cb}=0} \qquad h_{fb} = \left.\frac{i_c}{-i_e}\right|_{v_{cb}=0}$$

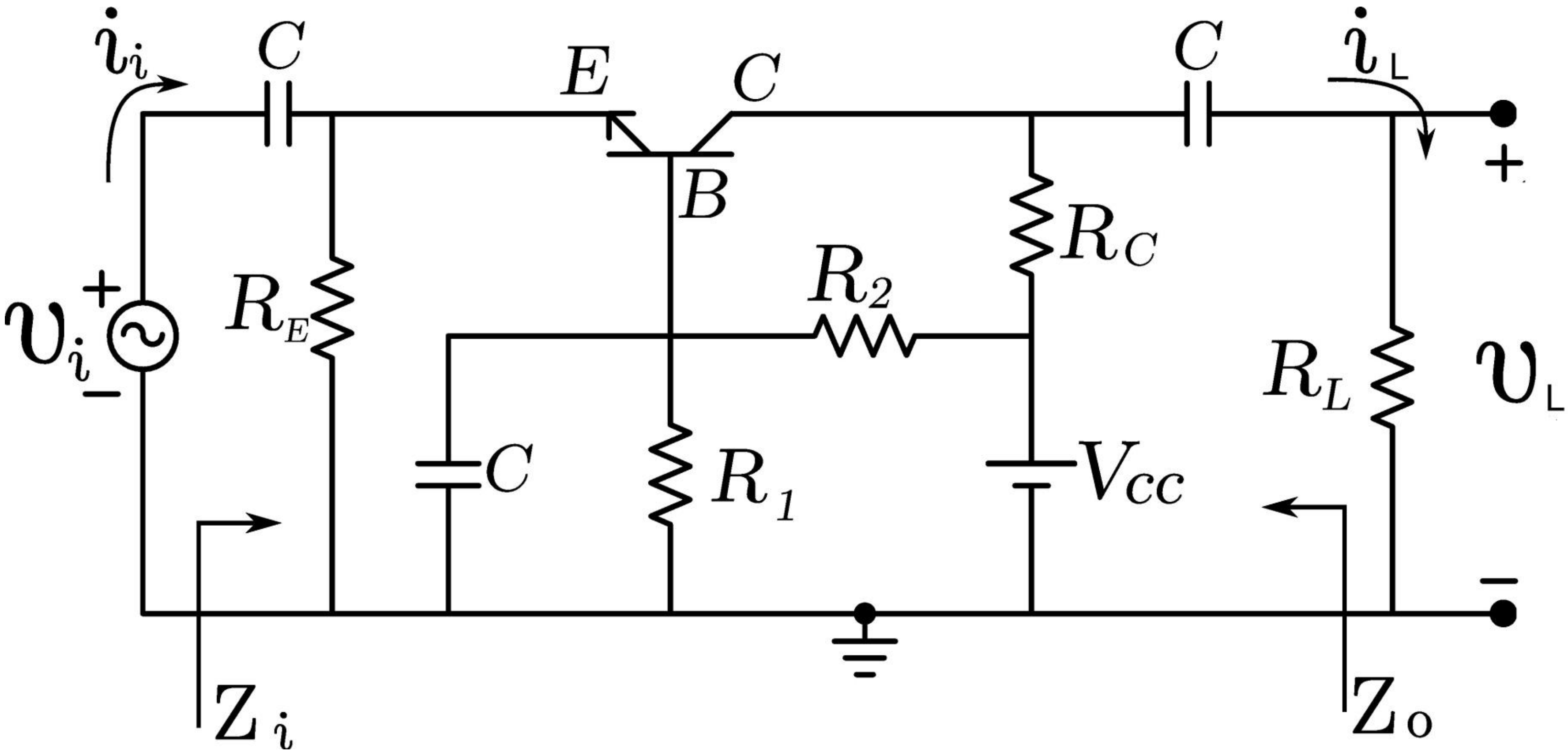
$$h_{rb} = \left.\frac{v_{eb}}{v_{cb}}\right|_{i_e=0} \qquad h_{ob} = \left.\frac{i_c}{v_{cb}}\right|_{i_e=0}$$

Relación de los parámetros híbridos de B.C y E.C

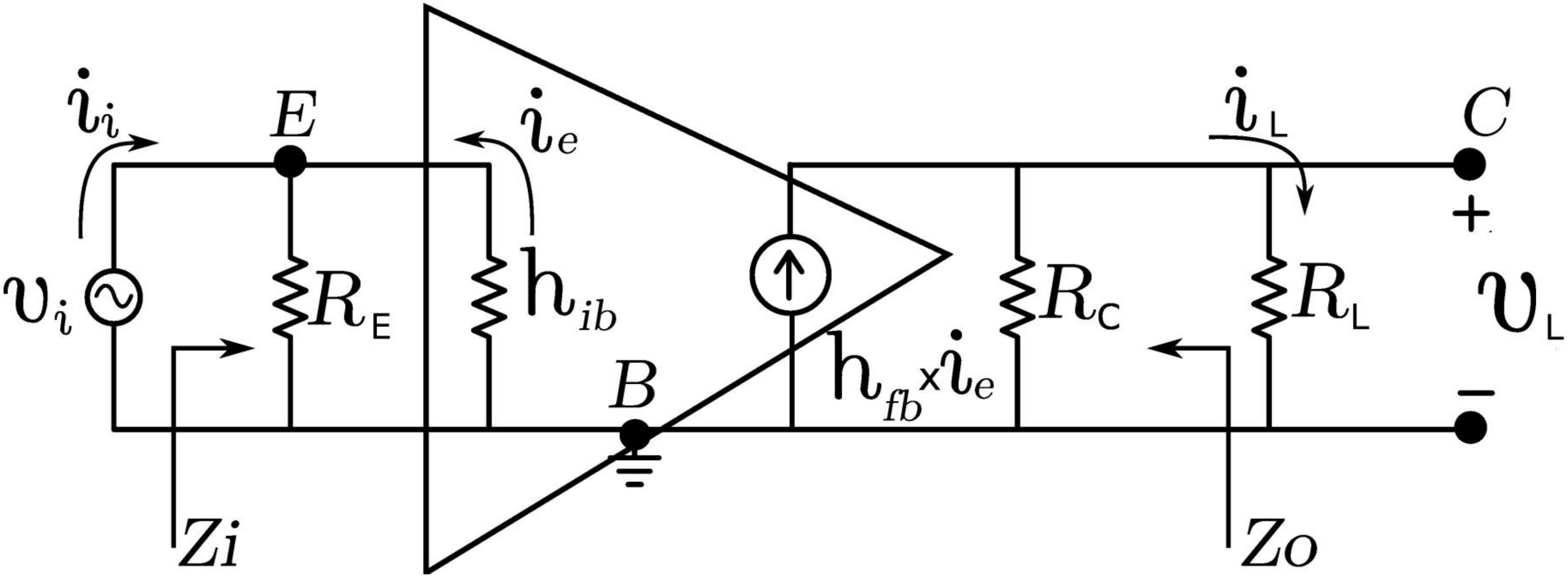
$$h_{ib} = \frac{v_{eb}}{-i_e} = \frac{-i_b h_{ie}}{-i_e} = \frac{-\cancel{i_b} h_{ie}}{-\cancel{i_b}(h_{fe}+1)} = \frac{h_{ie}}{(h_{fe}+1)}$$

$$h_{fb} = \frac{i_c}{-i_e} = \frac{\cancel{i_b} h_{fe}}{-\cancel{i_b}(h_{fe}+1)} = -\frac{h_{fe}}{(h_{fe}+1)} \cong -1$$

Etapa Amplificadora Base Común



Etapa Amplificadora Base Común (Cont.)



$$h_{ib} = \frac{h_{ie}}{h_{fe}+1} = \frac{25mV\ \cancel{h_{fe}}}{I_{CQ}}\frac{1}{\cancel{h_{fe}}} = \frac{25mV}{I_{CQ}}$$

$$Z_i = R_E // h_{ib} \qquad\qquad Z_o = R_C$$

Cálculo de la Ganancia de Corriente (Ai).

$$A_i = \frac{i_L}{i_i} = \frac{i_L}{i_e}\frac{i_e}{i_i}$$

$$i_L = h_{fb} i_e \frac{R_C \cancel{R_L}}{R_C + R_L}\frac{1}{\cancel{R_L}} \qquad \Rightarrow \qquad \frac{i_L}{i_e} = h_{fb}\frac{R_C}{R_C + R_L}$$

$$i_e = -i_i \frac{R_E \cancel{h_{ib}}}{R_E + h_{ib}}\frac{1}{\cancel{h_{ib}}} \qquad \Rightarrow \qquad \frac{i_e}{i_i} = -\frac{R_E}{R_E + h_{ib}}$$

Cálculo de la Ganancia de Corriente (Ai)(Cont.).

$$\mathrm{A}_i = -h_{fb}\,\frac{R_C}{R_C + R_L} \times \frac{R_e}{R_e + h_{ib}}$$

$$\mathrm{A}_i = -(-1)\,\frac{R_C}{R_C + R_L} \times \frac{R_e}{R_e + h_{ib}}$$

$$\mathrm{A}_i = \frac{R_C}{R_C + R_L} \times \frac{R_e}{R_e + h_{ib}} \qquad < 1$$

Cálculo de la Ganancia de Tensión (Av).

$$A_V = \frac{v_L}{v_i} = \frac{i_L R_L}{i_i Z_i} = A_i \frac{R_L}{Z_i} = -h_{fb} \frac{R_C}{R_C + R_L} \times \frac{R_e}{R_e + h_{ib}} \times \frac{R_L}{\dfrac{R_e h_{ib}}{R_e + h_{ib}}}$$

$$\mathrm{A}_V = \frac{R_C // R_L}{h_{ib}}$$

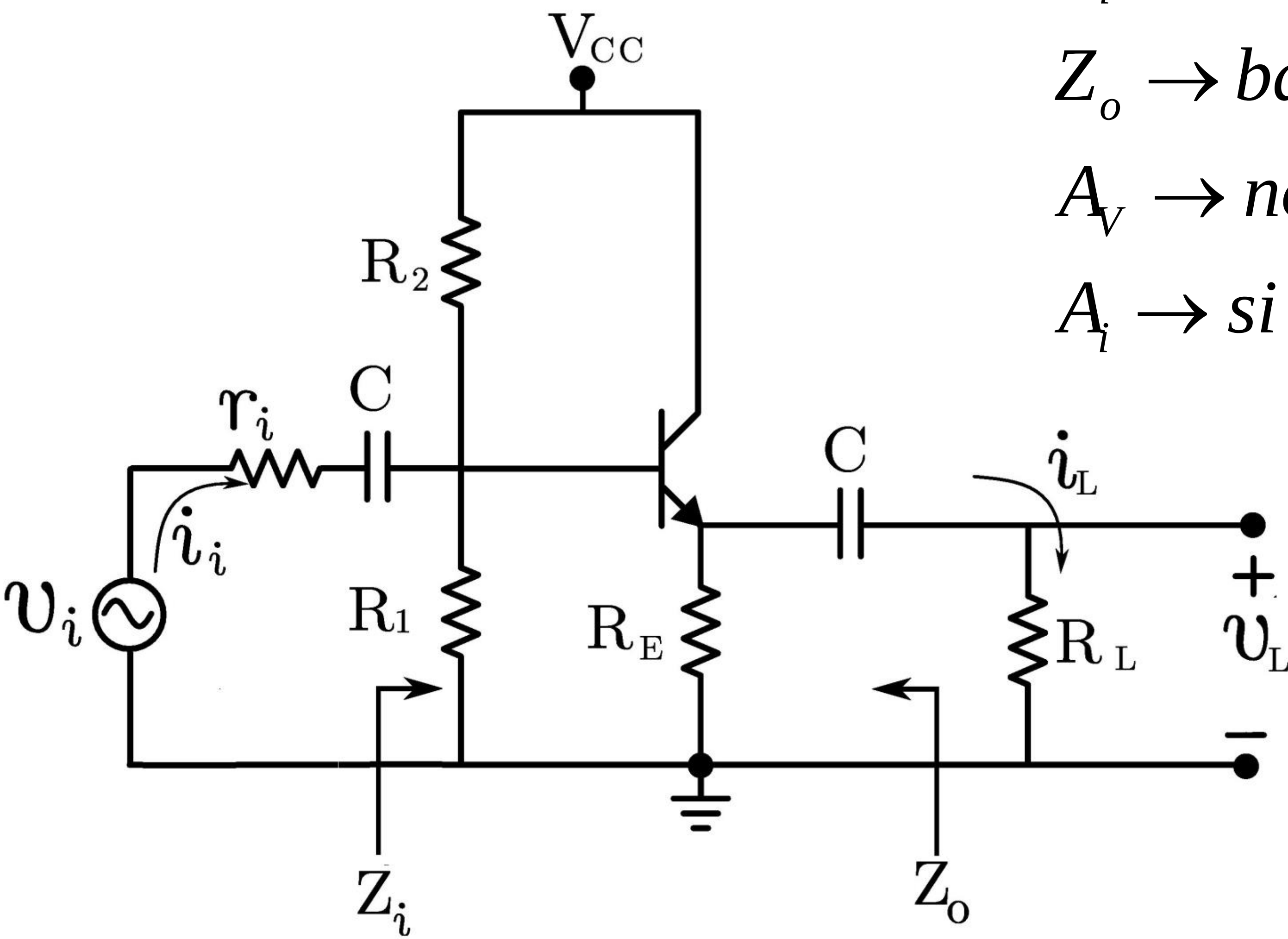
Etapa Amplificadora Colector Común

$$Z_i \rightarrow alta$$

$$Z_o \rightarrow baja$$

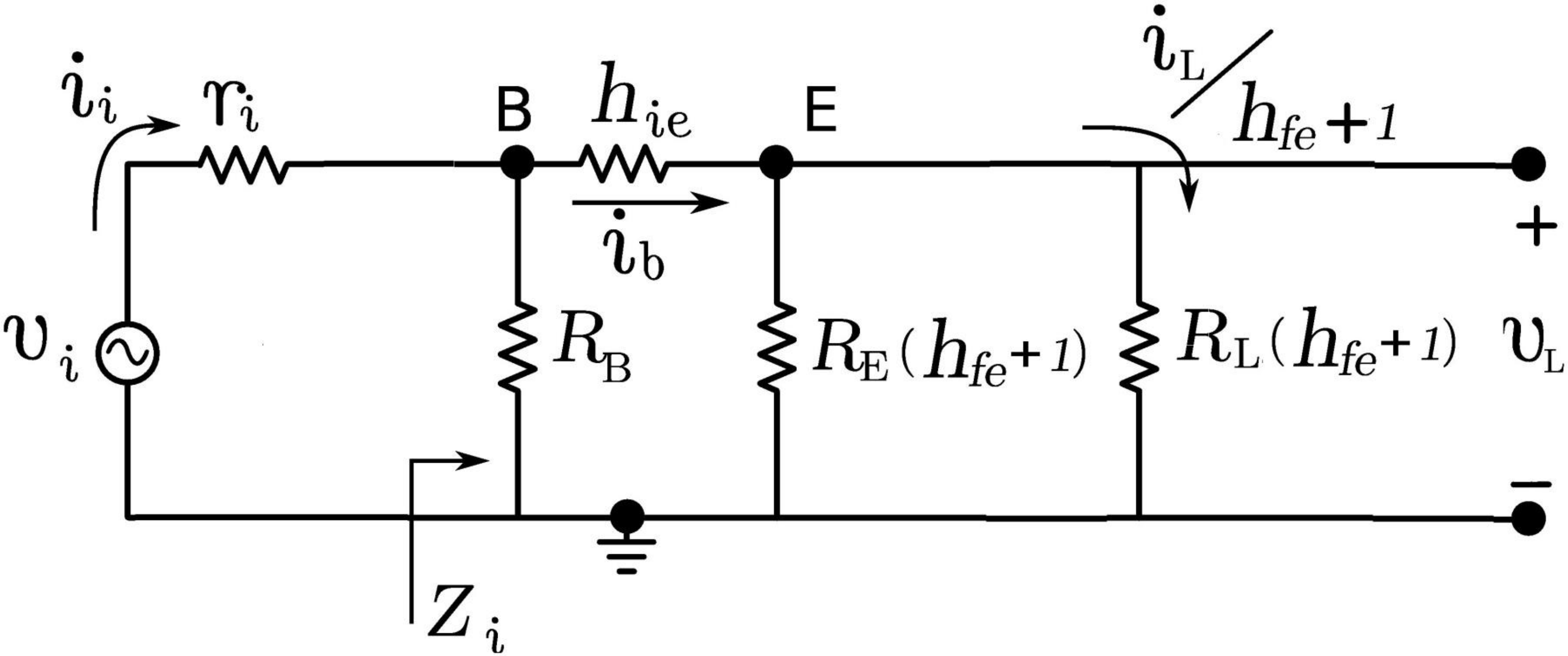
$$A_V \rightarrow no$$

$$A_i \rightarrow si$$



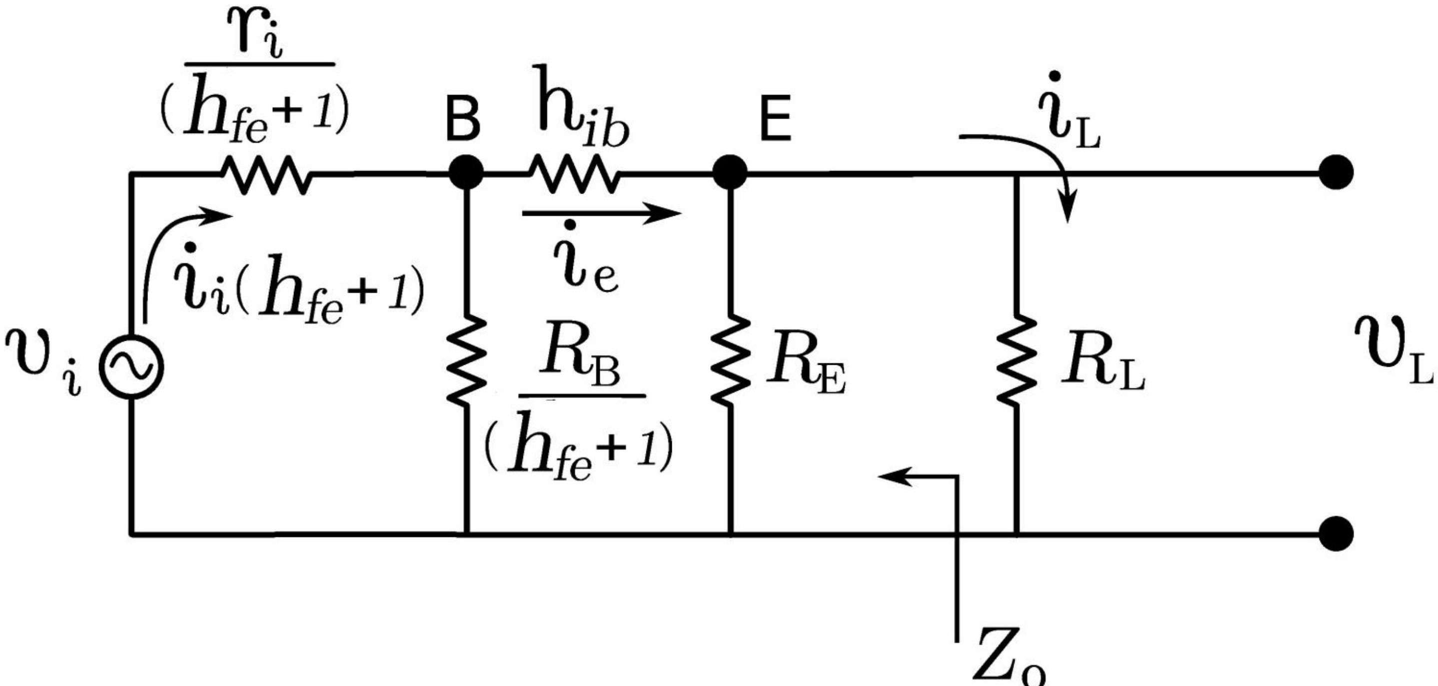
Circuito equivalente para pequeña señal.

Reflejando el emisor hacia la base.



$$Z_i = R_b \,//\left[h_{ie} + (R_E \,//\, R_L)(h_{fe}+1)\right]$$

Circuito equivalente para pequeña señal. Reflejando la base hacia el emisor.



$$Z_o = R_E \,//\left[h_{ib} + \frac{(r_i \,//R_b)}{h_{fe}+1} \right]$$

$$Si\ r_i = 0 \Rightarrow Z_o = R_E \,//h_{ib}$$

Ganancia de tensión Av.

$$A_V = \frac{v_L}{v_i} = \frac{v_L}{i_e}\frac{i_e}{i_i}\frac{i_i}{v_i}$$

$$v_L = i_e(R_E\,//\,R_L) \quad \Rightarrow \quad \frac{v_L}{i_e} = R_E\,//\,R_L$$

$$i_e = \frac{i_i h_{fe}\left[{R_B}/{h_{fe}}\,//\left(h_{ib} + R_E\,//\,R_L\right)\right]}{h_{ib} + R_E\,//\,R_L}$$

$$\frac{i_e}{i_i} = \cancel{h}_{fe}\,\frac{{R_B}/{\cancel{h}_{fe}} \times \left(h_{ib} + R_E\,//\,R_L\right)}{{R_B}/{h_{fe}} + \left(h_{ib} + R_E\,//\,R_L\right)}\,\frac{1}{h_{ib} + R_E\,//\,R_L}$$

$$\frac{i_e}{i_i} = \frac{R_B}{{R_B}/{h_{fe}} + \left(h_{ib} + R_E\,//\,R_L\right)}$$

Ganancia de tensión Av (Cont.).

$$i_i h_{fe} = \frac{v_i}{z'}$$

$$\frac{i_i}{v_i} = \frac{1}{h_{fe} z'} = \frac{1}{h_{fe}\left[\frac{r_i}{h_{fe}} + \frac{R_B}{h_{fe}} // \left(h_{ib} + R_E // R_L\right)\right]}$$

$$Suponiendo\ r_i = 0$$

$$A_V = (R_E // R_L) \times \frac{\cancel{R_B}}{\frac{R_B}{h_{fe}} + \left(h_{ib} + R_E // R_L\right)} \times \frac{1}{\frac{\frac{\cancel{R_B}}{\cancel{h_{fe}}} \times \left(h_{ib} + R_E // R_L\right)}{\frac{R_B}{h_{fe}} + \left(h_{ib} + R_E // R_L\right)}} \times \frac{1}{\cancel{h_{fe}}}$$

$$A_V = \frac{R_E // R_L}{h_{ib} + R_E // R_L} \qquad < \quad 1\ Siempre$$

Ganancia de Corriente Ai.

$$A_i = \frac{i_L}{i_i} = \frac{i_L}{i_e}\frac{i_e}{i_i}$$

$$i_L = i_e \frac{R_E \cancel{R_L}}{R_E + R_L} \times \frac{1}{\cancel{R_L}} \Rightarrow \frac{i_L}{i_e} = \frac{R_E}{R_E + R_L}$$

$$i_e = i_i \cancel{h}_{fe} \frac{\frac{R_B}{\cancel{h}_{fe}} \times (h_{ib} + R_E // R_L)}{\frac{R_B}{h_{fe}} + h_{ib} + R_E // R_L} \times \frac{1}{h_{ib} + R_E // R_L}$$

$$\frac{i_e}{i_i} = \frac{R_B}{\frac{R_B}{h_{fe}} + h_{ib} + R_E // R_L}$$

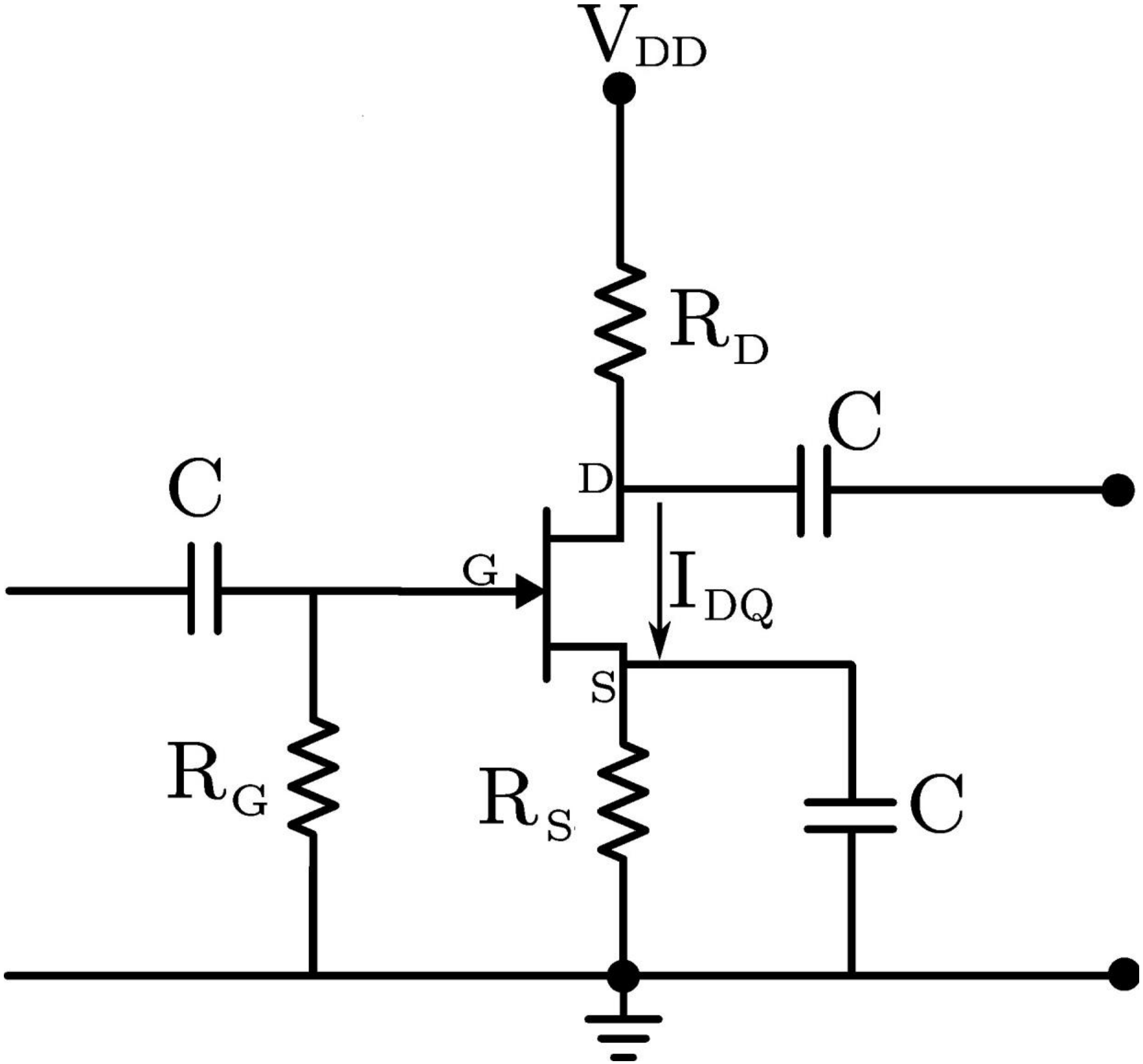
$$A_i = \frac{R_E}{R_E + R_L} \times \frac{R_B}{\frac{R_B}{h_{fe}} + h_{ib} + R_E // R_L}$$

Ganancia de Potencia (Ap)

$$A_P = A_V A_i$$

$$Bipolares \rightarrow Reflexion\ de\ impedancias \rightarrow entre\ Base\ y\ Emisor.$$

Etapa Amplificadora con FET

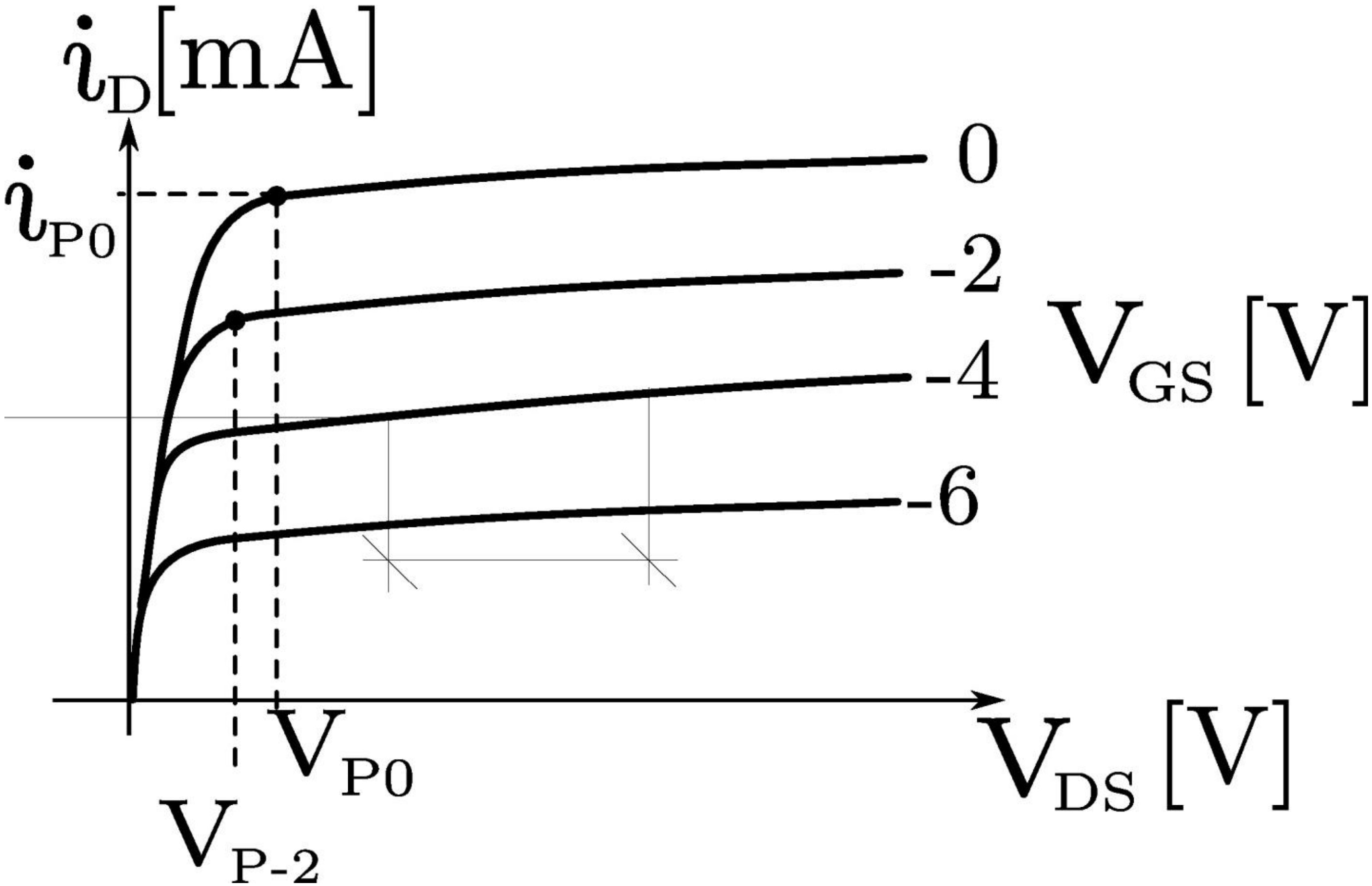


Etapa Amplificadora con FET (Cont.)

