Introducción a Circuitos Analógicos

Dispositivos Semiconductores

Maestría en Ciencias de la Ingeniería

Universidad de Buenos Aires, Facultad de Ingeniería

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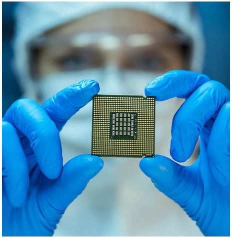
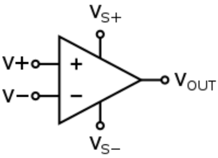
Tabla de contenido

Microelectrónica y Circuitos Integrados

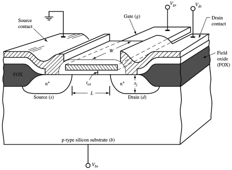
Diseño de sistemas electrónicos capaces de ser integrados en un mismo chip semiconductor.



$\Rightarrow$



$\Rightarrow$

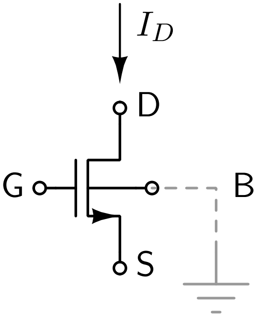


La tecnología dominante es CMOS.

Los elementos fundamentales para el diseño de circuitos analógicos son los MOSFET.

MOSFET: Simbología

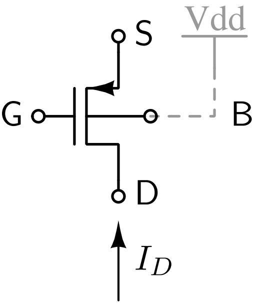
NMOS



$$I_{\mathsf{D}} = f(V_{\mathsf{GS}}, V_{\mathsf{DS}}, V_{\mathsf{BS}}) \geq 0$$

$$V_D \geq V_S \geq V_B = 0$$

PMOS



$$I_{\mathsf{D}} = f(V_{\mathsf{GS}}, V_{\mathsf{DS}}, V_{\mathsf{BS}}) \leq 0$$

$$V_D \leq V_S \leq V_B = V_{dd}$$

NMOS

$$I_{\mathsf{D}} = \begin{cases} \mu_n C'_{ox} \frac{W}{L} (m-1) V_{\mathsf{th}}^2 \exp\left(\frac{V_{\mathsf{GS}} - V_{\mathsf{T}}}{m\, V_{\mathsf{th}}}\right) & V_{\mathsf{GS}} \leq V_{\mathsf{T}} \\ \frac{\mu_n C'_{ox}}{2m} \frac{W}{L} \left(V_{\mathsf{GS}} - V_{\mathsf{T}}\right)^2 & V_{\mathsf{GS}} > V_{\mathsf{T}}; V_{\mathsf{DS}} \geq V_{\mathsf{DS(sat)}} \\ \mu_n C'_{ox} \frac{W}{L} \left(V_{\mathsf{GS}} - V_{\mathsf{T}} - \frac{m}{2} V_{\mathsf{DS}}\right) V_{\mathsf{DS}} & V_{\mathsf{GS}} > V_{\mathsf{T}}; V_{\mathsf{DS}} < V_{\mathsf{DS(sat)}} \end{cases}$$

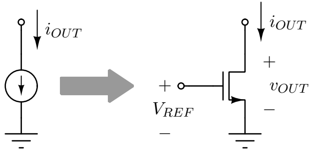
$$V_{\mathsf{T}}(V_{\mathsf{BS}}) = V_{\mathsf{T}0} + \gamma(\sqrt{-V_{\mathsf{BS}} - 2\psi_B} - \sqrt{-2\psi_B})$$

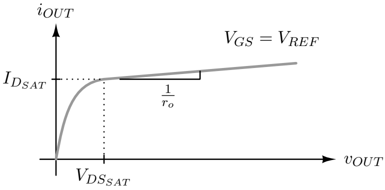
PMOS

$$I_{\mathsf{D}} = \begin{cases} -\mu_p C'_{ox} \frac{W}{L} (m-1) V_{\mathsf{th}}^2 \exp\left(-\frac{V_{\mathsf{GS}} - V_{\mathsf{T}}}{m\, V_{\mathsf{th}}}\right) & V_{\mathsf{GS}} \geq V_{\mathsf{T}} \\ -\frac{\mu_p C'_{ox}}{2m} \frac{W}{L} \left(V_{\mathsf{GS}} - V_{\mathsf{T}}\right)^2 & V_{\mathsf{GS}} < V_{\mathsf{T}}; V_{\mathsf{DS}} \leq V_{\mathsf{DS(sat)}} \\ -\mu_p C'_{ox} \frac{W}{L} \left(V_{\mathsf{GS}} - V_{\mathsf{T}} - \frac{m}{2} V_{\mathsf{DS}}\right) V_{\mathsf{DS}} & V_{\mathsf{GS}} < V_{\mathsf{T}}; V_{\mathsf{DS}} > V_{\mathsf{DS(sat)}} \end{cases}$$

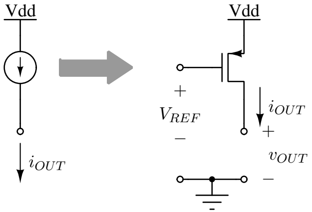
$$V_{\mathsf{T}}(V_{\mathsf{BS}}) = V_{\mathsf{T}0} - \gamma(\sqrt{V_{\mathsf{BS}} + 2\psi_B} - \sqrt{2\psi_B})$$

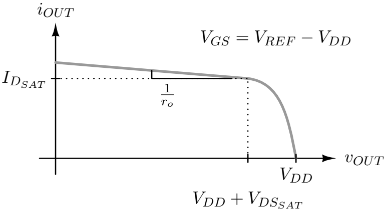
NMOS: Sumidero de corriente





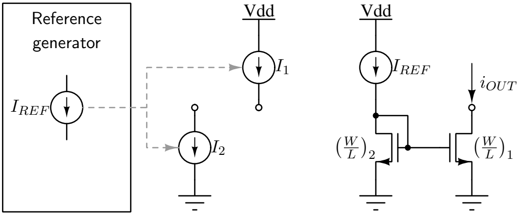
PMOS: Fuente de corriente





¿Cómo implementamos V_{REF}?

Hay muchas formas de generar una tensión de referencia.

