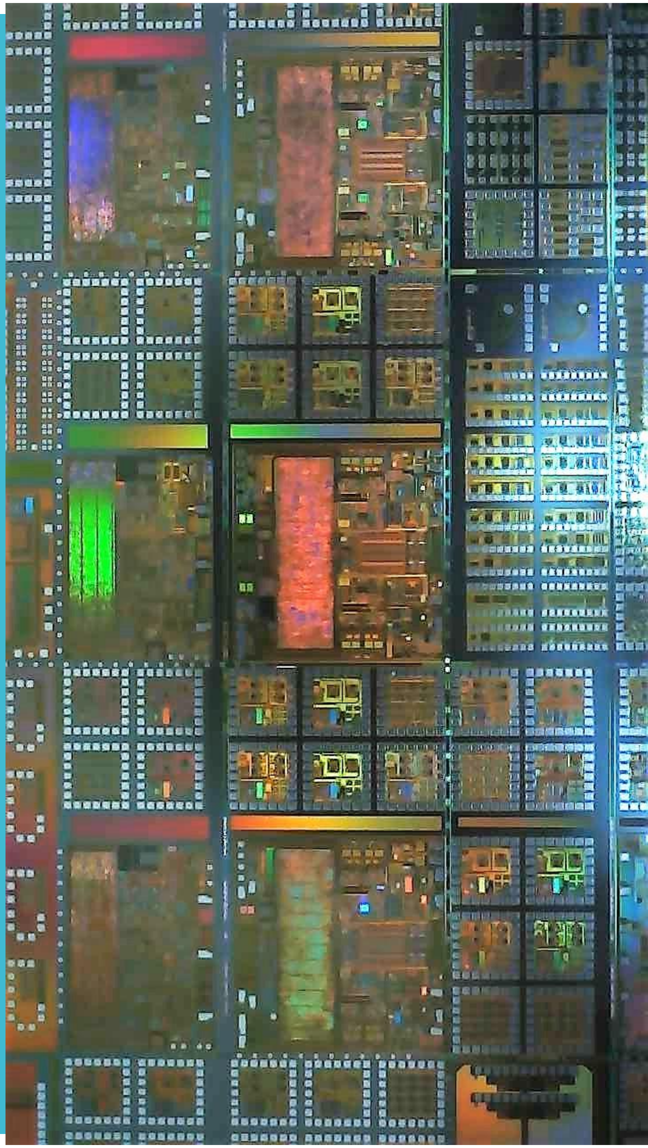
Diseño Analógico

2024



Calendario

Capítulo 1: Introducción

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- Clase 2: Cadence - Introducción y Circuitos monoetapas
- Clase 3: Par diferencial. Amplificador diferencial. Implementación básica

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Calendario

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- Clase 14: Circuitos auxiliares. Referencias, bandgap, osciladores

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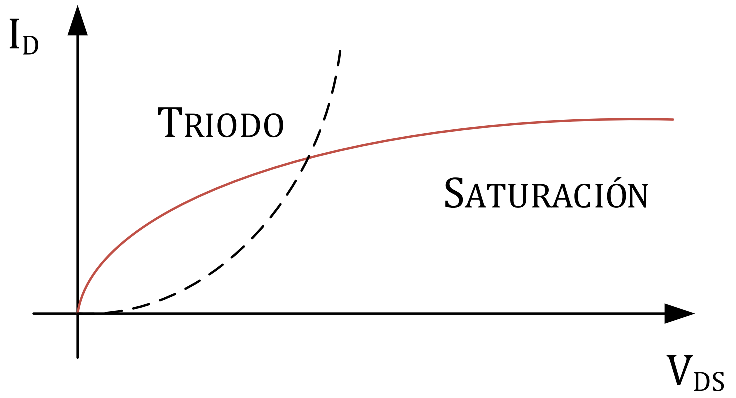
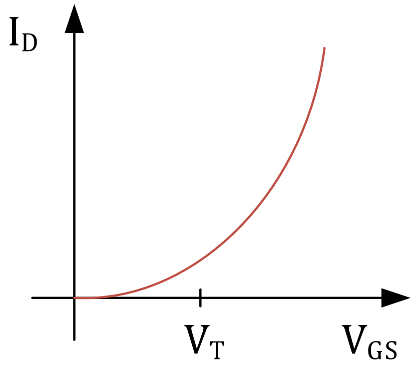
- **1.1 Transistor MOS**

1.1.1 Transferencias





1.1.2 Modos de Operación

- Subthreshold

  0V < VGS < VT

- Triodo

  VGS > VT , VDS < VGS - VT

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

- Saturación

VGS > VT , VDS > VGS - VT

$$\mathrm{ID} = \frac{1}{2}\mathrm{Kp}\frac{\mathrm{W}}{\mathrm{L}}(\mathrm{VGS} - \mathrm{VT})^2(1 + \lambda\mathrm{VDS})$$

Si λVDS << 1 →

$$\boxed{\mathrm{ID} = \frac{1}{2}\mathrm{Kp}\frac{\mathrm{W}}{\mathrm{L}}(\mathrm{VGS} - \mathrm{VT})^2}$$

$$\mathrm{Kp} = \mu\mathrm{o}.\,\mathrm{Cox}$$

μo: Zero field mobility

Cox: Gate oxide capacitance per unit area

$$\mathrm{Cox} = \frac{\varepsilon\mathrm{ox}}{\mathrm{tox}}$$

tox: Gate oxide thickness

εox: Oxide permittivity

εox = εo. εr

εo = 8.85 x 10^{-12} F/m

εr = 3.9 para SiO_2

$$VT = VT0 + \gamma\left[\sqrt{2\varphi f + VSB} - \sqrt{2\varphi f}\right]$$

VT0: Zero bias threshold voltage [V]

γ: Bulk threshold parameter [√V]

2φf: Strong inversion surface potential [V]

VSB: Source to Body voltage [V]

$$\lambda = \frac{1}{VA}$$

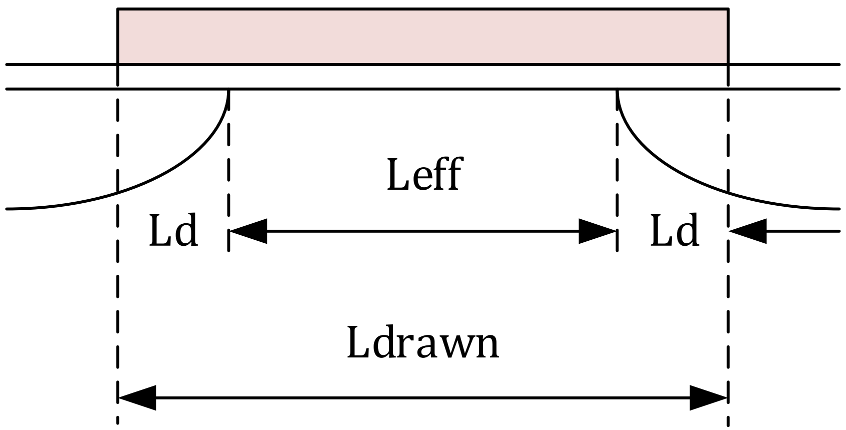
VA: Early voltage [V]

$$\lambda = \frac{1}{\mathrm{Leff}}\frac{d\mathrm{Xd}}{d\mathrm{VDS}}$$

Leff = Ldrawn – 2Ld - Xd

Ld: Lateral diffusion

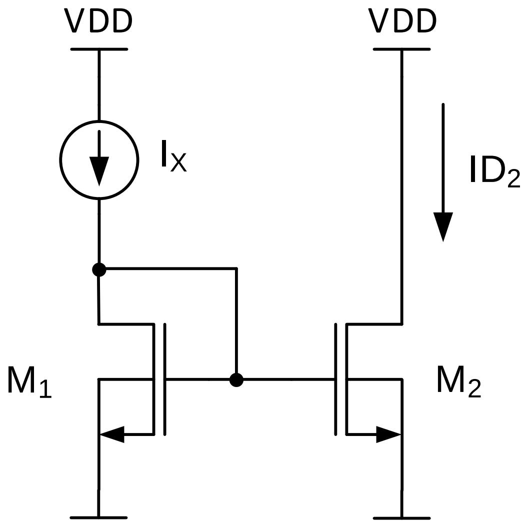
Xd: Depletion layer width



La variación de Xd con el voltaje VDS es compleja, por el hecho de que la distribución del campo en la región desierta del drain no es unidimensional. Por consiguiente, el cálculo de λ a partir de la estructura del dispositivo es difícil.

