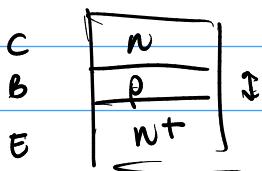


$$V_{CE} = V_C - V_E$$

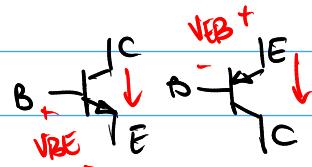
## Clase 1: Repaso Elementos Activos Transistor BJT

### 1. Estructura



Las terminales C-E  
no son intercambiables  
(dopado asimétrico)

### 2. Símbolo

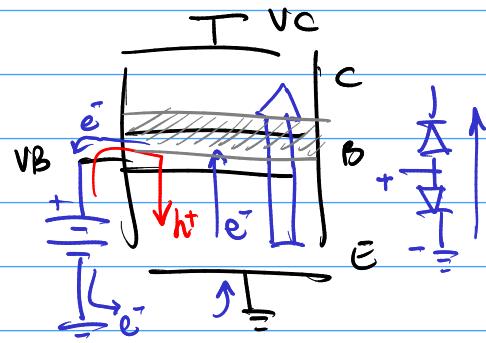


La flecha  
indica  
el emisor  
y la dirección  
de la corriente

### 3. Funcionamiento en activa directa

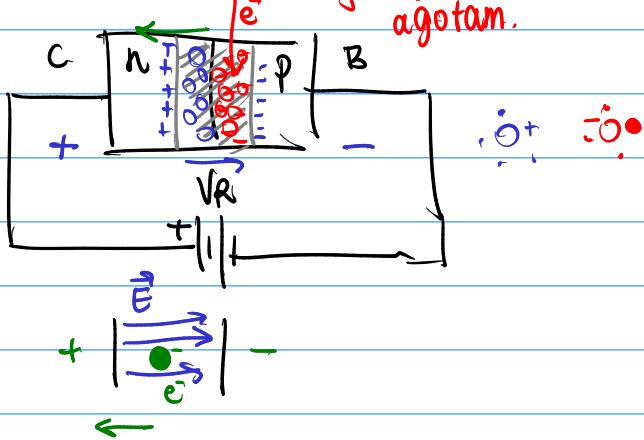
$$V_C > V_B$$

$$V_{CE} > V_{BE}$$

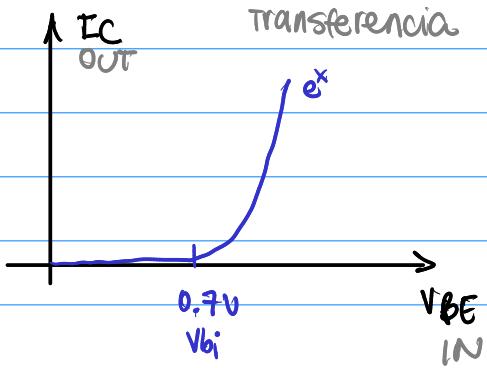


### 4. Acción del colector

Se "inyectan" electrones en la  
región de agotamiento.



### 5. Curvas características



La ecuación de Shockley:

$$I_C = I_S \cdot (e^{V_{BE}/nV_t} - 1)$$

n: Coeficiente de emisión ( $n \approx 1$ )

### 6. Variaciones de temperatura

$$V_t = k_B \cdot T \approx 25.85 \text{ mV}$$

$$\approx 26 \text{ mV}$$

$$@ T = 300 \text{ K}$$

$$T = 26.85^\circ\text{C}$$

$$I_C \propto I_S \cdot e^{V_{BE}/nV_t}$$

$$\frac{I_C}{I_S} = e^{V_{BE}/nV_t}$$

$$\ln \frac{I_C}{I_S} = \frac{V_{BE}}{nV_t}$$

$$I_S = \frac{A_e \cdot q \cdot D_n \cdot n_i^2}{N_B \cdot W_B}$$

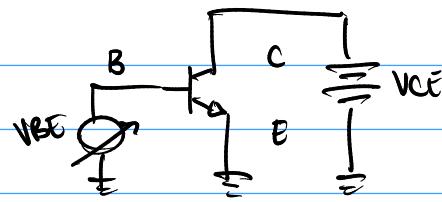
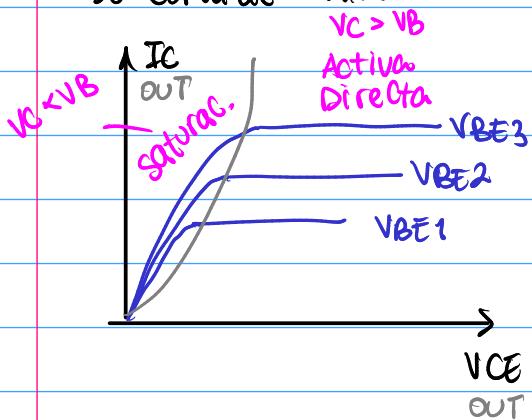
$$n_i(T) \approx 10^{10} \text{ cm}^{-3} @ 300 \text{ K}$$

se duplica con cada  $\Delta T = 10^\circ\text{C}$

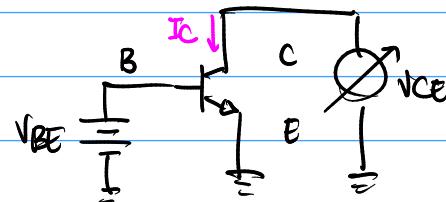
$$V_{BE} = nV_t \cdot \ln \frac{I_C}{I_S}$$

Círculo de medición  
curva de transferencia

5b. Curva de salida

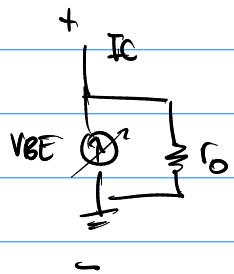
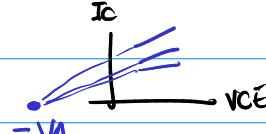
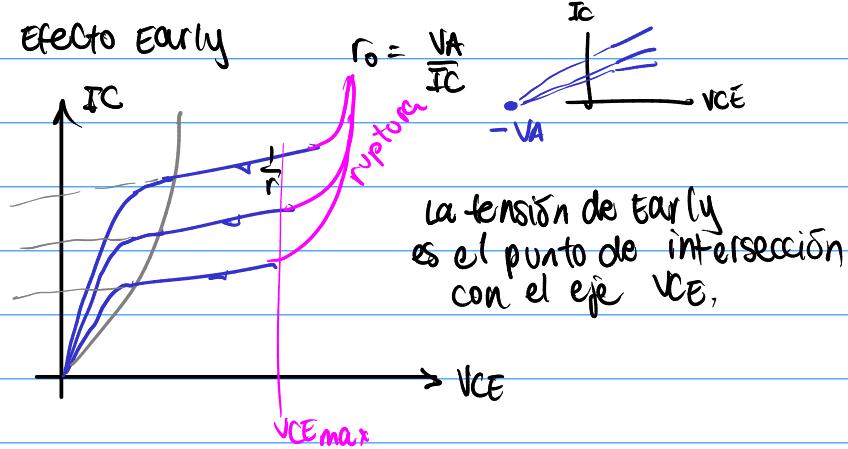


Círculo de medición  
curva de salida



7. Efectos no ideales

Efecto Early



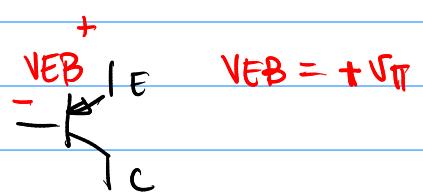
$$I_C = I_{CO} \cdot \left( e^{\frac{V_{BE}}{NVT}} - 1 \right) \cdot \left( 1 + \frac{V_{CE}}{V_A} \right)$$

$$I_C = I_{CO} + I_{CO} \frac{V_{CE}}{V_A}$$

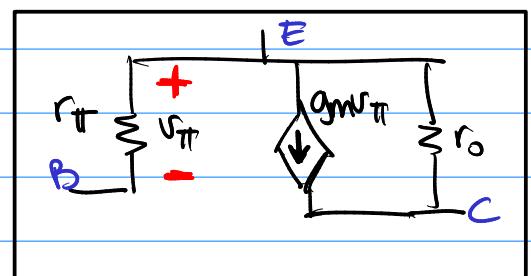
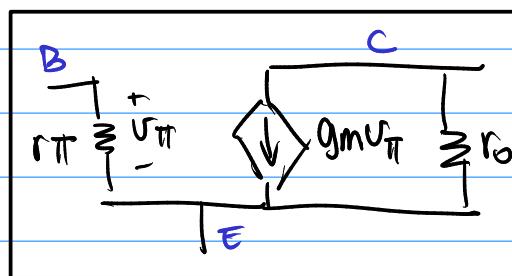
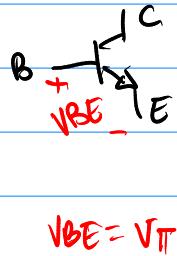
$\downarrow$

stn  
early

$V_{CE} = 2V$   
 $V_A = 5V$   
 $\frac{2}{5} = 40\%$



Modelo Pequeña señal ( $\pi$ )



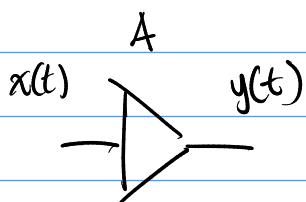
$$r_{\pi} = \frac{\beta}{g_m}$$

$$g_m = \frac{I_C}{V_T}$$

$$r_0 = \frac{V_A}{I_C}$$

## Clase 2: Introducción a Amplificadores

### 1. Símbolo

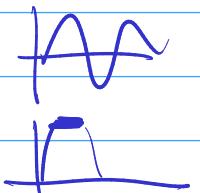
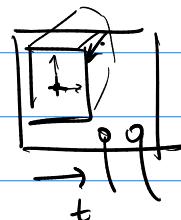
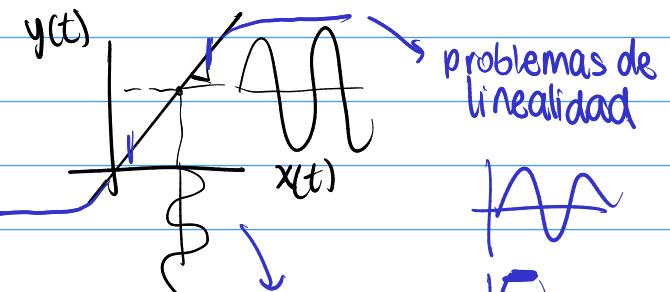


### 2. La ganancia es $A$ :

$$y(t) = A \cdot x(t)$$

$$A = \frac{y(t)}{x(t)}$$

3. La ganancia es la pendiente de la función de transferencia:



Si  $|A| > 1$ : Amplifica

(salida > entrada)

Si  $|A| = 1$ : Seguidor

(salida = entrada)

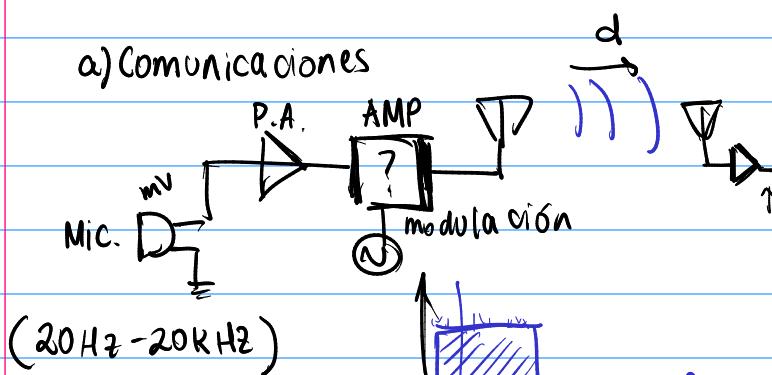
Si  $|A| < 1$ : Atenua

(salida < entrada)

La función de transferencia se puede medir en un osciloscopio modo XY

### 4. Aplicaciones de los amplificadores

#### a) Comunicaciones



(20 Hz - 20 kHz)

A  $\rightarrow 440$  Hz

B  $\rightarrow$

C  $\rightarrow$  Analizador de espectros

$$\omega = 2\pi f$$

$$\omega [\text{rad/s}]$$

$$\begin{array}{c} \text{20} \\ \text{20K} \end{array} \xrightarrow{\omega} f$$

El tamaño de la antena debe ser mayor que  $\lambda/4$ .

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{20 \text{ Hz}} \text{ m/s}$$

$$\lambda = 1.5 \times 10^7 \text{ m}$$

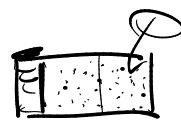
$$\frac{\lambda}{4} = 3750 \text{ km}$$

Radio AM: 530 kHz

FM: 88 MHz

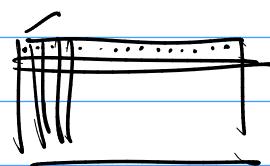
a 108 MHz

$$1 \text{ Hz} = \frac{1}{s}$$



## b) cámara fotográfica digital

B/N



1 pixel: 0 - 255

1080p:  $1920 \times 1080 \approx 2 \text{ MPx}$

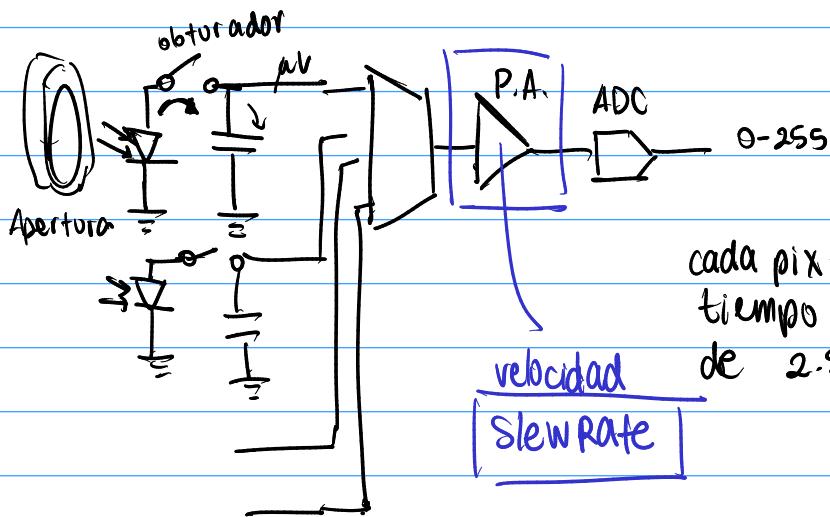


Apertura f 3.1

Tiempo de obturación

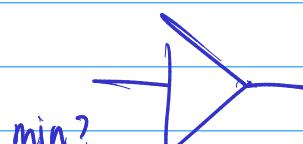
$\frac{1}{200}$

5ms



cada pixel tiene un  
tiempo de adquisición  
de 2.5 ns

Rango dinámico (DR)

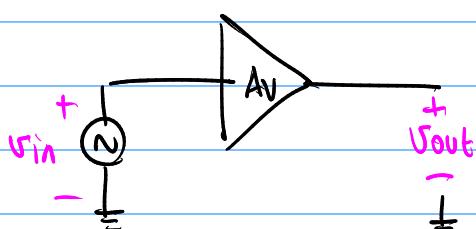


min?  
max?

$$DR = P_{\max} - P_{\min}$$

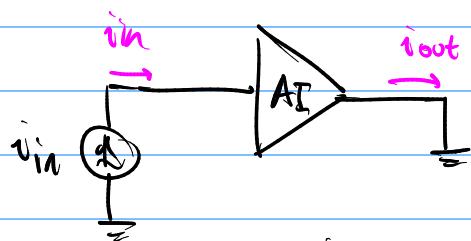
## 5. Tipos de amplificadores

### a) Amplificador de tensión



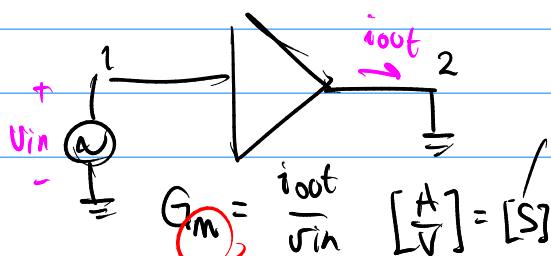
$$A_V = \frac{v_{out}}{v_{in}} \quad \left[ \frac{V}{V} \right] = [1]$$

### b) Amplificador de corriente



$$A_I = \frac{i_{out}}{i_{in}} \quad \left[ \frac{A}{A} \right] = [1]$$

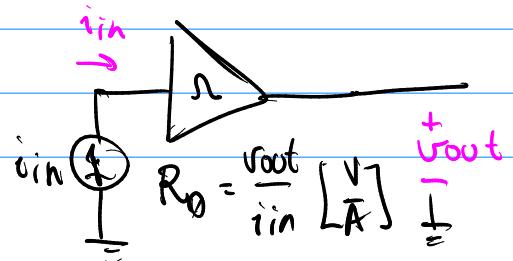
### c) Amplificador de transconductancia



$$G_m = \frac{i_{out}}{v_{in}} \quad \left[ \frac{A}{V} \right] = [S]$$

$$\begin{aligned} \text{Ohm} & \quad \Omega = \frac{V}{I} \\ \text{mho} & \quad \text{mho} = \frac{I}{V} \\ \text{V} & \quad V = \frac{I}{\Omega} \end{aligned}$$

### 4. Amp. de transresistencia



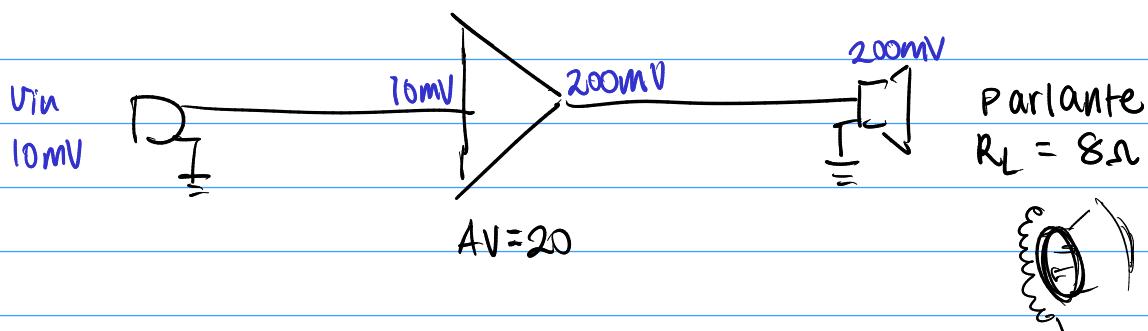
$$R_O = \frac{v_{out}}{i_{in}} \quad \left[ \frac{V}{A} \right] = \frac{V}{I}$$

$$i_C = g_m V_{BE}$$

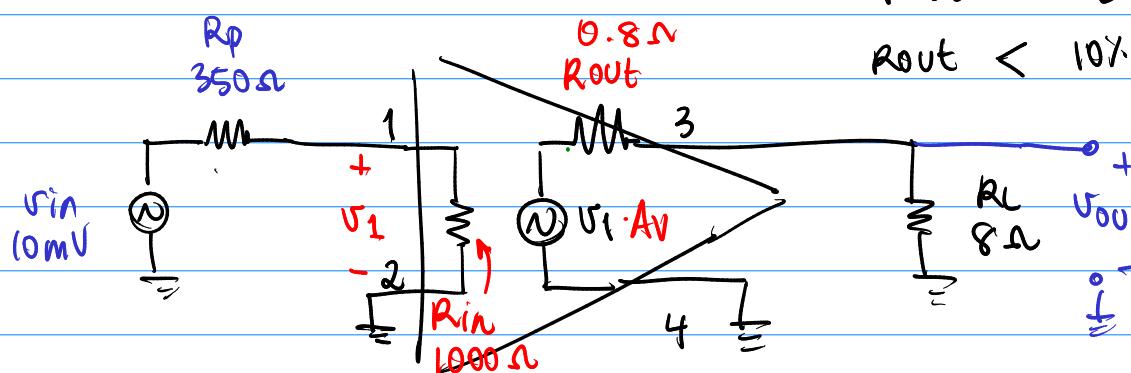
$$g_m = \frac{i_C}{V_{TF}}$$

Impedancias de entrada / salida:

En un circuito ideal:



Un amplificador no ideal:



$$\left( V_1 = \frac{(V_{in} \cdot R_{in})}{R_p + R_{in}} \right) \quad \left( V_{out} = \frac{V_1 \cdot AV \cdot R_L}{R_{out} + R_L} \right)$$

Ideal  
 $\frac{V_{out}}{V_{in}} = 20$

$$V_1 = \frac{(10 \text{ mV})(1000 \Omega)}{(350 \Omega + 1000 \Omega)}$$

$$V_1 = 7.41 \text{ mV}$$

$$V_{out} = \frac{(7.41 \text{ mV})(20)(8 \Omega)}{(0.8 \Omega + 8 \Omega)}$$

$$V_{out} = 134.7 \text{ mV}$$



Pérdidas:

$$\eta_E = \frac{200 - 134.7}{200} \times 100\% = 32.65\%$$

$$\eta_E = 32.65\%$$

No ideal:

$$\frac{V_{out}}{V_{in}} = \frac{134.7}{10} = 13.5$$

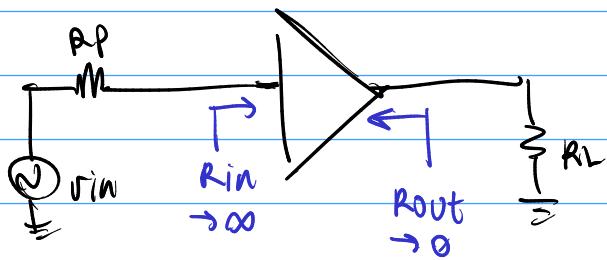
$$\frac{V_{out}}{V_{in}} = \left( \frac{R_{in}}{R_p + R_{in}} \right) \times \left( \frac{R_L}{R_{out} + R_L} \right) \times AV$$

$$= (0.741) \times (0.909) \times 20$$

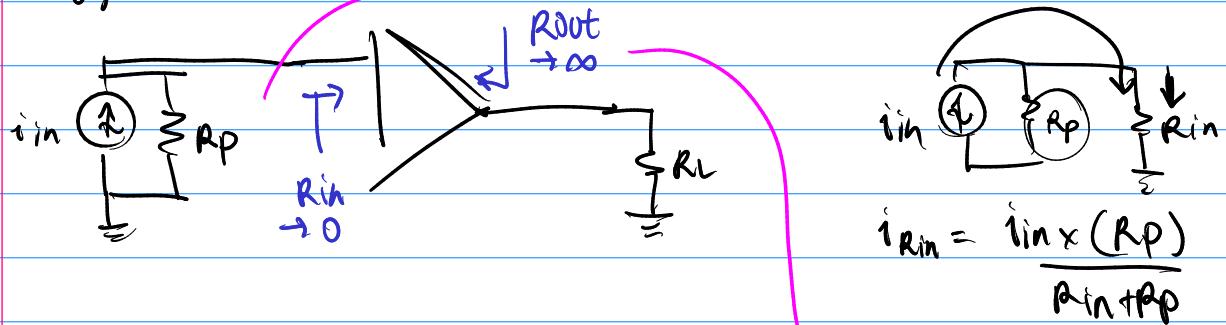
Pérdidas por acople de imp.

## Impedancias ideales

### a) Tensión



### b) Corriente

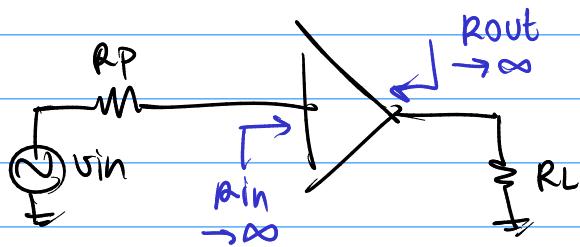


divisor de corriente  
en la entrada

Circuit diagram for current division at the input. A current source  $i_{in}$  is connected to the non-inverting input ( $\oplus$ ) of an ideal op-amp. The inverting input ( $\ominus$ ) is connected to ground through a resistor  $R_P$ . The output current is connected to the inverting input through a resistor  $R_L$ . The input resistance  $R_{in}$  is labeled as  $\rightarrow \infty$ .

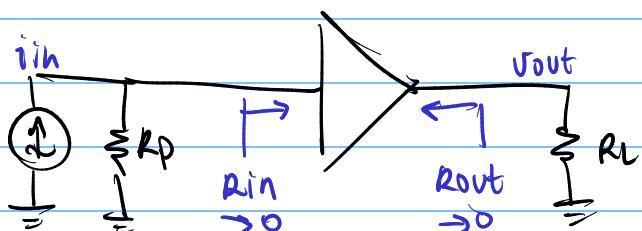
$$i_{Rin} = \frac{i_{in} \times (R_P)}{R_{in} + R_P}$$

### c) Transconductancia:



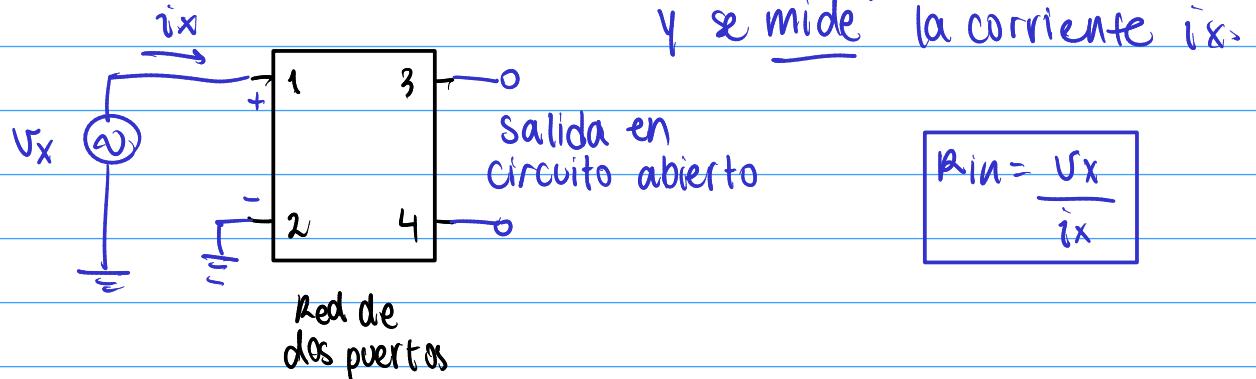
Circuit diagram for current division at the output. A current source  $i_{out}$  is connected to the inverting input ( $\ominus$ ) of an ideal op-amp. The non-inverting input ( $\oplus$ ) is connected to ground through a resistor  $R_P$ . The output current is connected to the inverting input through a resistor  $R_L$ . The input resistance  $R_{in}$  is labeled as  $\rightarrow \infty$ .

### d) Transresistencia:

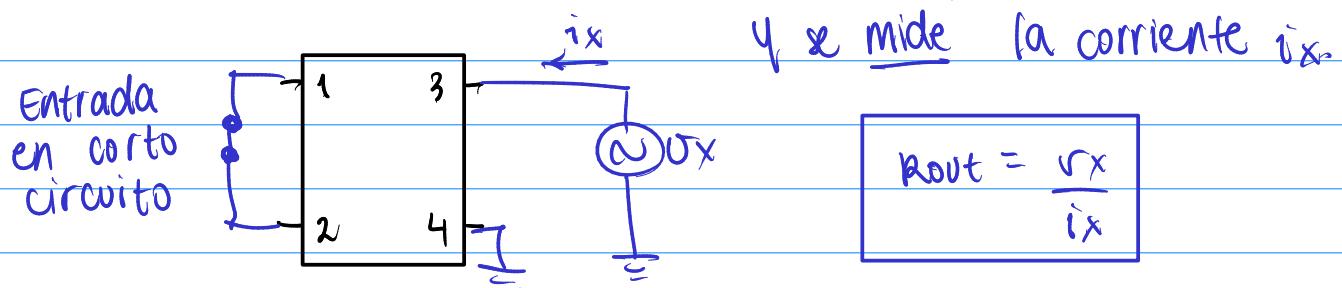


Medición de impedancias  $\rightarrow$  en corriente alterna

para medir  $R_{in}$ : se aplica una fuente de prueba  $v_x$

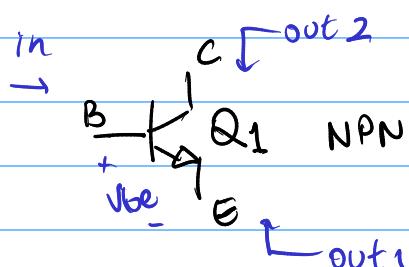


para medir  $R_{out}$ : se aplica una fuente de prueba  $v_x$



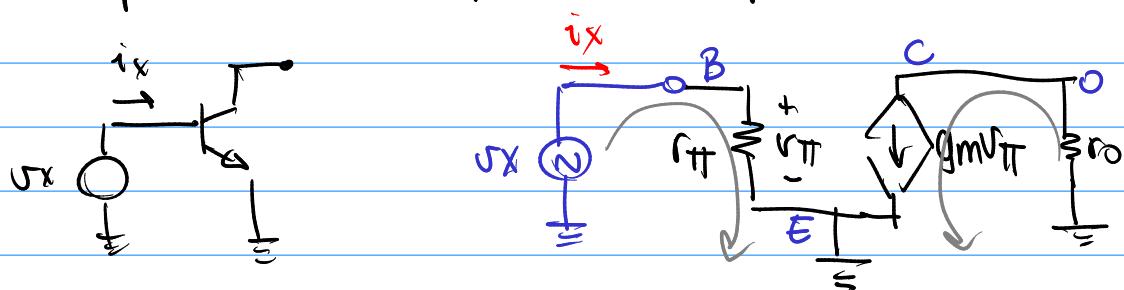
Ambas mediciones se hacen con las fuentes de CC apagadas.

Impedancias de un BJT



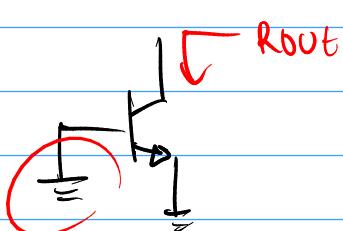
$R_1$	$L_1$
$R_2$	$C_1$
$Q_1$	$M_1$

Impedancia de entrada desde la base:

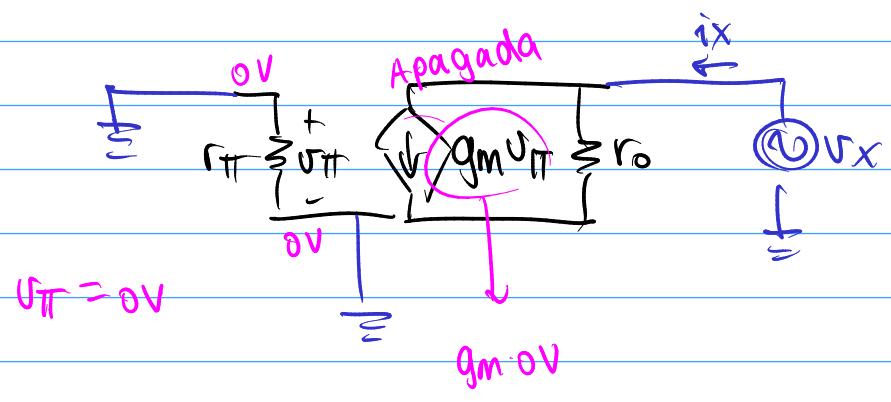


$$i_x = \frac{v_x}{r_{fe}} \Rightarrow \frac{v_x}{i_x} = r_{fe} = R_{in}$$

## Impedancia BJT desde el colector



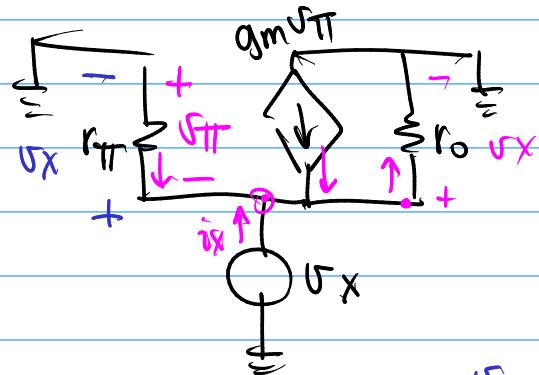
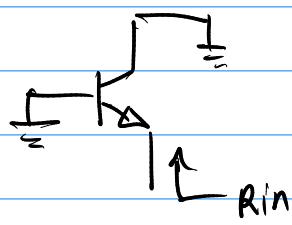
Entrada en corto



$$R_{out} = r_o \quad \rightarrow \text{con efecto Early}$$

$$R_{out} \rightarrow \infty \quad \rightarrow \text{sin efecto Early}$$

## Impedancia desde el emisor



La LCK en el emisor:

$$V_X = -V_T$$

$$10\Omega // 100\Omega$$

$$\approx 10\Omega$$

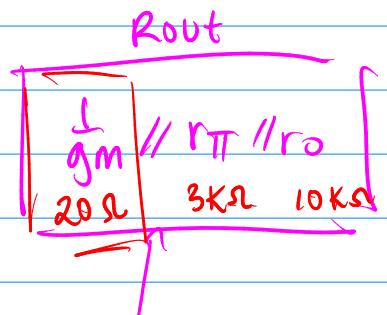
$$r_{TT}$$

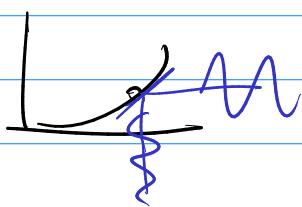
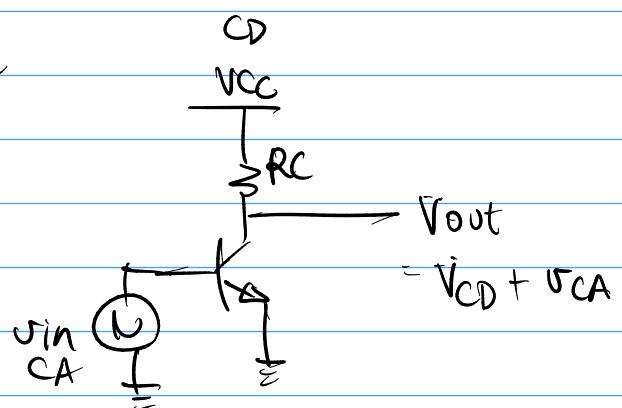
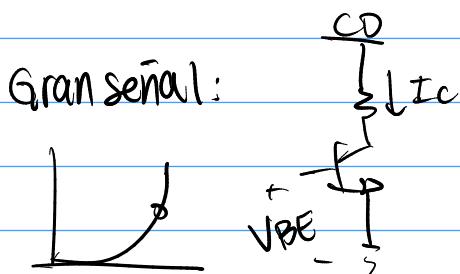
$$\frac{1}{gm} < \frac{\beta}{gm}$$

$$100$$

$$i_x = V_X \left( gm + \frac{1}{r_{TT}} + \frac{1}{r_o} \right)$$

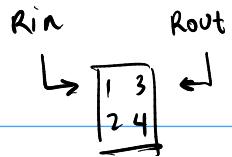
$$R_{out} = \frac{V_X}{i_x} = \frac{1}{gm + \frac{1}{r_{TT}} + \frac{1}{r_o}} = \frac{1}{\left(\frac{1}{gm}\right)^{-1} + r_{TT}^{-1} + r_o^{-1}}$$





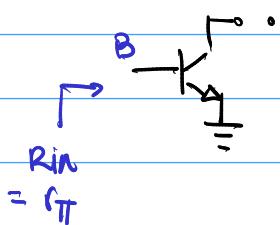
$$r_0 = \frac{V_A}{I_C}$$

### Clase 3: Polarización BJT



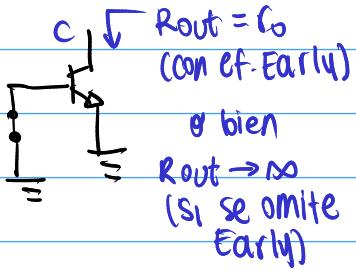
Impedancias BJT en corriente alterna.

Desde la base



$$R_{in} = r_{pi}$$

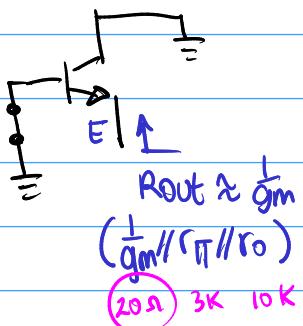
Desde el colector



$$R_{out} = r_o$$

(con ef. Early)  
o bien  
 $R_{out} \rightarrow \infty$   
(si se omite Early)

Desde el emisor

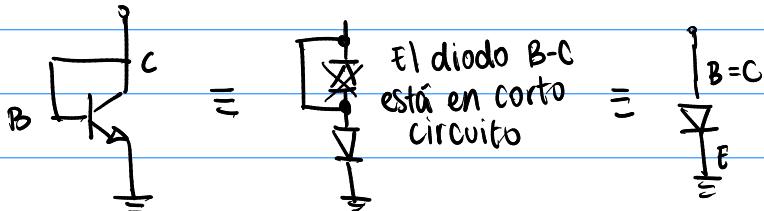


$$R_{out} \approx \frac{1}{g_m}$$

$$\left(\frac{1}{g_m} \parallel (r_{pi} \parallel r_o)\right)$$

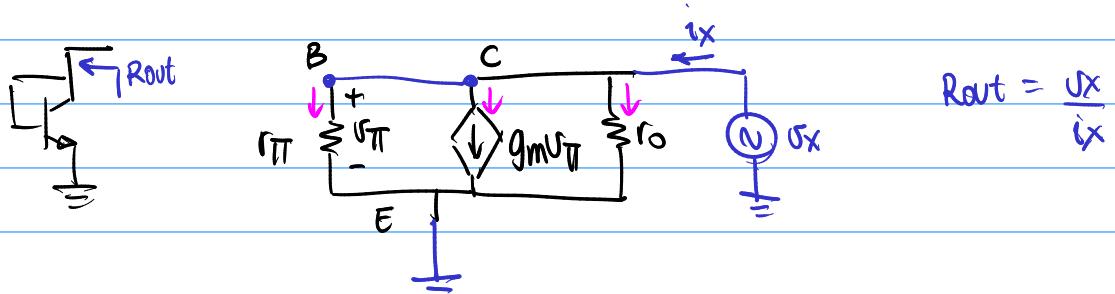
$$20 \Omega \quad 3K \quad 10K$$

Ejemplo: transistor conectado como diodo



Determine la impedancia desde el colector y desde el emisor.

Solución: desde el colector



Ecuación de nodos en la salida

la LCK en el colector:

$$i_x = \frac{v_x}{r_o} + g_m v_{tf} + \frac{v_{pi}}{r_{pi}}$$

Ecuación de mallas por  $r_{pi}$

$$v_x = v_{pi}$$

sustituyendo la ecuación de mallas:

$$i_x = \frac{v_x}{r_o} + g_m v_x + \frac{v_x}{r_{pi}}$$

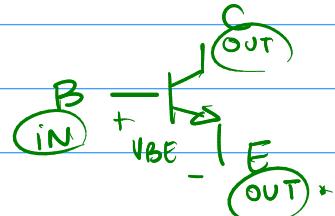
Factor común  $v_x$ :

$$i_x = \frac{v_x}{r_o} \left( \frac{1}{r_o} + g_m + \frac{1}{r_{\pi}} \right)$$

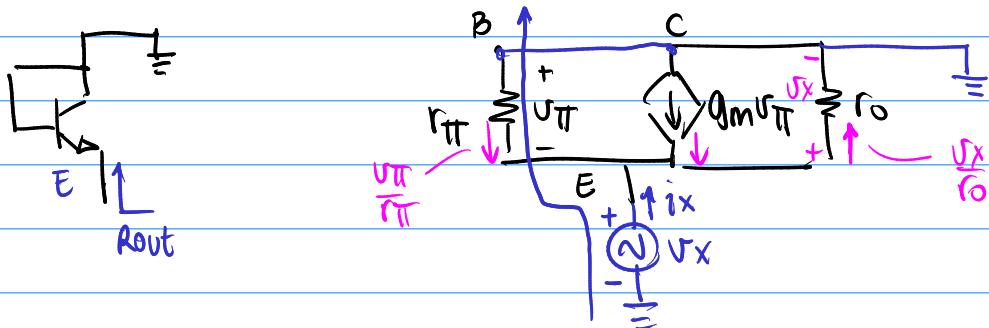
$$\frac{v_x}{i_x} = \frac{1}{\frac{1}{r_o} + g_m + \frac{1}{r_{\pi}}} \quad g_m = \left(\frac{1}{g_m}\right)^{-1}$$

$$\frac{v_x}{i_x} = \frac{1}{r_o^{-1} + \left(\frac{1}{g_m}\right)^{-1} + r_{\pi}^{-1}}$$

$$R_{out} = r_o \parallel \frac{1}{g_m} \parallel r_{\pi}$$



Solución: desde el emisor



La LCK en la salida (E):

$$i_x + \frac{v_{\pi}}{r_{\pi}} + g_m v_{\pi} = \frac{v_x}{r_o}$$

La LVK por la entrada (B):

$$-v_x - v_{\pi} = 0 \\ v_{\pi} = -v_x$$

Sustituyendo la LVK:

$$i_x + \frac{(-v_x)}{r_{\pi}} + g_m(-v_x) = \frac{v_x}{r_o}$$

$$i_x = \frac{v_x}{r_o} + \frac{v_x}{r_{\pi}} + g_m v_x$$

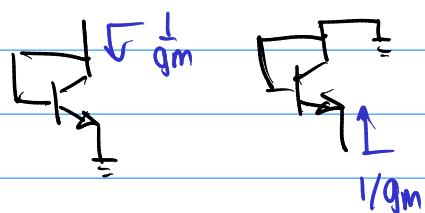
Factor común  $v_x$ :

$$i_x = v_x \left( \frac{1}{r_o} + \frac{1}{r_{\pi}} + g_m \right)$$

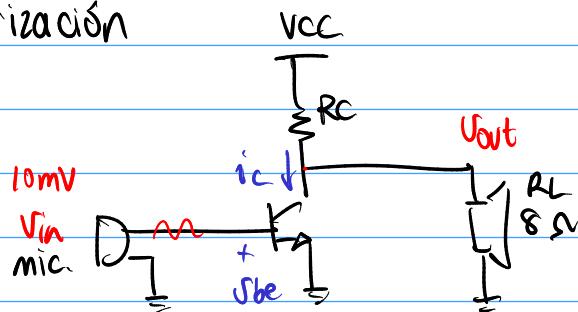
$$\frac{v_x}{i_x} = r_o \parallel r_{\pi} \parallel \frac{1}{g_m}$$

### Resumen

La impedancia del BJT conectado como diodo:



Polarización



$$A_v = \frac{V_{out}}{V_{in}} = \sigma$$

1) La transconductancia:

$$i_c = g_m \cdot v_{be}$$

Convierte tensión de entrada a corriente de salida.

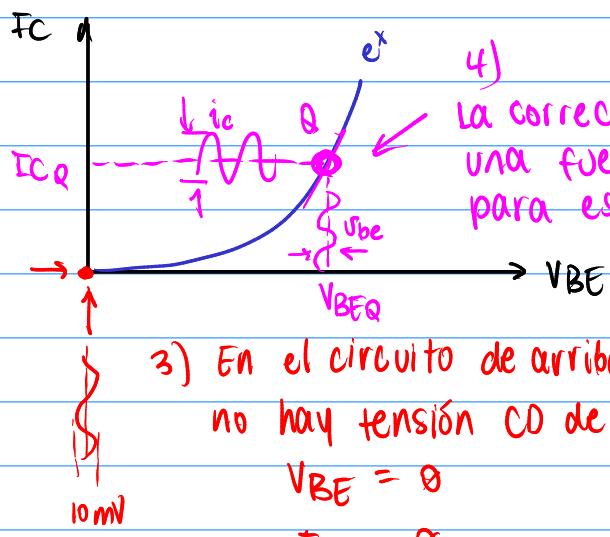
2) La resistencia  $R_C$  convierte  $i_c$  a una tensión de salida.

$$v_{RC} = i_c \times R_C$$

problema:

$$g_m = \frac{i_c}{v_t} = \frac{i_c}{26 \text{ mV}}$$

$$v_{in} \rightarrow g_m \rightarrow i_c \rightarrow R_C \rightarrow v_{out}$$



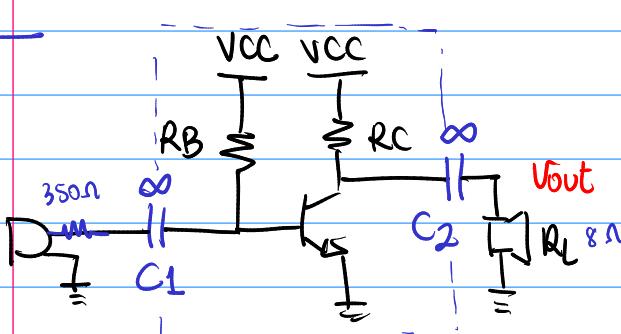
3) En el circuito de arriba, no hay tensión CC de base.

$$g_m = \frac{0}{26 \text{ mV}} = 0$$

$$V_{BE} = 0$$

$$I_C = 0$$

$$X_C = \frac{1}{j\omega C} \rightarrow \text{en CC, } \omega = 0 \quad X_C \rightarrow \infty$$



$C_1$  y  $C_2$  son condensadores de desacople.

Análisis del circuito (Superposición)

PASO 1. Gran señal (C.D.)

→ Se apagan las fuentes de C.A.  
 $v \rightarrow$  corto       $i \rightarrow$  abierto

→ Condensadores en CC son abiertos.

→ Se resuelve el punto de op. CC.

PASO 2. Pequeña señal (C.A.)

→ Se apagan fuentes de C.C.  
 $v \rightarrow$  corto       $I \rightarrow$  abierto

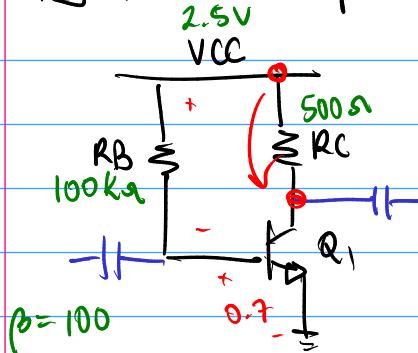
→ Condensadores en CA son "cortados".

$\frac{1}{j\omega C} \rightarrow 0$       en la frecuencia de interés.

→ Se resuelve  $A_v$ ,  $R_{in}$  y  $R_{out}$  con el modelo  $\pi$ .

## Paso I - Gran señal

### A] Polarización por resistencia de base



En CD, los condensadores están abiertos y aislan la fuente y la carga.

Con el modelo de tensión constante:

$$1. \text{ Suponer } V_{BE} = 0.7V *$$

$$2. V_{RB} = V_{CC} - V_{BE} = 2.5V - 0.7V = 1.8V$$

$$3. I_{RB} = I_B = \frac{V_{RB}}{R_B} = \frac{1.8V}{100k\Omega} = 18 \mu A$$

$$4. I_C = \beta I_B = (100)(18 \mu A) = 1.8mA$$

$$5. I_E = (\beta + 1)I_B = I_C + I_B = 1.818mA$$

$$6. V_C = V_{CC} - I_C R_C$$

$$V_C = 2.5V - (1.8mA)(500 \Omega)$$

$$V_C = 1.6V$$

7. Comprobar que Q1 está en Activación directa:

$$V_C > V_B$$

$$1.6V > 0.7V$$

8. ¿Cuál es la resistencia máxima de colector que hace que el circuito se mantenga en activa directa?

$$V_C > V_B$$

$$V_{CC} - I_C R_C > V_B \rightarrow \text{Todo constante excepto } R_C$$

$$V_{CC} - V_B > I_C R_C$$

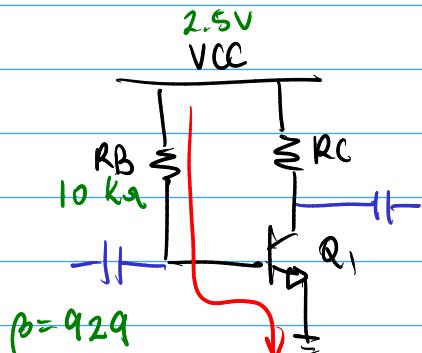
$$\frac{V_{CC} - V_B}{I_C} > R_C$$

$$R_C < \frac{V_{CC} - V_B}{I_C}$$

$$R_C < \frac{2.5V - 0.7V}{1.8mA}$$

$$R_C < 1k\Omega$$

## Solución de gran señal con el modelo exponencial



$$I_S = 3.88 \times 10^{-14} \text{ A}$$

(2N2222A de On Semi).

Si se omite el efecto Early:

$$I_C = I_S \cdot (e^{\frac{V_{BE}}{V_t}} - 1) \quad (1)$$

La malla por la base:

$$V_{CC} = I_B \cdot R_B + V_{BE}$$

$$V_{CC} = \frac{I_C}{\beta} R_B + V_{BE} \quad (2)$$

Se resuelve el sistema de ecuaciones:

$$\left\{ \begin{array}{l} I_C = I_S \cdot (e^{\frac{V_{BE}}{V_t}}) \\ I_C = \beta \left( \frac{V_{CC} - V_{BE}}{R_B} \right) \end{array} \right.$$

Método de solución 1: calculadora

Se igualan las ecuaciones:

$$I_S \cdot (e^{\frac{V_{BE}}{V_t}}) = \beta \left( \frac{V_{CC} - V_{BE}}{R_B} \right)$$

Se resuelve en calculadora con  $x = V_{BE}$

$$\Rightarrow V_{BE} = 755.57 \text{ mV}$$

Se sustituye el resultado en alguna de las dos:

$$I_C = I_S \cdot (e^{\frac{V_{BE}}{V_t}})$$

$$I_C = (3.88 \times 10^{-14} \text{ A}) (e^{755.57/26})$$

$$I_C = 162.03 \text{ mA}$$

$$V_B = V_{BE} = 755.6 \text{ mV}$$

$$V_E = 0$$

$$V_C = V_{CC} - I_C R_C > V_B$$

$$I_B = \frac{I_C}{\beta} = \frac{162.03 \text{ mA}}{929} = \underline{\hspace{2cm}}$$

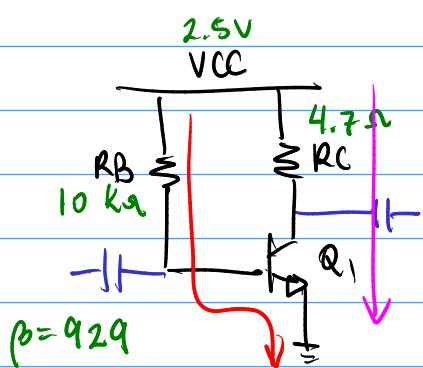
$$R_C < \frac{V_{CC} - V_B}{I_C}$$

$$I_E = (\beta + 1) I_B = (930) I_B = \underline{\hspace{2cm}}$$

$$R_C < \frac{2.5V - 0.75557}{162.03 \text{ mA}}$$

$$R_C < 10.766 \Omega$$

Solución con efecto Early:



$$I_S = 3.88 \times 10^{-14} \text{ A}$$

(2N2222A de  
on semi).

$$V_A = 16.5 \text{ V}$$

$$I_C = I_S \left( e^{\frac{V_{BE}}{V_T}} - 1 \right) \left( 1 + \frac{V_{CE}}{V_A} \right) \quad [1]$$

$$V_{CC} = I_B R_B + V_{BE}$$

$$V_{CC} = \frac{I_C}{\beta} R_B + V_{BE}$$

$$V_{BE} = V_{CC} - \frac{I_C}{\beta} R_B \quad [2]$$

$$V_{CC} = I_C R_C + V_{CE}$$

$$V_{CE} = V_{CC} - I_C R_C$$

[3]

$$I_C = I_S \left( e^{\left( \frac{V_{CC} - \frac{I_C}{\beta} R_B}{V_T} \right)} - 1 \right) \left( 1 + \frac{V_{CC} - I_C R_C}{V_A} \right)$$

La única variable es  $I_C$ . Se resuelve en calculadora.



solve ( $X = 3.88e-14 * (\exp((2.5 - (X/929) * 10e3) / (26e-3)) - 1) * (1 + (2.5 - X * 4.7) / (16.5))$ )

NATURAL LANGUAGE

MATH INPUT

EXTENDED KEYBOARD

EXAMPLES

UPLOAD

RANDOM

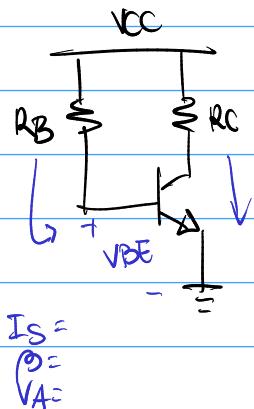
Solution over the reals

$$X = 0.162295$$

## Clase 4: polarización BJT

$$g_m = \frac{I_C}{V_T}$$

### I) Polarización por resistencia de base (polarización fija)



$$\left. \begin{array}{l} LVK_1: V_{CC} = I_B R_B + V_{BE} \\ LVK_2: V_{CC} = I_C R_C + V_{CE} \\ Shockley: I_C = I_S (e^{\frac{V_{BE}}{V_T}} - 1) \left( 1 + \frac{V_{CE}}{V_A} \right) \end{array} \right\}$$

$$I_C = I_S \left( e^{\frac{(V_{CC} - I_C R_B)}{V_T}} - 1 \right) \left( 1 + \frac{V_{CC} - I_C R_C}{V_A} \right)$$

La corriente  $I_C$  depende de  $\beta$ .  $I_C = \beta I_B$

El parámetro  $\beta$  depende de la temperatura, de la corriente  $I_C$ , variabilidad entre transistores, etc.

la polarización fija es muy susceptible a variaciones de  $\beta$ .

Ejemplo 1  $R_C = 10\Omega$      $R_B = 47k\Omega$      $I_S = 10^{-17} A$      $\beta = 100$   
 $V_A = 2V$      $V_{CC} = 2.5V$

Con  $\beta = 100$ , la corriente es  $I_{C0} = 3.511 \text{ mA}$

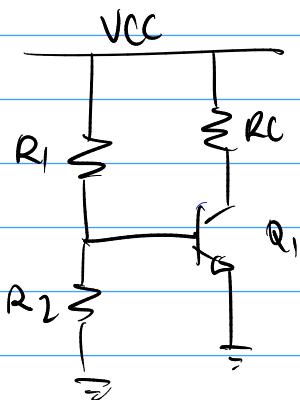
Con  $\beta = 100 \times 1-1$ , la corriente es  $I_{CE} = 3.856 \text{ mA}$   
 (un 10% más)

El porcentaje de error (relativo):

$$\gamma_E = \frac{|I_{teor} - I_{exp}|}{I_{teor}} \times 100\%$$

$$\gamma_E = -9.836\%$$

TB Polarización por divisor de tensión



Caso 1: si  $I_B$  es despreciable

las resistencias  $R_1$  y  $R_2$  mantienen fija la tensión de la base:

$$V_B = \frac{V_{CC} \times R_2}{R_1 + R_2}$$

si  $I_B \approx 0$

la mayoría de la corriente pasa por  $I_{R_1}$  y  $I_{R_2}$ .

Solución (omitiendo efecto Early)

$$I_C = I_S \cdot \left( e^{\frac{V_{CC} R_2}{R_1 + R_2} / V_T} - 1 \right)$$

$I_{R_1} \gg I_B$

$I_{R_1} > 10 I_B$

→ Esta ecuación es independiente de  $\beta$ .

Considerando el efecto Early:

$$I_C = I_S \cdot \left( e^{\frac{V_{CC} R_2}{R_1 + R_2} / V_T} - 1 \right) \left( 1 + \frac{V_{CE}}{V_A} \right)$$

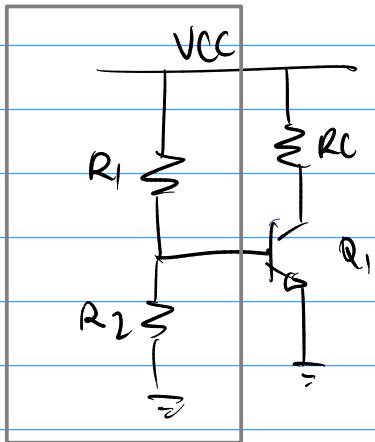
$$I_C = I_S \cdot \left( e^{\frac{V_{CC} R_2}{R_1 + R_2} / V_T} - 1 \right) \left( 1 + \frac{V_{CE} - I_C R_C}{V_A} \right)$$

→ Esta ecuación es independiente de  $\beta$ .

Esto significa que si  $\beta$  aumenta un 10%, la corriente de colector no varía.

El porcentaje de error es cero.

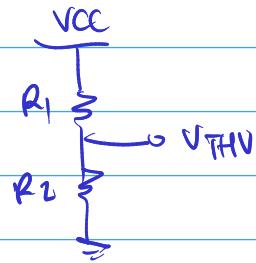
CASO 2: Si  $I_B$  NO es despreciable (sol. exacta)



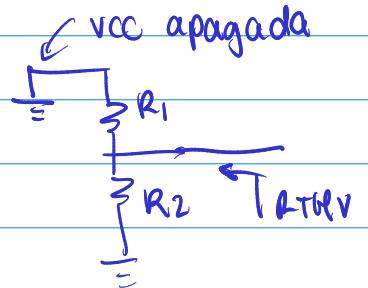
Equivalente de Thévenin

$V_{THV}$ :  
tensión de  
circuito  
abierto

$$V_{THV} = \frac{V_{CC} \times R_2}{R_1 + R_2}$$

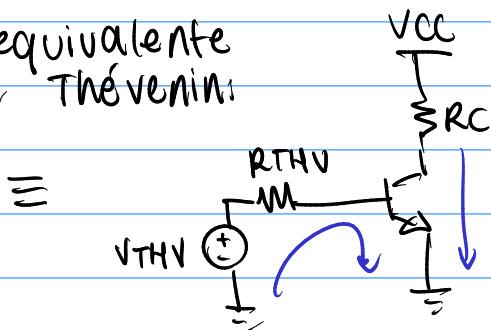


$R_{THV}$ :  
resistencia  
de salida  
con fuentes  
apagadas



$$R_{THV} = R_1 // R_2$$

El equivalente  
de Thévenin:



se analiza igual que el circuito  
de polarización fija

$$\left\{ \begin{array}{l} LVK1: V_{THV} = I_B R_{THV} + V_{BE} \\ LVK2: V_{CC} = I_C R_C + V_{CE} \\ \text{Shockley: } I_C = I_S \left( e^{\frac{V_{BE}(V_t)}{V_A}} - 1 \right) \left( 1 + \frac{V_{CE}}{V_A} \right) \end{array} \right.$$

## Limitaciones de polarización por div. de tensión:

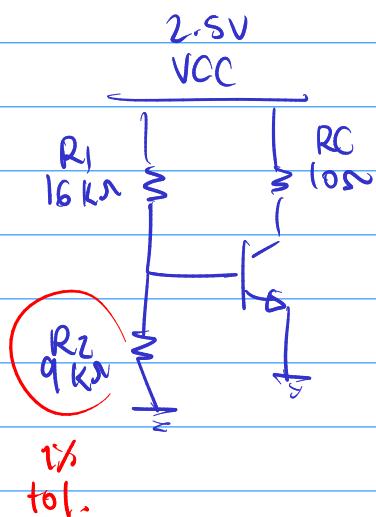
- Si  $I_B$  no es despreciable,  $I_C$  sigue dependiendo de  $\beta$ .  
Si se requiere  $V_B = 1.0V$  a partir de  $V_{CC} = 2.5V$

$$\begin{array}{c|c|c} R_2 = 2\Omega & R_2 = 2k\Omega & R_2 = 20k\Omega \\ R_3 = 3\Omega & R_1 = 3k\Omega & R_3 = 30k\Omega \end{array} \quad \begin{array}{c} \text{I} \\ \downarrow \\ \mu A \end{array}$$

$$I_R \approx A \quad I_R \approx mA \quad I_R \approx \mu A$$

seleccionando  $R_1$  y  $R_2$  correctamente  
se puede evitar este problema.

- Las resistencias  $R_1$  y  $R_2$  tienen tolerancias.