$$JFET \rightarrow i_D = f\left(v_{GS}\right)^{3/2} \qquad i_D = I_{PO}\left[1 + 3\frac{v_{GS}}{v_{PO}} + 2\left(-\frac{v_{GS}}{v_{PO}}\right)^{3/2}\right]$$

$$MOSFET \rightarrow i_D = f\left(v_{GS}\right)^2 \qquad i_D = I_{PO}\left(1 + \frac{v_{GS}}{v_{PO}}\right)^2$$

Características v-i del FET



Tensión de estrangulamiento, Voltaje de ruptura y corriente de saturación

$$v_{DS}(estriccion) = V_p = V_{po} + v_{GS}$$

$$Cuando\ v_{GS} = 0 \quad \Rightarrow \quad V_p = V_{po}$$

$$BV_{DSX} \cong BV_{DSO} + V_{GS}$$

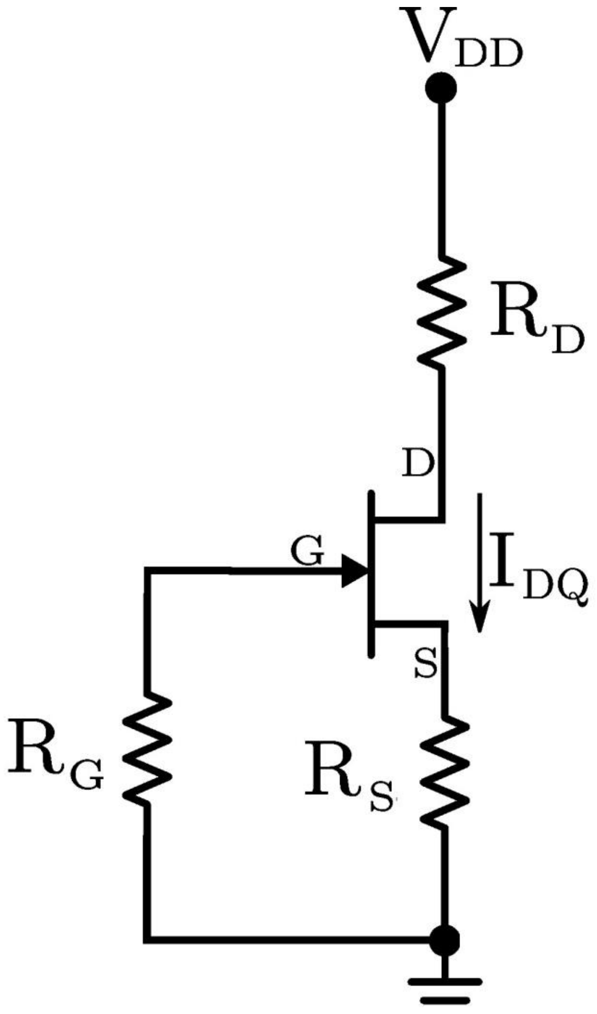
$$Donde\ BV_{DSO}\ es\ la\ tension\ de\ ruptura\ para\ V_{GS} = 0$$

$$I_{PO} \propto T^{-3/2}$$

$$I_{PO} = I'_{PO}\left(\frac{T_0}{T}\right)^{3/2}$$

$$Donde\ I'_{PO} = I_{PO}\Big|_{\substack{v_{GS}=0 \\ T=T_0}}$$

Polarización del JFET



$$Ecuacion\ de\ entrada:$$

$$V_{GSQ} = V_{GQ} - V_{SQ}$$

$$V_{GQ} = 0$$

$$V_{SQ} = I_{DQ} R_S$$

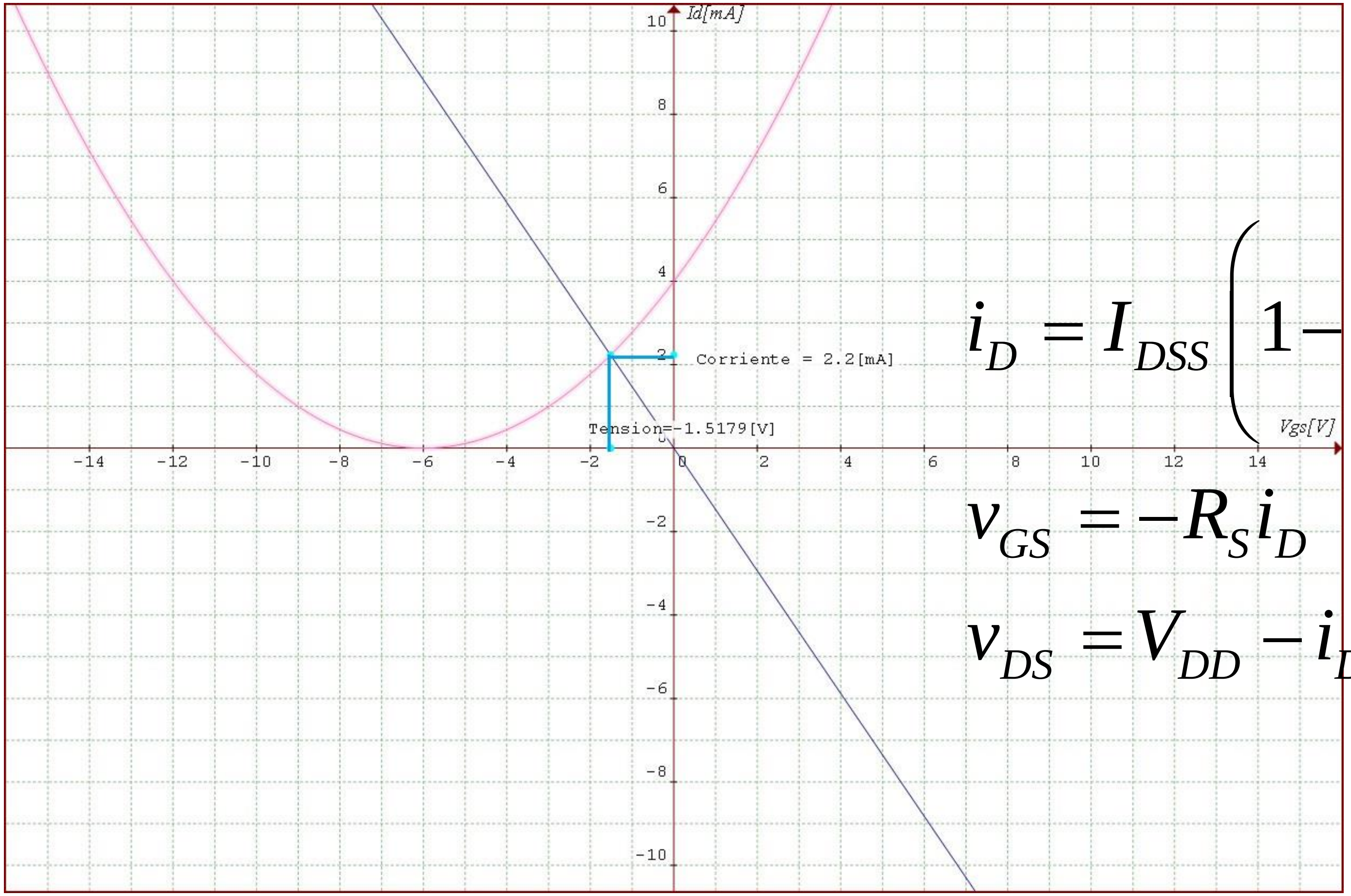
$$V_{GSQ} = 0 - I_{DQ} R_S = -I_{DQ} R_S$$

$$Ecuacion\ de\ salida:$$

$$V_{DD} = V_{DSQ} + I_{DQ}(R_D + R_S)$$

Análisis del JFET

- Método Grafico (Graphmatica):



$$i_D = I_{DSS}\left(1-\frac{v_{GS}}{v_{GS(off)}}\right)^2$$

$$v_{GS} = -R_S i_D$$

$$v_{DS} = V_{DD} - i_D\left(R_S + R_D\right)$$

Análisis del JFET

- Método Analítico:

$$i_D = I_{DSS}\left(1 - \frac{v_{GS}}{v_{GS(off)}}\right)^2$$

$$v_{GS} = -R_S i_D$$

$$i_D = I_{DSS}\left(1 - \frac{-R_S i_D}{v_{GS(off)}}\right)^2$$

$$A{i_D}^2 + Bi_D + C \Rightarrow i_{D(1,2)} = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}$$

$$v_{DS} = V_{DD} - i_D\left(R_S + R_D\right)$$

Diseño del JFET (Cont.)

- Para MES:

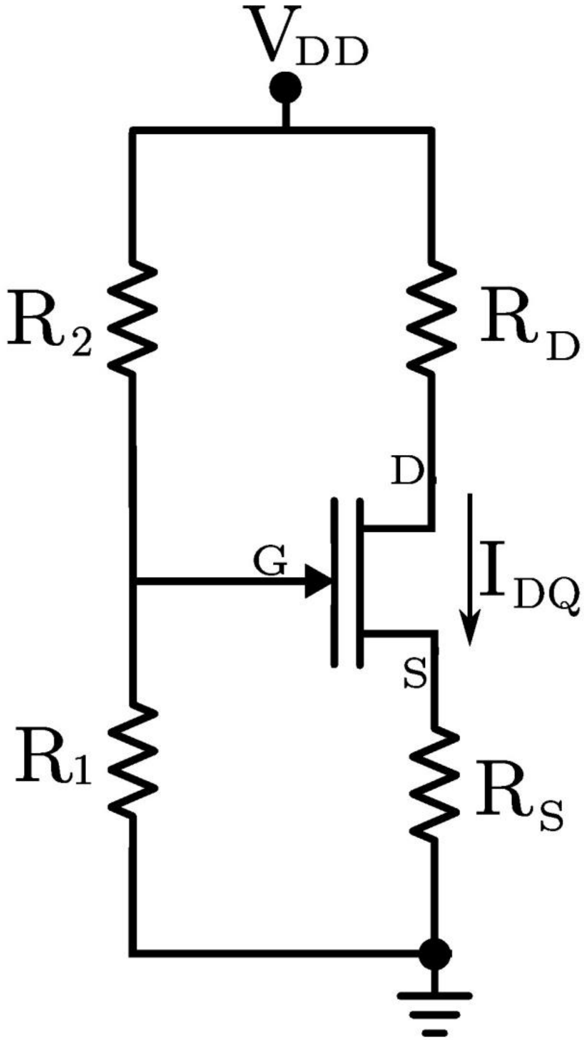
$$I_{DQ(MES)} = \frac{V_{DD}}{R_S + R_D + R_D // R_L}$$

$$i_D = I_{DSS}\left(1 - \frac{v_{GS}}{v_{GS(off)}}\right)^2 \Rightarrow v_{GS} = v_{GS(off)}\left(1 - \sqrt{\frac{i_D}{I_{DSS}}}\right)$$

$$R_S = -\frac{V_{GSQ}}{I_{DQ}}$$

$$v_{DS} = V_{DD} - i_D\left(R_S + R_D\right)$$

Polarización del MOSFET

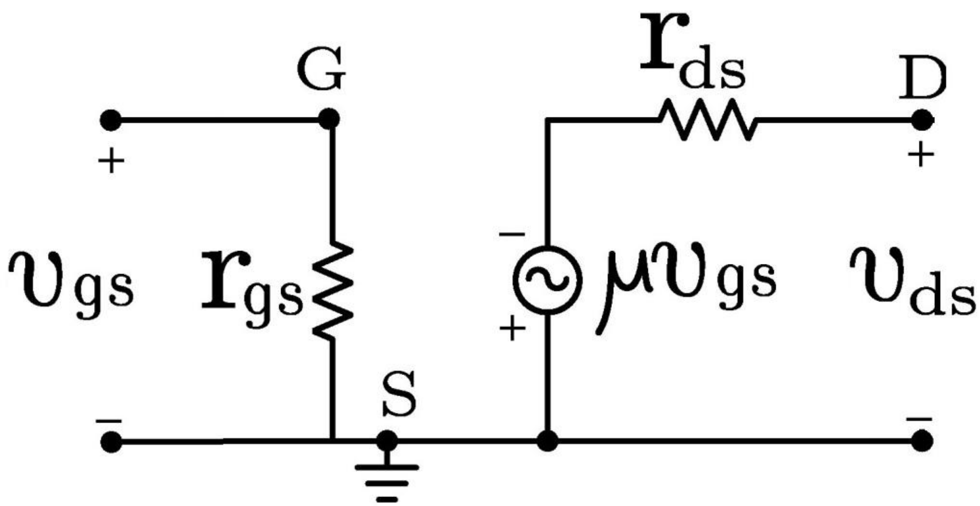


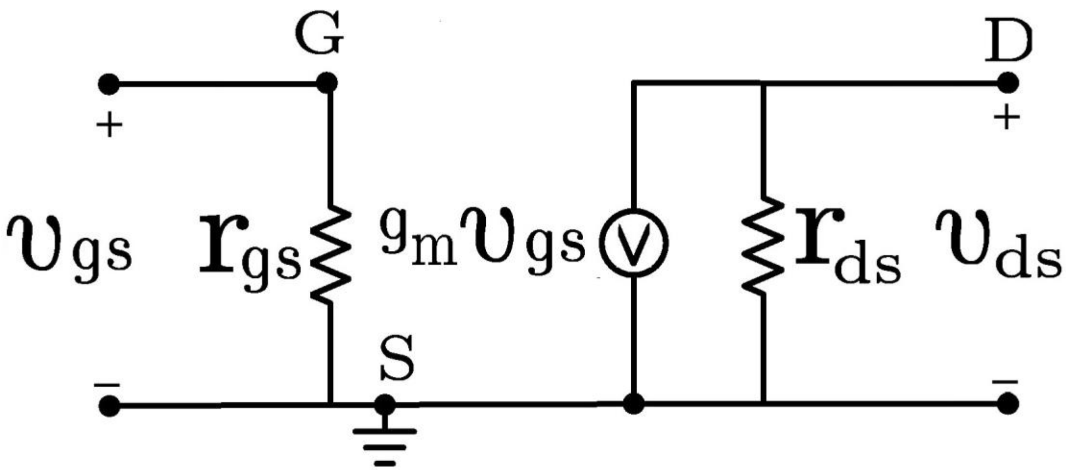
$$V_{GG} = \frac{V_{DD}}{R_1 + R_2} \times R_1$$

$$V_{GS} = V_{GG} - I_D R_S$$

$$V_{DD} = V_{DS} + I_D \left(R_D + R_S \right)$$

Circuito Equivalente FET





Parámetros Internos del FET

$$Impedancia\ de\ entrada:\ r_{gs} = \frac{\Delta v_{GS}}{\Delta i_G} = \left.\frac{v_{gs}}{i_g}\right|_{Punto\ Q} \rightarrow \infty$$

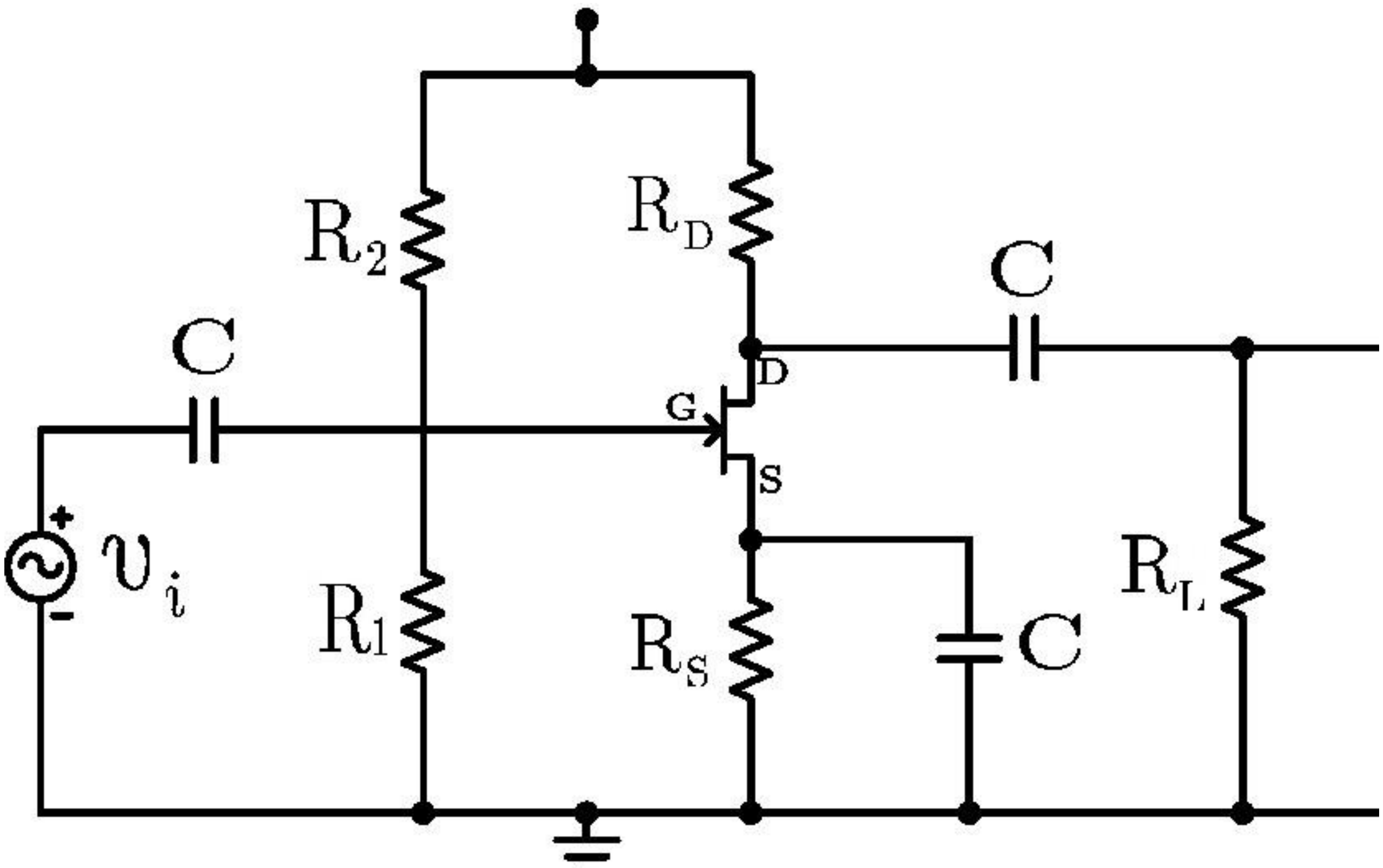
$$Ganancia\ de\ voltaje:\ \mu = \frac{\Delta v_{DS}}{\Delta v_{GS}} = \left.\frac{v_{ds}}{v_{gs}}\right|_{I_{DQ}=cte}$$

$$Impedancia\ de\ salida:\ r_{ds} = \frac{\Delta v_{DS}}{\Delta i_D} = \left.\frac{v_{ds}}{i_d}\right|_{V_{GSQ}=cte}$$

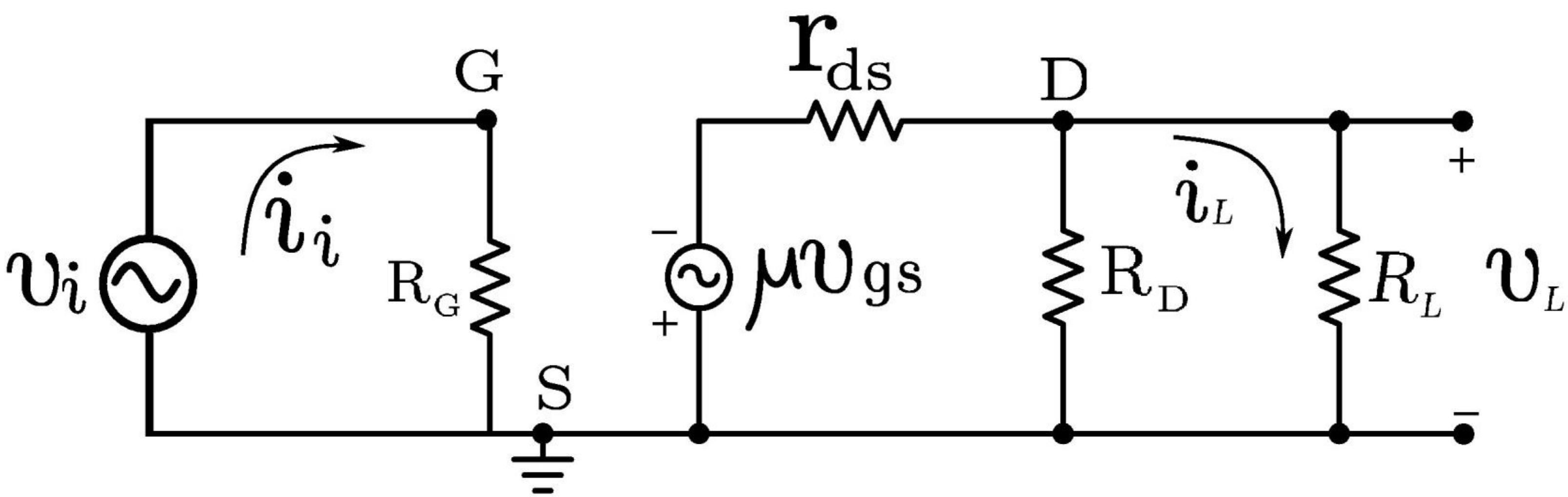
$$Transconductancia: g_m = \frac{\Delta i_D}{\Delta v_{GS}} = \left.\frac{i_d}{v_{gs}}\right|_{V_{DSQ=cte}}$$

$$\mu = r_{ds} g_m$$

Etapa amplificadora surtidor Común.



Circuito Equivalente Amplificador Surtidor Común



$$Z_i = R_G = R_1 // R_2$$

$$Z_o = R_D // r_{ds}$$

Ganancia tensión en surtidor común

$$A_V = \frac{v_L}{v_i} = \frac{v_L}{v_{gs}} \frac{v_{gs}}{v_i}$$

$$v_L = \frac{-\mu v_{gs}}{r_{ds} + R_D // R_L} \times R_D // R_L \Rightarrow \frac{v_L}{v_{gs}} = \frac{-\mu}{r_{ds} + R_D // R_L} \times R_D // R_L$$

$$v_{gs} = v_i \Rightarrow \frac{v_{gs}}{v_i} = 1$$

$$A_V = \frac{-\mu}{r_{ds} + R_D // R_L} \times R_D // R_L \times 1 = \frac{-\mu}{r_{ds} + R_D // R_L} \times R_D // R_L$$

Ganancia tensión en surtidor común (Cont.)

$$Si\ r_{ds} << R_D // R_L \Rightarrow A_V \cong -\mu$$

$$|A_V| < \mu$$

$$Si\ r_{ds} >> R_D // R_L \Rightarrow A_V \cong -\frac{\mu}{r_{ds}} \times R_D // R_L$$

$$A_V \cong -g_m \times R_D // R_L$$

$$Si\ R_L << R_d$$

$$A_V = -g_m R_L$$

Ganancia corriente en surtidor común

$$A_i = A_V \frac{Z_i}{R_L} = -\mu \frac{R_D // R_L}{r_{ds} + R_D // R_L} \times \frac{R_G}{R_L}$$

$$= -\mu \frac{R_D R_G}{r_{ds} + R_D // R_L} \times \frac{1}{R_D + R_L}$$

$$Si \; R_D // R_L << r_{ds}$$

$$R_L << R_D$$

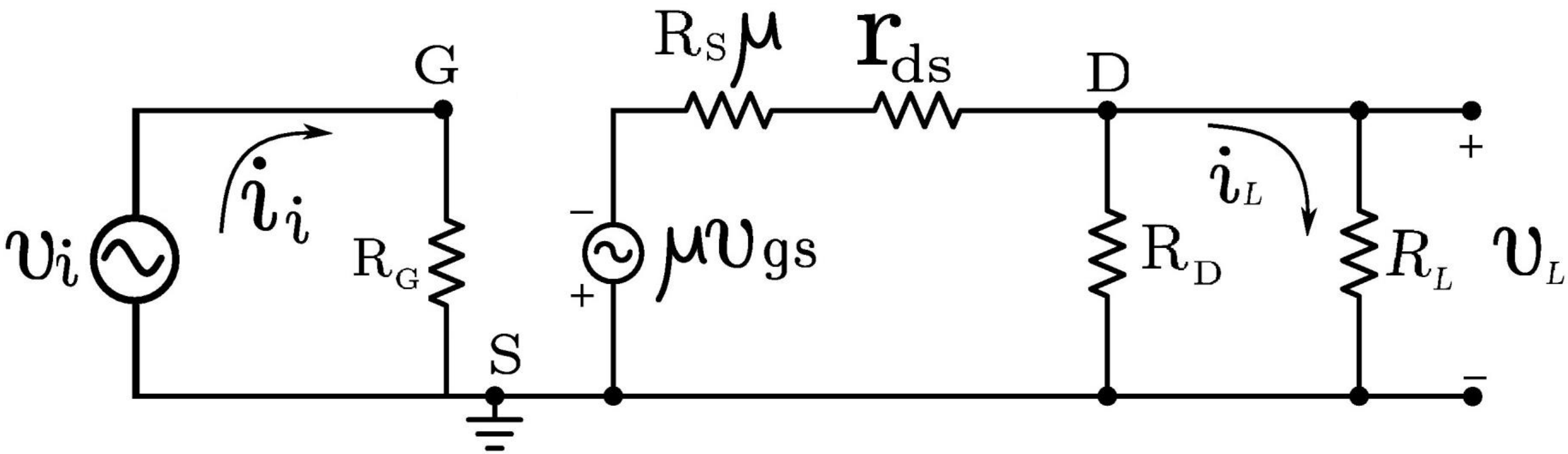
$$A_i \cong -g_m R_G$$

Reflexión de impedancia en transistores Bipolares y FET.