El valor de λ se suele obtener de datos experimentales.

Ejemplo: Espejo de corriente



$$VGS1 = VGS2$$

$$VDS1 = VGS1 \quad \rightarrow \quad \text{VGS1 será tal que ID1 = IX}$$

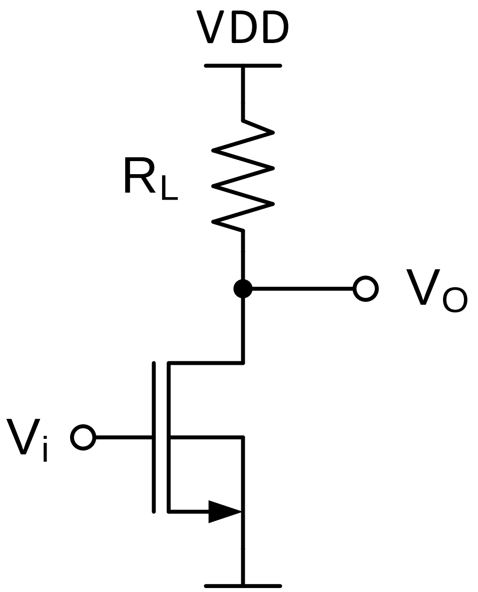
$$ID1 = \frac{1}{2} Kp \frac{W1}{L1} (VGS1 - VT)^2 \quad \rightarrow \quad VGS1 = \sqrt{\frac{2.ID1}{Kp \frac{W1}{L1}}} + VT$$

$$ID2 = \frac{1}{2} Kp \frac{W2}{L2} \left(\sqrt{\frac{2.ID1}{Kp \frac{W1}{L1}}} + VT - VT \right)^2$$

$$\boxed{ID2 = \frac{W2}{L2} \frac{L1}{W1} ID1}$$

$$\text{Si L1 = L2} \quad \rightarrow \quad ID2 = \frac{W2}{W1} ID1$$

Ejemplo: Ganancia de señal



$Kp = 120\mu A/V^2$, $RL = 100k\Omega$, $ID = 10\mu A$

$VDD = 3V$, $W = 10\mu m$, $L = 5\mu m$, $VT = 0.7V$

$$\frac{\Delta Vo}{\Delta Vi} = ?$$

Primero es necesario calcular el punto Q

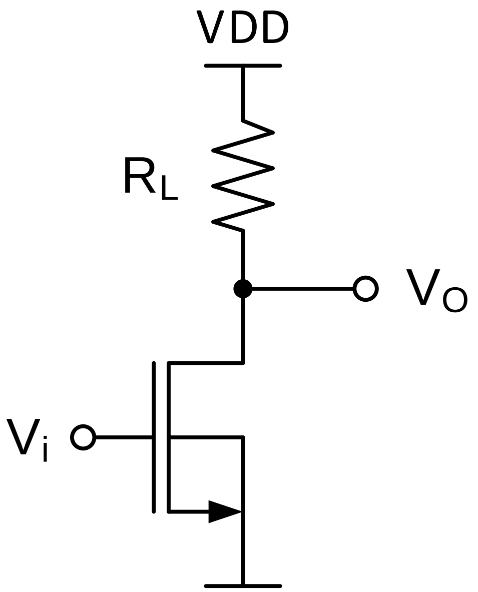
$$Vo = VDD - ID.RL$$

$$Vo = VDD - RL.\frac{1}{2}Kp\frac{W}{L}(Vi - VT)^2$$

$$Vi = ?$$

$$Vi = VT + \sqrt{\frac{2.ID}{Kp\,{}^{W}/_{L}}}$$

Ejemplo: Ganancia de señal



Kp = 120μA/V², RL = 100kΩ, ID = 10μA

VDD = 3V, W = 10μm, L = 5μm, VT = 0.7V

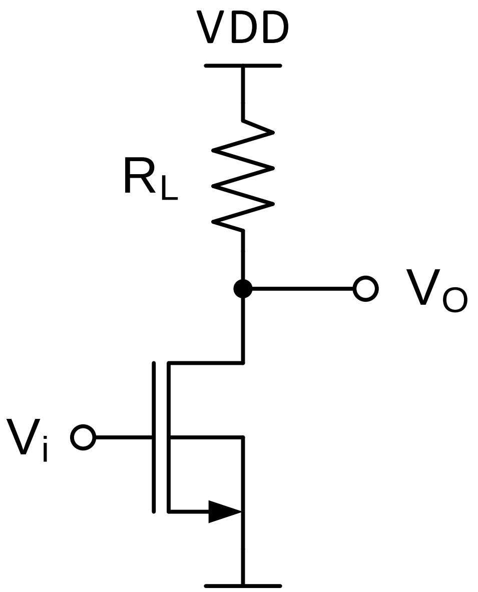
$$Vi = 0.7V + \sqrt{\frac{2x10\mu A}{120\mu A/V^2\,\frac{10\mu m}{5\mu m}}}$$

$$Vi = 0.7V + 0.289V = 0.989V$$

$$Vo = 3V - 100k\Omega.\frac{1}{2}120\mu A/V^2\,\frac{10\mu m}{5\mu m}(0.989V - 0.7V)^2$$