### Ejemplo 2

Si  $R_1$  y  $R_2$  tienen el valor nominal:

$$V_B = \frac{V_{CC} \times R_2}{R_1 + R_2} = \frac{(2.5V)(9k\Omega)}{(16k\Omega + 9k\Omega)}$$

$$V_{BE0} = 900 \text{ mV}$$

$$I_C = I_S e^{\frac{V_{BE}}{V_t}}$$

Si  $R_2$  tiene un 1% más que su valor nominal

$$V_B = \frac{V_{CC} \times 1.01 R_2}{R_1 + 1.01 R_2}$$

$$V_B = 905.7 \text{ mV}$$

$$I_C = I_S e^{\frac{(V_{BE0} + 5.7 \text{ mV})}{V_t}}$$

$$I_C = I_S e^{\frac{V_{BE0}}{V_t}} e^{\frac{5.7 \text{ mV}}{V_t}}$$

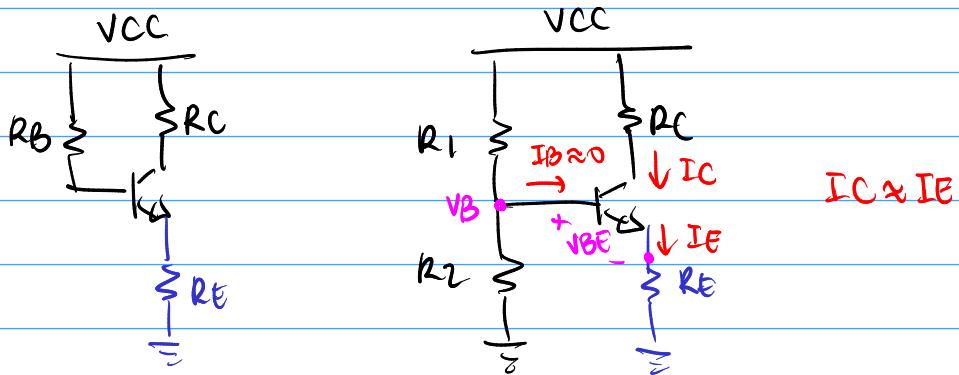
Corriente sin error

1.2451

24.5%

(degradación)

### C) Polarizaciones con degeneración de emisor



La tensión del emisor depende de la corriente  $I_E$ .

$$V_E = I_E \cdot R_E$$

En el circuito de la derecha, si  $I_B \approx 0 \Rightarrow I_C \approx I_E$

$$V_E = I_C \cdot R_E$$

$$V_{BE} = V_B - V_E$$

$$I_C = \frac{V_E}{R_E} \quad \leftarrow \quad V_E = V_B - V_{BE}$$

$$I_C = \frac{V_B - V_{BE}}{R_E}$$

$$\left\{ \begin{array}{l} I_C = \frac{\frac{VCC R_2}{R_1 + R_2} - V_{BE}}{R_E} \end{array} \right.$$

ec. 1 o  
ecuación del circuito

$$I_C = I_S (e^{\frac{V_{BE}}{V_T}} - 1) \left( 1 + \frac{V_{CE}}{V_A} \right)$$

ec. 2  
Shockley

con efecto Early,  
se necesita una tercera ecuación

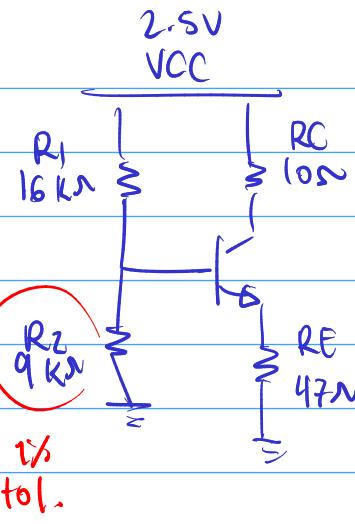
$$V_{CE} = V_C - V_E$$

$$V_{CE} = VCC - I_C R_C - (I_E R_E)$$

$$V_{CE} = VCC - I_C R_C - I_C R_E \rightarrow$$

ec. 3

LVIK por  
colector



$$I_S = 10^{-17} \text{ A}$$

$$\beta = 100$$

$$V_t = 26 \text{ mV}$$

### Ejemplo 3

La corriente IC sin error:

( $R_2$  con valor nominal)

$$V_B = 900 \text{ mV} \rightarrow \text{problema anterior}$$

$$V_E = I_C R_E$$

$$V_{BE} = 0.9 \text{ V} - I_C R_E$$

$$I_C = I_S (e^{V_{BE}/V_t} - 1)$$

$$I_C = 10^{-17} \text{ A} (e^{[0.9 \text{ V} - I_C(47 \Omega)]/V_t} - 1)$$

Por aprox. con calculadora:

$$I_C = 6210 \text{ mA}$$

La corriente con error:

(si  $R_2$  tiene un 1% más que su valor nominal):

$$I_C = 1.295 \text{ mA}$$

El porcentaje de error:

$$\frac{\Delta I_C}{I_C} = -6.95\%$$



(Antes el error era  
de 24.5%)

→ Con esto se demuestra que la resistencia de emisor absorbe parte del error por tolerancias en  $R_1$ ,  $R_2$ .

$$I_E = I_B + I_C \quad (1)$$

$$I_E = (\beta + 1) I_B \quad (2)$$

$$\beta I_B = I_C \quad (3)$$

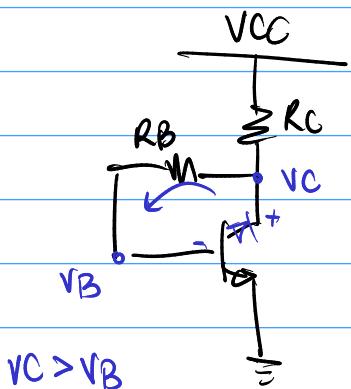
$$\beta = \frac{I_C}{I_B} \quad I_B \rightarrow -\frac{1}{\beta} I_C$$

Ganancia corriente de emisor común

$$\alpha = \frac{I_C}{I_E} = \frac{1}{1 + \frac{1}{\beta}} \frac{I_C}{I_E} \quad \alpha = \frac{\beta}{\beta + 1} \quad (4)$$

Ganancia corriente de base común

#### D) Autopolarización



$$LVK_1: V_{CC} = (I_B + I_C) R_C + I_B R_B + V_{BE}$$

$$V_{CC} = (1) I_E R_C + \frac{I_C}{\beta} R_B + V_{BE}$$

$$V_{CC} = (\beta + 1) I_B R_C + \frac{I_C}{\beta} R_B + V_{BE}$$

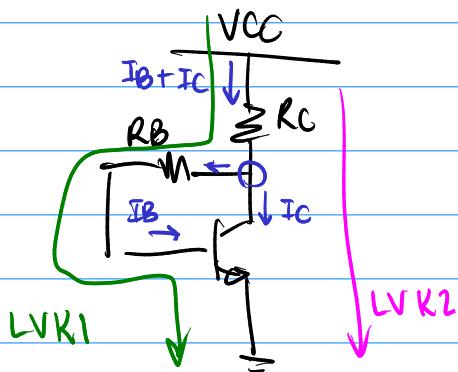
$$V_{CC} = (\beta + 1) \frac{I_C}{\beta} R_C + \frac{I_C}{\beta} R_B + V_{BE}$$

$$V_{CC} = \frac{I_C}{\alpha} R_C + \frac{I_C}{\beta} R_B + V_{BE} \quad [1]$$

$$LVK_2: V_{CC} = (I_B + I_C) R_C + V_{CE}$$

$$V_{CC} = I_E R_C + V_{CE}$$

$$V_{CC} = \frac{I_C}{\alpha} R_C + V_{CE} \quad [2]$$



Shockley:

$$I_C = I_S \left( e^{\frac{V_{BE}}{V_T}} - 1 \right) \left( 1 + \frac{V_{CE}}{V_A} \right) \quad [3]$$

Ejemplo 4:

$$R_C = 100 \Omega$$

$$R_B = 10 k\Omega$$

Q1: 2N2222

$$I_S = 3.88 \times 10^{-14} \text{ A}$$

$$\beta = 929$$

$$V_A = 16.5 \text{ V}$$

$$I_C = I_S \left( e^{\left[ \frac{V_{CC} - \frac{I_C}{\alpha} R_C - \frac{I_C}{\beta} R_B}{V_T} \right]} - 1 \right) \left( 1 + \frac{V_{CC} - \frac{I_C}{\alpha} R_C}{V_A} \right)$$

Solución en MATLAB.

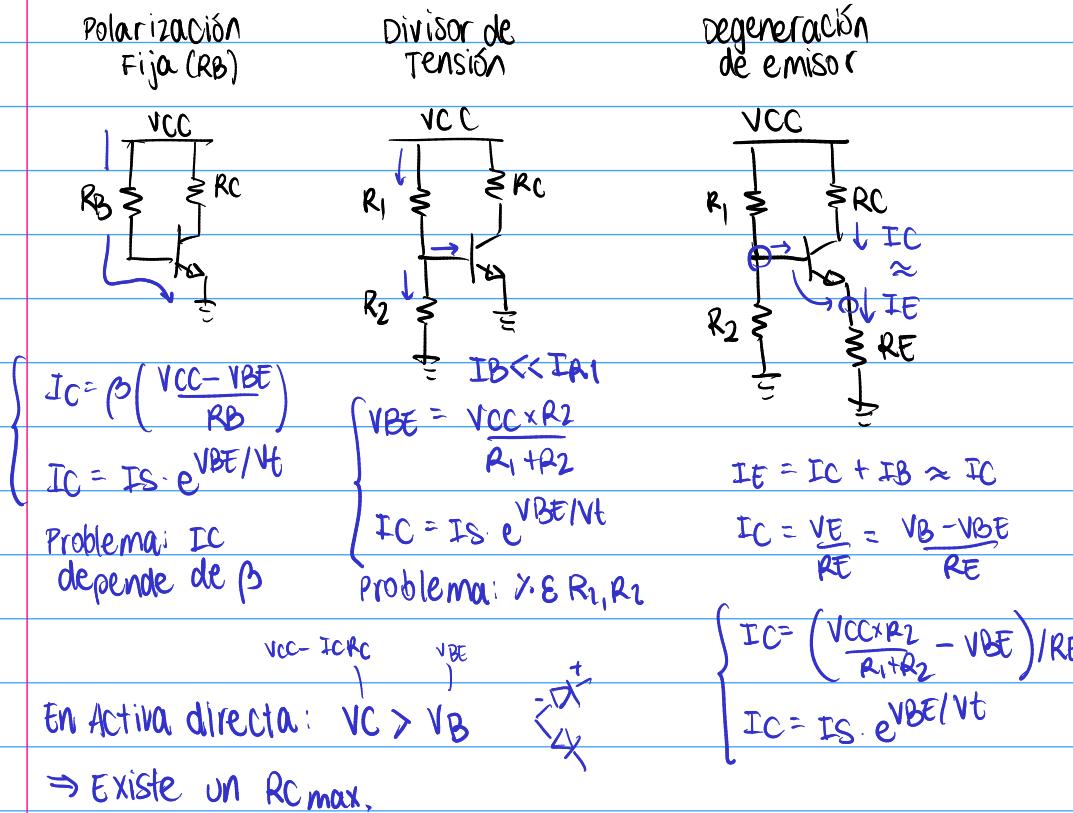
$$\boxed{I_C = 16.28 \text{ mA}}$$

Revisar si está en activa directa.

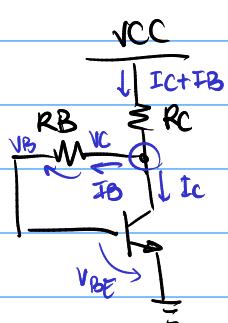
→ este circuito siempre está en activa directa.  $V_C > V_B$ .

## Clase 5: Emisor común

Análisis de CD (Gran señal): Permite establecer  $I_C$  controlada por  $V_{BE}$ .



Autopolarización



$$V_{CC} = (I_C + I_B)R_C + I_B R_B + V_{BE}$$

$$V_{CC} = I_C R_C + \frac{I_C}{\beta} R_C + \frac{I_C}{\beta} R_B + V_{BE}$$

$$V_{CC} = I_C \left( R_C + \frac{R_C}{\beta} + \frac{R_B}{\beta} \right) + V_{BE}$$

$$I_C = \frac{V_{CC} - V_{BE}}{R_C \left( \frac{\beta+1}{\beta} \right) + \frac{R_B}{\beta}}$$

$$I_C = I_S \cdot e^{\frac{V_{BE}}{V_T}}$$

Ventaja:

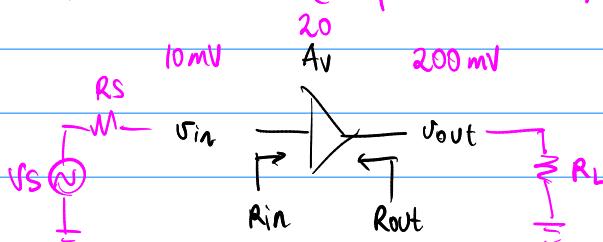
Siempre:  $V_C > V_B$   
en Activa Directa

$$R_C \left( 1 + \frac{1}{\beta} \right)$$

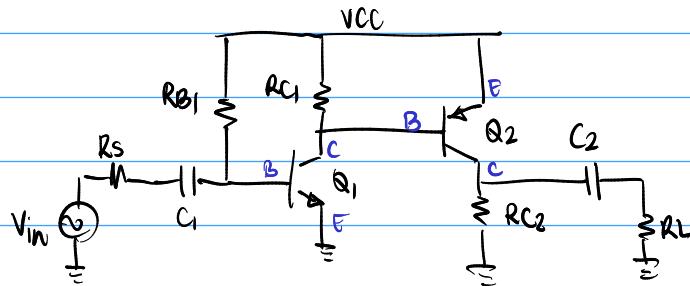
$$R_C \left( \frac{\beta+1}{\beta} \right)$$

$$R_C (1/\alpha)$$

Análisis de CA (Pequeña señal): Permite determinar  $A_v$ ,  $R_{in}$ ,  $R_{out}$ .



# Análisis de Circuitos Amplificadores (por superposición de fuentes)



## 1) Gran señal:

- Fuentes de CC encendidas
- Fuentes de CA apagadas
- $V \rightarrow \text{corto}$      $I \rightarrow \text{abierto}$
- Condensadores son un circuito abierto

$$X_C = \frac{1}{j\omega C} \quad \text{con } \omega \rightarrow 0$$

$X_C \rightarrow \infty$

## 2) Pequeña señal

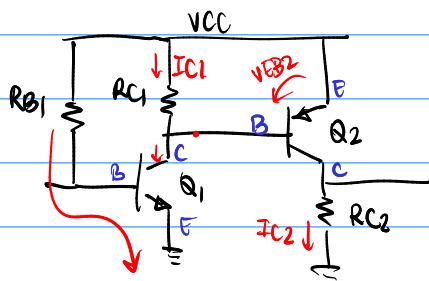
- Fuentes de CC apagadas
- $V \rightarrow \text{abierto}$      $I \rightarrow \text{corto}$
- Fuentes de CA encendidas
- Condensadores son un "corto circuito"

$$X_C = \frac{1}{j\omega C} \quad \text{con } \omega \neq 0$$

$C \rightarrow \infty$  IDEALES

Audio:  $f = 20 \text{ Hz} \dots 20 \text{ kHz}$

Son un corto circuito en las frecuencias de interés

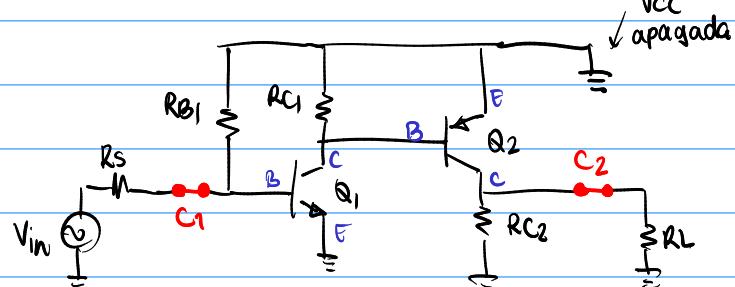


$$I_{C1} = \underline{\hspace{2cm}}$$

$$I_{C2} = \underline{\hspace{2cm}}$$

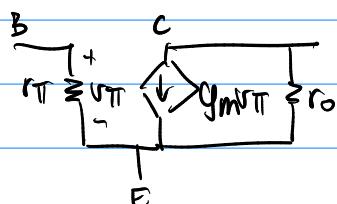
$$V_{BE1} = \underline{\hspace{2cm}}$$

$$V_{BE2} = \underline{\hspace{2cm}}$$



Luego se sustituye el modelo  $\pi$  de pequeña señal, con:

$$g_m = \frac{I_C}{V_t} \quad r_\pi = \frac{B}{g_m} \quad r_o = \frac{V_A}{I_C}$$



y resolver  $A_v, R_{in}, R_{out}$ .

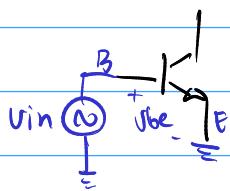
conjunto de circuitos que comparten características comunes.

## Topologías de Amplificadores

El transistor BJT tiene tres terminales.

La entrada se puede conectar:

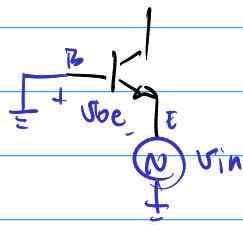
✓ En la base



$$V_{be} = V_B - V_E$$

$$V_{be} = V_{in}$$

✓ En el emisor

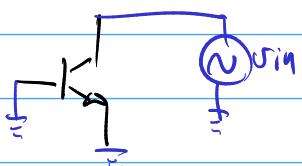


$$V_{be} = V_B - V_E$$

$$V_{be} = 0 - V_{in}$$

$$v_{be} = - V_{in}$$

✗ En el colector



Esta no funciona.

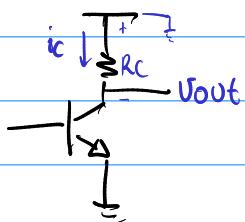
$V_{be}$  no depende de  $V_{in}$ .

$$V_{be} = 0$$

$$i_C = 0$$

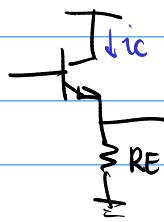
La salida se puede tomar: (C.A.)

✓ Del colector:



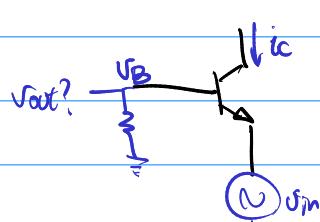
$$V_{out} = - i_C \cdot R_C$$

✓ Del emisor:



$$V_{out} = + i_C \cdot R_E$$

✗ De la base:



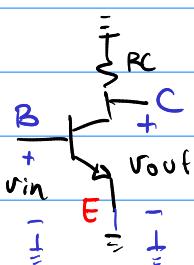
La tensión de base  
No depende de IC.

$$i_B \approx 0 \Rightarrow V_B \approx 0.$$

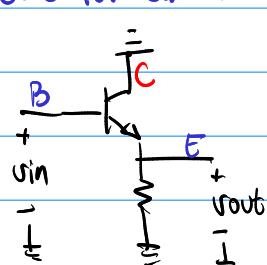
Las posibles combinaciones son:

Topología	in	out
Emisor Común	B	C
Collector Común	B	E
Base Común	E	C

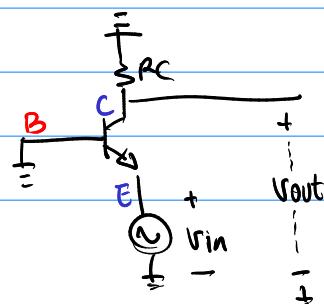
Emisor Común



Colector Común

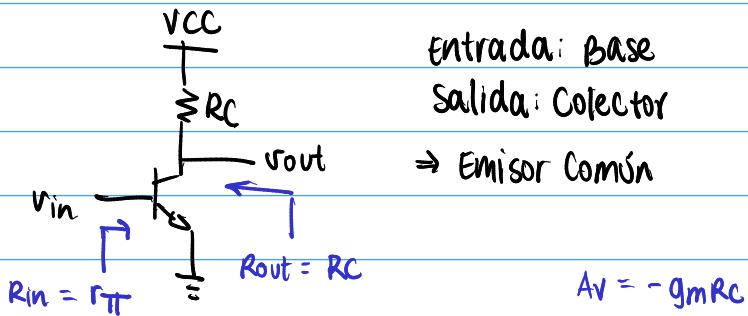


Base Común



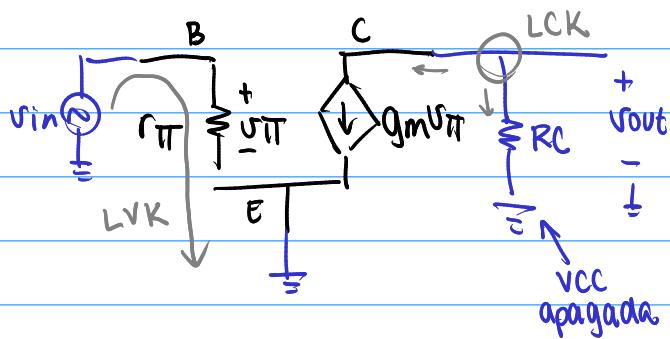
## Emisor Común

i) Análisis del nudo → Determinar  $A_v$ ,  $R_{in}$ ,  $R_{out}$ .



- Se asume que  $I_C$  es conocida
- No se muestra la polarización

Análisis de ganancia (sin efecto Early)



$$LVK: v_{in} = v_{\pi}$$

$$LCK: g_m v_{\pi} + \frac{v_{out}}{R_C} = 0$$

$$g_m v_{in} + \frac{v_{out}}{R_C} = 0$$

$$g_m v_{in} = -\frac{v_{out}}{R_C}$$

$$A_v = \frac{v_{out}}{v_{in}} = -g_m R_C$$

$$g_m \propto I_C$$

$$g_m = \frac{I_C}{V_T}$$

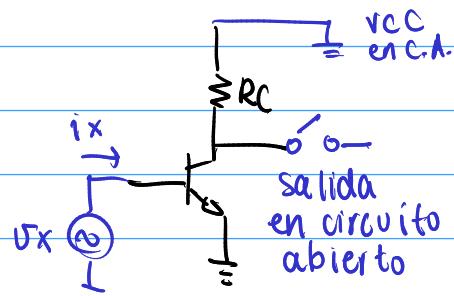
Para aumentar  $A_v$ :

$\left\{ \begin{array}{l} \text{Si } I_C \uparrow, g_m \uparrow, A_v \uparrow \\ \text{Si } R_C \uparrow, A_v \uparrow \end{array} \right.$

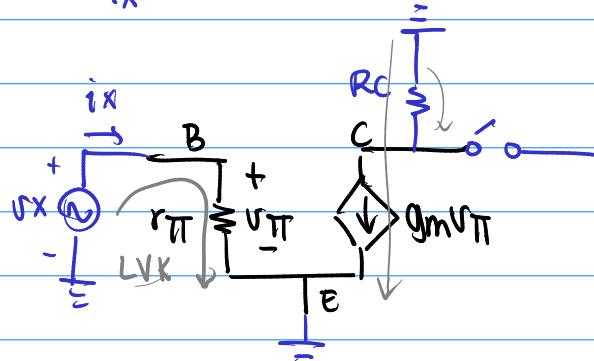
→ (existe un  $R_C$  max) → Activa Dire Cta

## Análisis de impedancias (sin efecto Early)

### Impedancia de entrada



$$R_{in} = \frac{U_x}{i_x}$$



$$-U_x + U_{\pi} = 0$$

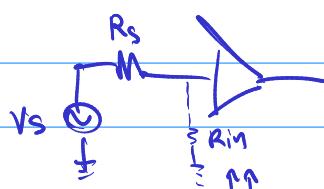
$$U_x = U_{\pi}$$

↓

$$i_x = \frac{U_{\pi}}{r_{\pi}} = \frac{U_x}{r_{\pi}}$$

$$R_{in} = \frac{U_x}{i_x} = r_{\pi}$$

$$R_{in} = r_{\pi}$$

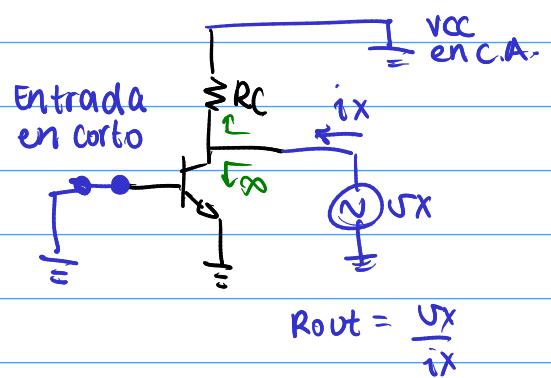


$R_{in}$  debe ser muy alta.

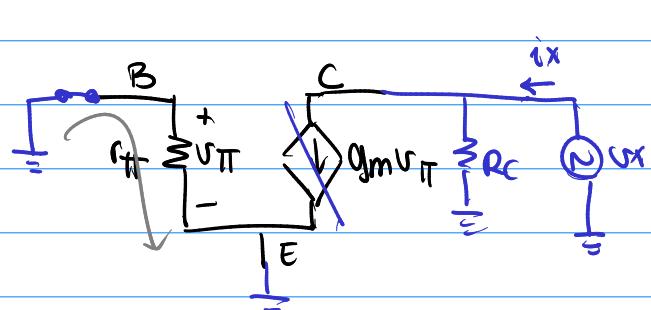
$$R_{in} = r_{\pi} = \frac{\beta}{g_m} = \frac{\beta V_t}{I_C}$$

Si  $I_C \uparrow$ ,  $A_v \uparrow$ , pero  $R_{in} \downarrow$ .

### Impedancia de salida



$$R_{out} = \frac{U_x}{i_x}$$



La fuente

$$U_{\pi} = U_B - U_E$$

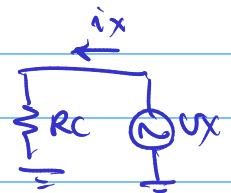
$$U_{\pi} = 0 - 0$$

$$U_{\pi} = 0$$

$$g_m U_{\pi} = 0$$

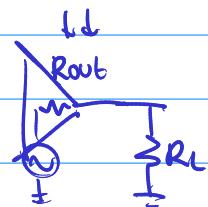
está apagada.

$$\frac{U_x}{i_x} = R_C$$



$$R_{out} = R_C$$

COMPROBOS

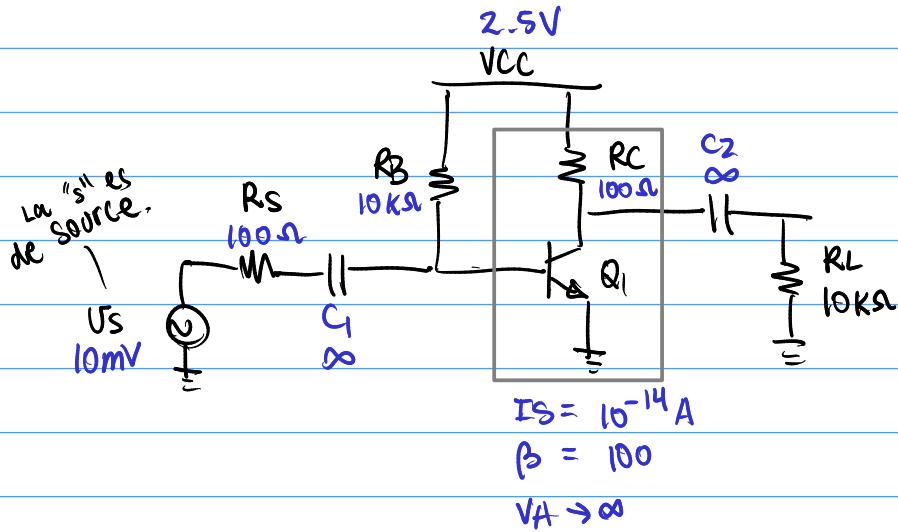


$R_{out}$  debe ser muy baja.

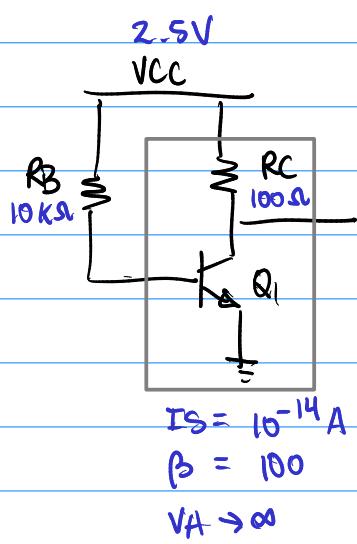
$$R_{out} = R_C$$

Si  $R_C \uparrow$ ,  $A_v \uparrow$ , pero  $R_{out} \uparrow$ .  
Además existe  $R_C$  max.

## Ejemplo práctico



## Análisis Gran Señal



La ec. del circuito:

$$IC = \beta \left( \frac{VCC - VBE}{RB} \right) \quad [1]$$

La ec. de Shockley:

$$IC = IS e^{VBE/Vt}$$

$$\frac{IC}{IS} = e^{VBE/Vt}$$

$$\ln \frac{IC}{IS} = \frac{VBE}{Vt}$$

$$VBE = Vt \ln \frac{IC}{IS} \rightarrow \text{se sustituye en [1]}$$

$$IC = \beta \left( \frac{VCC - Vt \ln \left( \frac{IC}{IS} \right)}{RB} \right) \quad \text{se resuelve para } IC.$$

$$X = 100 \left( 2.5V - \frac{26mV \ln \left( X / 10^{-14} \right)}{10k\Omega} \right)$$

shift + SOLVE

$$X = IC = 17.67 \text{ mA}$$

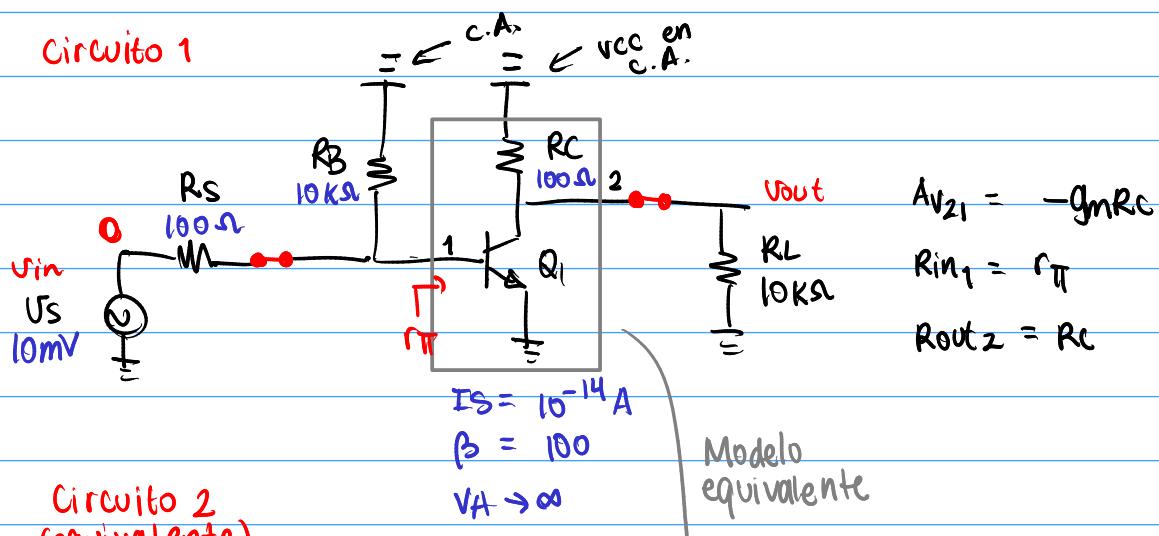
$$g_m = \frac{IC}{Vt} = \frac{17.67 \text{ mA}}{26 \text{ mV}} = 679.6 \text{ ms}$$

$$r_o = \frac{VA}{IC} = \infty$$

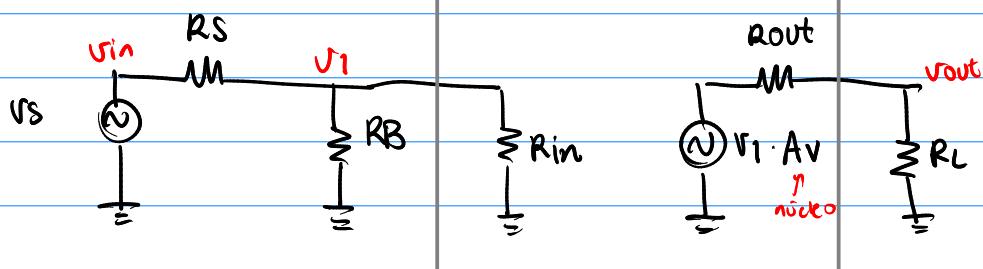
$$r_{\pi} = \frac{\beta}{g_m} = \frac{100}{679.6 \text{ ms}} = 147.14 \Omega$$

## Análisis de pequeña señal

Circuito 1



Circuito 2  
(equivalente)



Análisis del circuito 1:

$$A_{Vtotal} = \frac{V_2}{U_x} \times \frac{V_1}{V_0}$$

$$A_{Vtotal} = -g_m (R_C // R_L) \times \frac{(R_{in} // R_B)}{R_S + (R_{in} // R_B)}$$

Análisis Núcleo                          Div. entrada.

Análisis circuito 2:

$$V_{out} = \frac{V_1 \cdot A_V \cdot R_L}{R_{out} + R_L} \quad \text{con } V_1 = \frac{U_S \times (R_{in} // R_B)}{R_S + (R_{in} // R_B)}$$

$$V_{out} = \frac{U_S \times (-g_m R_C) \times R_L}{R_{out} + R_L} \times \frac{(R_{in} // R_B)}{R_S + (R_{in} // R_B)}$$

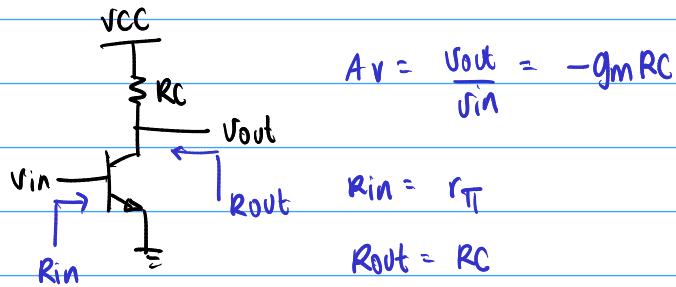
$$\boxed{V_{out} = \frac{(-g_m R_C) \times R_L}{R_{out} + R_L} \times \frac{(R_{in} // R_B)}{R_S + (R_{in} // R_B)}}$$

$R_C // R_L$

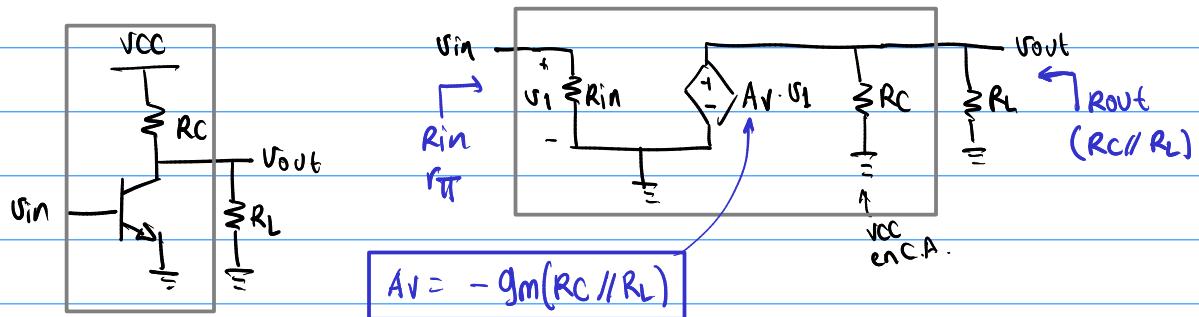
## Clase 6: Emisor Común II

Resumen: Núcleo (ideal,  $V_A \rightarrow \infty$ , sin efecto Early)

$$r_0 = \frac{V_A}{I_C}$$

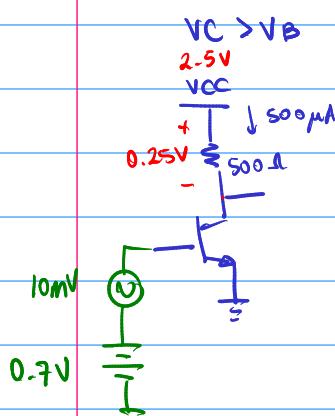


Si se coloca una resistencia de carga  $R_L$ :



Para este circuito, la carga es el paralelo de todas las resistencias del colector.

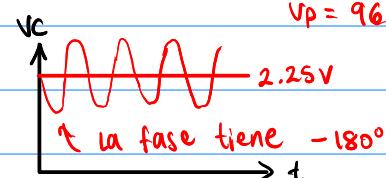
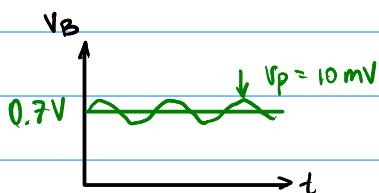
Ejemplo. Si  $g_m = \frac{1}{52\Omega}$ ,  $R_C = 500\Omega$ ,  $g_m = \frac{I_C}{V_t}$   $\Rightarrow I_C = g_m V_t = 500 \mu A$ .



- calcule la ganancia del circuito sin carga.

$$A_V = -g_m R_C = -\left(\frac{1}{52\Omega}\right)(500\Omega) = -9.61$$

$$\begin{aligned} V_p &= 10 \text{ mV} \times A_V \\ V_p &= 96.1 \text{ mV} \end{aligned}$$



- Si se conecta un parlante de  $R_L = 8\Omega$ , (1W) calcule la ganancia con la carga conectada.

$$A_V = -g_m(R_C // R_L) = -\left(\frac{1}{52\Omega}\right)(500\Omega // 8\Omega) \quad 7.874\Omega$$

Si  $|A_V| > 1 \Rightarrow$  Amplifica

Si  $|A_V| < 1 \Rightarrow$  Atenua

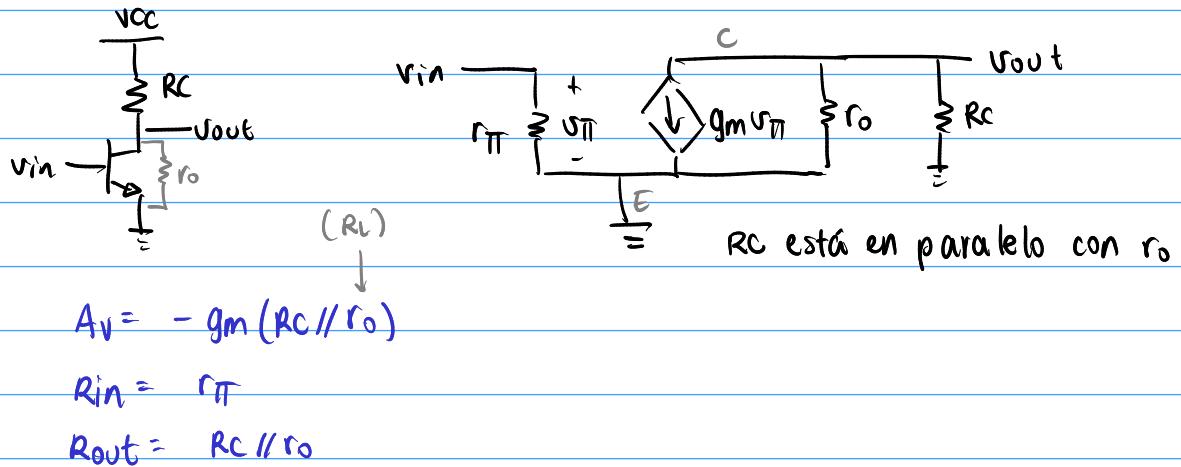
$|A_V| = 1 \Rightarrow$  Seguidor

$$A_V = -0.1514$$

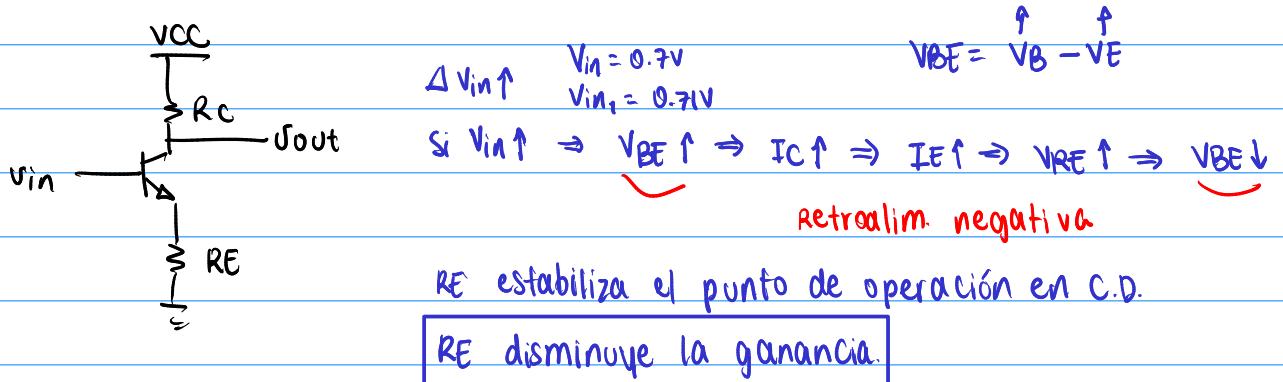
$\rightarrow$  Si  $V_{in} = 10 \text{ mV}_p$ ,  $V_{out} = 1.514 \text{ mV}_p$ .

El circuito de E.C. no permite conectar cargas pequeñas.

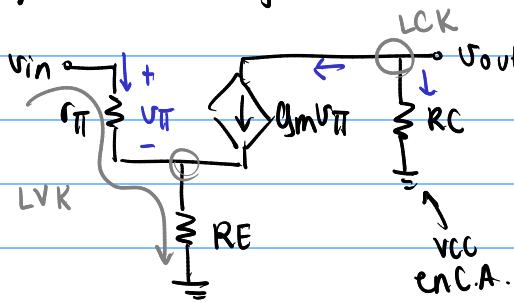
## Análisis del n\'ucleo con efecto Early



## An\'alisis del n\'ucleo con degeneraci\'on de emisor



### a) An\'alisis de ganancia



LCK en emisor:

$$\frac{U_{\pi}}{r_{\pi}} + g_m U_{\pi} = \frac{U_{RE}}{R_E}$$

Despejando URE:

$$U_{RE} = R_E \cdot U_{\pi} \left( \frac{1}{r_{\pi}} + g_m \right) [3]$$

LVK por la base:

$$U_{in} = U_{\pi} + U_{RE} [1]$$

LCK en colector:

$$\frac{U_{out}}{R_C} + g_m U_{\pi} = 0$$

Despejando Upi:

$$-\frac{U_{out}}{g_m R_C} = U_{\pi} [2]$$

$$A_v = \frac{U_{out}}{U_{in}}$$

Sustituyendo [3] en [1]:

$$v_{in} = v_{\pi} + RE \cdot v_{\pi} \left( \frac{1}{r_{\pi}} + g_m \right)$$

[3]

Factorizando  $v_{\pi}$ :

$$v_{in} = v_{\pi} \left( 1 + RE \left( \frac{1}{r_{\pi}} + g_m \right) \right)$$

Sustituyendo [2] en la ecuación anterior:

$$v_{in} = -\frac{v_{out}}{g_m R_C} \left( 1 + RE \left( \frac{1}{r_{\pi}} + g_m \right) \right)$$

Despejando la ganancia:

$$AV = \frac{v_{out}}{v_{in}} = \frac{-g_m R_C}{1 + RE \left( \frac{1}{r_{\pi}} + g_m \right)}$$

→ observe que si  $RE = 0$ ,  
 $AV = -g_m R_C$  ✓  
 (como antes)

$$AV = \frac{-g_m R_C}{1 + RE \left( \frac{g_m}{\beta} + g_m \right)}$$

$r_{\pi} = \frac{\beta}{g_m}$

$$AV = \frac{-g_m R_C}{1 + RE \frac{g_m}{\beta} + RE g_m} \cdot \frac{1/g_m}{1/g_m}$$

$$AV = \frac{-RC}{\frac{1}{g_m} + \frac{RE}{\beta} + RE} = \frac{-RC}{\frac{1}{g_m} + RE \left( \frac{\beta+1}{\beta} \right)}$$

$$= \frac{-RC}{\frac{1}{g_m} + RE \left( \frac{\beta+1}{\beta} \right)}^1$$

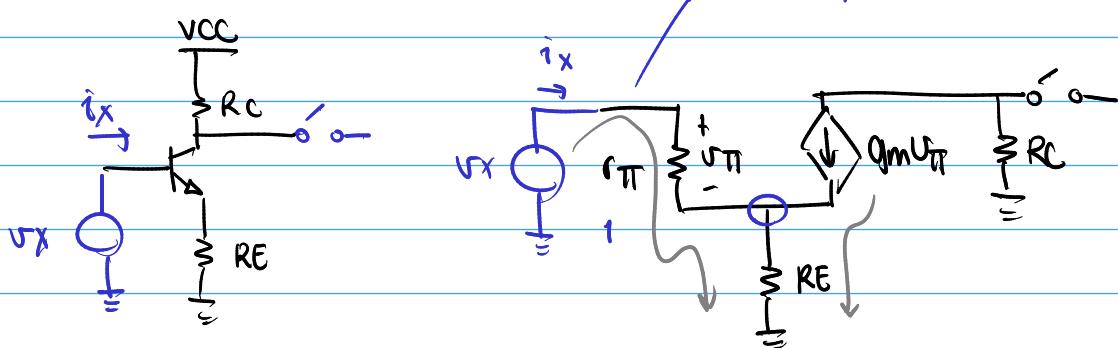
$$= \frac{-RC}{\frac{1}{g_m} + RE \left( \frac{1}{\beta} \right)}^1$$

La degeneración de emisor disminuye la ganancia  $\times$

$$AV = \frac{-RC}{\frac{1}{g_m} + RE}$$

b) Impedancia de entrada

$$i_x = \frac{v_T}{r_T} \Rightarrow v_T = i_x r_T *$$



LCK en emisor:

$$i_x + g_m v_T = i_{RE}$$

sustituyendo \*:

$$i_x + g_m (i_x r_T) = i_{RE}$$

$$i_x (1 + g_m r_T) = i_{RE}$$

$$r_T = \frac{\beta}{g_m}$$

$$g_m r_T = \beta$$

$$i_x (1 + \beta) = i_{RE}$$

$$U_{RE} = i_{RE} \times R_E$$

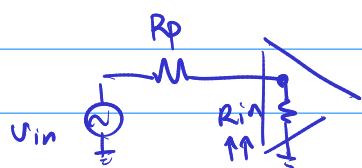
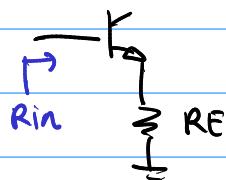
$$U_{RE} = i_x \cdot (1 + \beta) \cdot R_E$$

LVK1:

$$v_x = v_T + U_{RE}$$

$$v_x = i_x r_T + i_x (\beta + 1) R_E$$

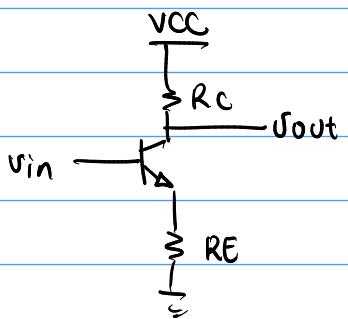
$$R_{in} = \frac{v_x}{i_x} = r_T + (\beta + 1) R_E$$



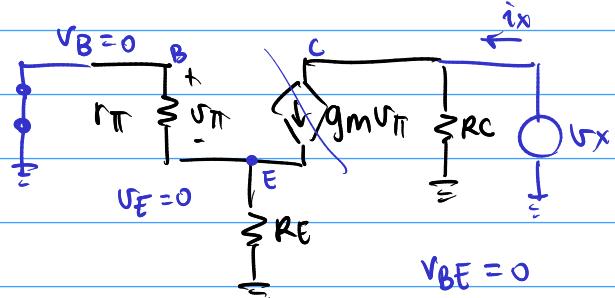
Reflexión de impedancias  
del emisor → base.

La degeneración de emisor mejora la impedancia de entrada.

### c) Impedancia de salida



Caso 1. Sin efecto Early



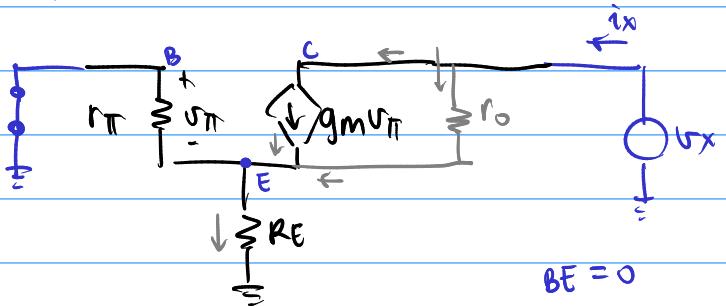
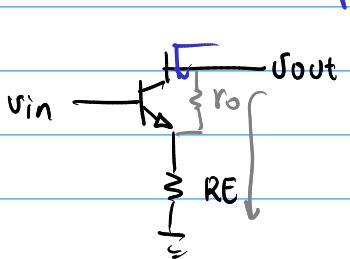
$$R_{out} = R_C$$

$$g_m v_{\pi} = 0$$

- La degeneración de emisor (si  $V_A \rightarrow \infty$ ) no modifica la impedancia de salida.
- $R_E$  no se refleja hacia el colector.

Caso 2. Con efecto Early

Se omite  $R_C$  para simplificar el análisis.

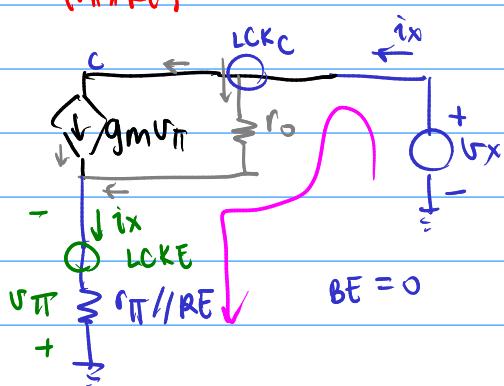


$$BE = 0$$

$r_{\pi}$  y  $R_E$  están en paralelo.

$$i_{(r_{\pi}/R_E)} = i_x$$

$$R_{out} = \frac{U_x}{i_x}$$



La LCK en el colector:

$$i_x = i_{r_o} + g_m v_{\pi} \quad [1]$$

La LCK en el emisor:

$$-v_{\pi} = i_x (r_{\pi} // R_E) \quad [2]$$

Partiendo de la ec. (1):

La LCK en el colector:

$$i_X = i_{C0} + g_m v_T$$

$$i_X = \frac{(v_X - v_T)}{r_0} + g_m v_T$$

$$i_X = \frac{v_X + v_T}{r_0} + g_m v_T$$

$$i_X = \frac{v_X}{r_0} + v_T \left( \frac{1}{r_0} + g_m \right)$$

Sustituyendo  $v_T$  de (2)

$$i_X = \frac{v_X}{r_0} + -i_X (r_T // R_E) \cdot \left( \frac{1}{r_0} + g_m \right)$$

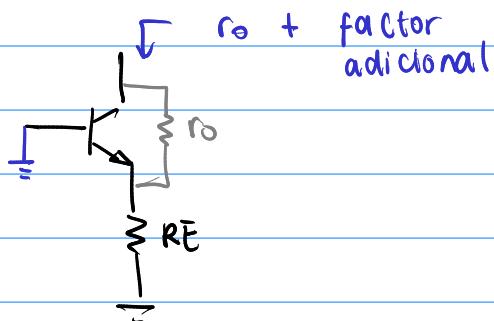
$$i_X + i_X (r_T // R_E) \cdot \left( \frac{1}{r_0} + g_m \right) = \frac{v_X}{r_0}$$

$$i_X \left( 1 + (r_T // R_E) \cdot \left( \frac{1}{r_0} + g_m \right) \right) = \frac{v_X}{r_0}$$

$$\frac{v_X}{i_X} = R_{out} = r_0 \left( 1 + (r_T // R_E) \cdot \left( \frac{1}{r_0} + g_m \right) \right)$$

$$R_{out} = r_0 + (r_T // R_E) (1 + g_m r_0)$$

impedancia desde el colector con efecto Early



$r_0 + \text{factor adicional}$

$$g_m = \frac{1}{52\Omega}$$

$$r_0 = \frac{V_A}{I_C} = \frac{5V}{500\mu A}$$

$$r_0 = 10k\Omega$$

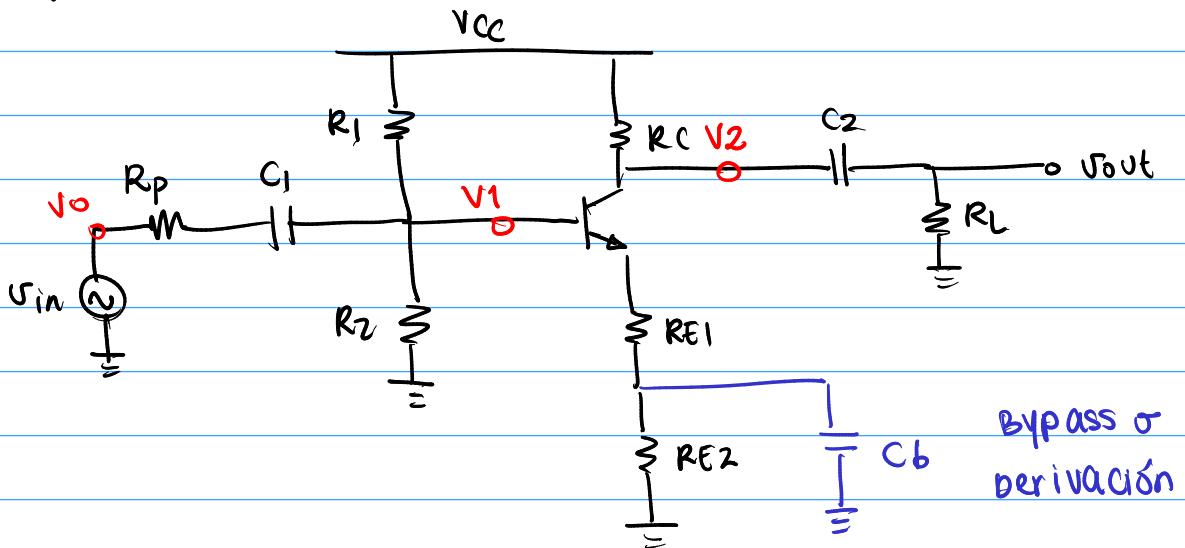
$$g_m r_0 = 192.31$$

$$R_{out} = 10k\Omega + (r_T // R_E)(192.31)$$

La degeneración del emisor aumenta

la impedancia de salida considerablemente.

Ejemplo completo:



$C_b$  es un abierto en C.D.:

$$\rightarrow RE = RE_1 + RE_2 \rightarrow \text{Alta}$$

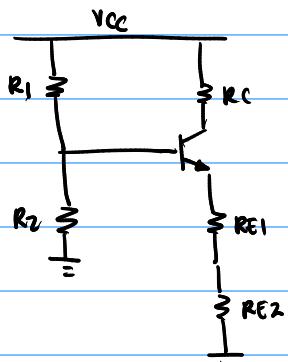
Estabilidad en CD.

$C_b$  es un cortocircuito en C.A.:

$$RE = RE_1 \rightarrow \text{Baja}$$

Mejora la ganancia en C.A.

### parte 1. Polarización



$$VB = \frac{V_{CC} \times R_2}{R_1 + R_2}$$

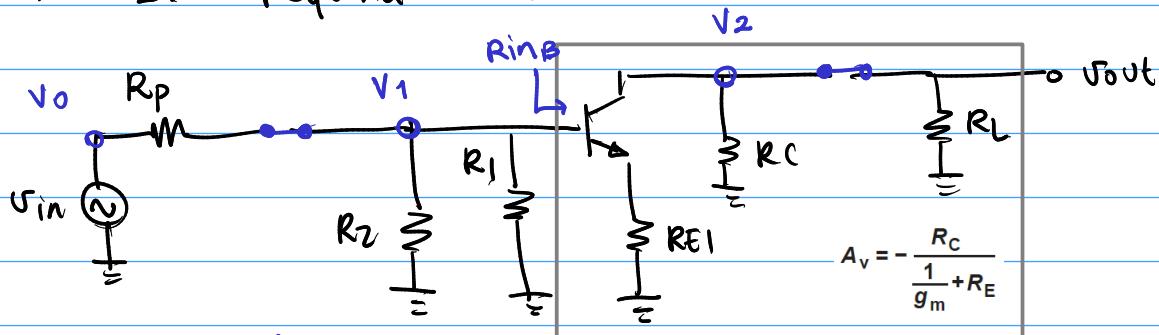
$$VE \approx IC (RE_1 + RE_2)$$

$$V_{BE} = VB - VE$$

$$\left\{ \begin{array}{l} V_{BE} = \frac{V_{CC} R_2}{R_1 + R_2} - IC (RE_1 + RE_2) \\ IC = I_S (e^{V_{BE}/V_t} - 1) \end{array} \right. \quad [1] \quad [2]$$

Se resuelve para  $IC, V_{BE}$ .

## Paso 2. Pequeña señal



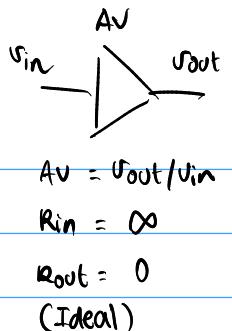
$\downarrow$  núcleo       $\downarrow$  div. en entrada

$$A_v = \frac{V_{out}}{V_{in}} = \frac{V_2}{V_1} \times \frac{V_1}{V_0}$$

$$V_1 = \frac{V_0 \times (R_1 // R_2 // R_{inB})}{R_p + (R_1 // R_2 // R_{inB})}$$

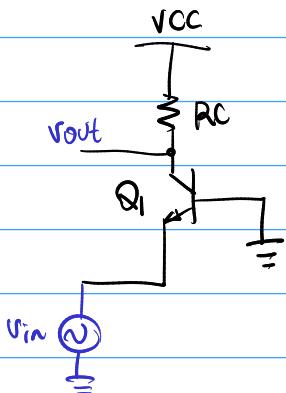
$$A_v = -\frac{(R_C // R_L)}{\frac{1}{g_m} + R_E} \times \frac{(R_1 // R_2 // R_{inB})}{R_p + (R_1 // R_2 // R_{inB})}$$

$$A_v = -\frac{(R_C // R_L)}{\frac{1}{g_m} + R_E} \times \frac{(R_1 // R_2 // [r_\pi + (\beta+1)R_{E1}])}{R_p + (R_1 // R_2 // [r_\pi + (\beta+1)R_{E1}])}$$



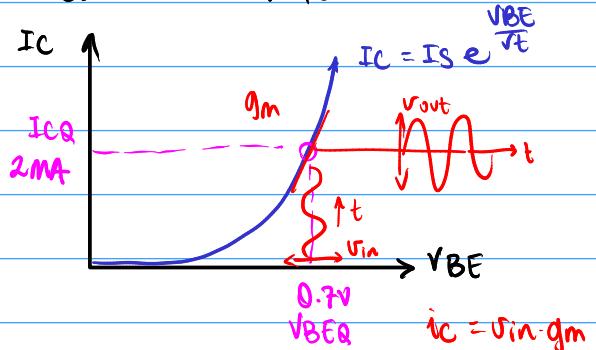
## Clase 7: Base Común

### Análisis del núcleo

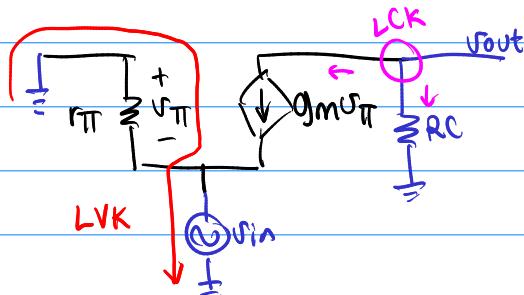


Entrada: emisor  
salida: colector  
→ Base común

curva de transferencia



### Análisis de ganancia (sin efecto Early)



$$A_V = \frac{v_{out}}{v_{in}}$$

$$LVK: v_{\pi} + v_{in} = 0$$

$$v_{\pi} = -v_{in} \quad [1]$$

$$LCK: g_m v_{\pi} + \frac{v_{out}}{R_C} = 0 \quad [2]$$

Sustituyendo [1] en [2]:

$$g_m (-v_{in}) + \frac{v_{out}}{R_C} = 0$$

Despejando la ganancia:

$$\frac{v_{out}}{v_{in}} = + g_m R_C$$

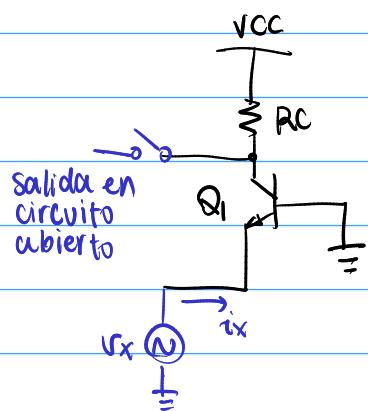
$$A_V = \frac{v_{out}}{v_{in}} = + g_m R_C$$

la ganancia es positiva

→ la fase de  $v_{out}$  es la misma que la de  $v_{in}$

→ La magnitud de  $A_V$  es la misma que para E.C.