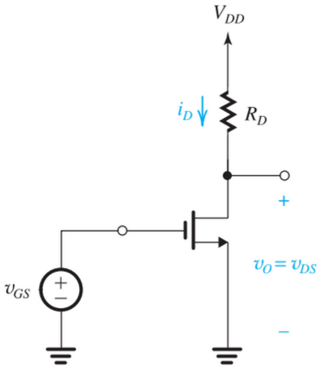


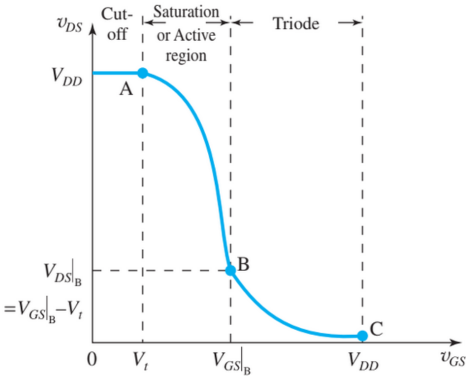
- Ambos transistores son idénticos (salvo W/L).
- $V_{\mathsf{GS}1} = V_{\mathsf{GS}2} = V_{\mathsf{GS}}$
- $I_{\mathsf{D}2} = I_{REF}$
- $I_{\mathsf{D}} = \frac{\mu_n C'_{ox}}{2m} \frac{W}{L} \left(V_{\mathsf{GS}} - V_{\mathsf{T}}\right)^2$

$$V_{\mathsf{GS}2} = V_{\mathsf{GS}} = V_{\mathsf{T}} + \sqrt{\frac{2m}{\mu_n C'_{ox} (W/L)_2} I_{REF}} \Rightarrow \left(V_{\mathsf{GS}} - V_{\mathsf{T}}\right)^2 = \frac{2m}{\mu_n C'_{ox} (W/L)_2} I_{REF}$$

$$\Rightarrow i_{OUT} = I_{\mathsf{D}1} = \frac{(W/L)_1}{(W/L)_2} I_{REF}$$

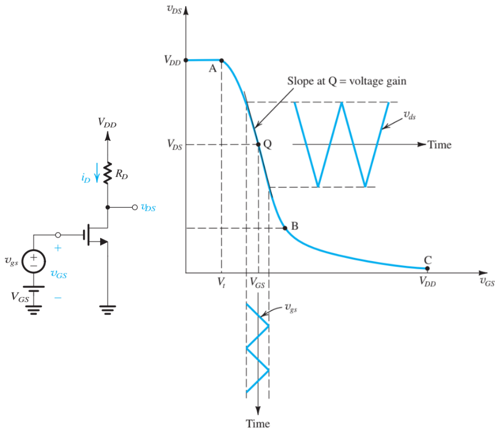
Variamos V_{GS} y vemos cómo responde V_{DS}.





$v_{\text{IN}} = v_{\text{GS}} \qquad v_{\text{OUT}} = v_{\text{DS}}$

Si queremos una relación lineal entre la salida y la entrada:



$$A_v = \frac{dv_{\mathsf{OUT}}}{dv_{\mathsf{IN}}}$$

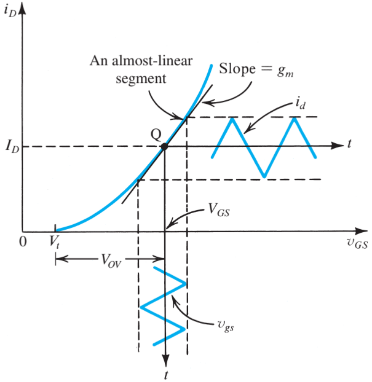
La relación entre v_{OUT} y v_{IN} debe parecerse a una recta.

Como el MOSFET no es lineal, hay que hacer aproximaciones $\rightarrow$ Modelo de pequeña señal

(Aceptamos cometer un error)

La región donde la pendiente es máxima es en Saturación.

Objetivo: Encontrar un modelo lineal que relaciones i_{D} con $(v_{\mathsf{GS}}; v_{\mathsf{DS}}; v_{\mathsf{BS}})$.



$$v_{\mathsf{GS}} = V_{\mathsf{GS}} + v_{gs}$$

$$i_{\mathsf{D}} = \frac{\mu_n C'_{ox}}{2m} \frac{W}{L} \left(V_{\mathsf{GS}} + v_{gs} - V_{\mathsf{T}}\right)^2$$

$$i_{\mathsf{D}} = \underbrace{\frac{\mu_n C'_{ox}}{2m} \frac{W}{L} \left(V_{\mathsf{GS}} - V_{\mathsf{T}}\right)^2}_{I_{\mathsf{D}}} +$$

$$+ \underbrace{2\frac{\mu_n C'_{ox}}{2m} \frac{W}{L} \left(V_{\mathsf{GS}} - V_{\mathsf{T}}\right) v_{gs}}_{i_d = \frac{di_{\mathsf{D}}}{dv_{\mathsf{GS}}} v_{gs}} +$$

$$+ \underbrace{\frac{\mu_n C'_{ox}}{2m} \frac{W}{L} v_{gs}^2}_{\text{Error}}$$

$$i_{\mathsf{D}} \approx I_{\mathsf{D}} + i_d$$

El error es despreciable si $v_{gs} \ll 2(V_{\mathsf{GS}} - V_{\mathsf{T}})$.

Generalizando el modelo de pequeña señal:

$$i_{\mathsf{D}} = f(v_{\mathsf{GS}}; v_{\mathsf{DS}}; v_{\mathsf{BS}}) = \underbrace{\frac{\mu_n C'_{ox}}{2m}}_{k} \frac{W}{L} \left(v_{\mathsf{GS}} - V_{\mathsf{T}}(v_{\mathsf{BS}})\right)^2 (1 + \lambda v_{\mathsf{DS}})$$

$$i_{\mathsf{D}} \approx I_{\mathsf{D}} \underbrace{(V_{\mathsf{GS}}; V_{\mathsf{DS}}; V_{\mathsf{BS}})}_{Q} + \underbrace{\left.\frac{\partial i_{\mathsf{D}}}{\partial v_{\mathsf{GS}}}\right|_Q}_{g_m} v_{gs} + \underbrace{\left.\frac{\partial i_{\mathsf{D}}}{\partial v_{\mathsf{DS}}}\right|_Q}_{g_o} v_{ds} + \underbrace{\left.\frac{\partial i_{\mathsf{D}}}{\partial v_{\mathsf{BS}}}\right|_Q}_{g_{mb}} v_{bs}$$

Para el MOSFET en Saturación:

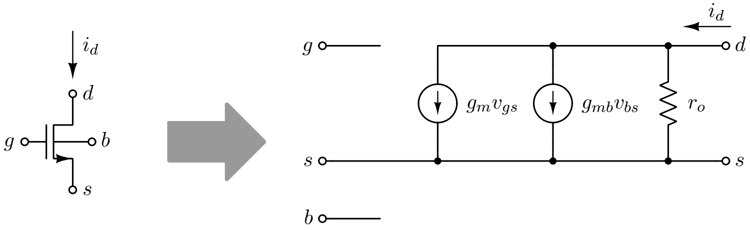
$$g_m = 2k\frac{W}{L} \left(V_{\mathsf{GS}} - V_{\mathsf{T}}\right) (1 + \lambda V_{\mathsf{DS}}) = 2\sqrt{\frac{k(W/L)I_{\mathsf{D}}}{1 + \lambda V_{\mathsf{DS}}}} = \frac{2I_{\mathsf{D}}}{V_{\mathsf{GS}} - V_{\mathsf{T}}}$$

$$g_o = k\frac{W}{L} \left(V_{\mathsf{GS}} - V_{\mathsf{T}}\right)^2 \lambda = \frac{\lambda I_{\mathsf{D}}}{1 + \lambda V_{\mathsf{DS}}} \Rightarrow r_o = \frac{1}{g_o} = \frac{V_{\mathsf{A}} + V_{\mathsf{DS}}}{I_{\mathsf{D}}}$$

$$g_{mb} = \left.\frac{\partial i_{\mathsf{D}}}{\partial V_{\mathsf{T}}}\right|_Q \left.\frac{\partial V_{\mathsf{T}}}{\partial v_{\mathsf{BS}}}\right|_Q = (-g_m)\left(-\frac{\gamma}{2\sqrt{-V_{\mathsf{BS}} - 2\psi_B}}\right) = \eta g_m$$