$$Vo = 1.998V$$

Ejemplo: Ganancia de señal



$Kp = 120\mu A/V^2$, $RL = 100k\Omega$, $ID = 10\mu A$

$VDD = 3V$, $W = 10\mu m$, $L = 5\mu m$, $VT = 0.7V$

$\text{Defino: } \Delta Vi = 10mV \quad \rightarrow$

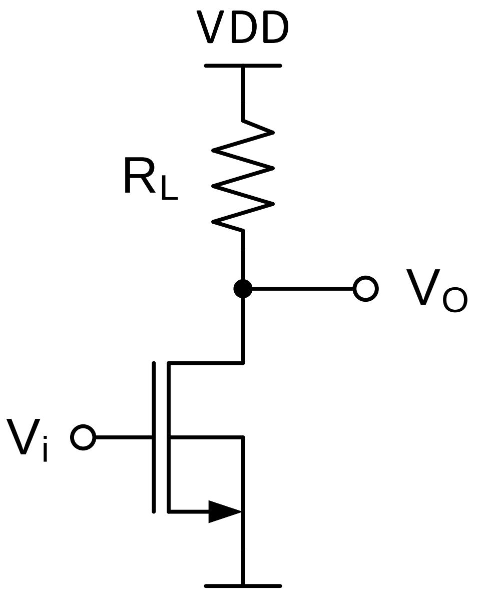
$Vi2 = 0.999V \quad \rightarrow$

$Vo2 = 1.927V$

$$\frac{\Delta Vo}{\Delta Vi} = \frac{1.927V - 1.998V}{0.999V - 0.989V}$$

$$\frac{\Delta Vo}{\Delta Vi} = -7.1\, {}^{V}/_{V}$$

Ejemplo: Ganancia de señal



$Kp = 120\mu A/V^2$, $RL = 100k\Omega$, $ID = 10\mu A$

$VDD = 3V$, $W = 10\mu m$, $L = 5\mu m$, $VT = 0.7V$

Defino: $\Delta Vi = 1mV \quad \rightarrow$

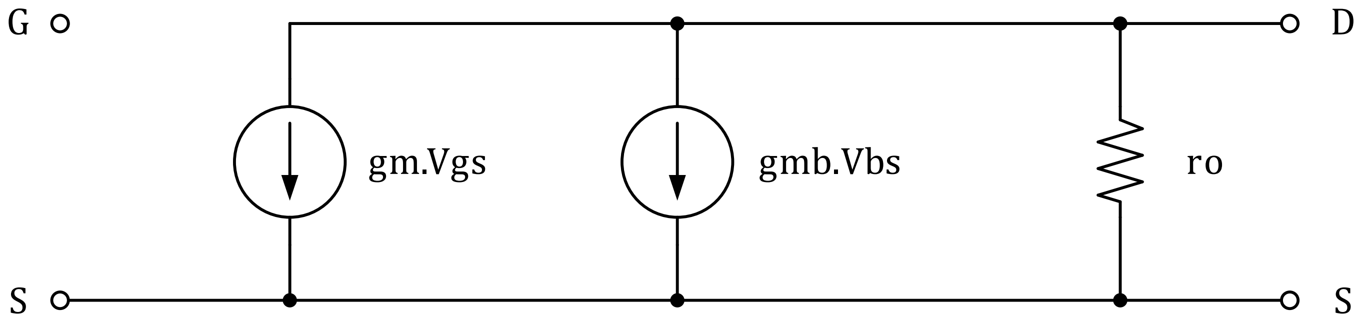
$Vi2 = 0.99V \quad \rightarrow$

$Vo2 = 1.991V$

$$\frac{\Delta Vo}{\Delta Vi} = \frac{1.991V - 1.998V}{0.99V - 0.989V}$$

$$\frac{\Delta Vo}{\Delta Vi} = -7.0\, {}^{V}\!/_{V}$$

1.1.3 Pequeña Señal



$$gm = \frac{dID}{dVGS} = Kp\frac{W}{L}(VGS - VT)(1 + \lambda VDS)$$

Si $\lambda VDS << 1$ →

$$\boxed{gm = kp\frac{W}{L}(VGS - VT) = \sqrt{2Kp\frac{W}{L}ID}}$$

$$\mathrm{gmb} = \frac{d\mathrm{ID}}{d\mathrm{VBS}} = -\mathrm{Kp}\frac{\mathrm{W}}{\mathrm{L}}(\mathrm{VGS}-\mathrm{VT})(1+\lambda\mathrm{VDS})\frac{d\mathrm{VT}}{d\mathrm{VBS}}$$

$$\frac{d\mathrm{VT}}{d\mathrm{VBS}} = -\frac{\gamma}{2\sqrt{2\varphi\mathrm{f}+\mathrm{VSB}}} = -\chi$$

$$\mathrm{gmb} = \gamma.\mathrm{Kp}\frac{\mathrm{W}}{\mathrm{L}}\frac{\mathrm{VGS}-\mathrm{VT}}{2\sqrt{2\varphi\mathrm{f}+\mathrm{VSB}}}(1+\lambda\mathrm{VDS})$$

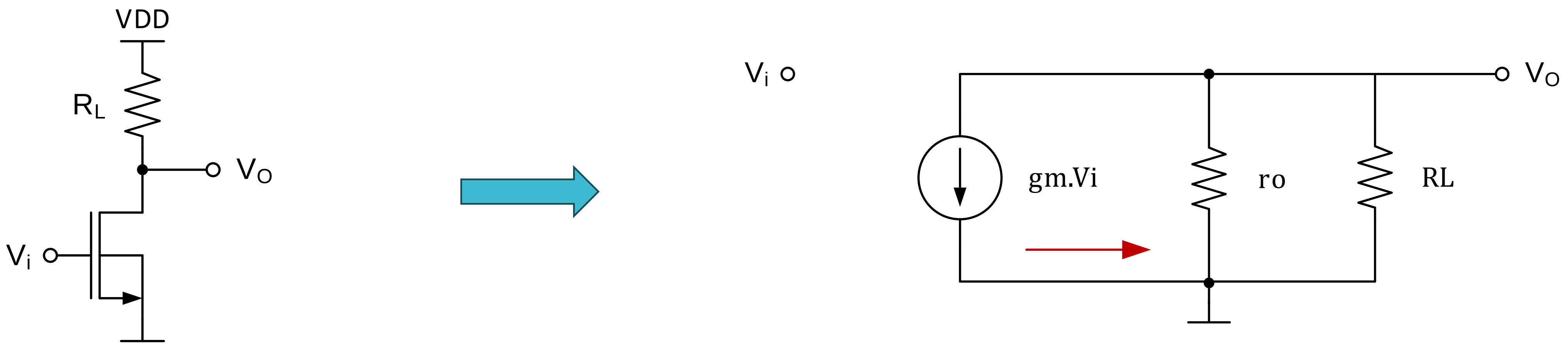
$$\frac{\mathrm{gmb}}{\mathrm{gm}} = \frac{\gamma}{2\sqrt{2\varphi\mathrm{f}+\mathrm{VSB}}} = \chi$$

Típicamente χ vale 0.1 a 0.3 →
gm es 3 a 10 veces más grande que gmb

$$\boxed{\mathrm{ro} = \frac{\mathrm{VA}}{\mathrm{ID}} = \frac{1}{\lambda\mathrm{ID}}}$$

$$\boxed{\mathrm{ro}\ \ \alpha\ \ \mathrm{Leff}}$$

Ejemplo de Ganancia - Continuación



$$gm = \sqrt{2Kp\frac{W}{L}ID} = \sqrt{2x120\mu A/V^2\frac{10\mu m}{5\mu m}10\mu A}$$

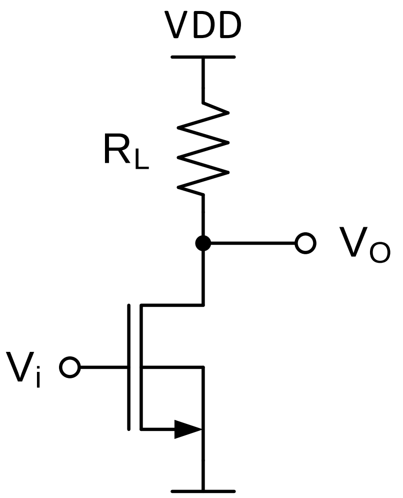
$$gm = 69.36\mu S$$

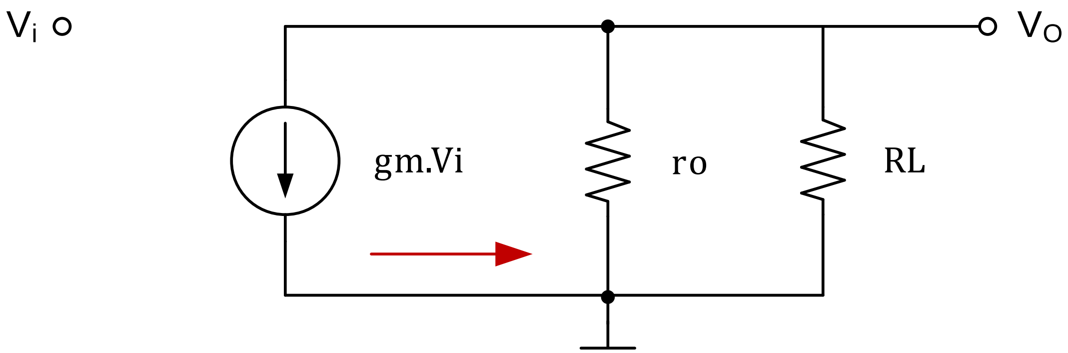
$$\frac{\Delta Vo}{\Delta Vi} = -gm.\,(ro\ //\ RL)$$

$$ro = \frac{1}{\lambda ID} \qquad \lambda = 0.01\ 1/V$$

$$ro = 10M\Omega$$

Ejemplo de Ganancia - Continuación





$$\frac{\Delta Vo}{\Delta Vi} = -69.36\mu S.\,(10M\Omega//\,100k\Omega)$$

$$\frac{\Delta Vo}{\Delta Vi} = -6.9\,{}^{V}/_{V}$$

$$\frac{\Delta Vo}{\Delta Vi} = -7.1\,{}^{V}/_{V}\quad (\Delta Vi = 10mV)$$

$$\frac{\Delta Vo}{\Delta Vi} = -7.0\,{}^{V}/_{V}\quad (\Delta Vi = 1mV)$$

Valores típicos, NMOS

$Kp = 100\mu A/V^2$, $ID = 10\mu A$

$W = 10\mu m$, $L = 5\mu m$, $\lambda = 0.01\ 1/V$

$$gm = \sqrt{2Kp\frac{W}{L}ID} = 63.25\mu S$$

$$\frac{1}{gm} = 15.81k\Omega$$

$$ro = \frac{1}{\lambda ID} = 10M\Omega$$

$$\boxed{ro \gg \frac{1}{gm}}$$

$$\boxed{gm.ro = 632.5 \gg 1}$$

Valores típicos, PMOS

$Kp = 30\mu A/V^2$, $ID = 10\mu A$

$W = 10\mu m$, $L = 5\mu m$, $\lambda = 0.02\ 1/V$

$$gm = \sqrt{2Kp\frac{W}{L}ID} = 34.64\mu S$$

$$\frac{1}{gm} = 28.87k\Omega$$

$$ro = \frac{1}{\lambda ID} = 5M\Omega$$

$$\boxed{ro \gg \frac{1}{gm}}$$

$$\boxed{gm.ro = 173.2 \gg 1}$$

- **1.2 Transistor Bipolar**

1.2.1 Operación en DC

$$IC = IS.e^{\frac{VBE}{VT}}\left(1 + \frac{VCE}{VA}\right)$$

$$IS = \frac{q.A.D_n.ni^2}{W_B.NA}$$ (NPN) IS típico de 10^{-16} a 10^{-14} A

A: Cross-sectional emitter area

N_A: Base doping density

ni: Silicon intrinsic carrier concentration

D_n: Electron diffusion parameter in the base

W_B: Base width

$$\boxed{VT = \frac{k.T}{q}}$$

$$Si \quad \frac{VCE}{VA} \ll 1 \quad \rightarrow \quad \boxed{IC = IS.e^{\frac{VBE}{VT}}}$$