- Comparativa

	Reflexión	
Bipolares	$E - B$ $i_e >> i_b$ $h_{fe} + 1$	$v = cte = \overset{\uparrow}{\underset{\downarrow}{I}} . \overset{\downarrow}{\underset{\uparrow}{R}}$ $(h_{ie}\ esta\ en\ B)$
FET	$D - S$ $v_d >> v_s$ $\mu + 1$	$i = cte = \dfrac{V \uparrow\downarrow}{R \uparrow\downarrow}$ $(r_{ds}\ esta\ en\ D)$

Surtidor Común Sin Capacitor de Desacople. Impedancias de Entrada y Salida.



$$Z_i = R_G$$

$$Z_o = R_d \, / / \left[r_{ds} + \mu R_S \right]$$

Surtidor Común Sin Capacitor de Desacople. Ganancia de Tensión y Corriente.

$$A_V = \frac{v_L}{v_i}$$

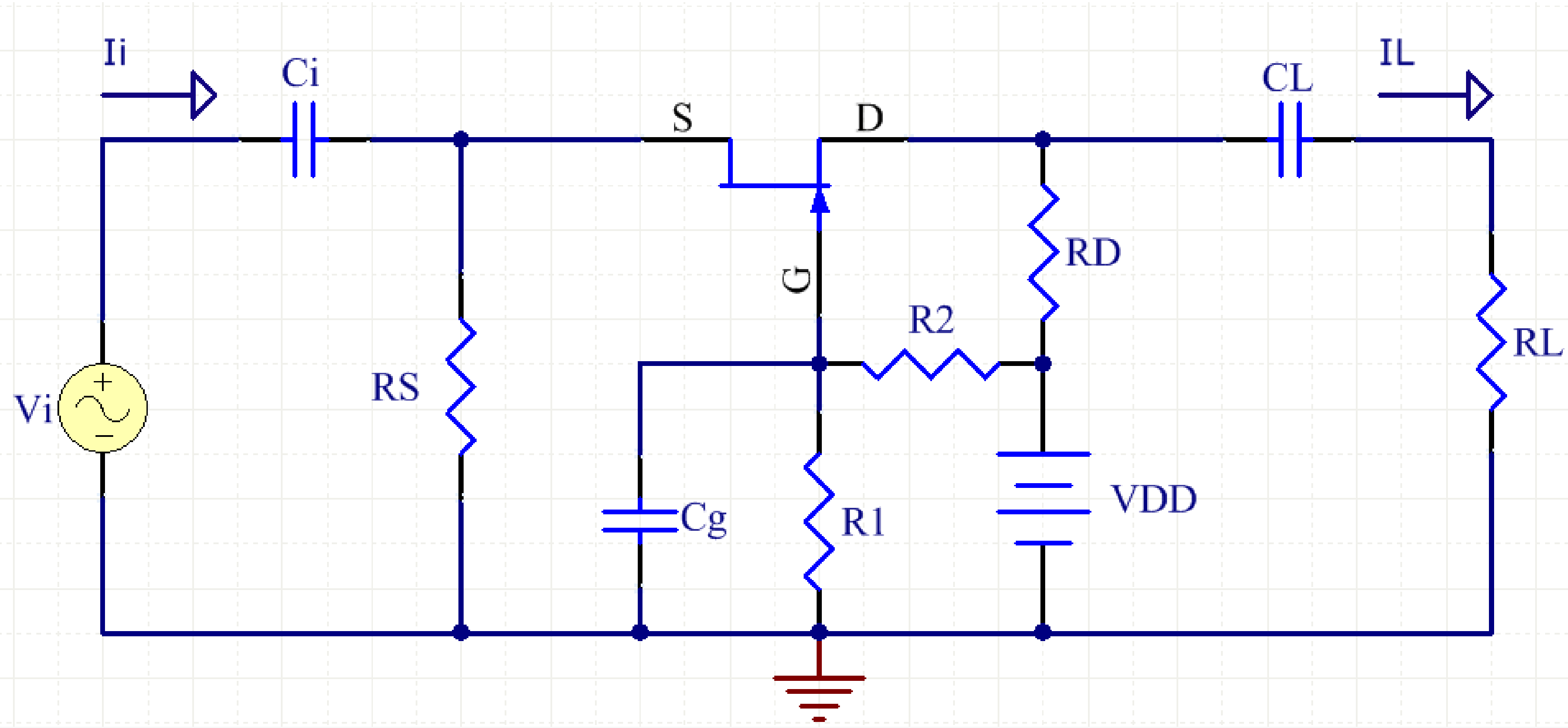
$$v_L = \frac{-\mu v_{gs}}{\mu R_S + r_{ds} + R_D // R_L} \times R_D // R_L \Rightarrow \frac{v_L}{v_{gs}} = -\mu \times \frac{R_D // R_L}{\mu R_S + r_{ds} + R_D // R_L}$$

$$como\ v_{gs} = v_i$$

$$A_V = -\mu \times \frac{R_D // R_L}{\mu R_S + r_{ds} + R_D // R_L}$$

$$A_i = \frac{i_L}{i_i} = \frac{\frac{v_L}{R_L}}{\frac{v_i}{z_i}} = \frac{v_L}{R_L}\frac{z_i}{v_i} = \frac{v_L}{v_i}\frac{z_i}{R_L} = A_V \frac{z_i}{R_L}$$

Etapa amplificadora con FET. Compuerta Común.



Etapa amplificadora con FET.
Compuerta Común. Ecuaciones de C.C

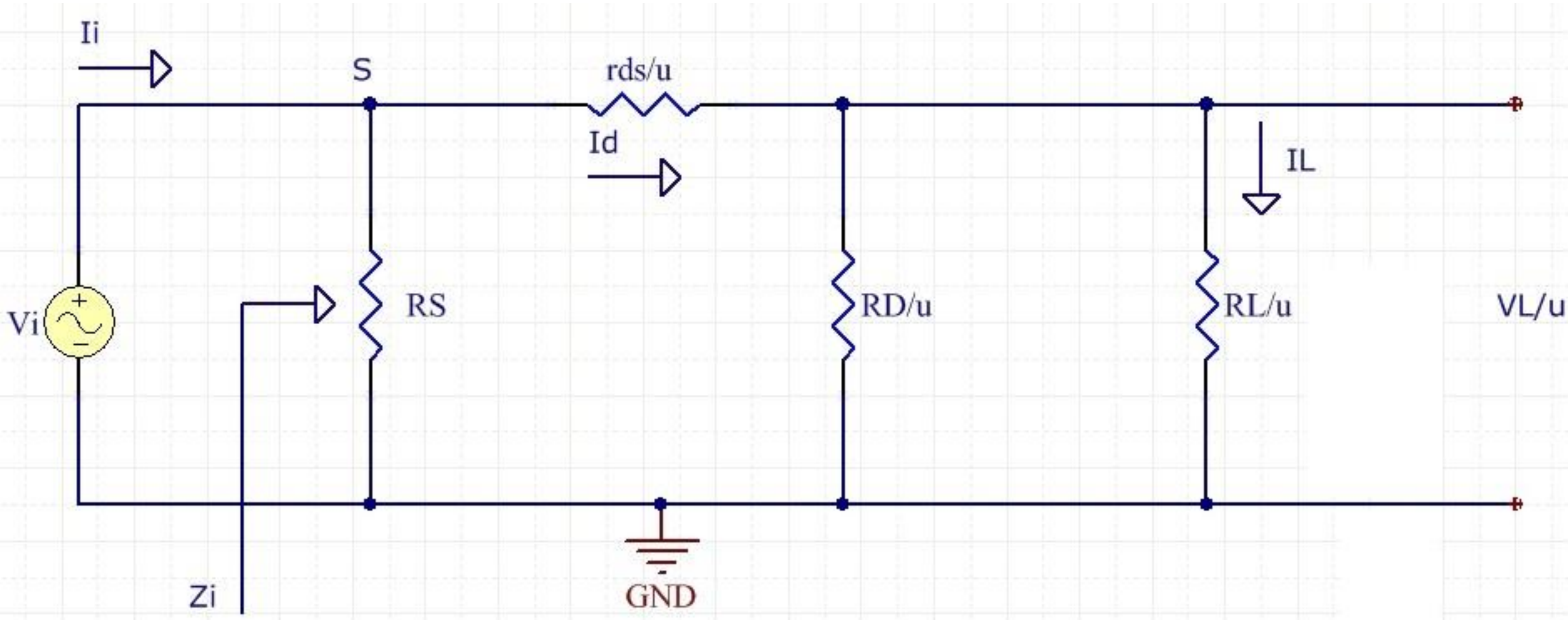
$$I_{DQ(MES)} = \frac{V_{DD}}{R_D + R_S + R_D // R_L + R_S}$$

$$V_{DSQ} = V_{DD} - I_{DQ}(R_D + R_S)$$

$$V_{GSQ} = V_{GG} - I_{DQ} R_S$$

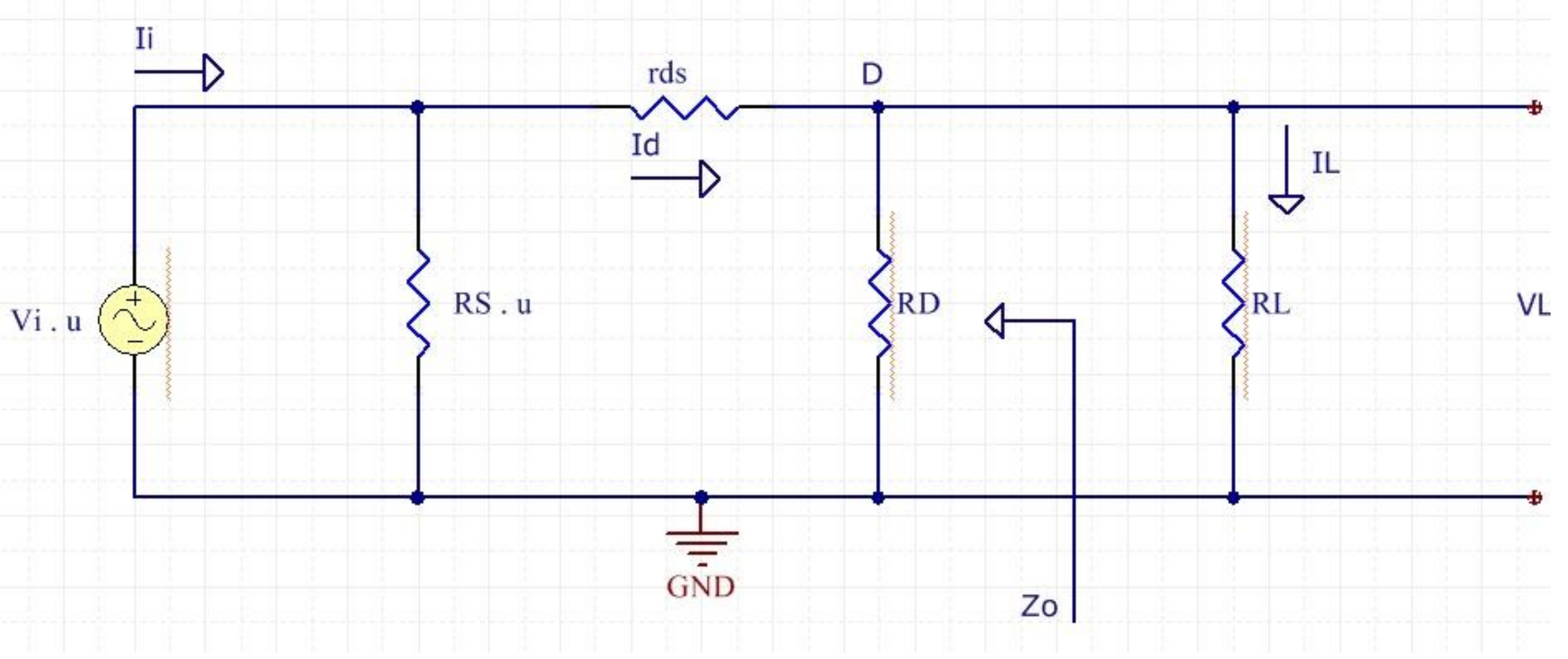
$$Donde\ V_{GG} = \frac{V_{DD}}{R_1 + R_2} R_1$$

Circuito Equivalente de Amplif. Compuerta Común. Reflejado al Surtidor.



$$Z_i = R_S \,//\left(\frac{r_{ds} + R_D \,//R_L}{\mu}\right)$$

Circuito Equivalente de Amplif. Compuerta Común. Reflejado al Drenador.



$$Sin\ \ r_i :\ Z_O = R_D\ //\ r_{ds}$$

$$Con\ r_i :\ Z_O = R_D\ //\left[\left(R_S\ //\ r_i\right)\mu + r_{ds}\right]$$

Etapa amplificadora con FET. Compuerta Común. Ganancia de Corriente

$$A_i = \frac{i_L}{i_i} = \frac{i_L}{i_d}\frac{i_d}{i_i}$$

$$i_L = i_d \frac{R_D \cancel{R_L}}{R_D + R_L}\frac{1}{\cancel{R_L}} \Rightarrow \frac{i_L}{i_d} = \frac{R_D}{R_D + R_L}$$

$$i_d = i_i \frac{\mu R_S \times (r_{ds} + R_D // R_L)}{\mu R_S + r_{ds} + R_D // R_L} \times \frac{1}{(r_{ds} + R_D // R_L)} \Rightarrow \frac{i_d}{i_i} = \frac{\mu R_S}{\mu R_S + r_{ds} + R_D // R_L}$$

$$A_i = \frac{R_D}{R_D + R_L} \times \frac{\mu R_S}{R_S \mu + r_{ds} + R_D // R_L}$$

$$A_i < 1$$

Etapa amplificadora con FET. Ganancia de Tensión

$$A_V = \frac{v_L}{v_i} = \frac{i_L R_L}{i_i Z_i} = A_i \frac{R_L}{Z_i}$$

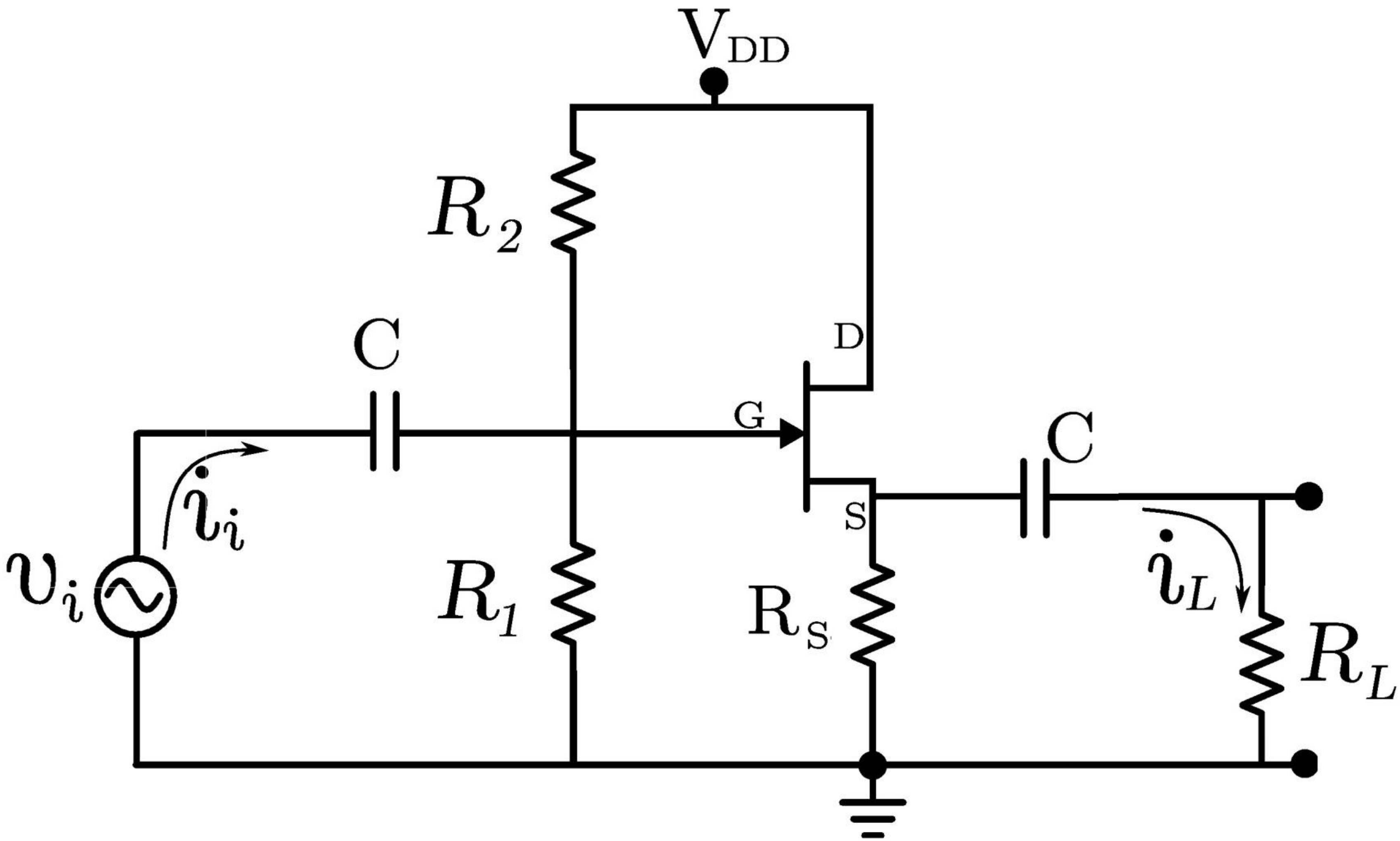
$$A_V = \frac{R_D}{R_D + R_L} \times \frac{\mu R_S}{R_S \mu + r_{ds} + R_D // R_L} \times \frac{R_L}{Z_i}$$

$$A_V = \frac{R_D}{R_D + R_L} \times \frac{\mu R_S}{R_S \mu + r_{ds} + R_D // R_L} \times \frac{R_L}{R_S // \left(\frac{r_{ds} + R_D // R_L}{\mu} \right)}$$

$$A_V = \frac{R_D}{R_D + R_L} \times \frac{\mu \cancel{R_S}}{R_S \mu + r_{ds} + R_D // R_L} \times \frac{R_L}{\frac{\cancel{R_S} \times \cancel{\mu} \left(\frac{r_{ds} + R_D // R_L}{\cancel{\mu}} \right)}{R_S \mu + \cancel{\mu} \left(\frac{r_{ds} + R_D // R_L}{\cancel{\mu}} \right)}}$$

$$= \frac{R_D // R_L}{r_{ds} + R_D // R_L} \mu$$

Etapa amplificadora Drenador Común



Diseño para M.E.S

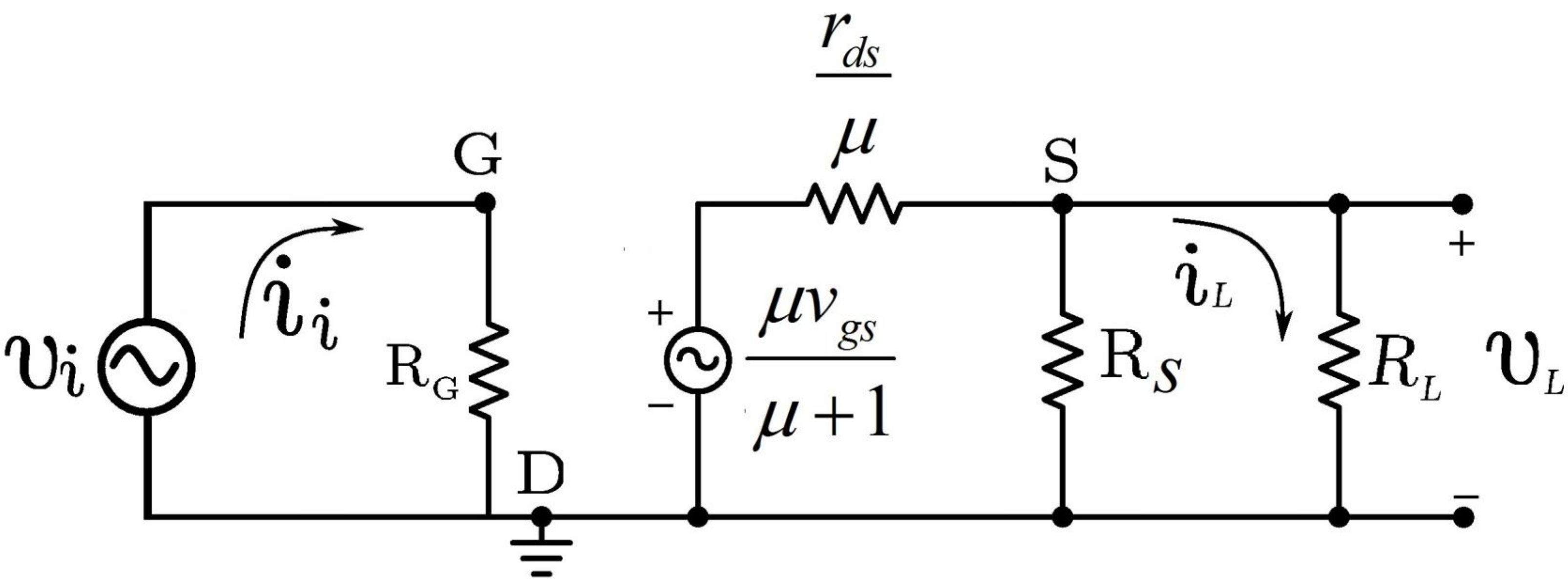
$$I_{DQ(MES)} = \frac{V_{DD}}{R_S + R_S // R_L}$$

$$V_{DD} = V_{DSQ} + I_{DQ} R_S$$

$$V_{GSQ} = V_{GG} - I_{DQ} R_S$$

$$Donde,\ V_{GG} = \frac{V_{DD}}{R_1 + R_2} \times R_1$$

Circuito Equivalente



$$Z_i = R_G$$

$$Z_o = R_S \,//\, \frac{r_{ds}}{\mu}$$

Ganancia de tensión

$$A_V = \frac{v_L}{v_i} = \frac{v_L}{v_{gs}} \frac{v_{gs}}{v_i}$$

$$v_L = \frac{v_{gs}}{\frac{r_{ds}}{\mu} + R_S // R_L} \times R_S // R_L \Rightarrow \frac{v_L}{v_{gs}} = \frac{R_S // R_L}{\frac{r_{ds}}{\mu} + R_S // R_L}$$

$$v_{gs} = v_i \Rightarrow \frac{v_{gs}}{v_i} = 1$$

$$A_V = \frac{R_S // R_L}{\frac{r_{ds}}{\mu} + R_S // R_L}$$

Ganancia de Corriente y Potencia

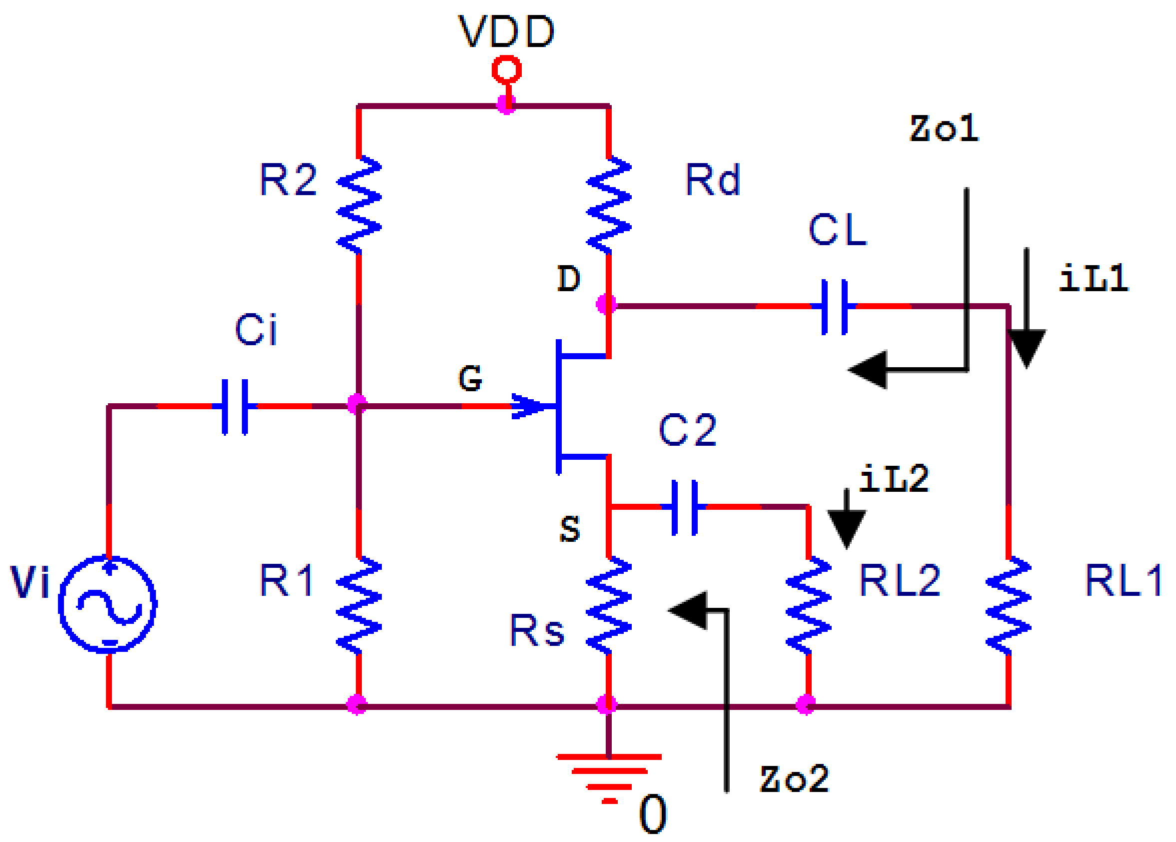
$$A_i = \frac{i_L}{i_i} = \frac{\dfrac{v_L}{R_L}}{\dfrac{v_i}{Z_i}} = \frac{v_L}{R_L}\frac{Z_i}{v_i} = \frac{v_L}{v_i}\frac{Z_i}{R_L} = A_V\frac{Z_i}{R_L}$$

$$A_i = \frac{R_S\,//\,R_L}{\dfrac{r_{ds}}{\mu} + R_S\,//\,R_L}\frac{R_G}{R_L}$$

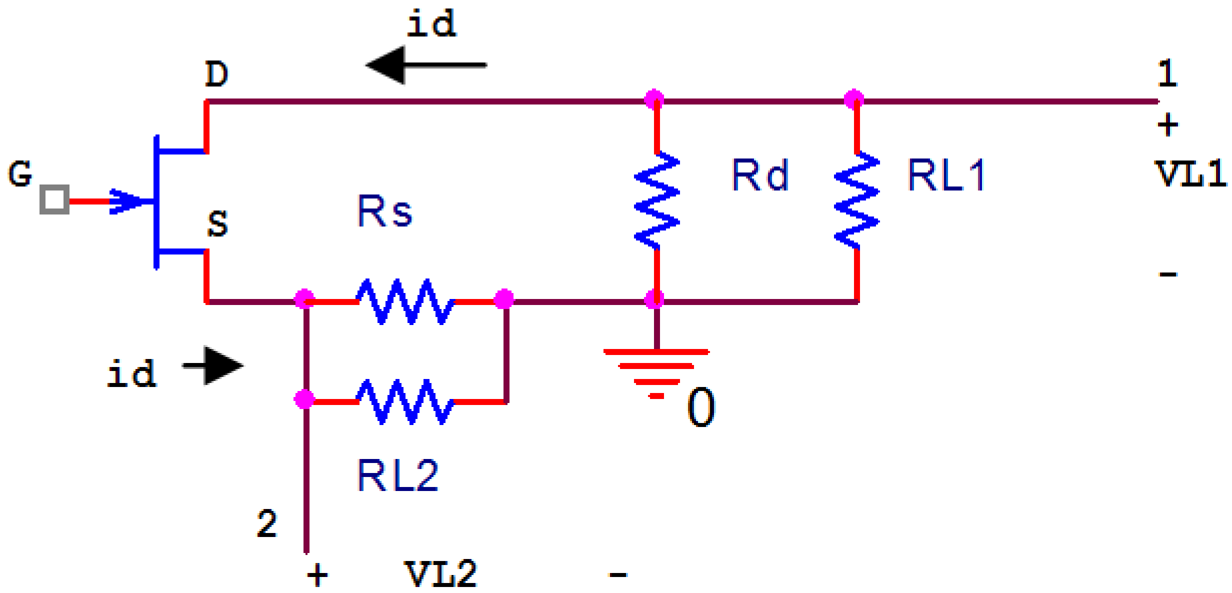
$$A_P = A_V A_i$$

Circuito Inversor de Fase

Tiene dos salidas de igual amplitud pero opuestas en fase.



Circuito para señal alterna.