Modelo de pequeña señal

... en régimen de Saturación

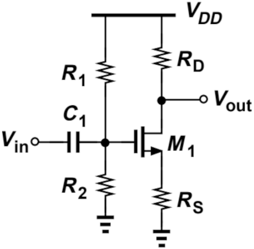


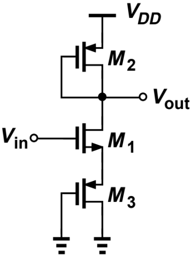
IMPORTANTE

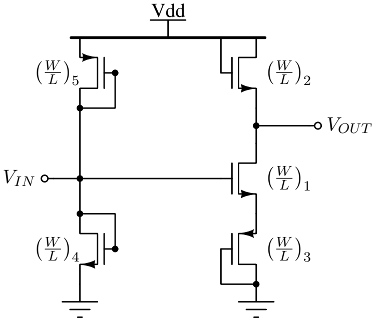
g_m; r_o y g_{mb} dependen de los valores de polarización. Entonces:

1. Se resuelve la polarización del circuito.
2. Se calculan los parámetros de pequeña señal.
3. Se resuelve el circuito equivalente de pequeña señal.

Polarización del MOSFET







T_2 a T_5: "Resistencias" no lineales.

T_1: "Amplificador".

Rama de referencia:

$$I_{\mathsf{D}5} = -I_{\mathsf{D}4}$$

$$k_p \left(\frac{W}{L}\right)_5 (V_{\mathsf{GS}5} - V_{\mathsf{T}p})^2 = k_n \left(\frac{W}{L}\right)_4 (V_{\mathsf{GS}4} - V_{\mathsf{T}n})^2$$

$$V_{\mathsf{GS}4} - V_{\mathsf{GS}5} = V_{\mathsf{DD}}$$

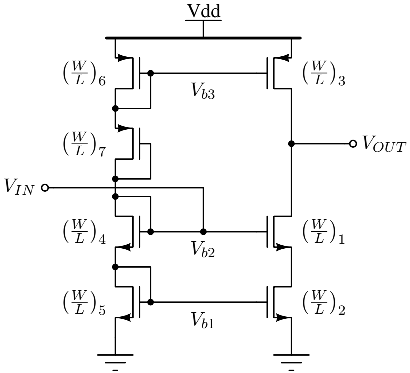
Rama de salida:

$$V_{\mathsf{GS}4} = V_{\mathsf{GS}1} - V_{\mathsf{GS}3}$$

$$I_{\mathsf{D}1} = I_{\mathsf{D}2} = -I_{\mathsf{D}3}$$

$$V_{\mathsf{DS}1} = V_{\mathsf{DD}} - V_{\mathsf{GS}2} + V_{\mathsf{GS}3}$$

$$V_{\mathsf{OUT}} = -V_{\mathsf{GS}3} + V_{\mathsf{DS}1} = V_{\mathsf{DD}} - V_{\mathsf{GS}2}$$



T_2 y T_3: Fuentes de corriente.

T_4 a T_7: Referencias.

T_1: "Amplificador".

Rama de referencia:

$$I_{\mathsf{D}5} = I_{\mathsf{D}4} = -I_{\mathsf{D}7} = -I_{\mathsf{D}6} = I_{REF}$$

$$V_{\mathsf{GS}5} + V_{\mathsf{GS}4} - V_{\mathsf{GS}7} - V_{\mathsf{GS}6} = V_{\mathsf{DD}}$$

Rama de salida:

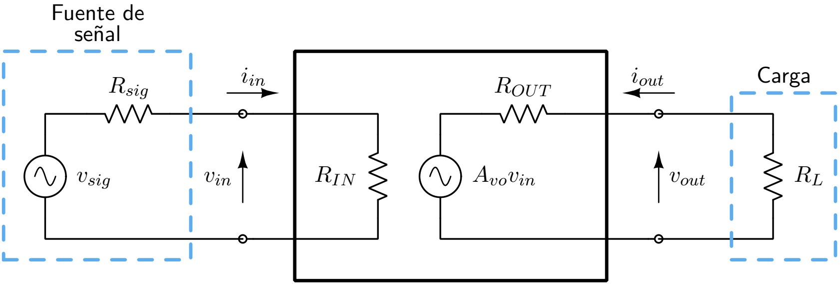
$$I_{\mathsf{D}1} = I_{\mathsf{D}2} = -I_{\mathsf{D}3}$$

$$V_{\mathsf{DS}2} = V_{b2} - V_{\mathsf{GS}1} = V_{\mathsf{GS}2}$$

$$V_{\mathsf{OUT}} = V_{\mathsf{DS}2} + V_{\mathsf{DS}1} = V_{\mathsf{DD}} + V_{\mathsf{DS}3}$$

Si $I_{\mathsf{D}1} = I_{REF} \Rightarrow (W/L)_1 = (W/L)_4; (W/L)_2 = (W/L)_5; (W/L)_3 = (W/L)_6$.
$(W/L)_{1\ldots6} \Leftrightarrow V_{\mathsf{GS}1\ldots6}$.
Nos queda $V_{\mathsf{GS}7} = V_{b2} - V_{b3} \Rightarrow (W/L)_7$.

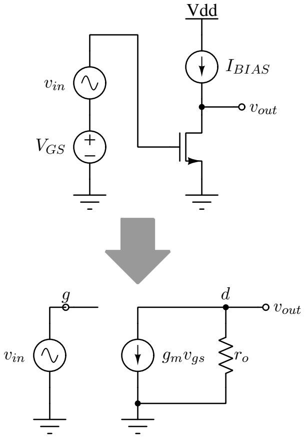
Macromodelo de Amplificador



$$A_{vo} = \left.\frac{v_{out}}{v_{in}}\right|_{i_{out}=0} \qquad R_{\mathsf{IN}} = \left.\frac{v_{in}}{i_{in}}\right|_{i_{out}=0} \qquad R_{\mathsf{OUT}} = \left.\frac{v_{out}}{i_{out}}\right|_{v_{in}=0}$$

$$v_{out} = A_{vo} v_{in} \frac{R_L}{R_{\mathsf{OUT}} + R_L} \qquad v_{in} = v_{sig} \frac{R_{\mathsf{IN}}}{R_{\mathsf{IN}} + R_{sig}}$$

Ganancia intrínseca del MOSFET



Al pasar al circuito equivalente de pequeña señal se pasivan las fuentes de continua:

- V $\rightarrow$Cortocircuito.
- I $\rightarrow$Circuito abierto.