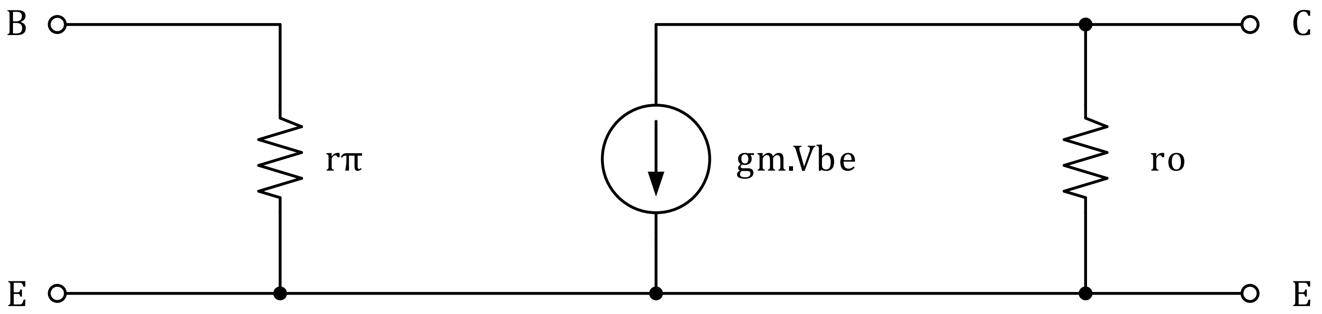
$$\boxed{\beta_F = \frac{IC}{IB}}$$

$$|IE| = IC + IB$$

$$|IE| = \frac{IC}{\alpha_F}$$

$$\alpha_F = \frac{\beta_F}{1 + \beta_F} \quad \rightarrow \quad \alpha_F < 1 \qquad (IC < IE)$$

1.2.2 Pequeña Señal



$$\mathrm{gm} = \frac{d\mathrm{IC}}{d\mathrm{VBE}}$$

$$\boxed{\mathrm{gm} = \frac{\mathrm{IC}}{\mathrm{VT}}}$$

$$\mathrm{r}\pi = \frac{vi}{ib} = \frac{vi}{ic}\beta\mathrm{o}$$

βo: Small signal current gain

Si βF es constante → $\beta_F = \beta o$ En general $\beta_F \approx \beta_F \approx \beta$

$$r\pi = \frac{vi}{ib} = \frac{vi}{ic}\beta = \frac{\beta}{gm}$$

$$\boxed{r\pi = \frac{\beta.VT}{IC}}$$

$$\boxed{\beta = r\pi.gm}$$

$$\boxed{ro = \frac{VA}{IC}}$$

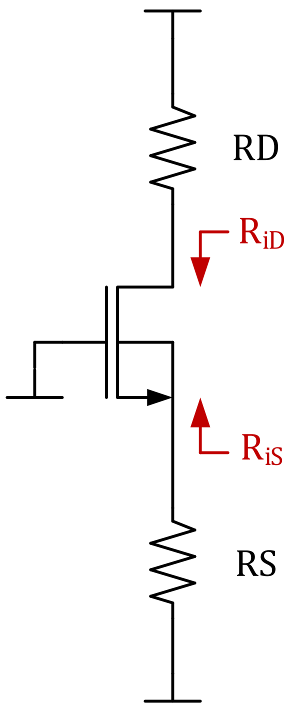
VA: Early voltage

$$ro = \frac{1}{\eta.gm} \qquad \eta = \frac{k.T}{q.VA}$$

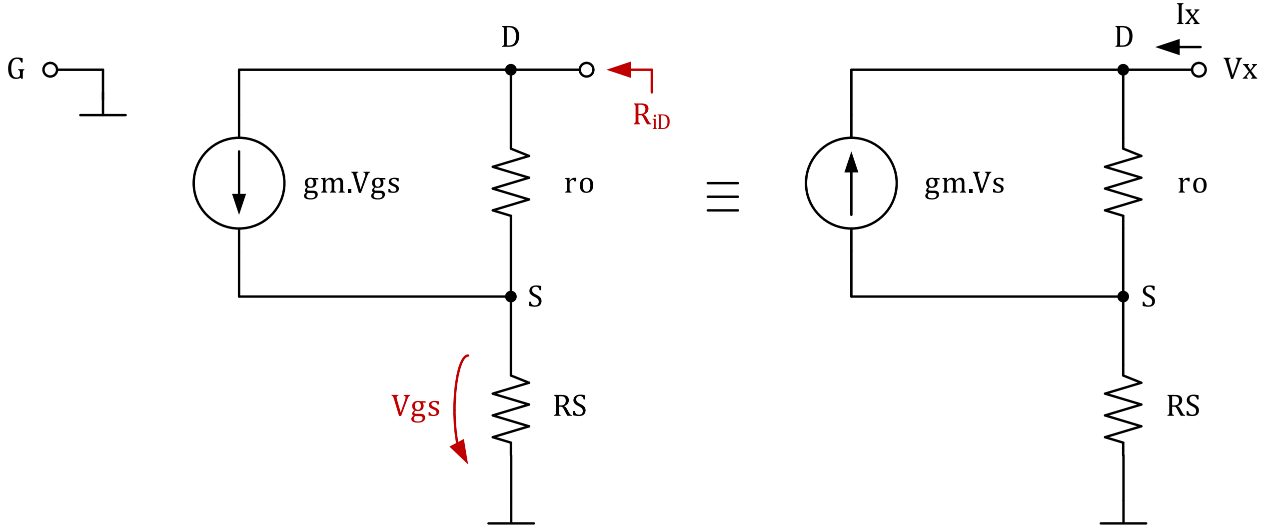
- **1.3 Cálculo de Parámetros de Pequeña Señal en Transistores MOS**

El objetivo de esta sección es definir una metodología para simplificar el cálculo de transferencias de pequeña señal. Para eso obtendremos las impedancias y ganancias típicas del transistor MOS