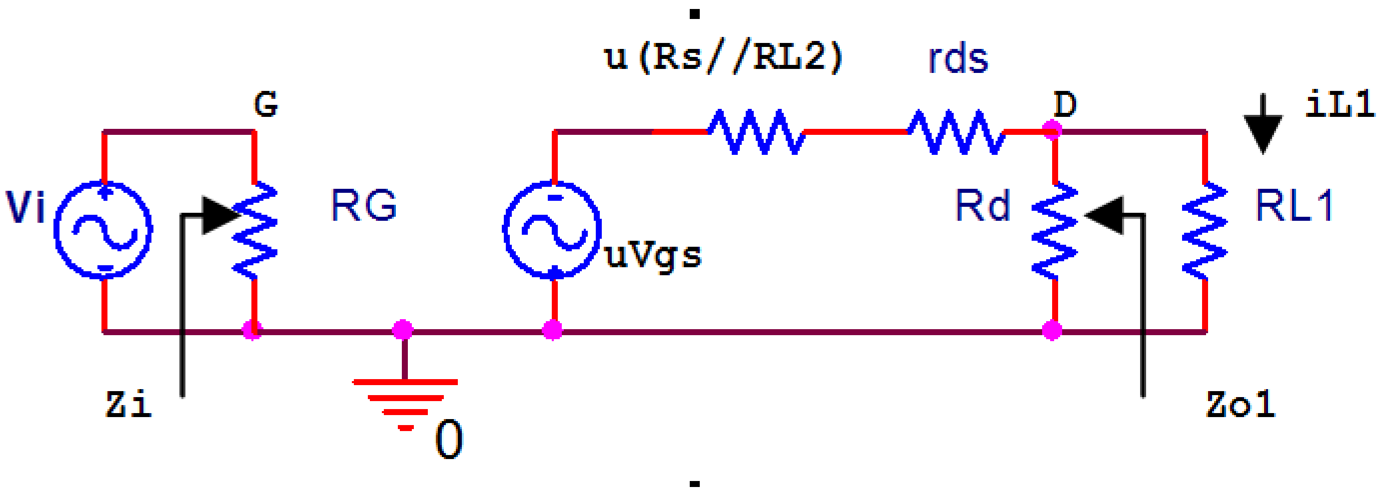
$$v_{L_1} = -i_d (R_D // R_{L_1})$$

$$v_{L_2} = i_d (R_S // R_{L_2})$$

$$v_{L_2} = -v_{L_1} \Rightarrow INVERSOR.$$

$$R_D // R_{L_1} = R_S // R_{L_2} \quad Condicion\ de\ inversor\ de\ fase.$$

Circuito Equivalente reflejado en el Drenador



$$Z_i = R_G$$

$$Z_{O_1} = R_D \, / / \left[r_{ds} + \mu (R_S \, / / R_{L_2}) \right]$$

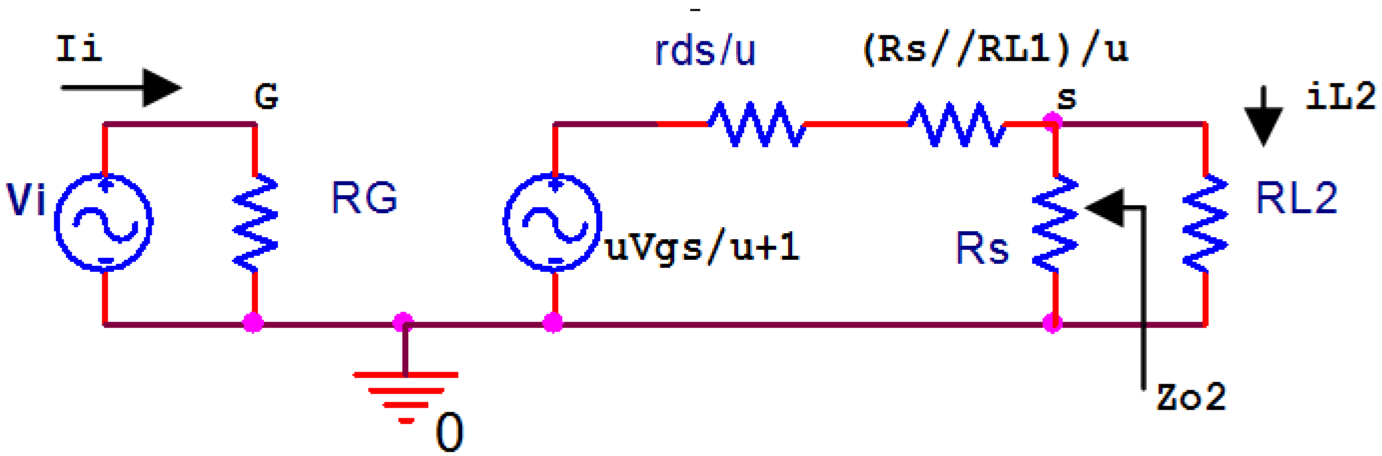
Ganancia de tensión Av1.

$$A_{V_1} = \frac{v_{L_1}}{v_i} = \frac{v_{L_1}}{v_{gs}} \frac{v_{gs}}{v_i}$$

$$v_{L_1} = \frac{-\mu v_{gs}}{(R_S // R_{L_2})\mu + r_{ds} + R_D // R_{L_1}} \times R_D // R_{L_1}$$

$$A_{V_1} = \frac{-\mu (R_D // R_{L_1})}{(R_S // R_{L_2})\mu + r_{ds} + R_D // R_{L_1}} < 1$$

Circuito Equivalente reflejado en el Surtidor



$$Z_{O_2} = R_S \, // \left[\frac{r_{ds} + (R_D \, // \, R_{L_1})}{\mu} \right]$$

Ganancia de tensión Av2.

$$A_{V_2} = \frac{v_{L_2}}{v_{gs}} = \frac{1}{\dfrac{r_{ds}}{\mu} + \dfrac{R_S // R_{L_2}}{\mu} + R_S // R_{L_2}} (R_S // R_{L_2})$$

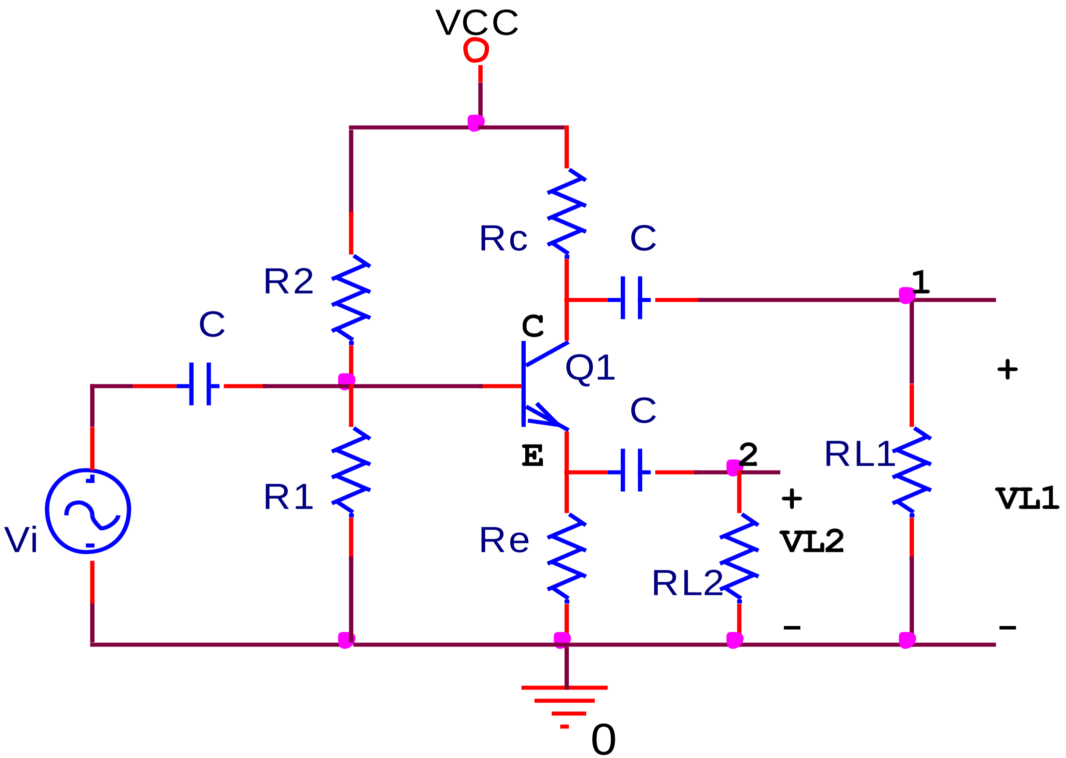
$$A_{V_2} = \frac{\mu (R_S // R_{L_2})}{r_{ds} + R_S // R_{L_2} + \mu (R_S // R_{L_2})}$$

Comparativa de Ganancias

$$A_{V_1} = \frac{-\mu(R_D // R_{L_1})}{(R_S // R_{L_2})\mu + r_{ds} + R_D // R_{L_1}}$$

$$A_{V_2} = \frac{\mu(R_S // R_{L_2})}{(R_S // R_{L_2})\mu + r_{ds} + R_S // R_{L_2}}$$

Inversor de Fase con Transistor Bipolar



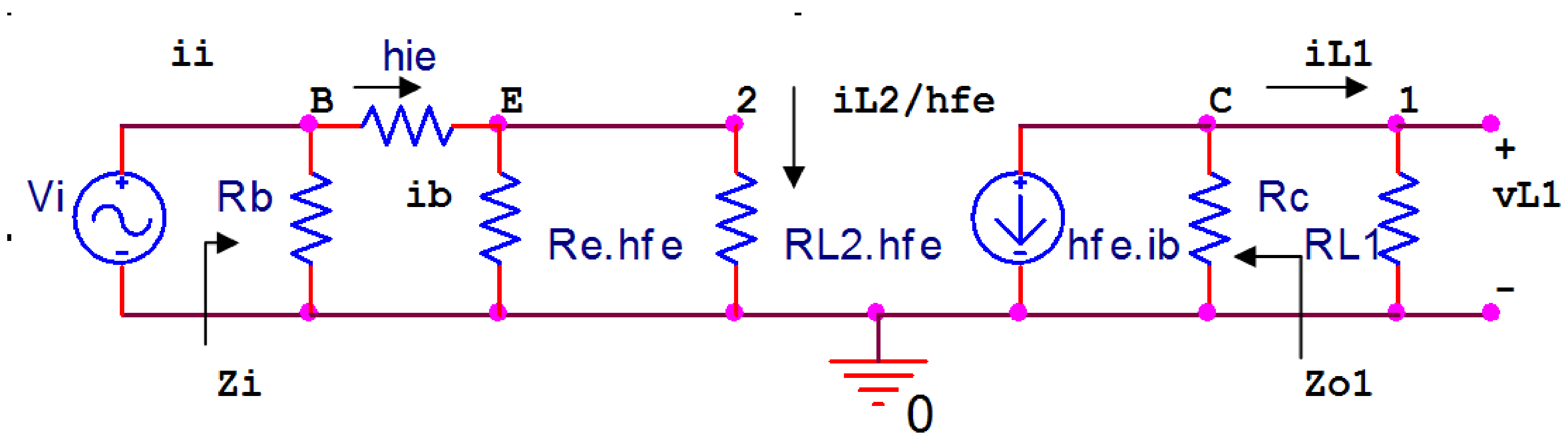
$$Condicion\ de\ inversor:$$

$$R_C // R_{L_1} = R_E // R_{L_2}$$

$$v_{L_1} = -v_{L_2}$$

$$i_C (R_C // R_{L_1}) = -i_C (R_E // R_{L_2})$$

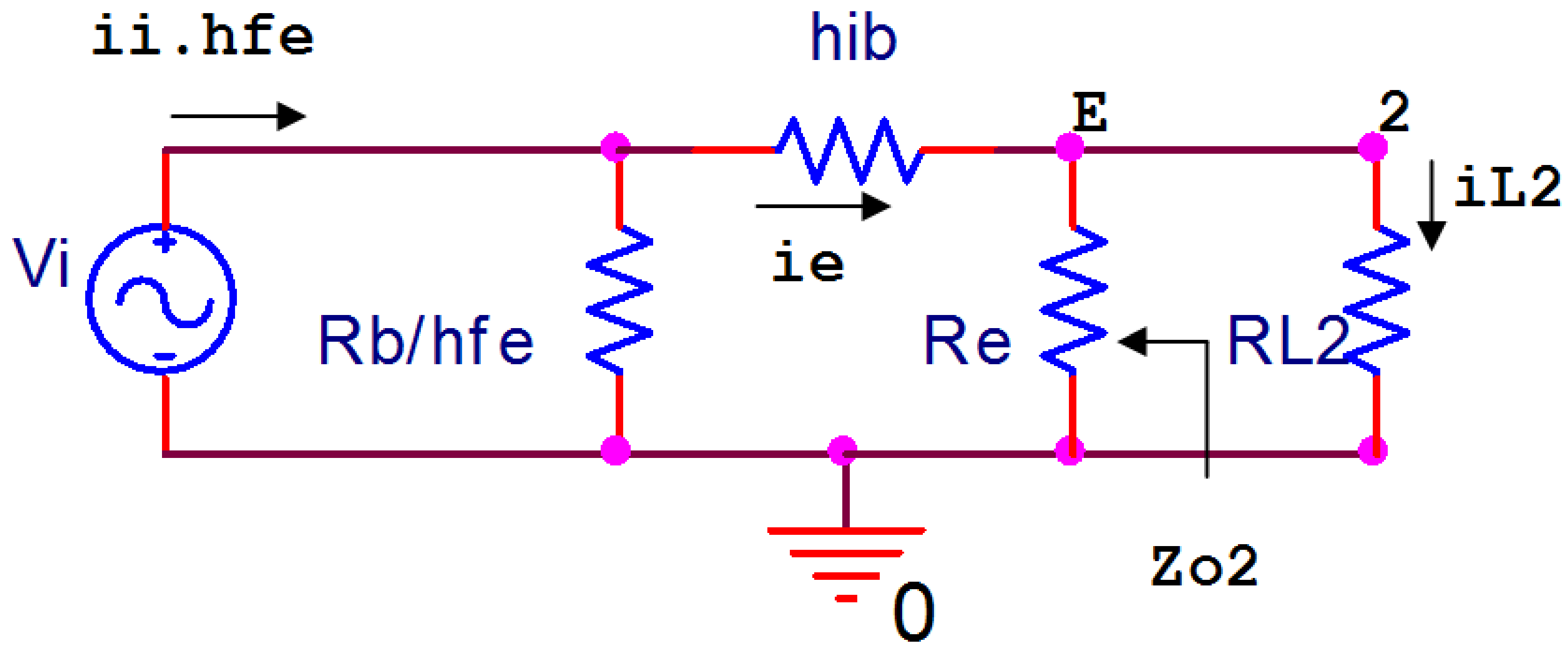
Inversor de Fase con Transistor Bipolar



$$Z_i = R_B // \left[h_{ie} + (R_E // R_{L_2}) h_{fe} \right]$$

$$Z_{O_1} = R_C$$

Inversor de Fase con Transistor Bipolar



$$Z_{O_2} = R_E \,/\,/ h_{ib}$$

Inversor de Fase con Transistor Bipolar

$$A_{V_1} = \frac{v_{L_1}}{v_i} = \frac{v_{L_1}}{i_b}\frac{i_b}{v_i}$$

$$v_{L_1} = -i_b h_{fe}\frac{R_C R_{L_1}}{R_C + R_{L_1}} \Rightarrow \frac{v_{L_1}}{i_b} = -h_{fe}\frac{R_C R_{L_1}}{R_C + R_{L_1}}$$

$$i_b = \frac{v_i}{h_{ie} + (R_e // R_{L_2})h_{fe}} \Rightarrow \frac{i_b}{v_i} = \frac{1}{h_{ie} + (R_e // R_{L_2})h_{fe}}$$

$$A_{V_1} = -h_{fe}\frac{R_C R_{L_1}}{R_C + R_{L_1}} \times \frac{1}{h_{ie} + (R_e // R_{L_2})h_{fe}}$$

Inversor de Fase con Transistor Bipolar

$$A_{V_2} = \frac{v_{L_2}}{v_i}$$

$$v_{L_2} = \frac{v_i}{h_{ie} + \left(\mathrm{R}_e // R_{L_2}\right) h_{fe}} \times \left(R_e // R_{L_2}\right) h_{fe} \Rightarrow$$

$$\frac{v_{L_2}}{v_i} = \frac{\left(R_e // R_{L_2}\right) h_{fe}}{h_{ie} + \left(\mathrm{R}_e // R_{L_2}\right) h_{fe}}$$

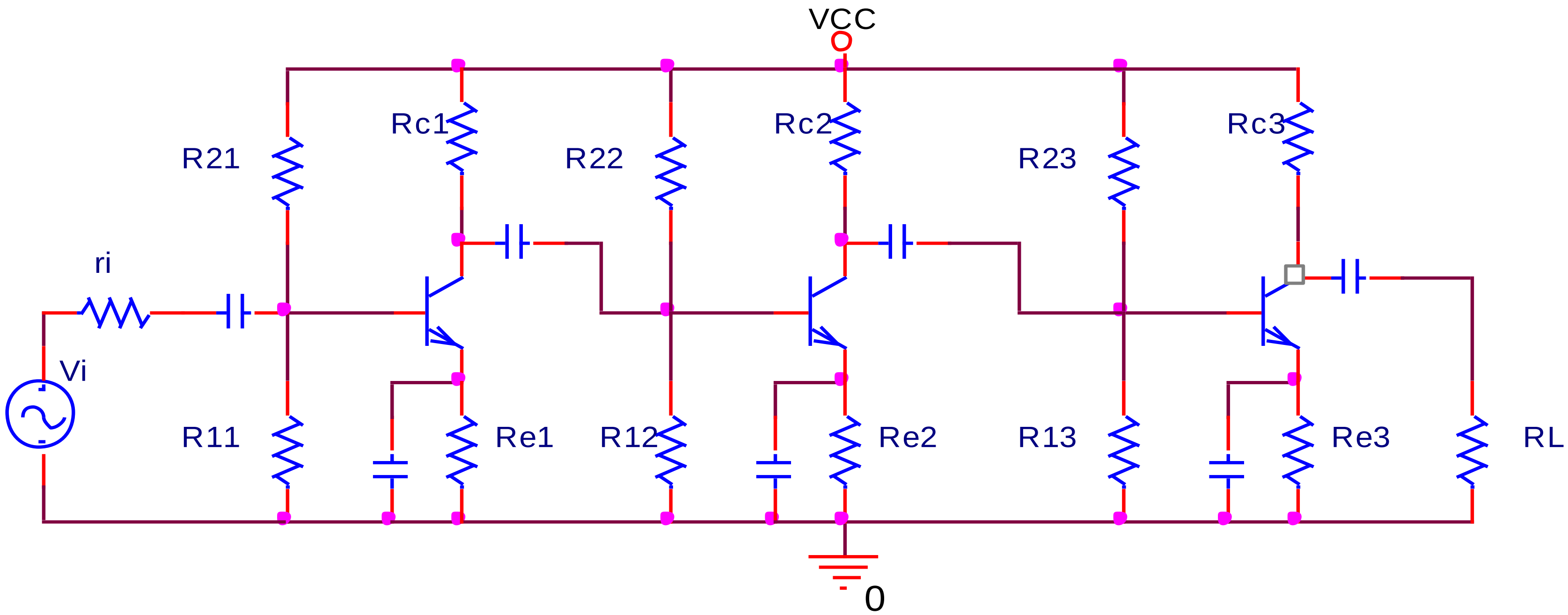
$$A_{V_2} = h_{fe} \frac{R_e R_{L_2}}{R_e + R_{L_2}} \times \frac{1}{h_{ie} + \left(\mathrm{R}_e // R_{L_2}\right) h_{fe}}$$

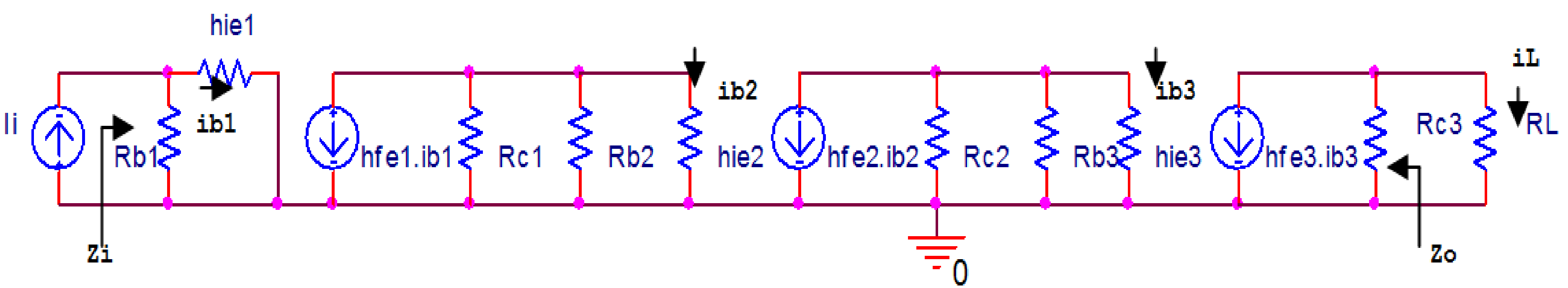
Comparativa de Ganancias

$$A_{V_1} = -h_{fe}\frac{R_C R_{L_1}}{R_C + R_{L_1}} \times \frac{1}{h_{ie} + (R_e // R_{L_2})h_{fe}}$$

$$A_{V_2} = h_{fe}\frac{R_e R_{L_2}}{R_e + R_{L_2}} \times \frac{1}{h_{ie} + \left(\mathrm{R}_e // R_{L_2}\right)h_{fe}}$$

Amplificador Multietapas





Amplificador Multietapas

$$A_i = \frac{i_L}{i_{b_3}} \frac{i_{b_3}}{i_{b_2}} \frac{i_{b_2}}{i_{b_1}} \frac{i_{b_1}}{i_i}$$

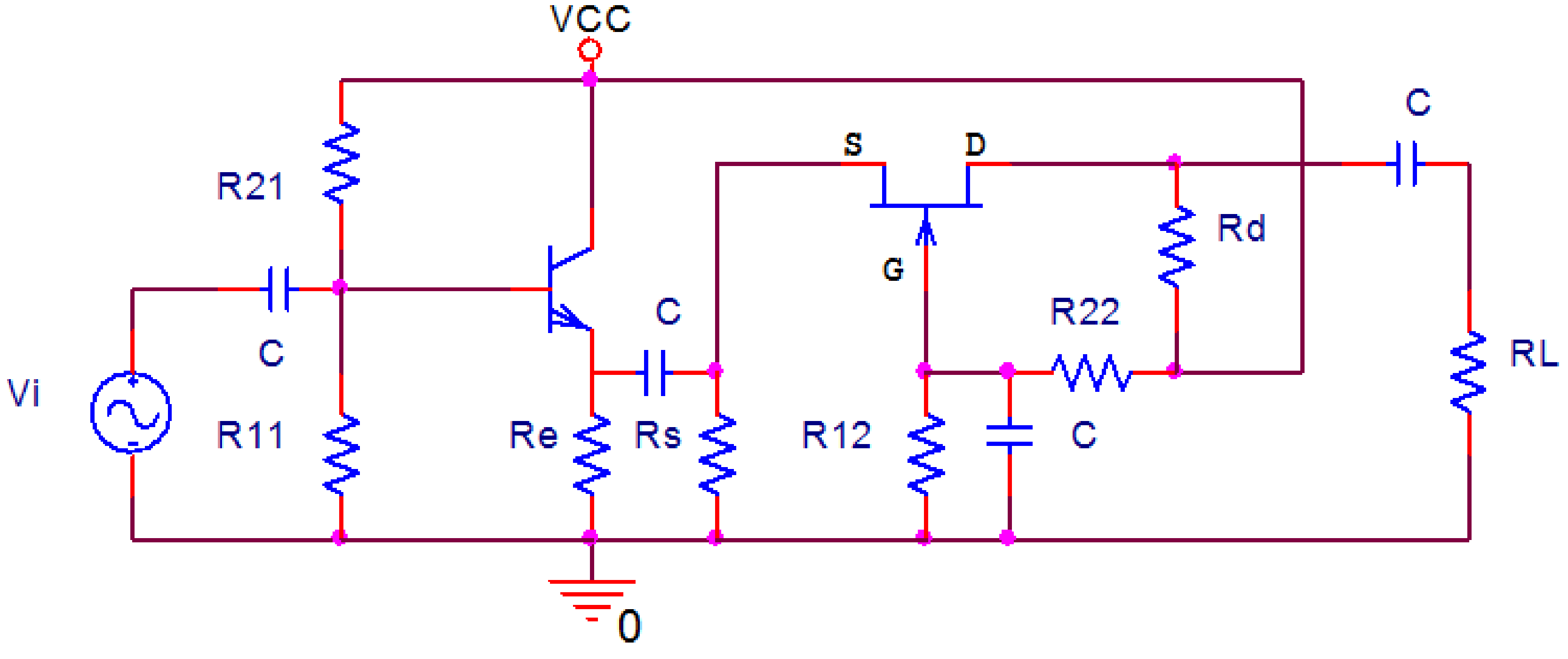
$$= (-h_{fe3}) \frac{R_{C_3}}{R_{C_3} + R_L} (-h_{fe2}) \frac{R'_{b3}}{R'_{b3} + h_{ie3}} (-h_{fe1}) \frac{R'_{b2}}{R'_{b2} + h_{ie2}} \frac{R_{b1}}{R_{b1} + h_{ie1}}$$

$$Si \begin{cases} R_L << R_{C_3} \\ h_{ie3} << R'_{b3} \\ h_{ie2} << R'_{b2} \\ h_{ie1} << R_{b1} \end{cases} \Rightarrow A_i = (-h_{fe})^n \begin{cases} si\ n\ es\ par\ A_i = h_{fe}{}^n \\ si\ n\ es\ impar\ A_i = -h_{fe}{}^n \end{cases}$$

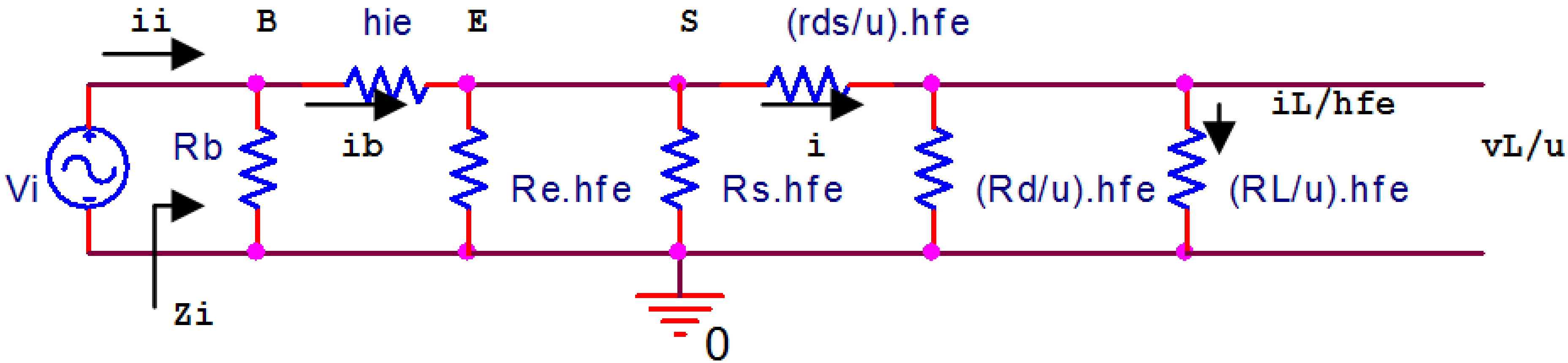
$$Z_O = R_{C3}$$

$$Z_i = R_{b1} // h_{ie1}$$

Colector Común-Compuerta Común

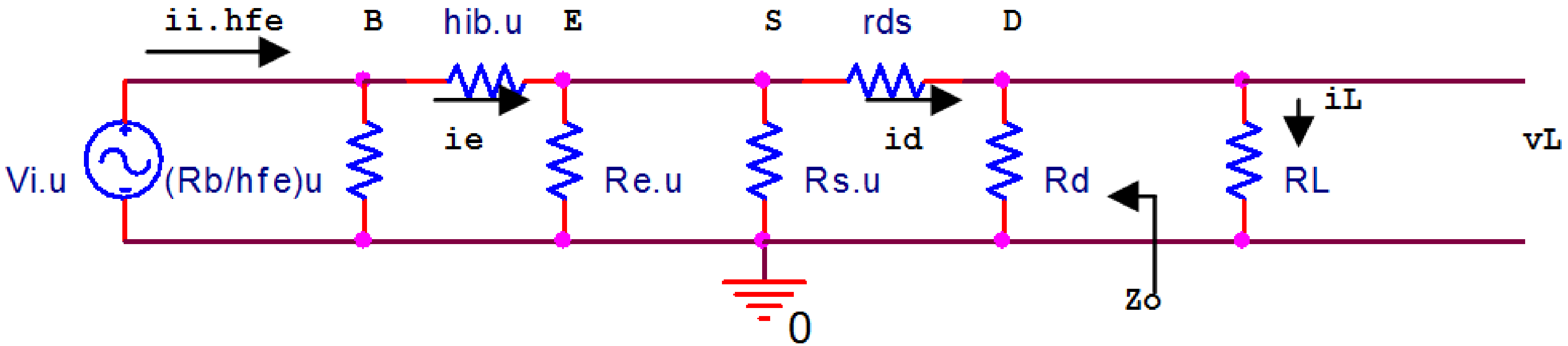


Circuito Equivalente Reflejado en la Base



$$Z_i = R_b \,//\, \left\{ h_{ie} + \left[\left(R_e \,//\, R_S \right) h_{fe} \,//\, \left(\frac{r_{ds} + R_d \,//\, R_L}{\mu} \right) h_{fe} \right] \right\}$$

Circuito Equivalente reflejado en el Drenador



$$Z_O = R_d \, // \left[r_{ds} + \left(R_e \, // R_S \right) \mu \, // \frac{h_{ie}}{h_{fe}} \mu \right]$$

$Con\ r_i$

$$Z_O = R_d \, // \left[r_{ds} + \left(R_e \, // R_S \right) \mu \, // \left(\frac{h_{ie}}{h_{fe}} \mu + \frac{r_i \, // R_b}{h_{fe}} \mu \right) \right]$$

Ganancia de Corriente

$$A_i = \frac{i_L}{i_i} = \frac{i_L}{i_d}\frac{i_d}{i_e}\frac{i_e}{i_i}$$

$$i_L = i_d \frac{R_d \cancel{R_L}}{R_d + R_L}\frac{1}{\cancel{R_L}} \Rightarrow \frac{i_L}{i_d} = \frac{R_d}{R_d + R_L}$$

$$i_d = i_e \frac{\left[\left(R_e //R_S\right)\mu\right]//\left[r_{ds} + \left(R_d //R_L\right)\right]}{r_{ds} + \left(R_d //R_L\right)} \Rightarrow \frac{i_d}{i_e} = \frac{\left[\left(R_e //R_S\right)\mu\right]//\left[r_{ds} + \left(R_d //R_L\right)\right]}{r_{ds} + \left(R_d //R_L\right)}$$

$$i_e = i_i h_{fe} \frac{\dfrac{R_b}{h_{fe}}\mu //\left\{h_{ib}\mu + \left[\left(R_e //R_S\right)\mu //\left(r_{ds} + R_d //R_L\right)\right]\right\}}{\left\{h_{ib}\mu + \left[\left(R_e //R_S\right)\mu //\left(r_{ds} + R_d //R_L\right)\right]\right\}}$$

$$\frac{i_e}{i_i} = h_{fe} \frac{\dfrac{R_b}{h_{fe}}\mu //\left\{h_{ib}\mu + \left[\left(R_e //R_S\right)\mu //\left(r_{ds} + R_d //R_L\right)\right]\right\}}{\left\{h_{ib}\mu + \left[\left(R_e //R_S\right)\mu //\left(r_{ds} + R_d //R_L\right)\right]\right\}}$$