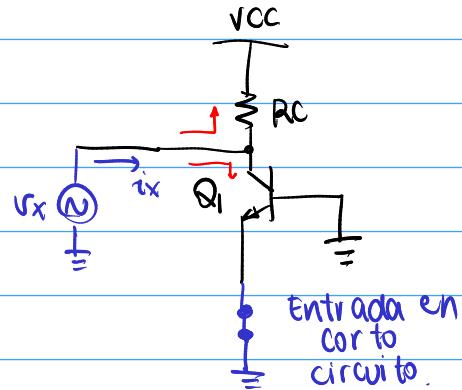
## Impedancia de entrada



$$R_{in} = \frac{1}{gm} \parallel r_o \parallel r_T$$

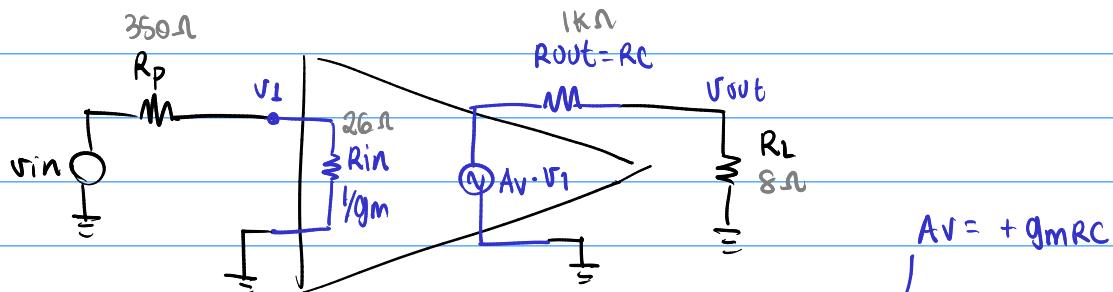
$$R_{in} \approx \frac{1}{gm}$$

## Impedancia de salida



$$R_{out} = R_C \parallel r_o$$

## Limitaciones del circuito como Amplificador de tensión



La mayor parte de  $V_{in}$  se pierde en la entrada.

$$V_1 = \frac{V_{in} \times R_{in}}{R_p + R_{in}}$$

$$\frac{V_1}{V_{in}} = \frac{R_{in}}{R_p + R_{in}} = \frac{26\Omega}{350\Omega + 26\Omega}$$

$$A_v = 0.069 = 6.9\%$$

sólo llega el 6.9% de  $V_{in}$

$$\frac{V_{out}}{V_{in}} = \frac{V_1}{V_{in}} \times \frac{V_{out}}{V_1}$$

$$\frac{V_{out}}{V_{in}} = 0.069 \times 0.00794 \times A_v$$

Las pérdidas en la salida:

$$\frac{V_{out}}{V_1} = \frac{A_v \cdot V_1 \times R_L}{R_{out} + R_L}$$

$$\frac{V_{out}}{V_1} = \frac{A_v \cdot R_L}{R_{out} + R_L}$$

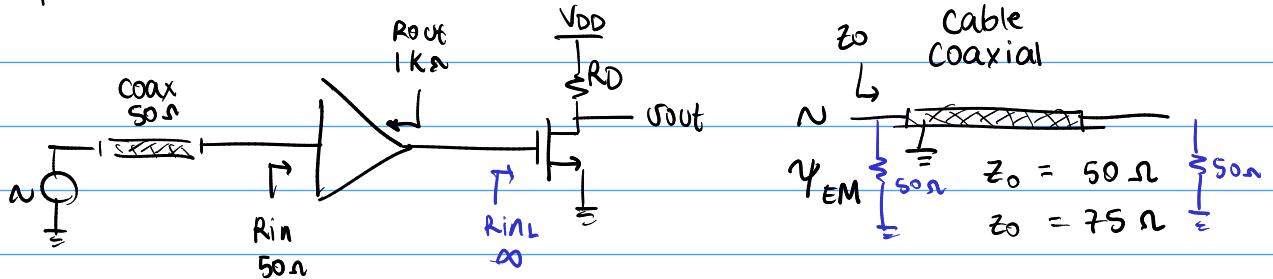
$$\frac{V_{out}}{V_1} = \frac{A_v \cdot 8\Omega}{1k\Omega + 8\Omega}$$

$$\frac{V_{out}}{V_1} = A_v \cdot 0.00794$$

A la salida llega el 0.79% de la señal  $A_v \cdot V_1$ .

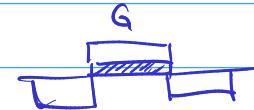
## Aplicaciones de base común

mm wave - RF

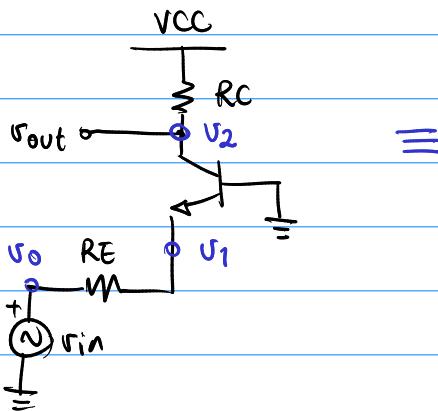


Máxima transf.  
de potencia ✓  
en la entrada

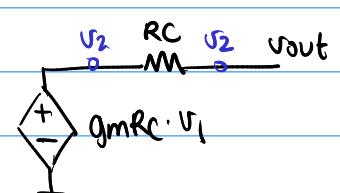
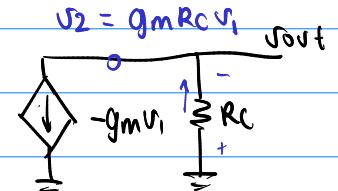
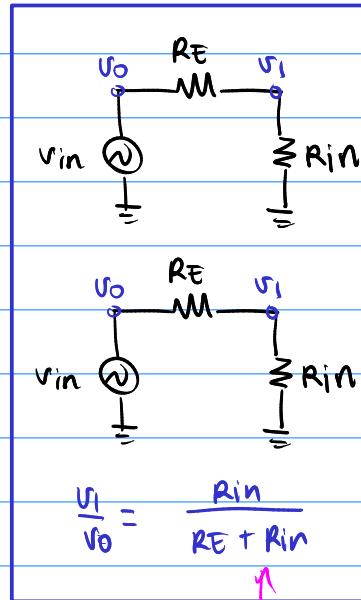
carga ideal ✓



Base común con RE en serie



En este circuito, RE  
puede verse como la  
impedancia parásita de V\_in.



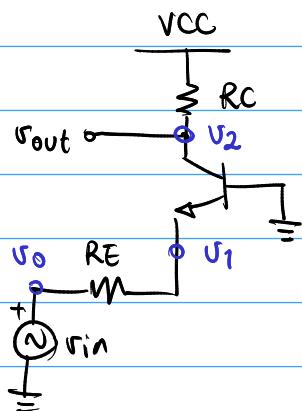
$$\frac{V_2}{V_1} = +gmRC$$

Pérdidas por  
acople en la  
entrada

$$\begin{aligned} \frac{V_{out}}{V_{in}} &= \frac{V_2}{V_1} \times \frac{V_1}{V_0} = +gmRC \times \frac{R_{in}}{RE + R_{in}} \\ &= +gmRC \times \frac{1/gm}{RE + 1/gm} \end{aligned}$$

$A_V = \frac{RC}{RE + 1/gm}$
------------------------------

Impedancia de entrada y salida:



$$R_{in} = R_E + 1/g_m \parallel r_o \parallel r_T$$

$$R_{in} \approx R_E + 1/g_m$$

sin efecto Early,

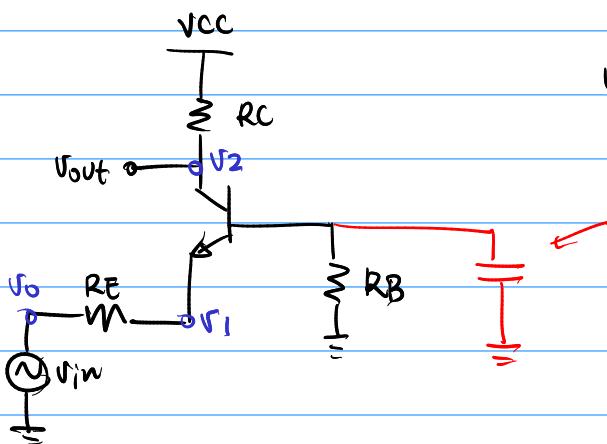
$$R_{out} = R_C$$

con efecto Early,

$$R_{out} = R_C \parallel [(1+g_m r_o)(R_E \parallel r_T) + r_o]$$

recordar que la impedancia desde el colector con efecto Early aumenta si existe  $R_E$  (degeneración de emisor).

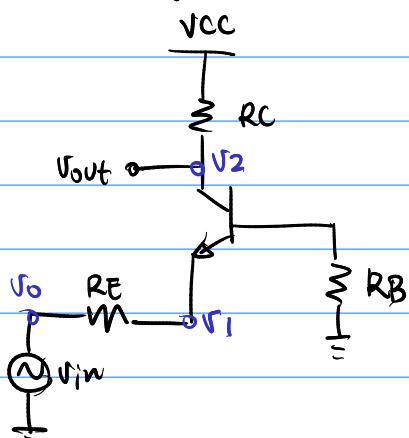
Base común con resistencia de base



la resistencia de base depende del circuito de polarización.

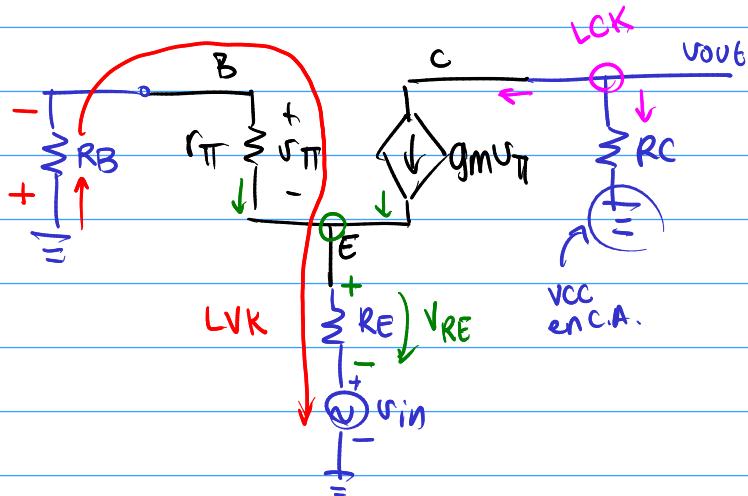
si se utiliza un condensador  $C_b$  (bypass o derivación),  $R_B$  desaparece y queda el mismo circuito de la sección anterior.

Análisis de ganancia con  $R_B$



Este circuito no se reduce a ninguna de las configuraciones anteriores.

Se resuelve por modelo  $\pi$ .



Observe que la corriente de base se calcula como:

$$i_{RB} = \frac{V_{\pi\pi}}{r_{\pi\pi}} \quad [0]$$

$$LVK: \quad V_{RB} + V_{\pi\pi} + V_{RE} + V_{in} = 0$$

$$i_{RB} \cdot R_B + V_{\pi\pi} + i_{RE} \cdot R_E + V_{in} = 0 \quad [1]$$

$$LCK_c: \quad g_m V_{\pi\pi} + \frac{V_{out}}{R_C} = 0$$

Despejando  $V_{\pi\pi}$ :

$$V_{\pi\pi} = -\frac{V_{out}}{g_m R_C} \quad [2]$$

$$LCK_E: \quad i_{RB} + g_m V_{\pi\pi} = i_{RE} \quad [3]$$

Sustituyendo [0] y [3] en [1]:

$$\frac{V_{\pi\pi}}{r_{\pi\pi}} \cdot R_B + V_{\pi\pi} + (i_{RB} + g_m V_{\pi\pi}) \cdot R_E + V_{in} = 0$$

$$\frac{V_{\pi\pi}}{r_{\pi\pi}} \cdot R_B + V_{\pi\pi} + \left( \frac{V_{\pi\pi}}{r_{\pi\pi}} + g_m V_{\pi\pi} \right) \cdot R_E + V_{in} = 0$$

Factorizando  $V_{\pi\pi}$ :

$$V_{\pi\pi} \left( \frac{R_B}{r_{\pi\pi}} + 1 + \frac{R_E}{r_{\pi\pi}} + g_m R_E \right) = -V_{in}$$

Sustituyendo la ecuación [2]:

$$\left( \frac{-V_{out}}{g_m R_C} \right) \left( \frac{R_B}{r_{\pi\pi}} + 1 + \frac{R_E}{r_{\pi\pi}} + g_m R_E \right) = -V_{in}$$

Despejando la ganancia:

$$A_V = \frac{v_{out}}{v_{in}} = \frac{+ g_m R_C}{\frac{R_B}{r_T} + 1 + \frac{R_E}{g_m R_T} + g_m R_E} \times \frac{\frac{1}{g_m}}{\frac{1}{g_m}}$$

$$A_V = \frac{R_C}{\frac{R_B}{g_m r_T} + \frac{1}{g_m} + \frac{R_E}{g_m R_T} + R_E}$$

donde  $r_T = \frac{\beta}{g_m}$

$$g_m r_T = \beta$$

$$A_V = \frac{R_C}{\frac{R_B}{\beta} + \frac{1}{g_m} + \frac{R_E}{\beta} \left( \frac{1}{\beta} + 1 \right)}$$

$$A_V = \frac{R_C}{\frac{R_B}{\beta} + \frac{1}{g_m} + \frac{(\beta+1) R_E}{\beta}}$$

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

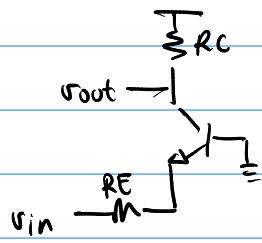
Según el libro:

$$A_V = \frac{R_C}{\frac{R_B}{\beta+1} + \frac{1}{g_m} + R_E}$$

→ observe que si  $R_E = 0$   
y  $R_B = 0$ , queda

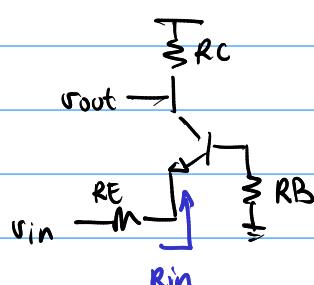
$$A_V = g_m R_C$$

Ganancia sin  $R_B$



$$A_v = \frac{R_C}{\frac{1}{g_m} + R_E}$$

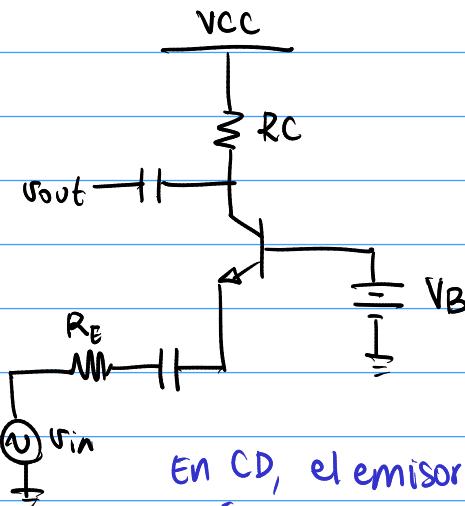
Ganancia con  $R_B$



La impedancia de salida desde el emisor es:

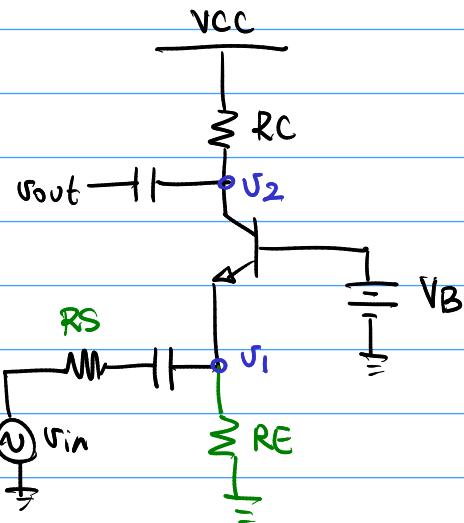
$$R_{in} = \frac{1}{g_m} + \frac{R_B}{\beta+1}$$

## Base común con polarización



En CD, el emisor  
está "al aire"  
(circuito abierto)

No hay camino a tierra para IC.



El problema se resuelve al  
conectar una resistencia a  
tierra en el emisor.

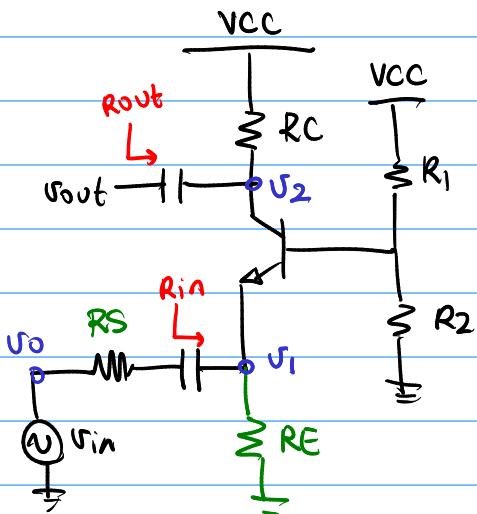
$$\frac{v_2}{v_i} = g_m R_C$$

Si  $R_B = 0$

$$\frac{v_2}{v_i} = \frac{R_C}{\frac{1}{g_m} + \frac{R_B}{\beta + 1}}$$

Si  $R_B \neq 0$

La configuración completa:



$$R_B = R_1 // R_2$$

$$\frac{v_2}{v_i} = \frac{R_C}{\frac{1}{g_m} + \frac{R_1 // R_2}{\beta + 1}}$$

$$\frac{v_1}{v_o} = \frac{R_E // \left[ \frac{1}{g_m} + \frac{R_1 // R_2}{\beta + 1} \right]}{R_S + R_E // \left[ \frac{1}{g_m} + \frac{R_1 // R_2}{\beta + 1} \right]}$$

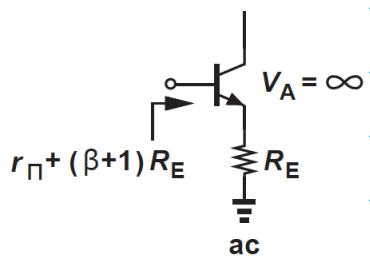
Rin  
imp. del emisor

La ganancia total es:

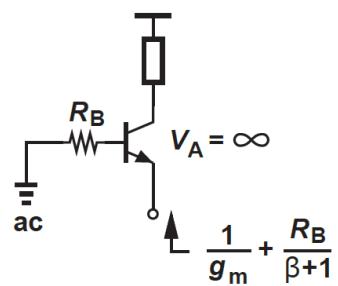
$$\frac{v_{out}}{v_{in}} = \frac{R_C}{\frac{1}{g_m} + \frac{R_1 // R_2}{\beta + 1}} \times \frac{R_E // \left[ \frac{1}{g_m} + \frac{R_1 // R_2}{\beta + 1} \right]}{R_S + R_E // \left[ \frac{1}{g_m} + \frac{R_1 // R_2}{\beta + 1} \right]}$$

$\boxed{\begin{aligned} R_{out} &= R_C \\ &\text{(in Early)} \end{aligned}}$

## Reflexión de impedancias:

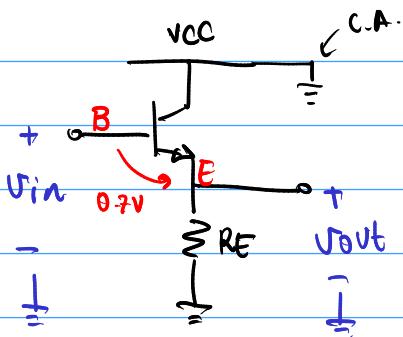


La impedancia de emisor  
se refleja en la base,  
multiplicada por  $(\beta+1)$



La impedancia de base  
se refleja en el emisor,  
dividida por  $(\beta+1)$

## Clase 8: colector común (seguidor de Emisor)



entrada: Base

salida: Emisor

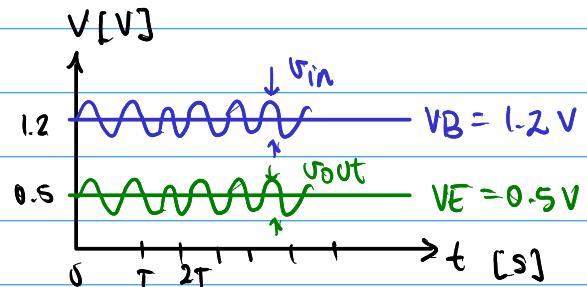
→ Colector común

$$AV \approx 1 = \frac{V_{out}}{V_{in}}$$

$V_{BE}$  es constante

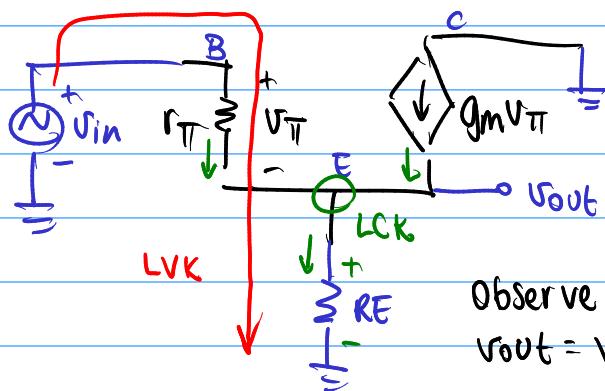
$V_B \uparrow \Rightarrow V_E \uparrow$

$V_B \downarrow \Rightarrow V_E \downarrow$



### Análisis del núcleo

#### Ganancia de tensión



LVK:

$$-V_{in} + V_{\pi} + V_{RE} = 0$$

$$-V_{in} + V_{\pi} + V_{out} = 0 \quad [1]$$

LCK:

$$g_m V_{\pi} + \frac{V_{\pi}}{r_{\pi}} = \frac{V_{RE}}{R_E}$$

$$g_m V_{\pi} + \frac{V_{\pi}}{r_{\pi}} = \frac{V_{out}}{R_E}$$

$$V_{\pi} \left[ g_m + \frac{1}{r_{\pi}} \right] = \frac{V_{out}}{R_E} \quad [2]$$

Despejando  $V_{\pi}$  de [1]:

$$V_{\pi} = V_{in} - V_{out} \quad [3] \quad [CE]$$

Sustituyendo en [2]:

$$(V_{in} - V_{out}) \left[ g_m + \frac{1}{r_{\pi}} \right] = \frac{V_{out}}{R_E}$$

$$v_{in} \left( g_m + \frac{1}{r_{\pi}} \right) - v_{out} \left( g_m + \frac{1}{r_{\pi}} \right) = \frac{v_{out}}{R_E}$$

$$v_{in} \left( g_m + \frac{1}{r_{\pi}} \right) = v_{out} \left( g_m + \frac{1}{r_{\pi}} \right) + \frac{v_{out}}{R_E}$$

$$v_{in} \left( g_m + \frac{g_m}{\beta} \right) = v_{out} \left( g_m + \frac{g_m}{\beta} + \frac{1}{R_E} \right)$$

$$\frac{v_{out}}{v_{in}} = \frac{\left( g_m + \frac{g_m}{\beta} \right)}{\left( g_m + \frac{g_m}{\beta} + \frac{1}{R_E} \right)} = \frac{g_m \left( 1 + \frac{1}{\beta} \right)}{g_m \left( 1 + \frac{1}{\beta} \right) + \frac{1}{R_E}}$$

$$\frac{v_{out}}{v_{in}} = \frac{g_m \left( \frac{\beta+1}{\beta} \right)}{g_m \left( \frac{\beta+1}{\beta} \right) + \frac{1}{R_E}} \approx \frac{g_m}{g_m + \frac{1}{R_E}} \times \frac{\frac{1}{g_m}}{\frac{1}{g_m}} \times \frac{R_E}{R_E}$$

$$\boxed{\frac{v_{out}}{v_{in}} = \frac{R_E}{R_E + \frac{1}{g_m}}}$$

Regla de diseño:

$$R_E > \frac{1}{g_m}$$

$$R_E > 10 \left( \frac{1}{g_m} \right)$$

$$R_E \approx 260 \Omega$$

Por ejemplo:

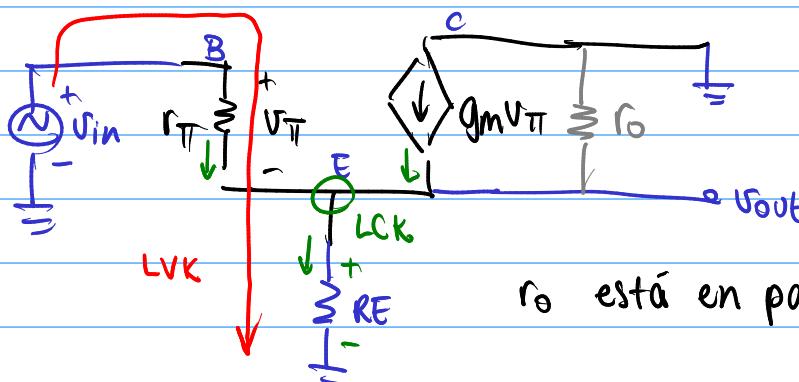
$$1mA$$

$$g_m = \frac{I_C}{V_T}$$

$$g_m = \frac{1}{26} S$$

$$\frac{1}{g_m} = 26 \Omega$$

Inclusión del efecto Early:

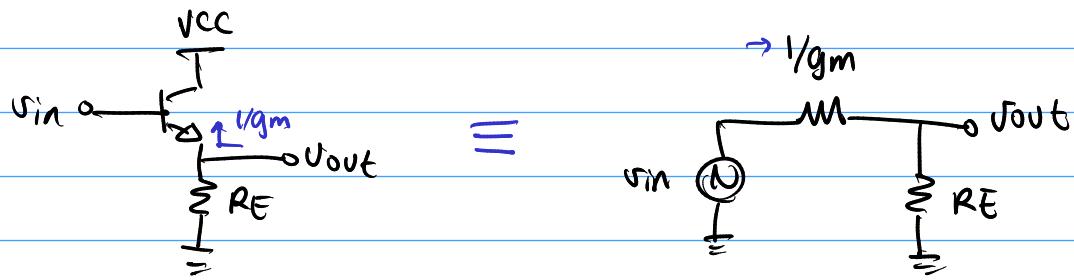


$$A_V \approx 1$$

$r_o$  está en paralelo con  $R_E$ .

$$\boxed{\frac{v_{out}}{v_{in}} = \frac{R_E // r_o}{R_E // r_o + \frac{1}{g_m}}}$$

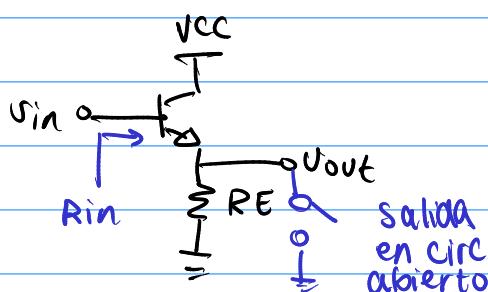
## Interpretación de la ganancia



$$\frac{v_{out}}{v_{in}} = \frac{R_E}{R_E + \frac{1}{g_m}} \equiv v_{out} = \frac{v_{in} \times R_E}{R_E + \frac{1}{g_m}}$$

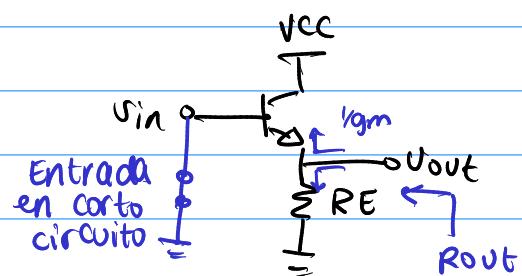
La ganancia del seguidor de emisor es la misma que la ganancia de un divisor de tensión.

### Impedancia de entrada



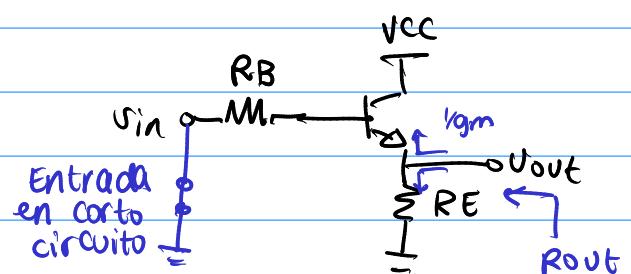
$$R_{in} = r_T + (\beta + 1)R_E$$

### Impedancia de salida



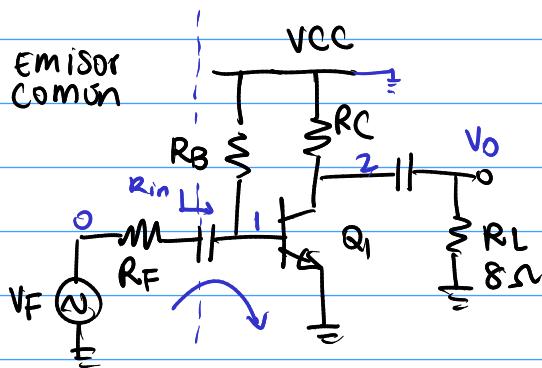
$$R_{out} = \frac{1}{g_m} \parallel R_E$$

Con resistencia de base:



$$R_{out} = \left( \frac{1}{g_m} + \frac{R_B}{\beta T_1} \right) \parallel R_E$$

## Aplicaciones del seguidor de emisor: Aceptación de impedancia



$$V_I = \frac{V_O \times R_{in}}{R_F + R_{in}}$$

$$R_{in} = r_{\pi} // R_B$$

EN C.A. los condensadores son un corto circuito.

$$\frac{V_I}{V_O} = \frac{r_{\pi} // R_B}{R_F + r_{\pi} // R_B}$$

$$\frac{V_O}{V_F} = \frac{V_2}{V_1} \times \frac{V_I}{V_O}$$

$$\frac{V_O}{V_F} = -g_m (R_C // R_L) \times \frac{r_{\pi} // R_B}{R_F + r_{\pi} // R_B}$$

emisor común

El problema es que  $R_L$  disminuye la ganancia.

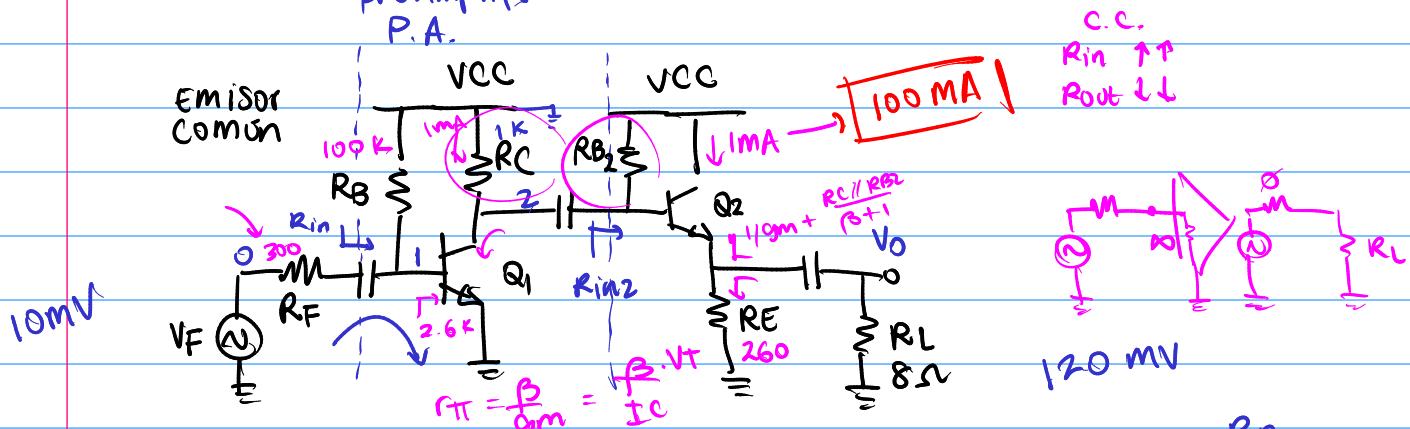
$$R_C = 1k\Omega$$

$$g_m R_C = \frac{1}{26} \times 1k\Omega = 38.5$$

$$R_L = 8\Omega$$

$$g_m (R_C // R_L) = \frac{1}{26} \times (1k // 8\Omega) = 0.305$$

preAmplif.  
P.A.



$$\frac{V_O}{V_F} = -g_m (R_C // R_{in2}) \times \frac{r_{\pi} // R_B}{R_F + r_{\pi} // R_B} \times \frac{R_E // R_L}{\frac{R_C // R_B2 + g_m + R_E // R_L}{\beta + 1}}$$

debe ser 10 veces  $R_C$   
para que  $R_C // R_{in2} \approx R_C$   
y no se pierda ganancia.

$$P_{RL} = \frac{V^2}{R_L}$$

$$= (\underline{120 \text{ mV}})^2 / 8\Omega$$

$$= 1.8 \text{ mW}$$

$\approx 1 ?$

## Emitter Follower (E.F.)

$$R_{in2} = R_{B2} \parallel \left[ r_{\pi 2} + (\beta + 1) R_E \right]$$

$\sim 100k \parallel$

$r_{\pi 2}$  muy alto  
 $\sim 30k\Omega$

$$\beta = 100$$

$$R_{B2} = 100k\Omega$$

$$I_{C1} = I_{C2} = 1mA$$

$$g_m1 = g_m2 = \frac{1}{26\Omega}$$

$$R_E = 26\Omega \quad (10 \times \frac{1}{g_m})$$

$$R_C = 1k\Omega$$

$$r_{\pi 2} = \frac{\beta}{g_m} = \frac{100}{1/26} = 2.6k\Omega$$

$$R_{in2} = 100k \parallel [2.6k + 26k\Omega]$$

$$R_{in2} = 22.24k\Omega$$

$$-g_m(R_C \parallel R_{in2})$$

$$= -\frac{1}{26\Omega} \times (1k \parallel 22.24k)$$

$$= -\frac{1}{26} \times (0.957k\Omega)$$

$$= \boxed{36.81} \leftarrow$$

$$A_{Vcc} = \frac{R_E \parallel R_L}{R_C \parallel R_{B2} + \frac{1}{g_m} + R_E \parallel R_L}$$

$$A_{VF} = \frac{26\Omega \parallel 8\Omega}{100k\Omega \parallel 100k\Omega + \frac{1}{426\Omega} + 26\Omega \parallel 8\Omega}$$

$$= \frac{7.761\Omega}{990.1 \parallel 26\Omega + 7.761\Omega}$$

$$= \frac{7.761\Omega}{9.901\Omega + 26\Omega + 7.761\Omega}$$

$$= 0.1778$$

Si se aumenta  $I_{C E F}$ ,  
los parámetros en rojo  
disminuyen

$$I_C = 100mA$$

$$g_m = \frac{100mA}{26mV} = \frac{100}{26} S$$

$$\frac{1}{g_m} = 0.26\Omega$$

$$AV = 0.433$$

1 2 3  
4 5 6



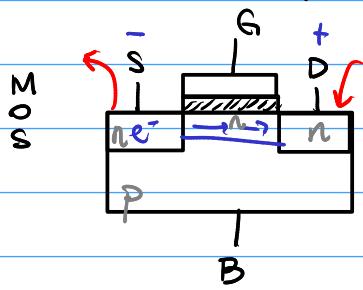
Transistores modernos

FinFET  
HEMT  
GAAFET



## Clase 9: Repaso MOSFET

Estructura (NMOS)



D: Drain (Drenador)

S: Source (Fuente) (Surtidor)

G: Gate (Compuesta)

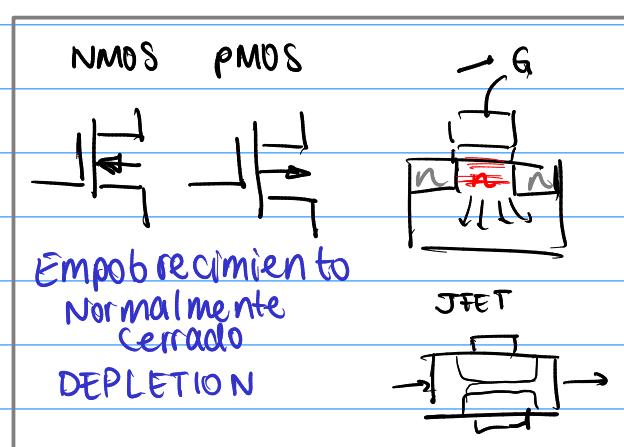
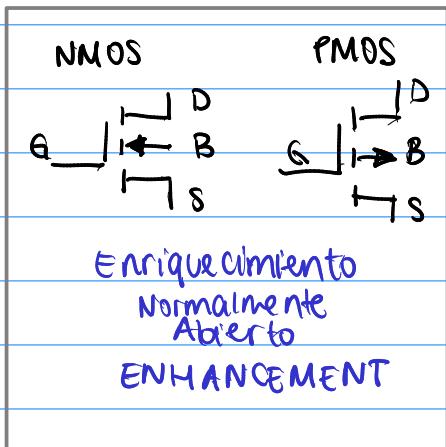
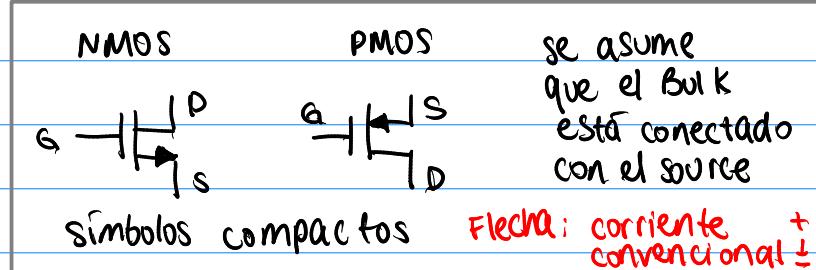
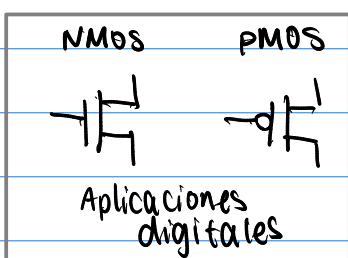
Short-channel effects

$$1 \text{ Å} = 0.1 \text{ nm}$$

Source Follower = Seguidor Fuente = Drenador comón

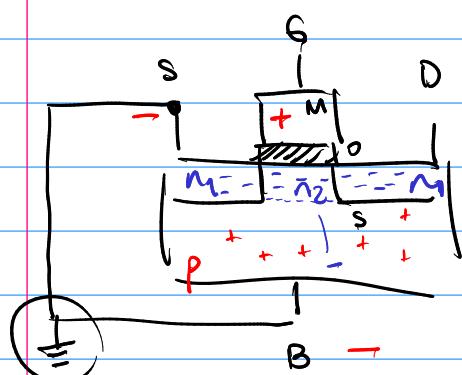
B: Bulk (Substrato)

Símbolo



Funcionamiento NMOS

$$C_{ox} = \frac{\epsilon_0 \epsilon_{ox}}{t_{ox}} \quad \epsilon_{ox} = 3.9$$



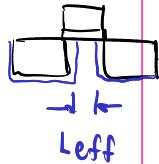
El sustrato B. se conecta al potencial más bajo del circuito.

Dependiendo de VGS:

1. Acumulación ( $V_G < 0$ )
2. Banda plana ( $V_G \approx 0$ )
3. Agotamiento ( $V_G > 0$ )
4. Inversión débil ( $V_G > V_{th}$ )
5. Inversión fuerte ( $V_G \gg V_{th}$ )

$V_{GS}$  es la variable de control del transistor.

$V_{th}$ : tensión de umbral



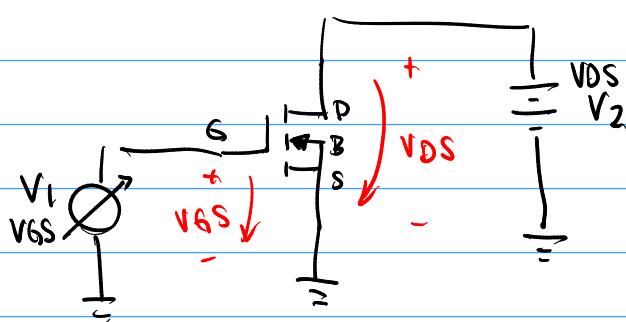
Ion implantation  
Annealing

CS 500nm

$L_{\text{drawn}} = 600 \text{ nm}$   $L_{\text{eff}} = 500 \text{ nm}$

## Curvas características

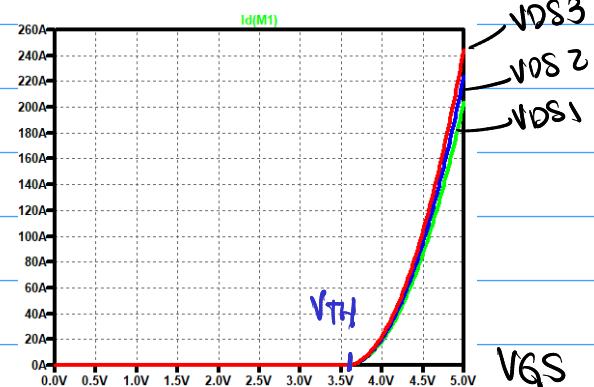
CURVA de transferencia



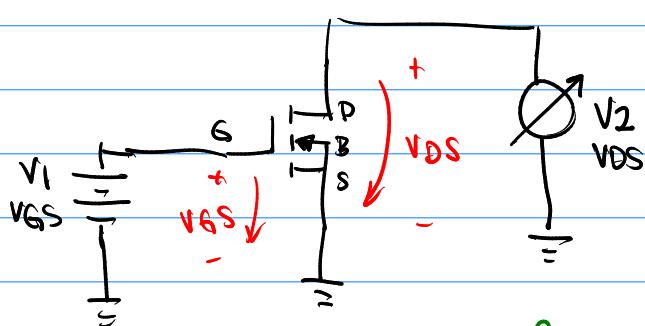
ID

IRF244N

con  $\lambda \neq 0$



CURVA de salida



ID

IRF244N

lineal

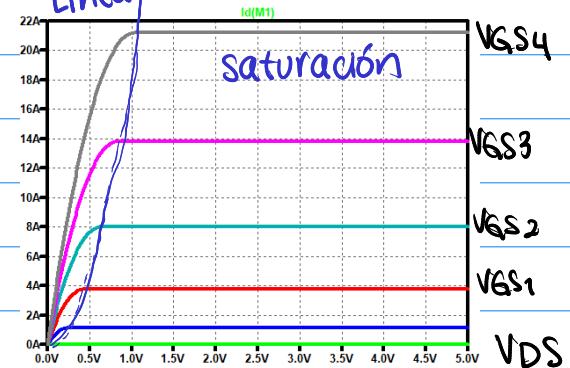
VGS4

VGS3

VGS2

VGS1

VDS



Regiones de operación

XFAB  
 $L = 180 \text{ nm}$

$$Cox^1 = \frac{\epsilon_0 \epsilon_{ox}}{t_{ox}} [\text{F/m}^2]$$

$$k^1 = \mu_n Cox^1$$

$$Cox = Cox^1 \cdot W \cdot L [F]$$

$$K = \mu_n Cox^1 \frac{W}{L}$$

AMP

Saturación  $\rightarrow$  Fuente I controlada por VGS

$$VDS \geq VGS - V_{TH}$$

[V<sup>-1</sup>] · [V]

CLM

$$ID = \frac{1}{2} \mu_n Cox^1 \frac{W}{L} (VGS - V_{TH})^2 (1 + \lambda VDS) \quad \text{mod. largo canal}$$

$$ID = \frac{1}{2} k^1 \frac{W}{L} (VGS - V_{TH})^2 (1 + \lambda VDS)$$



$$ID = \frac{1}{2} K \frac{W}{L} (VGS - V_{TH})^2 (1 + \lambda VDS) \quad \begin{matrix} [A] \\ [V^2] \end{matrix}$$

Transconductancia

$$K = 100 \mu\text{A}/\text{V}^2$$

Activa Directa

$VBE/V_T$

$$I_C = I_S e^{\frac{VBE}{V_T}} \propto A_E$$

Linear (Triodo) → Resistencia controlada por VGS

$$VDS \leq VGS - VTH$$

$$ID = \mu_n Cox \frac{W}{L} \left[ (VGS - VTH)VDS - \frac{VDS^2}{2} \right]$$



$$ID = K \cdot \frac{W}{L} \left[ (VGS - VTH)VDS - \frac{VDS^2}{2} \right]$$

$$ID = K \left[ (VGS - VTH)VDS - \frac{VDS^2}{2} \right]$$

$$R_{CH} = \frac{VDS}{ID} \quad \text{para la parte lineal}$$

$$ID = K \left[ (VGS - VTH)VDS - \frac{VDS^2}{2} \right]$$

lejos del borde  
de saturación

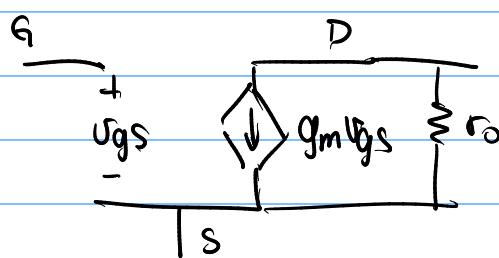
$$R_{CH} = \frac{VDS}{ID} = \frac{1}{K(VGS - VTH)}$$

BJT  
early

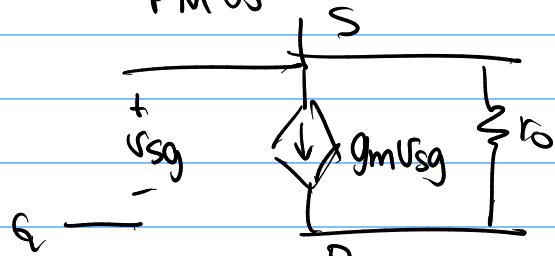
MOS  
modulación

Modelo de pequeña señal

NMOS



PMOS



$$g_m = ? \quad \text{tres ecuaciones}$$

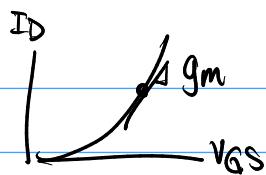
$$r_o = \frac{1}{2ID}$$

$$g_m = \mu_n Cox \frac{W}{L} (VGS - VTH)$$

$$g_m = \frac{2ID}{VGS - VTH}$$

$$g_m = \sqrt{2 \mu_n Cox \frac{W}{L} ID}$$

válidas en saturación



$$g_m = \left. \frac{\partial I_D}{\partial V_{GS}} \right|_Q$$

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

$$\frac{d}{dx} (x-a)^2$$

$$= 2(x-a) \cdot 1$$

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

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

Dividiendo 1 entre 2:

tres variables

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

$I_D$   
 $V_{GS}$

$g_m = \frac{2 I_D}{V_{GS} - V_{TH}}$  [3]

$W/L$

Despejando  $V_{GS} - V_{TH}$  de [1]:

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

y sustituimos en [2]:

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

[4]

$$g_m = \sqrt{\frac{2 I_D (\mu_n C_{ox} \frac{W}{L})^2}{\mu_n C_{ox} \frac{W}{L}}} \Rightarrow$$

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

$$C_{ox} = \frac{\epsilon_0}{t_{ox}} \cdot \frac{8.854 \times 10^{-12} \text{ F/m}}{\checkmark}$$

$$= \frac{3.9 \times 8.854 \times 10^{-12} \text{ F/m}}{1.38 \times 10^{-8} \text{ m}}$$

$$= 2.48 \times 10^{-3} \frac{\text{F}}{\text{m}^2}$$

$$2.48 \times 10^{-3} \frac{\text{F}}{\text{m}^2} \times \frac{(1\text{m})^2}{(10^6 \mu\text{m})^2}$$

$$2.48 \times 10^{-15} \frac{\text{F}}{\text{mm}^2} = 2.48 \text{ fF}/\mu\text{m}^2$$

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

$$(S\mu A) = \frac{1}{2} \mu_n \left( 2.53 \frac{\text{fF}}{\mu\text{m}^2} \right) \left( \frac{45 \times 0.6\mu\text{m}}{0.6\mu\text{m}} \right) (0.663 - 0.670)^2$$

?

$$K = \mu_n C_{ox} \frac{W}{L}$$

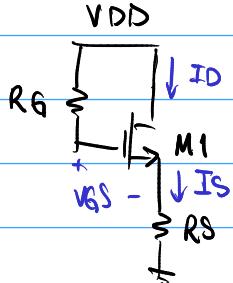
$$\cdot \text{op} \xrightarrow{VGS} ID$$

Clase 10: Polarización MOSFET

→ Punto de operación

Saturación / Lineal

1. polarización fija ( $\lambda = 0$ )



$$LVK: V_{DD} = \cancel{V_{PG}}^0 + V_{GS} + V_{RS}$$

$$V_{DD} = V_{GS} + I_D \cdot R_S$$

$$I_D = \frac{V_{DD} - V_{GS}}{R_S}$$

$$I_G = 0$$

$$I_D = I_S$$

$$I_{RG} = 0$$

$$V_G = V_{DD}$$

$$V_{DS} \geq V_{GS} - V_{TH} \rightarrow \text{saturación}$$

$$V_D - V_S \geq V_G - V_S - V_{TH}$$

$$V_{DD} \geq \underbrace{V_{DD} - V_{TH}}$$

menor que  $V_{DD}$  ✓

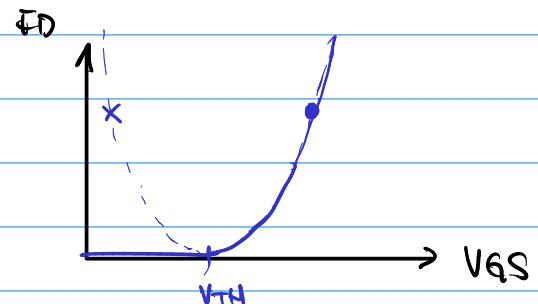
⇒ si está en saturación.

$$\begin{aligned} I_B &= I_C \\ I_E &= I_B + I_C = (\beta + 1)I_B \\ I_E &= I_C \\ \alpha &= \frac{\beta}{\beta + 1} \end{aligned}$$

$$I_D = \frac{1}{2} \mu_n C_o x' \frac{W}{L} (V_{GS} - V_{TH})^2$$

Se resuelve el sistema:

$$\left\{ \begin{array}{l} I_D = \frac{V_{DD} - V_{GS}}{R_S} \\ I_D = \frac{1}{2} \mu_n C_o x' \frac{W}{L} (V_{GS} - V_{TH})^2 \end{array} \right.$$



se igualan las ecuaciones:

$$\frac{V_{DD} - V_{GS}}{R_S} = \frac{1}{2} \mu_n C_o x' \frac{W}{L} (V_{GS} - V_{TH})^2 \quad \leftarrow \text{esta se puede resolver con calculadora}$$

$$\frac{V_{DD} - V_{GS}}{R_S} = \frac{1}{2} K (V_{GS}^2 - 2V_{GS} \cdot V_{TH} + V_{TH}^2)$$

$$\frac{2(V_{DD} - V_{GS})}{K \cdot R_S} = V_{GS}^2 - 2V_{GS} \cdot V_{TH} + V_{TH}^2$$

$$V_{GS}^2 + V_{GS} \left( \frac{2V_{GS} - 2V_{TH}}{K \cdot R_S} \right) + \left( V_{TH}^2 - \frac{2V_{DD}}{K \cdot R_S} \right) = 0$$

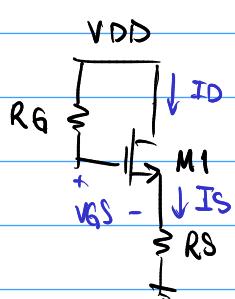
$$ax^2 + bx + c = 0$$

$$\Delta = b^2 - 4ac$$

$$x = \frac{-b \pm \sqrt{\Delta}}{2a}$$

## 2. polarización fija ( $\lambda \neq 0$ )

3 variables



$$ID = \frac{1}{2} \mu n C_{ox} \frac{W}{L} (VGS - VTH)^2 (1 + \lambda VDS) \quad [1]$$

LVIK por el gate

$$VDD = \cancel{ID RG} + VGS + ID RS$$

$$VGS = VDD - ID RS \quad [2]$$

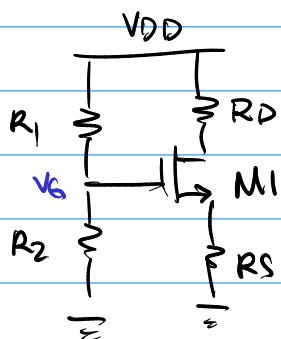
LVIK por el drain

$$VDD = VDS + ID RS$$

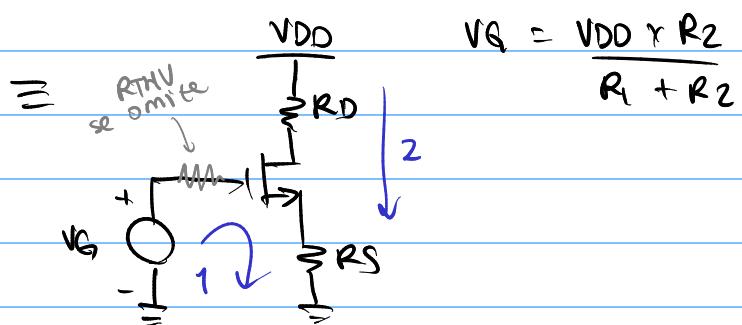
$$VDS = VDD - ID RS \quad [3]$$

se resuelve el sistema de tres ecuaciones.

## 3. polarización por divisor de tensión



El divisor de tensión es exacto porque no hay corriente  $IS$ .  
→ No hace falta eq. Thévenin



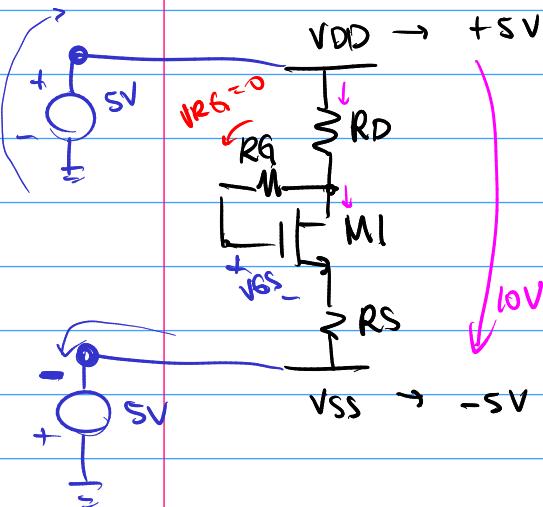
$$\text{LVIK1: } VGS = VGS + ID RS \quad [1]$$

$$\text{LVIK2: } VDD = ID RD + VDS + RS \quad [2]$$

$$ID = \frac{1}{2} \mu n C_{ox} \frac{W}{L} (VGS - VTH)^2 (1 + \lambda VDS) \quad [3]$$

Observe que si  $\lambda = 0$ , se resuelve solo con [1] y [3].  
(no hace falta la [2])

#### 4. Autopolarización



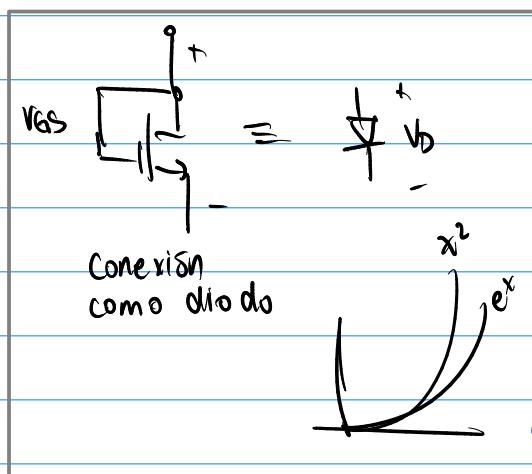
$$V_S = V_D \Rightarrow V_{DS} \geq V_{GS} - V_{TH}$$

Está en saturación.

$$LVK: +V_{DD} = I_D R_D + I_D R_G + V_{GS} + I_S R_S + V_{SS}$$

$$V_{DD} - V_{SS} = I_D (R_D + R_S) + V_{GS}$$

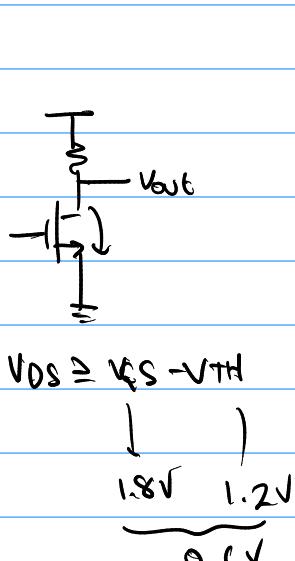
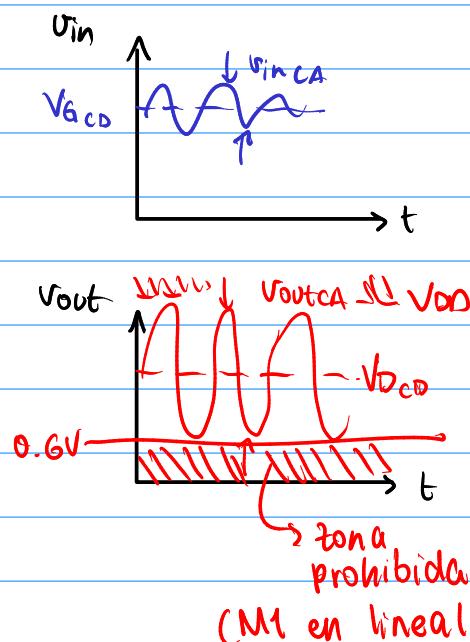
$$I_D = \frac{V_{DD} - V_{SS} - V_{GS}}{R_D + R_S}$$



$$I_D = \frac{1}{2} K (V_{GS} - V_{TH})^2$$

Si  $\lambda = 0$ , se resuelven ambas ecuaciones.

Si  $\lambda \neq 0$ , se requiere una tercera ecuación:  
LVK por drain.



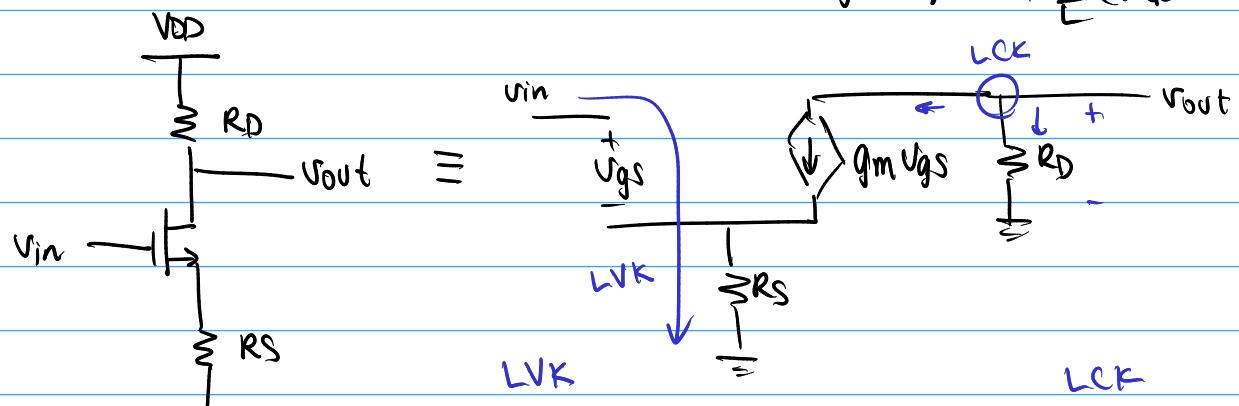
Rail-to-rail  
amplifiers

$$V_{GS} - V_{TH} = \frac{V_{ov}}{\text{overdrive}}$$

$$g_m = \frac{2ID}{(V_{GS} - V_{TH})}$$

$$g_m = \sqrt{2\mu_n C_o x \frac{W}{L} I_D}$$

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



$$V_{in} = V_{gs} + i_{RS} \cdot R_S$$

$$g_m V_{gs} + \frac{V_{out}}{R_D} = 0$$

$$V_{in} = V_{gs} + g_m V_{gs} R_S$$

$$V_{in} = V_{gs} (1 + g_m R_S)$$

$$V_{gs} = -\frac{V_{out}}{g_m R_D}$$

Combinando ecuaciones:

$$V_{in} = -\frac{V_{out}}{g_m R_D} (1 + g_m R_S)$$

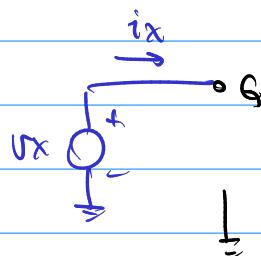
$$A_V = \frac{V_{out}}{V_{in}} = \frac{-g_m R_D}{1 + g_m R_S} \times \frac{1/g_m}{1/g_m}$$

$$A_V = \frac{-R_D}{\frac{1}{g_m} + R_S}$$

$$A_V = \frac{-R_C}{\frac{1}{g_m} + R_E}$$

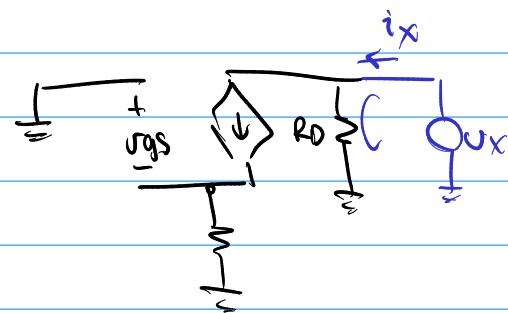
Similar a E.C.