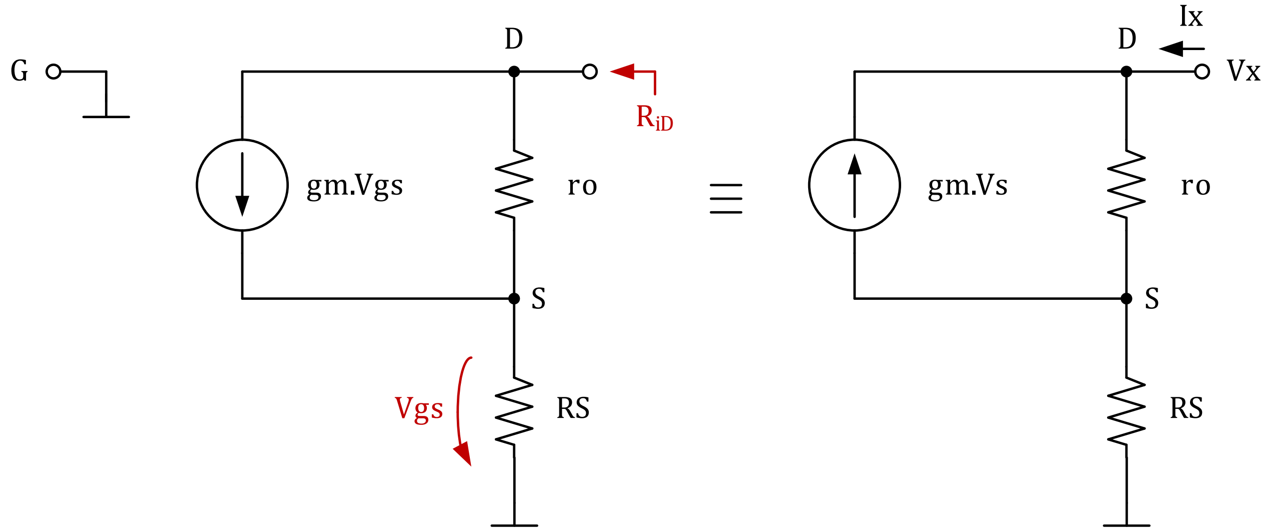
1.3.1 Impedancias



R_{iD}



R_{iD}



$Vx = Ix.RS + (Ix + gm.VS)\ .\ ro$

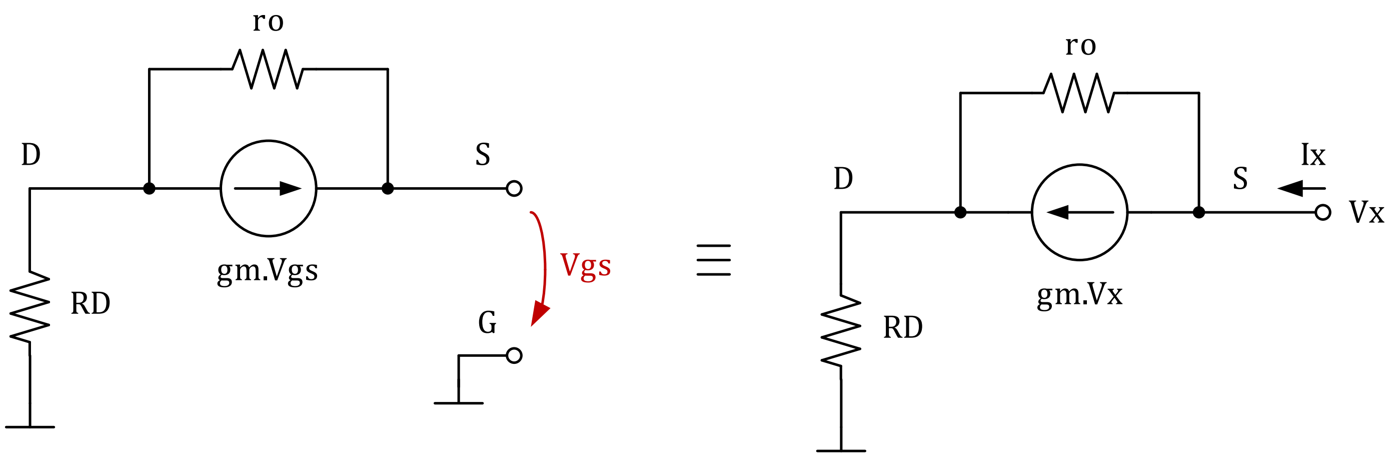
$VS = Ix.RS$

$Vx = Ix.RS + Ix.ro + Ix.gm.ro.RS$

$\boxed{R_{iD} = gm.ro.RS + ro + RS}$

Si $RS = 0 \rightarrow R_{iD} = ro$

R_{iS}



$$Vx = Ix.RD + (Ix - gm.Vx) \, . \, ro$$

$$Vx.(1 + gm.ro) = Ix.(RD + ro)$$

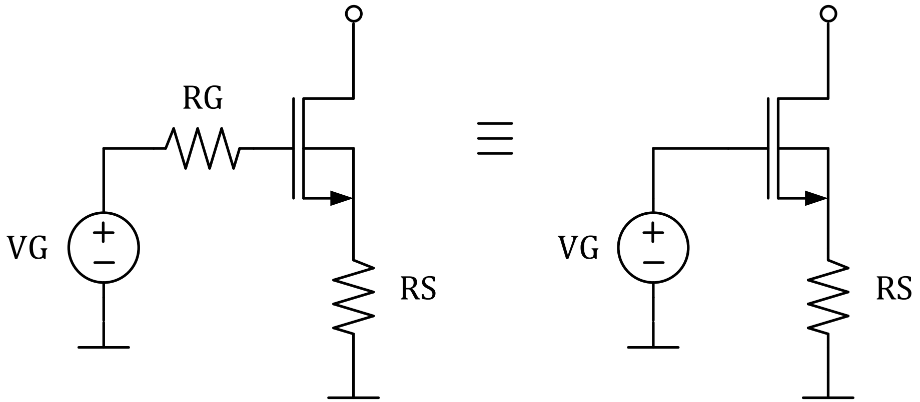
$$R_{IS} = \frac{RD + ro}{1 + gm.ro}$$

$$\boxed{R_{IS} \approx \frac{RD + ro}{gm.ro}}$$

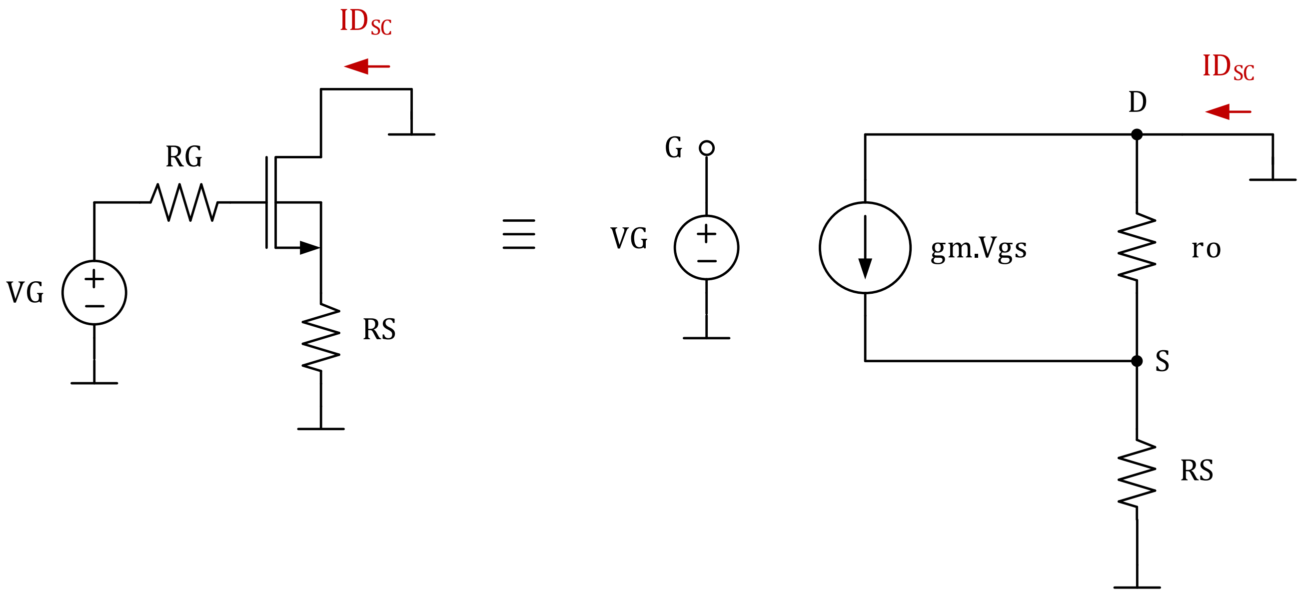
Si RD = 0 → $R_{iS} = 1 / gm$

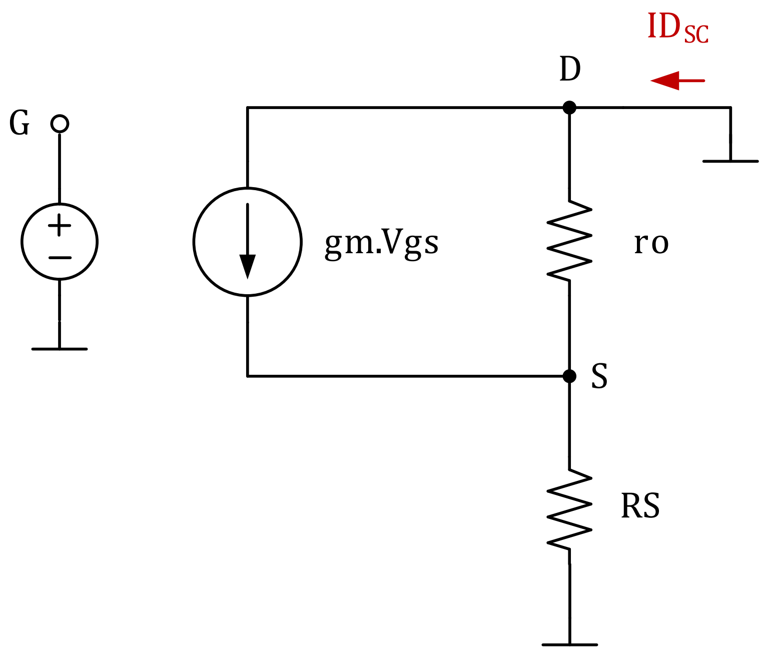
1.3.2 Ganancias

$\boxed{ID_{SC}}$ (Corriente de drain de cortocircuito)