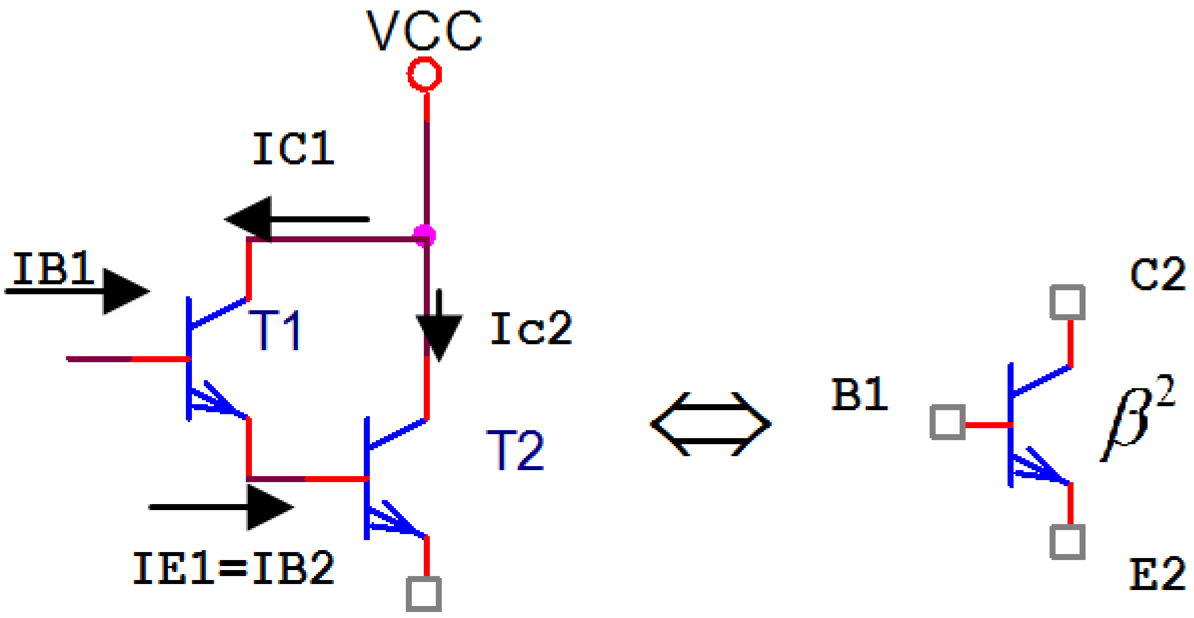
Ganancias de Ai, Av y Ap

$$A_i = \frac{R_d}{R_d + R_L} \frac{\left[\left(R_e // R_S\right)\mu\right] // \left[r_{ds} + \left(R_d // R_L\right)\right]}{r_{ds} + \left(R_d // R_L\right)} h_{fe} \frac{\frac{R_b}{h_{fe}}\left\{h_{ib}\mu + \left[\left(R_e // R_S\right)\mu // \left(r_{ds} + R_d // R_L\right)\right]\right\}}{\left\{h_{ib}\mu + \left[\left(R_e // R_S\right)\mu // \left(r_{ds} + R_d // R_L\right)\right]\right\}}$$

$$A_V = \frac{v_L}{v_i} = \frac{i_L R_L}{i_i Z_i} = A_i \frac{R_L}{Z_i}$$

$$A_P = A_V A_i$$

Par Darlington



$$I_{E_1} \cong I_{C_1} \cong I_{B_2}$$

$$En\ C.C: \qquad I_{C_2} \cong \beta_1 \beta_2 I_{B_1}$$

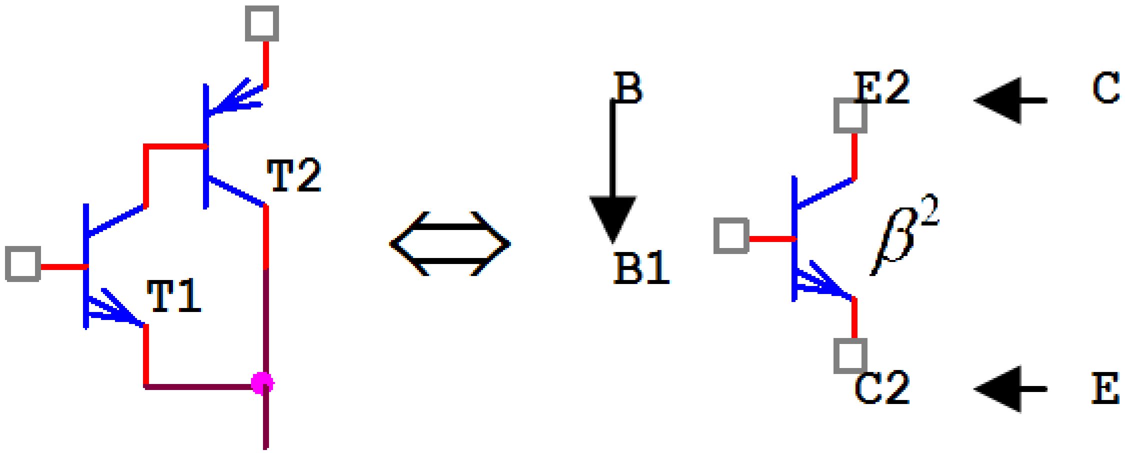
$$En\ C.A: \qquad i_{c_2} \cong h_{fe1} h_{fe2} i_{b_1}$$

$$Si\ \mathrm{T1}\ y\ \mathrm{T2}\ son\ iguales:$$

$$En\ C.C: \qquad I_{C_2} \cong \beta^2 I_{B_1}$$

$$En\ C.A: \qquad i_{c_2} \cong h_{fe}^2 i_{b_1}$$

Par Complementario (PNP y NPN)



$$Conexiones:$$

$$C_1 = B_2$$

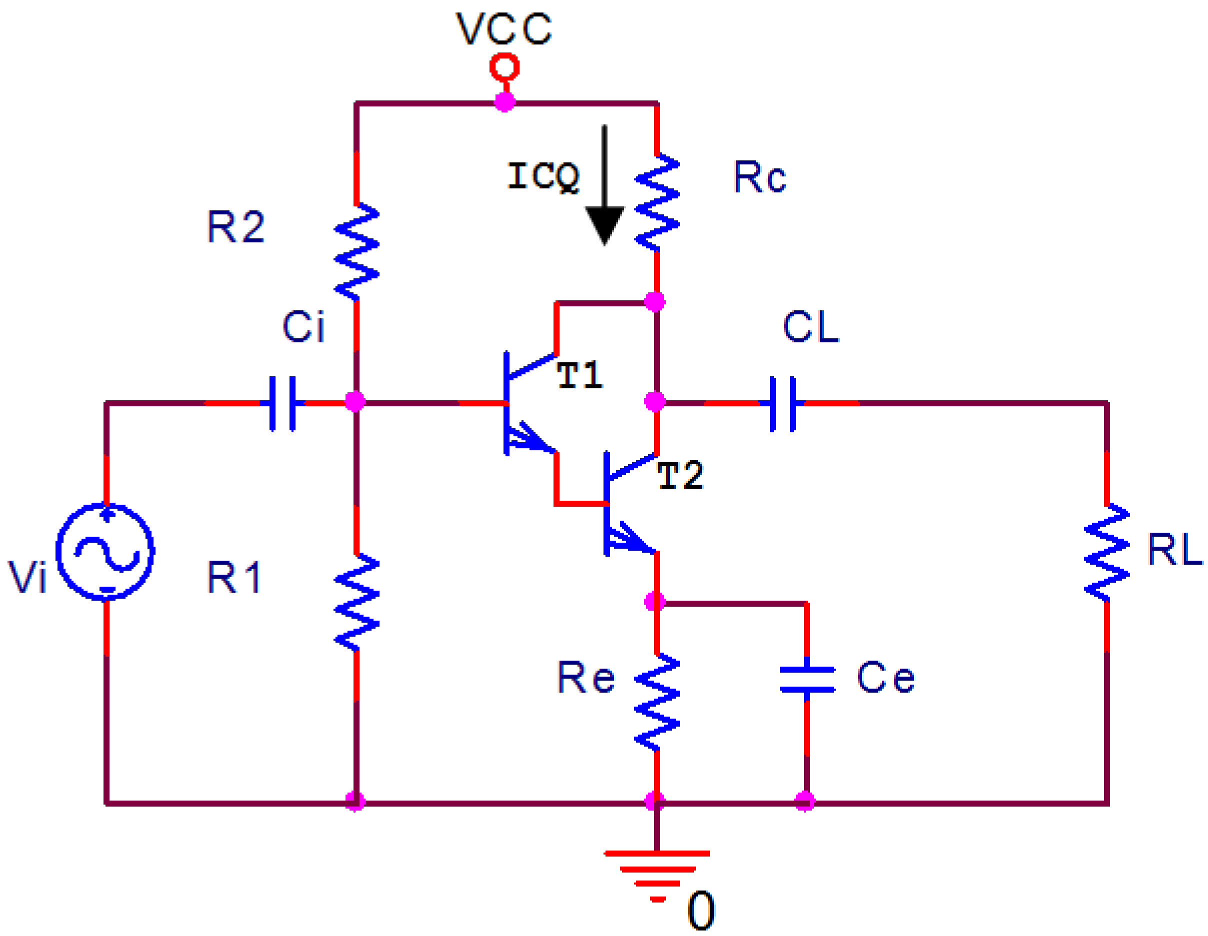
$$E_1 = C_2$$

$$Corrientes:$$

$$En\ C.C: \qquad I_{C_2} = \beta^2 I_{B_1}$$

$$En\ C.A: \qquad i_{c_2} = h_{fe}^2 i_{b_1}$$

Amplificador Darlington. Salida por Colector



Analisis:

$$I_{CQ_2} = \frac{V_{BB} - 2V_{BE}}{\frac{R_b}{\beta^2} + R_e}$$

$$I_{BQ_2} = I_{CQ_1} = \frac{I_{CQ_2}}{\beta}$$

$$I_{BQ_1} = \frac{I_{CQ_1}}{\beta} = \frac{I_{CQ_2}}{\beta^2}$$

$$V_{CEQ_2} = V_{CC} - I_{CQ_2}\left(R_C + R_e\right)$$

$$V_{CEQ_1} = V_{CEQ_2} - V_{BE}$$

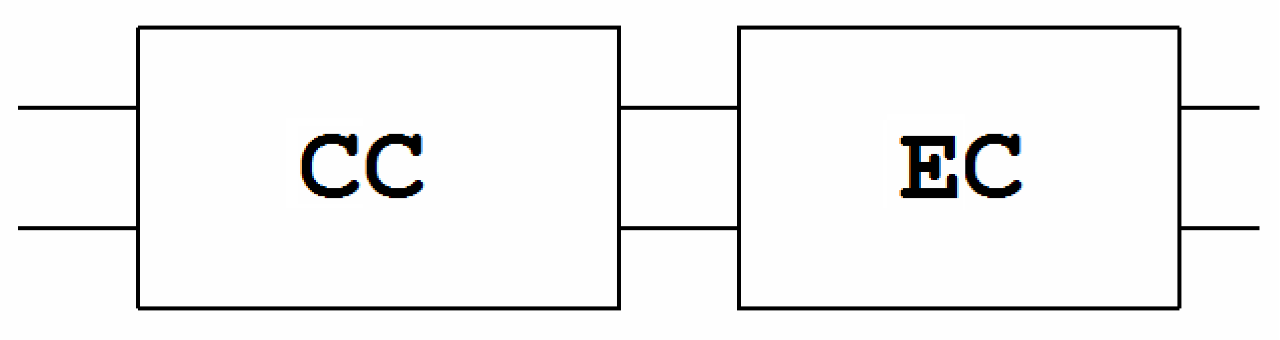
Diseño:

$$R_b = \frac{\beta^2 R_e}{10}$$

$$V_{BB} = \frac{I_{CQ_2}}{\beta^2} R_b + 2V_{be} + I_{CQ_2} R_e$$

Amplificador Darlington. Salida por Colector

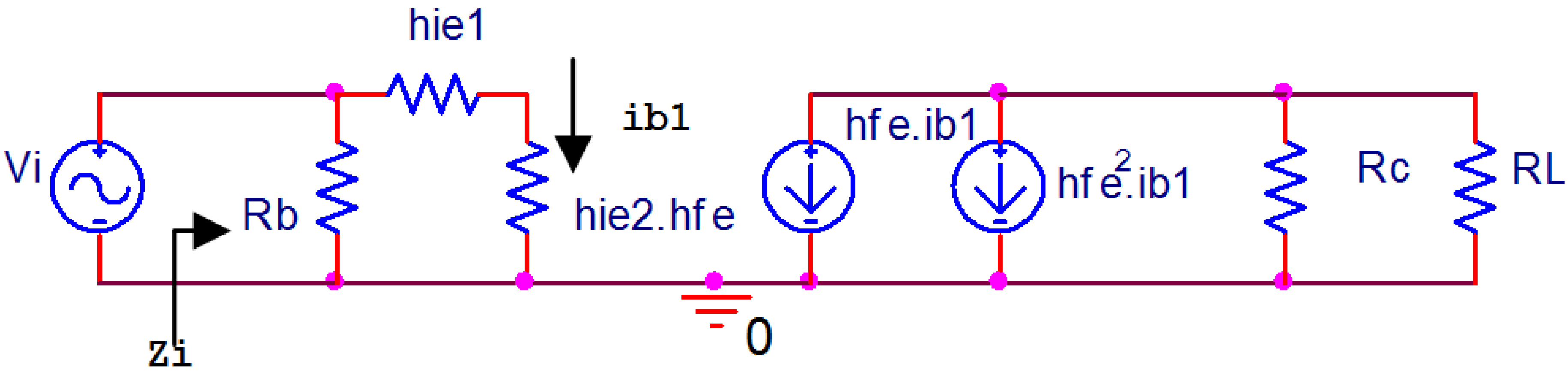
Para alterna tenemos:



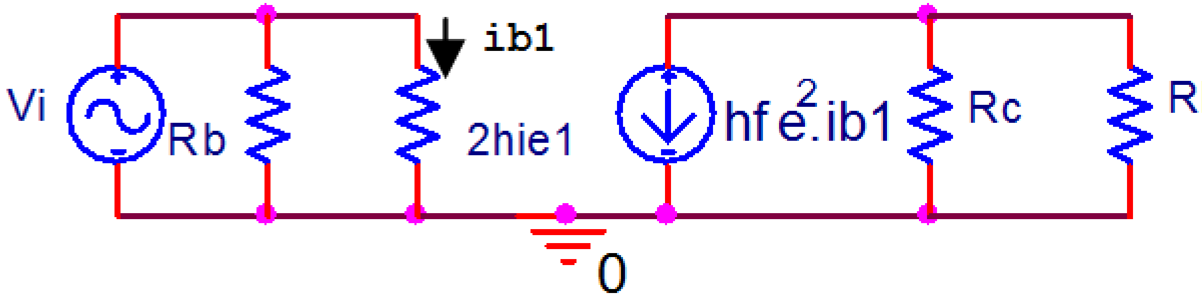
Tiene ganancia de corriente pero no de tension.

Tiene ganancia de corriente y de tension.

Circuito Equivalente para C.A



$$h_{ie_1} = \frac{25mV.h_{fe}}{I_{CQ_1}} = \frac{25mV.h_{fe}}{\frac{I_{CQ_2}}{h_{fe}}} = \underbrace{\frac{25mV.h_{fe}}{I_{CQ_2}}}_{h_{ie_2}} h_{fe} = h_{ie_2} h_{fe}$$



Zi, Zo, Ai y Av

$$Z_i = R_b \,//\, 2h_{ie_1}$$

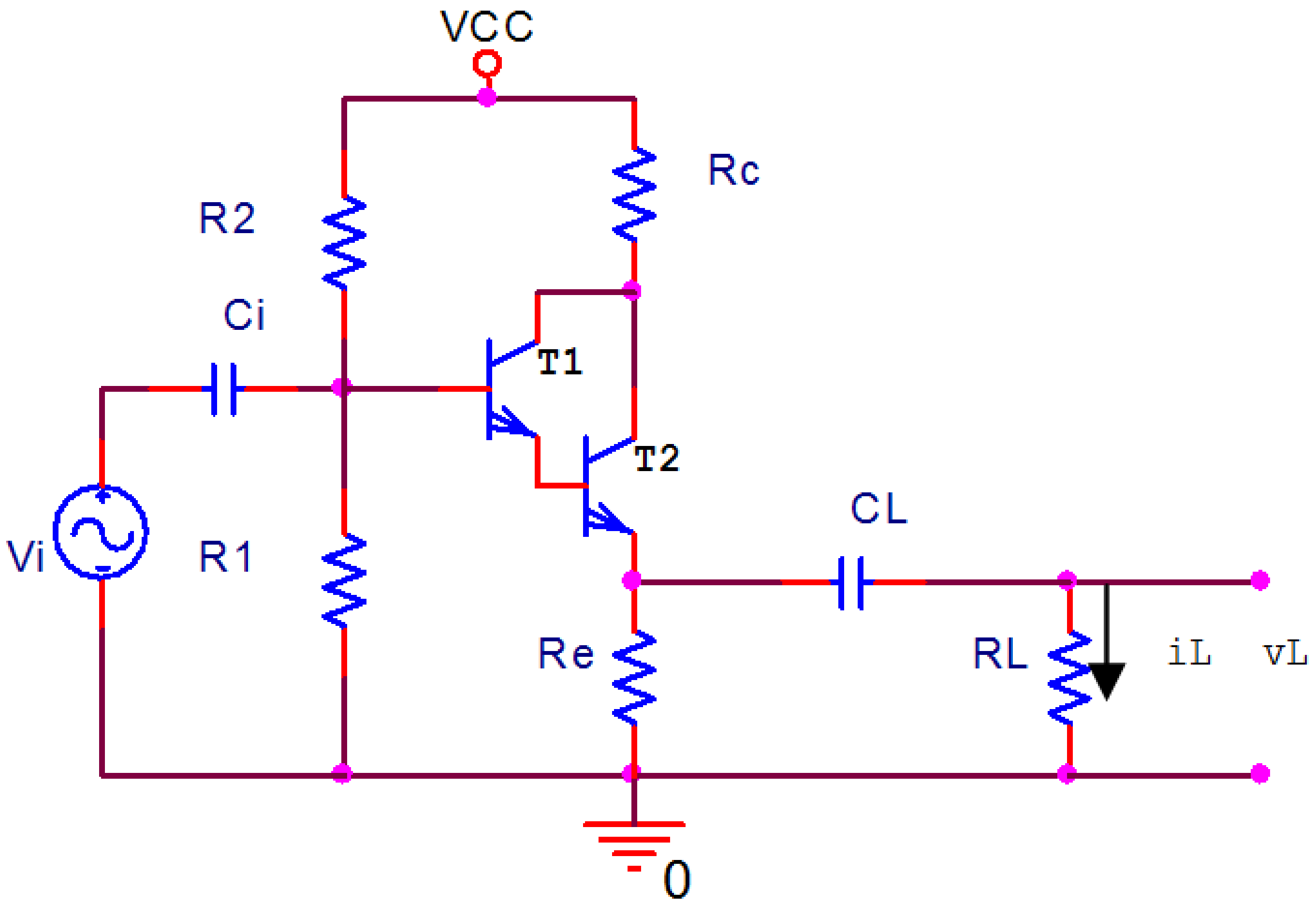
$$Z_O = R_C$$

$$A_i = \frac{i_L}{i_i} = \frac{i_L}{i_{b_1}} \frac{i_{b_1}}{i_i} = -h_{fe}{}^2 \frac{R_C}{R_C + R_L} \frac{R_b}{R_b + 2h_{ie_1}}$$

$$A_V = A_i \frac{R_L}{Z_i} = -h_{fe}{}^2 \frac{R_C}{R_C + R_L} \frac{R_b}{R_b + 2h_{ie_1}} \frac{R_L}{\frac{R_b \times 2h_{ie_1}}{R_b + 2h_{ie_1}}}$$

$$A_V = -h_{fe}{}^2 \frac{R_C}{R_C + R_L} \frac{R_L}{2h_{ie_1}}$$

Amplificador Darlington. Salida por Emisor



Amplificador Darlington. Salida por Emisor

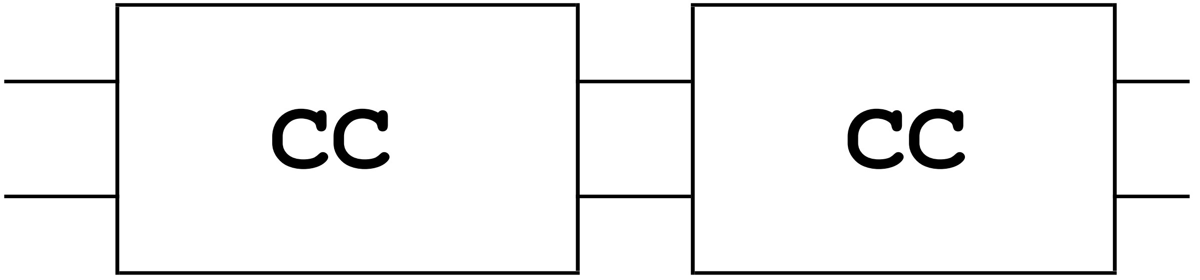
I_{CQ} *para Maxima Excursion Simetrica.*

$$I_{CQ,MES} = \frac{V_{CC}}{2R_C + R_E + R_E\,//\,R_L}$$

$$I_{CQ,MES} = \frac{V_{CC}}{\underbrace{R_C + R_E}_{R_{CC}} + \underbrace{R_C + (R_E\,//\,R_L)}_{R_{CA}}}$$

Amplificador Darlington. Salida por Emisor

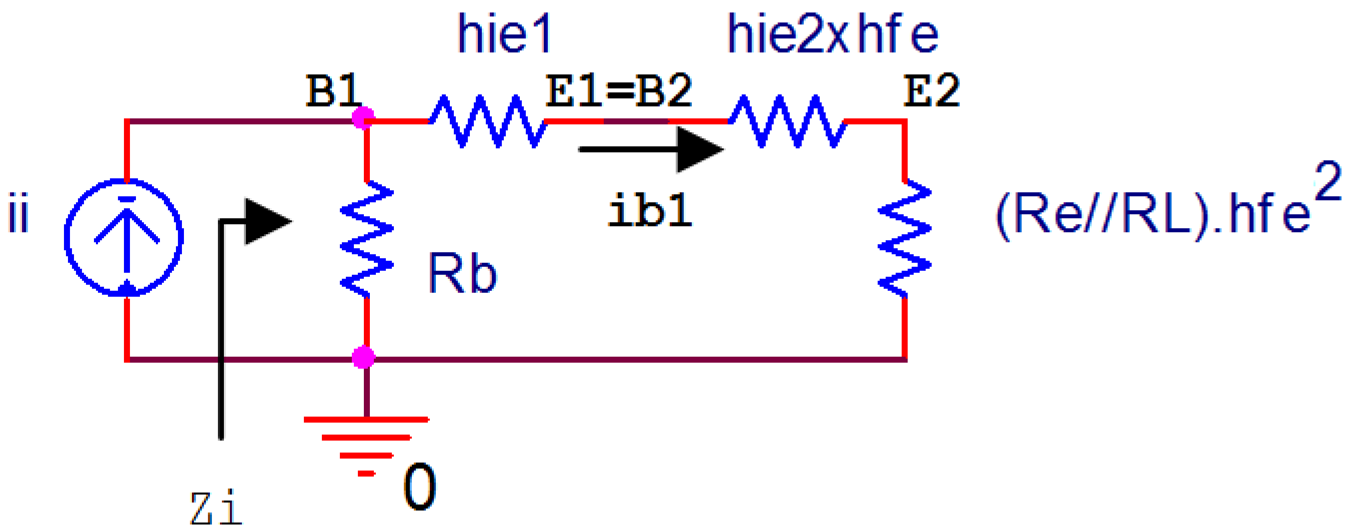
Para alterna tenemos :



Tiene ganancia de corriente pero no de tension.

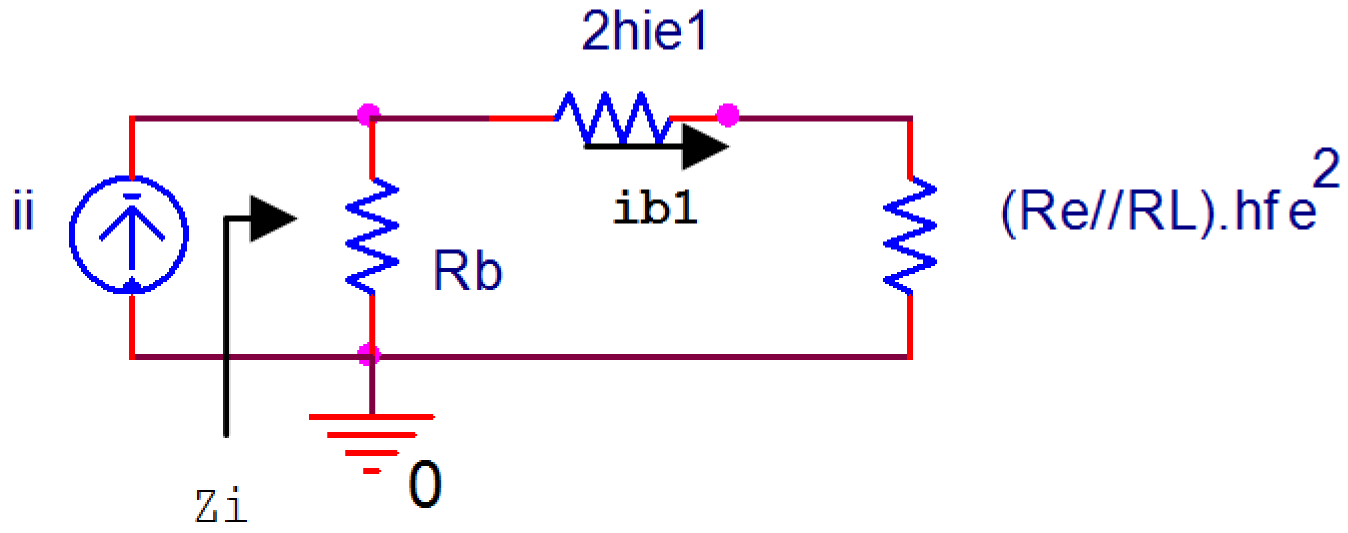
Tiene ganancia de corriente pero no de tension.

Circuito Equivalente para C.A para calcular Zi



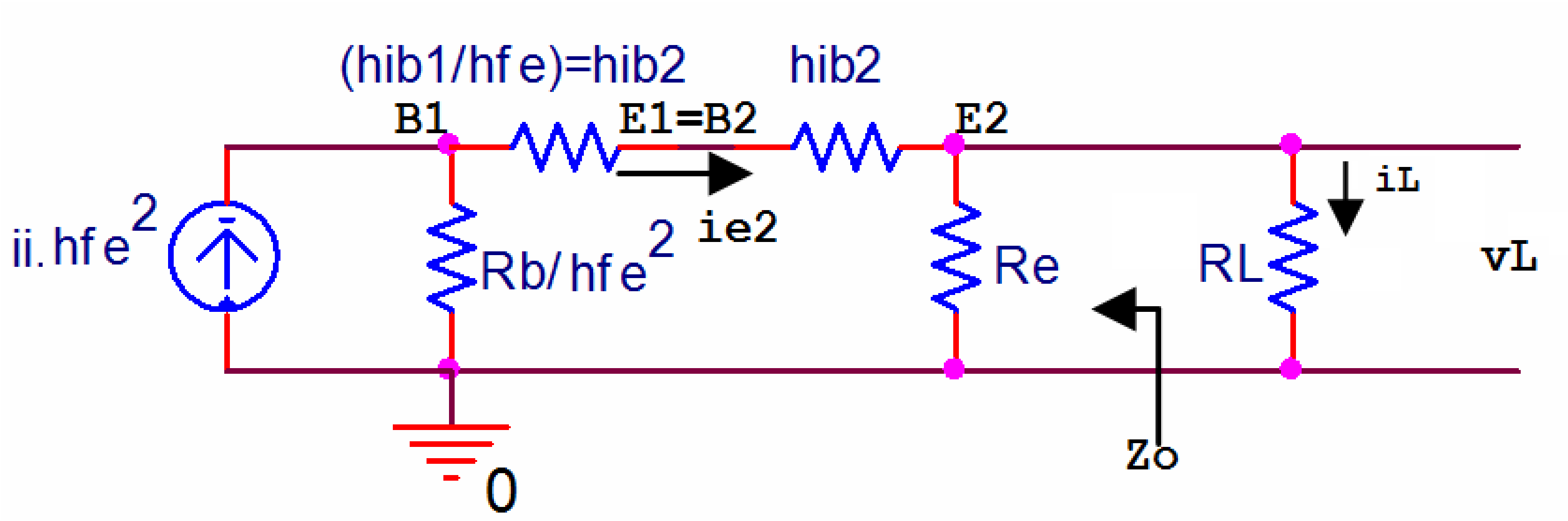
$$h_{ie1} = h_{fe}\frac{25mV}{I_{CQ1}} = h_{fe}\frac{25mV}{\dfrac{I_{CQ2}}{h_{fe}}} = h_{ie2} \times h_{fe}$$

Circuito Equivalente para C.A para calcular Zi



$$Z_i = R_b // \left[2.h_{ie1} + (R_E // R_L) h_{fe}^2 \right]$$

Circuito Equivalente para C.A para calcular Zo



$$h_{ib2} = \frac{25mV}{I_{CQ2}} = \frac{25mV}{I_{CQ1}h_{fe}} = \frac{h_{ib1}}{h_{fe}}$$

$$Z_O = R_e \, / / \left(2h_{ib2} + \frac{R_b}{h_{fe}^2} \right)$$

Ganancia de Corriente Ai

$$A_i = \frac{i_L}{i_i} = \left(\frac{i_L}{i_{e_2}}\right)\left(\frac{i_{e_2}}{i_i}\right) = \left(\frac{R_E}{R_E + R_L}\right)\left(h_{fe}^2 \frac{\frac{R_b}{h_{fe}^2}}{\frac{R_b}{h_{fe}^2} + 2h_{ib2} + R_E // R_L}\right)$$

$$Si: \ \frac{R_b}{h_{fe}^2} >> 2h_{ib2} + R_E // R_L$$

$$A_i = \left(\frac{R_E}{R_E + R_L}\right) h_{fe}^2$$

Ganancia de Tensión Av

$$A_V = A_i \frac{R_L}{Z_i} = \frac{(R_e//R_L)h_{fe}^2}{\underbrace{\left\{\frac{R_b\left[2h_{ie1} + (R_e//R_L)h_{fe}^2\right]}{R_b + 2h_{ie1} + (R_e//R_L)h_{fe}^2}\right\}}_{Z_i}} \frac{R_b}{R_b + \underbrace{2h_{ib2}h_{fe}^2}_{2h_{ie1}} + (R_E//R_L)h_{fe}^2}$$

$$A_V = \frac{h_{fe}^2(R_e//R_L)}{\left(R_e//R_L\right)h_{fe}^2 + 2h_{ie1}} < 1$$

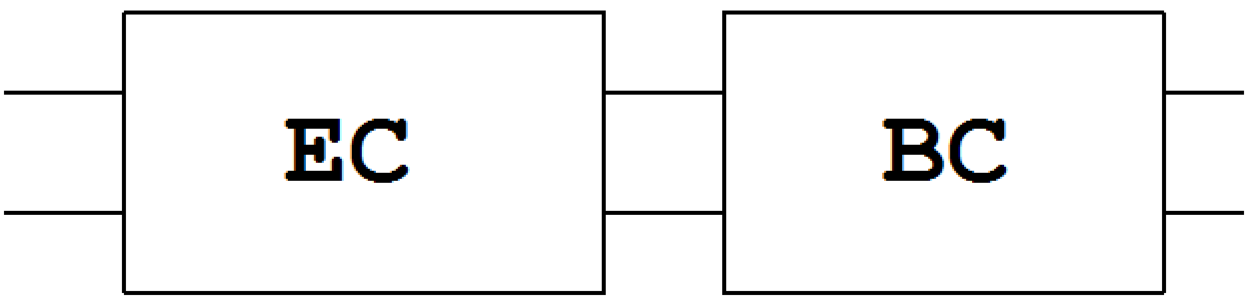
Amplificador Cascodo.