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

$g_m v_{gs}$ se enciende y circula por r_o:

$$v_{out} = -g_m v_{in} r_o$$

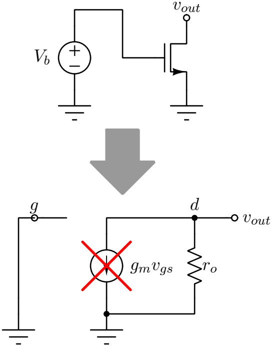
$$\Rightarrow \frac{v_{out}}{v_{in}} = -g_m r_o$$

$$a_{vi} \triangleq g_m r_o \approx 10\ldots30 \Rightarrow \frac{1}{g_m} \ll r_o$$

(si v_{in} se conecta al source $\Rightarrow a_{vi} = (g_m + g_{mb}) r_o = (1+\eta) g_m r_o$)

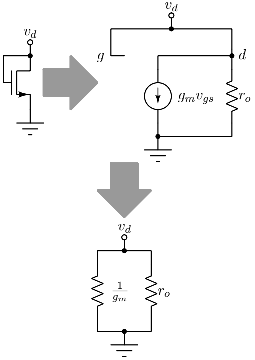
La ganancia intrínseca es una cota máxima a la ganancia que puede obtenerse con un único transistor.

Fuente de Corriente

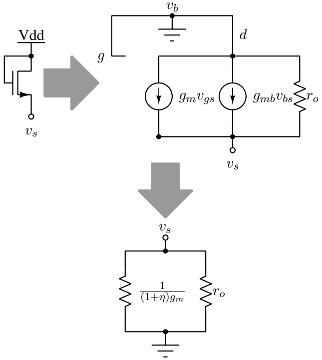


$$r_{cs} = r_o$$

Modo Diodo

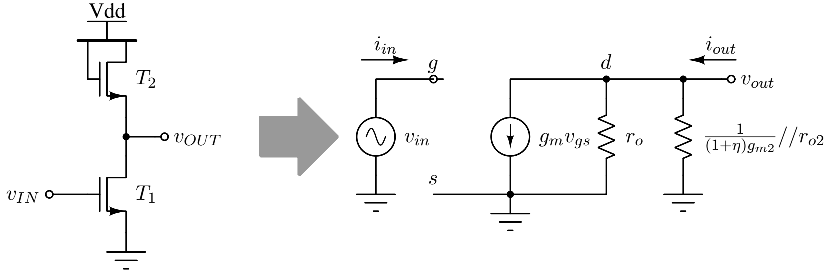


$$r_d = \frac{1}{g_m} // r_o$$



$$r_s = \frac{1}{(1+\eta)g_m} // r_o$$

Source Común con carga "diodo"



Ganancia

$$A_{vo} = \left.\frac{v_{out}}{v_{in}}\right|_{i_{out}=0} = -g_m(r_o//[(1+\eta)g_{m2}]^{-1}//r_{o2})$$

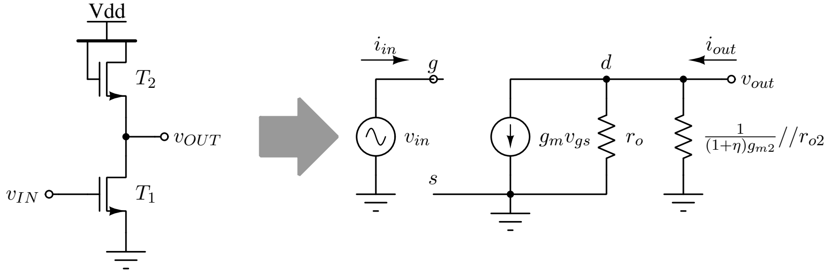
$$v_{gs} = v_{in}; \quad v_{out} = -g_m(r_o//[(1+\eta)g_{m2}]^{-1}//r_{o2})v_{in}$$

Resistencia de entrada

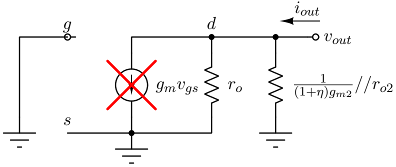
$$R_{\mathsf{IN}} = \left.\frac{v_{in}}{i_{in}}\right|_{i_{out}=0} \to \infty$$

$$i_{in} = i_g = 0$$

Source Común con carga “diodo”



Resistencia de salida

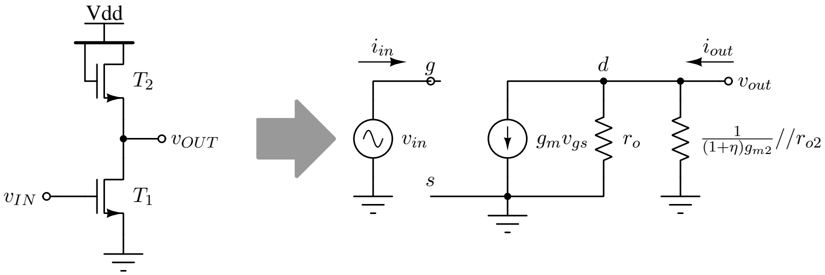


$$R_{\mathsf{OUT}} = \left.\frac{v_{out}}{i_{out}}\right|_{v_{in}=0} = r_o//[(1+\eta)g_{m2}]^{-1}//r_{o2}$$

$$v_{in} = v_{gs} = 0 \Rightarrow g_m v_{gs} = 0$$

$$i_{out} = \frac{v_{out}}{r_o//[(1+\eta)g_{m2}]^{-1}//r_{o2}}$$

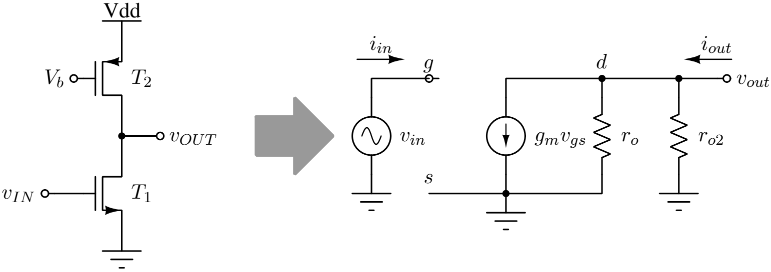
Source Común con carga "diodo"



$$A_{vo} = -g_m(r_o // [(1+\eta)g_{m2}]^{-1} // r_{o2}) \approx \frac{-g_m}{(1+\eta)g_{m2}} \approx -\frac{1}{(1+\eta)}\sqrt{\frac{(W/L)_1}{(W/L)_2}}$$

$$R_{\mathsf{OUT}} = r_o // [(1+\eta)g_{m2}]^{-1} // r_{o2} \approx \frac{1}{(1+\eta)} \frac{1}{g_{m2}}$$

Source Común con carga fuente de corriente



Ganancia

$$A_{vo} = \left.\frac{v_{out}}{v_{in}}\right|_{i_{out}=0} = -g_m(r_o//r_{o2})$$

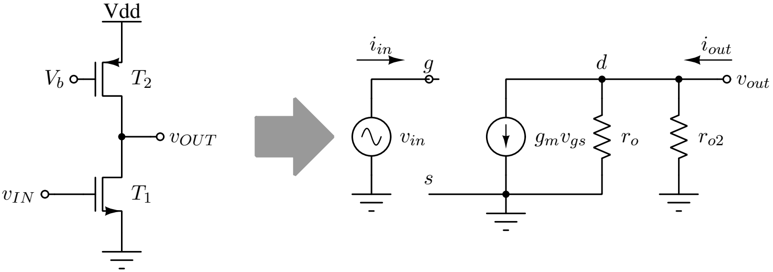
$$v_{gs} = v_{in}; \quad v_{out} = -g_m(r_o//r_{o2})$$