Impedancia de entrada:



$$\boxed{R_{in} \rightarrow \infty}$$

Impedancia de salida:

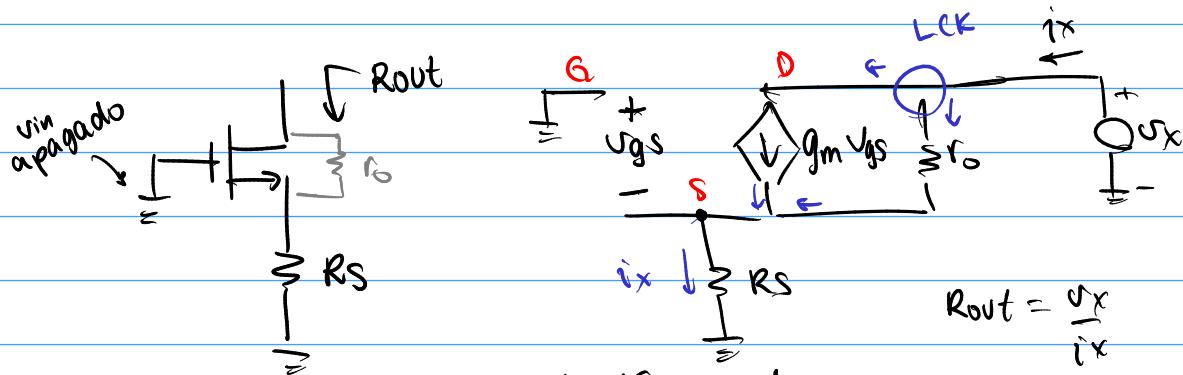


$$V_{gs} = 0$$

$$\boxed{R_{out} = R_D}$$

para amplificadores avanzados \*

Impedancia desde el drain con  $\lambda \neq 0$



LVK por gate

$$V_{GS} + V_S = 0$$

$$V_S = -V_{GS}$$

La tensión en el source:

$$V_S = i_x R_S = -V_{GS}$$

La LVK en el drain:

$$i_x = g_m V_{GS} + i_{ro}$$

$$i_x = g_m (-i_x R_S) + \frac{U_X - U_{RS}}{R_0}$$

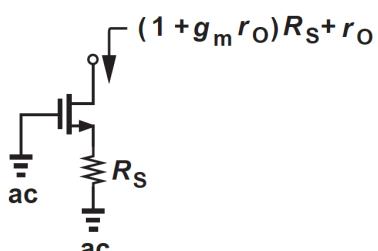
$$i_x = g_m (-i_x R_S) + \frac{U_X}{R_0} + \frac{V_{GS}}{R_0}$$

$$i_x = g_m (-i_x R_S) + \frac{U_X}{R_0} - \frac{i_x R_S}{R_0}$$

$$i_x \left( 1 + g_m R_S + \frac{R_S}{R_0} \right) = \frac{U_X}{R_0}$$

$$\frac{U_X}{i_x} = R_0 \left( 1 + g_m R_S + \frac{R_S}{R_0} \right)$$

$$R_{out} = r_0 + g_m R_S r_0 + R_S$$

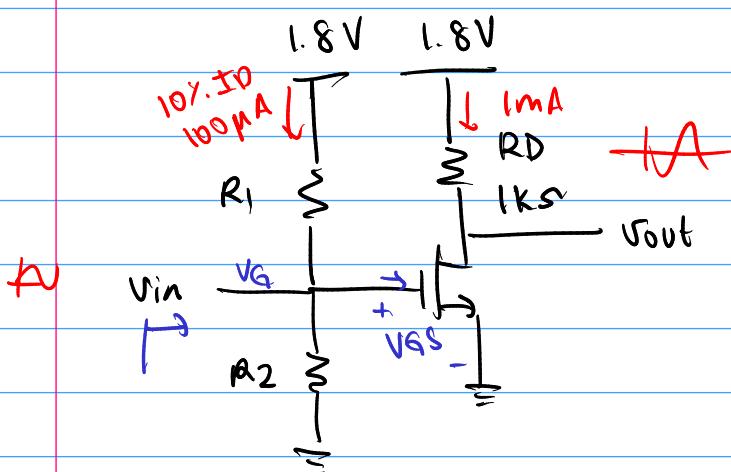


$$R_{out} = r_0 + R_S (1 + g_m r_0)$$

$$R_{out} = r_0 (1 + g_m R_S) + R_S$$

Ejemplo 7.4 (p 315)

Tecnología de 180 nm



$$\mu_n C_{ox}^{-1} = 100 \mu A/V^2$$

$$V_{TH} = 0.5 V$$

$$\lambda = 0$$

$$I_D = 1 \text{ mA}$$

$$\frac{W}{L} = \frac{10}{0.18} \mu = 55,55$$

Shockley:

$$I_C = I_S e^{\frac{V_{BE}}{V_T}}$$

$$V_{BE} = V_T \ln \frac{I_C}{I_S}$$

1. Determine  $V_{GS}$  para diseñar la polarización del circuito.

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

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

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

$$V_{GS} = \sqrt{\frac{2(1 \text{ mA})}{(100 \mu A) \left(\frac{10}{0.18}\right)}} + 0.5 \text{ V}$$

$$V_{GS} = 0.6 \text{ V} + 0.5 \text{ V}$$

$$\boxed{V_{GS} = 1.1 \text{ V}}$$

2. Calcule el valor de  $R_1$  y  $R_2$ , si el circuito de polarización consume un 10% de la corriente  $I_D$ .

$$I_{R_1} = 10\% \cdot I_D = 0.1 \cdot I_D = 0.1 \times 1 \text{ mA} = 100 \mu\text{A}$$

$$\left. \begin{array}{l} V_G = 1.1 \text{ V} \\ V_{DD} = 1.8 \text{ V} \end{array} \right\} \begin{array}{l} V_G = \frac{V_{DD} \times R_2}{R_1 + R_2} \quad [1] \\ I_{R_1} = \frac{V_{DD}}{R_1 + R_2} \quad [2] \end{array}$$

De la ec. 2:

$$R_1 + R_2 = \frac{V_{DD}}{I_{R_1}} = \frac{1.8 \text{ V}}{100 \mu\text{A}} = 18 \text{ k}\Omega$$

De la ec. 1:

$$V_G = \frac{V_{DD} \cdot R_2}{R_1 + R_2} \Rightarrow R_2 = \frac{V_G \times (R_1 + R_2)}{V_{DD}}$$

$$R_2 = \frac{1.1 \text{ V}}{1.8 \text{ V}} \cdot (18 \text{ k}\Omega)$$

$$R_2 = 11 \text{ k}\Omega$$

$$R_1 = 18 \text{ k}\Omega - R_2$$

$$R_1 = 7 \text{ k}\Omega$$

3. Determine la ganancia y las impedancias de entrada y salida del amplificador.

$$AV = -g_m R_D \quad g_m = \sqrt{2 I_D / \mu_n C_{ox} \cdot \frac{W}{L}} = 3.33 \text{ mS}$$

$$g_m = \frac{2 I_D}{V_G - V_{TH}} = \frac{2(1 \text{ mA})}{1.1 \text{ V} - 0.5 \text{ V}} = \frac{2 \text{ mA}}{0.6 \text{ V}} = 3.33 \text{ mS}$$

$$AV = -3.333 \text{ mV} \times 1 \text{ k}\Omega = \boxed{-3.33}$$

$$R_{in} = R_1 \parallel R_2 = 11 \text{ k}\Omega \parallel 7 \text{ k}\Omega = \boxed{4.2778 \text{ k}\Omega}$$

$$R_{out} = R_D = \boxed{1 \text{ k}\Omega}$$

Examen I  
Semana 8

Capítulos 4, 5, 6, 7  
Materia hasta V semana 6

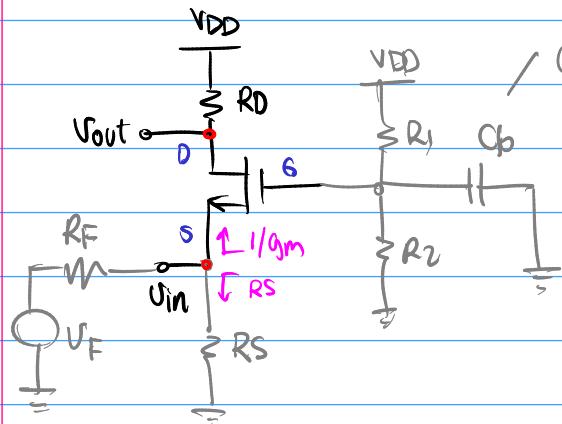
L28 1pm ~ 5pm //

Examen I: S8  
Lunes 28 de marzo  
1:00 pm - 5:00 pm

C4 BST  
CS Amp B  
CG MOS  
CT Amp M

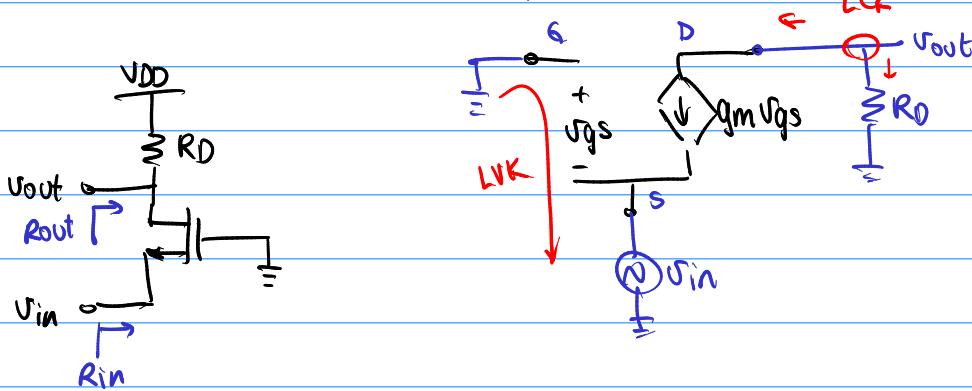
## Clase 11 : Compuerta Común (C.G.) Common Gate

- Tarea I: S8  
En grupos 2, 3, 4 personas.  
Diseño amp. CG.  
Domingo 3 abril 23:59



$C_b$  es opcional:  
 $R_1$  y  $R_2$  no deberían afectar  
las ecuaciones de ganancia  
porque el gate aísla esta  
impedancia.

Análisis del núcleo ( $\lambda = 0$ )



La LVK por el gate:  
 $+u_{gs} + u_{in} = 0$

$$u_{gs} = -u_{in}$$

$$\boxed{R_{in} = 1/g_m}$$

La LCK en el drain:

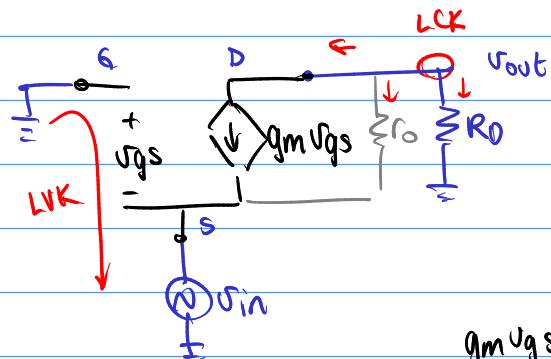
$$g_m u_{gs} + \frac{u_{out}}{R_D} = 0$$

Combinando ecuaciones:

$$g_m (-u_{in}) = -\frac{u_{out}}{R_D}$$

$$\boxed{\frac{u_{out}}{u_{in}} = g_m R_D}$$

## Análisis del núcleo ( $\lambda \neq 0$ )



$$gm v_{gs} + \frac{v_{out}}{R_D} + \frac{v_{out} - v_{in}}{r_o} = 0$$

$$v_{gs} = -v_{in}$$

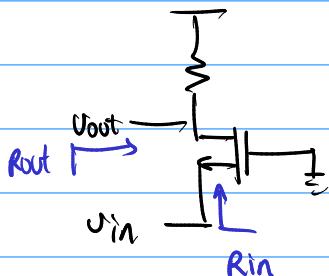
$$gm(-v_{in}) + \frac{v_{out}}{R_D} + \frac{v_{out}}{r_o} - \frac{v_{in}}{r_o} = 0$$

$$v_{out} \left( \frac{1}{R_D} + \frac{1}{r_o} \right) = v_{in} \left( gm + \frac{1}{r_o} \right)$$

$$A_V = \frac{v_{out}}{v_{in}} = \frac{gm + \frac{1}{r_o}}{\frac{1}{R_D} + \frac{1}{r_o}}$$

$$A_V = \left( gm + \frac{1}{r_o} \right) \left( R_D // r_o \right)$$

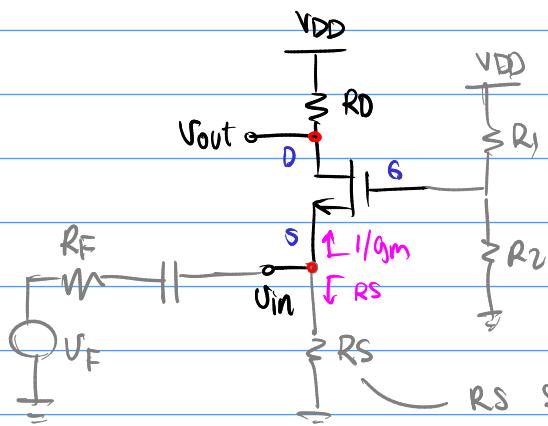
$$gm \cdot R_D$$



$$R_{in} = \left( \frac{1}{gm} // r_o \right)$$

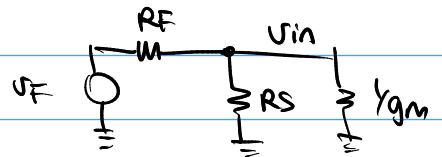
$$R_{out} = R_D // r_o$$

Análisis de la configuración completa:



$R_S$  se incluye para que exista un camino de CD a tierra.

El equivalente en la entrada:



$$\underline{V_{in}} = \frac{(R_S || \underline{gm})}{VF + (R_S || \underline{gm})}$$

↓  
pérdida por acople en la entrada.

$$\frac{\underline{V_{out}}}{VF} = A_{V\text{total}} = \frac{\underline{V_{out}}}{\underline{V_{in}}} \times \frac{\underline{V_{in}}}{VF}$$

núcleo                          div. entrada

$$\frac{\underline{V_{out}}}{VF} = +gm RD \times \frac{(R_S || \underline{gm})}{RF + (R_S || \underline{gm})}$$

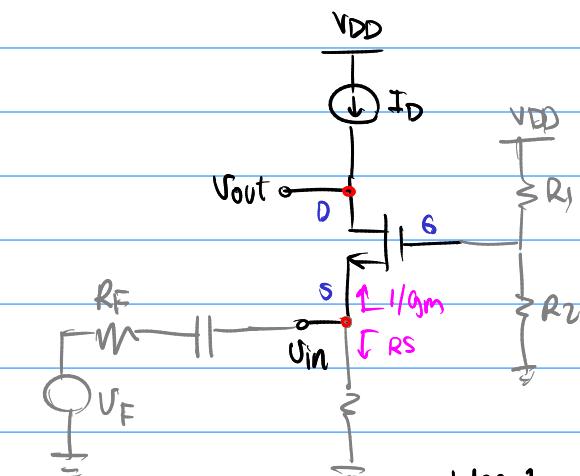
→ Si  $R_S = 0$ , este término se hace cero. No hay ganancia.

Si se desea maximizar esta ecuación,

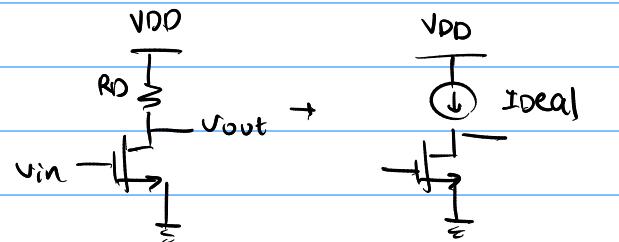
$R_D \uparrow$       o bien       $R_S$

↓  
 $R_S$  también debe ser alto.

Se sustituye  $R_D$  por una fuente I:



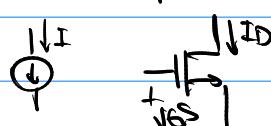
Fuente común



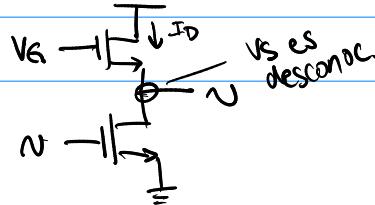
$$AV = -gm RD$$

$$AV \rightarrow -gm(\infty)$$

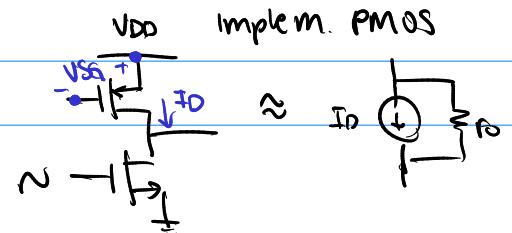
Ideal      Implem. NMOS



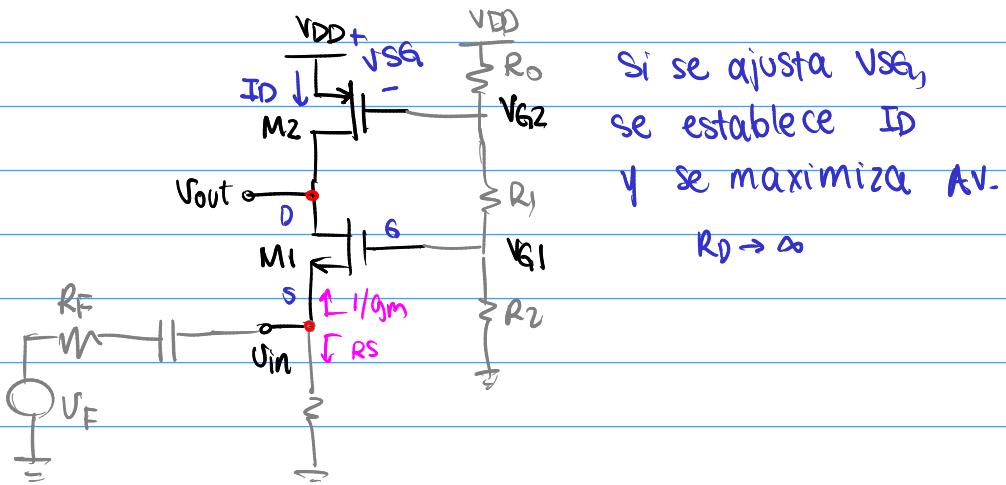
Idea 1



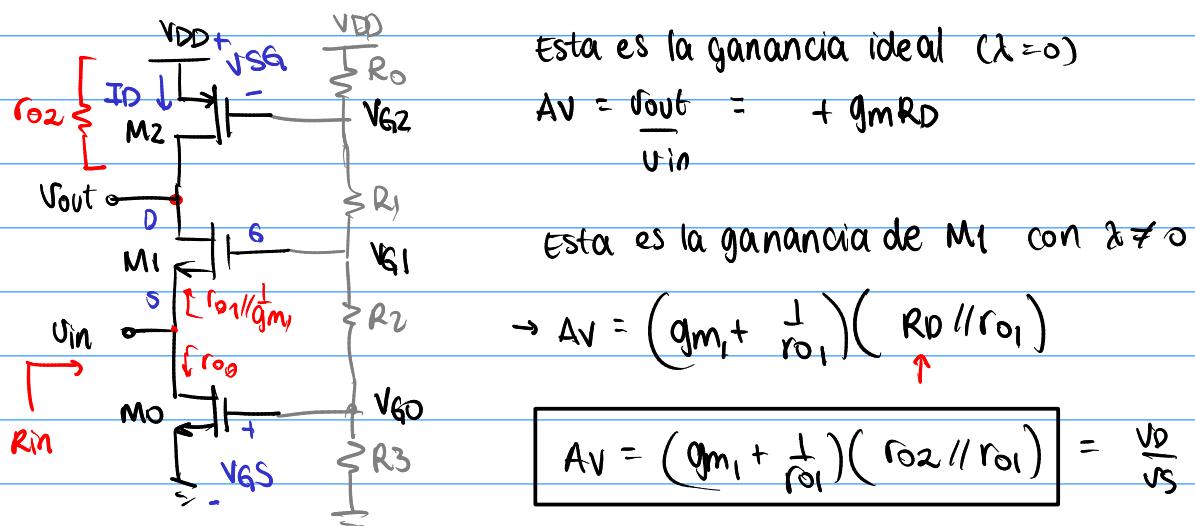
Idea 2:



La resistencia  $R_D$  se reemplaza por un PMOS conectado como fuente I:



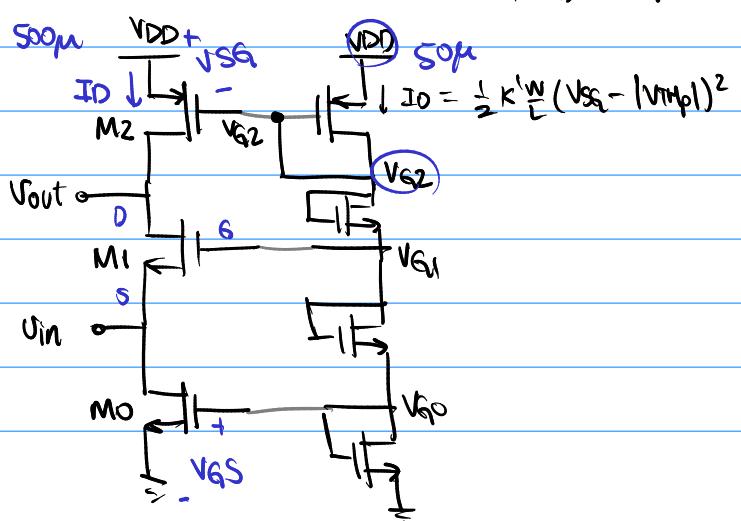
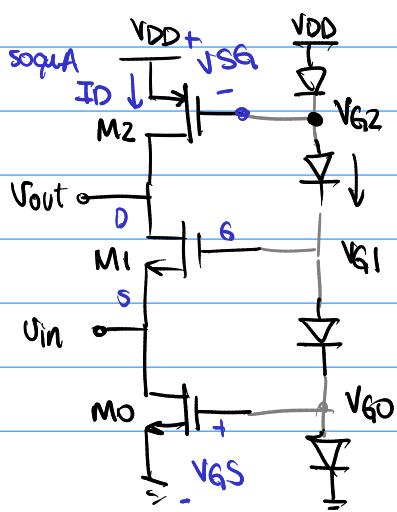
Ahora se reemplaza  $r_s$  por un NMOS:



$$R_{in} = r_{D0} // (r_{D1} // g_{m1})$$

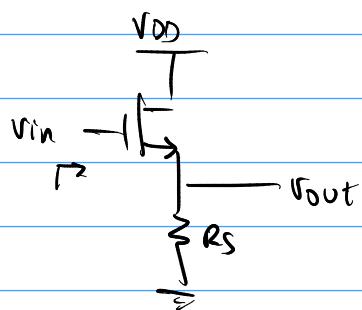
$$F_T = \frac{1}{2} e^{\frac{V_D}{V_T}} \propto V_D^2$$

Se reemplazan las resistencias por diodos:



Common Drain  
Collector

Common



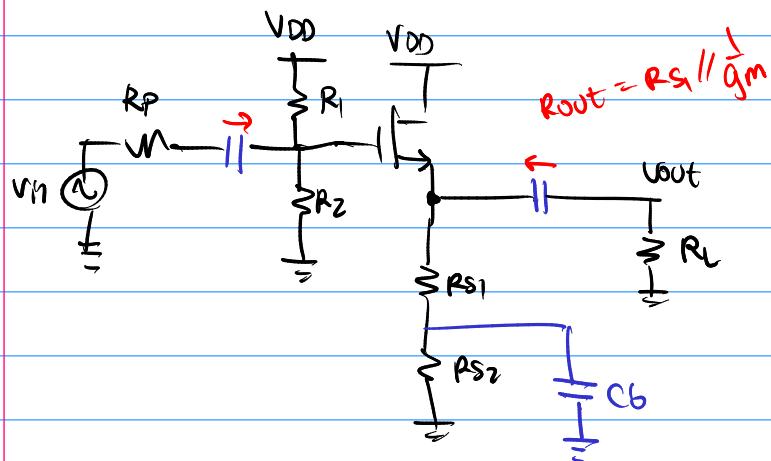
$$V_{out} = \frac{V_{in} \times R_S}{\frac{1}{g_m} + R_S}$$

$$A_V = \frac{R_S}{\frac{1}{g_m} + R_S}$$

$$R_{in} \rightarrow \infty$$

$$R_{out} = \frac{1}{g_m} // R_S$$

$$R_{in} = R_1 // R_2$$



$$V_G = \frac{V_{in} \times (R_1 // R_2)}{R_P + (R_1 // R_2)}$$

$$V_{out} = V_G \times A_V^{\text{nucleo}}$$

$$\frac{V_{out}}{V_G} = \frac{R_{S1} // R_L}{\frac{1}{g_m} + R_{S1} // R_L}$$

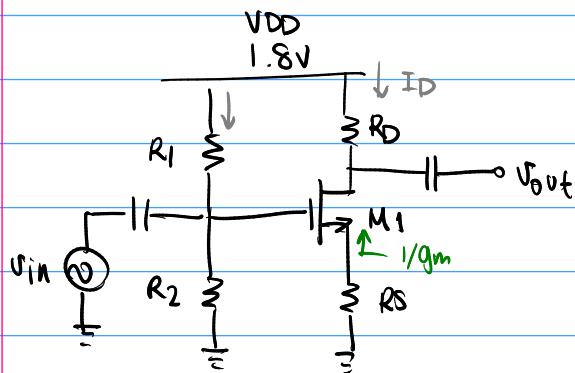
Total

$$A_V = \frac{V_{out}}{R_{in}} = \frac{(R_1 // R_2)}{R_P + (R_1 // R_2)} \times \frac{R_{S1} // R_L}{\frac{1}{g_m} + R_{S1} // R_L}$$

## Clase 12: práctica Amplificadores MOSFET

### 7.60 Common Source

Tecnología



$$V_{DD} = 1.8V$$

$$V_{TH} = 0.5V$$

$$M_n C_o x l = k' = 200 \mu A/V^2$$

$$\lambda = 0$$

Requerimientos

$$\rightarrow A_V = -4 [V/V]$$

$$\rightarrow P = 2 \text{ mW (total)}$$

$$\rightarrow R_1 \text{ y } R_2 \text{ consumen } < 5\% P_{\text{total}}$$

$$\rightarrow V_{RS} \approx 200 \text{ mV} \rightarrow \text{Criterio de diseño 2 para } R_S.$$

$$\rightarrow V_{OV} = V_{GS} - V_{TH} \approx 300 \text{ mV}$$

No se va a aplicar en este ejemplo.

Calcule el valor de  $I_D$ ,  $R_S$ ,  $R_O$ ,  $R_1$ ,  $R_2$ ,  $W/L$ .

Solución.

$$P_{\text{total}} = 2 \text{ mW} = V_{DD} \times I_{\text{total}}$$

$$I_{\text{total}} = \frac{P_{\text{total}}}{V_{DD}} = \frac{2 \text{ mW}}{1.8V} = 1.111 \text{ mA}$$

$$I_{\text{total}} = I_D + I_{R_{12}} \rightarrow I_D = 95\% I_{\text{total}}$$

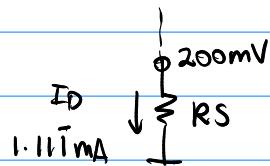
$$I_D = 0.95 \times 1.111 \text{ mA}$$

$$I_D = 1.0555 \text{ mA}$$

$$I_{R_{12}} = 5\% I_{\text{total}}$$

$$I_{R_{12}} = 0.05 \times 1.111 \text{ mA}$$

$$I_{R_{12}} = 55.55 \mu A$$



$$R_S = \frac{V_{RS}}{I_D} = \frac{200 \text{ mV}}{1.0555 \text{ mA}} = 189.47 \Omega$$

$$R_S = 189.47 \Omega$$

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

$$g_m = \frac{2I_D}{V_{GS} - V_{TH}} = \frac{2(1.0555 \text{ mA})}{300 \text{ mV}}$$

$$g_m = 7.037 \text{ MS}$$

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

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

$$AV = -4 = \frac{-R_D}{\frac{1}{g_m} + R_S}$$

$$\Rightarrow R_D = -AV \cdot \left( \frac{1}{g_m} + R_S \right)$$

$$R_D = -(-4) \cdot \left( \frac{1}{7.037 \text{ MS}} + 189.47 \Omega \right)$$

$$R_D = 1.326 \text{ k}\Omega$$

→ Es alta, podría poner a M<sub>1</sub> en la región lineal (triodo)

Verificar saturación:

$$V_{DS} \geq V_{GS} - V_{TH}$$

$$V_D - V_S \geq 300 \text{ mV}$$

$$V_{DD} - I_D R_D - V_S \geq 300 \text{ mV}$$

$$1.8V - (1.055 \text{ mA})(1.326 \text{ k}\Omega) - 200 \text{ mV} \geq 300 \text{ mV}$$

$$0.2003V \geq 300 \text{ mV}$$

No se cumple la ecuación.

→ El transistor está en la región lineal.

→ El requerimiento de AV no se puede cumplir con las condiciones del enunciado.

**A** → Una posibilidad es aumentar I<sub>D</sub> → aumenta g<sub>m</sub>

**B** → Otra posibilidad es calcular R<sub>Dmax</sub> y A<sub>Vmax</sub> que se puede lograr con la limitante de potencia.

→ Mantiene P<sub>total</sub> pero no cumple AV.

**C** → otra posibilidad es aumentar V<sub>DD</sub> por lo menos a V<sub>DD</sub> = 1.9V para tener más V<sub>D</sub> con la misma polarización. Mantiene AV pero no cumple P<sub>total</sub>.

A Si se aumenta  $I_D$  a 2 mA

$$I_D = 2 \text{ mA}$$

$$g_m = \frac{2 I_D}{V_{GS} - V_{TH}} = \frac{2(2 \text{ mA})}{300 \text{ mV}} = 13.33 \text{ mS}$$

$$A_V = -4 = \frac{-R_D}{g_m + R_S} \Rightarrow R_D = 4 \left( \frac{1}{13.33 \text{ mS}} + 189.47 \Omega \right) = 1057.88 \Omega$$

$$V_{RD} = 2.1157 \text{ V } X$$

Aumentar  $I_D$  no resuelve el problema.

C Si se aumenta  $V_{DD}$  a 2.5 V:

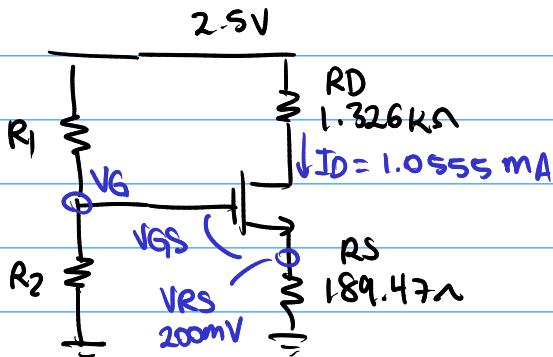
$$V_{DS} \geq V_{GS} - V_{TH}$$

$$V_{DD} - I_D R_D - V_S \geq V_{GS} - V_{TH}$$

$$2.5 \text{ V} - (1.055 \text{ mA})(1.326 \text{ k}\Omega) - 200 \text{ mV} > 300 \text{ mV}$$

$$0.9 \text{ V} > 0.3 \text{ V}$$

Sí está en saturación.



$$V_{GS} - V_{TH} = 300 \text{ mV}$$

$$V_{GS} = 300 \text{ mV} + V_{TH}$$

$$V_{GS} = 300 \text{ mV} + 0.5 \text{ V}$$

$$V_G = V_{RS} + V_{GS}$$

$$V_G = 0.2 \text{ V} + 0.8 \text{ V} = 1 \text{ V}$$

$$I_{R_{1,2}} = 55.55 \mu\text{A} = \frac{V_{DD}}{R_1 + R_2} \Rightarrow R_1 + R_2 = \frac{V_{DD}}{I_{R_{1,2}}} = \frac{2.5 \text{ V}}{55.55 \mu\text{A}}$$

$$R_1 + R_2 = 45 \text{ k}\Omega$$

$$V_G = 1 \text{ V} = \frac{V_{DD} \times R_2}{R_1 + R_2} \Rightarrow R_2 = \frac{V_G (R_1 + R_2)}{V_{DD}}$$

$$R_2 = \frac{1 \text{ V}}{2.5 \text{ V}} (45 \text{ k}\Omega)$$

$$R_2 = \frac{2}{5} (45 \text{ k}\Omega)$$

$$R_2 = 18 \text{ k}\Omega$$

$$R_1 = 27 \text{ k}\Omega$$

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

↙ 200  $\mu A/V^2$   
1.111 mA      300 mV

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

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

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

$$\frac{W}{L} = \frac{2(1.05 \text{ mA})}{(200 \mu A/V^2)(0.3V)^2}$$

$$\frac{W}{L} = 117.28$$

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

$$\frac{W}{L} = \frac{7.037 \text{ mS}}{(200 \mu A/V^2)(300 \text{ mV})}$$

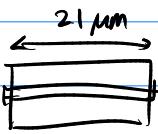
$$\frac{W}{L} = 117.28$$

Si  $L = 180 \text{ nm}$

$$W = 117.28 \times 180 \text{ nm}$$

$$W = 21.111 \mu\text{m}$$

$$\frac{W}{L} = \frac{21.111}{0.18}$$



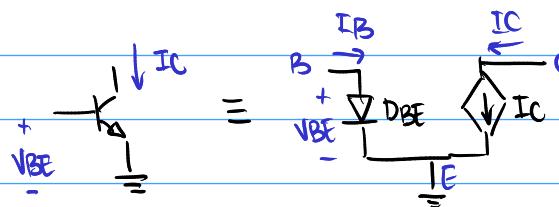
$$\frac{W}{L} = \frac{g_m^2}{2 \mu_n C_{ox} I_D}$$

$$\frac{W}{L} = \frac{(7.037 \text{ mS})^2}{2(200 \mu A/V^2)(1.055 \text{ mA})}$$

$$\frac{W}{L} = 117.28$$

## Clase 13: Cascode como fuente de corriente

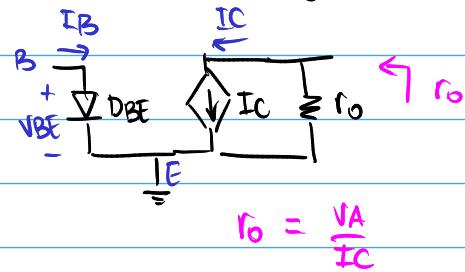
Un transistor BJT



$I_E = I_B + I_C$

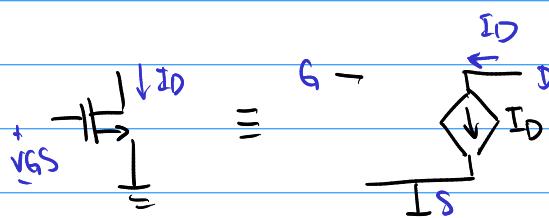
$I_C = \beta I_B$

Con efecto Early



$r_o = \frac{V_A}{I_C}$

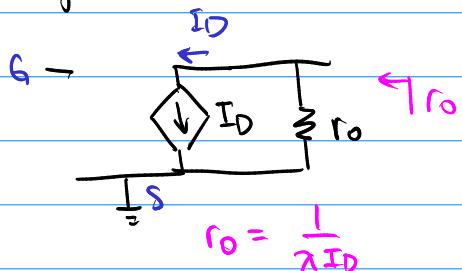
Un transistor MOSFET



$I_S = I_D$

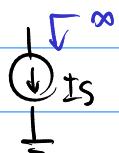
$I_G = 0$

Con modulación de longitud de canal:

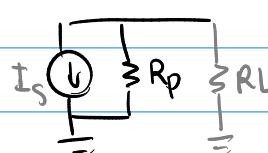


$r_o = \frac{1}{2 I_D}$

Fuente ideal



Fuente no ideal

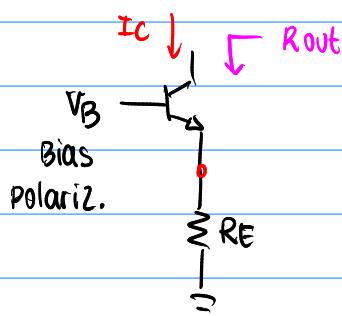


Divisor de corriente

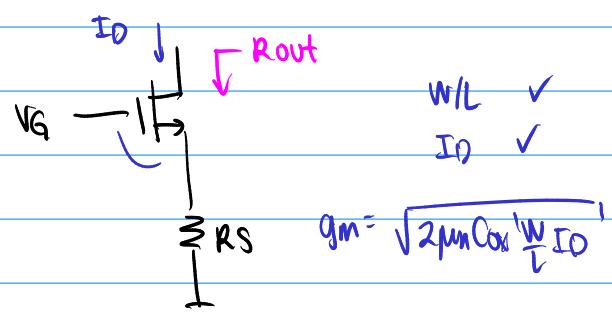
$I_{RL} = \frac{I_S \times R_p}{R_L + R_p}$

Una fuente I ideal tiene  $R_p \rightarrow \infty \Rightarrow I_{RL} \approx I_S$ Si  $R_p$  es bajo, existen pérdidas de corriente en  $R_p$ .

Impedancia de salida con degeneración



$R_{out} = (1 + g_m r_o)(R_E // r_T) + r_o$



$R_{out} = (1 + g_m r_o) R_S + r_o$

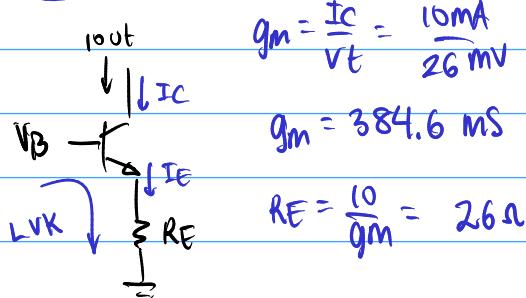
$g_m = \sqrt{2 \mu n C_{ox} \frac{W}{L} I_D}$

Ejemplo: determine  $V_B$  requerida para obtener  $I_{out} = 10 \text{ mA}$  si se tiene  $R_E = 10/\text{g}_m$ ,  $I_S = 10^{-14} \text{ A}$ ,  $\beta = 100$ .

$$\beta = \frac{I_C}{I_B} = 100$$

$$\rightarrow \alpha = \frac{I_C}{I_E} \approx 1$$

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



$$g_m = \frac{I_C}{V_t} = \frac{10 \text{ mA}}{26 \text{ mV}}$$

$$g_m = 384.6 \text{ MS}$$

$$R_E = \frac{10}{g_m} = 26 \Omega$$

$$I_E = (\beta + 1) I_B$$

$$I_E = (\beta + 1) \frac{I_C}{\beta}$$

$$\text{LVK: } V_B = V_{BE} + I_E \cdot R_E$$

$$V_B = V_{BE} + \frac{I_C}{\alpha} R_E$$

$$I_E = \frac{\beta+1}{\beta} I_C$$

$$\text{Shockley: } I_C = I_S (e^{\frac{V_{BE}}{V_t}} - 1)$$

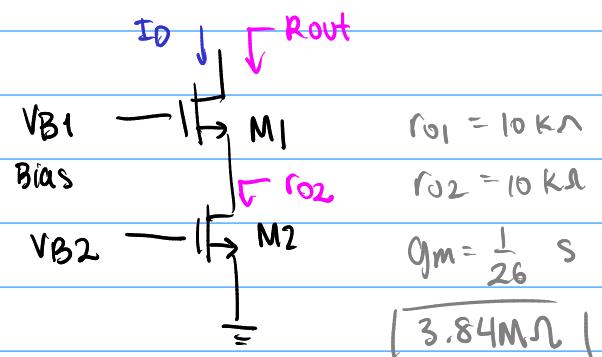
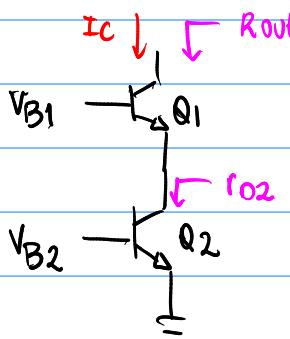
$$V_{BE} = V_t \ln \frac{I_C}{I_S} = 26 \text{ mV} \ln \frac{10 \text{ mA}}{10^{-14} \text{ A}} = 718.4 \text{ mV}$$

$$V_E = I_E \cdot R_E = \frac{(\beta+1)}{\beta} I_C \times 26 \Omega = 262.6 \text{ mV}$$

$$V_B = 981 \text{ mV}$$

### CASCODEO:

Impedancia de salida con degeneración por otro transistor



$$R_{out} = (1 + g_m r_{o1}) (R_E \parallel r_{T1}) + r_{o1}$$

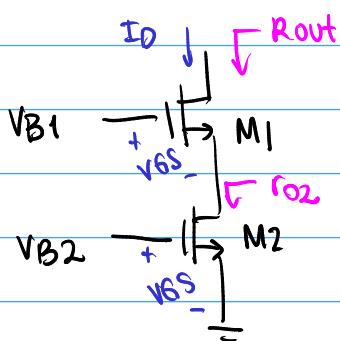
$$R_{out} = (1 + g_m r_{o1}) (r_{o2} \parallel r_{T1}) + r_{o1}$$

$$R_{out} = (1 + g_m r_{o1}) R_S + r_{o1}$$

$$R_{out} = (1 + g_m r_{o1}) r_{o2} + r_{o1}$$

Diseño de una fuente de corriente cascode MOSFET:

Si se quiere suministrar  $I_D = 500 \mu A$  con transistores NMOS, donde  $\mu_n C_{ox}^1 = 100 \mu A/V^2$ ,  $L = 180 \text{ nm}$ ,  $\frac{W}{L} = \frac{10}{0.18}$ ,  $V_{TH} = 0.5 \text{ V}$



a) Determine  $V_{B1}$  y  $V_{B2}$  si los transistores operan en saturación. omita modulación para este punto.

b) Determine el valor de  $\lambda$  máximo si se desea que  $R_{out} > 400 \text{ k}\Omega$ .

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

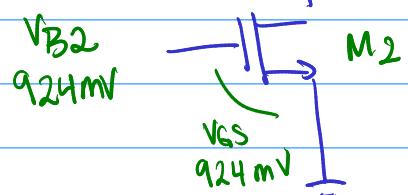
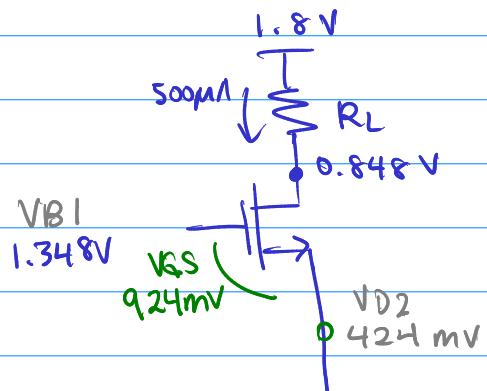
$$(V_{GS} - V_{TH})^2 = \frac{2 I_D}{\mu_n C_{ox}^1 \frac{W}{L}}$$

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

$$V_{GS} = \sqrt{\frac{2 I_D}{\mu_n C_{ox}^1 \frac{W}{L}}} + V_{TH}$$

$$V_{GS} = \sqrt{\frac{2(500 \mu A)}{(100 \mu A/V^2)(\frac{10}{0.18})}} + 0.5 \text{ V}$$

$$V_{GS} = 924.3 \text{ mV}$$



$$V_{DS2} > V_{GS2} - V_{TH}$$

$$924 \text{ mV} - 0.5 \text{ V}$$

$$V_{DS2} > 424 \text{ mV}$$

$$V_{B1} > V_{D2} + V_{GS}$$

$$V_{B1} > 424 \text{ mV} + 924 \text{ mV}$$

$$\boxed{V_{B1} > 1.348 \text{ V}}$$

b) Determinar  $\lambda$  para  $R_{out} = 400 \text{ k}\Omega$

$$R_{out} = (1 + g_m r_o) r_o + r_o$$

$$R_{out} = \left(1 + g_m \cdot \frac{1}{\lambda I_D}\right) \frac{1}{\lambda I_D} + \frac{1}{\lambda I_D}$$

$$g_m = \sqrt{2 \mu_n C_{ox} \frac{W}{L} I_D} = \sqrt{2(100 \mu\text{A}/\text{V}^2) \left(\frac{10}{0.18}\right) (500 \mu\text{A})}$$

$$g_m = 2.357 \text{ mS}$$

Se resuelve numéricamente:

$$(400 \text{ k}\Omega) = \left[ \left(1 + (2.357 \text{ mS}) \left(\frac{1}{X \cdot (500 \mu\text{A})}\right)\right) \times \frac{1}{X \cdot (500 \mu\text{A})} \right] + \frac{1}{X \cdot (500 \mu\text{A})}$$

 **WolframAlpha** computational intelligence.

solve(  $400e3 = \left(1 + (2.357e-3 * (1/(X*500e-6))) * (1/(X*500e-6)) + (1/(X*500e-6)), X\right)$  )

NATURAL LANGUAGE

MATH INPUT

EXTENDED KEYBOARD

EXAMPLES

UPLOAD

RANDOM

Input interpretation

solve	$400 \times 10^3 = \left(1 + 2.357 \times 10^{-3} \times \frac{1}{X \times 500 \times 10^{-6}}\right) \times \frac{1}{X \times 500 \times 10^{-6}} + \frac{1}{X \times 500 \times 10^{-6}}$	for	X
-------	---	-----	---

Results

More digits

Exact forms

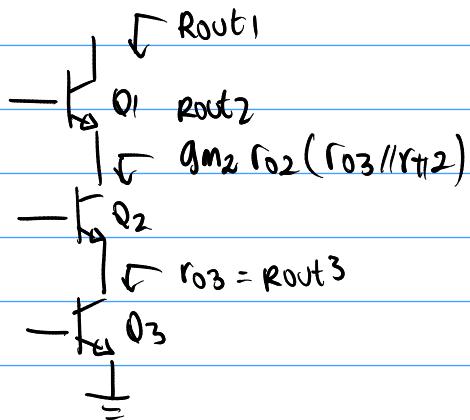
Step-by-step solution

$$X \approx -0.14861$$

$$X \approx 0.15861$$

$$\lambda_{\max} = 0.15861 \text{ V}^{-1}$$

cascodos con tres transistores?



$$r_{\pi 2} = \frac{\beta_2}{g_{m2}}$$

$$\approx g_{m2} r_{02} (\approx r_{\pi 2})$$

$$\approx g_{m2} r_{02} \frac{\beta_2}{g_{m2}}$$

$$R_{out2} \approx \beta_2 r_{02}$$

$$R_{out1} = g_{m1} r_{01} (R_{out2} \parallel r_{\pi 1})$$

$$R_{out1} = g_{m1} r_{01} (\beta_2 r_{02} \parallel r_{\pi 1})$$

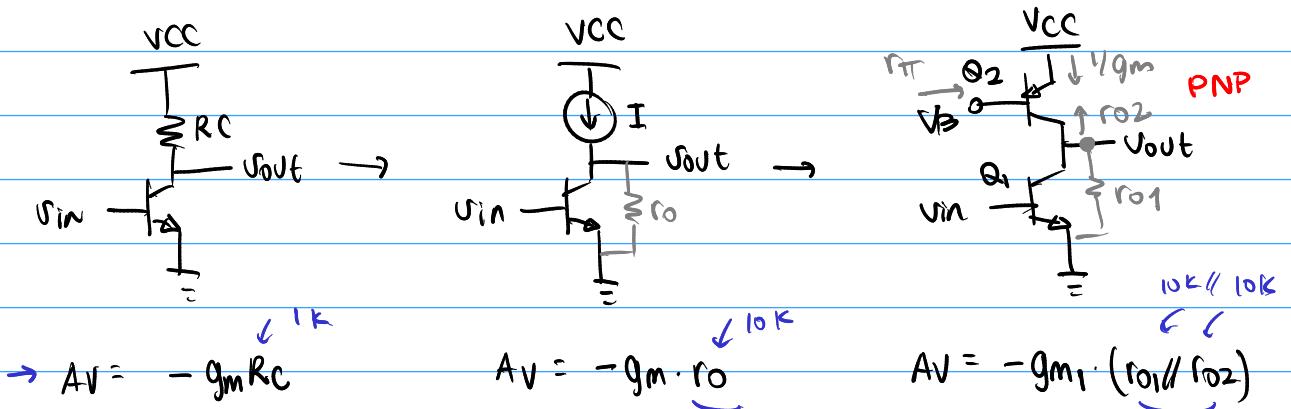
$$\approx g_{m1} r_{01} (\approx r_{\pi 1})$$

$$\approx g_{m1} r_{01} \frac{\beta_1}{g_{m1}}$$

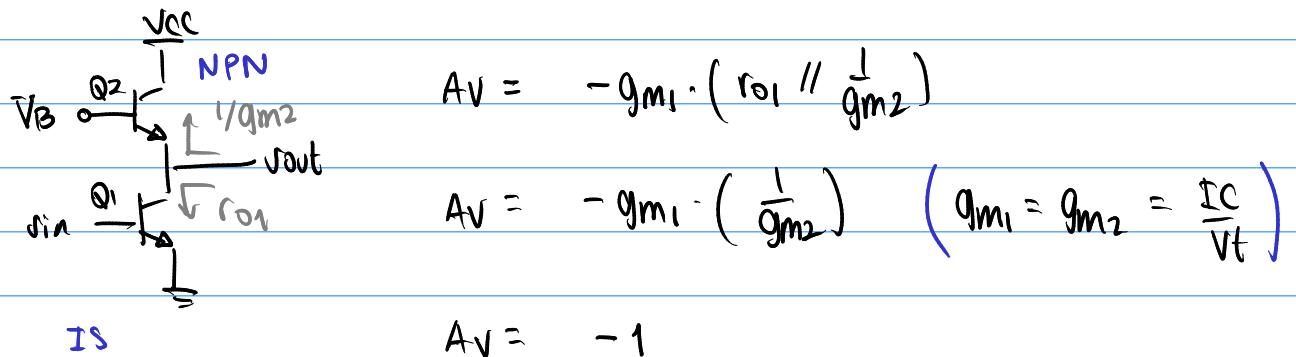
$R_{out1} \approx \beta_1 r_{01}$

## Clase 14: Cascode como amplificador

para maximizar  $A_V$  en un emisor común:



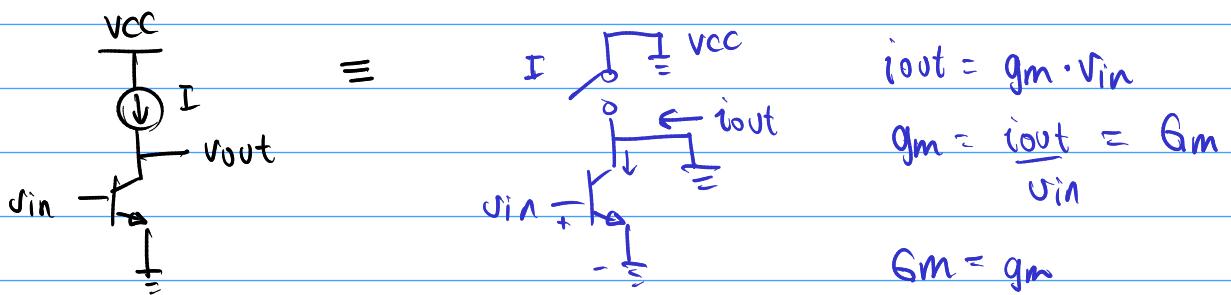
Observe que si  $Q_2$  es un NPN, no funciona:



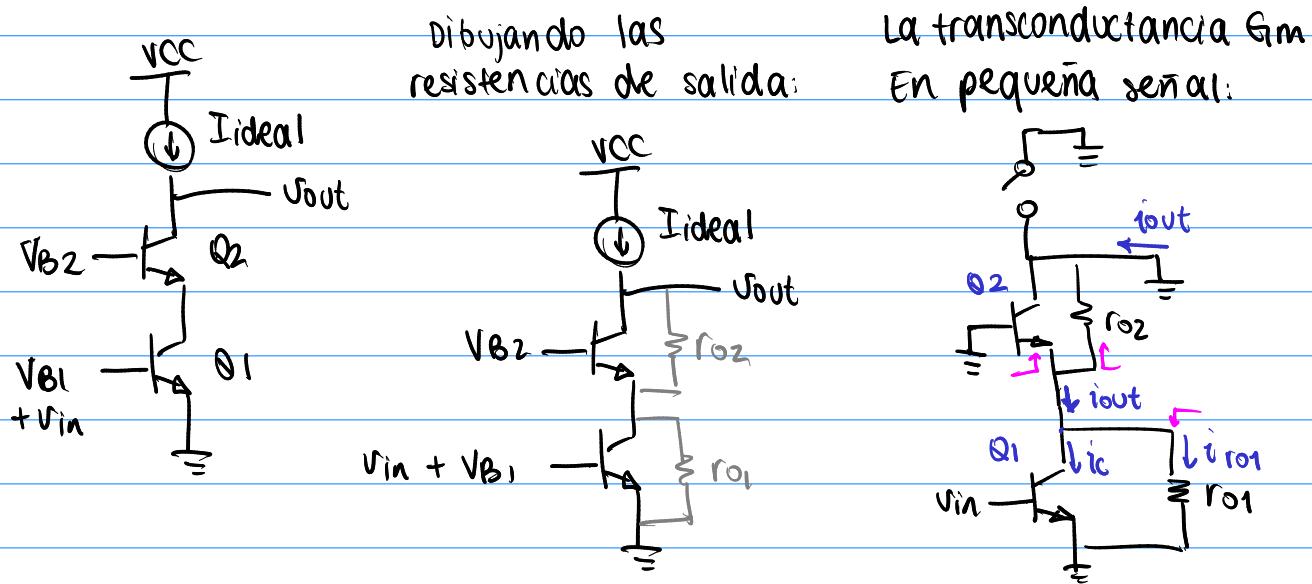
**Teorema 1:** La ganancia de un circuito se calcula como  $|A_V| = G_m \cdot R_{out}$

**Teorema 2:** La transconductancia  $G_m$  se obtiene poniendo la salida del circuito en corto (en C.A.) y despejando  $G_m = \frac{r_{out}}{v_{in}}$

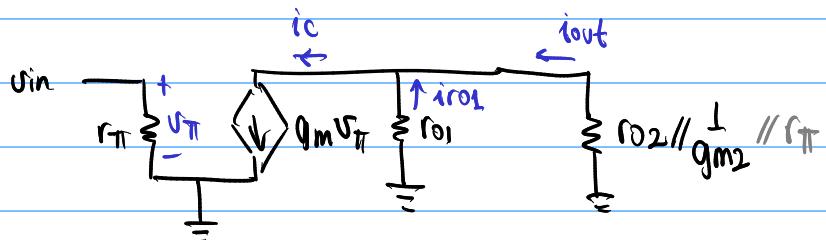
Ejemplo: determine  $G_m$  para el siguiente circuito:



El Amplificador Cascode:



Utilizando el modelo  $\pi$  para  $Q_1$ :

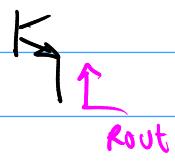


$$i_C = g_m v_{\text{in}}$$

$$i_{\text{out}} = \frac{i_C \times r_{\text{o}1}}{r_{\text{o}2} // \frac{1}{g_m r_{\text{\pi}2}} + r_{\text{o}1}}$$

$$i_{out} = g_m v_{in} \times r_{o1}$$

$$r_{o2} \parallel \frac{1}{g_m} \parallel (r_{\pi 2} + r_{o1})$$



$$G_m = \frac{i_{out}}{v_{in}} = \frac{g_m r_{o1}}{r_{o2} \parallel \frac{1}{g_m} \parallel (r_{\pi 2} + r_{o1})}$$

$$R_{out} = \frac{1}{g_m} \parallel r_{o1} \parallel r_{\pi 2}$$

$$R_{out} \approx \frac{1}{g_m}$$

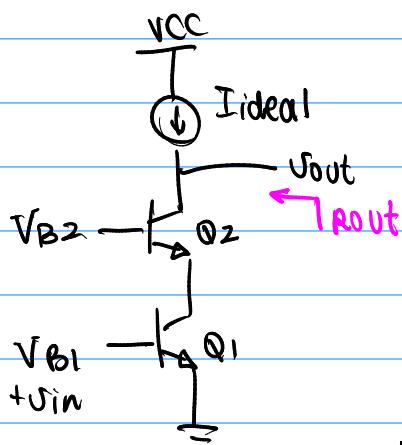
$$G_m \approx \frac{g_m r_{o1}}{\frac{1}{g_m} + r_{o1}}$$

$$\frac{20\text{A}}{10\text{K}} + \frac{10\text{K}}{r_{o1}} = 10.02 \approx r_{o1}$$

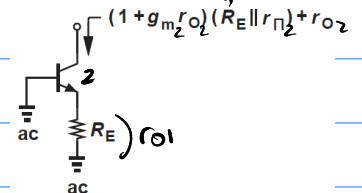
$$G_m \approx \frac{g_m r_{o1}}{r_{o1}}$$

$$G_m \approx g_m$$

La ganancia del amplificador cascode es:



$$G_m = g_m$$



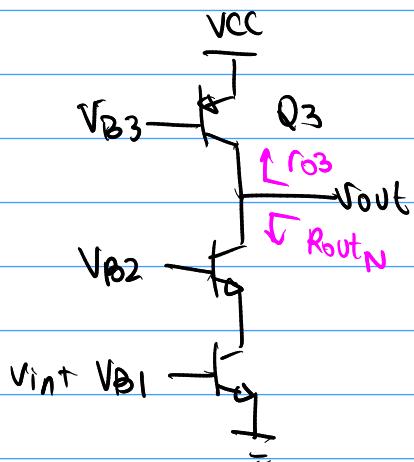
$$R_{out} = (1 + g_m r_{o2}) (r_{o1} \parallel r_{\pi 2}) + r_{o2}$$

$$|Av| = G_m \cdot R_{out}$$

$$|Av| = g_m \cdot [(1 + g_m r_{o2})(r_{o1} \parallel r_{\pi 2}) + r_{o2}]$$

$$Av = -g_m \cdot [(1 + g_m r_{o2})(r_{o1} \parallel r_{\pi 2}) + r_{o2}]$$

Un cascode con fuente PNP:

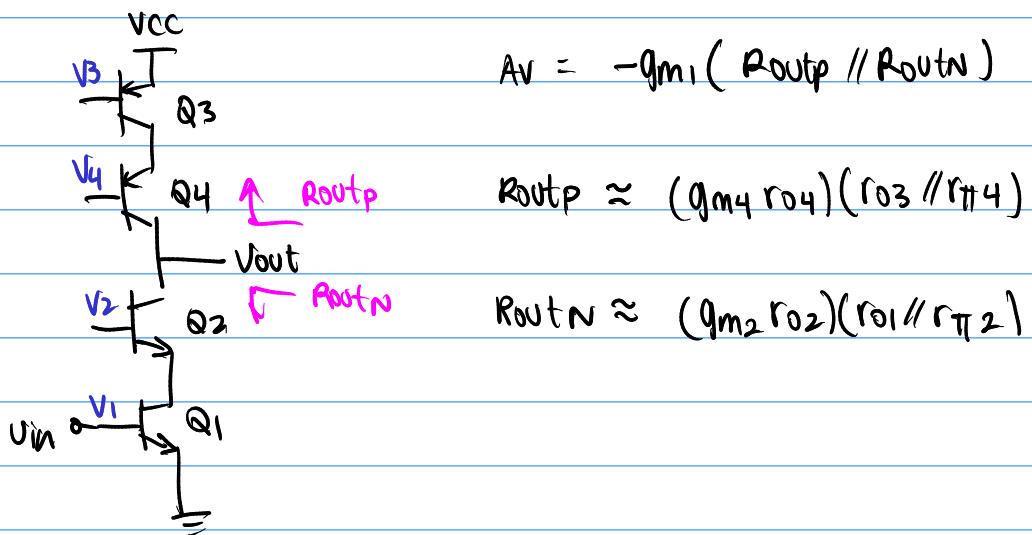


$$R_{out} = r_{o3} \parallel R_{out,N}$$

$$A_v = -g_{m1} \times \frac{r_{o3} \parallel R_{out,N}}{10k \quad 500k\Omega}$$

$$A_v \approx -g_{m1} \cdot r_{o3}$$

El amplificador cascode completo:



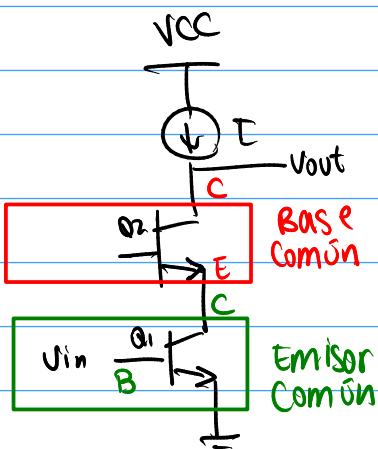
$$A_v = -g_{m1} (R_{out,p} \parallel R_{out,N})$$

$$R_{out,p} \approx (g_{m4} r_{\pi 4})(r_{o3} \parallel r_{\pi 4})$$

$$R_{out,N} \approx (g_{m2} r_{\pi 2})(r_{o1} \parallel r_{\pi 2})$$



Cálculo de  $A_V$ : solución alternativa



$$A_{V2} = \frac{V_{C2}}{V_{E2}} = +g_{m2} [(g_{m2} r_o)(r_{o1} // r_{\pi 2})]$$

$$A_{V1} = \frac{V_{C1}}{V_{B1}} = -g_{m1} \cdot (r_{o1} // r_{o2} // \frac{1}{g_{m2} // r_{\pi 2}})$$

$$A_V = A_{V1} \times A_{V2}$$

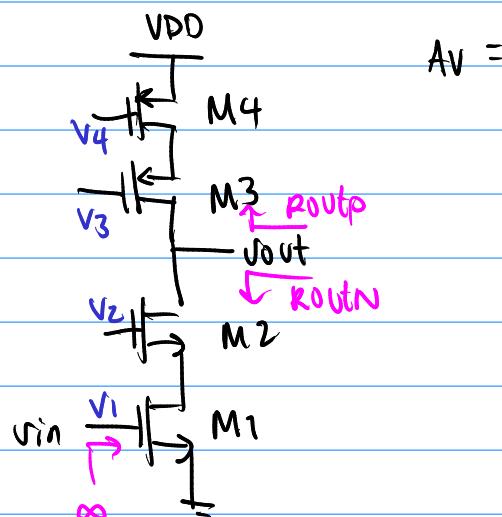
$$A_V = -g_{m1} \cdot (r_{o1} // r_{o2} // \frac{1}{g_{m2} // r_{\pi 2}}) g_{m2} [(g_{m2} r_o)(r_{o1} // r_{\pi 2})]$$

$$A_V = -g_{m1} \cdot \frac{1}{g_{m2}} \cdot g_{m2} \cdot [R_{outN}]$$

$$A_V = -g_{m1} \cdot R_{outN}$$

$$A_V = -g_{m1} \cdot [(g_{m2} r_o)(r_{o1} // r_{\pi 2})]$$

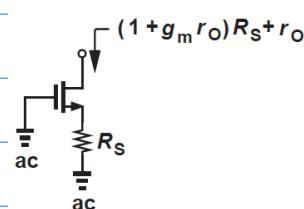
El cascode MOSFET completo:



$$A_V = -g_{m1} (R_{outN} // R_{outP})$$

$$R_{outN} = (1 + g_{m2} r_o) r_{o1} + r_{o2}$$

$$R_{outP} = (1 + g_{m3} r_o) r_{o4} + r_{o3}$$

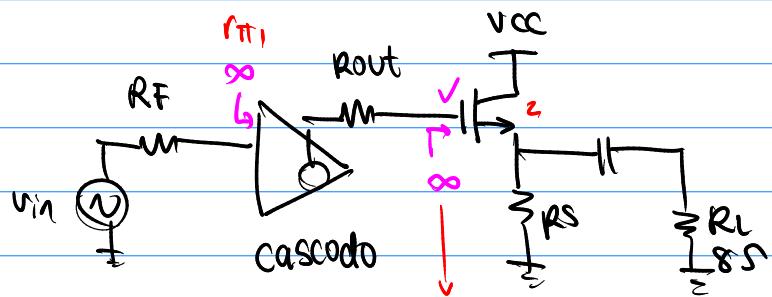


Nota importante: este circuito funciona sin carga

Si se conecta  $R_L$ :

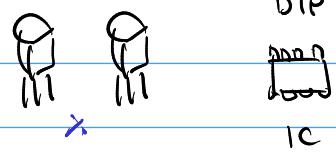
$$A_V = -g_m \cdot (R_{outN} \parallel R_{outP} \parallel R_L)$$

El amplificador necesita una etapa de salida como acople de impedancia:



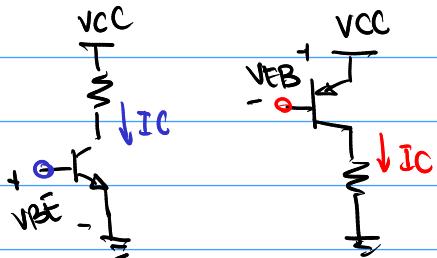
$$[r_{T2} + (\beta + 1)(R_S // R_L)] \times$$

## Clase 15: Espejos de Corriente



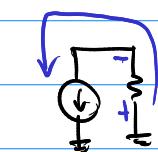
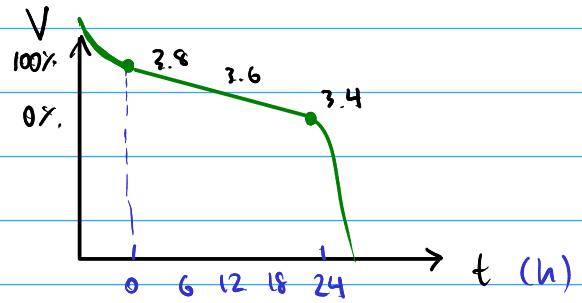
DIP  
logic  
IC

Transistor como fuente I

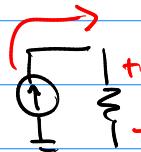


$$I_C = I_S \cdot e^{V_{BE}/V_T}$$

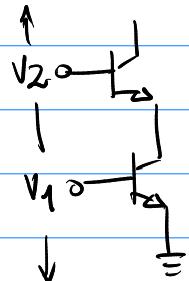
Bateria



Current  
Sink  
(sumidero)



Current  
Source  
(Fuente)



Si  $V_{CC}$  varia,  
 $V_B$  cambia,  
 $I_C$  cambia.