Cascodo Como Amplificador, mejora el ancho del banda.

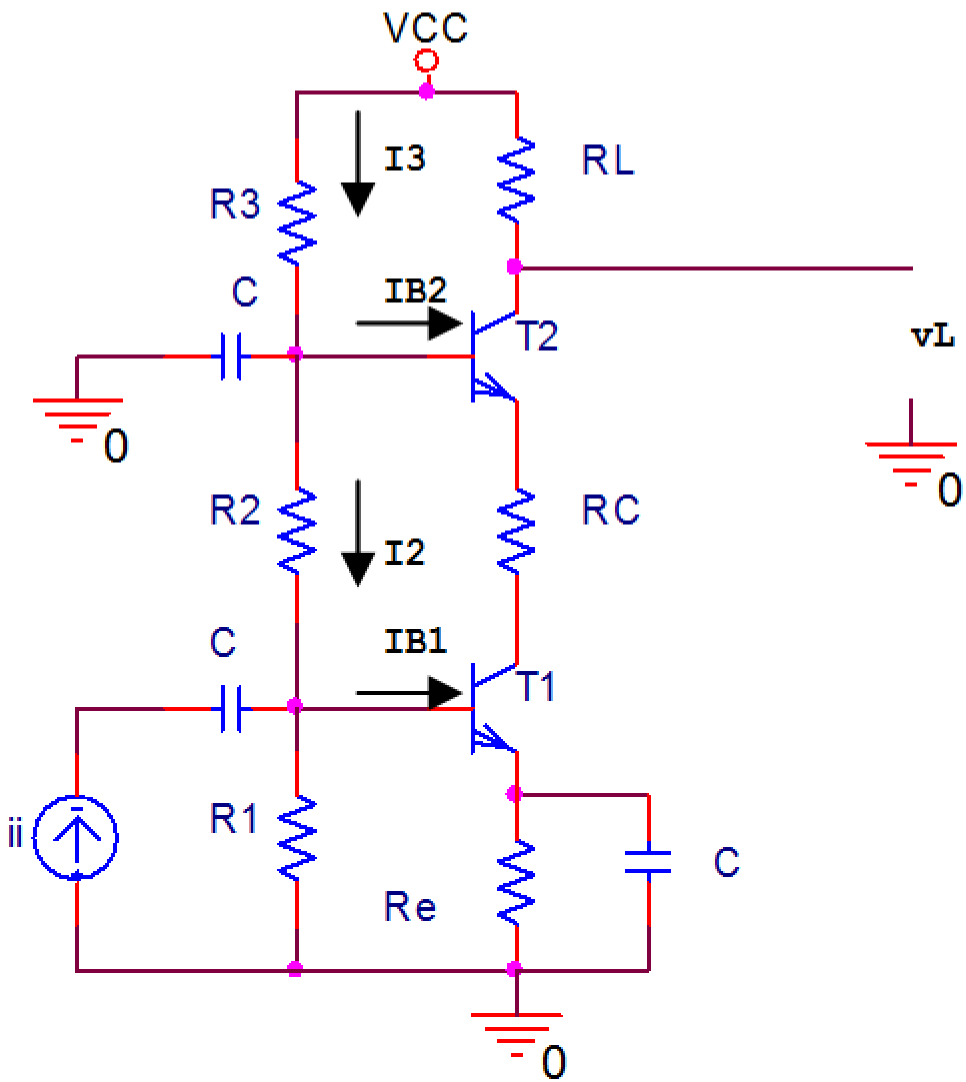
Evita disminucion de ganancia por realimentacion.

Cascodo Como Desplazador de nivel de C.C, sin variacion de la ganancia de tension A_V

Version Amplificador



Amplificador Cascodo.



$$I_{B_2} << I_3$$

$$I_{B_1} << I_2$$

$$V_{B_2} = \frac{V_{CC}}{R_1 + R_2 + R_3} \times \left(R_1 + R_2\right)$$

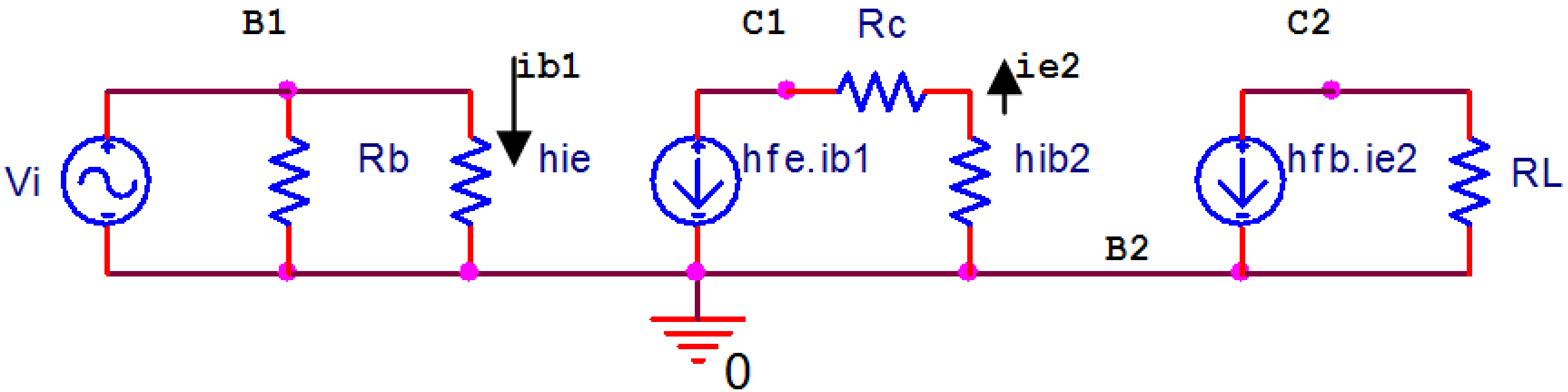
$$V_{B_1} = \frac{V_{B_2}}{R_1 + R_2} \times R_1$$

$$I_{CQ_1} \cong \frac{V_{B_1} - V_{BE_1}}{R_E} = I_{CQ_2}$$

$$V_{CEQ_1} = V_{B_2} - V_{BE_2} - I_{CQ_1}\left(R_C + R_E\right)$$

$$V_{CEQ_2} = V_{CC} - V_{CEQ_1} - I_{CQ_1}\left(R_L + R_C + R_E\right)$$

Circuito Equivalente para pequeña señal

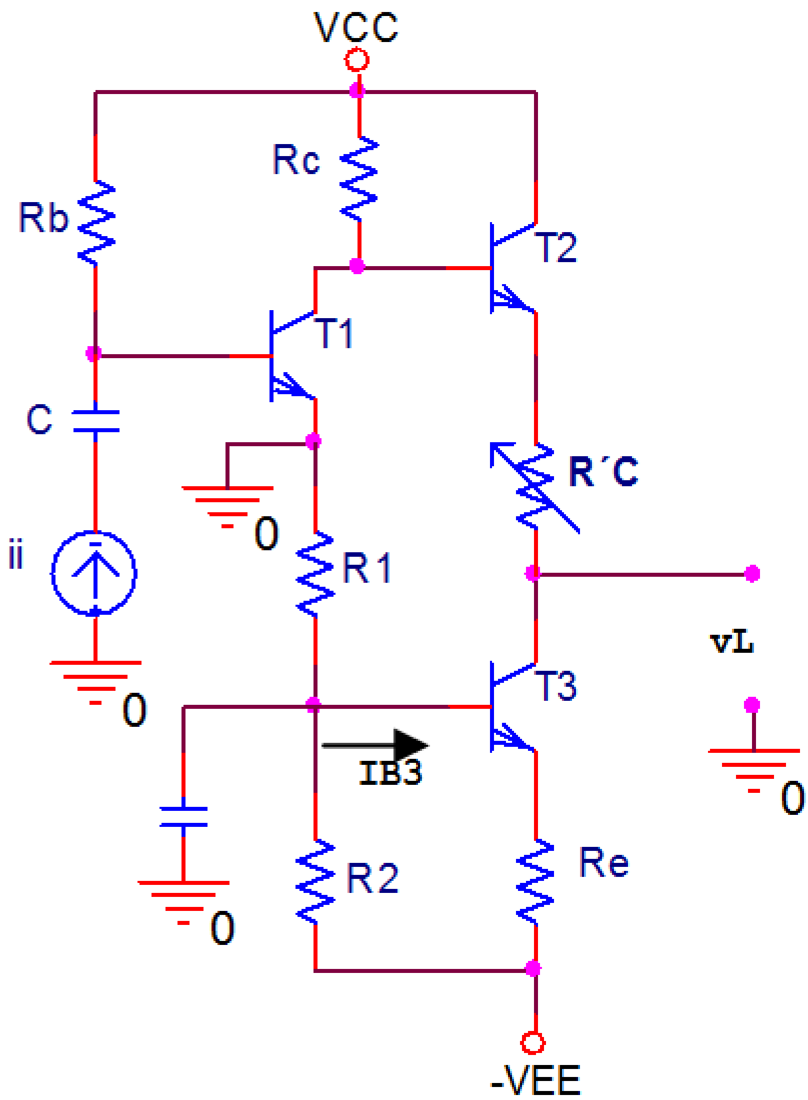


$$A_i = \frac{i_L}{i_i} = \frac{i_L}{i_{e_2}} \frac{i_{e_2}}{i_{b_1}} \frac{i_{b_1}}{i_i} = \left(-h_{fb}\right) h_{fe} \frac{R_b}{R_b + h_{ie_1}} \cong -h_{fe} \frac{R_b}{R_b + h_{ie_1}}$$

$$BW = f\left({}^{1}\!/_{C_M} \right) \qquad \begin{cases} C_M : Capacidad\ de\ Miller \\ \quad (de\ realimentacion). \end{cases}$$

$$C_M = C_{bc}(1 + g_m R_L) \qquad (R_L \ equivale\ a\ h_{ib_2})$$

Cascodo como desplazador de nivel.



$$I_{B_3} \cong 0$$

$$V_{B_3} = -\frac{V_{EE}}{R_1 + R_2} R_1$$

$$V_{E_3} = V_{B_3} - V_{BE}$$

$$I_{EQ_3} = \frac{V_{E_3} - (-V_{EE})}{R_e}$$

$$I_{EQ_3} = \frac{V_{E_3} + V_{EE}}{R_e}$$

$$V_{E_2} = I_{EQ_3} R_C^{'} + V_L$$

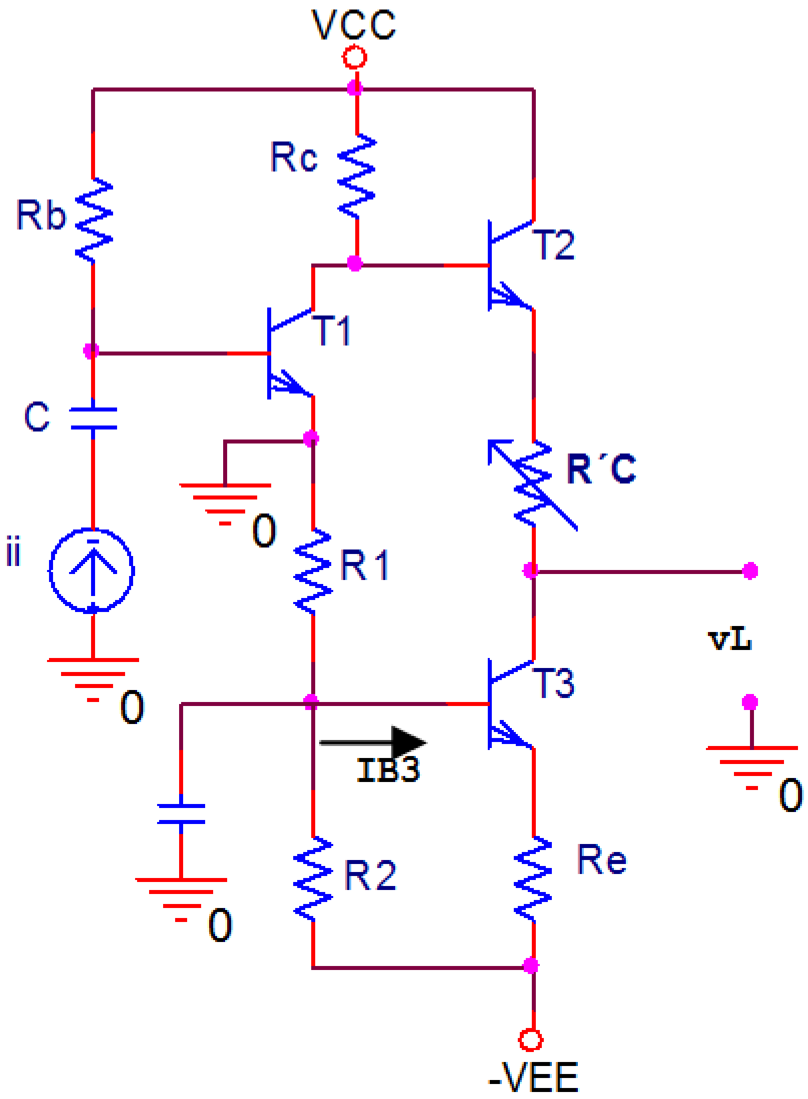
$$V_{B_2} = V_{E_2} + V_{BE}$$

$$I_{CQ_1} = \frac{V_{CC} - V_{B_2}}{R_C}$$

$$I_{BQ_1} = \frac{I_{CQ_1}}{\beta_1}$$

$$R_b = \frac{V_{CC} - V_{BE}}{I_{BQ_1}}$$

Cascodo como desplazador de nivel.



Suponemos que R_b *es fija y varia* $R_C^{`}$:

$$I_{BQ_1} = \frac{V_{CC} - V_{BE}}{R_b}$$

$$I_{CQ_1} = \beta_1 I_{BQ_1}$$

$$V_{B_2} = V_{CC} - I_{CQ_1} R_C$$

$$V_{E_2} = V_{B_2} - V_{BE}$$

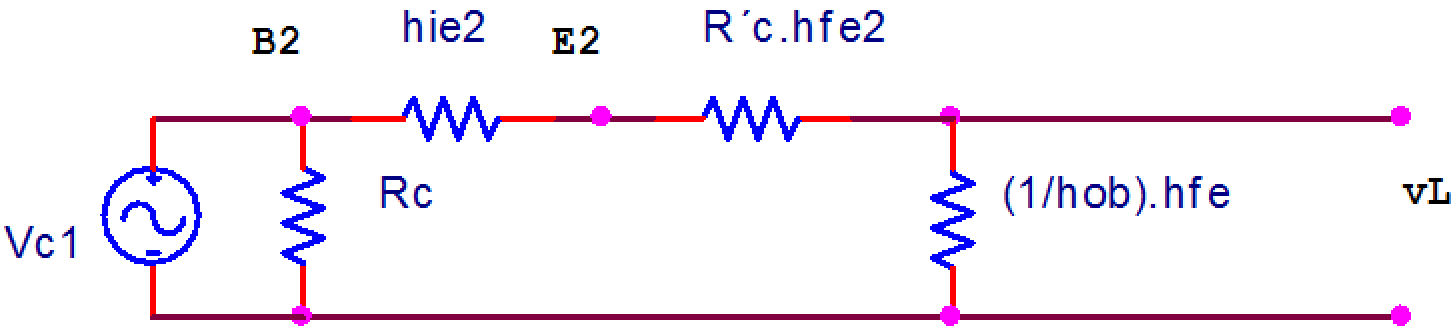
$$I_{EQ_3} = \frac{V_{E_2} - V_L}{R_C^{`}} \quad \Rightarrow \quad R_C^{`} = \frac{V_{E_2} - V_L}{I_{EQ_3}}$$

$$V_{B_3} = \frac{-V_{EE}}{R_1 + R_2} R_1$$

$$V_{E_3} = V_{B_3} - V_{BE}$$

$$I_{EQ_3} = \frac{V_{E_3} + V_{EE}}{R_e}$$

Cascodo como desplazador de nivel

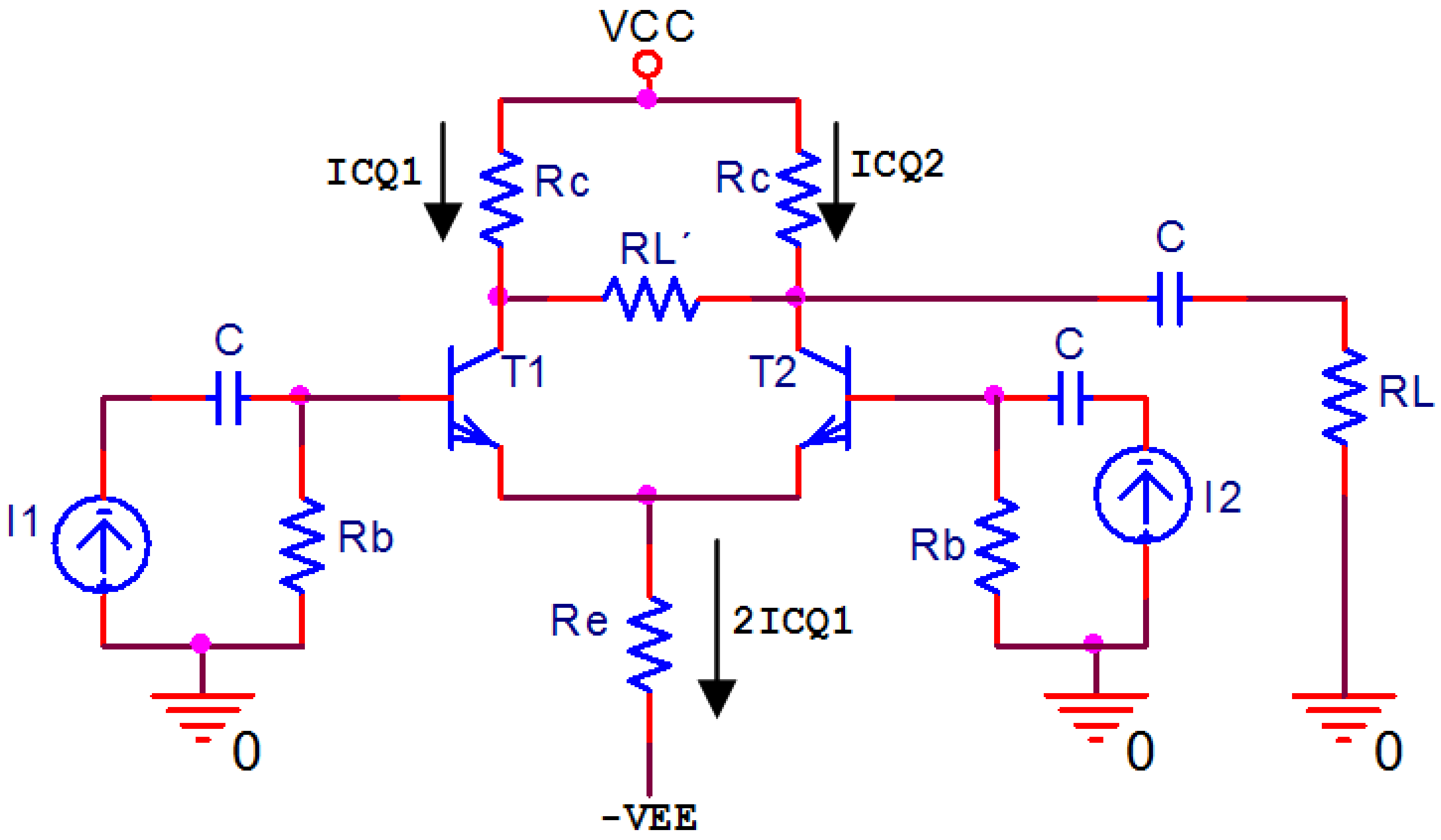


$$v_L = \frac{v_{c_1}}{\underbrace{h_{ie_2} + R_C^{`} h_{fe_2}}_{despreciando} + \frac{h_{fe}}{h_{ob}}} \frac{h_{fe}}{h_{ob}} \cong v_{c_1}$$

$$A_V = \frac{v_L}{v_{c_1}} \cong 1$$

Amplificador Diferencial.

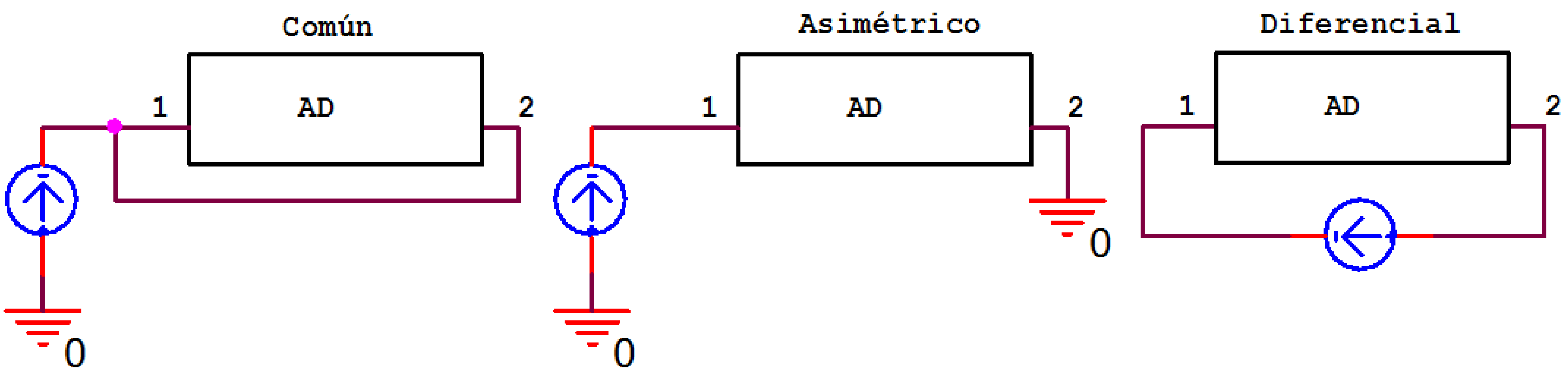
Elimina o atenua los ruidos de origen externo presentes en las entradas.



$T_1 = T_2$ $\qquad$ $I_{CQ_1} = I_{CQ_2}$

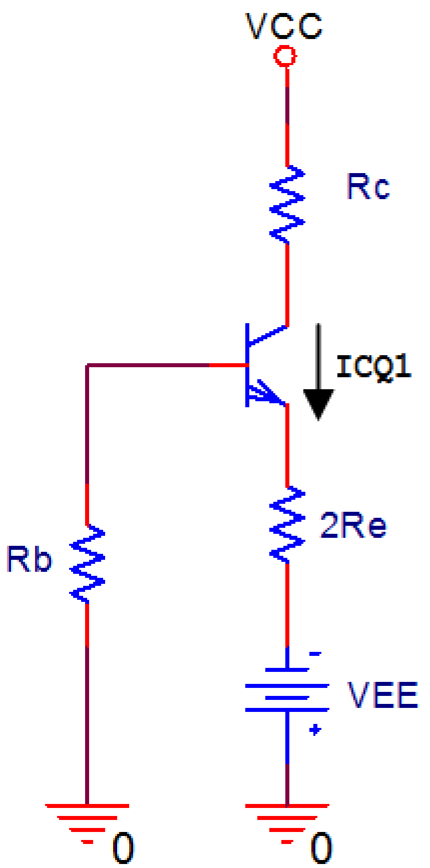
Amplificador Diferencial.

$$Entradas\begin{cases} Comun \\ Asimetrico \\ Diferencial \end{cases} \qquad Salidas\begin{cases} Asimetrica \rightarrow Atenua\ Ruido \\ Diferencial \rightarrow Elimina\ el\ Ruido \end{cases}$$



Amplificador Diferencial.

Analisis de punto de reposo



$$V_{R_e} = 2I_{CQ_1}R_e = I_{CQ_1}2R_e$$

$$I_{CQ_1} = \frac{V_{EE} - V_{BE}}{\frac{R_b}{\beta} + 2R_e} = I_{CQ_2}$$

$$V_{CEQ_1} = V_{CC} - (-V_{EE}) - I_{CQ_1}(R_C + 2R_e)$$

$$= V_{CC} + V_{EE} - I_{CQ_1}(R_C + 2R_e)$$

$$= V_{CEQ_2} \quad (Si\ R_C\ son\ iguales)$$

Amplificador Diferencial.

$$Definiciones:$$

$$Corriente\ en\ modo\ comun: \quad i_c = \frac{i_1 + i_2}{2}$$

$$Corriente\ en\ modo\ diferencial: \quad i_d = i_2 - i_1$$

$$Ganancia\ en\ modo\ comun: \quad A_c = \left.\frac{i_L}{i_c}\right|_{i_d=0}$$

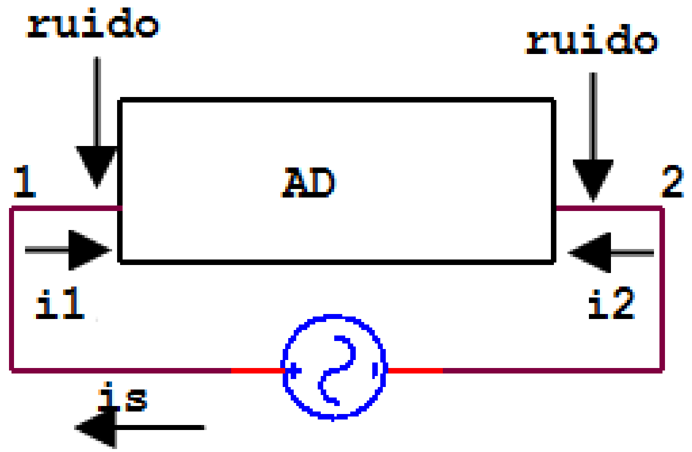
$$Ganancia\ en\ modo\ diferencial: \quad A_d = \left.\frac{i_L}{i_d}\right|_{i_c=0}$$

$$Corriente\ de\ salida: \quad i_L = \underbrace{A_c i_c}_{Ruido} \pm \underbrace{A_d i_d}_{Señal}$$

$$A_d >> A_c \quad (es\ deseable).$$

$$Relacion\ de\ rechazo\ a\ modo\ comun: \quad RRMC = \frac{A_d}{A_c} \rightarrow \infty$$

Amplificador Diferencial.