Resistencia de entrada

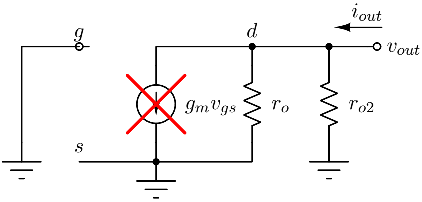
$$R_{\mathsf{IN}} = \left.\frac{v_{in}}{i_{in}}\right|_{i_{out}=0} \rightarrow \infty$$

$$i_{in} = i_g = 0$$

Source Común con carga fuente de corriente



Resistencia de salida

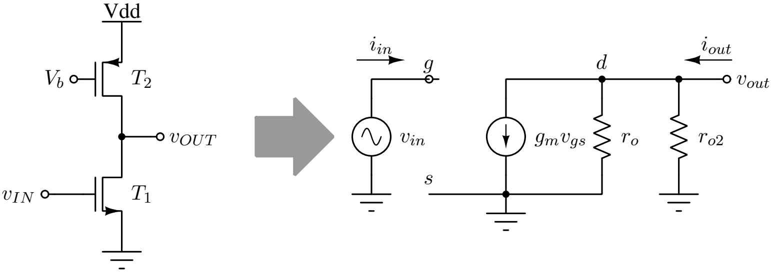


$$R_{\mathsf{OUT}} = \left.\frac{v_{out}}{i_{out}}\right|_{v_{in}=0} = r_o // r_{o2}$$

$$v_{in} = v_{gs} = 0 \Rightarrow g_m v_{gs} = 0$$

$$i_{out} = \frac{v_{out}}{r_o // r_{o2}}$$

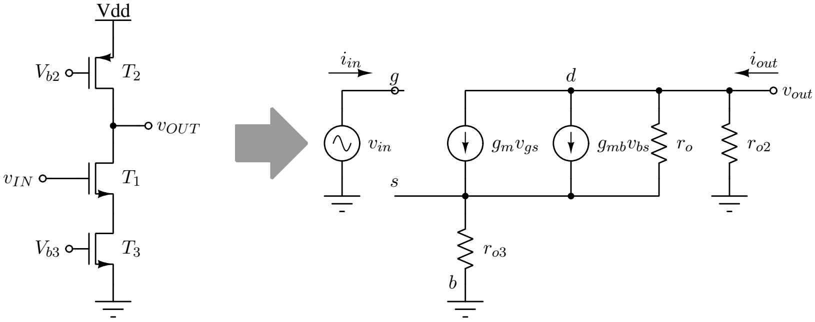
Source Común con carga fuente de corriente



$$A_{vo} = -g_m(r_o//r_{o2}) \approx -\frac{g_m r_o}{2}$$

$$R_{\mathsf{OUT}} = r_o//r_{o2} \approx \frac{r_o}{2}$$

Source Común degenerado con carga fuente de corriente



$$i_g = 0 \Rightarrow R_{\mathsf{IN}} \to \infty$$

T_3 intenta mantener $I_{\mathsf{D}1}$ constante mediante un lazo de realimentación.

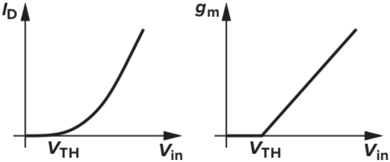
Si lo logra, $R_{\mathsf{OUT}} \to \infty$. $\Rightarrow$ El lazo de realimentación aumenta R_{OUT}.

Si lo logra, $A_v \to 0$. $\Rightarrow$ El lazo de realimentación disminuye A_v.

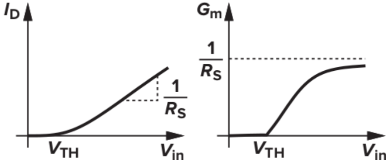
¿Para qué degenerar el circuito?

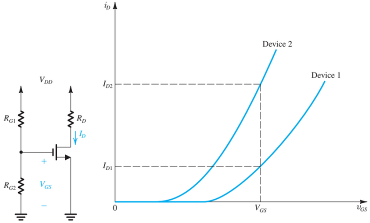
- Mejora la linealización.
- El circuito es más robusto frente a variaciones del proceso de fabricación.

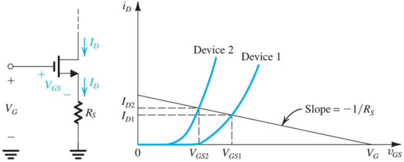
Sin degeneración de Source



Con degeneración de Source

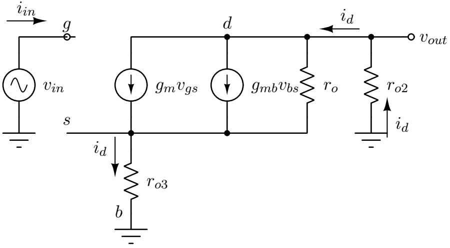






Source Común degenerado con carga fuente de corriente

Ganancia



$$i_d = g_m v_{gs} + g_{mb} v_{bs} + \frac{v_{ds}}{r_o}$$

$$v_{gs} = v_{in} - v_s;\ v_{bs} = -v_s;\ v_{ds} = v_{out} - v_s$$

$$i_d = g_m(v_{in} - v_s) - g_{mb} v_s + \frac{v_{out} - v_s}{r_o}$$

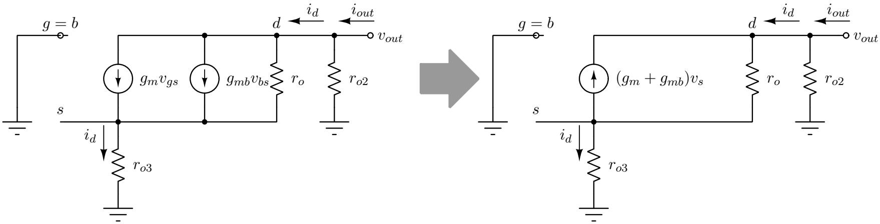
$$v_s = i_d r_{o3} \qquad v_{out} = -i_d r_{o2}$$

$$i_d = g_m(v_{in} - i_d r_{o3}) - g_{mb} i_d r_{o3} - \frac{i_d r_{o2} + i_d r_{o3}}{r_o}$$

$$\Rightarrow i_d \left(1 + (g_m + g_{mb}) r_{o3} + \frac{r_{o2} + r_{o3}}{r_o}\right) = g_m v_{in}$$

$$\Rightarrow A_{vo} = \frac{-g_m r_{o2}}{1 + (g_m + g_{mb}) r_{o3} + \frac{r_{o2}+r_{o3}}{r_o}} = \frac{-g_m r_o r_{o2}}{r_o + r_{o2} + r_{o3} + (g_m + g_{mb}) r_o r_{o3}}$$

Esto parece un bardo... ¿cómo me lo voy a acordar?

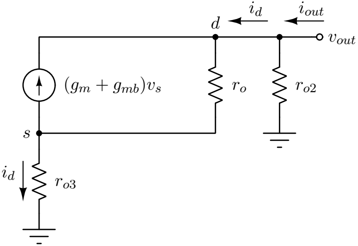


$$i_{out} = i_d + i_{r_{o2}} \Rightarrow R_{\mathsf{OUT}} = r_d // r_{o2} \quad \text{donde } r_d = \frac{v_d}{i_d} = \frac{v_{out}}{i_d}$$

El aumento en i_d genera un aumento en v_s.