Equivalente de Norton





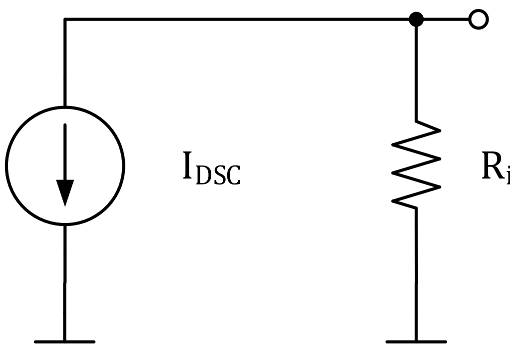
$$Vgs = VG - ID_{SC}.RS$$

$$ID_{SC}.RS + (IDSC - gm.Vgs)\ .\ ro = 0$$

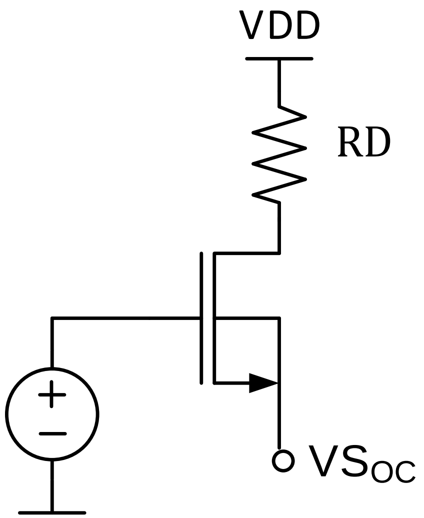
$$ID_{SC}.RS + ID_{SC}.ro = gm.VG.ro - ID_{SC}.RS.gm.ro$$

$$\boxed{ID_{SC} = VG\frac{gm.ro}{gm.ro.RS + RS}}$$

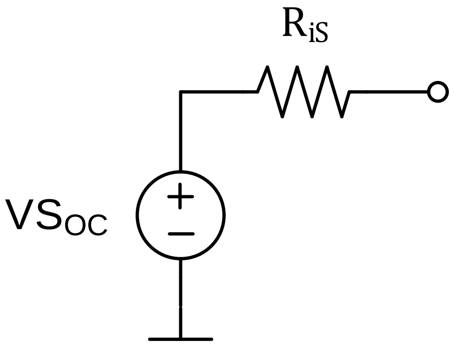
Si $RS = 0$ → $ID_{SC} = VG.gm$



$\boxed{VS_{OC}}$ (Tensión de source de circuito abierto)

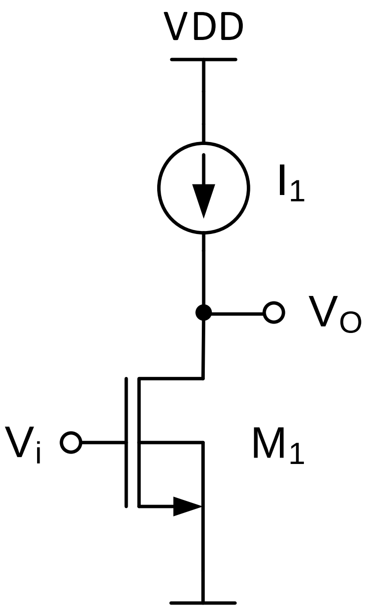


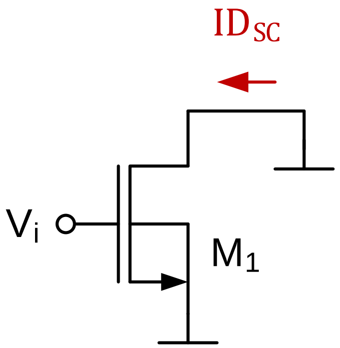
$$\boxed{VS_{SC} = VG \frac{gm.\,ro}{1 + gm.\,ro}} \rightarrow VS_{OC} \approx VG$$