Corrientes de entrada con entrada diferencial.

$$i_1 = i_s + i_r$$

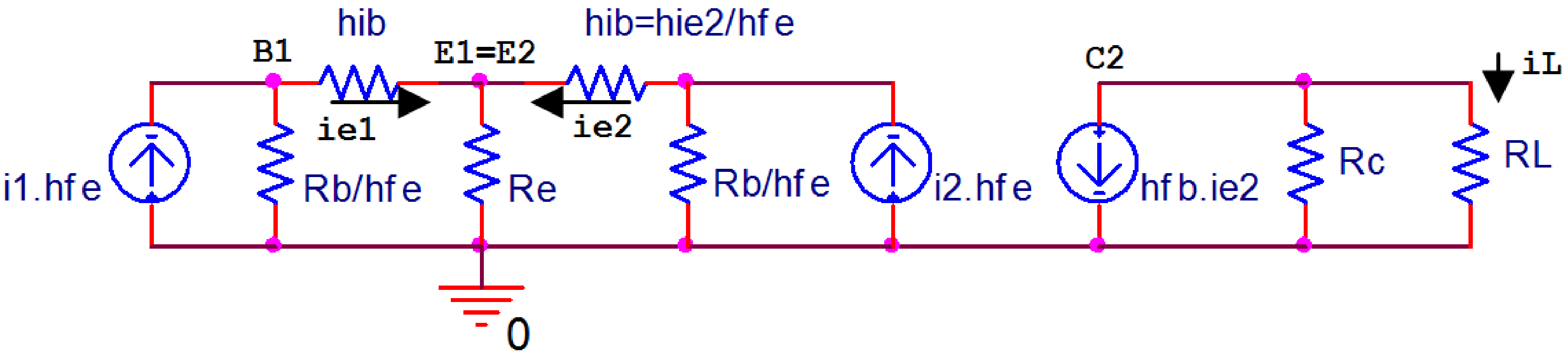
$$i_2 = -i_s + i_r \qquad\qquad i_s = señal \qquad i_r = ruido$$

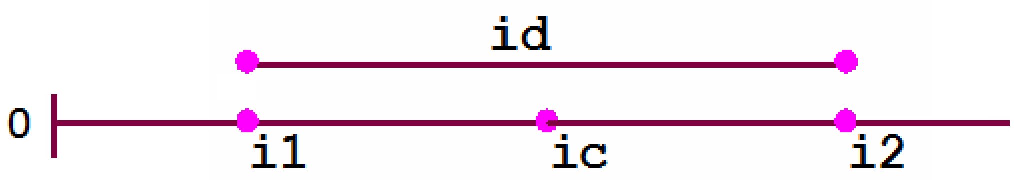
$$i_c = \frac{i_s + i_r - i_s + i_r}{2} = \frac{2i_r}{2} = i_r$$

$$i_d = -i_s + i_r - i_s - i_r = -2i_s \Rightarrow i_s = -\frac{i_d}{2}$$

Amplificador Diferencial.

Circuito equivalente reflejado al emisor.

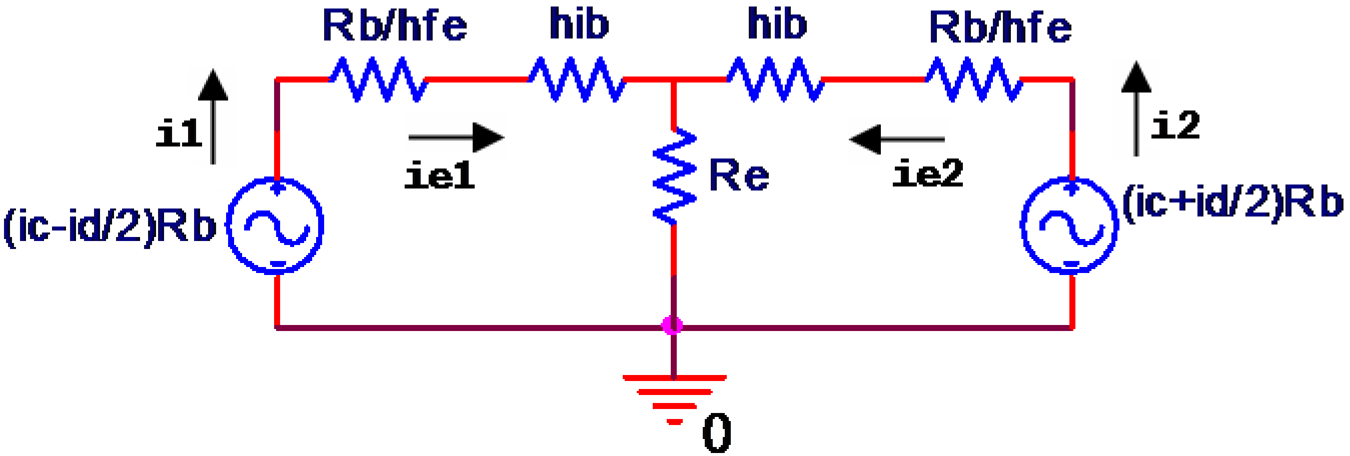




$$i_1 = i_c - \frac{i_d}{2}$$

$$i_2 = i_c + \frac{i_d}{2}$$

Amplificador Diferencial.



$$Si\begin{cases} i_1 = i_2 \Rightarrow i_d = 0 \Rightarrow i_{e_1} = i_{e_2} \\ i_1 = -i_2 \Rightarrow i_c = 0 \Rightarrow \begin{cases} i_d = 2i_1 = -2i_2 \\ i_{e_1} = -i_{e_2} \end{cases} \end{cases}$$

Amplificador Diferencial.

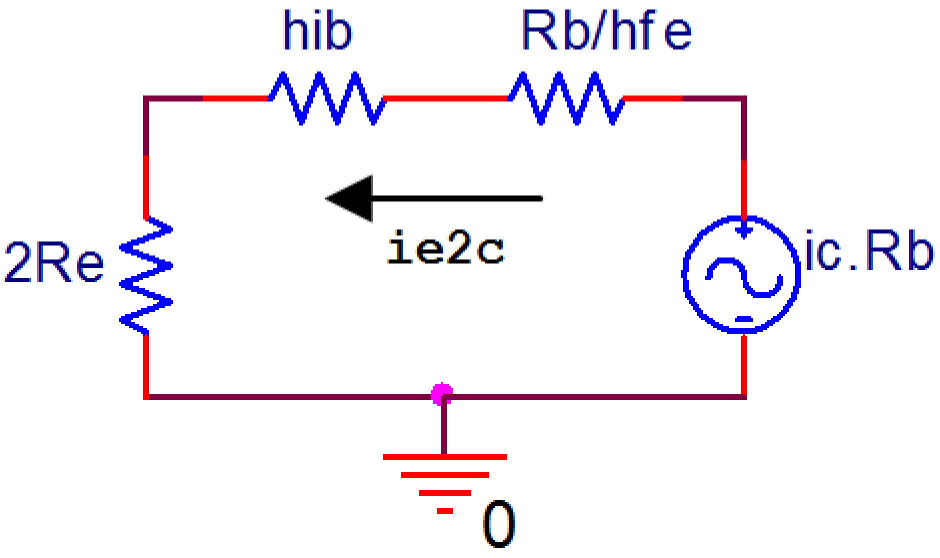
$$En\ la\ malla\ de\ salida\ vemos\ que:$$

$$i_L = f\left(i_{e_2}\right)$$

$$i_{e_2} = f\left(i_c; i_d\right)$$

$$Caso\ si:\ i_1 = i_2 = i_c; \quad i_d = 0$$

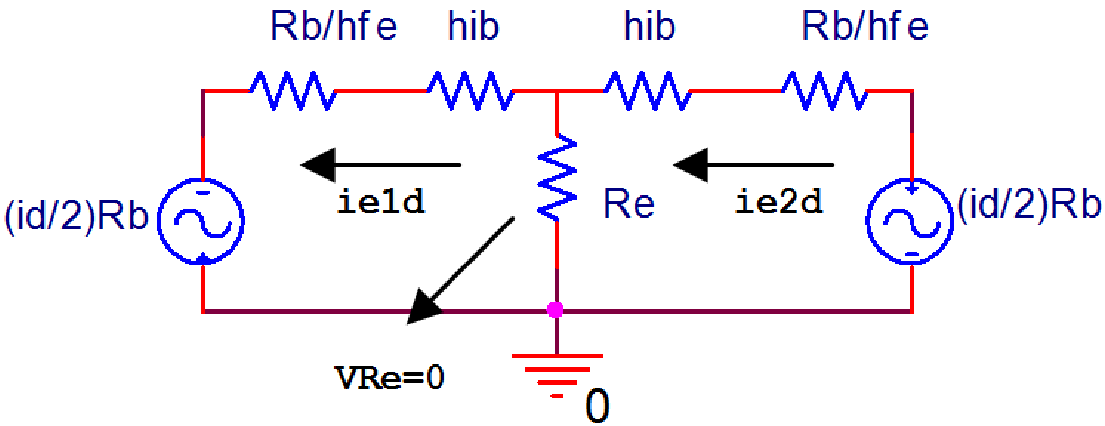
$$v_e = 2 i_{e_{2c}} R_e$$

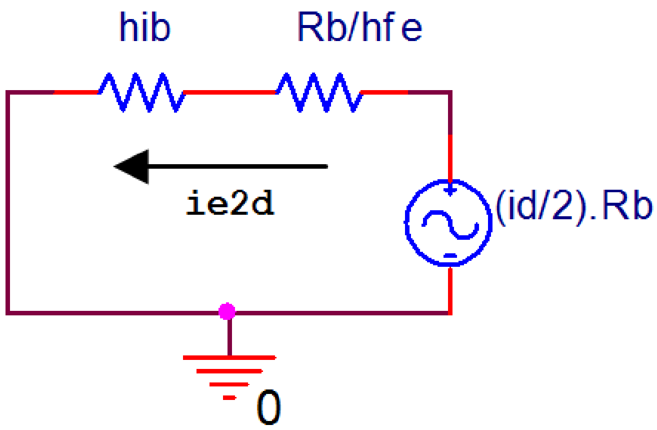


$$i_{e_{2c}} = \frac{R_b}{2R_e + h_{ib} + R_b/h_{fe}}\, i_c$$

Amplificador Diferencial.

$$Caso\ si:\ i_1 = -i_2; \quad i_c = \frac{-i_2 + i_2}{2} = \frac{0}{2} = 0$$





$$i_{e_{2d}} = \frac{R_b}{2\left(h_{ib} + {R_b}/{h_{fe}}\right)} i_d$$

Amplificador Diferencial.

$$i_{e_2} = i_{e_{2c}} + i_{e_{2d}}$$

$$= \frac{R_b i_c}{2R_e + h_{ib} + {R_b}/{h_{fe}}} + \frac{R_b i_d}{2\left(h_{ib} + {R_b}/{h_{fe}}\right)}$$

$$i_L = -h_{fb} i_{e_2} \frac{R_c}{R_c + R_L}$$

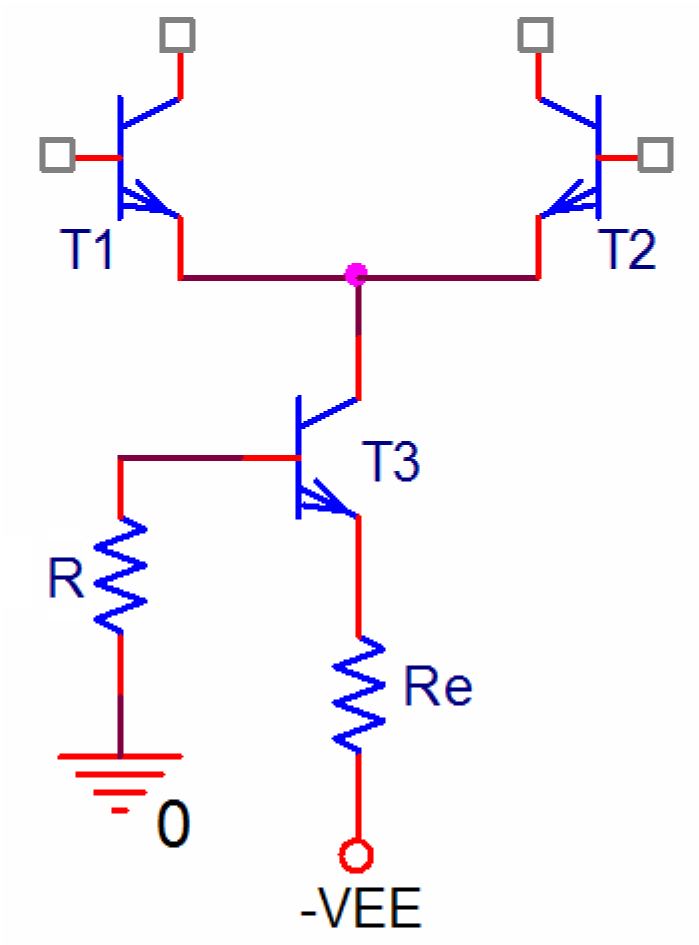
$$i_L = \left(-h_{fb} \frac{R_c}{R_c + R_L}\right) \frac{R_b}{2R_e + h_{ib} + {R_b}/{h_{fe}}} i_c + \left(-h_{fb} \frac{R_c}{R_c + R_L}\right) \frac{R_b}{2\left(h_{ib} + {R_b}/{h_{fe}}\right)} i_d$$

$$RRMC = \frac{A_d}{A_c} = \frac{2R_e + h_{ib} + {R_b}/{h_{fe}}}{2\left(h_{ib} + {R_b}/{h_{fe}}\right)}$$

$$Si: \quad R_e >> h_{ib} + {R_b}/{h_{fe}} \Rightarrow RRMC = \frac{R_e}{h_{ib} + {R_b}/{h_{fe}}}$$

Amplificador Diferencial.

Fuente de corriente constante :



$$R_e \to {}^{1}\!\!/\!_{h_{oe}}$$

Amplificador Diferencial.

$$\textit{Analisis en corriente continua}:$$

$$I_{CQ_3} = \frac{V_{EE} - V_{BE}}{\frac{R}{\beta_3} + R_e} = 2I_{CQ_1} = 2I_{CQ_2}$$

$$V_{E_1} = V_{E_2} = -V_{BE} - \frac{I_{CQ_1}}{\beta} R_b$$

$$V_{C_1} = V_{CC} - I_{CQ_1} R_C$$

$$V_{CEQ_1} = V_{C_1} - V_{E_1} = V_{CC} - I_{CQ_1} R_C + V_{BE} + \frac{I_{CQ_1}}{\beta} R_b$$

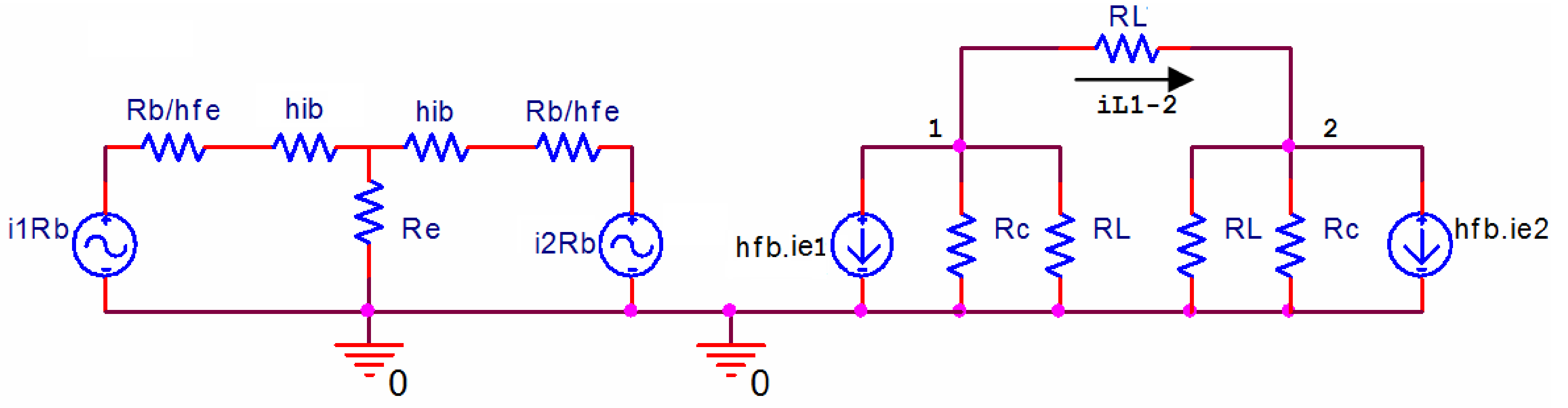
$$= V_{CEQ_2} \qquad \left(Si\ R_{C_1} = R_{C_2} = R_C \right)$$

$$V_{CEQ_3} = V_{E_1} - I_{CQ_1} 2R_e + V_{EE}$$

$$= -V_{BE} - \frac{I_{CQ_1}}{\beta} R_b - I_{CQ_3} R_e + V_{EE}$$

Amplificador Diferencial.

Circuito Equivalente:



$$i_{e_1} = \frac{R_b}{2R_e + h_{ib} + R_b/h_{fe}} i_c - \frac{R_b}{2\left(h_{ib} + R_b/h_{fe}\right)} i_d$$

$$i_{e_2} = \frac{R_b}{2R_e + h_{ib} + R_b/h_{fe}} i_c + \frac{R_b}{2\left(h_{ib} + R_b/h_{fe}\right)} i_d$$

Amplificador Diferencial.

$$Salida\ Asimetrica:$$

$$i_{L_{Asim}} = -h_{fb}\frac{R_C}{R_C+R_L}i_{e_2} = \left(-h_{fb}\frac{R_C}{R_C+R_L}\right)\frac{R_b}{2R_e+h_{ie}+R_b/h_{fe}}i_c$$

$$+\left(-h_{fb}\frac{R_C}{R_C+R_L}\right)\frac{R_b}{2\left(h_{ib}+R_b/h_{fe}\right)}i_d$$

$$i_{L_{Asim}} = A_c i_c - A_d i_d \ \ Cuando\ la\ salida\ es\ por\ \mathrm{T}_1$$

$$i_{L_{Asim}} = A_c i_c + A_d i_d \ \ Cuando\ la\ salida\ es\ por\ \mathrm{T}_2$$

Amplificador Diferencial.

$$Salida\ Diferencial:$$

$$i_{L(1-2)} = h_{fb} i_{e_2} \frac{R_C}{2R_C + R_L} + \ldots\ (pasivando\ la\ fuente\ 1)$$

$$= h_{fb} i_{e_2} \frac{R_C}{2R_C + R_L} - h_{fb} i_{e_1} \frac{R_C}{2R_C + R_L}$$

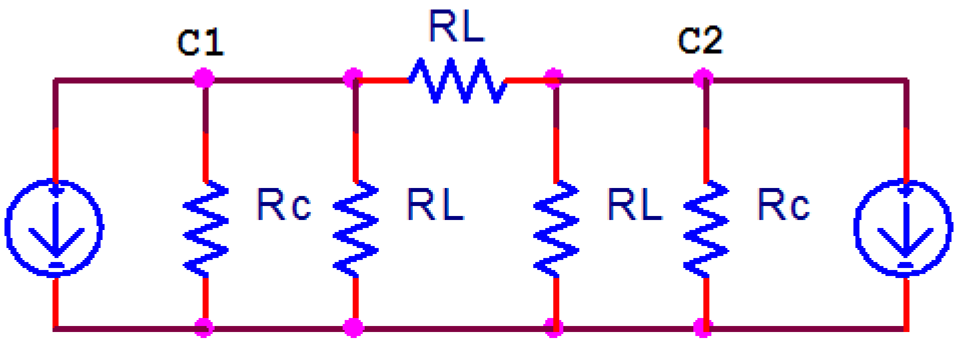
$$= h_{fb} \frac{R_C}{2R_C + R_L} \left(i_{e_2} - i_{e_1} \right)$$

$$= \underbrace{h_{fb} \frac{R_C}{2R_C + R_L} \frac{R_d}{h_{ib} + R_b / h_{fe}}}_{A'_d} i_d$$

$$i_{L(1-2)} = A'_d i_d \quad \rightarrow \quad A'_c = 0 \quad \Rightarrow \quad RRMC = \infty$$

Amplificador Diferencial.

Impedancia de Salida.



Salida Asimetrica

$$Z_O = R_C$$

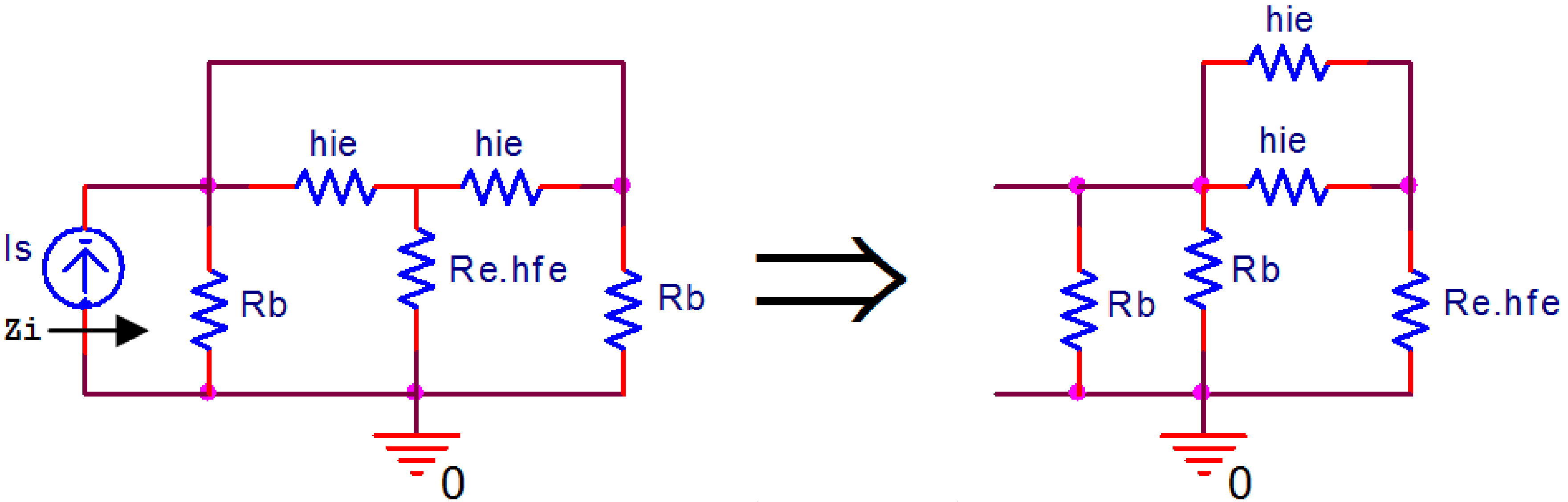
Salida Simetrica o Diferencial

$$Z_O = 2R_C$$

Amplificador Diferencial.

Impedancia de entrada

Entrada comun :



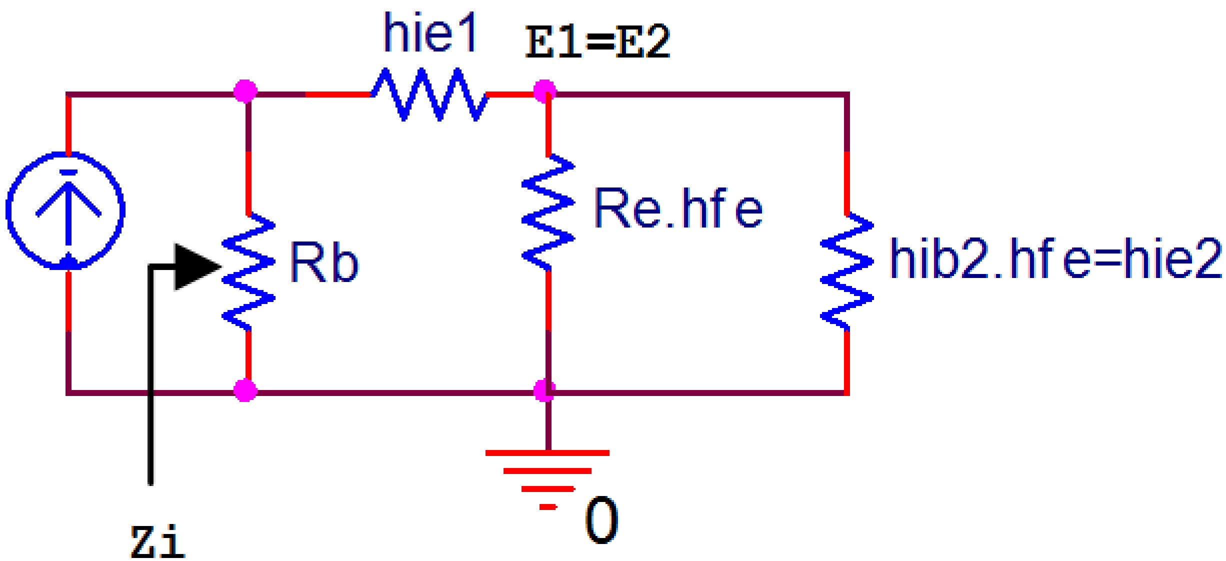
$$Z_i = \frac{R_b}{2} // \left(\frac{h_{ie}}{2} + R_e h_{fe} \right)$$

$$\left.\begin{array}{l} R_e h_{fe} >> \dfrac{h_{ie}}{2} \\ R_e h_{fe} >> \dfrac{R_b}{2} \end{array}\right\} Z_i = \frac{R_b}{2}$$

Amplificador Diferencial.

Impedancia de entrada

Entrada Asimetrica



$$Z_i = R_b // \left[h_{ie} + \left(h_{ie} // R_e h_{fe} \right) \right]$$

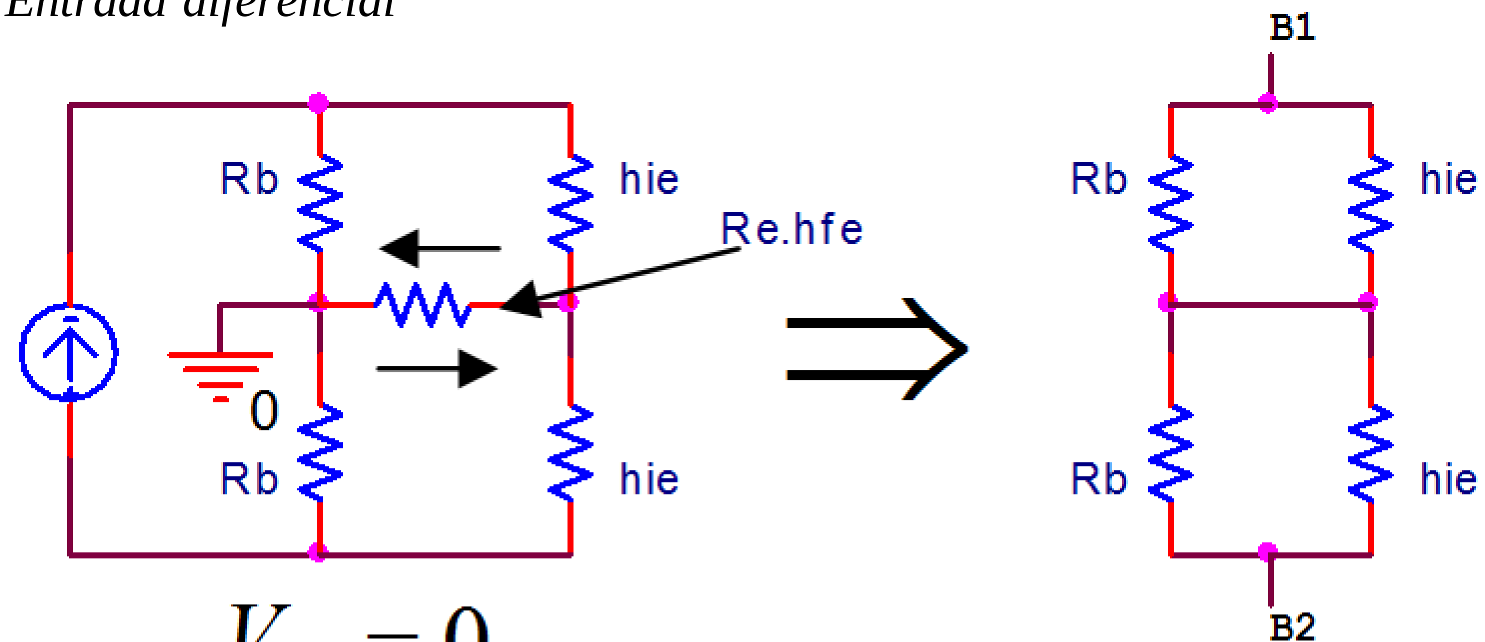
$$Si: \; R_e h_{fe} >> h_{ie} \Rightarrow Z_i = R_b // 2h_{ie}$$

$$Si: \; 2h_{ie} << R_b \Rightarrow Z_i = 2h_{ie}$$

Amplificador Diferencial.

Impedancia de entrada

Entrada diferencial

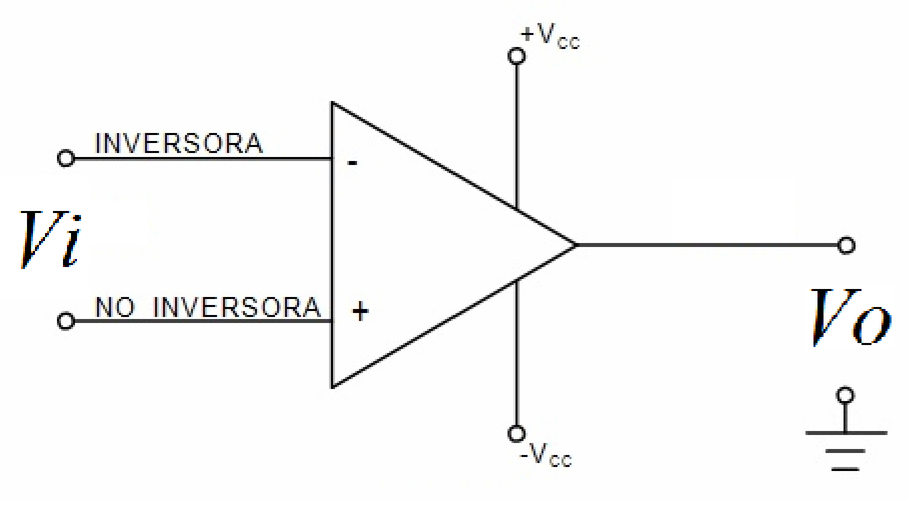


$$V_{R_e} = 0$$

$$Z_i = 2\left(R_b // h_{ie}\right)$$

El Amplificador Operacional.