Esto enciende la fuente controlada oponiéndose al aumento de i_d.

$$\Rightarrow R_{\mathsf{OUT}} \uparrow$$



$$r_d = \frac{v_{out}}{i_d}$$

$$i_d = \frac{v_{ds}}{r_o} - (g_m + g_{mb})v_s \qquad v_s = i_d r_{o3}$$

$$i_d = \frac{v_{out} - i_d r_{o3}}{r_o} - (g_m + g_{mb}) i_d r_{o3}$$

$$\Rightarrow v_{out} = i_d \left(r_o + r_{o3} + (g_m + g_{mb}) r_o r_{o3} \right)$$

$$\Rightarrow r_d = r_o + r_{o3} + (g_m + g_{mb}) r_o r_{o3}$$

$$\Rightarrow R_{\mathsf{OUT}} = r_d // r_{o2} = \frac{r_{o2} \left(r_o + r_{o3} + (g_m + g_{mb}) r_o r_{o3} \right)}{r_o + r_{o2} + r_{o3} + (g_m + g_{mb}) r_o r_{o3}}$$

Source Común degenerado con carga fuente de corriente

Interpretemos los resultados...

Supongamos que...

- $a_{vi} = g_m r_o \gg 1.$
- $g_{mb} = \eta g_m < g_m \Rightarrow g_m + g_{mb} \approx g_m.$

Resistencia de Salida

$$r_d = r_o + r_{o3} + (g_m + g_{mb}) r_o r_{o3} \approx r_o + r_{o3} + a_{vi} r_{o3} \approx (1 + a_{vi}) r_{o3}$$

$$\Rightarrow R_{\mathsf{OUT}} \approx r_{o2} // [(1 + a_{vi}) r_{o3}] = \frac{(1 + a_{vi}) r_{o2} r_{o3}}{r_{o2} + (1 + a_{vi}) r_{o3}}$$

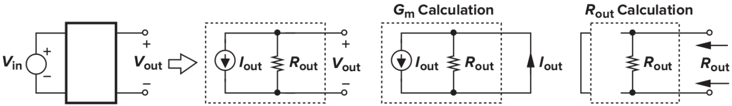
(Si bien $a_{vi} r_{o3} \gg r_{o2}$ ya veremos como compensarlo...)

Gracias a la realimentación, el drain "ve" la resistencia conectada al Source multiplicada por la ganancia intrínseca

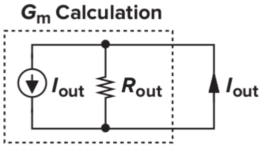
Ganancia

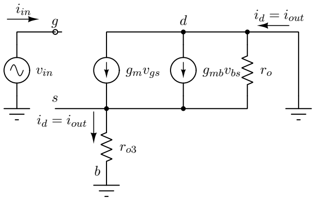
$$A_{vo} = \frac{-g_m r_o r_{o2}}{r_o + r_{o2} + r_{o3} + (g_m + g_{mb}) r_o r_{o3}}$$

$$= \underbrace{\frac{-g_m r_o}{r_o + r_{o3} + (g_m + g_{mb}) r_o r_{o3}}}_{-G_m} \underbrace{\frac{r_{o2}\left(r_o + r_{o3} + (g_m + g_{mb}) r_o r_{o3}\right)}{r_o + r_{o2} + r_{o3} + (g_m + g_{mb}) r_o r_{o3}}}_{R_{\mathrm{OUT}}}$$



Transconductancia





$$i_d = g_m v_{gs} + g_{mb} v_{bs} + \frac{v_{ds}}{r_o}$$

$$v_{gs} = v_{in} - v_s; \;\; v_{bs} = v_{ds} = -v_s = -i_d r_{o3}$$

$$i_d = g_m(v_{in} - v_s) - g_{mb} v_s - \frac{v_s}{r_o}$$

$$i_d = g_m v_{in} - i_d \left(g_m + g_{mb} + \frac{1}{r_o} \right) r_{o3}$$

$$i_d \left[1 + \left(g_m + g_{mb} + \frac{1}{r_o} \right) r_{o3} \right] = g_m v_{in}$$

$$\Rightarrow G_m = \frac{i_d}{v_{in}} = \frac{g_m r_o}{r_o + r_{o3} + (g_m + g_{mb}) r_o r_{o3}}$$

Source Común degenerado con carga fuente de corriente

Interpretemos los resultados...

Supongamos que...

- $a_{vi} = g_m r_o \gg 1$.
- $g_{mb} = \eta g_m < g_m \Rightarrow g_m + g_{mb} \approx g_m$.

$$G_m = \frac{g_m r_o}{r_o + r_{o3} + (g_m + g_{mb}) r_o r_{o3}} \approx \frac{a_{vi}}{r_o + r_{o3} + a_{vi} r_{o3}} \approx \frac{a_{vi}}{r_o + a_{vi} r_{o3}} = \frac{g_m}{1 + g_m r_{o3}}$$

Podemos pensar a r_{o3} como un elemento que sensa corriente y suma tensión, modificando la transconductancia del amplificador mediante un lazo de realimentación.

$$\begin{aligned} G_m &\to G_{m,cl} \\ g_m &\to G_{m,ol} \\ r_{o3} &\to R_f \end{aligned}$$

$$\Rightarrow G_{m,cl} = \frac{G_{m,ol}}{1 + G_{m,ol} R_f}$$

Source Común degenerado con carga fuente de corriente

Interpretemos los resultados...

$$A_{vo} = \frac{-g_m r_o r_{o2}}{r_o + r_{o2} + r_{o3} + (g_m + g_{mb}) r_o r_{o3}} = \underbrace{\frac{-g_m r_o r_{o2}}{r_o + r_{o2}}}_{A_{vo}^{\text{s/deg}}} \underbrace{\frac{r_o + r_{o2}}{r_d + r_{o2}}}_{<1}$$

El efecto de la realimentación es disminuir la ganancia.

Además, podemos escribir la ganancia en función de la ganancia intrínseca:

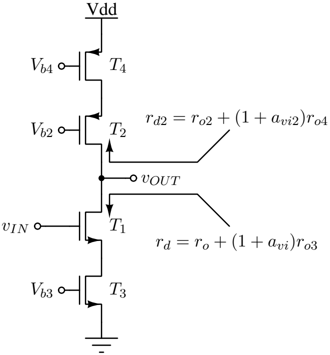
$$A_{vo} = \frac{-g_m r_o r_{o2}}{r_o + r_{o2} + r_{o3} + (g_m + g_{mb}) r_o r_{o3}} = -a_{vi} \frac{r_{o2}}{r_d + r_{o2}}$$

- Si la fuente de corriente que carga al circuito es ideal $\Rightarrow r_{o2} \rightarrow \infty \Rightarrow A_{vo} = a_{vi}$.
- Si la carga presenta una resistencia mucho menor que el drain del transistor ($r_{o2} \ll r_d$), la ganancia disminuye considerablemente.

¿Cómo logro un valor óptimo de ganancia?

Al calcular R_{OUT} en el circuito, todos los Gates se conectan a GND.