- **1.4 Circuitos Monoetapas**

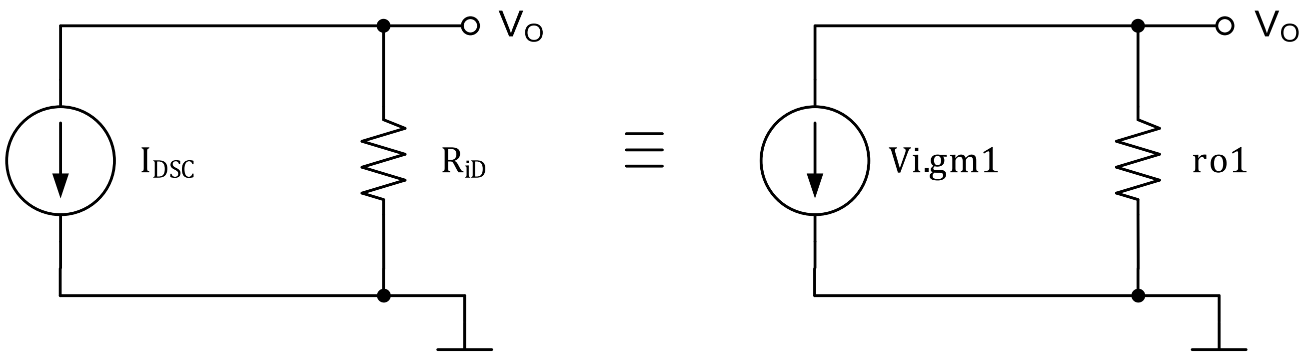
  1.4.1 Carga Ideal





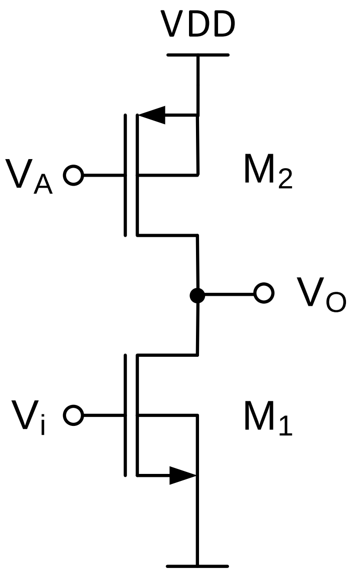
$ID_{SC} = Vi.gm1$

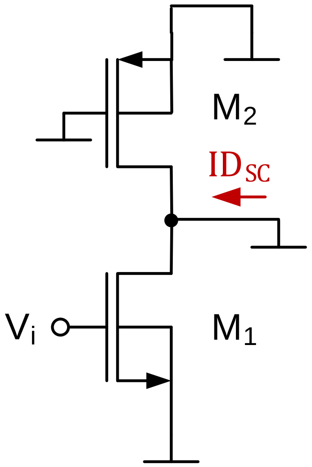
$R_{iD} = ro1$



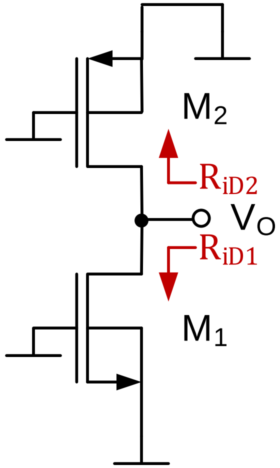
$$\boxed{Vo = -Vi.gm1.ro1}$$

1.4.2 Carga Activa

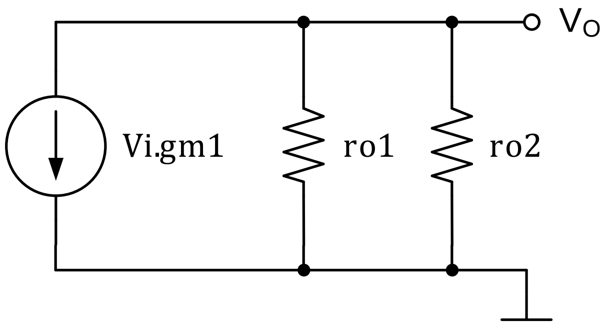




$ID_{SC} = Vi.gm1$

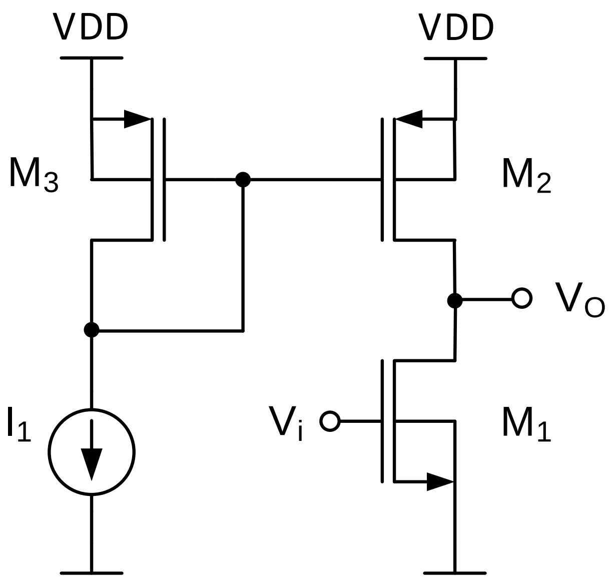


$R_{iD} = ro1 \,//\, ro2$



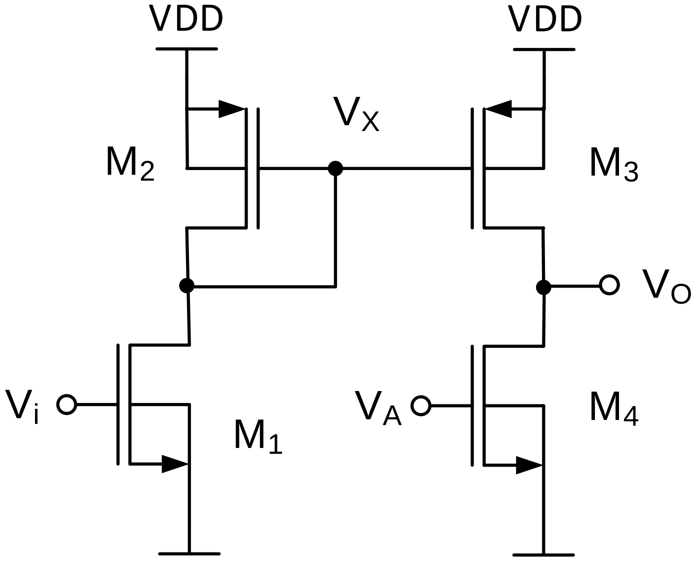
$\boxed{Vo = -\,Vi.gm1.(ro1//ro2)}$

1.4.3 Carga Activa v2

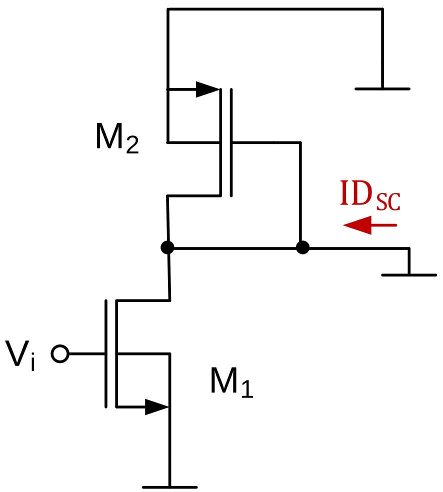


$$\boxed{Vo = -Vi.gm1.(ro1//ro2)}$$

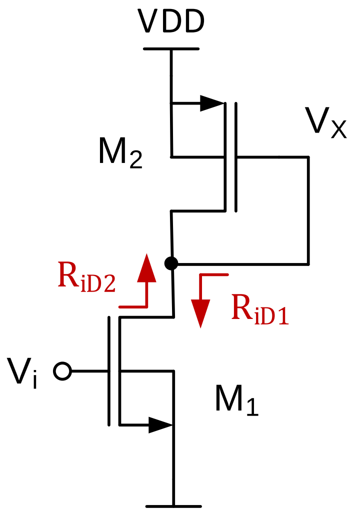
1.4.4 Carga Activa v3



- Vx / Vi