Problema: Limitaciones  
por  $\beta$ ,  $T$ ,  $\Delta V_{BE}$ ,  $\times R$ ...  
 $\Delta V_{CC}$

Existen fuentes de tensión muy estables ante  $\beta$ ,  $T$ ,  $\times R$ , etc.

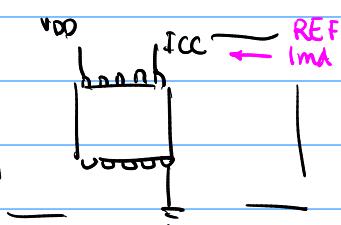
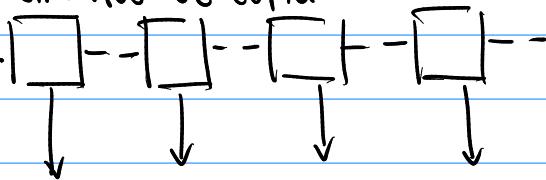
Una implementación es el Bandgap Reference

→ Circuito complejo, no es buena idea construir  
uno para cada fuente de corriente.

1 mA  
exacto  
IREF

Espejos de corriente

Circuitos de copia



MEMS  
capacitive  
pressure  
sensor

$$\frac{1}{T} C \quad \frac{1}{T} \Delta C$$

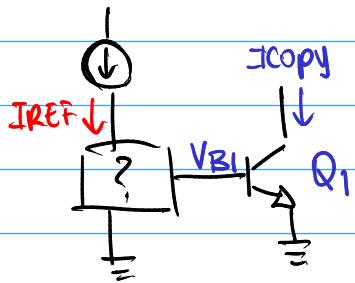
VLSI  
very large scale of  
integration

$9 \times 10^9$  Tx.

## Espejo de corriente

Para el transistor Q<sub>1</sub>:

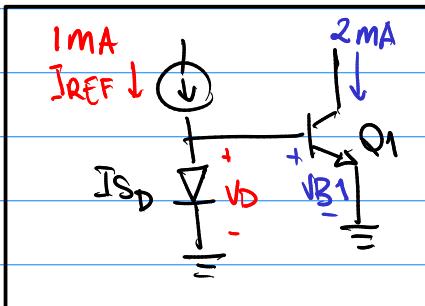
$$I_{\text{copy}} = I_{\text{ref}}$$



$$I_{S1} \cdot e^{V_B1 / V_t} = I_{\text{copy}}$$

Despejando V<sub>B1</sub>:

$$V_B1 = V_t \cdot \ln \frac{I_{\text{copy}}}{I_{S1}} \quad [1]$$



El circuito de la izquierda  
debe colocar una tensión V<sub>B1</sub>  
y el elemento que tiene este  
comportamiento es un diodo.

$$V_D = V_t \cdot \ln \frac{I_{\text{ref}}}{I_{SD}} \quad [2]$$

Si se igualan ambas ecuaciones:

$$\cancel{V_t} \cancel{\ln} \frac{I_{\text{copy}}}{I_{S1}} = \cancel{V_t} \cancel{\ln} \frac{I_{\text{ref}}}{I_{SD}}$$

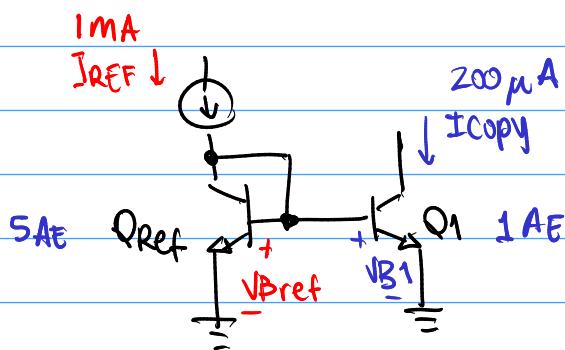
$$\frac{I_{\text{copy}}}{I_{S1}} = \frac{I_{\text{ref}}}{I_{SD}}$$

$$I_{\text{copy}} = \frac{I_{S1} \times I_{\text{ref}}}{I_{SD}}$$

$$n = \frac{I_{S1}}{I_{SD}}$$

$$I_{\text{copy}} = n \times I_{\text{ref}}$$

El espejo de corriente BJT:

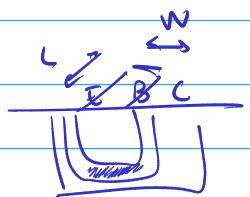


$$n = \frac{I_S}{I_{S\text{ref}}}$$

$$I_{\text{COPY}} = n \times I_{\text{ref}}$$

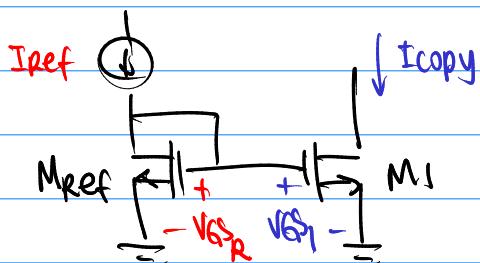
$$I_S = \frac{A_E I D_n n_i^2}{N_B W_B}$$

ctes.      ctes.      cte      cte



El área AE se puede cambiar en Synopsys, Cadence, Mentor Gr.

El espejo de corriente MOSFET:



$$I_{\text{COPY}} = \frac{1}{2} K' \frac{W_1}{L_1} (V_{GS_1} - V_{TH1})^2$$

$$V_{GS_1} = \sqrt{\frac{2 I_{\text{COPY}}}{K' \frac{W_1}{L_1}}} + V_{TH1}$$

$$I_{\text{REF}} = \frac{1}{2} K' \frac{W_R}{L_R} (V_{GS_R} - V_{THR})^2$$

$$V_{GS_R} = \sqrt{\frac{2 I_{\text{REF}}}{K' \frac{W_R}{L_R}}} + V_{THR}$$

se igualan ambas ecuaciones:

$$\sqrt{\frac{2 I_{\text{COPY}}}{K' \frac{W_1}{L_1}}} + V_{TH1} = \sqrt{\frac{2 I_{\text{REF}}}{K' \frac{W_R}{L_R}}} + V_{THR}$$

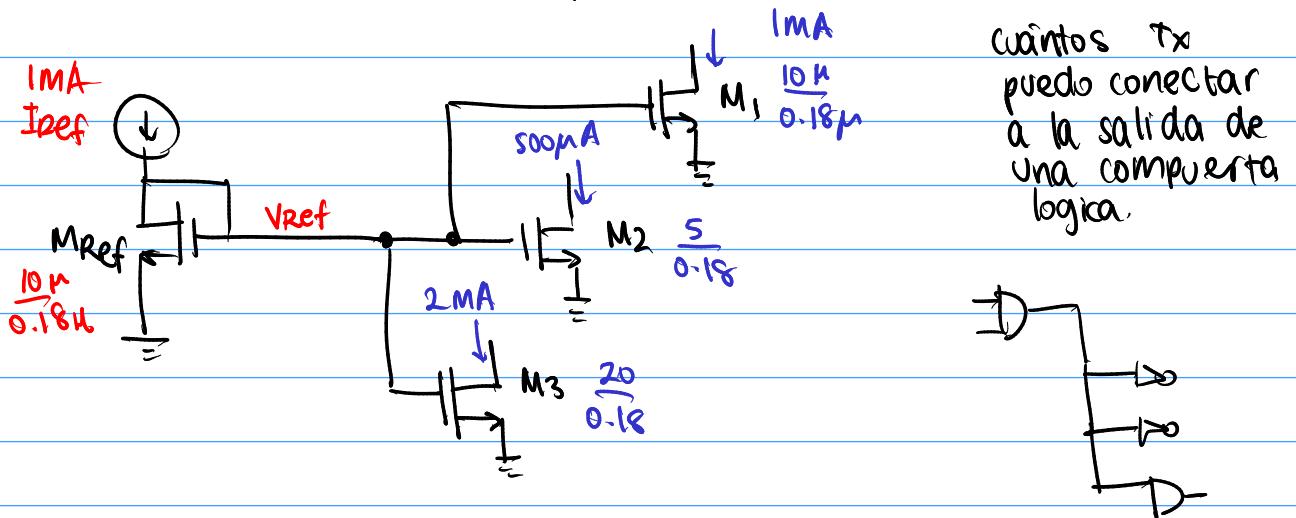
$$I_{\text{COPY}} = I_{\text{REF}} \cdot \frac{W_1 / L_1}{W_R / L_R}$$

$$I_{\text{COPY}} = n \cdot I_{\text{REF}}$$

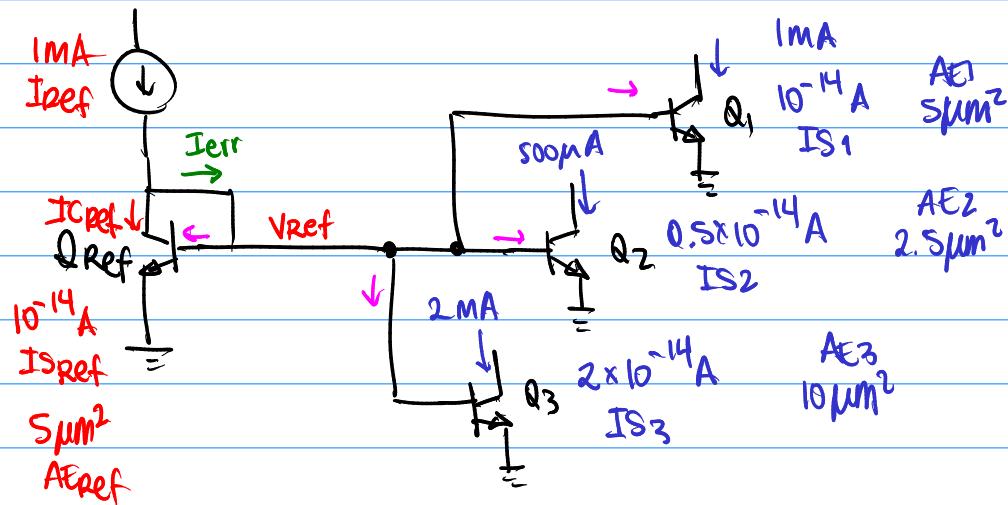
$$n = \frac{W_1 / L_1}{W_R / L_R}$$

Para construir varias copias:

FANOUT:



cuántos Tx  
puedo conectar  
a la salida de  
una compuerta  
lógica.



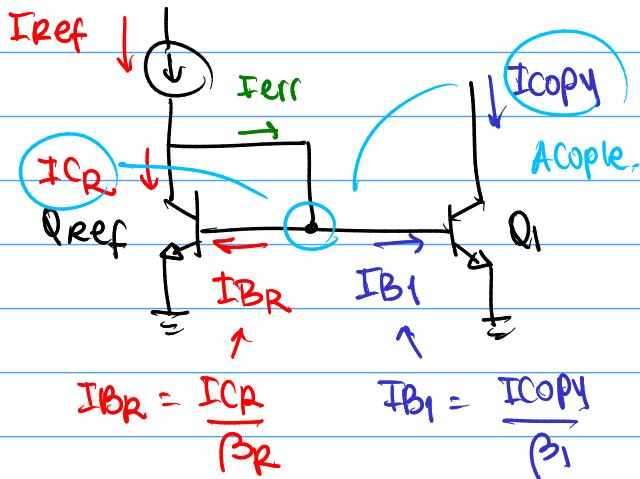
$I_{CRef}$  define a  $V_{Ref}$ .

LCK:

$$I_{CRef} = I_{Ref} - I_{err} \rightarrow$$

$$I_{err} = \sum I_{B_n}$$

Espejo BJT con error por IB:



LCK en Colector de  $Q_{ref}$ :

$$I_{CR} = I_{ref} - I_{err}$$

$\Delta$

$$\frac{I_{copy}}{n} = I_{ref} - \left( \frac{I_{CR}}{\beta_R} + \frac{I_{copy}}{\beta_1} \right)$$

$$\frac{I_{copy}}{n} = I_{ref} - \frac{I_{copy}}{n \cdot \beta_R} - \frac{I_{copy}}{\beta_1}$$

$$\frac{I_{copy}}{n} + \frac{I_{copy}}{n \cdot \beta_R} + \frac{I_{copy}}{\beta_1} = I_{ref}$$

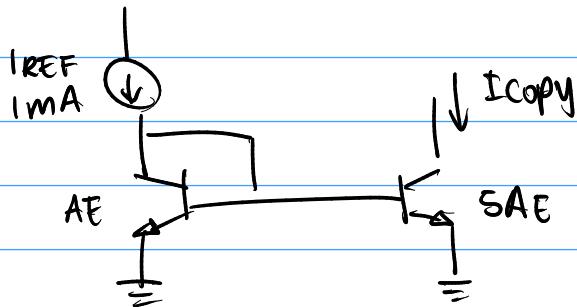
$$I_{copy} \left( \frac{1}{n} + \frac{1}{\beta_R \cdot n} + \frac{1}{\beta_1} \right) = I_{ref}$$

$$I_{copy} = \frac{I_{ref}}{\frac{1}{n} + \frac{1}{\beta_R \cdot n} + \frac{1}{\beta_1}} \times \frac{n}{n}$$

$$I_{copy} = \frac{n \times I_{ref}}{1 + \frac{1}{\beta} + \frac{n}{\beta}}$$

$$I_{copy} = \frac{n \times I_{ref}}{1 + \frac{1}{\beta}(n+1)}$$

Ejemplo: en el circuito mostrado,  
suponga  $\beta_R = \beta_1 = 100$ ,



Determine el error en  
Icopy, producto de  
las corrientes de base.

Caso ideal:

$$I_{\text{copy}} = n \cdot I_{\text{ref}}$$

$$I_{\text{copy}} = \frac{SAE}{AE} \cdot I_{\text{ref}}$$

$$I_{\text{copy}} = 5 \times 1 \text{ mA}$$

$$I_{\text{copy}} = 5 \text{ mA}$$

Caso con error:

$$I_{\text{copy}} = \frac{n \cdot I_{\text{ref}}}{1 + \frac{1}{\beta}(n+1)}$$

$$I_{\text{copy}} = \frac{5 \cdot 1 \text{ mA}}{1 + \frac{1}{100}(5+1)}$$

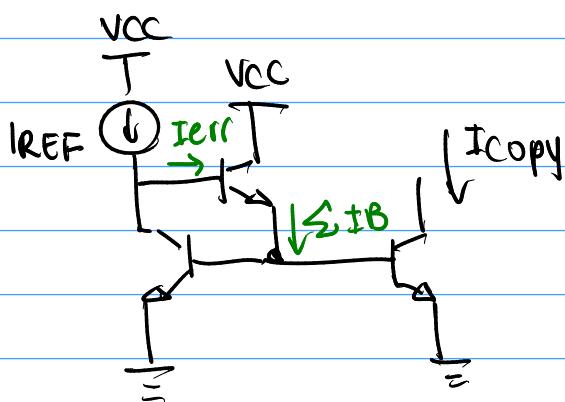
$$I_{\text{copy}} = 4.717 \text{ mA}$$

$$\% \epsilon = \frac{I_{\text{teor}} - I_{\text{err}}}{I_{\text{teor}}} \times 100\%$$

$$\% \epsilon = \frac{5 \text{ mA} - 4.717 \text{ mA}}{5 \text{ mA}} \times 100\%$$

$$\% \epsilon = 5.66\%$$

para solucionar el error por  $I_B$ ,  
se agrega otro transistor:



El transistor extra reduce  
el error por corrientes  $I_B$   
por un factor  $\beta+1$ :

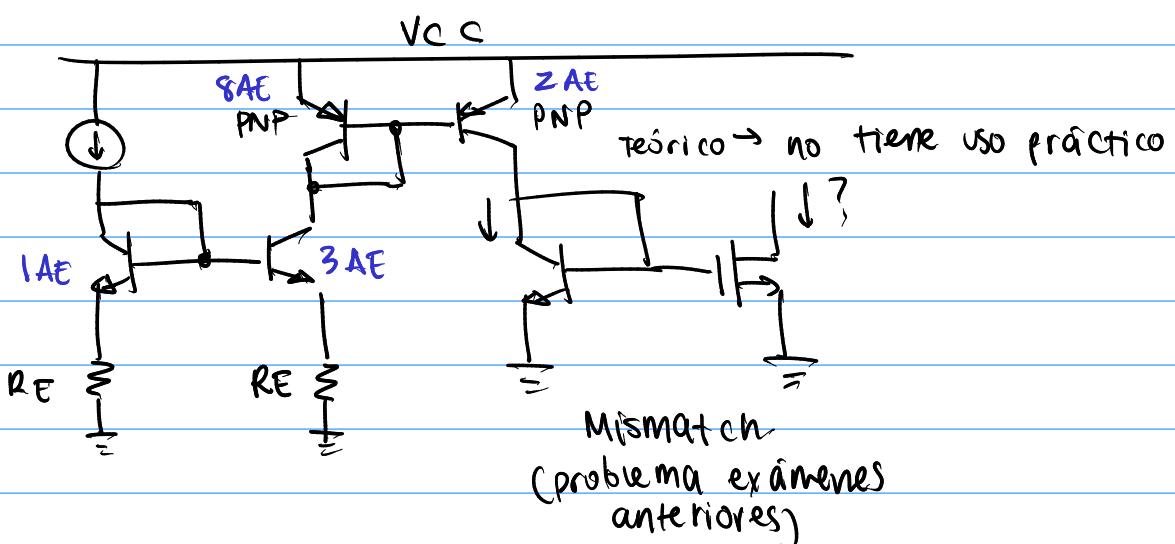
$$I_{err} = \frac{\Sigma I_B}{\beta+1}$$

$$I_{copy} = \frac{n \times I_{Ref}}{1 + \frac{1}{\beta^2} (n+1)}$$

para el problema anterior,  
si se usa esta compensación:

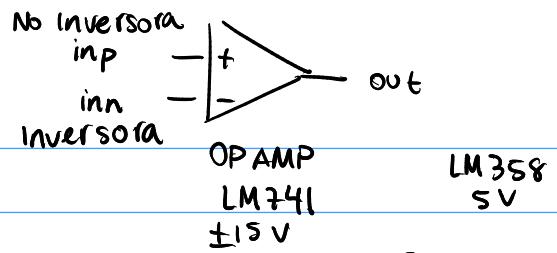
$$I_{copy} = \frac{5 \times 1mA}{1 + \frac{1}{100^2} (5+1)} = 4.997 \text{ mA}$$

$$\gamma \cdot \varepsilon = 0.06 \gamma.$$

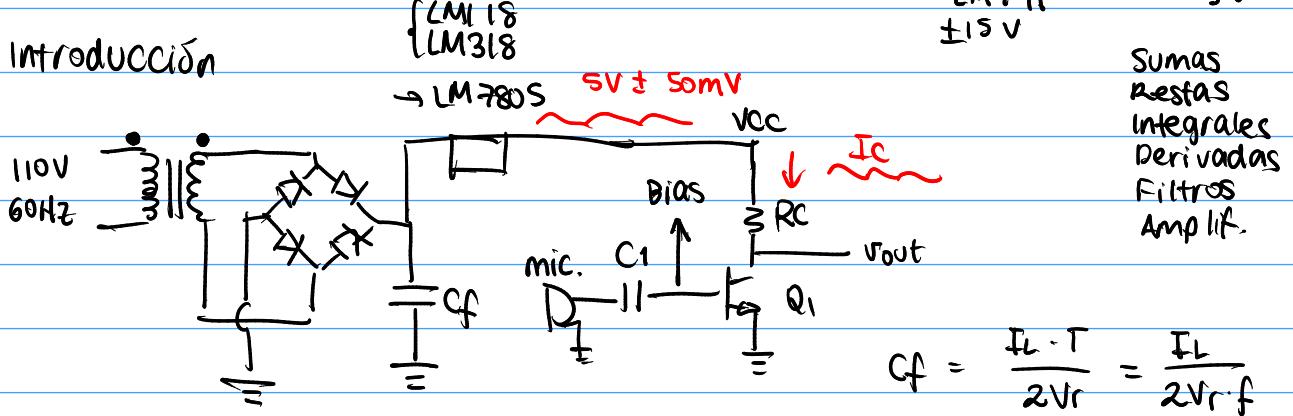


# Capítulo 10 Razavi

## Clase 16: par diferencial

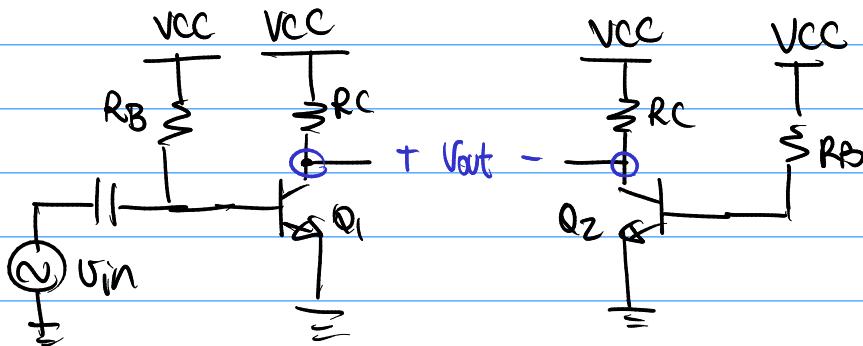


### Introducción



La salida del amplificador tiene ruido de 120 Hz.

Solución al problema de ruido:



Si ambos transistores son idénticos:

$$V_{\text{out}} = V_{C_1} - V_{C_2} \rightarrow \underline{\text{diferencia}}$$

En el colector C1:

$$\underbrace{V_{C_1}}_{CD} + \underbrace{A_V \cdot U_{\text{in}}}_{CA} + \underbrace{V_r(t)}_{\text{Ruido}}$$

Gran señal

En el colector C2:

$$V_{C_2} + \underbrace{V_r(t)}_{\text{Ruido}}$$

$$V_{\text{out}} = V_{C_1} - V_{C_2} \quad \text{se cancela el ruido!}$$

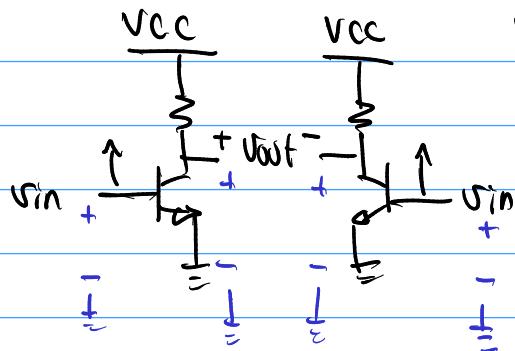
$$= V_{C_1} + A_V \cdot U_{\text{in}} + V_r(t) - V_{C_2} - V_r(t)$$

Sólo queda la ganancia.

El circuito cancela señales comunes a ambos lados.

En el circuito anterior, Q<sub>2</sub> no amplifica.

Si se conecta v<sub>in</sub> a ambos lados:



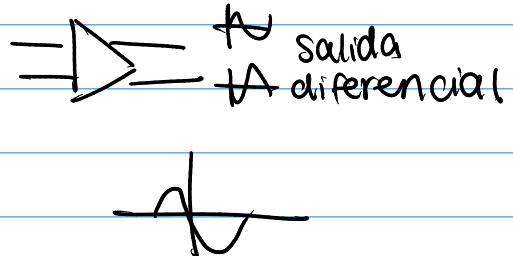
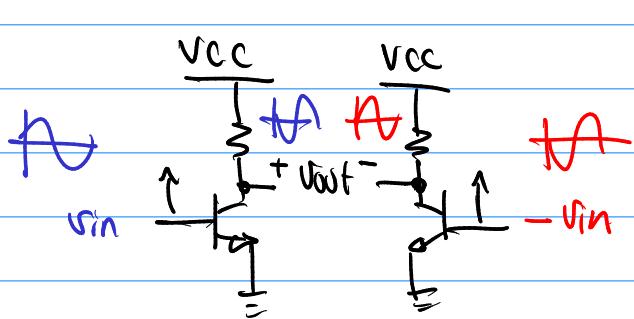
$$v_{out} = v_{C_1} - v_{C_2}$$

$$= \cancel{v_{C_1} + A_{V1} \cdot v_{in} + v_f} - (\cancel{v_{C_2} + A_{V2} \cdot (-v_{in}) + v_f}) \\ = 0 \quad (\text{IDEAL})$$

Si v<sub>in</sub> es común a ambos lados, entonces se cancela.

Señales en modo común producen salida  $\approx 0$ .

La mejor opción es conectar v<sub>in</sub> en forma diferencial.



$$v_{in} = \sin \omega t$$

$$-v_{in} = -\sin \omega t$$

$$v_{out} = v_{out1} - v_{out2}$$

$$v_{out} = A \cdot \sin(\omega t - \pi) - A \cdot \sin(\omega t)$$

$$v_{out} = -A \cdot \sin(\omega t) - A \cdot \sin(\omega t)$$

$$v_{out} = -2A \sin(\omega t) = -2A v_{in}$$

Otra forma:

$$v_{out} = v_{out1} - v_{out2}$$

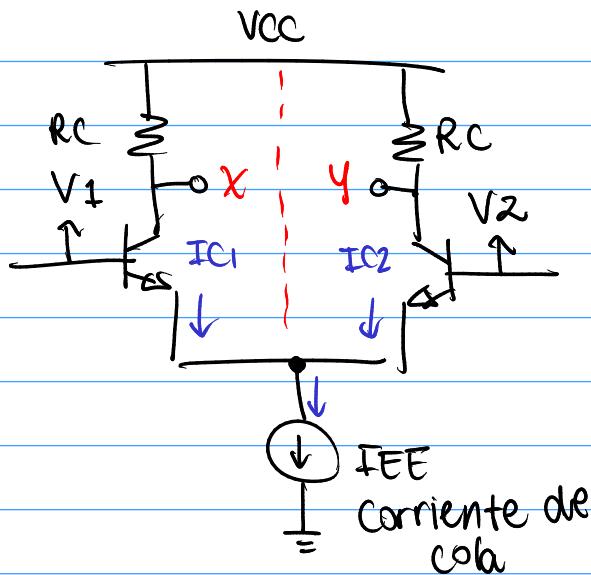
$$v_{out} = \cancel{v_{C_1} + A_v \cdot v_{in} + v_f} - (\cancel{v_{C_2} + A_v \cdot (-v_{in}) + v_f})$$

$$v_{out} = 2A_v \cdot v_{in} \Rightarrow$$

$$\boxed{\frac{v_{out}}{v_{in}} = 2A_v}$$

## Par diferencial en CD

**Simétrico**



V<sub>CM</sub>: tensión de modo común (polarización)

$$I_{C1} + I_{C2} = I_{EE}$$

En ausencia de  $V_{in}$ , el circuito está en equilibrio si  $V_1 = V_2 = V_{CM}$ .

[A]

Si las tensiones  $V_1$  y  $V_2$  son iguales, se cumple que

$$V_{CM} = V_1 = V_2$$

$$I_{C1} = I_{C2}$$

$$I_C + I_C = I_{EE}$$

$$2I_C = I_{EE}$$

$$I_C = \frac{I_{EE}}{2}$$

$$V_X = V_{CC} - I_{C1}R_C$$

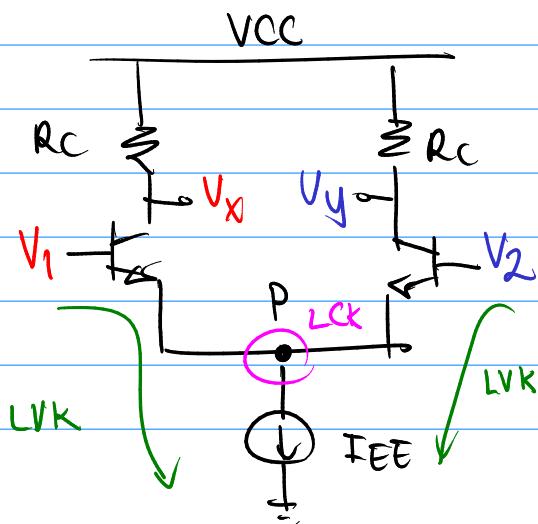
$$V_Y = V_{CC} - I_{C2}R_C$$

$$V_X = V_Y = V_{CC} - \frac{I_{EE}}{2}R_C$$

$$V_{out} = V_X - V_Y = 0$$

[B]

Si  $V_1 \neq V_2$ , se necesita hacer el análisis de gran señal para encontrar  $V_X$  y  $V_Y$ . (p 448-452)



$$V_X = V_{CC} - I_{C1} \cdot R_C$$

$$V_Y = V_{CC} - I_{C2} \cdot R_C$$

$$V_{out} = V_X - V_Y$$

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

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

$$V_1 = V_{BE1} + V_p$$

$$V_2 = V_{BE2} + V_p$$

$$V_1 - V_{BE1} = V_p = V_2 - V_{BE}$$

$$V_1 - V_t \ln \frac{I_{C1}}{I_S} = V_p = V_2 - V_t \ln \frac{I_{C2}}{I_S}$$

$$V_1 - V_2 = V_t \ln \frac{I_{C1}}{I_S} - V_t \ln \frac{I_{C2}}{I_S}$$

$$V_1 - V_2 = V_t \ln \frac{\cancel{I_{C1}/I_S}}{\cancel{I_{C2}/I_S}}$$

$$V_1 - V_2 = V_t \ln \frac{I_{C1}}{I_{C2}}$$

$$\boxed{\frac{V_1 - V_2}{V_t} = \ln \frac{I_{C1}}{I_{C2}}} *$$

$$\frac{(V_1 - V_2)/V_t}{I_{C2} e} = I_{C1}$$

$$I_{EE} = I_{C1} + I_{C2}$$

$$I_{C2} = I_{EE} - I_{C1}$$

$$(I_{EE} - I_{C1}) e^{(V_1 - V_2)/V_t} = I_{C1}$$

$$I_{EE} e^{(V_1 - V_2)/V_t} - I_{C1} e^{(V_1 - V_2)/V_t} = I_{C1}$$

$$I_{EE} e^{(V_1 - V_2)/V_t} = I_{C1} \left( 1 + e^{(V_1 - V_2)/V_t} \right)$$

$$\boxed{I_{C1} = \frac{I_{EE} \cdot e^{(V_1 - V_2)/V_t}}{1 + e^{(V_1 - V_2)/V_t}}}$$

Si  $V_1 = V_2$ ,

$$I_{C1} = \frac{I_{EE}}{2} ?$$

Retomando la ecuación \*:

$$\frac{V_1 - V_2}{Vt} = \ln \frac{I_{C_1}}{I_{C_2}}$$

$$e^{\frac{V_1 - V_2}{Vt}} = \frac{I_{C_1}}{I_{C_2}}$$

$$I_{C_2} = \frac{\frac{I_{C_1}}{(V_1 - V_2)/Vt}}{e}$$

$$I_{C_2} = \frac{IEE - I_{C_1}}{e^{(V_1 - V_2)/Vt}}$$

$$I_{C_2} \left( 1 + \frac{1}{e^{(V_1 - V_2)/Vt}} \right) = \frac{IEE}{e^{(V_1 - V_2)/Vt}}$$

$$I_{C_2} \left( e^{(V_1 - V_2)/Vt} + 1 \right) = IEE$$

$$I_{C_2} = \frac{IEE}{e^{(V_1 - V_2)/Vt} + 1}$$

Si  $V_1 = V_2$ ,

$$I_{C_2} = \frac{IEE}{2} ?$$

La tensión de salida es  $V_{out} = V_x - V_y$

$$V_{out} = -RC (I_{C_1} - I_{C_2})$$

$$V_{out} = -RC \left[ \frac{IEE \cdot e^{(V_1 - V_2)/Vt}}{e^{(V_1 - V_2)/Vt} + 1} - \frac{IEE}{e^{(V_1 - V_2)/Vt} + 1} \right]$$

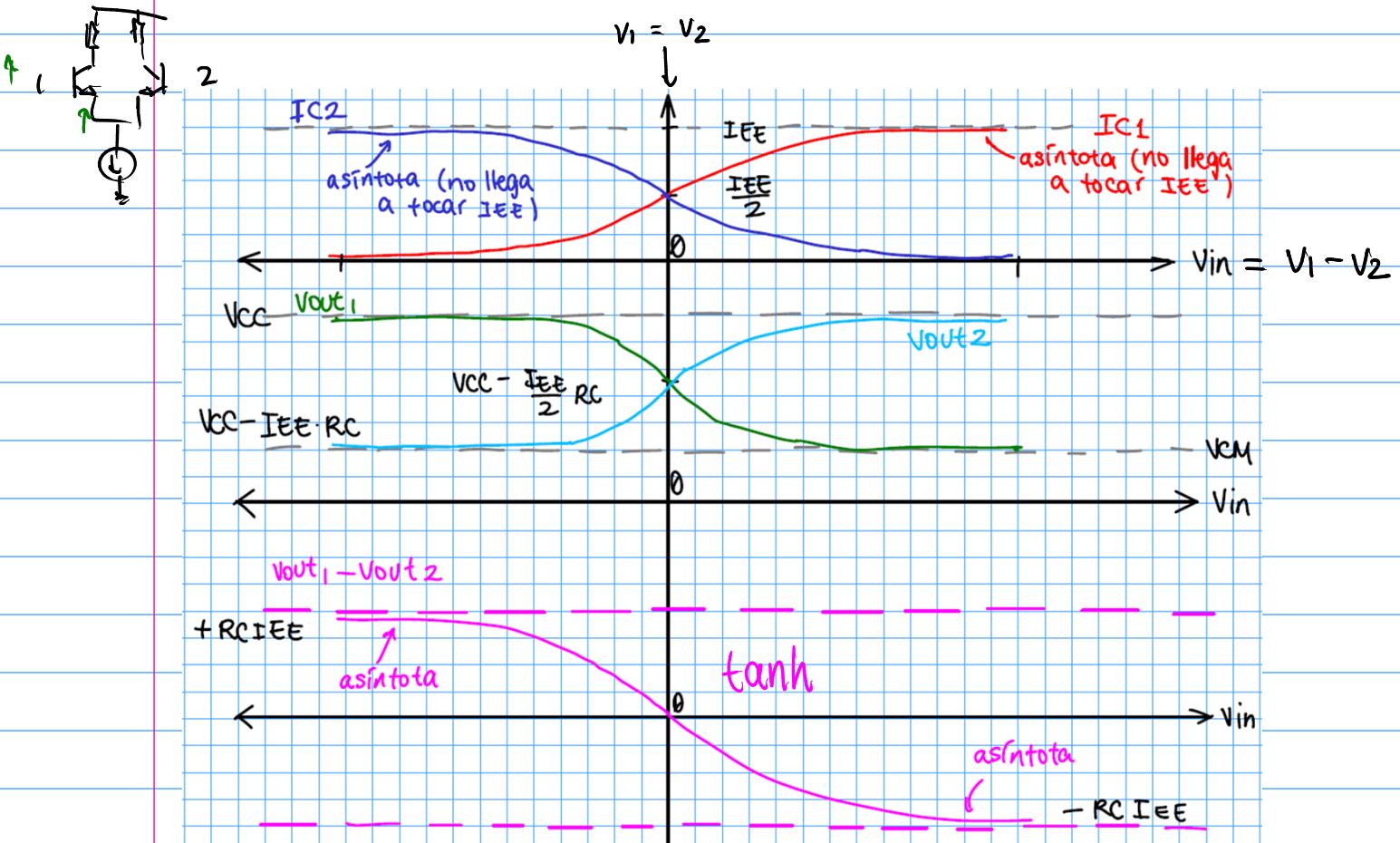
$$V_{out} = -RC IEE \left[ \frac{e^{(V_1 - V_2)/Vt} - 1}{e^{(V_1 - V_2)/Vt} + 1} \right]$$

Esta ecuación tiene la forma:

$$\frac{e^{2z} - 1}{e^{2z} + 1} = \tanh(z)$$

$V_{out} = V_x - V_y = -RC \cdot I_{EE} \cdot \tanh\left(\frac{V_1 - V_2}{2V_t}\right)$

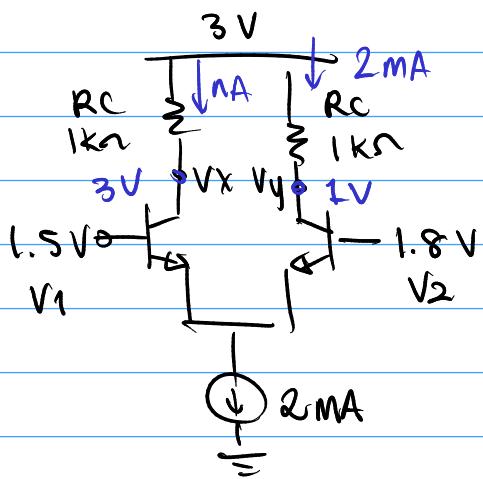
Nivel de CP en la salida si las tensiones  $V_1$  y  $V_2$  NO son iguales.



Ejemplo: Determinar  $V_{out} = V_x - V_y$

$$I_{C1} =$$

$$I_{C2} =$$



$$I_{C1} = \frac{I_{EE} \cdot e^{(V_1 - V_2)/V_t}}{1 + e^{(V_1 - V_2)/V_t}}$$

$$I_{C2} = \frac{I_{EE}}{e^{(V_1 - V_2)/V_t} + 1}$$

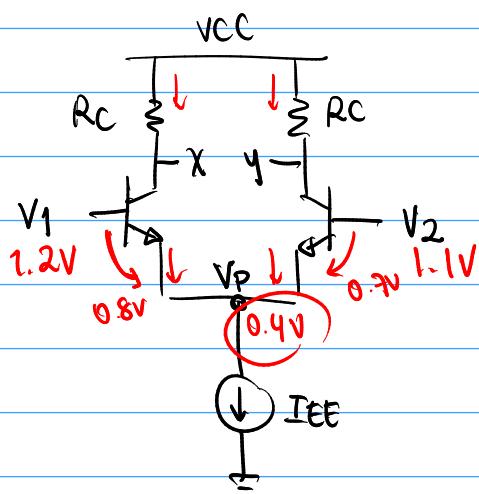
$$V_{out} = V_x - V_y = -R_C \cdot I_{EE} \cdot \tanh\left(\frac{V_1 - V_2}{2V_t}\right)$$

```

>> IC1 = 2e-3*exp((1.5-1.8)/26e-3)/(1
+ exp((1.5-1.8)/26e-3))
IC1 = 1.9496e-08
>> IC2 = 2e-3/(1 + exp((1.5-1.8)/26e-3))
IC2 = 2.0000e-03
>> Vout = -1e3*2e-3*tanh((1.5-1.8)/(2*26e-3))
Vout = 2.0000

```

## Clase 17: Par diferencial II

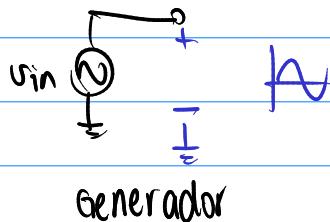


señales comunes en  $V_1$  y  $V_2$   
se cancelan a la salida.

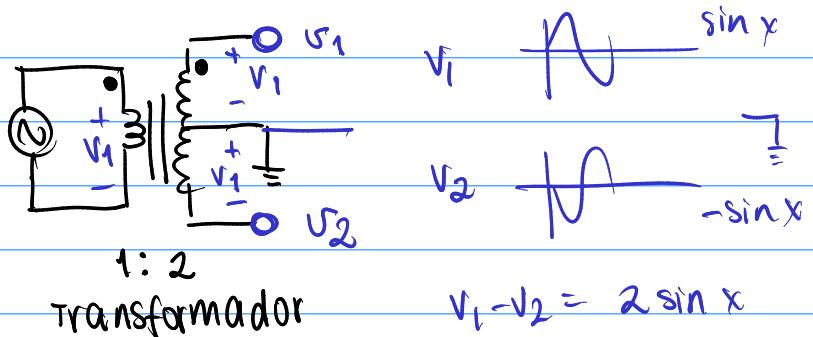
señales distintas en  $V_1$  y  $V_2$   
sí se reflejan en la salida.

Si  $V_1$  y  $V_2$  son señales  
diferenciales, la salida tiene  
ganancia máxima.

Señal modo común



señal diferencial ( $V_2 = -V_1$ )



En CD:

- Si  $V_1 = V_2 = V_{CM}$  (common mode)

se cumple  $I_{C1} = I_{C2} = \frac{I_{EE}}{2}$

$$V_x = V_y = V_{CC} - \frac{I_{EE}}{2} R_C \Rightarrow V_{out} = V_x - V_y = 0$$

- Si  $V_1 \neq V_2$  (un lado más polarizado que el otro)

$$I_{C1} = \frac{I_{EE} \cdot e^{(V_1 - V_2)/V_t}}{1 + e^{(V_1 - V_2)/V_t}}$$

$$V_{out} = -R_C I_{EE} \cdot \tanh\left(\frac{V_1 - V_2}{2V_t}\right)$$

$$I_{C2} = \frac{I_{EE}}{1 + e^{(V_1 - V_2)/V_t}}$$

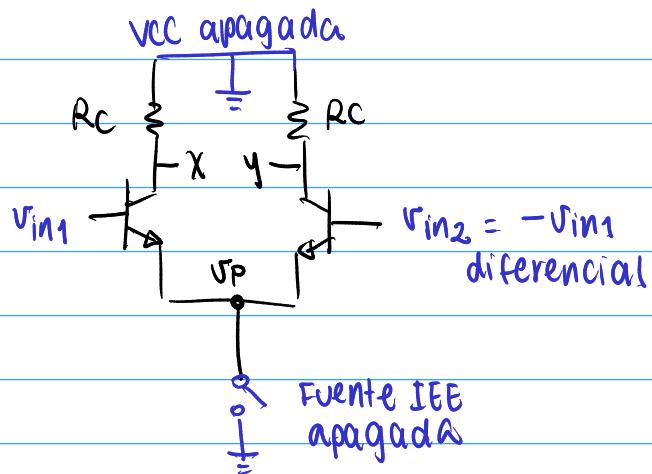
$$I_{C2} = I_{EE} - I_{C1}$$

$$V_{BE1} = V_t \ln \frac{I_{C1}}{I_{S1}}$$

$$V_{BE2} = V_t \ln \frac{I_{C2}}{I_{S2}}$$

$$V_1 - V_{BE1} = V_p = V_2 - V_{BE2}$$

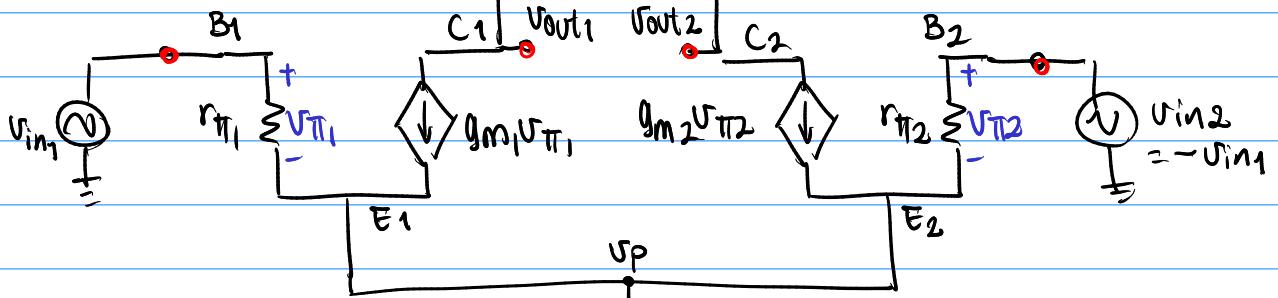
## El par diferencial en CA.



Entrada:

$$V_{in_{DM}} = V_{in_1} - V_{in_2}$$

Differential Mode



$$\Delta V_{DM} = \frac{V_{out_{DM}}}{V_{in_{DM}}} = \frac{V_{out_2} - V_{out_1}}{V_{in_2} - V_{in_1}}$$

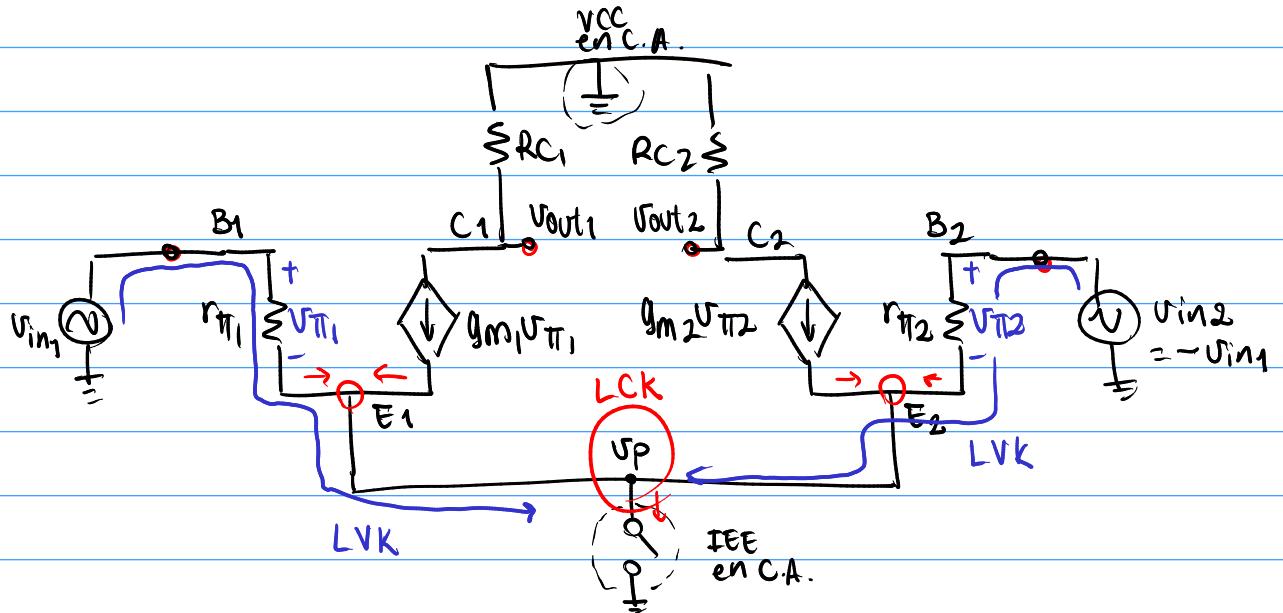
IEE en C.A.

Suponiendo que el par diferencial está equilibrado (balanceado) con  $I_{C1} = I_{C2} = \frac{IEE}{2}$

$$g_{m1} = g_{m2} = \frac{I_C}{V_t} = \frac{IEE}{2V_t}$$

$$r_{\pi 1} = r_{\pi 2} = \frac{f_{\pi 1}}{g_{m1}} = \frac{f_{\pi 2}}{g_{m2}} = \frac{\beta}{g_m}$$

## Análisis de pequeña señal:



$$LVK: \quad V_{in1} = V_{\pi_1} + V_p$$

$$V_p = V_{in1} - V_{\pi_1}$$

$$V_{in2} = V_{\pi_2} + V_p$$

$$V_p = V_{in2} - V_{\pi_2}$$

$$V_{in1} - V_{\pi_1} = V_p = V_{in2} - V_{\pi_2} \quad (1)$$

$$\text{Como } V_{in2} = -V_{in1}$$

$$V_{in1} - V_{\pi_1} = -V_{in1} - V_{\pi_2}$$

$$2V_{in1} = V_{\pi_1} - V_{\pi_2} \quad (2)$$

LCK en P:

$$\frac{V_{\pi_1}}{r_{\pi_1}} + g_m V_{\pi_1} + \frac{V_{\pi_2}}{r_{\pi_2}} + g_m V_{\pi_2} = 0 \quad (3)$$

$$\text{Como } g_m = g_m \text{ y } r_{\pi_1} = r_{\pi_2} = r_{\pi}$$

$$\frac{V_{\pi_1}}{r_{\pi}} + g_m V_{\pi_1} + \frac{V_{\pi_2}}{r_{\pi}} + g_m V_{\pi_2} = 0$$

Factorizando:

$$v_{\pi_1} \left( \frac{1}{r_{\pi}} + g_m \right) + v_{\pi_2} \left( \frac{1}{r_{\pi}} + g_m \right) = 0$$
$$\cancel{v_{\pi_1} \left( \frac{1}{r_{\pi}} + g_m \right)} = - \cancel{v_{\pi_2} \left( \frac{1}{r_{\pi}} + g_m \right)}$$
$$v_{\pi_1} = -v_{\pi_2} \quad (4)$$

Sustituyendo (4) en (2):

$$2v_{in_1} = v_{\pi_1} - (-v_{\pi_1})$$

$$2v_{in_1} = 2v_{\pi_1}$$

$$v_{in_1} = v_{\pi_1}$$

$$v_{in_2} = v_{\pi_2}$$

Sustituyendo en la ec. (1):

$$v_{in_1} - v_{\pi_1} = v_p = v_{in_2} - v_{\pi_2}$$

$$v_{in_1} - v_{in_1} = v_p = v_{in_2} - v_{in_2}$$

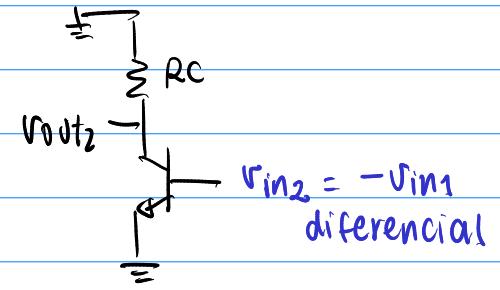
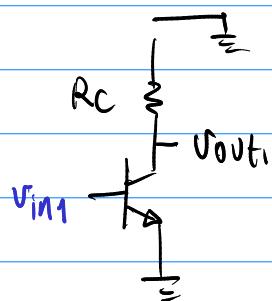
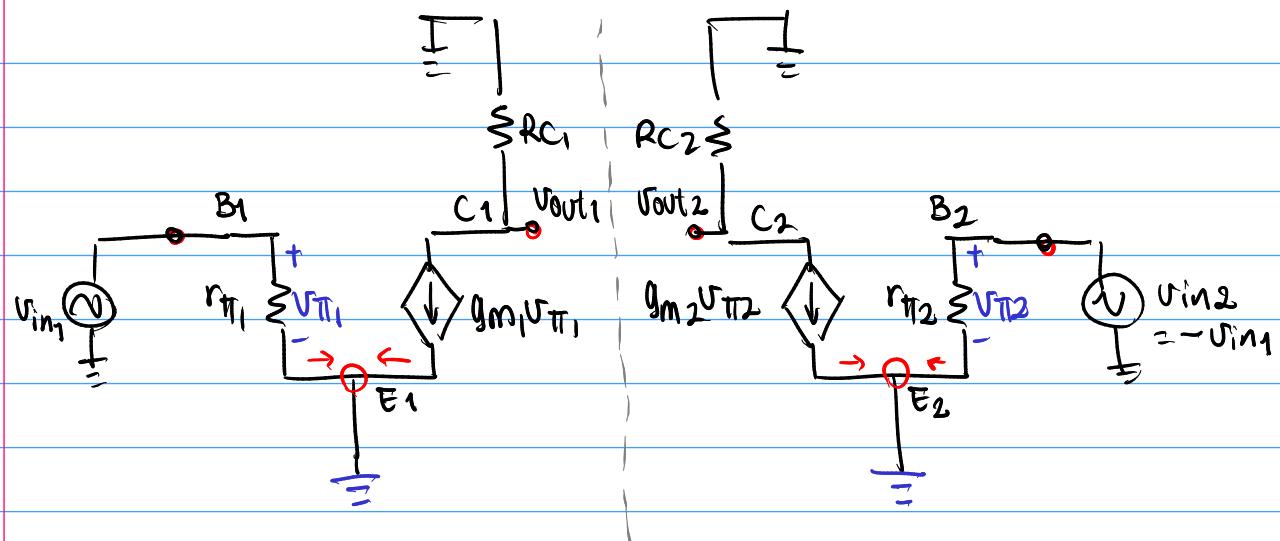
$$0 = v_p = 0$$

$$v_p = 0$$

$\Rightarrow v_p$  es una tierra virtual en C.A.  
Tiene  $\emptyset$  V en C.A.

$\Rightarrow v_p$  NO es tierra en C.D.  
NO tiene  $\emptyset$  V en C.D.

La tierra virtual permite partir el circuito en dos:



$$V_{out1} = -g_m R_C V_{in1}$$

$$V_{out2} = -g_m R_C V_{in2}$$

$$V_{out1} - V_{out2} = -g_m R_C V_{in1} - (-g_m R_C V_{in2})$$

$$V_{out1} - V_{out2} = -g_m R_C (V_{in1} - V_{in2})$$

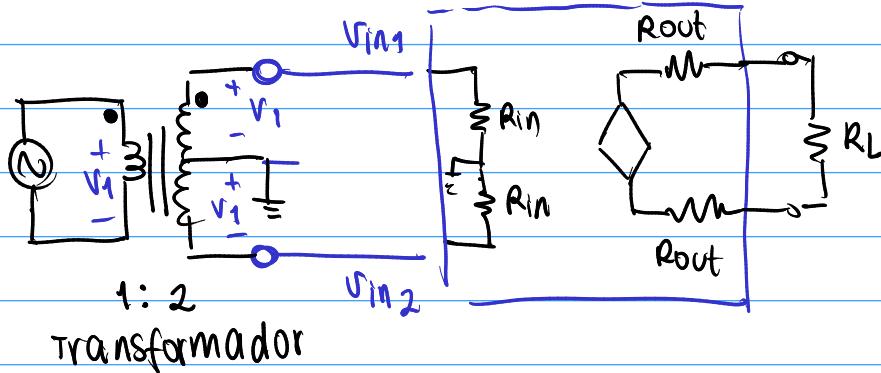
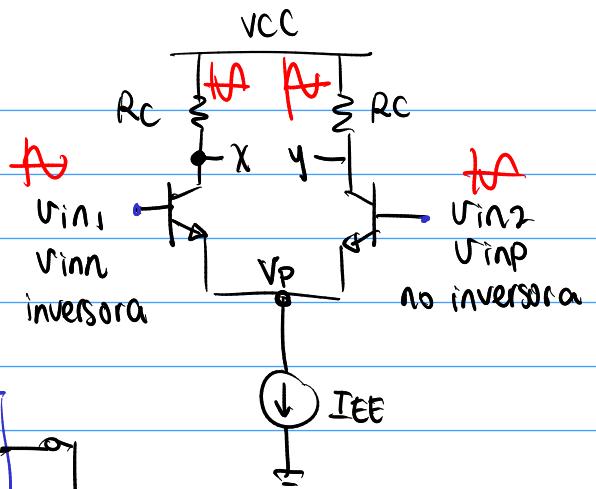
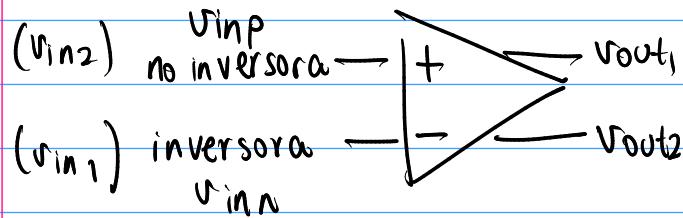
$$A_{V_{DM}} = \frac{V_{out1} - V_{out2}}{V_{in1} - V_{in2}} = -g_m R_C$$

Si se sustituye  $V_{in2} = -V_{in1}$  y  $V_{out2} = -V_{out1}$ :

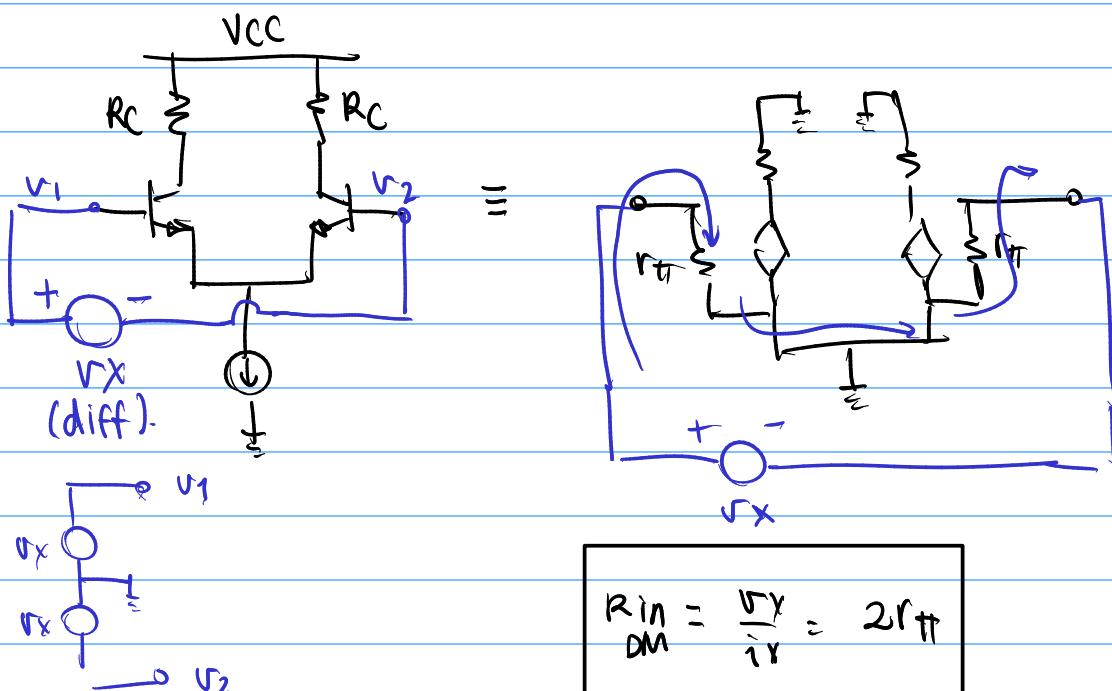
$$A_V = \frac{V_{out1} - (-V_{out1})}{V_{in1} - (-V_{in1})} = \frac{2V_{out1}}{2V_{in1}} = \frac{V_{out1}}{V_{in1}} = -g_m R_C$$

Es la ganancia de modo común de 1/2 circuito.