Realiza operaciones matemáticas analógicas, se lo encuentra como un circuito integrado.

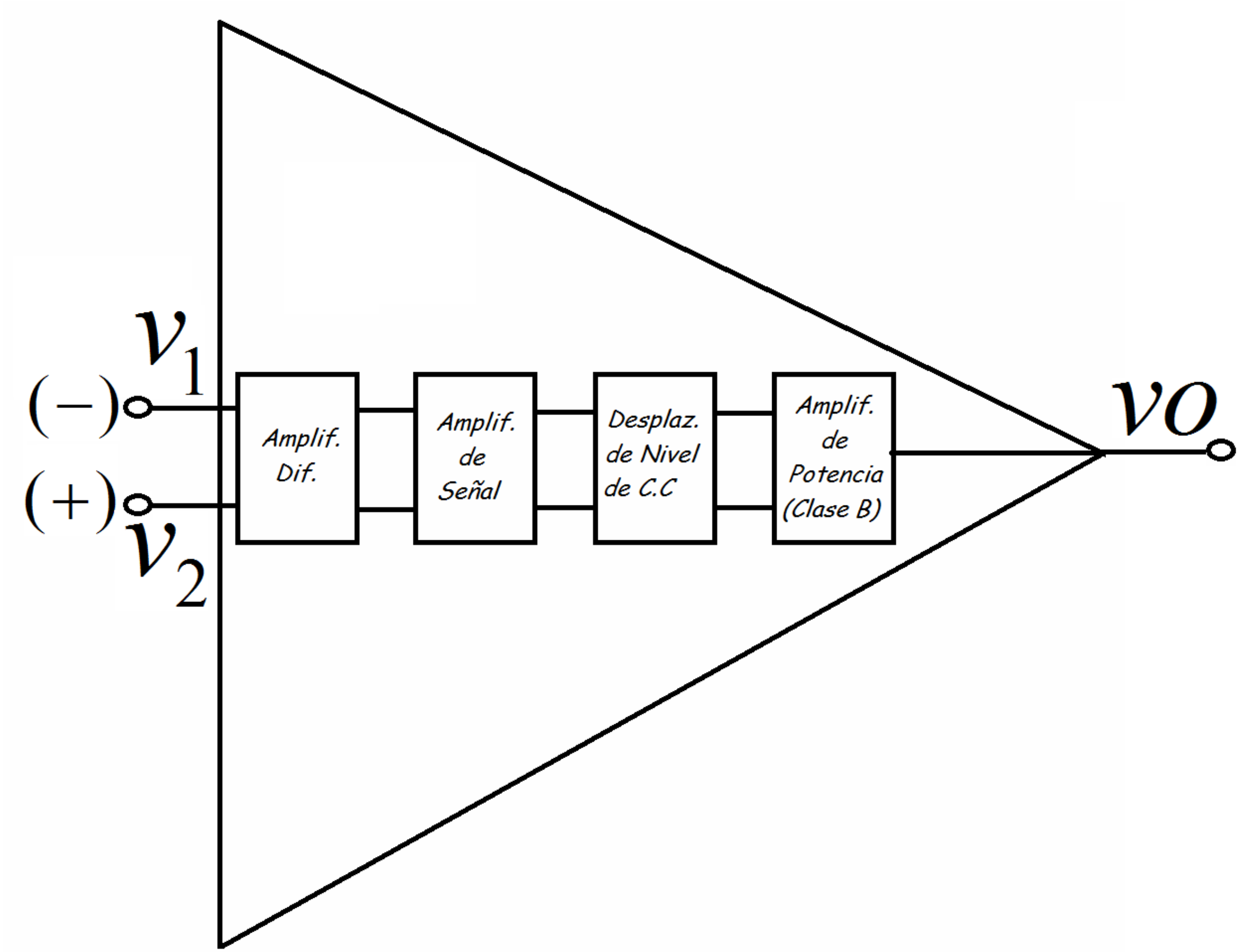


Por la entrada inversora si se introduce una señal, a la salida saldrá invertida.

La tensión entre los terminales de entrada es vi y la salida es vo.

El Amplificador Operacional.

CIRCUITO INTERNO:



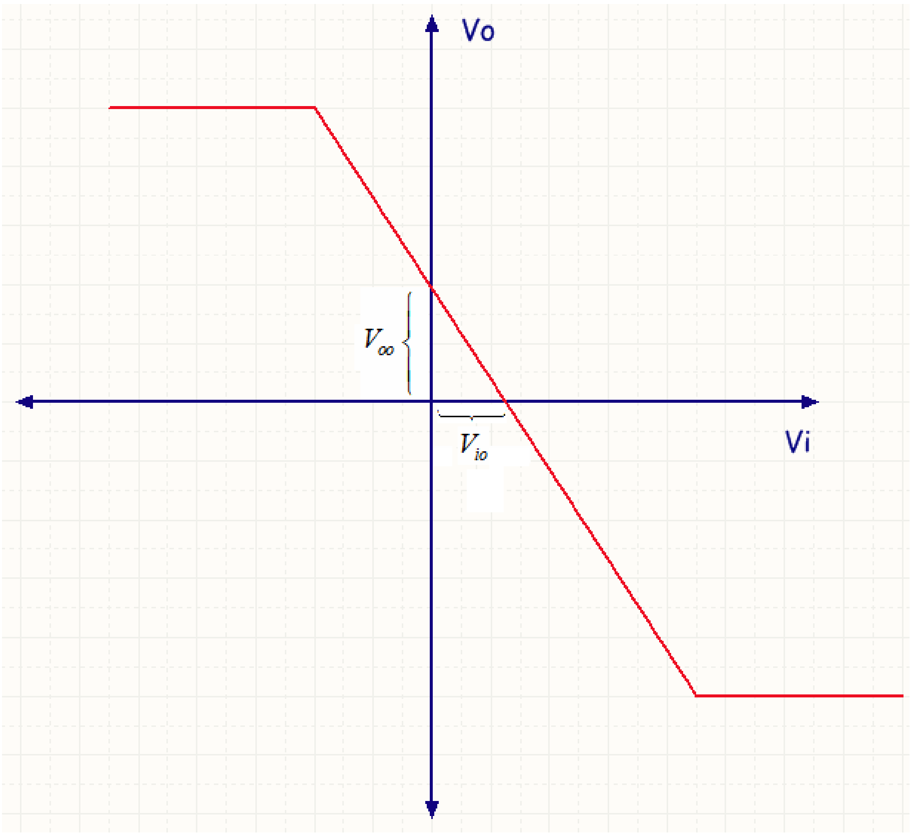
El Amplificador Operacional.

CARACTERÍSTICAS IDEALES:

- Ganancia de tensión infinita.
- Ancho de banda infinito.
- Impedancia de entrada infinita.
- RRMC infinita.
- Impedancia de salida nula.
- Ruido nulo.
- Corriente de polarizacion nula.
- Tiempo Crecimiento nulo

El Amplificador Operacional.

- Tensión de offset nulo (es la tensión de salida para cuando la entrada es cero, se denomina Voo).
- Voltaje de entrada de offset, es la tensión que hay en la entrada cuando la tensión a la salida es cero, se denomina Vio.



El Amplificador Operacional.

$$El\ corto\ circuito\ virtual\ se\ basa\ en:$$

$$Z_i = \infty$$

$$A_V = \infty$$

$$Si\ suponemos:$$

$$v_o \neq 0$$

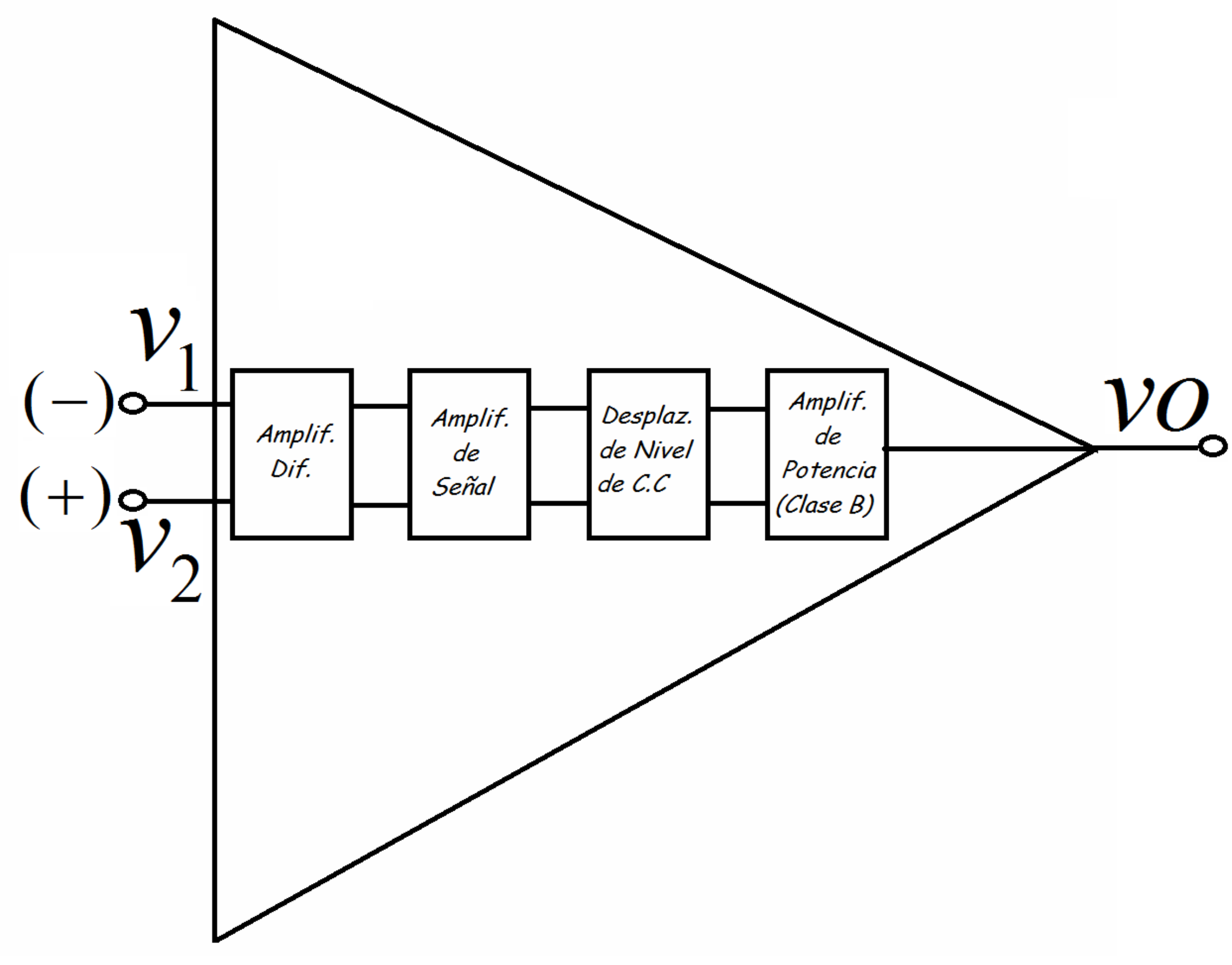
$$A_V = \frac{v_o}{v_i}$$

$$v_i = \frac{v_o}{A_V} = \frac{v_0}{\infty} = 0$$

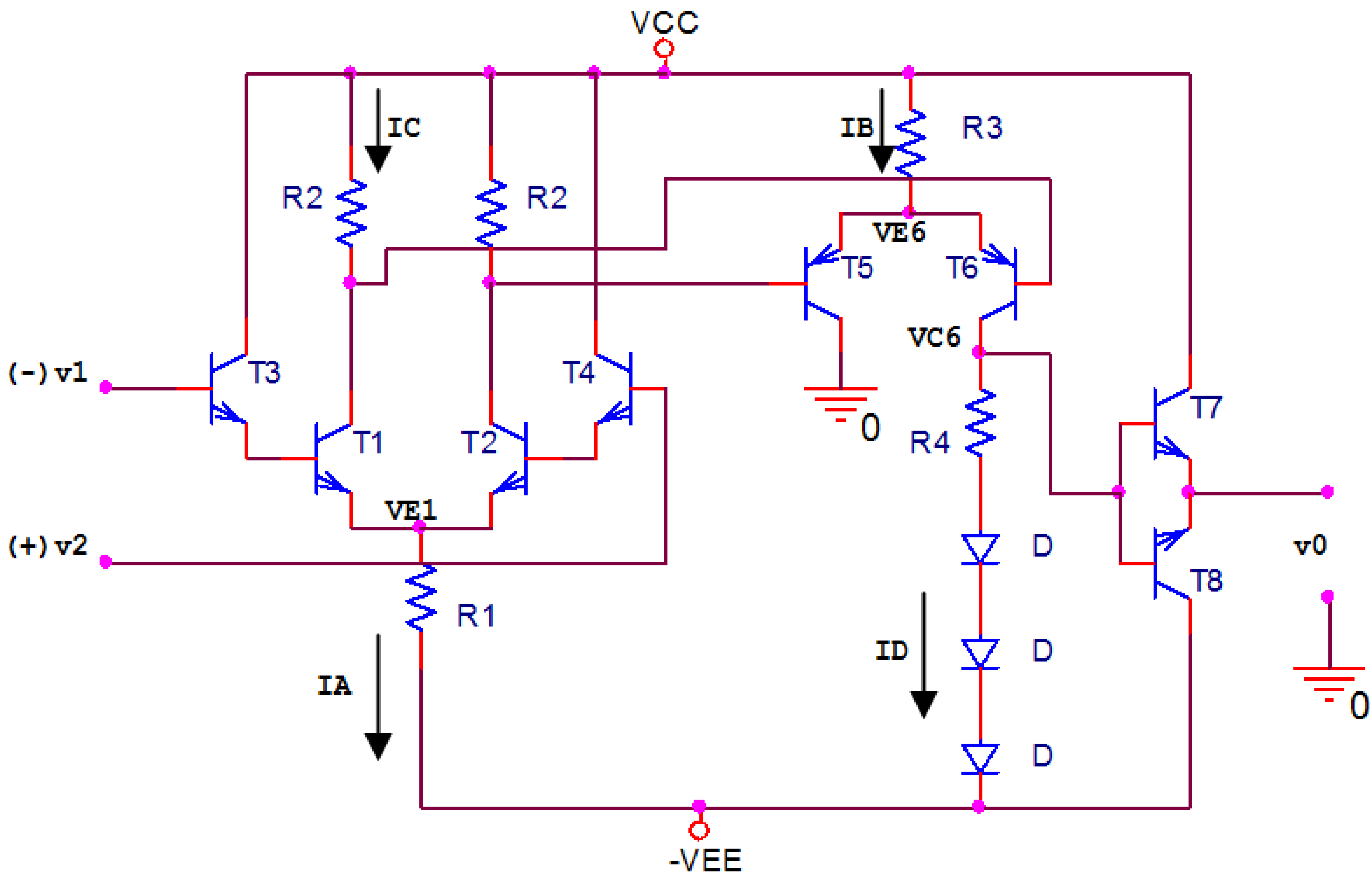
El Amplificador Operacional.

- La ganancia de voltaje infinita es a lazo abierto.
- Si ponemos un voltaje en una entrada, en la otra entrada tenemos la misma tensión.
- La tensión de ambas entradas es la misma debido a que tenemos una alta impedancia de entrada.
- Si en un terminal, hay masa, en el otro hay masa virtual, ya que si fuera real su corriente se iría directamente a masa.

El Amplificador Operacional.



Estructura interna del Amplificador Operacional.



Le agregamos un par Darlington para aumentar la impedancia de entrada.

Buscamos la relacion de resistencia para que las salida sea cero.

Estructura interna del Amplificador Operacional.

$$\left.\begin{array}{l} v_1 = 0 \\ v_2 = 0 \end{array}\right\} v_o = 0 \left| \begin{array}{l} I_b << I_C \cong I_E \\ V_{BE} = V_D \\ V_{CC} = V_{EE} \end{array}\right.$$

$$V_{E_1} = -2V_D$$

$$I_A = \frac{V_{EE} - 2V_D}{R_1} = 2I_C$$

$$I_C = \frac{I_A}{2} = \frac{V_{EE} - 2V_D}{2R_1}$$

$$V_{C_1} = V_{CC} - I_C R_2 = V_{CC} - \frac{V_{EE}}{2R_1} R_2 + \frac{\cancel{2} V_D}{\cancel{2} R_1} R_2$$

$$V_{E_6} = V_{CC} - \frac{V_{EE}}{2R_1} R_2 + \frac{R_2}{R_1} V_D + V_D$$

Estructura interna del Amplificador Operacional.

$$I_B = \frac{V_{CC} - V_{E_6}}{R_3} = \frac{V_{CC}}{R_3} - \frac{V_{CC}}{R_3} + V_{EE}\frac{R_2}{2R_1R_3} - \frac{R_2}{R_1R_3}V_D - \frac{V_D}{R_3}$$

$$I_{C_6} = \frac{I_B}{2} = \frac{R_2}{2R_1 2R_3}V_{EE} - \frac{R_2V_D}{2R_1R_3} - \frac{V_D}{2R_3} = \frac{R_2}{2R_1 2R_3}V_{EE} - \frac{V_D}{2R_3}\left(\frac{R_2}{R_1} + 1\right)$$

$$V_{C_6} = I_{C_6}R_4 + 3V_D - V_{EE} = \frac{R_2R_4}{2R_1 2R_3}V_{EE} - \frac{R_4}{2R_3}\frac{R_2 + R_1}{R_1}V_D + 3V_D - V_{EE} = V_0 = 0$$

$Sacamos\ factor\ comun:$

$$V_{C_6} = V_{EE}\left[\frac{R_2R_4}{2R_1 2R_3} - 1\right] + V_D\left[-\frac{R_2R_4}{2R_1R_3} - \frac{R_4}{2R_3} + 3\right] = 0$$

$$[\quad] = [\quad] = 0\ (nos\ independizamos\ de\ V_{EE}\ y\ V_D)$$

$$\left.\begin{array}{l} \dfrac{R_2R_4}{4R_1R_3} = 1 \\ \\ \dfrac{R_2R_4}{2R_1R_3} + \dfrac{R_4}{2R_3} = 3 \end{array}\right\} Deben\ cumplirse\ estas\ dos\ condiciones.$$

Estructura interna del Amplificador Operacional.

$$Si:\ h_{fe} = 100$$

$$R_3 = R_1 = 5K\Omega$$

$$R_4 = R_2 = 10K\Omega$$

$$\frac{R_2 R_4}{4R_1 R_3} = 1$$

$$\frac{10K\Omega \times 10K\Omega}{4 \times 5K\Omega \times 5K\Omega} = 1$$

$$\frac{100K\Omega}{100K\Omega} = 1$$

$$1 = 1$$

$$\frac{R_2 R_4}{2R_1 R_3} + \frac{R_4}{2R_3} = 3$$

$$\frac{10K\Omega \times 10K\Omega}{2 \times 5K\Omega \times 5K\Omega} + \frac{10K\Omega}{2 \times 5K\Omega} = 3$$

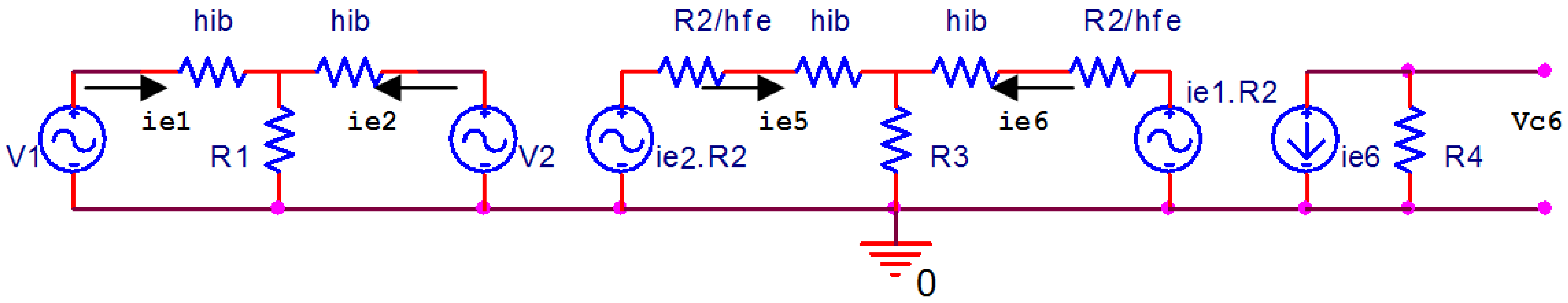
$$\frac{100K\Omega}{50K\Omega} + \frac{10K\Omega}{10K\Omega} = 3$$

$$2+1=3$$

$$3=3$$

Estructura interna del Amplificador Operacional.

- Circuito Equivalente para C.A.



- No consideramos en el circuito híbrido al par Darlington, debido a que no dan ganancia al circuito.
- Despreciamos en el híbrido las resistencias dinámicas de los diodos, debido a que R4 es mucho mayor.

Estructura interna del Amplificador Operacional.

$$v_c = \frac{v_1 + v_2}{2} \qquad i_{e_1} = \frac{v_c}{2R_1 + h_{ib}} - \frac{v_d}{2h_{ib_1}}$$

$$v_d = v_2 - v_1 \qquad i_{e_1} = \frac{v_c}{2R_1 + h_{ib}} - \frac{v_d}{2h_{ib_1}}$$

$$\frac{i_{e_1} + i_{e_2}}{2} = \frac{\cancel{2} v_c}{2R_1 + h_{ib}} \frac{1}{\cancel{2}} = \frac{v_c}{2R_1 + h_{ib}}$$

$$i_{e_2} - i_{e_1} = \frac{2v_d}{2h_{ib}} = \frac{v_d}{h_{ib}}$$

$$v_c' = \left(\frac{i_{e_1} + i_{e_2}}{2} \right) R_2 = \frac{v_c R_2}{2R_1 + h_{ib}}$$

$$v_d' = \left(i_{e_1} - i_{e_2} \right) R_2 = \frac{v_d R_2}{h_{ib}}$$

$$v_c' - \frac{v_d'}{2} = \frac{v_c R_2}{2R_1 + h_{ib}} - \frac{v_d R_2}{2h_{ib}}$$

$$v_c' + \frac{v_d'}{2} = \frac{v_c R_2}{2R_1 + h_{ib}} + \frac{v_d R_2}{2h_{ib}}$$

Estructura interna del Amplificador Operacional.

Nos interesa sacar i_{e_6} :

$$i_{e_6} = i_{e_{6c}} + i_{e_{6d}} = \frac{R_2 \times v_c}{2R_1 + h_{ib}} \frac{1}{2R_3 + h_{ib_6} + \frac{R_2}{h_{fe}}} + \frac{R_2 \times v_d}{h_{ib_1}} \frac{1}{2\left(h_{ib_6} + \frac{R_2}{h_{fe}}\right)}$$

$$v_o \cong v_{c_6} = i_{e_6} R_4 = \frac{R_2 R_4}{\underbrace{\left(2R_1 + h_{ib_1}\right)\left(2R_3 + h_{ib_6} + \frac{R_2}{h_{fe}}\right)}_{A_c}} v_c + \frac{R_2 R_4}{\underbrace{2h_{ib_1}\left(h_{ib_6} + \frac{R_2}{h_{fe}}\right)}_{A_d}} v_d$$

$$v_0 = A_c v_c + A_d v_d$$

$$RRMC = \frac{A_d}{A_c} = \frac{\left(2R_1 + h_{ib_1}\right)\left(2R_3 + h_{ib_6} + \frac{R_2}{h_{fe}}\right)}{2h_{ib_1}\left(h_{ib_6} + \frac{R_2}{h_{fe}}\right)}$$

Estructura interna del Amplificador Operacional

$$Si:\ h_{fe} = 100$$

$$R_3 = R_1 = 5K\Omega$$

$$R_4 = R_2 = 10K\Omega$$

$$V_{CC} = V_{EE} = 12V$$

$$V_D = V_{BE} = 0.7V$$

Reemplazamos en las y nos da:

$I_A = 2.25mA$ $\qquad V_{C_1} = 0.7V$ $\qquad V_{C_6} = 0$

$I_{C_1} = 1.13mA$ $\qquad V_{E_6} = 1.4V$ $\qquad h_{ie_6} = 2.35K\Omega$

$h_{ie_1} = 2.21K\Omega$ $\qquad I_B = 2.12mA$ $\qquad h_{ib_6} = 0.023K\Omega$

$h_{ib_1} = 0.0221K\Omega$ $\qquad I_{C_6} = 1.06mA$

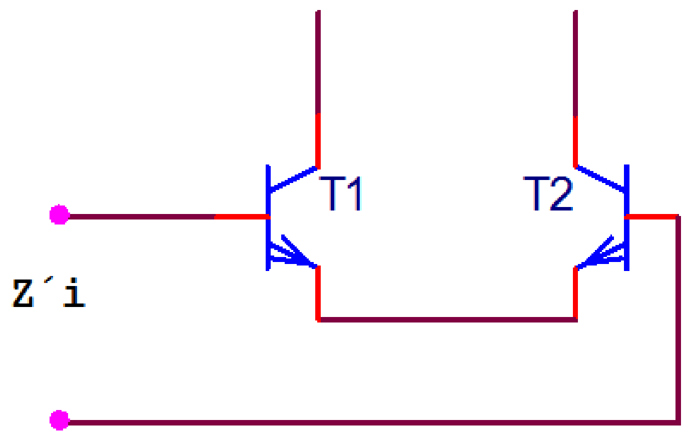
Con estos datos la RRMC es igual a 18745,

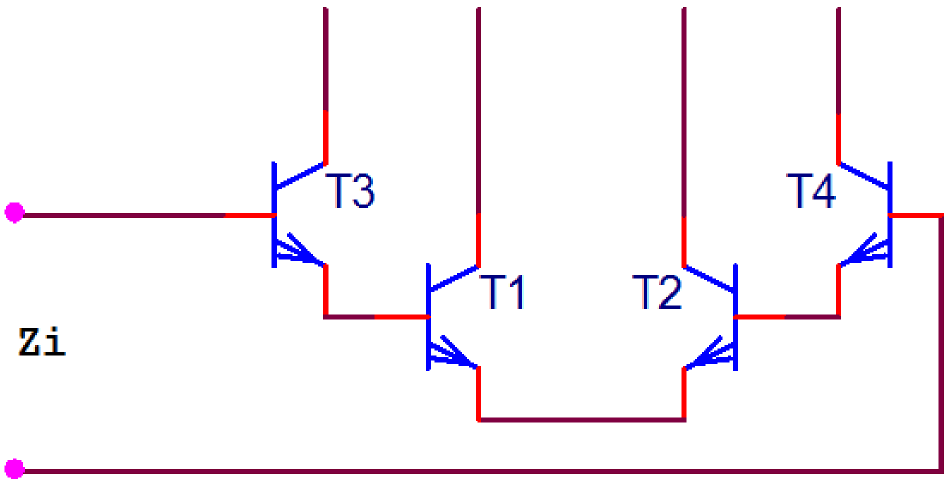
en decibeles, la $RRMC = 20\log 18745 = 85dB$

Estructura interna del Amplificador Operacional.

- Impedancia de entrada:

Vemos la diferencia en la impedancia de entrada de entrada al agregar el par Darlington.





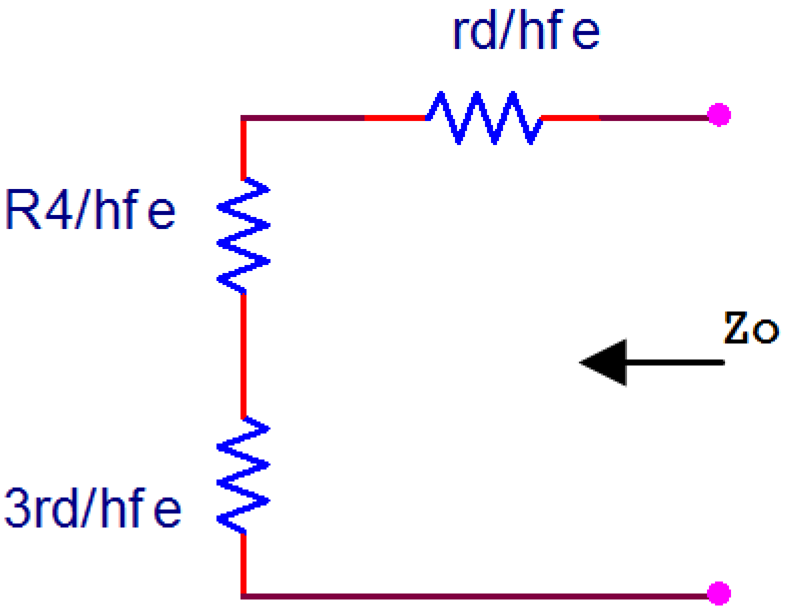
$$Z_i' = 2h_{ie} \cong 4.42K$$

$$Z_i = 2h_{ie_3} + 2h_{ie_1}h_{fe} = 4h_{ie_3} = 4h_{ie_1}h_{fe} = 2x4.42K\Omega \times 100 = 884K\Omega$$

Con el par Darlington logramos aumentar 200 veces la impedancia de entrada.

Estructura interna del Amplificador Operacional.

- Impedancia de salida:



$$Z_O = \frac{R_4}{h_{fe}} + \frac{4r_d}{h_{fe}} \cong \frac{R_4}{h_{fe}} = \frac{10K}{100} = 100\Omega$$

La impedancia de salida varia normalmente entre 80 y 200 Ohms