Desde el nodo de salida, queda un circutio "simétrico":



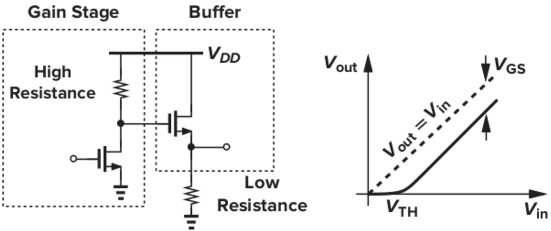
$$r_d = r_o + (1 + g_m r_o)r_{o3}$$

$$r_{d2} = r_{o2} + (1 + g_{m2} r_{o2})r_{o4}$$

$$R_{\mathsf{OUT}} = r_d // r_{d2} \approx (1 + g_m r_o)\frac{r_{o3} r_{o4}}{r_{o3} + r_{o4}} \approx (1 + g_m r_o)\frac{r_o}{2}$$

$$A_{vo} = -a_{vi}\frac{r_{d2}}{r_d + r_{d2}} = \frac{-g_m r_o[r_{o2} + (1 + g_{m2} r_{o2})r_{o4}]}{r_o + (1 + g_m r_o)r_{o3} + r_{o2} + (1 + g_{m2} r_{o2})r_{o4}} \approx \frac{-g_m r_o}{2}$$

Drain Común (Source Follower)



La aplicación de Source Común es como etapa de ganancia.

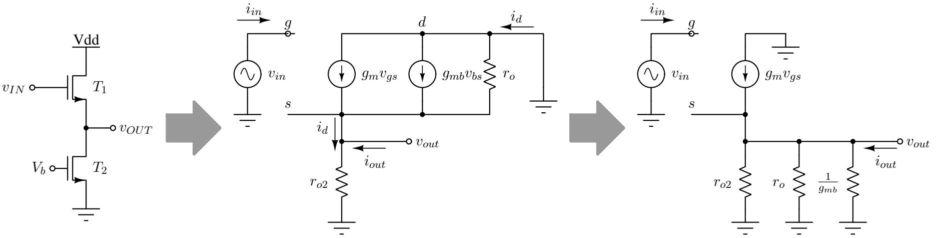
Sin embargo, la alta R_{OUT} hace que la ganancia en funcionamiento caiga en caso de conectar una impedancia de carga baja.

Es necesario incluir una etapa buffer para evitar la caída de ganancia.

Características de un Buffer de tensión ideal

- $R_{\text{IN}} \to \infty$.
- $R_{\text{OUT}} = 0$.
- $A_v = 1$.

El Drain Común presenta esas características.



Resistencia de Entrada

$$i_{in} = i_g = 0 \Rightarrow R_{\text{IN}} \to \infty$$

Ganancia

$$v_{out} = g_m v_{gs} (r_{o2} // r_o // {g_{mb}}^{-1})$$

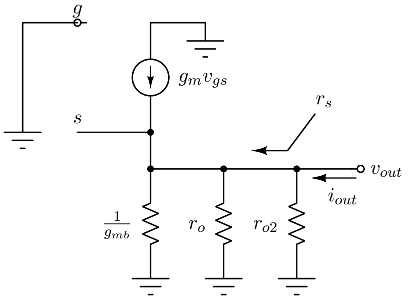
$$v_{gs} = v_{in} - v_{out} \qquad R_{S,eq} \triangleq r_{o2} // r_o // {g_{mb}}^{-1}$$

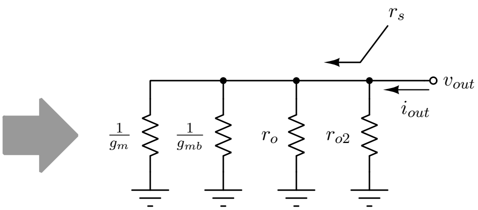
$$v_{out} = g_m (v_{in} - v_{out}) R_{S,eq}$$

$$A_{vo} = \left. \frac{v_{out}}{v_{in}} \right|_{i_{out}=0} = \frac{g_m R_{S,eq}}{1 + g_m R_{S,eq}} \approx \frac{g_m}{g_{mb} + g_m} = \frac{1}{\eta + 1}$$

Drain Común (Source Follower)

Resistencia de Salida

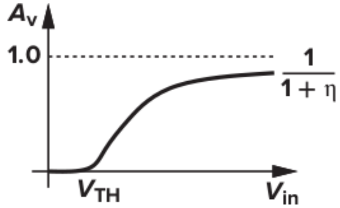


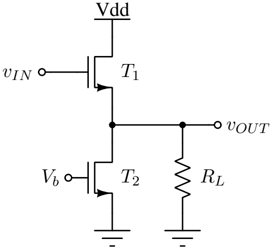


$$v_{gs} = v_{in} - v_{out} = -v_{out}$$

La fuente de corriente controlada se redefine como una resistencia de valor $\frac{1}{g_m}$.
Por simple inspección:

$$R_{\mathsf{OUT}} = {g_m}^{-1} // r_o // {g_{mb}}^{-1} // r_{o2} = r_s // r_{o2} \approx r_s = \frac{1}{(1+\eta)g_m}$$



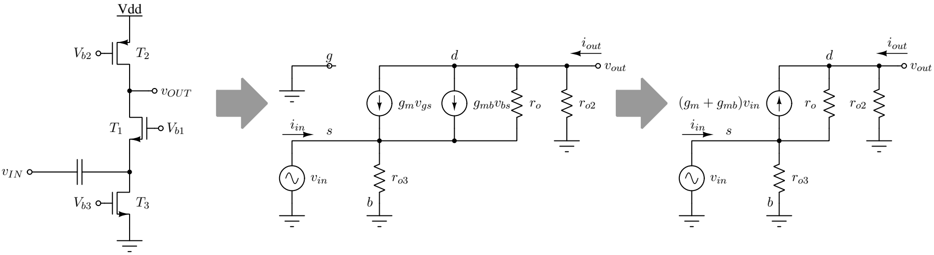


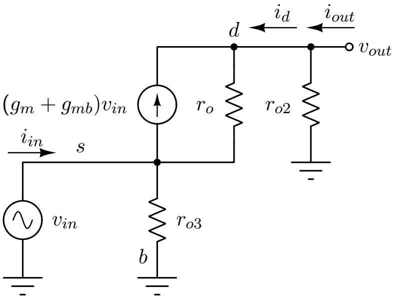
- Body Effect
  - La ganancia está limitada por el efecto Body.
  - Al alejar V_{IN} de V_{T}, $A_{vo} \to \frac{1}{\eta+1}$.
  - Al aumentar V_{OUT}, $\eta \to 0$.
  - Mejor implementar con PMOS, con bulk aislado.
- Efecto de carga
  - R_L forma parte de $R_{S,eq}$.
  - Si R_L es baja (sin g_{mb}) $R_{S,eq} \approx R_L$:

$$\Rightarrow A_v \approx \frac{g_m R_L}{1 + g_m R_L}$$

  - Si $g_m R_L \ll 1 \Rightarrow A_v \approx g_m R_L \ll 1$

Gate Común


Vdd
V_{b2}
T_2
v_{OUT}
T_1
V_{b1}
v_{IN}
V_{b3}
T_3
g
d
i_{out}
v_{out}
$g_m v_{gs}$
$g_{mb} v_{bs}$
r_o
r_{o2}
i_{in}
s
v_{in}
r_{o3}
b
$(g_m + g_{mb})v_{in}$