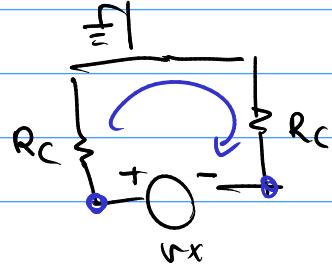
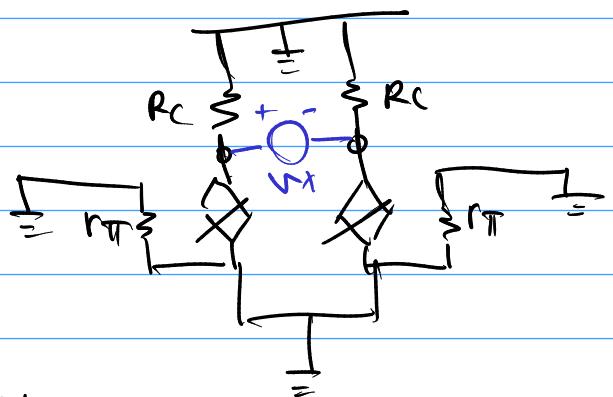
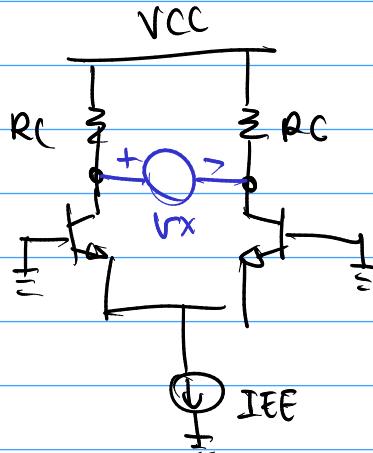
## El par diferencial:



## Impedancia de entrada:

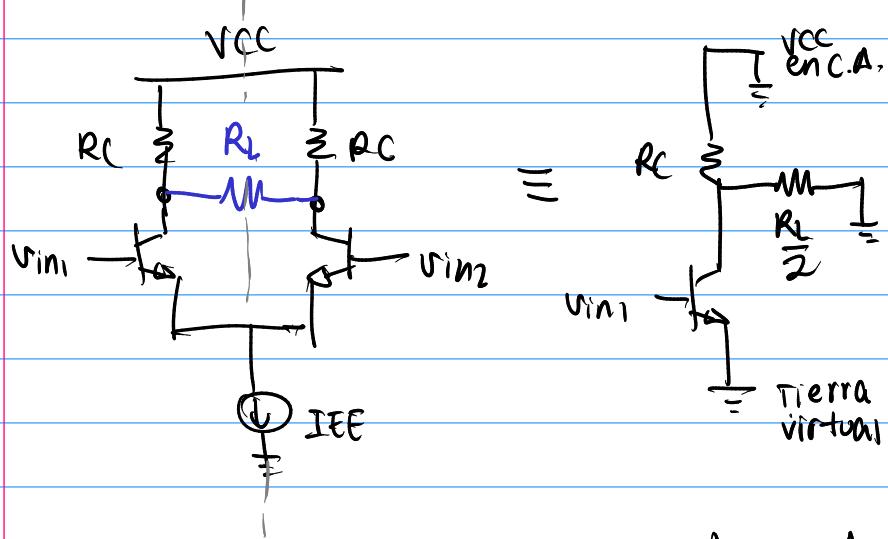


## Impedancia de salida



$$R_{out} = 2 R_C$$

Circuito con carga  $R_L$ :

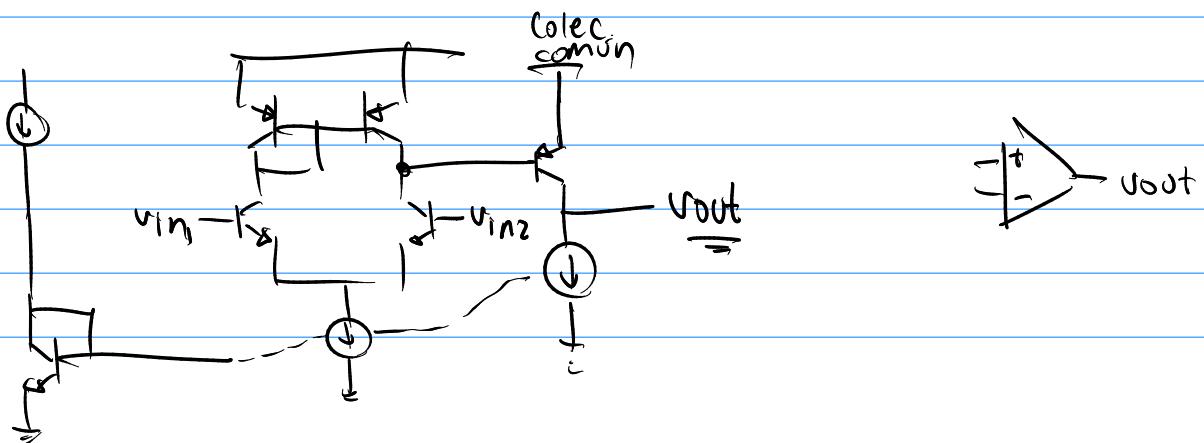


$$A_{VDM} = A_{VCM} v_2$$

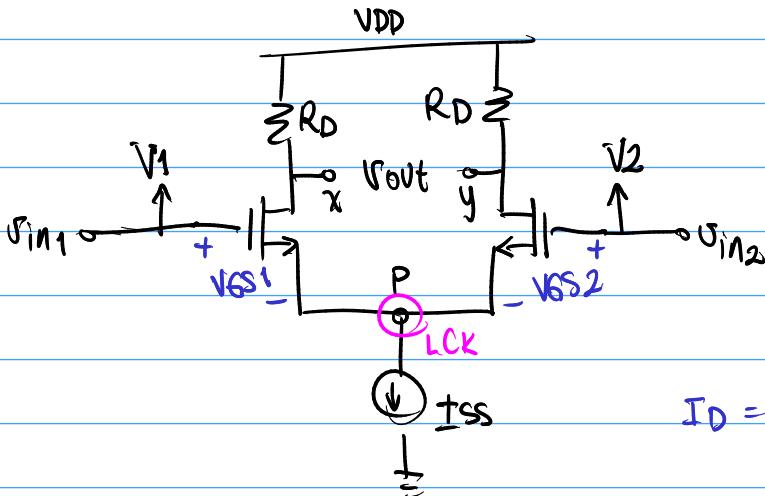
1/2 Circuito,

$$A_{VDM} = -g_m (R_C \parallel \frac{R_L}{2})$$

spoiler: clase 18-19.



## Clase 18: Par Diferencial MOSFET



Polarización

- OP
- step
- dc

→ CA

Ganancias ✓ | respuesta de frecuencia ✓

$$V_{in2} = -V_{in1}$$

Entrada diferencial

En saturación

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

$$V_{GS} = \sqrt{\frac{2ID}{\mu_n C_{ox} \frac{W}{L}}} + V_{TH}$$

Análisis de gran señal

$$V_x = VDD - ID_1 RD$$

$$V_y = VDD - ID_2 RD$$

$$V_{out} = V_x - V_y$$

$$V_{out} = VDD - ID_1 RD - (VDD - ID_2 RD)$$

$$V_{out} = -RD (ID_1 - ID_2)$$

$$LVK: \quad V_1 = V_{GS1} + V_p$$

$$V_p = V_1 - V_{GS1}$$

$$V_2 = V_{GS2} + V_p$$

$$V_p = V_2 - V_{GS2}$$

$$V_1 - V_{GS1} = V_p = V_2 - V_{GS2}$$

$$V_1 - \left( \sqrt{\frac{2ID_1}{\mu_n C_{ox} \frac{W_1}{L_1}}} + V_{TH1} \right) = V_p = V_2 - \left( \sqrt{\frac{2ID_2}{\mu_n C_{ox} \frac{W_2}{L_2}}} + V_{TH2} \right) [1]$$

$$LCK \text{ en } P: \quad ID_1 + ID_2 = ISS \quad [2]$$

$$V_1 - \sqrt{\frac{2ID_1}{K_1}} - V_{TH1} = V_2 - \sqrt{\frac{2(ISS-ID_1)}{K_2}} - V_{TH2}$$

se despeja  $ID_1$

$$V_1 - V_2 + \cancel{V_{TH2} - V_{TH1}} = \sqrt{\frac{2ID_1}{K_1}} - \sqrt{\frac{2(ISS - ID_1)}{K_2}} \quad [3]$$

Elevando al cuadrado:

$$(V_1 - V_2)^2 = \frac{2ID_1}{K_1} - 2\sqrt{\frac{4ID_1(ISS - ID_1)}{K_1 K_2}} + \frac{2(ISS - ID_1)}{K_2}$$

$$\begin{aligned} (V_1 - V_2)^2 - 2\frac{ID_1}{K} - 2\frac{(ISS - ID_1)}{K} &= -2 \cdot \frac{2}{K} \cdot \sqrt{ID_1(ISS - ID_1)} \\ -\frac{K}{4}(V_1 - V_2)^2 + \frac{ID_1}{2} + \frac{ISS - ID_1}{2} &= \sqrt{ID_1(ISS - ID_1)} \end{aligned}$$

Elevando al cuadrado

$$\left[ \frac{ISS}{2} - \frac{K}{4}(V_1 - V_2)^2 \right]^2 = ID_1(ISS - ID_1)$$

$$ID_1^2 - ID_1 ISS + \left[ \frac{ISS}{2} - \frac{K}{4}(V_1 - V_2)^2 \right]^2 = 0$$

$$a = 1$$

$$b = -ISS$$

$$c = \left[ \frac{ISS}{2} - \frac{K}{4}(V_1 - V_2)^2 \right]^2$$

$$ID_1 = \frac{-b \pm \sqrt{\Delta}}{2a} \quad \Delta = b^2 - 4 \cdot a \cdot c$$

$$ID_1 = \frac{ISS}{2} \pm \frac{\sqrt{ISS^2 - 4 \cdot 1 \cdot \left[ \frac{ISS}{2} - \frac{K}{4}(V_1 - V_2)^2 \right]^2}}{2}$$

$$ID_1 = \frac{ISS}{2} \pm \sqrt{\frac{ISS^2}{4} - \left[ \frac{ISS}{2} - \frac{K}{4}(V_1 - V_2)^2 \right]^2}$$

Se retoma la ec [1]:

$$V_1 - \sqrt{\frac{2(I_{SS} - I_{D2})}{\mu_n C_{ox} \frac{W_1}{L_1}}} = V_2 - \sqrt{\frac{2I_{D2}}{\mu_n C_{ox} \frac{W_2}{L_2}}}$$

$$V_2 - V_1 = \sqrt{\frac{2I_{D2}}{\kappa}} - \sqrt{\frac{2(I_{SS} - I_{D2})}{\kappa}}$$

:

tiene la misma forma que [3],  
con  $V_2 - V_1$  en lugar de  $V_1 - V_2$ .

$$I_{D2} = \frac{I_{SS}}{2} \pm \sqrt{\frac{I_{SS}^2}{4} - \left[ \frac{I_{SS}}{2} - \frac{\kappa}{4}(V_2 - V_1)^2 \right]^2}$$

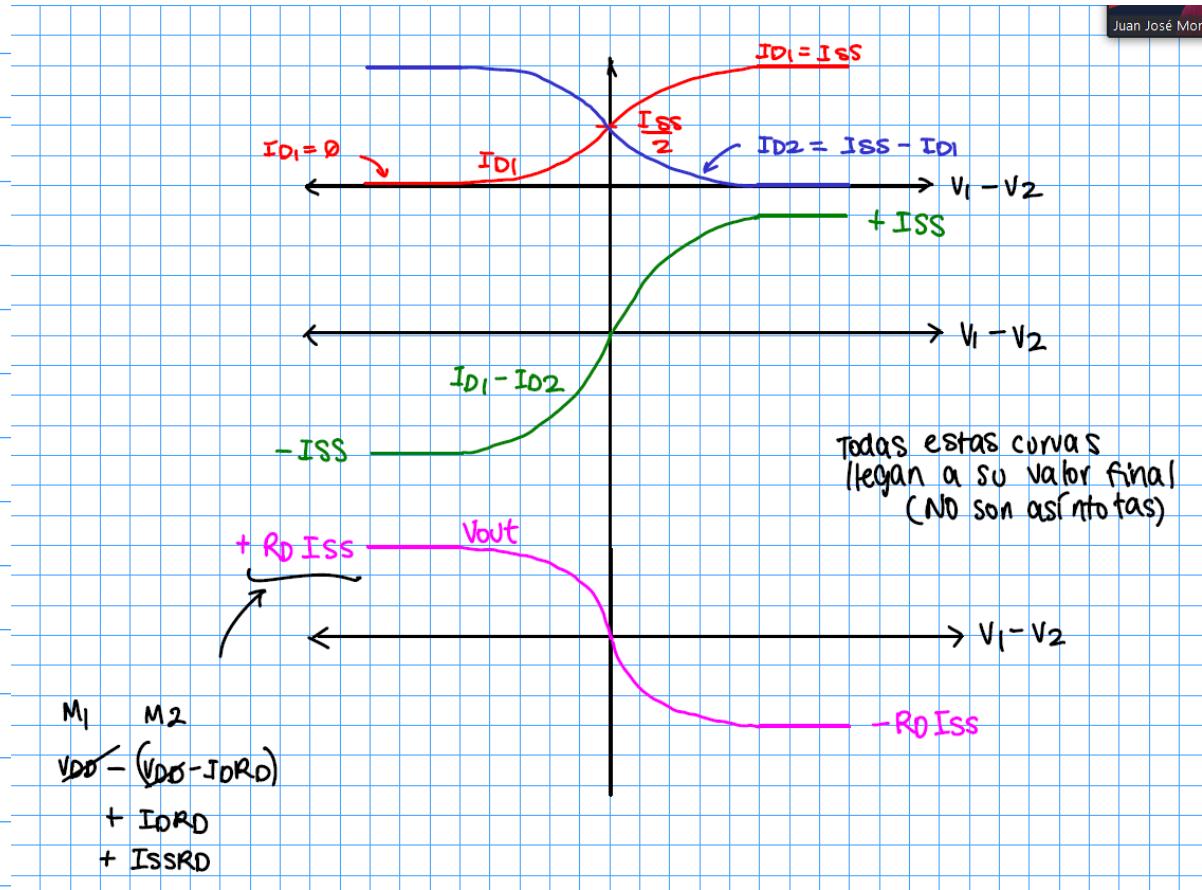
$$0 \leq I_{D1} \leq I_{SS}$$

$$0 \leq I_{D2} \leq I_{SS}$$

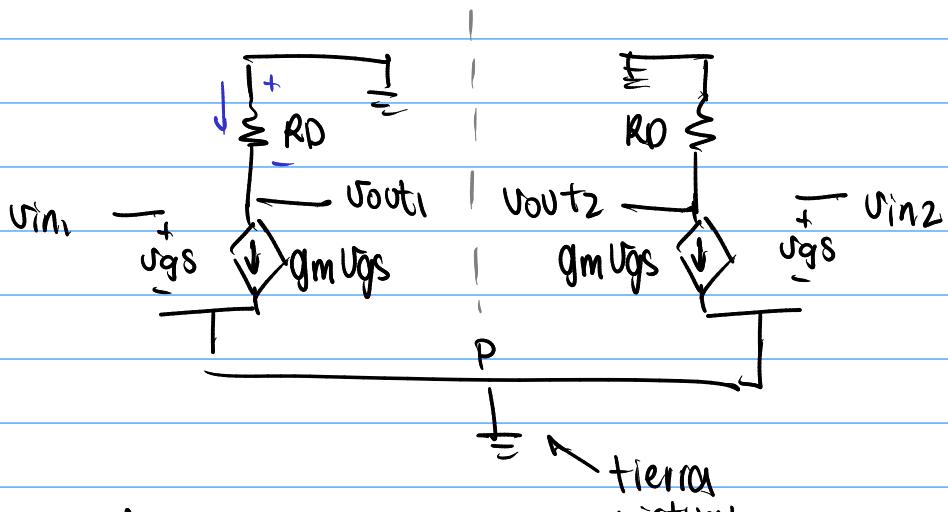
$$V_{out} = -R_o(I_{D1} - I_{D2})$$



sustituir ambas  
ecuaciones ...



Análisis de pequeña señal  
suponiendo  $V_1 = V_2 = V_{CM}$



$$V_{out1} = -g_m V_{in1} R_D$$

$$V_{out2} = -g_m V_{in2} R_D$$

$$V_{out1} - V_{out2} = -g_m V_{in1} R_D + g_m V_{in2} R_D$$

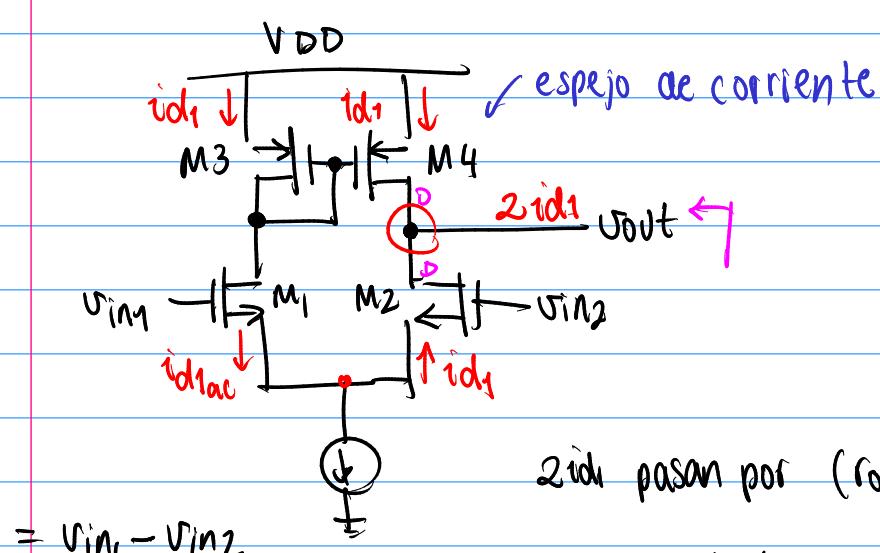
$$V_{out1} - V_{out2} = -g_m R_D (V_{in1} - V_{in2})$$

$$A_{V_{DM}} = \frac{V_{out1} - V_{out2}}{V_{in1} - V_{in2}} = -g_m R_D$$

$$R_{in} = \infty$$

$$R_{out} = 2 R_D$$

Par diferencial con carga activa



$I_{D3} = I_{D4}$   
más estable  $\Delta V_1 \Delta V_2$   
siempre balanceado

$$= V_{in1} - V_{in2}$$

$$= V_{in1} - (-V_{in1})$$

$$2V_{in1}$$

$$V_{out} = 2id_1 (r_{o2} // r_{o4})$$

$$V_{out} = 2 g_m V_{in1} (r_{o2} // r_{o4})$$

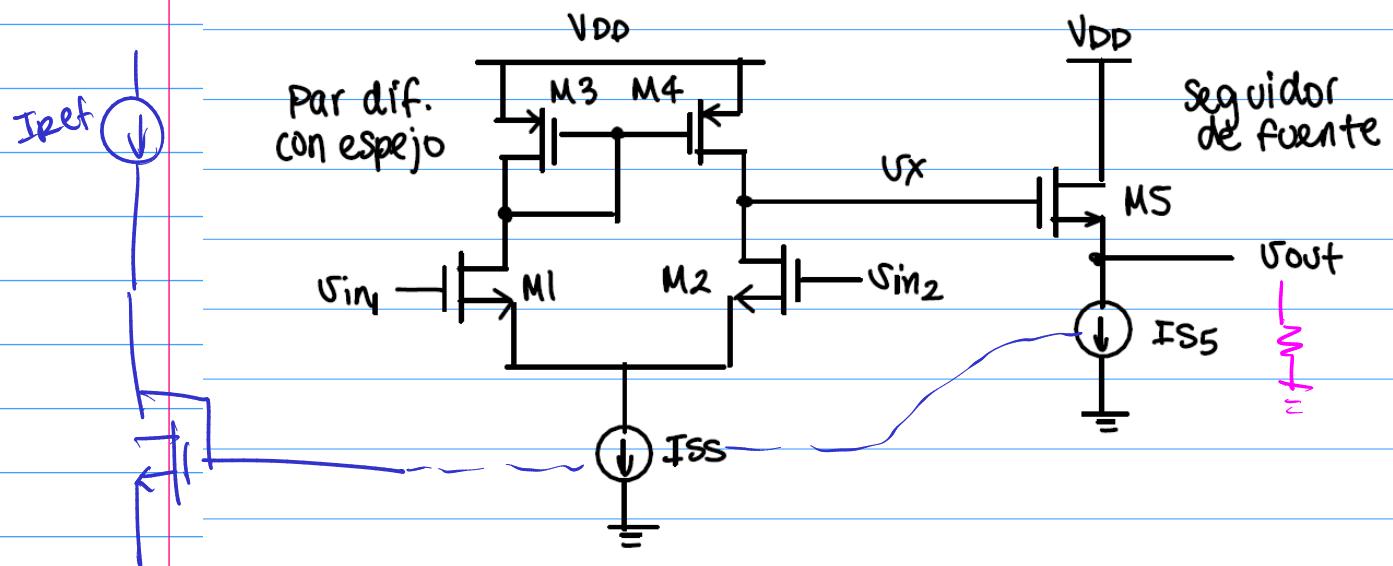
$$A_{V_{DM-CM}} = \frac{V_{out}}{V_{in1} - V_{in2}} = g_m (r_{o2} // r_{o4})$$

$$r_o = \frac{1}{2 \tau D}$$

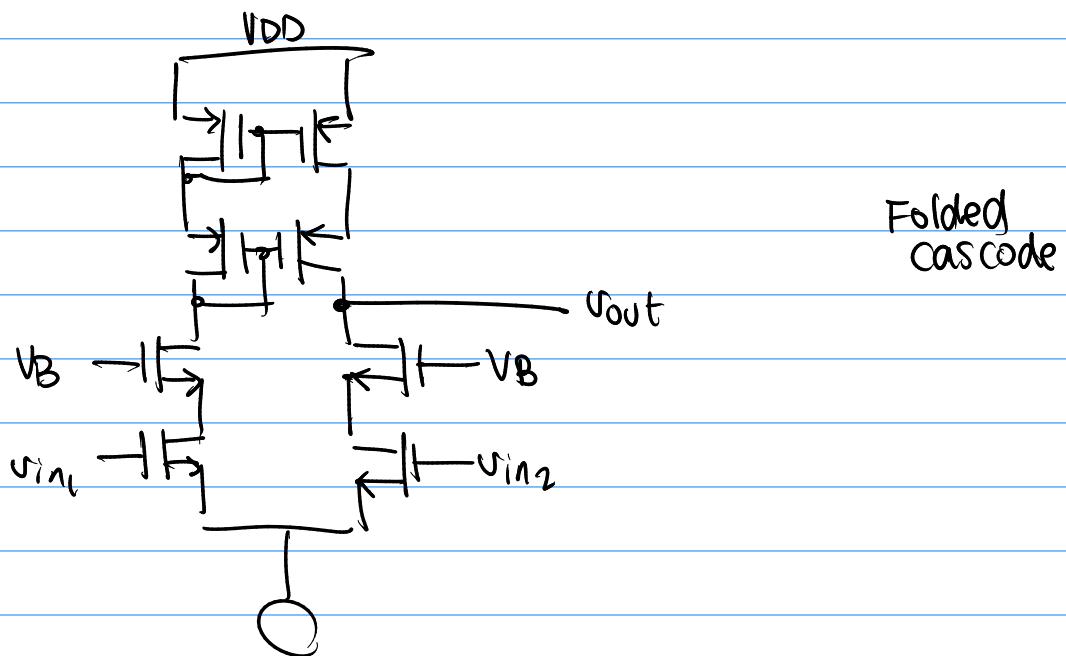
$$0.01 \text{ V}^{-1}$$

$$0.1 \text{ V}^{-1}$$

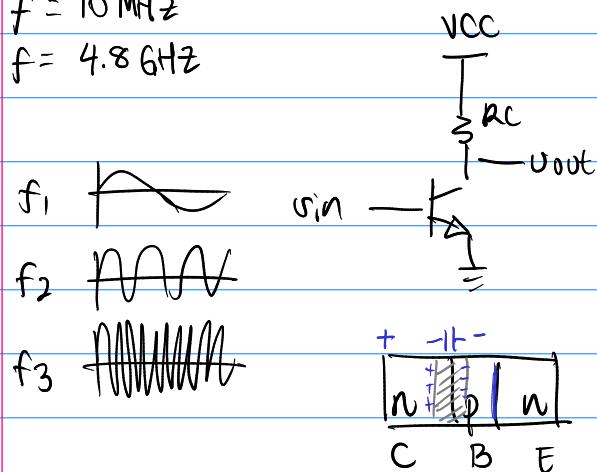
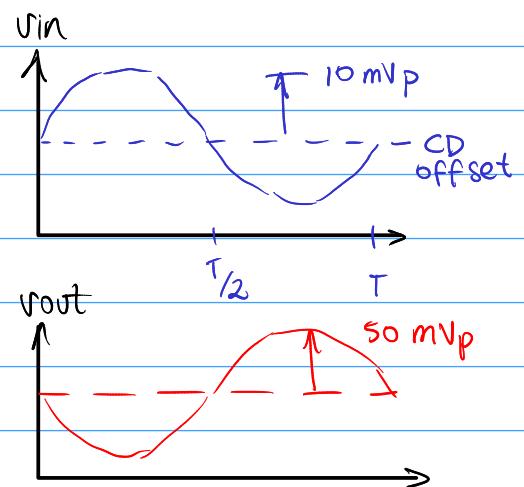
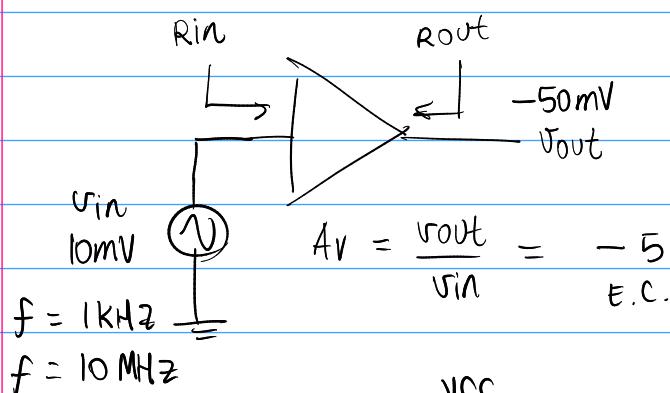
## Amplificador Operacional completo



Amp. op. cascode telescopico



## Clase 19: Respuesta en frecuencia



$$\frac{1}{T} X_C = \frac{1}{j\omega C}$$

Los amplificadores pierden ganancia cuando aumenta la frecuencia.

## Análisis de respuesta en frecuencia

• OP

• STEP

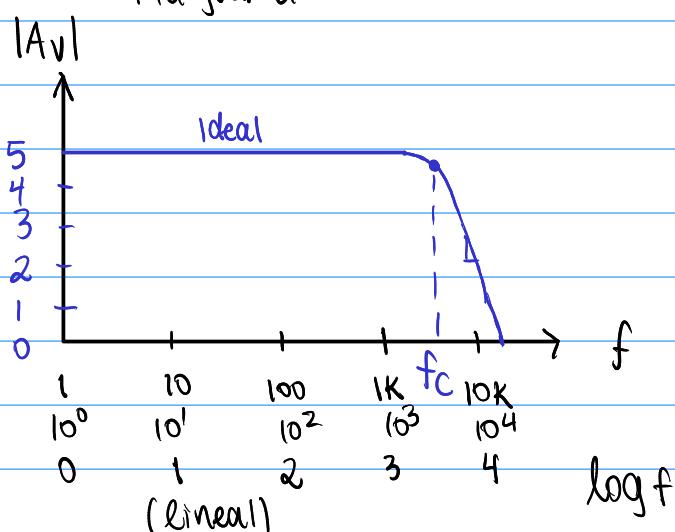
• TRAN

• DC

• AC

Respuesta en frecuencia

Diagrama de Bode

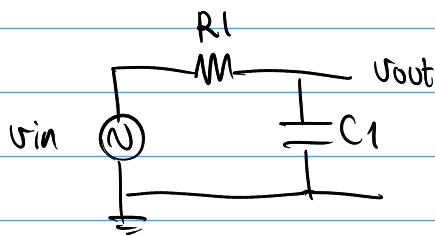


$$V_{out} = A_v \cdot V_{in}$$

$$A_v(\omega)$$

## Circuito RC (filtro pasivo)

$$\omega = 2\pi f$$



Paso bajo



$$X_C = \frac{1}{j\omega C_1}$$

$$CD: \omega \rightarrow 0$$

$$X_C \rightarrow \infty$$

Obtenga una ecuación para  $AV(\omega)$

$$U_{out} = \frac{U_{in} \times \frac{1}{j\omega C_1}}{R_1 + \frac{1}{j\omega C_1}}$$

$$AV(\omega) = \frac{U_{out}}{U_{in}} = \frac{\frac{1}{j\omega C_1}}{R_1 + \frac{1}{j\omega C_1}}$$

$$AV(j\omega) = \frac{\frac{1}{j\omega C_1}}{R_1 + \frac{1}{j\omega C_1}} \times \frac{j\omega C_1}{j\omega C_1} = \frac{1}{j\omega R_1 C_1 + 1}$$

$$s = j\omega$$

$H(j\omega)$  en forma canónica

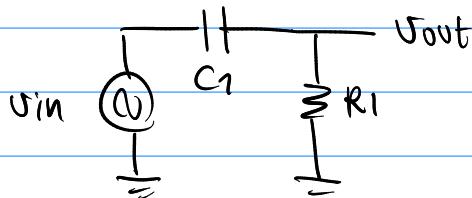
$$H(j\omega) = \frac{A_0 \cdot \left(1 + \frac{j\omega}{\omega_{z1}}\right) \left(1 + \frac{j\omega}{\omega_{z2}}\right) \dots}{\left(1 + \frac{j\omega}{\omega_{p1}}\right) \left(1 + \frac{j\omega}{\omega_{p2}}\right) \dots}$$

ceros

polos

+1: forma canónica

## Circuito paso altas



$$U_{out} = \frac{U_{in} \times R_1}{\frac{1}{j\omega C_1} + R_1}$$

$$AV(j\omega) = \frac{U_{out}}{U_{in}} = \frac{R_1}{\frac{1}{j\omega C_1} + R_1} \times \frac{j\omega C_1}{j\omega C_1}$$

$$AV(j\omega) = \frac{j\omega C_1 R_1}{1 + j\omega C_1 R_1}$$

los términos que multiplican  
a  $j\omega$  son el inverso de los  
polos.

pasa bajas

$$H(j\omega) = \frac{1}{j\omega R_1 C_1 + 1}$$

pasa altas

$$H(j\omega) = \frac{j\omega R_1 C_1}{j\omega R_1 C_1 + 1}$$

$$j\omega R_1 C_1 = \frac{j\omega}{\omega_{p1}}$$

$$\omega_{p1} = \frac{1}{R_1 C_1}$$

$$\frac{j\omega}{1/(R_1 C_1)} = \left( \frac{j\omega}{\frac{1}{R_1 C_1}} \right) j\omega R_1 C_1$$

$\rightarrow j\omega R_1 C_1$  es cero  
sólo si  $j\omega = 0$

$\rightarrow$  cero en el  
origen.

$$\omega_{p1} = \frac{1}{R_1 C_1}$$

$$f_{p1} = \frac{\omega_{p1}}{2\pi} = \frac{1}{2\pi R_1 C_1}$$

Reglas de Bode:

$$s = j\omega$$

$$H(s) = \frac{A_0 \cdot (1 + \frac{s}{\omega_{z1}}) \cdots}{(1 + \frac{s}{\omega_{p1}}) \cdots}$$

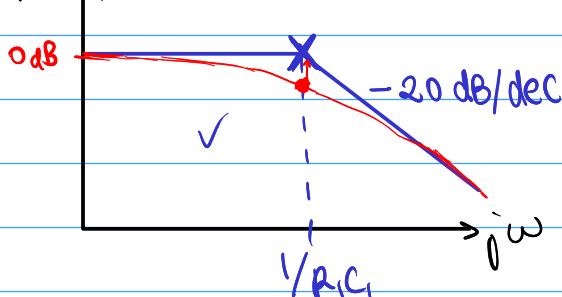
1. Cada cero incrementa  
la pendiente de  $H(s)$   
en  $+20$  dB/dec

2. Cada polo disminuye  
la pendiente de  $H(s)$   
en  $-20$  dB/dec

Pasa bajas

$$H(j\omega) = \frac{1}{j\omega R_1 C_1 + 1}$$

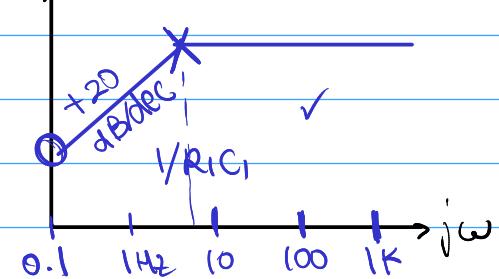
|Av|



Pasa altas

$$H(j\omega) = \frac{j\omega R_1 C_1}{j\omega R_1 C_1 + 1}$$

|Av|



- No tiene ceros

• Tiene un polo en  $\omega_p = \frac{1}{R_1 C_1}$

- Cero en origen

• Polo en  $\omega_p = \frac{1}{R_1 C_1}$

La ganancia se puede expresar en unidades lineales:

$$AV = \frac{V_{out}}{V_{in}}$$

$$\frac{50mV}{10mV} = \boxed{5} \text{ V/V}$$

Definición de ganancia (dB) para potencias:

$$A_p \text{ dB} = 10 \cdot \log \frac{P_2}{P_1}$$

→  $P_2$ : potencia de salida (W)

→  $P_1$ : potencia de entrada (W)

$$10mW \rightarrow 50mW$$

$$AP_{dB} = 10 \cdot \log \frac{50mW}{10mW}$$

$$A_p = \frac{P_2}{P_1} = \frac{50mW}{10mW} = 5$$

$$AP_{dB} = 10 \log 5$$

$$AP_{dB} = 6.99 \text{ dB}$$

Definición de ganancia (dB) para tensiones:

$$AV_{dB} = 10 \cdot \log \frac{V_o^2 / R}{V_i^2 / R}$$

potencia por una carga

$$P = I \cdot V$$

$$P = \frac{V}{R} \cdot V$$

$$P = V^2 / R$$

$$AV_{dB} = 20 \cdot \log |AV|$$

Si  $AV = 5$ ,

$$AV_{dB} = 20 \log 5 = 13.98 \text{ dB}$$

$$\text{dBm} : 10 \log \frac{P}{1 \text{ mW}}$$

Conversión de dB a unidades lineales:

$$Av_{\text{dB}} = 14 \text{ dB} \rightarrow |Av| ?$$

$$Av_{\text{dB}} = 20 \log |Av|$$

¿Qué significa  
o dB?

$$\frac{Av_{\text{dB}}}{20} = \frac{\log |Av|}{10} \rightarrow Av = 10^{(\frac{Av_{\text{dB}}}{20})}$$

$$Av = 1$$

$$Av = 10^{(Av_{\text{dB}}/20)}$$

¿Qué significa  
-3 dB?

$$Av = 10^{(14 \text{ dB}/20 \text{ dB})}$$

$$\rightarrow Av = 10^{(-3/20)}$$

$$Av = 5.0119$$

$$Av = 0.707$$

$$Av = \frac{1}{\sqrt{2}}$$

para el pasa bajas:

$$\omega_c = \frac{1}{R_1 C_1} \quad |H(j\omega)| = \frac{1}{\sqrt{1^2 + (\omega R_1 C_1)^2}} = \frac{1}{\sqrt{2}}$$

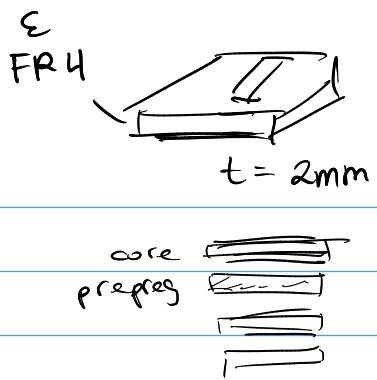
$$= \frac{1}{\sqrt{1^2 + (\omega R_1 C_1)^2}} = \frac{1}{\sqrt{2}}$$

$$\sqrt{1^2 + \omega^2 R_1^2 C_1^2} = \sqrt{2}$$

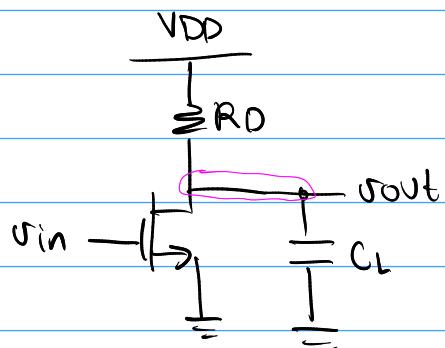
$$1^2 + \omega^2 R_1^2 C_1^2 = 2$$

$$\omega^2 R_1^2 C_1^2 = 1$$

$$\omega = \frac{1}{R_1 C_1}$$

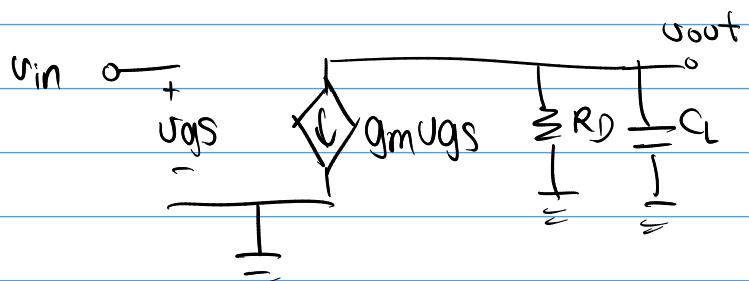


respuesta en frecuencia: fuente común



$C_L$  es la capacitancia total en el nodo de salida.

función de transferencia:

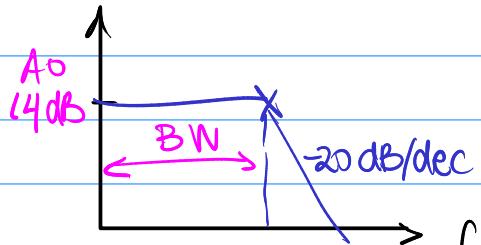


$$v_{in} = v_{gs} \quad g_m v_{gs} + \frac{v_{out}}{R_D // X_{CL}} = 0$$

$$AV = -g_m (R_D // X_{CL})$$

$$AV = -g_m \cdot \frac{R_D \times \frac{1}{j\omega C_L} \times j\omega C_L}{R_D + \frac{1}{j\omega C_L} j\omega C_L}$$

$|AV_{dB}|$



$$f_p = \frac{1}{2\pi R_D C_L}$$

$$AV = -\frac{g_m \cdot R_D}{j\omega C_L R_D + 1} \cdot \underbrace{\omega_p}_{wp} A_0$$

$$A_{dB} = 20 \log |-g_m R_D|$$

$A_0$ : ganancia de banda plana

BW: Bandwidth: Ancho de banda

GBP: Gain-bandwidth product  
es CONSTANTE en un circuito.

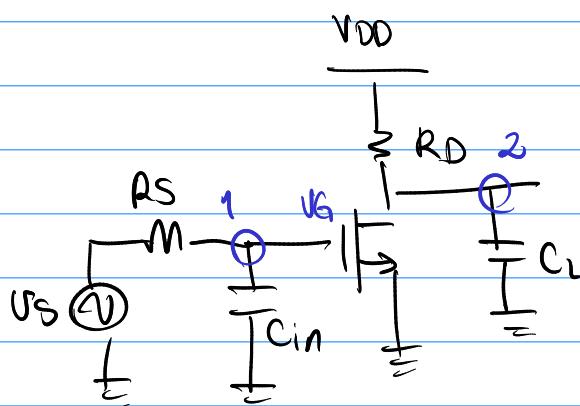
$$\text{GBP} = A_0 \cdot \text{BW}$$

Teorema: Asociación de polos con nodos

En el circuito anterior, se observó que existe un polo si el nodo de salida tiene un camino R-C a tierra.

Cada nodo con un camino R-C a tierra contribuye con un polo a  $H(s)$ .

$$\omega_p = \frac{1}{RC}$$



Nodo 1:

$$V_Q = \frac{V_S \times X_{Cin}}{R_S + X_{Cin}}$$

$$\frac{V_Q}{V_S} = \frac{1/j\omega_{Cin}}{R_S + j\omega_{Cin}} \times \frac{j\omega_{Cin}}{j\omega_{Cin}}$$

$$\frac{V_Q}{V_S} = \frac{1}{j\omega R_S C_{in} + 1}$$

Teorema:

$$\omega_{p1} = \frac{1}{R_S C_{in}}$$

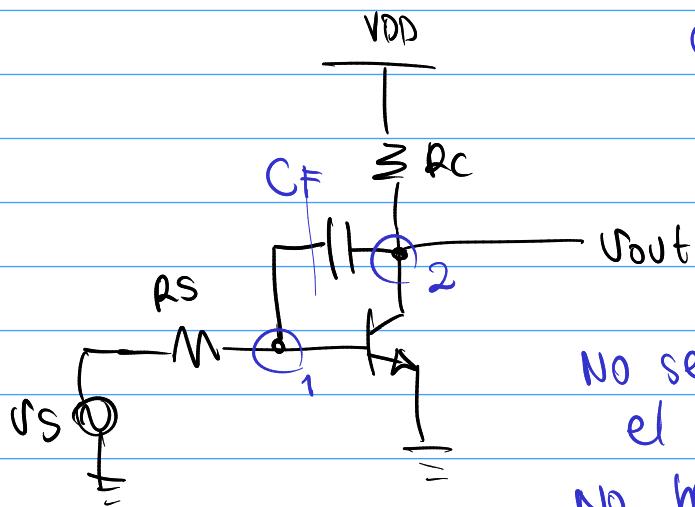
$$\omega_{p1} = \frac{1}{R_S C_{in}}$$

$$\omega_{p2} = \frac{1}{R_D \cdot C_L}$$

$$A_O = -g_m R_D$$

La ganancia de banda plana se calcula al omitir  $C_{in}$  y  $C_L$ .

En circuitos más complejos:



$C_F$  es un condensador flotante.

No se puede aplicar el teorema anterior.

No hay C a tierra.

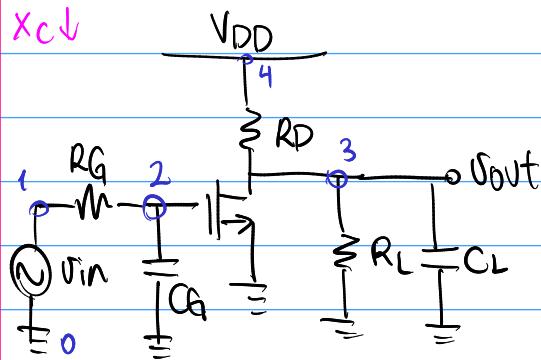
→ Se necesita el teorema de Miller.

$$s = j\omega$$

## Clase 20: Modelos de alta frecuencia BJT y MOSFET

Teorema 1: cada nodo con un camino RC a tierra contribuye con un polo a  $H(s)$

Si  $\omega \uparrow$



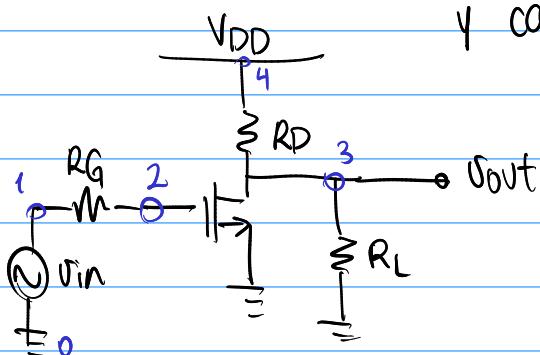
$$\textcircled{2} \quad \omega_{p_2} = \frac{1}{R_G \times C_G}$$

$$\textcircled{3} \quad \omega_{p_3} = \frac{1}{(R_D // R_L) \times C_L}$$

$$H(j\omega) = \frac{A_0}{(1 + \frac{\omega}{\omega_{p_1}})(1 + \frac{\omega}{\omega_{p_2}})}$$

Netlist: lista de todos los componentes y nodos.

Para encontrar  $A_0$ : desconecto los condensadores y calculo la ganancia de banda plana.



$$A_0 = -g_m \cdot (R_D // R_L)$$

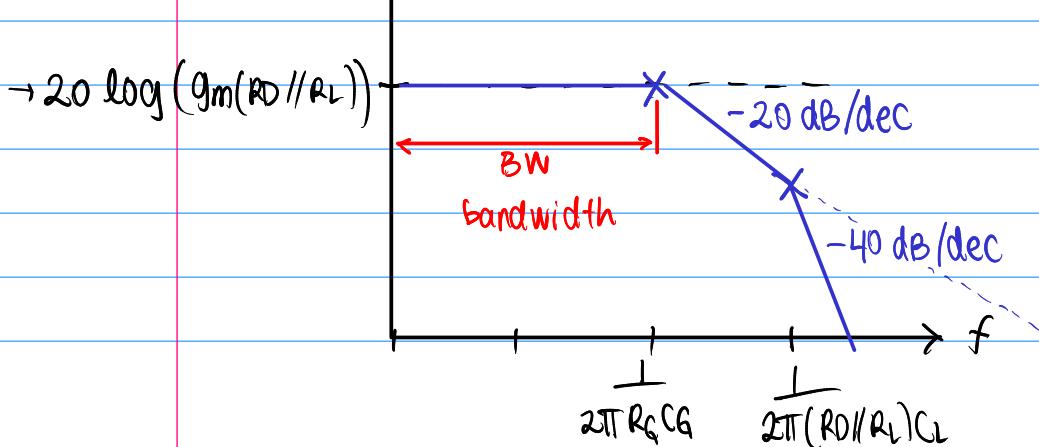
La ganancia del circuito es:

$$H(j\omega) = \frac{-g_m \cdot (R_D // R_L)}{(1 + \omega R_G C_G)(1 + \omega (R_D // R_L) C_L)}$$

$$0\text{dB} \Rightarrow A_V = 1$$

$$-3\text{dB} \Rightarrow A_V = 0.707$$

$$|A_V| \text{ dB}$$

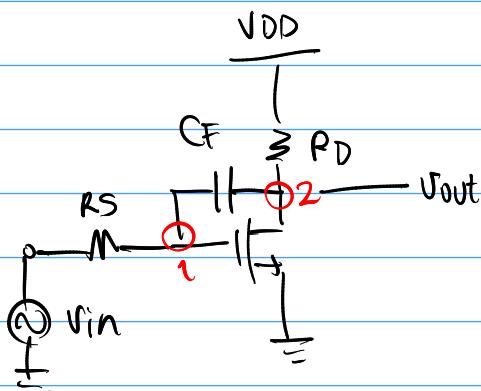


$$\omega = 2\pi f$$

$$f = \frac{\omega}{2\pi}$$

$$X_C = \frac{1}{j\omega C_1} \quad \frac{1}{j\omega C_2}$$

## Condensadores flotantes



El condensador CF es un condensador flotante.

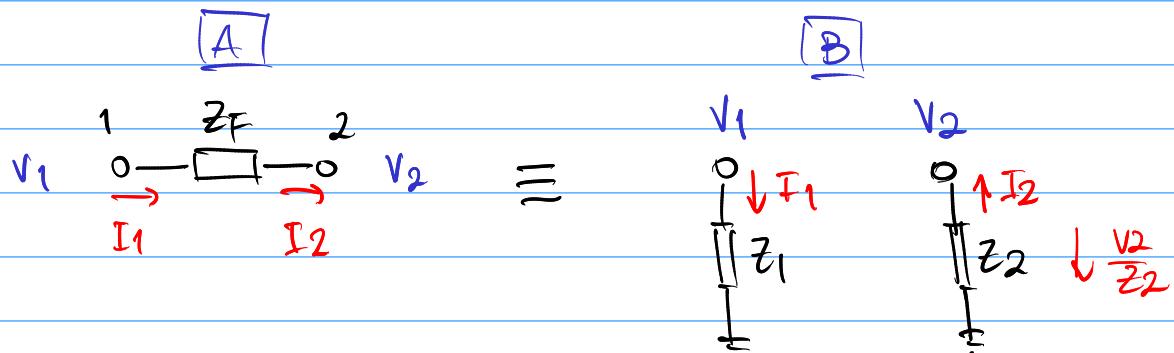
No existe C a tierra en el nodo 1 ni el nodo 2.

No se puede utilizar el teorema 1.

### Teorema de Miller:

Una impedancia flotante se puede descomponer en dos impedancias equivalentes a tierra.

El circuito no debe "sentir" ese cambio.



La corriente que entrega el nodo 1:

$$I_1 = \frac{V_1 - V_2}{Z_F} \quad \text{Circuito A}$$

Debe ser igual a la corriente que fluye por  $Z_1$ :

$$I_1 = \frac{V_1}{Z_1} \quad \text{Circuito B}$$

La corriente que recibe el nodo 2:

$$I_2 = \frac{V_1 - V_2}{Z_F} \quad \text{Circuito A}$$

Debe ser igual a la que fluye por  $Z_2$

$$I_2 = -\frac{V_2}{Z_2} \quad \text{Circuito B}$$

Igualando y despejando  $z_1$ :

$$\frac{V_1 - V_2}{Z_F} = \frac{V_1}{Z_1}$$

$$Z_1 = \frac{V_1 \cdot Z_F}{V_1 - V_2}$$

$$Z_1 = \frac{V_1 \cdot Z_F}{V_1 \left(1 - \frac{V_2}{V_1}\right)} \text{ F.C. } V_1$$

$$Z_1 = \frac{Z_F}{\left(1 - \frac{V_2}{V_1}\right)}$$

$$Z_1 = \frac{Z_F}{\left(1 - A_{21}\right)}$$

donde  $A_{21}$  es la ganancia  
del nodo 2 al nodo 1.

$$A_{21} = Av = -gmfd$$

Para condensadores:

$$\frac{1}{j\omega C_1} = \frac{1}{j\omega C_F \left(1 - A_{21}\right)}$$

$$C_1 = C_F \left(1 - A_{21}\right)$$

Observe que si  $A_{21} = -1$ ,

$$C_1 = 2C_F \quad y \quad C_2 = 2C_F$$

Igualando y despejando  $z_2$ :

$$\frac{V_1 - V_2}{Z_F} = -\frac{V_2}{Z_2}$$

$$Z_2 = \frac{-V_2}{V_1 - V_2} \times Z_F$$

$$Z_2 = \frac{-V_2}{-(V_2 - V_1)} \times Z_F$$

$$Z_2 = \frac{V_2}{V_2 \left(1 - \frac{V_1}{V_2}\right)} \times Z_F \text{ F.C. } V_2$$

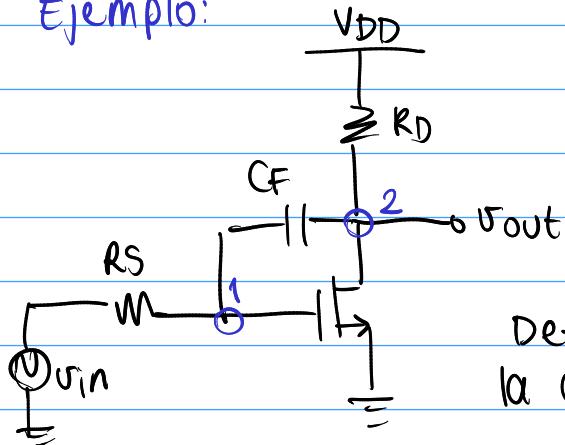
$$Z_2 = \frac{Z_F}{\left(1 - \left(\frac{V_2}{V_1}\right)^{-1}\right)}$$

$$Z_2 = \frac{Z_F}{\left(1 - \frac{1}{A_{21}}\right)}$$

$$\frac{1}{j\omega C_2} = \frac{1}{j\omega C_F \left(1 - \frac{1}{A_{21}}\right)}$$

$$C_2 = C_F \left(1 - \frac{1}{A_{21}}\right)$$

Ejemplo:



Componentes

$$C_F = 80 \text{ fF}$$

$$R_D = 2 \text{ k}\Omega$$

$$R_S = 2 \text{ k}\Omega$$

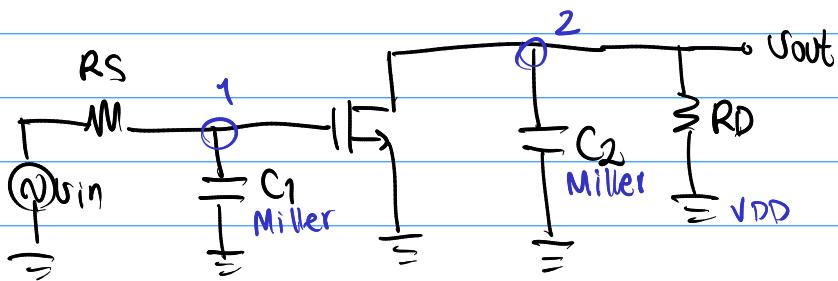
TECH

$$\lambda = 0$$

$$g_m = \frac{1}{150\Omega} = \frac{1}{150} \text{ S}$$

Determine  $A_V(j\omega)$  y construya la gráfica de Bode de  $|A_V|$  en dB.

Solución: en pequeña señal:



$$\begin{aligned} A_V &= A_{21} = -g_m R_D \\ &= -\frac{1}{150\Omega} \times 2 \text{ k}\Omega \\ &= -13.333 \end{aligned}$$

$$|A_V|_{dB} = 20 \log |A_V|$$

$$|A_V|_{dB} = 22.5 \text{ dB}$$

$$C_1 = C_F \times (1 - A_{21})$$

$$C_2 = C_F \times \left(1 - \frac{1}{A_{21}}\right)$$

$$C_1 = 80 \text{ fF} \times (1 - (-13.3))$$

$$C_2 = 80 \text{ fF} \times \left(1 - \left(\frac{1}{-13.3}\right)\right)$$

$$C_1 = 80 \text{ fF} \times (14.3)$$

$$C_2 = 80 \text{ fF} \times (1.075)$$

$C_1 = 1.1467 \text{ pF}$

$C_2 = 86 \text{ fF}$

$$f_{p1} = \frac{1}{2\pi \cdot R_S \cdot C_1}$$

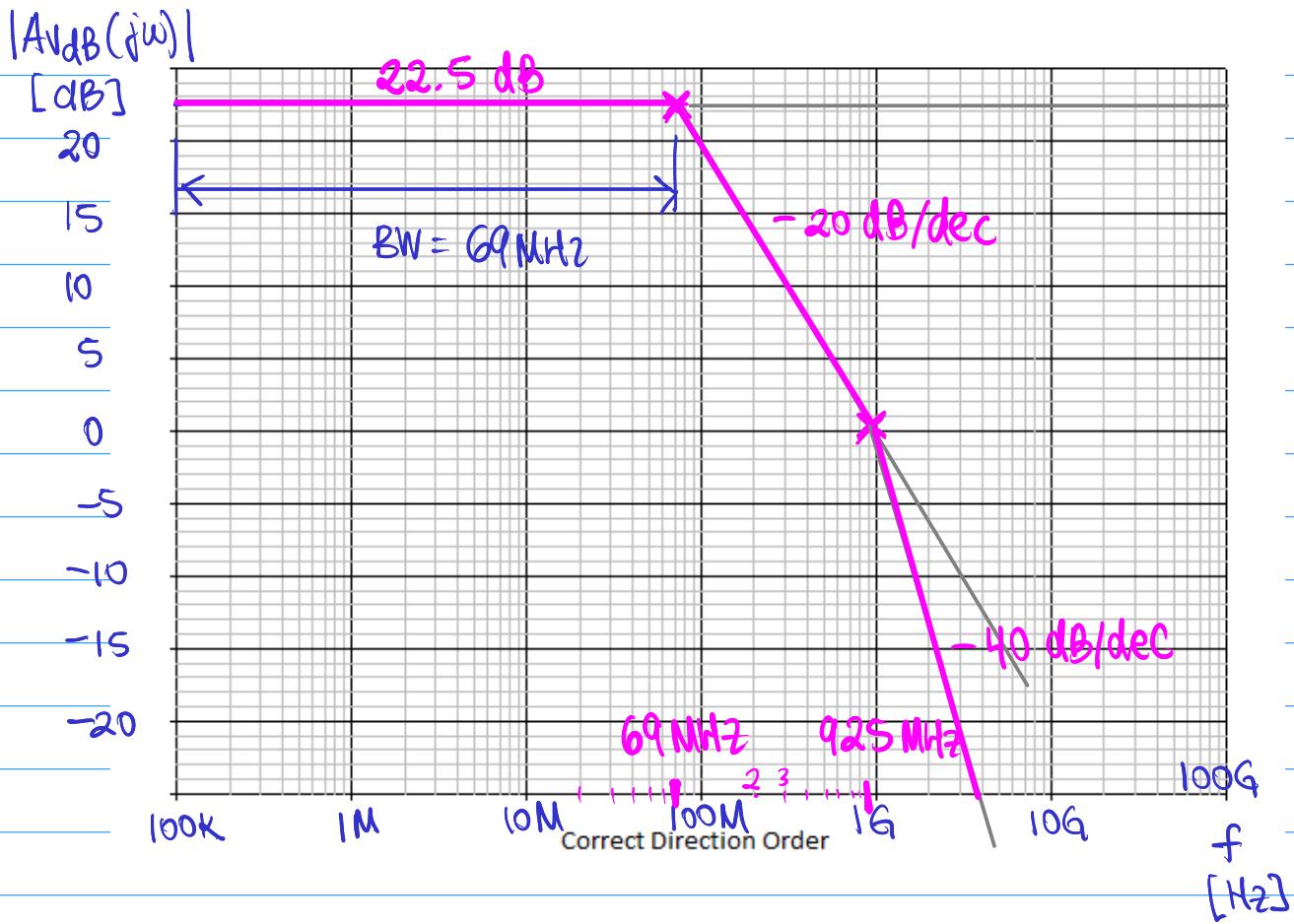
$$f_{p2} = \frac{1}{2\pi \cdot R_D \cdot C_2}$$

$$f_{p1} = 69.39 \times 10^6 \text{ Hz}$$

$$f_{p2} = 925.3 \times 10^6 \text{ Hz}$$

$f_{p1} = 69.39 \text{ MHz}$

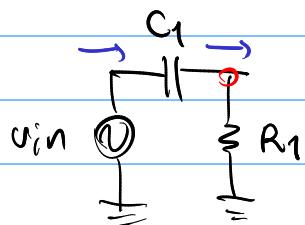
$f_{p2} = 925.3 \text{ MHz}$



Teorema 2: Ceros en el origen

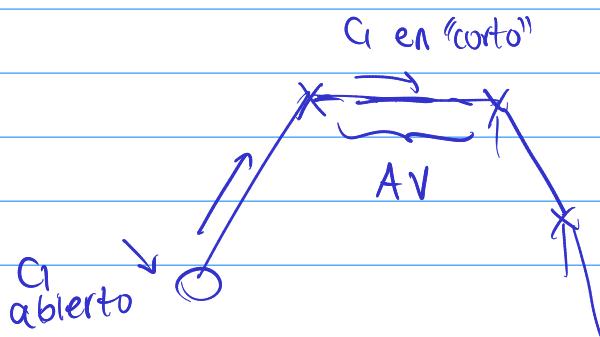
Un condensador en serie con el camino de la señal introduce un cero en el origen.

Circuito pasa altas



$$\frac{U_{out}}{U_{in}} = \frac{j\omega R_1}{j\omega C_1 + R_1} \times \frac{j\omega C_1}{j\omega C_1}$$

$$\frac{U_{out}}{U_{in}} = \frac{j\omega R_1 C_1}{1 + j\omega R_1 C_1}$$



## Modelos de HF

HF : High Frequency

RF : Radio Frequency  
mm-wave Frequencies

$$\lambda = \frac{c}{f} \rightarrow 3 \times 10^8 \text{ m/s}$$

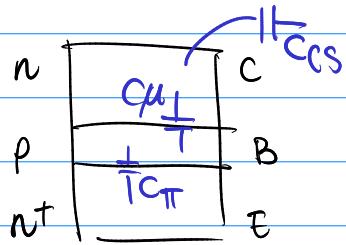
$$1 \text{ mm} = 0.001 \text{ m}$$

$$f = \frac{c}{\lambda} = \frac{3 \times 10^8 \text{ m/s}}{1 \times 10^{-3} \text{ m}}$$

$$f = 300 \text{ GHz}$$

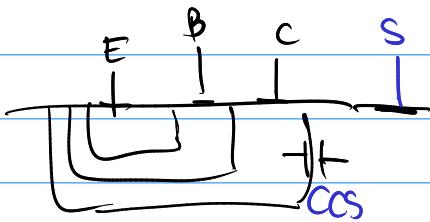
millimeter-wave.

### Modelo $\pi$ HF BJT

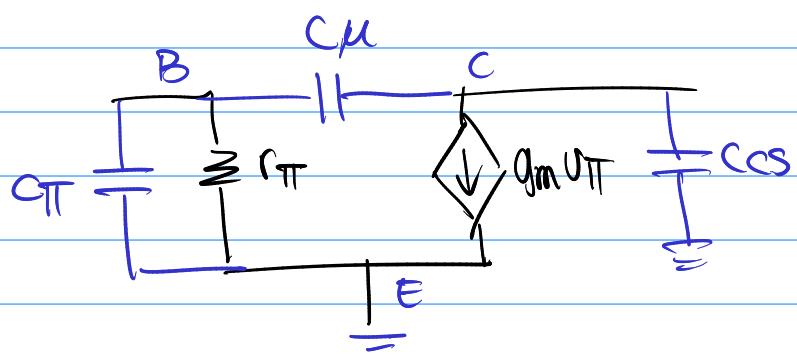
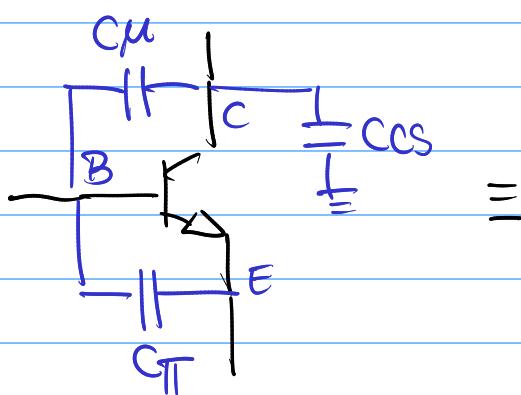


$C_\pi$ : capacitancia B-E en directa  
(pequeña)

$C_\mu$ : capacitancia B-C en reversa  
(alta)

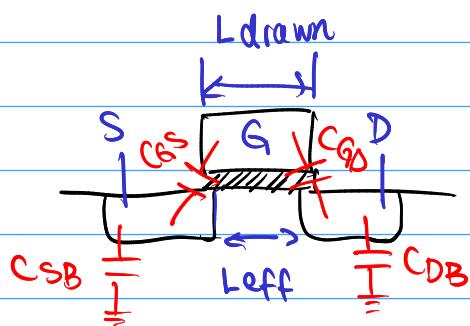


$CCS$ : capacitancia  
 $C_{JS}$  colector - sustrato  
(SPICE)

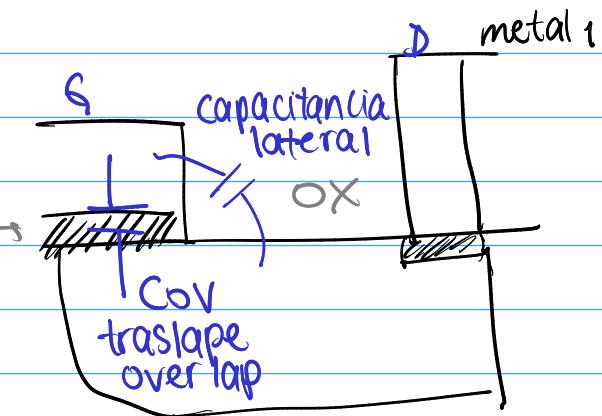


# Modelo de HF MOSFET

Ion implantation  
Annealing



$$L_{eff} = L_{drawn} - 2AL$$

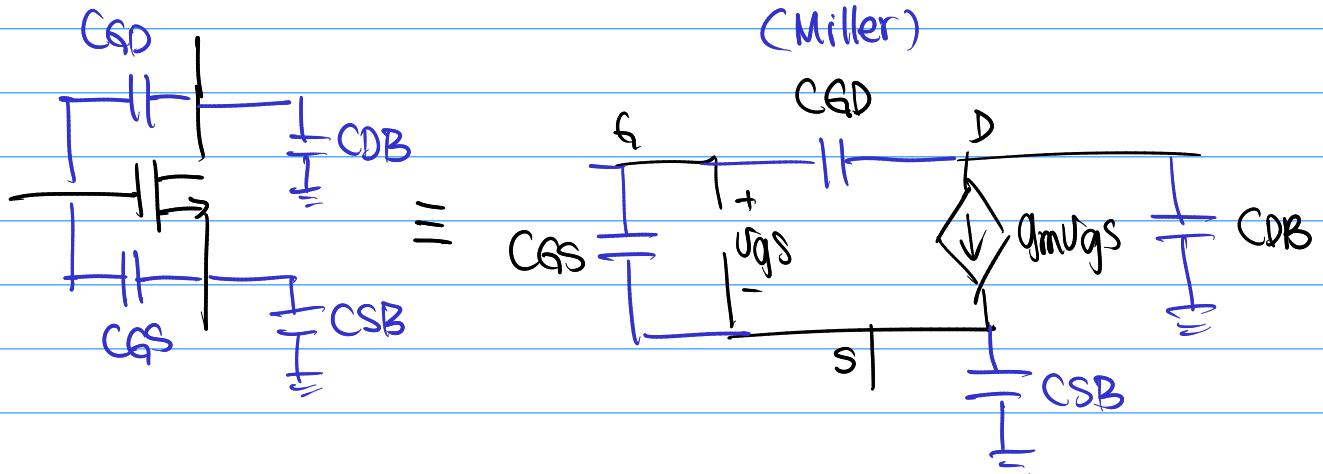


$C_{SB}$  : source - bulk

$C_{DB}$  : drain - bulk

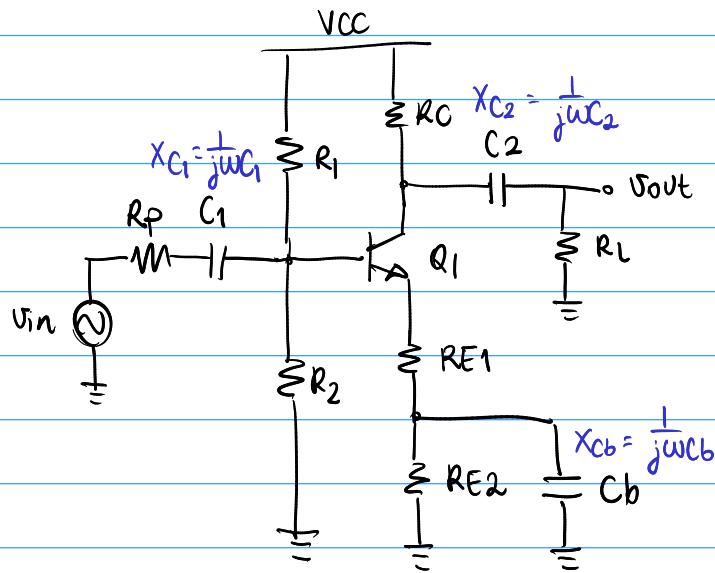
$C_{GD}$  : gate - drain

$C_{GS}$  : gate - source



## Clase 21: Respuesta de frecuencia CE y CS

Pasos de solución para el análisis de respuesta en frecuencia



1. Gran señal ( $X_C \rightarrow \infty$ )

Polarización (.op)

$I_C$        $V_{BE}$

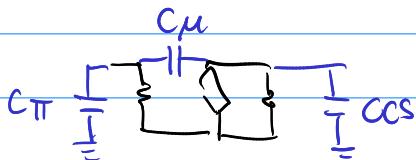
2. Parámetros de  
pequeña señal

$g_m$        $r_\pi$        $r_o$

2b. calcular las ganancias  
de banda plana.  
( $C_{ext}$  en corto)

### 3. Pequeña señal

$C_1$ ,  $C_2$  y  $C_b$  son condensadores externos al transistor. ( $\mu F$ )



$C_{pi}$ ,  $C_{mu}$  y  $C_{CS}$  son condensadores  
parásitos internos del transistor.  
(nF - fF)

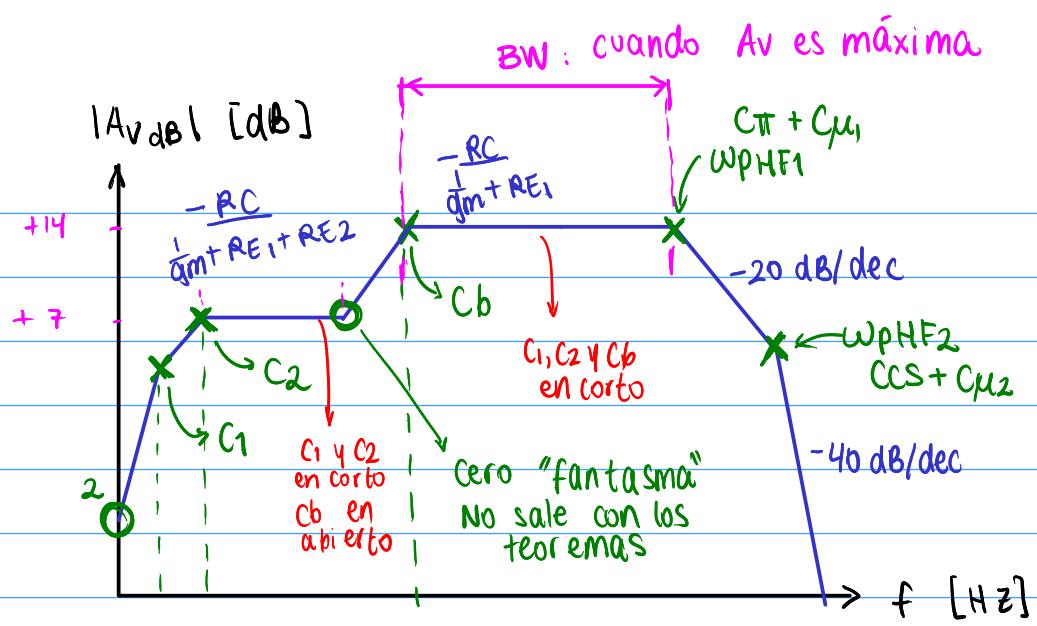
Los condensadores se van poniendo en cortocircuito en orden, de mayor a menor.

#### 3a) Pequeña señal en baja frecuencia (1 Hz - kHz)

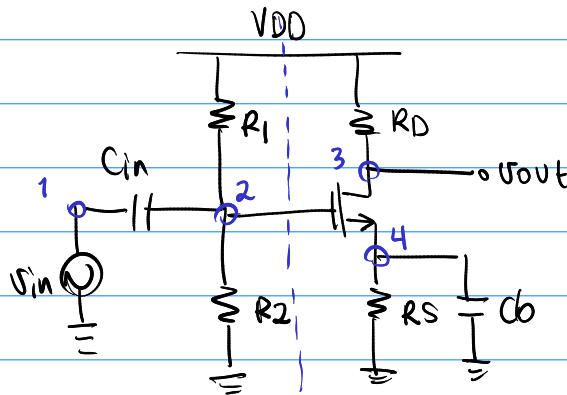
- Se reemplazan  $C_1$ ,  $C_2$ ,  $C_b$  por el equivalente en impedancia  $X_C = \frac{1}{j\omega C}$
- Suponer  $C_{pi}$ ,  $C_{mu}$ ,  $C_{CS}$  son abiertos.
- Se aplican teoremas para calcular los polos y ceros de baja frecuencia.

#### 3b) Pequeña señal en alta frecuencia (MHz - GHz)

- Se consideran  $C_1$ ,  $C_2$ ,  $C_b$  como cortocircuitos.
- se aplican teoremas para calcular los polos y ceros de  $C_{pi}$ ,  $C_{mu}$ ,  $C_{CS}$ .



### Análisis de fuente común



1. Gran señal ( $C \rightarrow \text{abiertos}$ )

$I_D$ ,  $V_{GS}$ ,  $g_m$ ,  $r_o$  conocidos.

2. Pequeña señal (LF)

Por teoremas

$$w_{p2} = \frac{1}{(R_1 // R_2) \times C_{in}}$$

$$w_{p4} = \frac{1}{(R_S // \frac{1}{g_m}) \times C_b}$$

$$A_O = -g_m R_D \quad \theta \quad \frac{-R_D}{\frac{1}{g_m} + R_S}$$

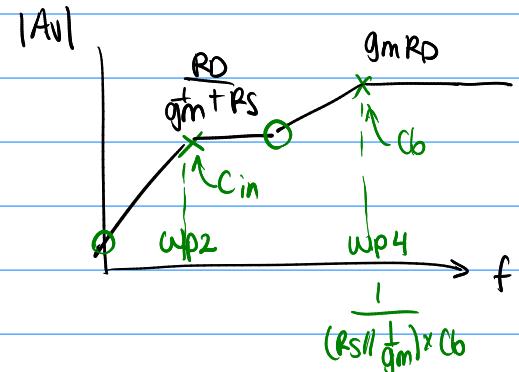
$$A_V = \frac{A_O \cdot (\omega)}{(1 + \frac{\omega}{w_{p2}})(1 + \frac{\omega}{w_{p4}})}$$

$$\frac{V_3}{V_2} = \frac{-R_D}{\frac{1}{g_m} + (R_S // \frac{1}{j\omega C_b})}$$

$$\frac{V_2}{V_1} = \frac{R_1 // R_2}{\frac{1}{j\omega C_1} + R_1 // R_2}$$

$$A_V(j\omega) = \frac{-R_D}{\frac{1}{g_m} + (R_S // \frac{1}{j\omega C_b})} \times \frac{R_1 // R_2}{\frac{1}{j\omega C_1} + R_1 // R_2}$$

Esta ecuación se debe reacomodar hasta encontrar la forma canónica de manera algebraica.



reacomodando en forma canónica:

$$\begin{aligned}
 A_V(j\omega) &= \frac{-RD}{\frac{1}{gm} + \frac{RS \cdot \frac{1}{j\omega Cb}}{RS + \frac{1}{j\omega Cb}}} \times \frac{\frac{R_1 // R_2}{\frac{1}{j\omega C_1} + R_1 // R_2}}{\frac{1}{j\omega C_1}} \times \frac{j\omega C_1}{j\omega C_1} \\
 &= \frac{-RD}{\frac{1}{gm} + \frac{\cancel{RS}}{\cancel{j\omega Cb} + 1}} \times \frac{R_1 // R_2 \cdot j\omega C_1}{1 + R_1 // R_2 \cdot j\omega C_1} \\
 &= \frac{-RD}{\frac{1}{gm} + \frac{RS}{j\omega RS Cb + 1}} \times \frac{j\omega RS Cb + 1}{j\omega RS Cb + 1} \times \frac{j\omega (R_1 // R_2) C_1}{j\omega (R_1 // R_2) C_1 + 1} \\
 &= \frac{-RD(j\omega RS Cb + 1)}{\frac{j\omega RS Cb + 1}{gm} + RS} \times \frac{gm}{gm} \times \frac{j\omega (R_1 // R_2) C_1}{j\omega (R_1 // R_2) C_1 + 1} \\
 &= \frac{-gmRD(j\omega RS Cb + 1)}{[j\omega RS Cb + 1 + gmRS] \times (j\omega (R_1 // R_2) C_1 + 1)} \\
 &\quad \text{factor común} \\
 &= \frac{-gmRD(j\omega RS Cb + 1)}{(1 + gmRS) \left( \frac{j\omega RS Cb}{1 + gmRS} + 1 \right) \times (j\omega (R_1 // R_2) C_1 + 1)}
 \end{aligned}$$

este cero aparece con ND  
 los teoremas

cero en origen

$$A_V(j\omega)_{FC} = \frac{-gmRD(R_1 // R_2)C_{in}}{(1 + gmRS)(1 + j\omega RS Cb)(1 + j\omega (R_1 // R_2)C_{in})}$$

$$A_D = \frac{-gmRD(R_1 // R_2)C_1}{(1 + gmRS)}$$

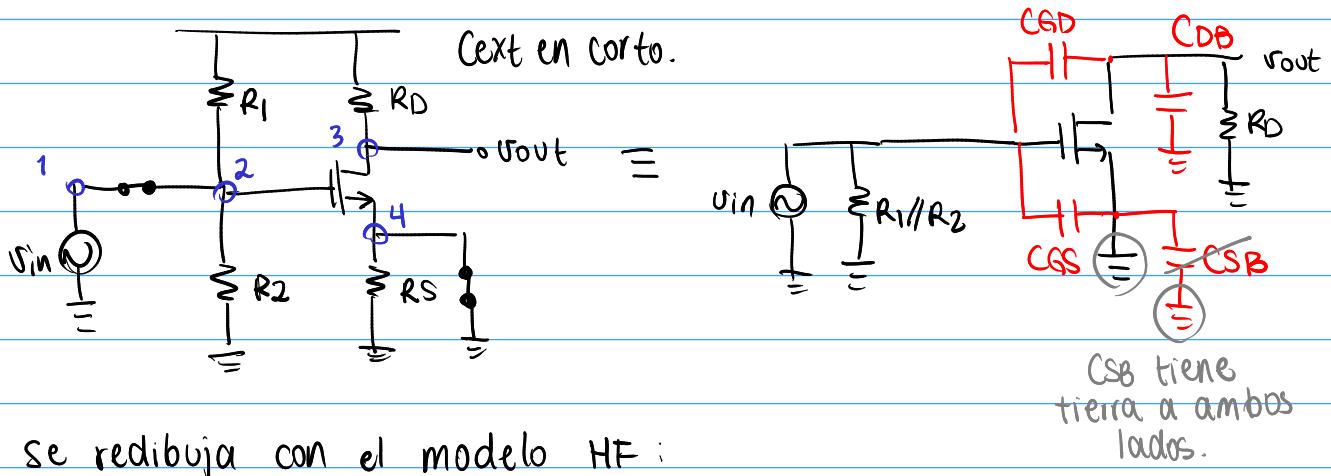
$$w_{p1} = \frac{1 + gmRS}{RS Cb} = \frac{1}{(RS // \frac{1}{gm}) \times Cb}$$

$$w_{z1} = 0$$

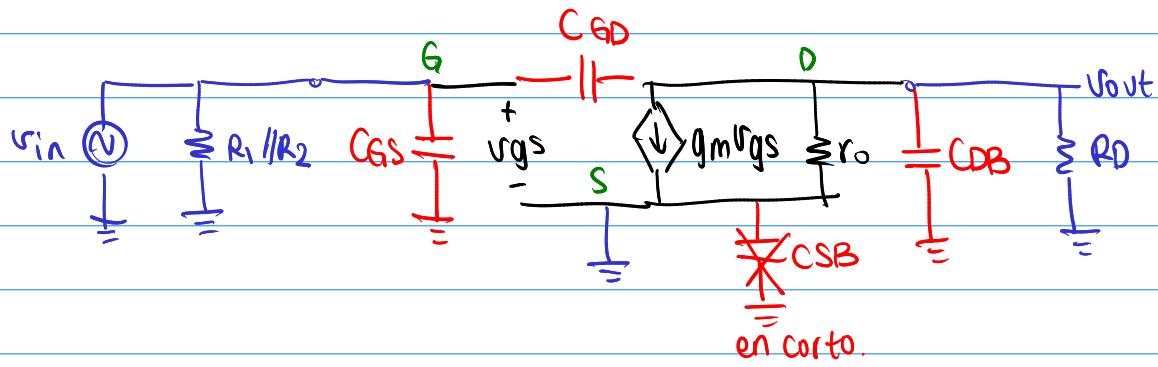
$$w_{p2} = \frac{1}{(R_1 // R_2)C_{in}}$$

$$w_{z2} = \frac{1}{RS Cb}$$

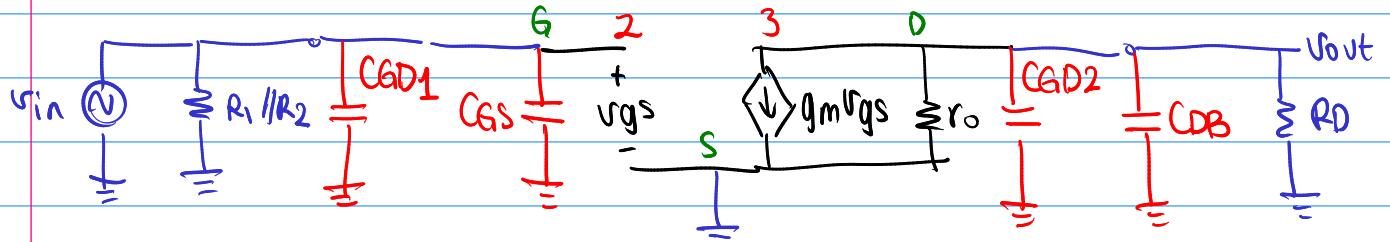
## Análisis p.eq. señal en alta frecuencia (HF)



se redibuja con el modelo HF:



CGD se descompone por Miller:



$$CGD_1 = CGD(1 - A_{32})$$

$$CGD_1 = CGD(1 - (-gmRD))$$

$$CGD_1 = \underbrace{CGD(1 + gmRD)}$$

*muy grande*

$$CGD_2 = CGD(1 - \frac{1}{A_{32}})$$

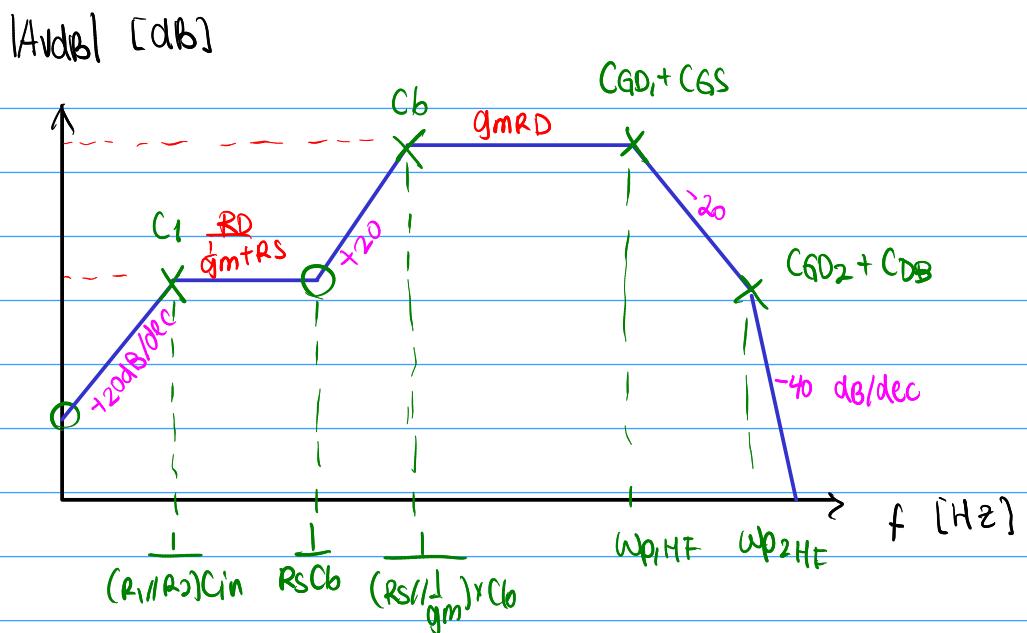
$$CGD_2 = CGD(1 - \frac{1}{-gmRD})$$

$$CGD_2 = CGD(1 + \underbrace{\frac{1}{gmRD}}_{\approx 1})$$

La capacitancia de entrada es la que limita la respuesta en frecuencia.

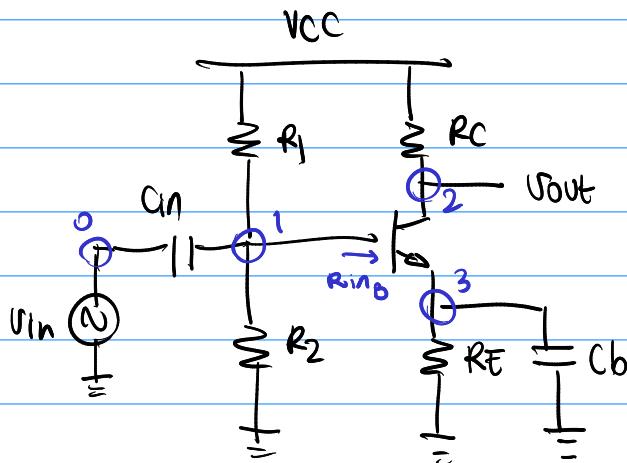
$$\omega_{p1, HF} = \frac{1}{(R_1//R_2) \times (CGD_1 + CGS)}$$

$$\omega_{p2, HF} = \frac{1}{(r_o/(RD)) \times (CGD_2 + CDB)}$$



Un ejemplo con números: 11.15 p526

Con transistores bipolares:



Por teoremas

$$C_{in}: \omega_{p1} = \frac{1}{(R_1 \parallel R_2 \parallel (r_{\pi} + (\beta + 1)R_E) \times C_{in})}$$

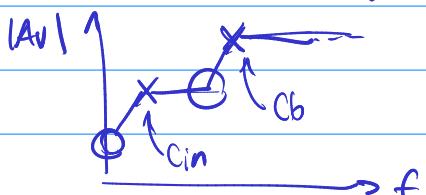
$$C_b: \omega_{p3} = \frac{1}{(R_E \parallel \frac{1}{g_m}) \times C_b}$$

aquí iría  $+ \frac{R_B}{\beta + 1}$   
pero  $C_{in}$  pone la base  
a tierra.

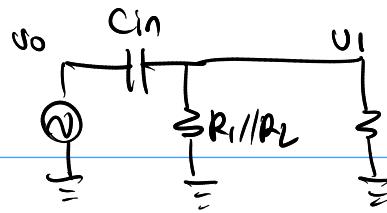
$$AV = \frac{-RC}{\frac{1}{g_m} + RE} \quad \text{o} \quad -g_m R_C$$

$C_b$  cerrado

$$C_{in}: \omega_{2r} = 0 \quad \text{cero en el origen}$$



Análisis directo



$$R_{inB} = r_{\pi} + (\beta+1) \left( R_E \parallel \frac{1}{j\omega C_b} \right)$$

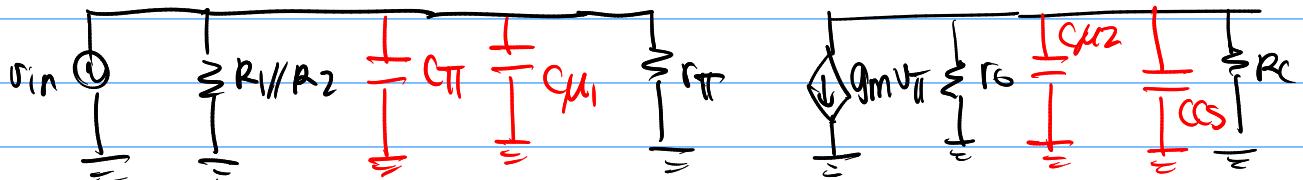
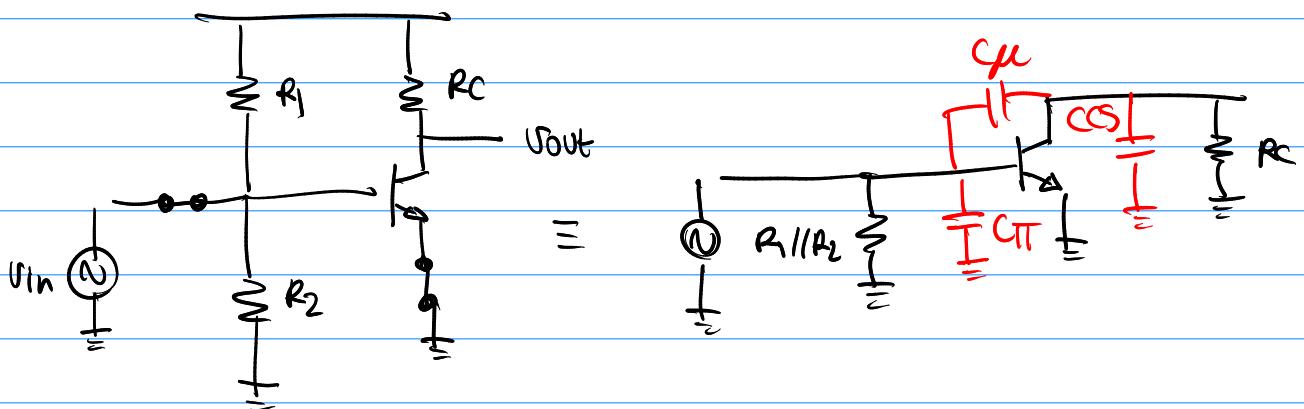
$$AV(j\omega) = \frac{V_2}{V_1} \times \frac{U_1}{V_0}$$

$$= \frac{-RC}{gm + (RE \parallel \frac{1}{j\omega C_b})} \times$$

$$\frac{\left[ r_{\pi} + (\beta+1) \left( RE \parallel \frac{1}{j\omega C_b} \right) \right] \parallel R_1 \parallel R_2}{j\omega C_{in} + \left[ r_{\pi} + (\beta+1) \left( RE \parallel \frac{1}{j\omega C_b} \right) \right] \parallel R_1 \parallel R_2}$$

"intentar" reacomodar esto en forma canónica!

Polos de alta frecuencia



$$C_{\mu 1} = C_{\mu} (1 - A_{21})$$

$$C_{\mu 2} = C_{\mu} (1 - \frac{1}{A_{21}})$$

$$\omega_{P1HF} = \frac{1}{(R_1 \parallel R_2 \parallel R_F) \times (C_{\pi} + C_{\mu 1})}$$

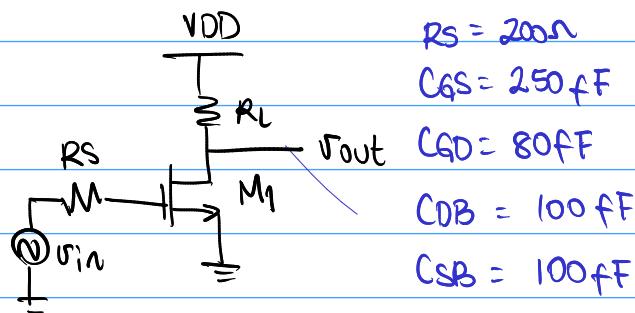
$$A_{21} = -gm R_C$$

$$\omega_{P2HF} = \frac{1}{(R_G \parallel R_C)(C_{CS} + C_{\mu 2})}$$

Clase 22: Respuesta en frecuencia CB CG

Reaso: CE y CS - fuente emisor

Ejemplo 11.18 Razavi



$$R_S = 200\Omega$$

$$R_L = 2k\Omega$$

$$C_{GS} = 250\text{ fF}$$

$$g_m = \frac{1}{150\Omega}$$

$$C_{GD} = 80\text{ fF}$$

$$C_{DB} = 100\text{ fF}$$

$$C_{SB} = 100\text{ fF}$$

Grafique la respuesta en frecuencia  $|AV(j\omega)|$  del amplificador mostrado.

para estos problemas,  
se parte de que ya se  
conoce el punto de op.

$$g_m = \frac{1}{150\Omega} = \frac{2ID}{V_{GS} - V_{TH}}$$

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

se despeja  $ID$ , luego  $V_{GS}$ ...

### Solución

#### 1) Análisis en baja frecuencia

revisar condensadores externos en el circuito.

$C_{in}$

$C_{out}$

$C_b$

(desacoplo)

(bypass)

usar los teoremas

Teorema de polos en cada nodo  $w_p = \frac{1}{RC}$

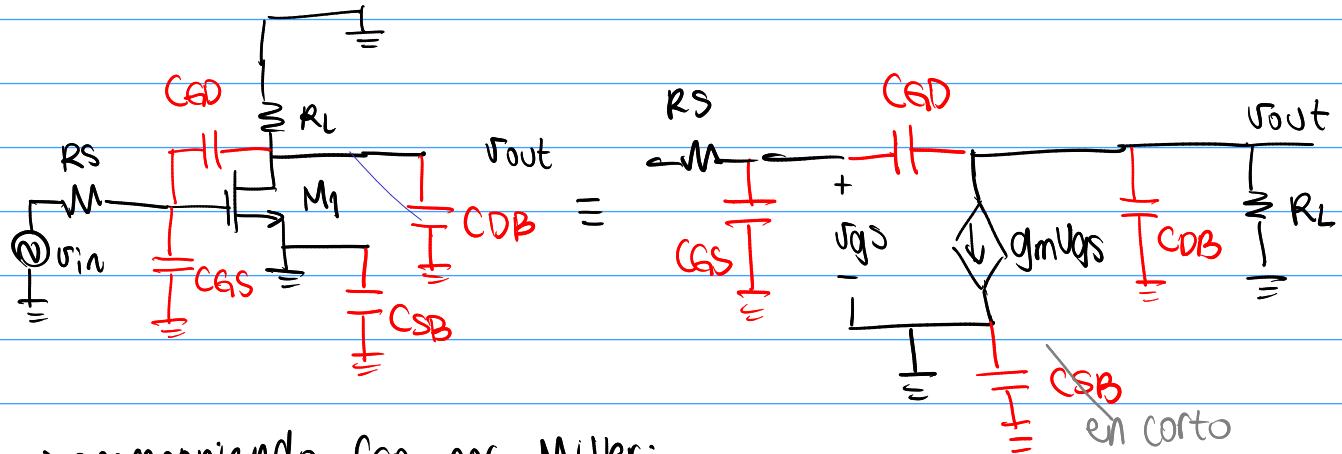
Teorema de ceros en el origen.

$$AV = -g_m R_L = -\frac{1}{150\Omega} \times 2k\Omega = -13.333$$

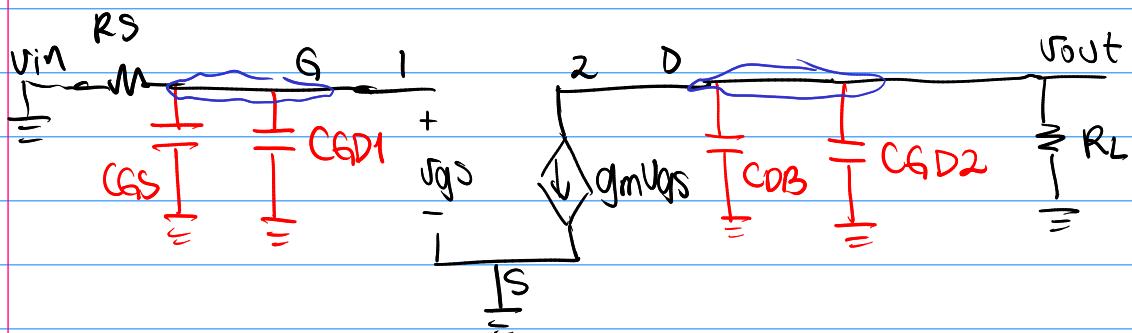
## 2. Respuesta en alta frecuencia

condensadores externos son cortocircuitos

Dibujar el modelo eq. CA con cond. internos



descomponiendo CGD por Miller:



$$CGD_1 = CGD(1 - A_{21})$$

$$CGD_1 = 80 \text{ fF} (1 - (-13.33))$$

$$CGD_1 = 1.1466 \text{ pF}$$

$$CGD_2 = CGD(1 - \frac{1}{A_{21}})$$

$$CGD_2 = 80 \text{ fF} (1 + \frac{1}{13.33})$$

$$CGD_2 = 86 \text{ fF}$$

$$\omega_{PHF1} = \frac{1}{RS \times (CGS + CGD_1)} \quad \text{teorema 1}$$

$$\omega_{PHF2} = \frac{1}{RL \times (CDB + CGD_2)}$$

$$\omega_{PHF1} = \frac{1}{(200\Omega) \times (250 \text{ fF} + 1.1466 \text{ pF})}$$

$$\omega_{PHF2} = \frac{1}{(2 \text{ k}\Omega) \times (100 \text{ fF} + 86 \text{ fF})}$$

$$\omega_{PHF1} = 3.58 \times 10^9 \text{ rad/s}$$

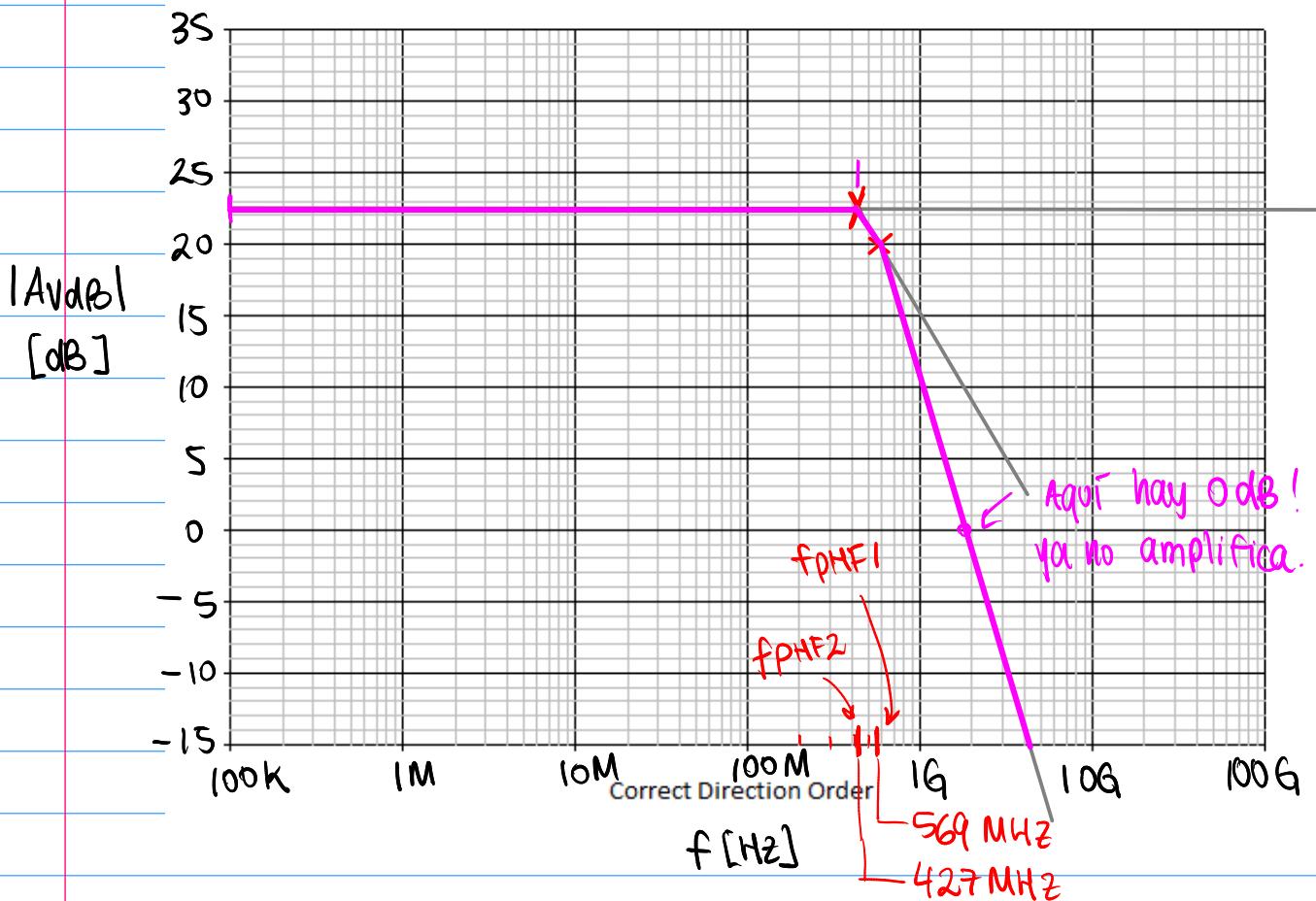
$$\omega_{PHF2} = 2.688 \times 10^9 \text{ rad/s}$$

$$\omega = 2\pi f \Rightarrow f = \frac{\omega}{2\pi}$$

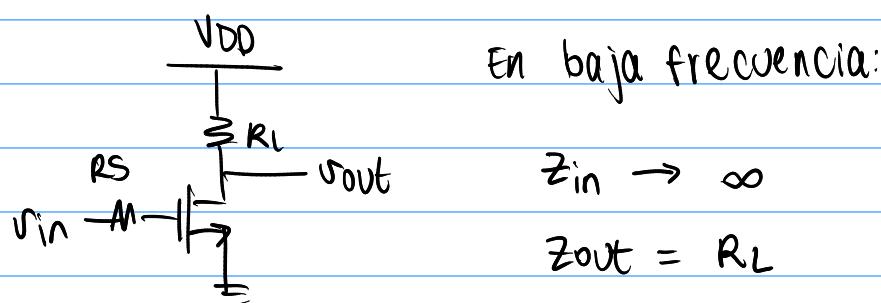
$$f_{PHF2} = 427.84 \text{ MHz}$$

$$f_{PHF1} = \frac{\omega}{2\pi} = 569.79 \text{ MHz}$$

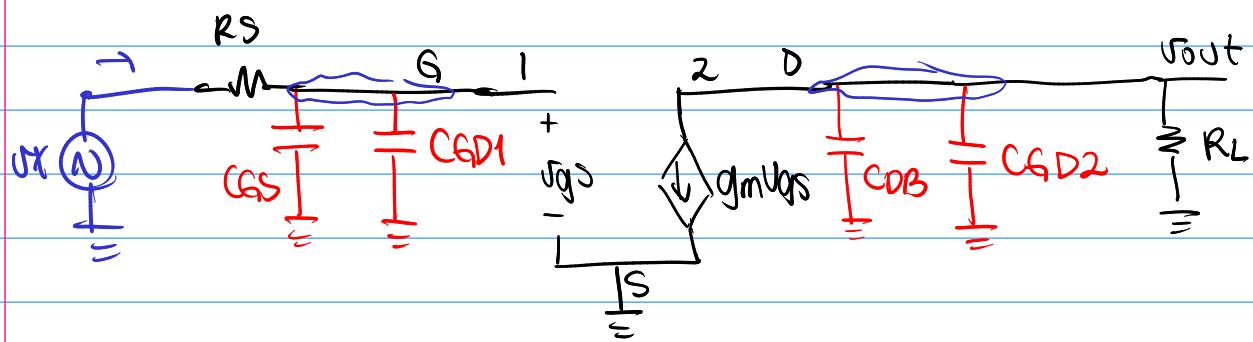
$$|AvdB| = 20 \log |-13.333| = 22.5$$



### Análisis de impedancias del circuito



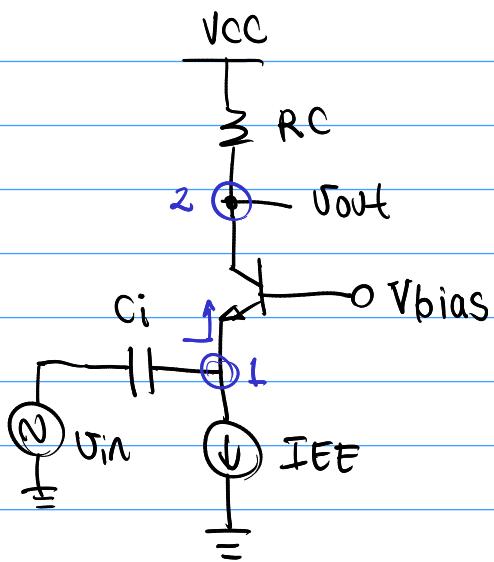
En alta frecuencia:



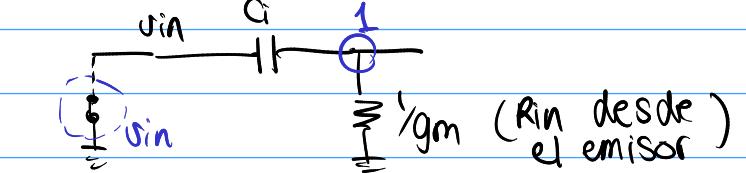
$$Z_{in}(j\omega) = R_S + \left( \frac{1}{j\omega C_{GS}} \parallel \frac{1}{j\omega C_{GD1}} \right)$$

$$Z_{out}(j\omega) = R_L \parallel \frac{1}{j\omega C_{DS}} \parallel \frac{1}{j\omega C_{GD2}}$$

# Respuesta en frecuencia CB y CG



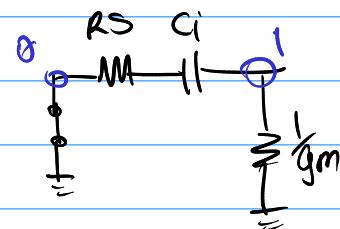
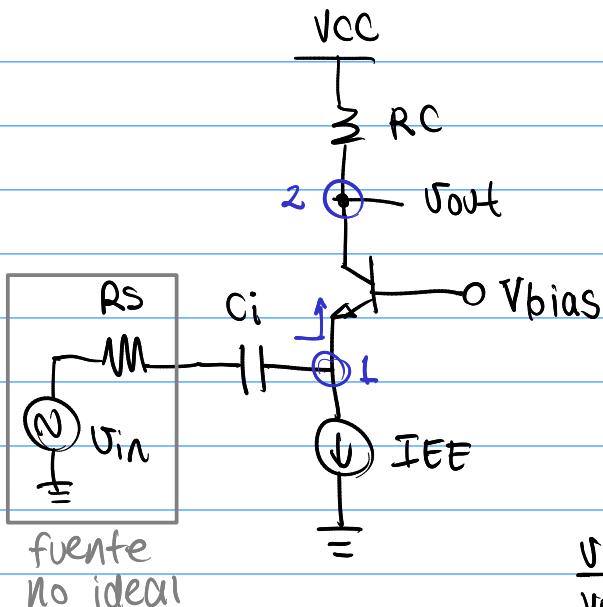
Análisis de baja frecuencia:



$$\omega_{p1} = \frac{1}{R_{load} \times C_i}$$

$\omega_{p2} = \text{no tiene capacitancia}$   
 $\rightarrow \text{no hay polo en 2}$

Si la fuente de tensión tiene impedancia  $R_s$ :



No se aplica teorema  $\frac{1}{R_{load}}$

La única opción es análisis directo.

$$\frac{V_1}{V_0} = \frac{\frac{1}{gm}}{R_s + \frac{1}{j\omega C_i} + \frac{1}{gm}} \times \frac{j\omega C_i}{j\omega C_i}$$

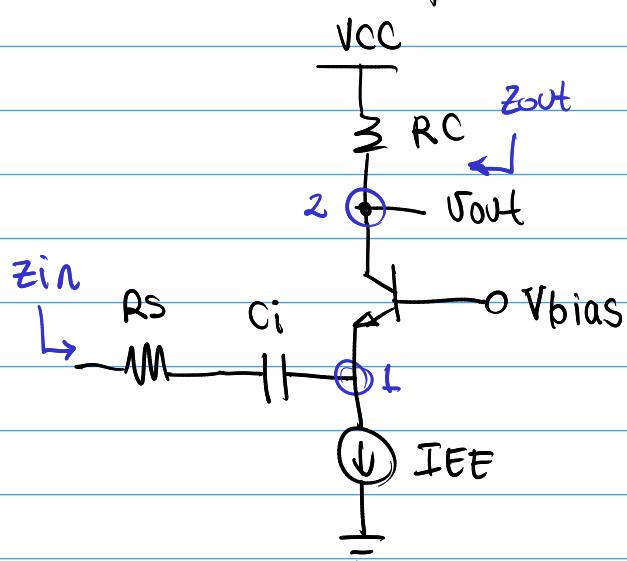
$$j\omega C_i (R_s + \frac{1}{gm})$$

$$\frac{V_1}{V_0} = \frac{\frac{1}{gm} \times j\omega C_i}{(R_s + \frac{1}{gm}) j\omega C_i + 1} \quad \text{cero en origen}$$

$$\frac{j\omega}{\omega_{p1}}$$

$$\text{Polo en } \omega_p = \frac{1}{(R_s + \frac{1}{gm}) C_i}$$

## Impedancias en baja frecuencia



sin efecto Early

$$Z_{in} = R_S + \frac{1}{j\omega C_i} + \underbrace{\frac{1}{g_m} \parallel r_T}_{\approx \frac{1}{g_m}}$$

$$Z_{out} = R_C$$

$$\approx \frac{1}{g_m}$$

con efecto Early

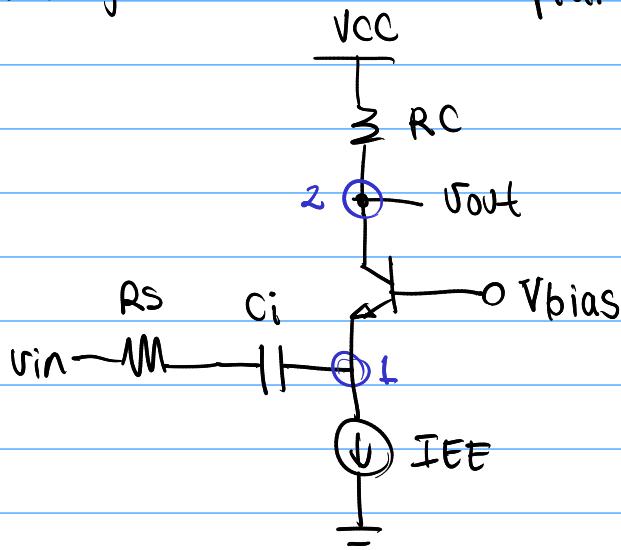
$$Z_{in} = R_S + \frac{1}{j\omega C_i} + \left( \frac{1}{g_m} \parallel r_T \parallel r_o \right)$$

$$Z_{in} \approx R_S + \frac{1}{j\omega C_i} + \frac{1}{g_m}$$

$$Z_{out} = R_C \parallel [ (1 + g_m r_o) (R_E \parallel r_{\pi}) + r_o ]$$

$$Z_{out} = R_C \parallel [ (1 + g_m r_o) \left( (R_S + \frac{1}{j\omega C_i}) \parallel r_T \right) + r_o ]$$

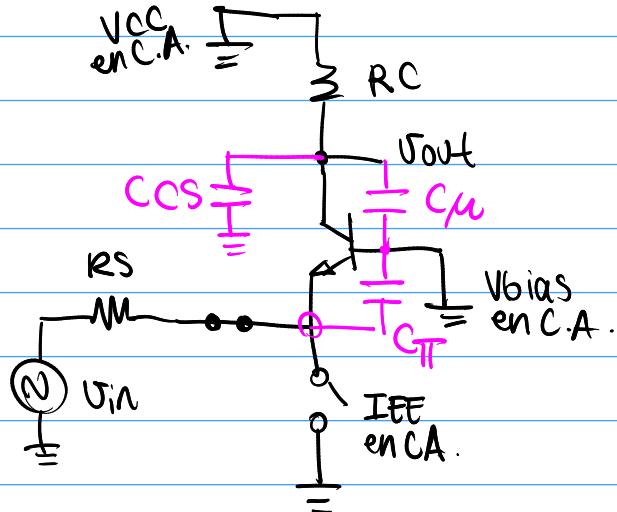
La ganancia de banda plana:



Suponemos  $C_i$  en corto

$$AV = \frac{RC}{\frac{1}{gm} + RS}$$

## Análisis de alta frecuencia

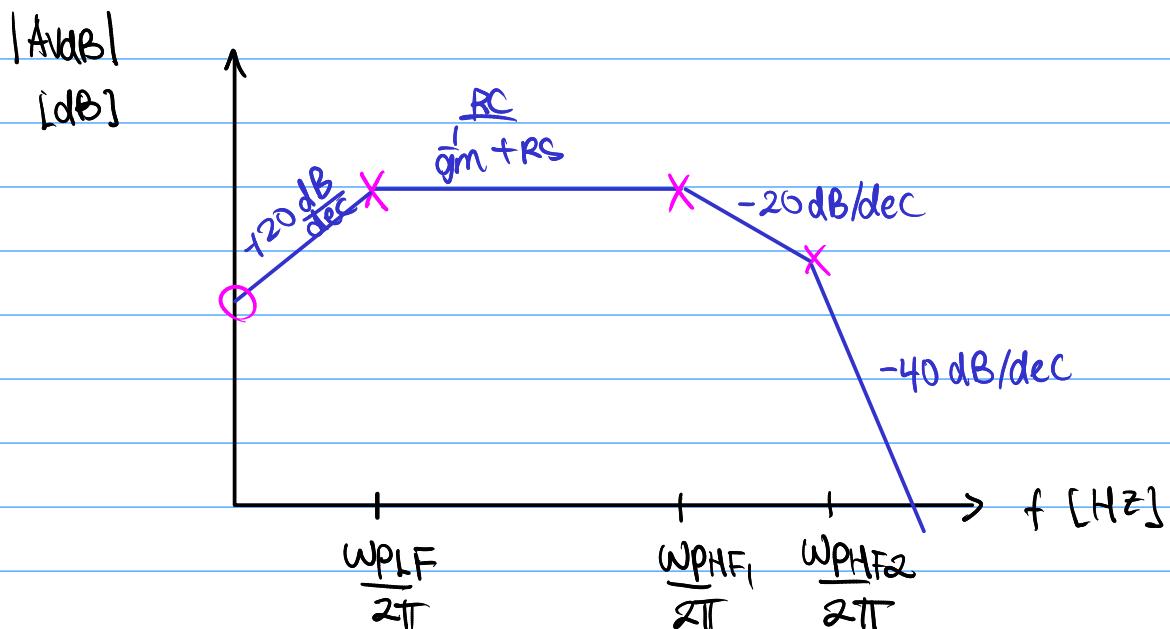
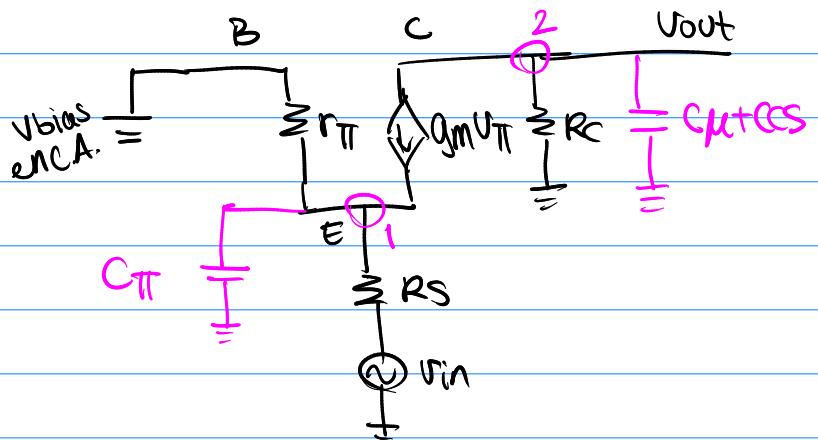


Como la base está conectada a tierra,  
→ No hay capacitancia flotante.

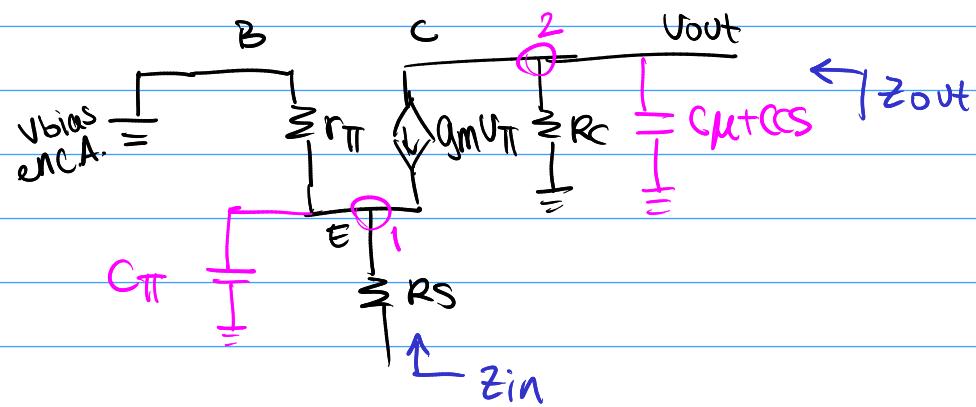
→ No hay efecto Miller.

$$\omega_{PHF_1} = \frac{1}{(f_T / (R_S / g_m) + C_\pi)}$$

$$\omega_{PHF_2} = \frac{1}{R_C \times (C_\mu + C_{CS})}$$



## Análisis de impedancias en alta frecuencia



Impedancia de entrada (con salida en circuito abierto)

$$z_{in}(j\omega) = R_S + r_{\pi} \parallel \frac{1}{g_m} \parallel \frac{1}{j\omega C_{\pi}}$$

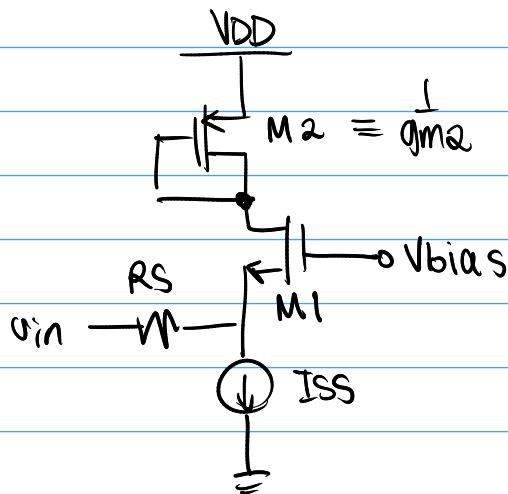
Impedancia de salida (con entrada en cortocircuito)

$$z_{out}(j\omega) = R_C \parallel \left[ \frac{1}{j\omega C_{\pi}} \parallel \frac{1}{j\omega C_{CS}} \right]$$

o bien

$$z_{out}(j\omega) = R_C \parallel \left[ \frac{1}{j\omega(C_{\pi} + C_{CS})} \right]$$

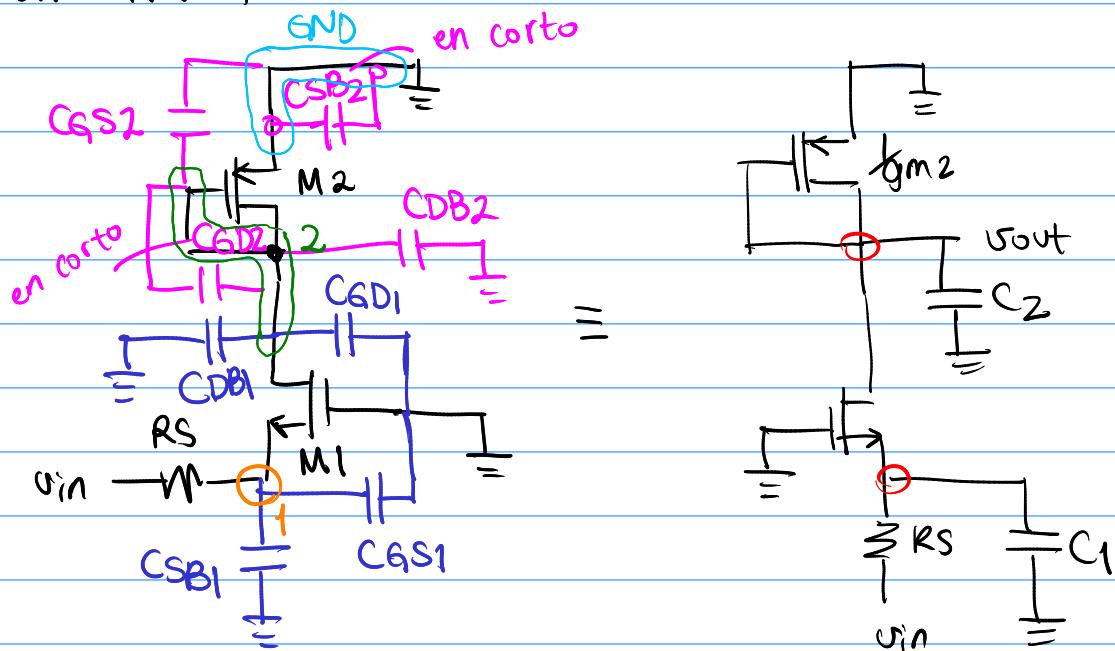
### Ejemplo 11.19 (C6)



Si no hay C<sub>ext</sub>,  
el circuito es ideal  
en baja frecuencia.

$$A_V = \frac{\frac{1}{g_m 2}}{\frac{1}{g_m 1} + R_S}$$

En alta frecuencia:



$$C_1 = C_{SB_1} + C_{GS_1}$$

$$C_2 = C_{DB_1} + C_{AD_1} + C_{DB_2} + C_{GS_2}$$

C<sub>GD<sub>2</sub></sub> en corto

C<sub>SB<sub>2</sub></sub> en corto

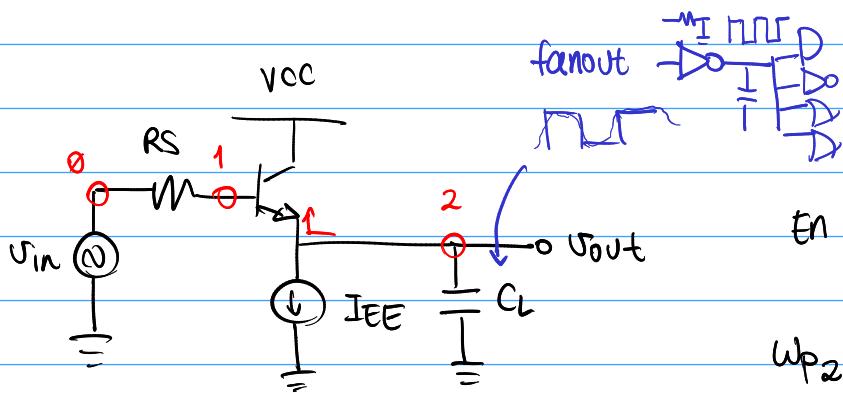
$$\omega_{PHT1} = \frac{1}{(R_S || \frac{1}{g_m 1}) \times C_1}$$

$$\omega_{PHT2} = \frac{1}{g_m 2 \times C_2}$$

9:35 - 9:45

Iniciamos la  
clase a las  
9:45

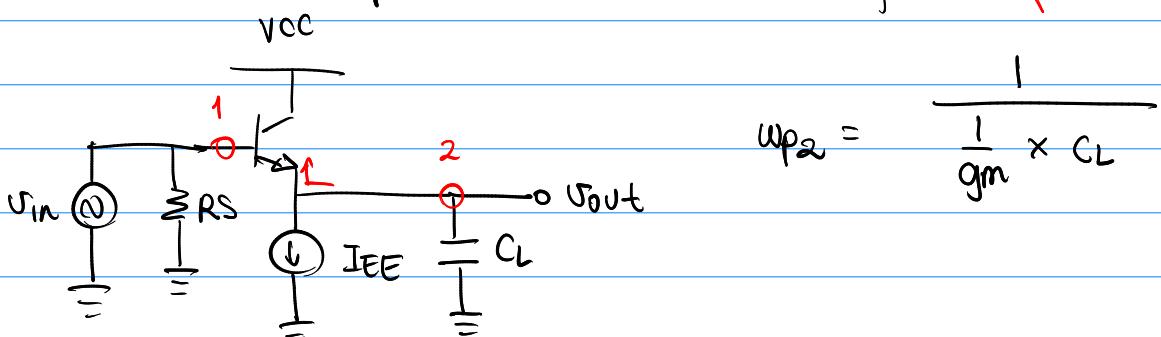
### Clase 23: CC y CD (seguidores)



en baja frecuencia:

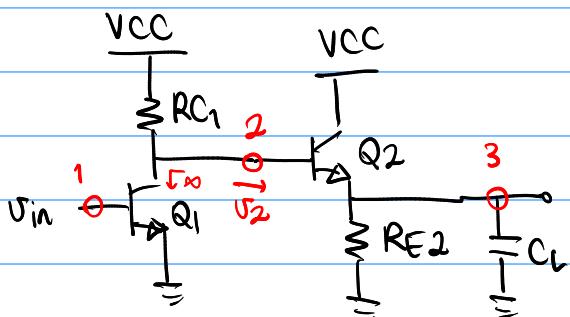
$$w_{p2} = \left[ \frac{1}{g_m} + \frac{R_S}{\beta + 1} \right] \times C_L$$

Si la resistencia  $R_S$   
hubiera estado en paralelo con  $V_{in}$ :



$$w_{p2} = \frac{1}{\frac{1}{g_m} \times C_L}$$

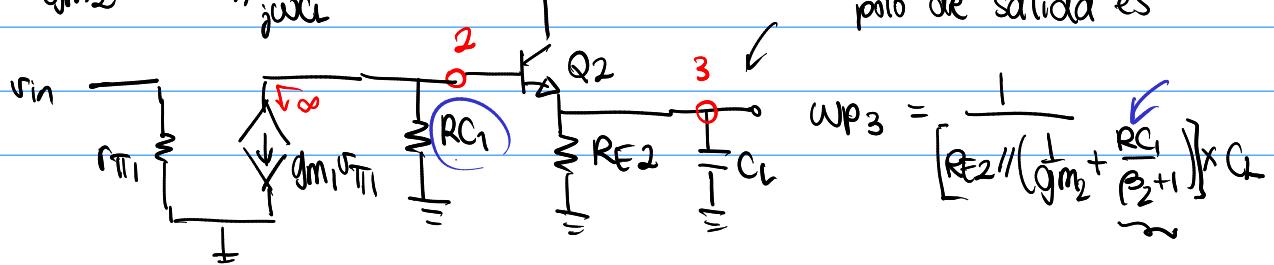
En etapas compuestas



Un transistor  $Q_1$   
como amplificador  
no es exactamente  
una fuente  $V_{in}$  ideal.

$$A_{V1} = -g_{m1} \left( R_{C1} / \left( r_{T2} + (\beta_2 + 1) \left( R_{E2} / \frac{1}{j\omega C_L} \right) \right) \right) = \frac{V_2}{V_1}$$

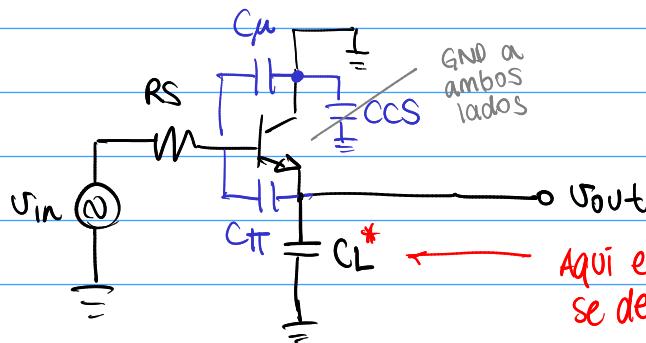
$$A_{V2} = \frac{R_{E2} / \frac{1}{j\omega C_L}}{g_{m2} + R_{E2} / \frac{1}{j\omega C_L}} = \frac{\sqrt{3}}{\sqrt{2}}$$



Por teorema, el  
polo de salida es

$$w_{p3} = \frac{1}{\left[ R_{E2} / \left( g_{m2} + \frac{R_C1}{\beta_2 + 1} \right) \right] \times C_L}$$

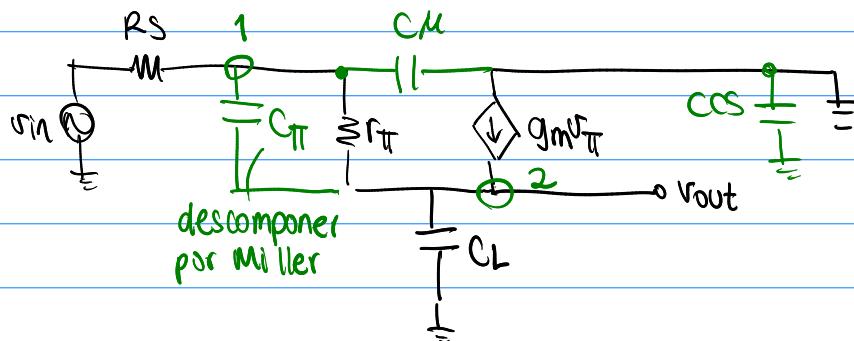
En alta frecuencia:



Aquí el libro indica que  $C_L$  se deja como parte del análisis de alta frecuencia.