$$v_{out} = -i_d r_{o2}$$

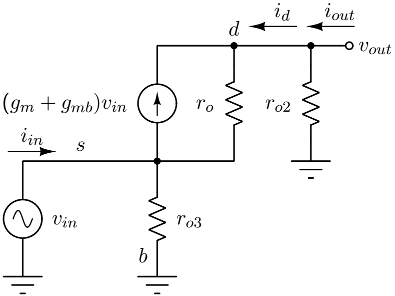
$$i_d = -(g_m + g_{mb})v_{in} + \frac{v_{ds}}{r_o}$$

$$= -(g_m + g_{mb})v_{in} + \frac{v_{out} - v_{in}}{r_o}$$

$$v_{out} = \left[(g_m + g_{mb})v_{in} - \frac{v_{out} - v_{in}}{r_o}\right] r_{o2}$$

$$v_{out}(r_o + r_{o2}) = v_{in}((g_m + g_{mb})r_o + 1)r_{o2}$$

$$A_{vo} = \left.\frac{v_{out}}{v_{in}}\right|_{i_{out}=0} = \frac{((g_m + g_{mb})r_o + 1)r_{o2}}{r_o + r_{o2}} \approx (1+\eta)g_m(r_o//r_{o2})$$



$$i_{in} = i_{r_{o3}} + i_s \Rightarrow R_{\mathsf{IN}} = r_{o3}//r_s$$

$$r_s = \frac{v_s}{i_s} = \frac{v_{in}}{-i_d}$$

$$-i_d = (g_m + g_{mb})v_{in} + \frac{v_{in} - v_{out}}{r_o}$$

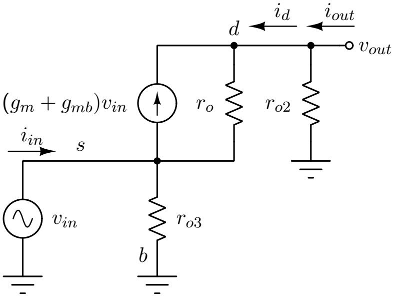
$$v_{out} = -i_d r_{o2}$$

$$\Rightarrow -i_d = \left(g_m + g_{mb} + \frac{1}{r_o}\right) v_{in} - \frac{-i_d r_{o2}}{r_o}$$

$$-i_d(r_o + r_{o2}) = v_{in}\left(g_m + g_{mb} + \frac{1}{r_o}\right) r_o$$

$$\Rightarrow r_s = \frac{r_o + r_{o2}}{r_o} \frac{1}{g_m + g_{mb} + \frac{1}{r_o}} = \frac{r_o + r_{o2}}{r_o} ({g_m}^{-1}//{g_{mb}}^{-1}//r_o)$$

$$\approx \frac{r_o + r_{o2}}{r_o} \frac{1}{(1+\eta)g_m}$$



$$r_s = \frac{1}{g_m + g_{mb} + \frac{1}{r_o}} + \frac{r_{o2}}{(g_m + g_{mb})r_o + 1}$$

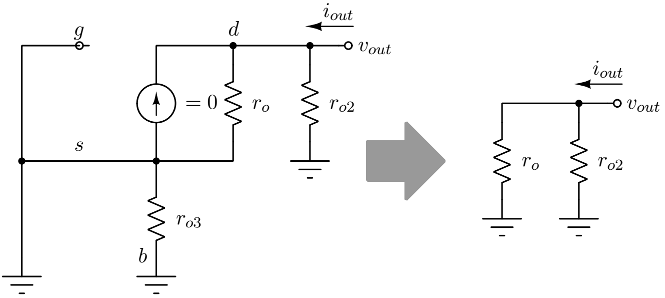
El primer término es equivalente a R_{OUT} del Drain Común.

La resistencia en el Drain se vea desde el source atenuada en $\sim (g_m + g_{mb})r_o$.

$$R_{\mathsf{IN}} = r_s // r_{o3} \approx r_s = \frac{r_o + r_{o2}}{r_o} \frac{1}{(1+\eta)g_m}$$

Gate Común

Resistencia de salida



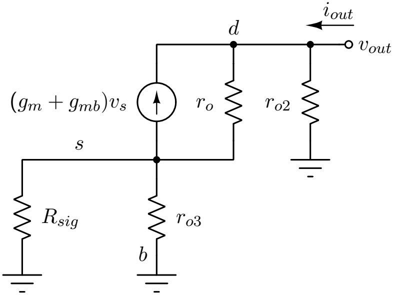
Al cortocircuitar la entrada, el Source se conecta a tierra, al igual que Gate y Bulk.

$\Rightarrow v_{gs} = v_{bs} = 0 \Rightarrow$ No se enciende la fuente de corriente controlada.

Por simple inspección:

$$R_{\text{OUT}} = r_o // r_{o2}$$

En este caso, el análisis es igual a R_{OUT} del SC con degeneración de Source:



$$r_d = \frac{v_{out}}{i_d} \qquad R_{S,eq} = R_{sig}//r_{o3}$$

$$i_d = \frac{v_{ds}}{r_o} - (g_m + g_{mb})v_s \qquad v_s = i_d R_{S,eq}$$

$$i_d = \frac{v_{out} - i_d R_{S,eq}}{r_o} - (g_m + g_{mb}) i_d R_{S,eq}$$

$$\Rightarrow v_{out} = i_d \left(r_o + R_{S,eq} + (g_m + g_{mb}) r_o R_{S,eq}\right)$$

$$\Rightarrow r_d = r_o + (1 + (g_m + g_{mb}) r_o) R_{S,eq}$$

La resistencia en el Source se vea desde el Drain amplificada en $\sim (g_m + g_{mb}) r_o$.

$$\Rightarrow R_{\text{OUT}} = r_d // r_{o2} = \frac{r_{o2}\left(r_o + R_{S,eq} + (g_m + g_{mb}) r_o R_{S,eq}\right)}{r_o + r_{o2} + R_{S,eq} + (g_m + g_{mb}) r_o R_{S,eq}} \approx \frac{a_{vi} r_{o2} R_{S,eq}}{r_{o2} + a_{vi} R_{S,eq}}$$

Comparación

	SC(d)	SC(fc)	SC(deg)	DC	GC
A_{vo}	$\sim \frac{1}{\eta}\frac{g_m}{g_{m2}}$	$-g_m(r_o//r_{o2})$	$-a_{vi}\frac{r_{o2}}{r_d+r_{o2}}$	$\sim \frac{g_m R_L}{1+g_m R_L}$	$\sim (1+\eta)g_m(r_o//r_{o2})$
R_{IN}	∞	∞	∞	∞	$\frac{r_o+r_{o2}}{r_o}\frac{1}{(1+\eta)g_m}$
R_{OUT}	$\sim \frac{1}{\eta}\frac{1}{g_{m2}}$	$r_o//r_{o2}$	$\sim \frac{a_{vi}r_{o2}r_{o3}}{r_{o2}+a_{vi}r_{o3}}$	$\sim \frac{1}{g_m}$	$\sim \frac{a_{vi}r_{o2}R_{S,eq}}{r_{o2}+a_{vi}R_{S,eq}}$