(Considerar que  $C_L$  es de HF).

Con el modelo  $\pi$  de alta frecuencia:



$$AV_{21} = \frac{RE}{gm + RE} \quad \lim_{RE \rightarrow \infty} AV_{21} = 1 \quad AV_{21} \approx 1$$

$$C_{\pi 1} = C_{\pi}(1 - A_{21}) = C_{\pi}(1 - 1) = 0$$

$$C_{\pi 2} = C_{\pi}(1 - \gamma A_{21}) = C_{\pi}(1 - 1) = 0$$

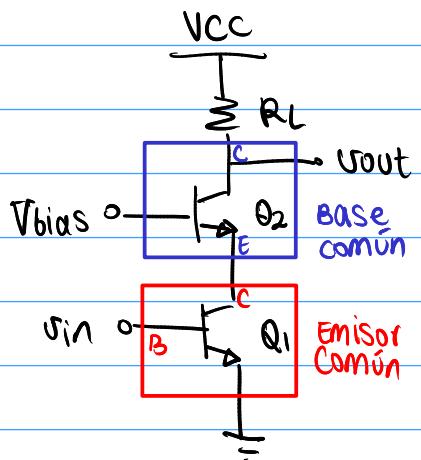
Este problema requiere análisis directo.

El análisis directo no se va a desarrollar como parte de los contenidos.

Se adjunta como de muestra (informativa).

No entra en examen.

## Respuesta de frecuencia caso oido



Base común

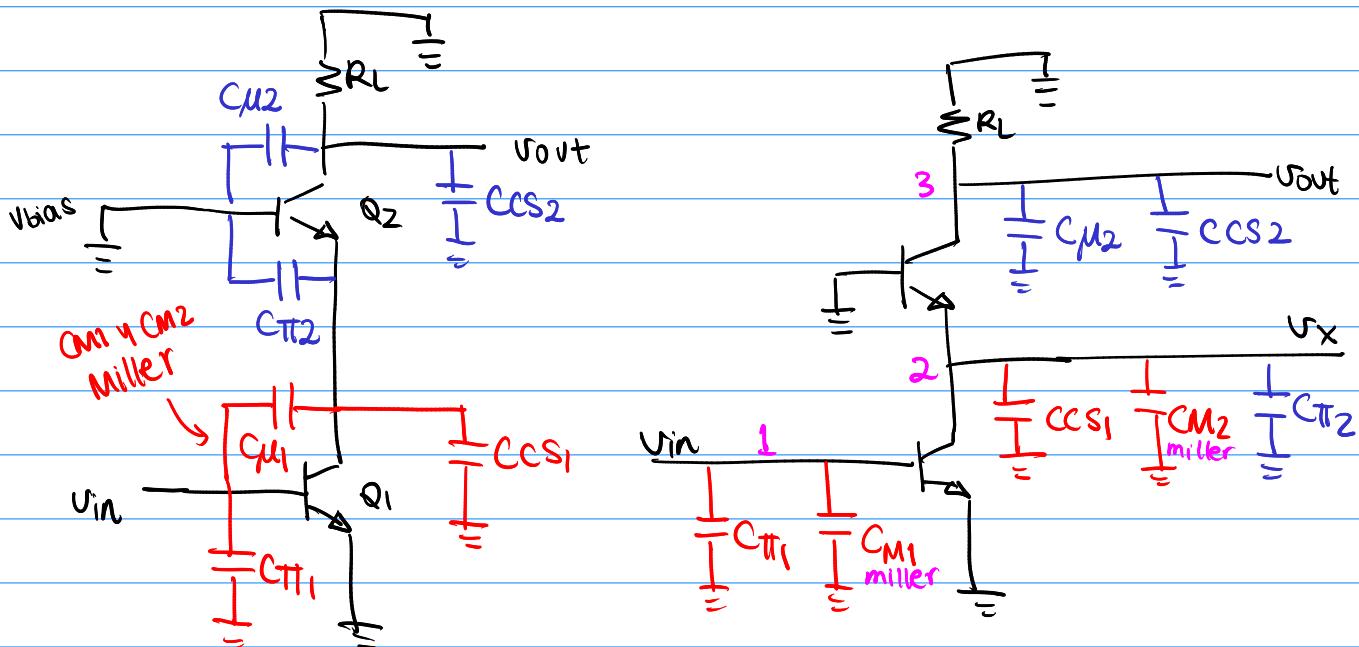
No tiene efecto Miller ✓

Impedancia de entrada baja ( $\frac{1}{g_m}$ ) ✗

Emitor común

Impedancia de entrada alta ( $r_{\pi}$ ) ✓

sufre de efecto Miller ✗



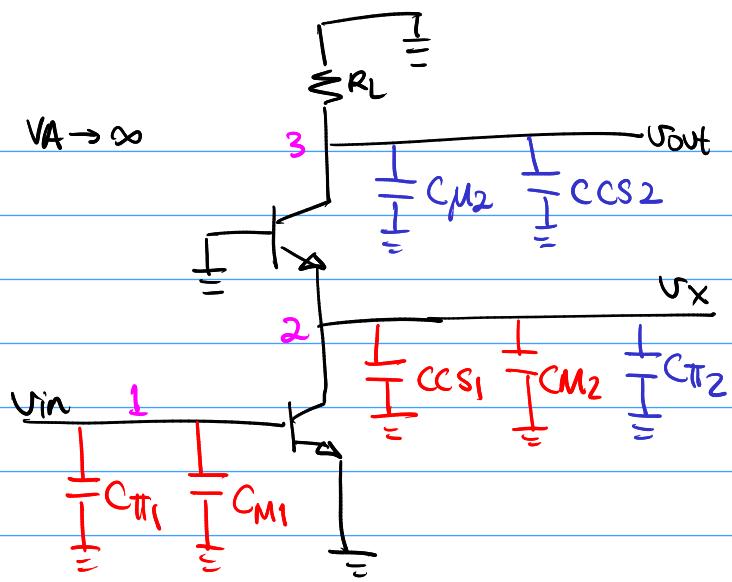
$$A_{21} = \frac{V_x}{V_{in}} = -g_{m1} \times \frac{1}{g_{m2}} \rightarrow A_{21} \approx -1$$

$$g_{m1} = \frac{I_{C1}}{V_t} \quad g_{m2} = \frac{I_{C2}}{V_t}$$

$$g_{m1} = g_{m2}$$

$$CM_1 = CM_1(1 - A_{21}) = CM_1(1 - -1) = 2CM_1$$

$$CM_2 = CM_1(1 - \frac{1}{A_{21}}) = CM_1(1 - \frac{1}{-1}) = 2CM_1$$



$$I_D = \frac{1}{2} k' \frac{W}{L} (V_{GS} - V_{TH})^2 (1 + \lambda)$$

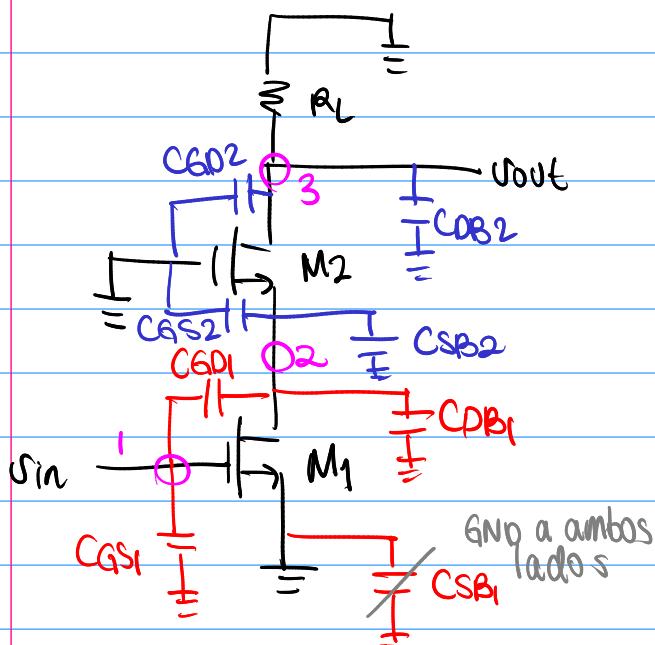
BSIM

$$\omega_{p1} = \frac{1}{f_{pi1} \times (C_{pi1} + 2Cm1)}$$

$$\omega_{p2} = \frac{1}{\frac{1}{gm2} \times (CCS1 + 2Cm1 + Cpi2)}$$

$$\omega_{p3} = \frac{1}{RL \times (Cm2 + CCS2)}$$

### Cascode MOSFET



$$gm_1 = \sqrt{2\mu_n Cox \frac{W_1}{L_1} ID_1}$$

$$gm_2 = \sqrt{2\mu_n Cox \frac{W_2}{L_2} ID_2}$$

$$AV_{M1} = -gm_1 \times \frac{1}{gm_2}$$

$$AV_{M1} = -\sqrt{\frac{W_1/L_1}{W_2/L_2}}$$

miller

$$C_1 = C_{SS1} + C_{M1}$$

$$C_2 = C_{DB1} + C_{SB2} + C_{SS2} + C_{M2}$$

$$C_3 = C_{GD2} + C_{DB2}$$

miller  $C_{M1} = C_{GD1}(1 - AV_{M1})$

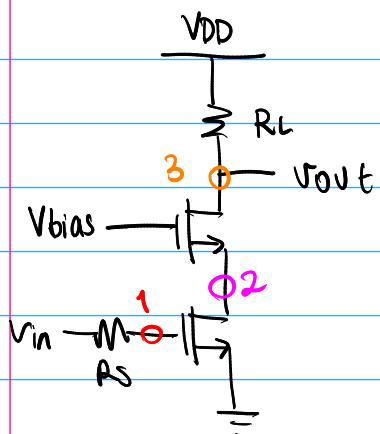
miller  $C_{M2}(1 - \frac{1}{AV_{M1}})$

$$\omega_{p1} = \frac{1}{\omega \times C_1} \rightarrow \text{no existe}$$

$$\omega_{p2} = \frac{1}{gm_2 \times C_2}$$

$$\omega_{p3} = \frac{1}{RL \times C_3}$$

### Ejemplo 11.25 p 544 - 545



$$R_S = 200 \Omega$$

$$C_{GS} = 250 \text{ fF}$$

$$C_{GD} = 80 \text{ fF}$$

$$C_{DB} = 100 \text{ fF}$$

$$C_{SB} = 100 \text{ fF}$$

$$g_{m1} = g_{m2} = \frac{1}{150 \Omega}$$

$$R_L = 2 \text{ k}\Omega$$

$$A_{21} = -\frac{g_{m1}}{g_{m2}}$$

$$\frac{W_1}{L_1} = \frac{W_2}{L_2}$$

$$A_{21} = -1$$

### Cálculos

$$C_I = C_{GS1} + C_{GD1} \left( 1 + \frac{g_{m1}}{g_{m2}} \right)$$

$$C_I = C_{GS1} + 2C_{SD1}$$

$$C_I = 250 \text{ fF} + 2(80 \text{ fF})$$

$$C_I = 410 \text{ fF}$$

$$R_I = R_S = 200 \Omega$$

$$\omega_{PHF1} = \frac{1}{(200 \Omega)(410 \text{ fF})}$$

$$\omega_{PHF1} = 1.22 \times 10^{10} \text{ rad/s}$$

$$f_{PHF1} = \frac{\omega_p}{2\pi} = 1.94 \text{ GHz}$$

$$C_2 = C_{GS2} + C_{DB1} + C_{SB2} + C_{GD1} \left( 1 - \frac{1}{A_{21}} \right)$$

$$C_2 = 250 \text{ fF} + 100 \text{ fF} + 100 \text{ fF} + 2 \times 80 \text{ fF}$$

$$C_2 = 610 \text{ fF}$$

$$R_2 = \frac{1}{g_{m2}} = 150 \Omega$$

$$C_3 = C_{GD2} + C_{DB2}$$

$$C_3 = 80 \text{ fF} + 100 \text{ fF}$$

$$C_3 = 180 \text{ fF}$$

$$R_3 = 2 \text{ k}\Omega$$

$$\omega_{PHF2} = \frac{1}{(150 \Omega)(610 \text{ fF})} = 1.093 \times 10^{10} \text{ rad/s}$$

$$\omega_{PHF3} = \frac{1}{(2 \text{ k}\Omega)(180 \text{ fF})}$$

$$f_{PHF2} = \frac{\omega}{2\pi} = 1.74 \text{ GHz}$$

$$\omega_{PHF3} = 2.7 \times 10^6 \text{ rad/s}$$

$$f_{PHF3} = 442.1 \text{ MHz}$$

### $|Av|dB$

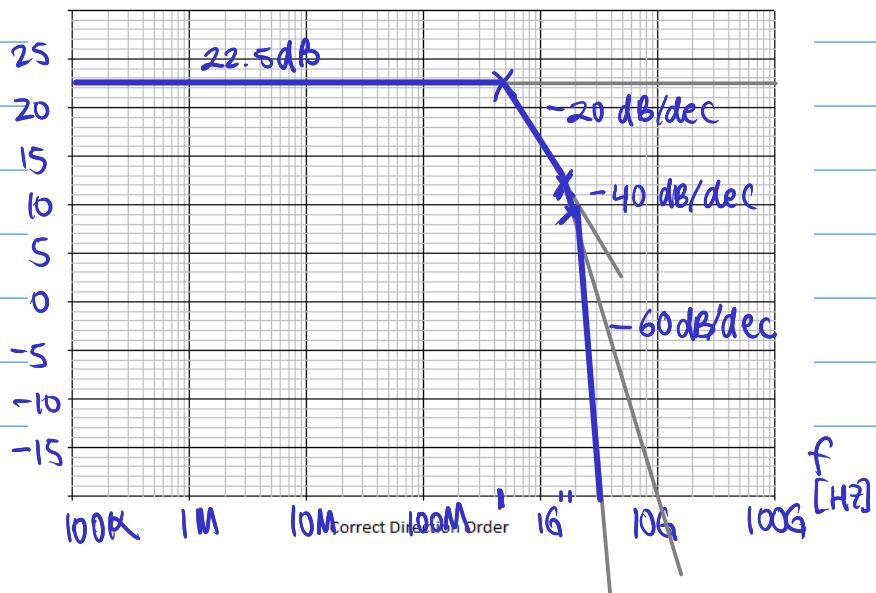
$$Av = -g_{m1} \times R_L$$

$$Av = -\frac{1}{150 \Omega} \times 2 \text{ k}\Omega$$

$$Av = -13.333$$

$$AvdB = 20 \log 13.333$$

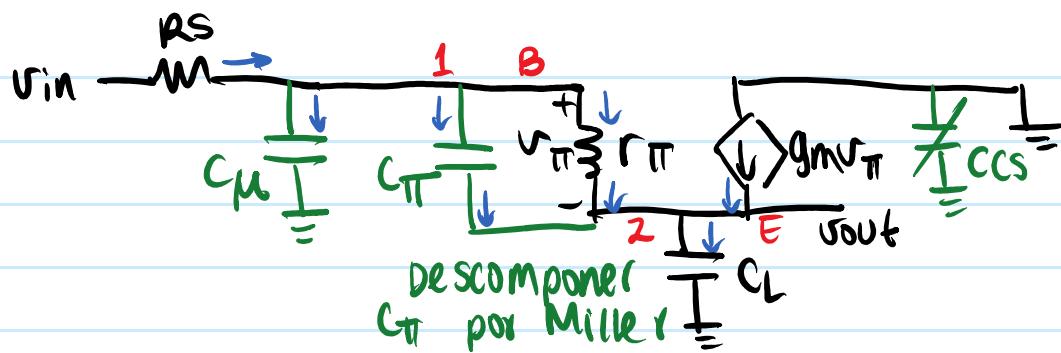
$$AvdB = 22.5 \text{ dB}$$



# Análisis directo: solución modelo $\pi$ por LCK y LUK

viernes, 19 de junio de 2020 18:35

PS35



LCK en nodo 1: (entrada)

$$\frac{V_{in} - (V_{\pi} + V_{out})}{R_S} = \frac{V_{\pi} + V_{out}}{1/C_{\mu} \cdot s} + \frac{V_{\pi}}{1/C_{\pi} \cdot s} + \frac{V_{\pi}}{R_{\pi}} \quad (1)$$

LCK en nodo 2: (salida)

$$(2) \frac{V_{out}}{1/s \cdot C_L} = g_m V_{\pi} + \frac{V_{\pi}}{R_{\pi}} + \frac{V_{\pi}}{1/C_{\pi} \cdot s} \rightarrow \text{despejar } V_{\pi}$$

$$V_{\pi} \left( g_m + \frac{1}{R_{\pi}} + s \cdot C_{\pi} \right) = s \cdot C_L \cdot V_{out}$$

$$V_{\pi} = \frac{s \cdot C_L \cdot V_{out}}{g_m + \frac{1}{R_{\pi}} + s \cdot C_{\pi}} \rightarrow \text{sustituir en (1)}$$

Factorizar primero  $V_{\pi}$  antes de sustituir

$$\frac{V_{in} - (V_{\pi} + V_{out})}{R_S} = \frac{V_{\pi} + V_{out}}{1/C_{\mu} \cdot s} + \frac{V_{\pi}}{1/C_{\pi} \cdot s} + \frac{V_{\pi}}{R_{\pi}} \quad (1)$$

$$\frac{V_{in}}{R_S} - \frac{V_{out}}{R_S} - sC_{\mu}V_{out} = sC_{\mu}V_{\pi} + \frac{V_{\pi}}{\frac{1}{R_S}} + sC_{\pi}V_{\pi} + \frac{V_{\pi}}{R_{\pi}}$$

$$\frac{V_{in}}{R_S} - \frac{V_{out}}{R_S} - sC_{\mu}V_{out} = V_{\pi} \left( sC_{\mu} + \frac{1}{R_S} + sC_{\pi} + \frac{1}{R_{\pi}} \right)$$

$$\frac{V_{in}}{R_S} = \frac{V_{out}}{R_S} + sC_{\mu}V_{out} + \left( \frac{s \cdot C_{\mu} \cdot V_{out}}{g_m + \frac{1}{R_{\pi}} + sC_{\pi}} \right) \left( sC_{\mu} + \frac{1}{R_S} + sC_{\pi} + \frac{1}{R_{\pi}} \right)$$

# Análisis directo CC (continuación)

viernes, 19 de junio de 2020 18:44

$$\frac{V_{in}}{R_S} = \frac{V_{out}}{R_S} + sC_M V_{out} + \left( \frac{s \cdot C_L \cdot V_{out}}{g_m + \frac{1}{r_{II}} + sC_{II}} \right) \left( sC_M + \frac{1}{R_S} + sC_{II} + \frac{1}{r_{II}} \right)$$

$$\frac{V_{in}}{R_S} = V_{out} \left( \frac{1}{R_S} + sC_M + \frac{(sC_L)}{\frac{g_m + \frac{1}{r_{II}} + sC_{II}}{sC_M + \frac{1}{R_S} + sC_{II}}} \right)$$

$$\frac{V_{out}}{V_{in}} = \frac{R_S}{\left( \frac{1}{R_S} + sC_M + \frac{(sC_L)}{\frac{g_m + \frac{1}{r_{II}} + sC_{II}}{sC_M + \frac{1}{R_S} + sC_{II}}} \right)}$$

La solución del libro (después de aproximar) es:

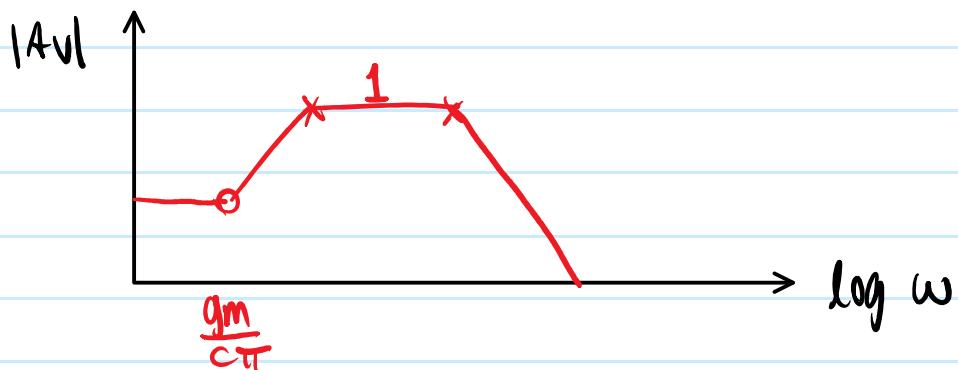
$$\frac{V_{out}}{V_{in}} \approx \frac{1 + \frac{C_{II} \cdot s}{g_m}}{as^2 + bs + 1}$$

$$a = \frac{R_S}{g_m} (C_M C_{II} + C_M C_L + C_{II} C_L)$$

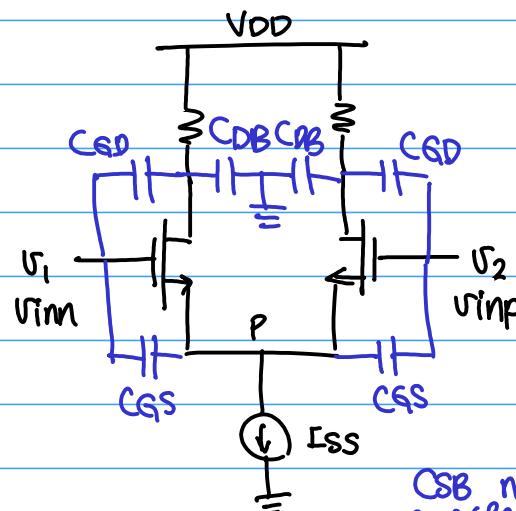
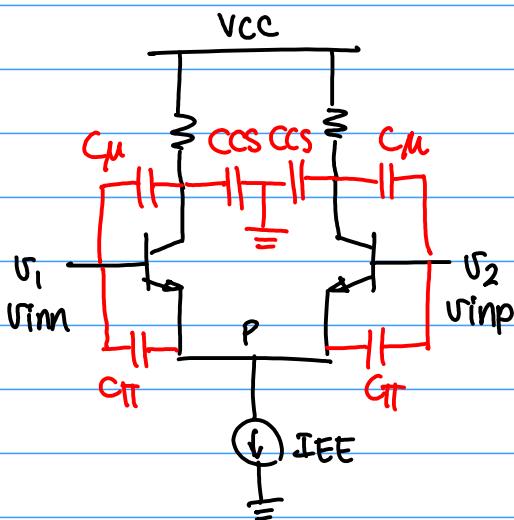
$$b = R_S C_M + \frac{C_{II}}{g_m} + \left( 1 + \frac{R_S}{r_{II}} \right) \frac{C_L}{g_m}$$

cero en  $\omega_2 = \frac{g_m}{C_{II}}$

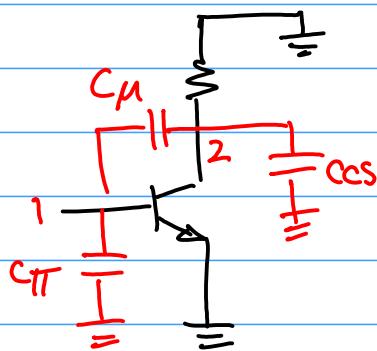
polos en las raíces  
de  $as^2 + bs + 1$



## Clase 24: Respuesta de Frecuencia Par Diferencial PS46 - 549



Ambos circuitos son simétricos con respecto al nodo P.



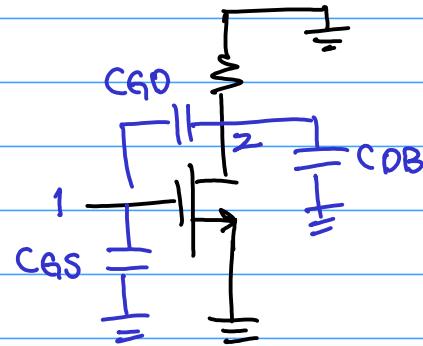
Dividir  $C_{\mu}$  por Miller

$$C_1 = C_{\pi} + C_{\mu}(1 - A_{21})$$

$$C_2 = C_{CS} + C_{\mu}(1 - \frac{1}{A_{21}})$$

$$\omega_{P1} = \frac{1}{R_{\pi} \times C_1}$$

$$\omega_{P2} = \frac{1}{R_C \times C_2}$$



Dividir  $C_{GD}$  por Miller

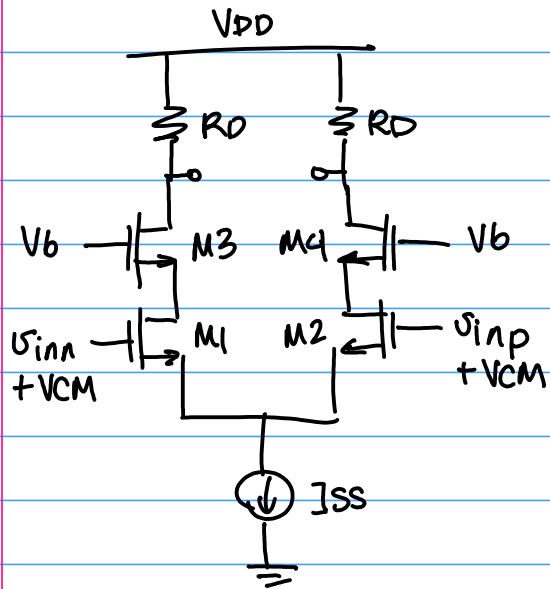
$$C_1 = C_{GS} + C_{GD}(1 - A_{21})$$

$$C_2 = C_{DB} + C_{GD}(1 - \frac{1}{A_{21}})$$

$$\omega_{P1} = \frac{1}{R_D \times C_1} \rightarrow 0 \text{ (no existe polo)}$$

$$\omega_{P2} = \frac{1}{R_C \times C_2}$$

## par diferencial cascode

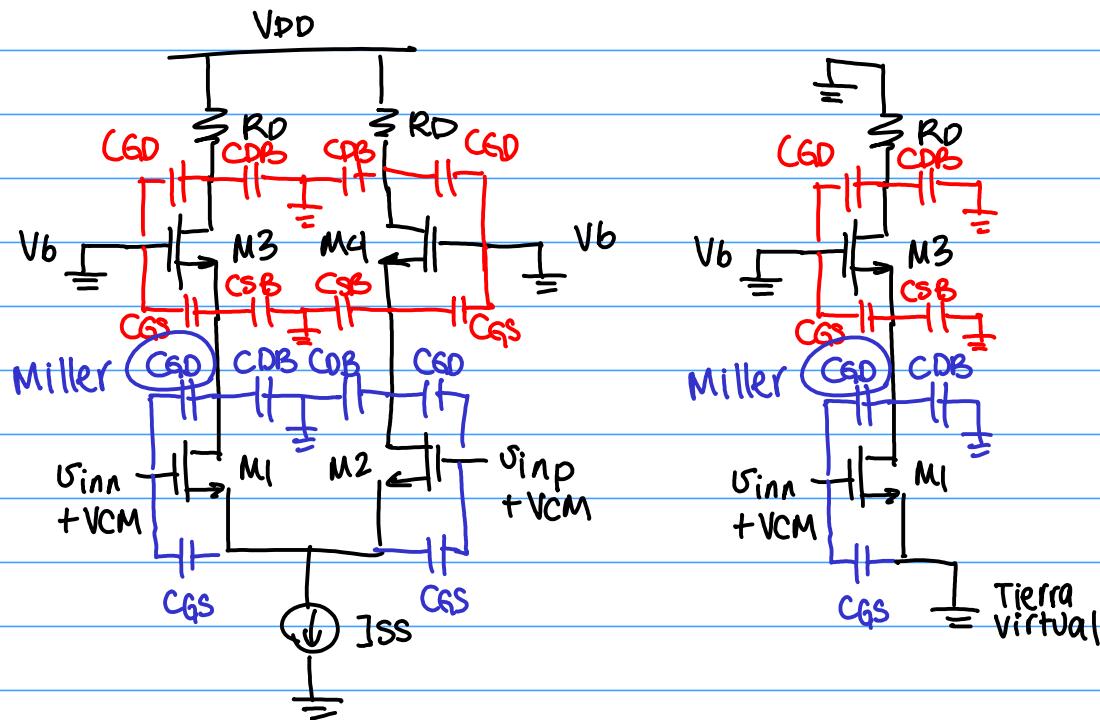


$$A_V = -g_{m2} \times (R_D / (R_D \cdot r_{o2} \cdot r_{o4} \cdot g_{m4}))$$

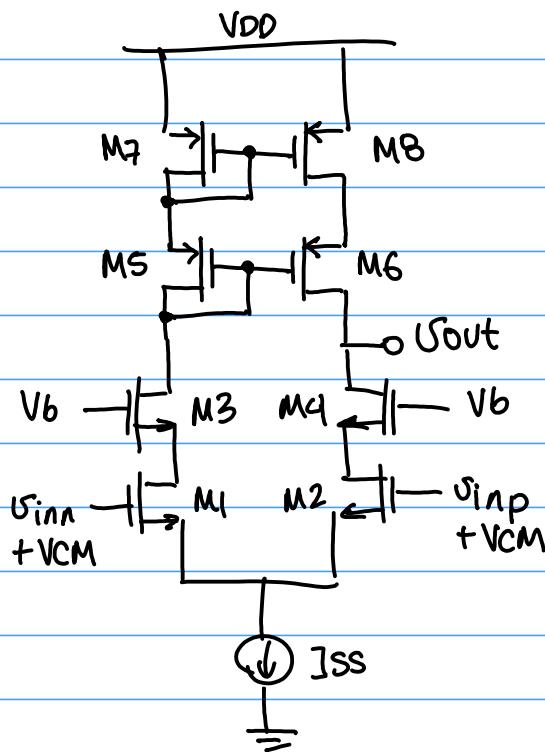
↑  
limita la ganancia  
imp. de salida del cascode

$$R_{out} = R_D / (R_D \cdot r_{o2} \cdot r_{o4} \cdot g_{m4})$$

↑  
limita R<sub>out</sub>



## El Par Dif. Cascode completo:

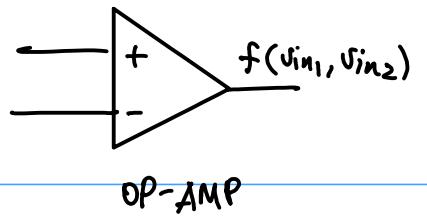


$$AV = -g_m 2 \times \left( r_{o2} r_{o4} g_m 4 \parallel r_{o6} r_{o8} g_m 6 \right)$$

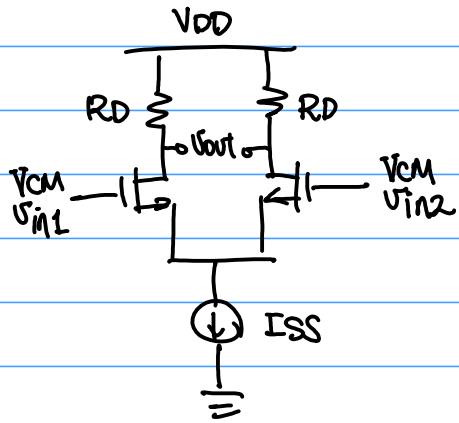
Muy Alto!

Este circuito no permite conectar una carga baja a la salida  $\Rightarrow$  PIERDE GANANCIA

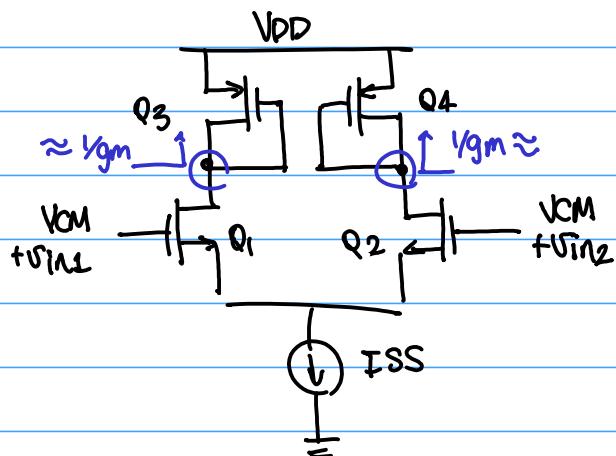
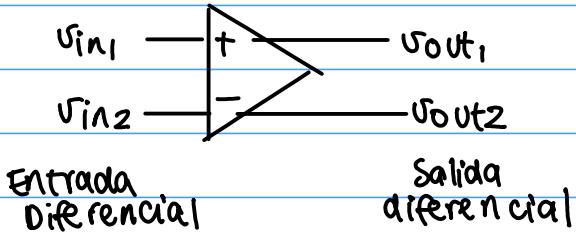
$$R_{out} = r_{o2} r_{o4} g_m 4 \parallel r_{o6} r_{o8} g_m 6$$



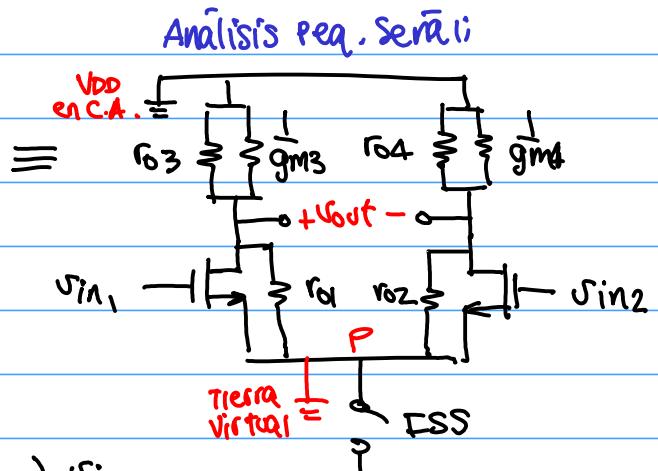
## Clase 18: Amplificador operacional



$$AV_{DM} = -g_m R_D = \frac{v_{out1} - v_{out2}}{v_{in1} - v_{in2}}$$



Conexión de Q3 y Q4 como diodos.



$$v_{out1} = -g_m \cdot (r_o1 // r_o3 // \frac{1}{g_m3}) \cdot v_{in1}$$

$$v_{out2} = -g_m \cdot (r_o2 // r_o4 // \frac{1}{g_m4}) \cdot v_{in2}$$

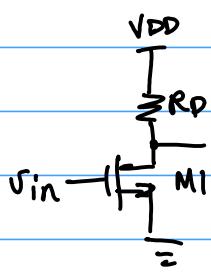
donde se puede establecer  
 $g_m1 = g_m2 = g_m3 = g_m4$

Suponiendo  $r_o > \frac{1}{g_m}$   $\rightarrow v_{out1} \approx -g_m \cdot \frac{1}{g_m3} \cdot v_{in1} \approx -1$

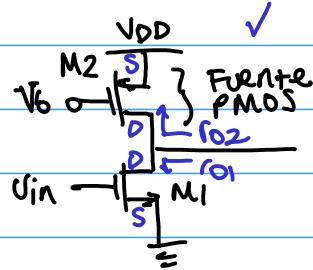
$\rightarrow v_{out2} \approx -g_m \cdot \frac{1}{g_m4} \cdot v_{in2} \approx -1$

$$AV = \frac{v_{out1} - v_{out2}}{v_{in1} - v_{in2}} = \frac{-v_{in1} - (-v_{in2})}{v_{in1} - v_{in2}} = \frac{-(v_{in1} - v_{in2})}{v_{in1} - v_{in2}} = -1$$

Recordando fuente común:



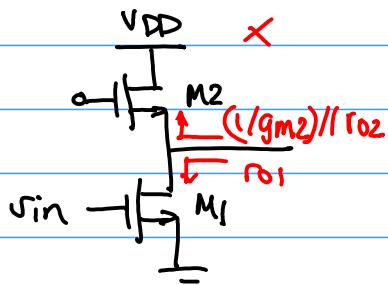
mejora



$$AV = -g_m R_D$$

$$AV = -g_{m1} \cdot (r_{02} // r_{01})$$

Fuente  
NMOS  
conexión  
incorrecta



$$AV = -g_{m1} (r_{01} // r_{02} // \frac{1}{g_{m2}})$$

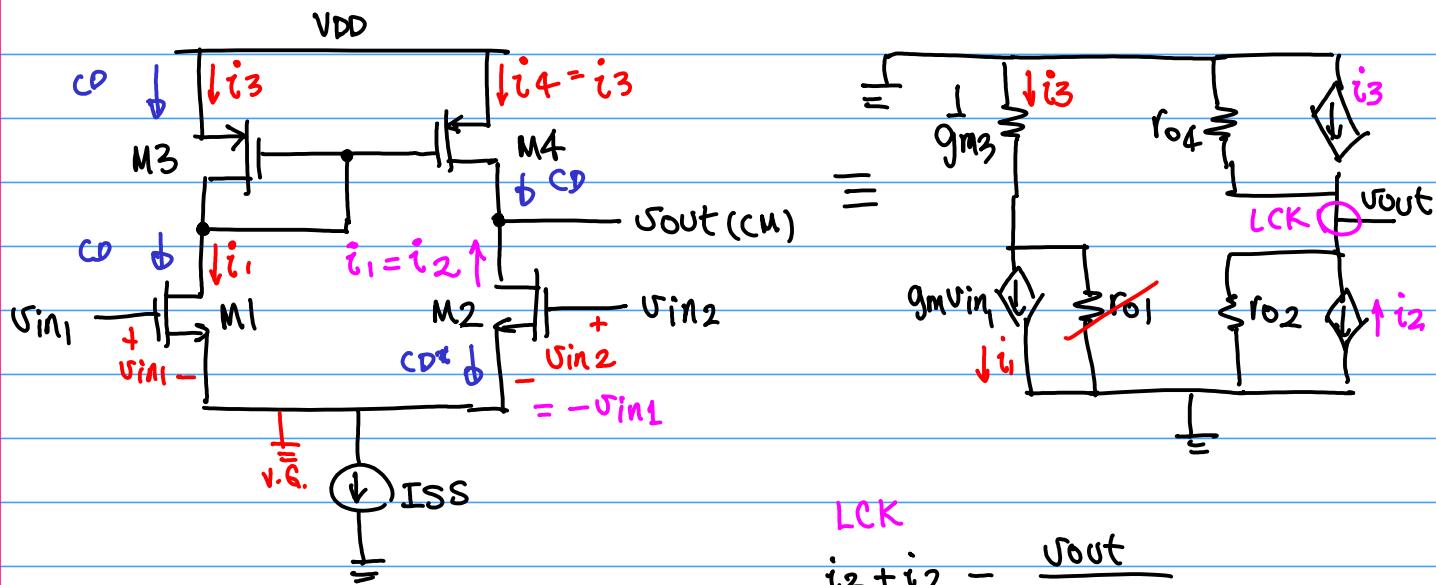
$$AV \approx -g_{m1} \times \frac{1}{g_{m2}}$$

par diferencial con carga activa (p482)

$$AV \approx -1$$

El circuito con PMOS M3 y M4 como espejo de corriente:

Convierte la salida diferencial a una salida de modo común.



El divisor de corriente M1 y M3:

$$g_m V_{in1} = i_3 + i_{r01}$$

$$i_3 = \frac{g_m V_{in1} \times r_{01}}{\frac{1}{g_{m3}} + r_{01}}$$

$$\text{Si } r_{01} \gg \frac{1}{g_{m3}}, \quad i_3 = g_m V_{in1}$$

$$r_{03} \gg \frac{1}{g_{m3}}$$

$$i_{r01} \approx 0$$

$$i_3 + i_2 = \frac{V_{out}}{r_{02} // r_{04}}$$

$$\approx i_1 + i_2 = \frac{V_{out}}{r_{02} // r_{04}}$$

$$g_m V_{in1} - g_m V_{in2} = \frac{V_{out}}{r_{02} // r_{04}}$$

$$g_m (V_{in1} - V_{in2}) = \frac{V_{out}}{r_{02} // r_{04}}$$

$$\frac{V_{out}}{V_{in1} - V_{in2}} = g_m (r_{02} // r_{04})$$

Ejemplo:

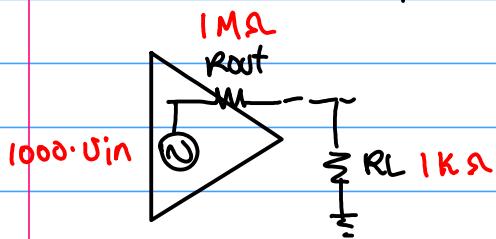
$$Si \lambda = 0.01 \text{ V}^{-1}, g_m = 1 \text{ mS}, I_{SS} = 100 \mu\text{A}$$

calcule  $A_V$  del par diferencial con carga activa.

$$r_o = \frac{1}{\lambda I_D} = \frac{1}{(0.01 \text{ V}^{-1})(50 \mu\text{A})} = 2 \text{ M}\Omega$$

$$A_V = g_m \cdot (r_{o2}/r_{o4}) = 1 \text{ mS} \times 1 \text{ M}\Omega = 1000$$

Observación: el par diferencial que se ha estudiado  
funciona SIN CARGA.  $R_{out} = 1 \text{ M}\Omega$



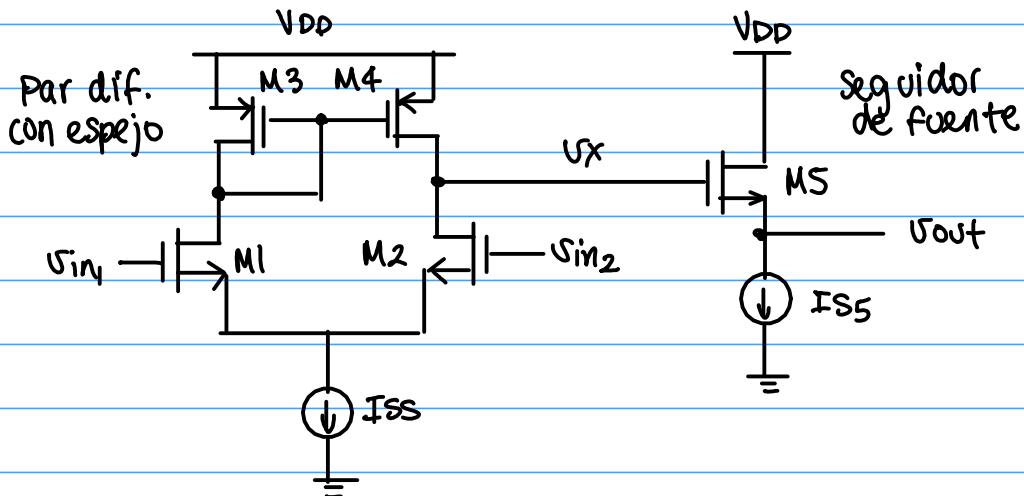
$$A_V = g_m (r_{o2}/r_{o4}/R_L)$$

$$A_V = 1 \text{ mS} (2 \text{ M}\Omega / 2 \text{ M}\Omega / 1 \text{ k}\Omega)$$

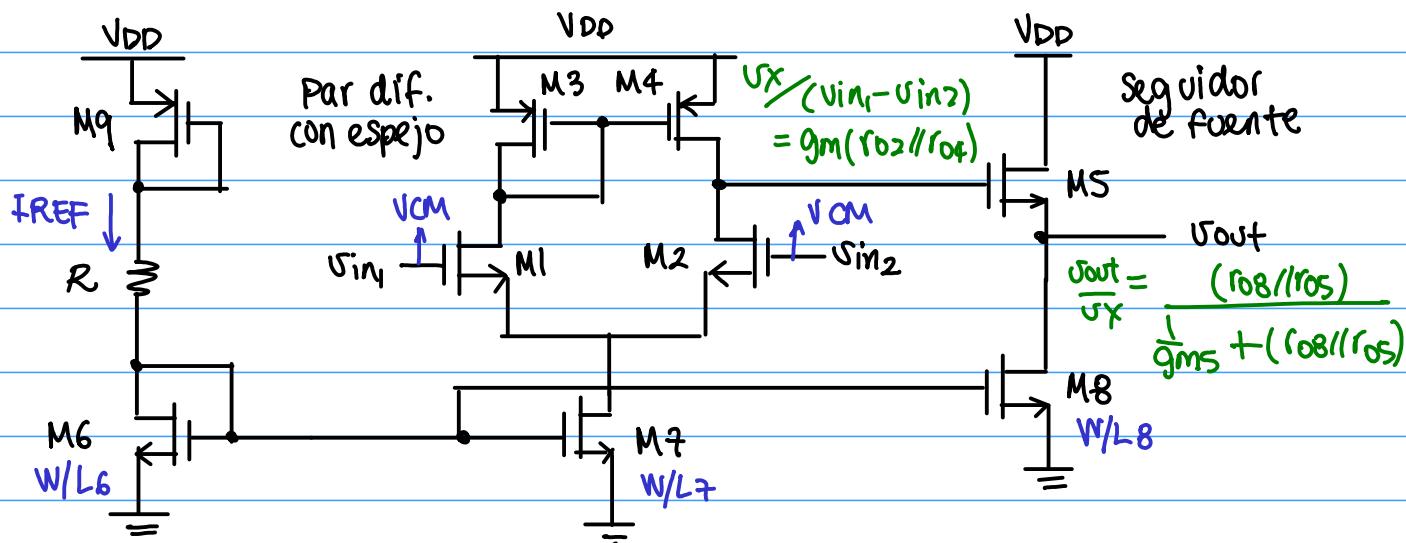
$$A_V = 1 \text{ mS} \times 1 \text{ k}\Omega$$

$$\boxed{A_V = 1} \times$$

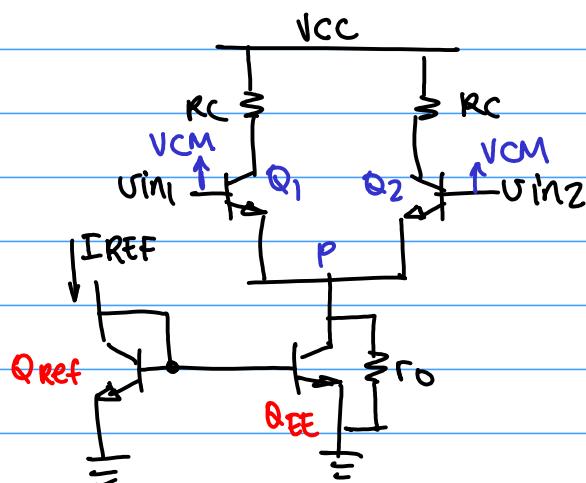
### Amplificador Operacional Completo



## Amplificador operacional con polarización MOS



Ganancia de modo común



Si se usa una fuente ideal,  
 $V_{CM} \uparrow$ ,  $V_P \uparrow$ ,  $V_{BE}$  cte,  $I_{EE}$  cte.

Si se usa una fuente no ideal,  
 $V_{CM} \uparrow \rightarrow V_P \uparrow$ ,  $i_{ro1} \uparrow$ ,  $I_{EE} \uparrow$   
 $\rightarrow I_{Q1} \uparrow$  y  $I_{Q2} \uparrow$   
 $\rightarrow V_{C1} \downarrow$  y  $V_{C2} \downarrow$

si el circuito es asimétrico,

$$|A_{DM}| = g_m \cdot R_C$$

$$A_{CM} = \frac{\Delta V_{out}}{\Delta V_{CM}}$$

$$V_{out1} \neq V_{out2} \text{ en C.D.}$$

$$\boxed{V_{out} \neq 0}$$

Esto es un problema, porque  $V_{CM}$  puede tener rizo de C.D que estaría siendo amplificado y aparece en  $V_{out}$ .

$$\tilde{V_{CM}} = \tilde{V_{CM}} \Rightarrow V_{out} \sim = A_{CM} \cdot V_{CM}$$

(debería cancelarse!)

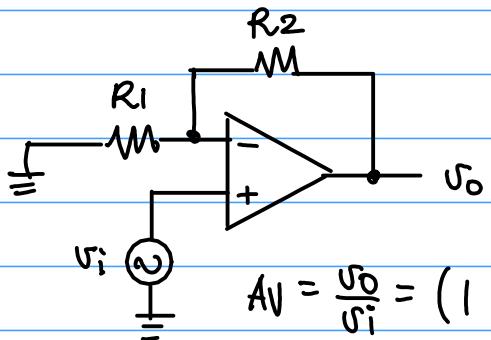
$$CMRR = \frac{A_{DM}}{A_{CM} - A_{DM}}$$

Common-mode rejection ratio

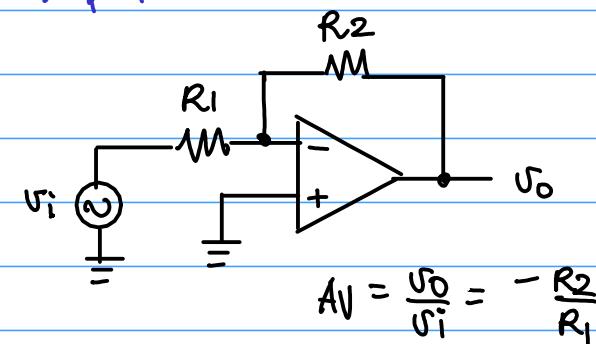
## Aplicaciones de los OP-AMP

(introducción al curso de circuitos integrados)

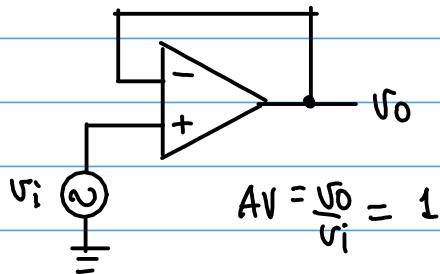
### Amplificador No inversor



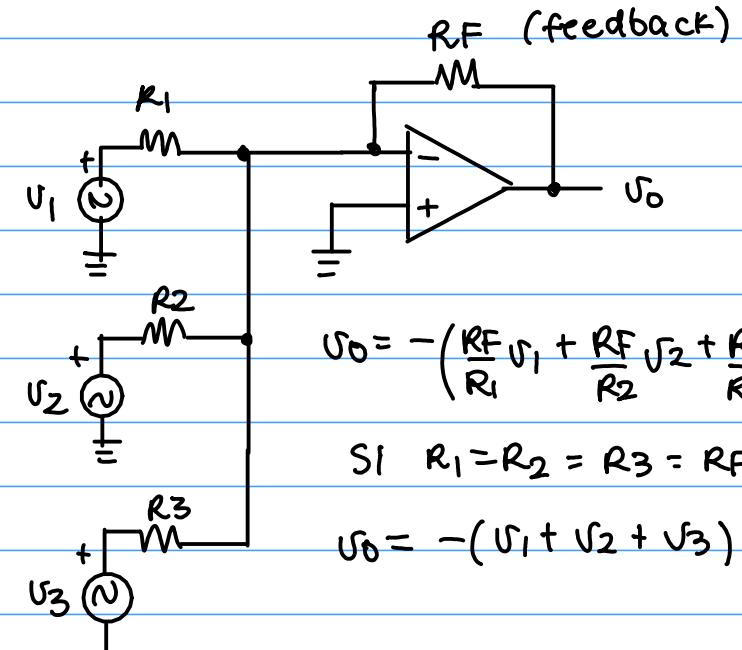
### Amplificador Inversor



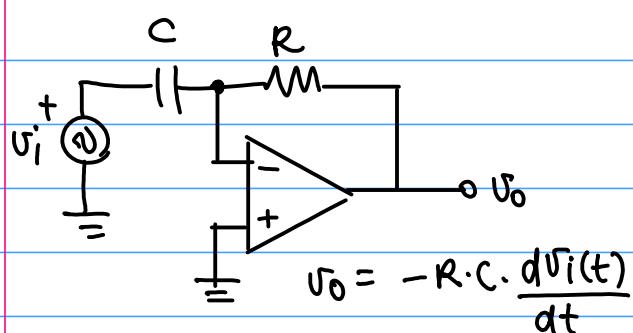
### Amplificador Seguidor



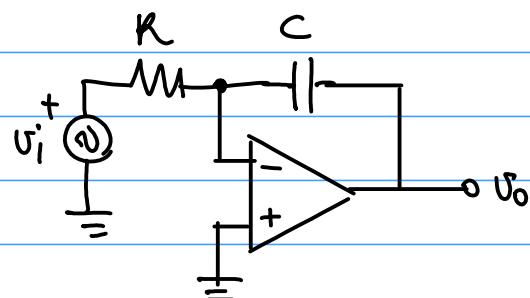
### Amplificador Sumador



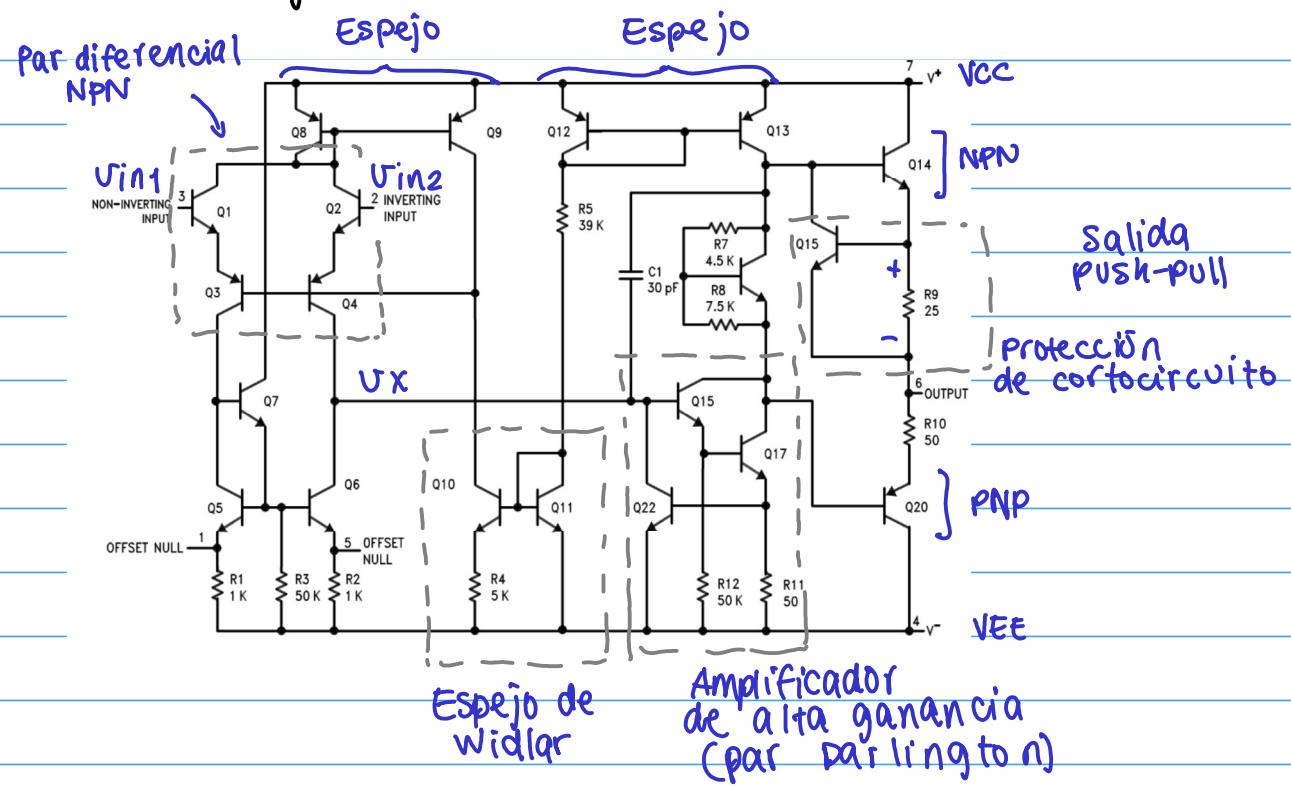
### Amplificador diferenciador



### Amplificador integrador



## El circuito integrado LM741



## El OP-AMP LM386