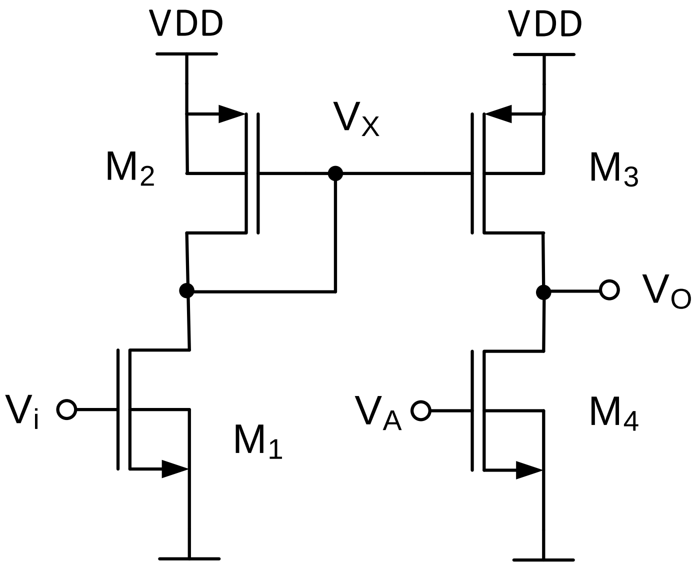


$ID_{SC} = Vi.gm1$



$R_{iD} = ro1 \,//\, (1/gm2) \approx 1/gm2$

$$Vx = -Vi\frac{gm1}{gm2}$$



- Vo / Vx

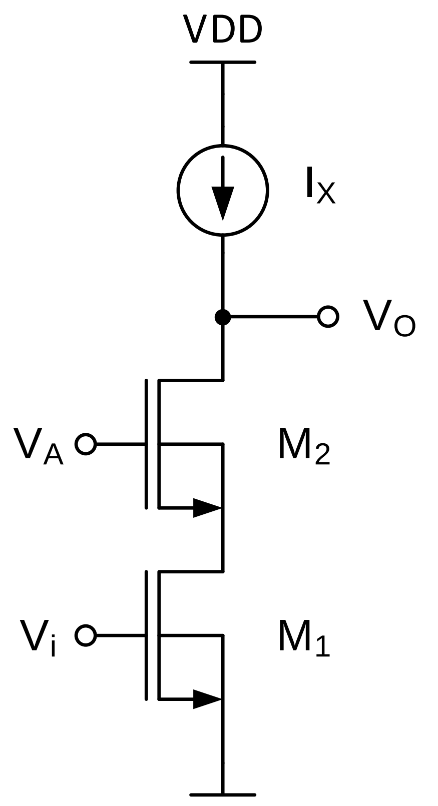
$$Vo = - Vx.gm3.(ro3//ro4)$$

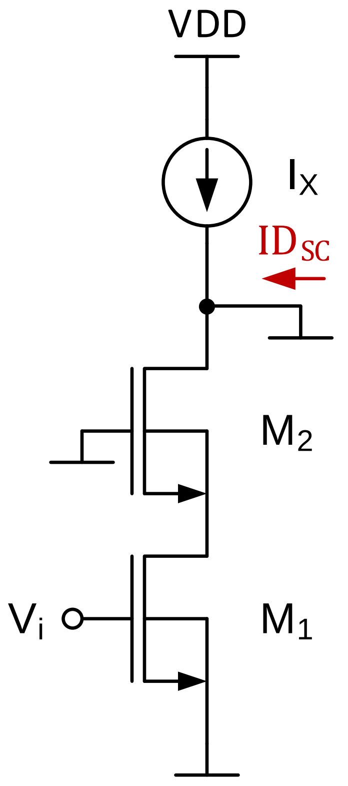
- Vo / Vi

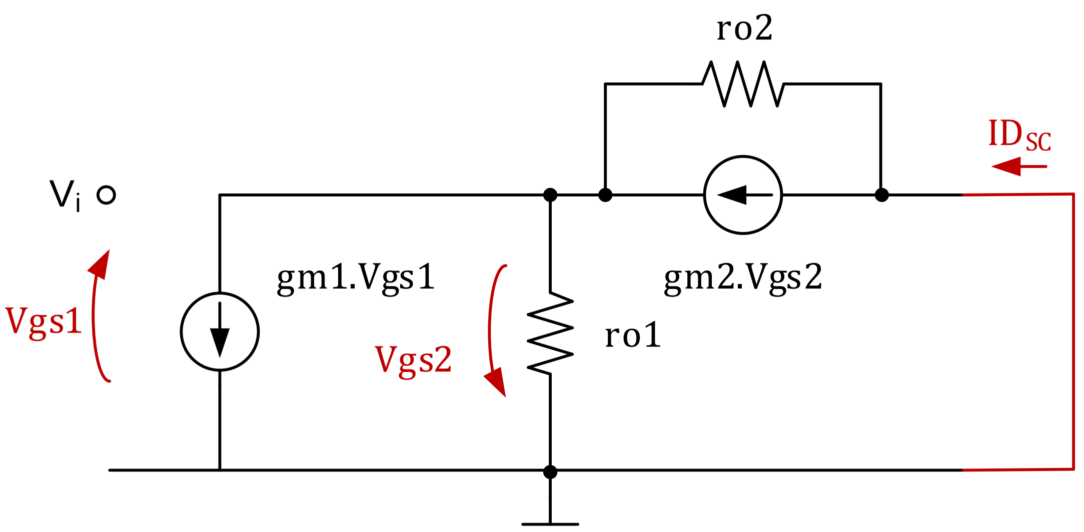
$$Vo = Vi\frac{gm3}{gm2}gm1(ro3//ro4\ ) \qquad \text{(Cambio de signo)}$$

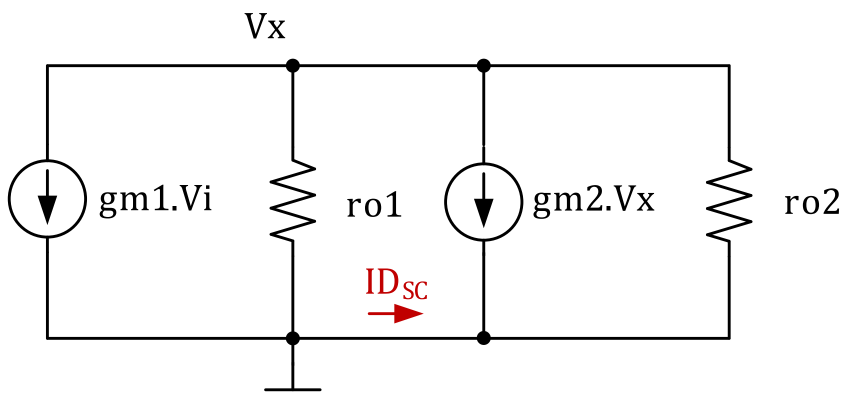
Si M2 = M3 → $\boxed{Vo = Vi.gm1.(ro3//ro4)}$

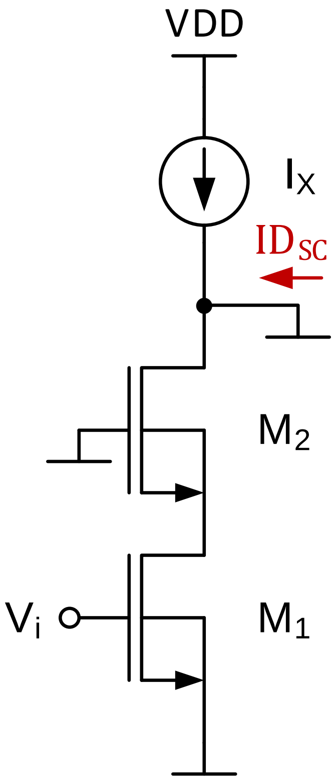
1.4.5 Cascode

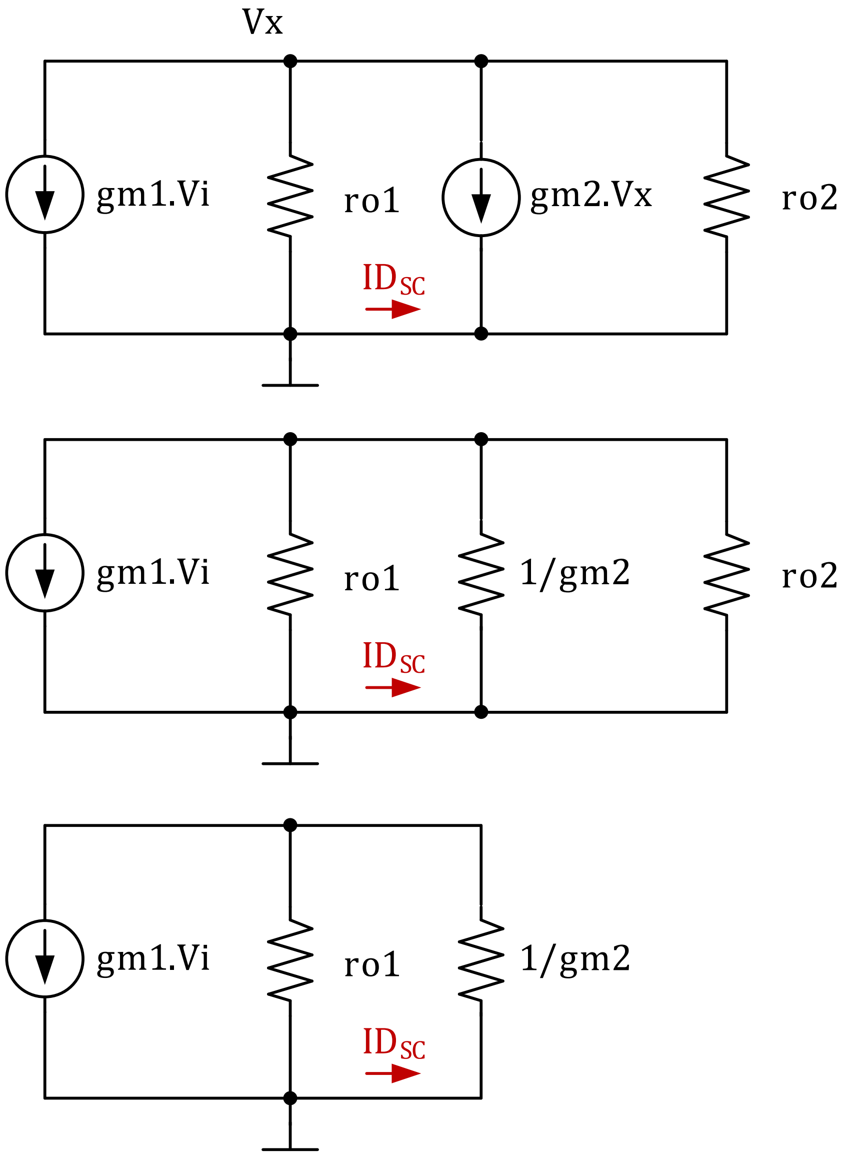

VDD
IX
VO
VA
M2
Vi
M1


VDD
IX
IDSC
M2
Vi
M1


ro2
IDSC
Vi
gm1.Vgs1
gm2.Vgs2
Vgs1
ro1
Vgs2


Vx
gm1.Vi
ro1
gm2.Vx
ro2
IDSC

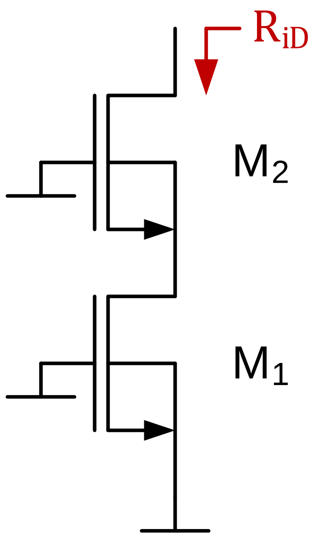




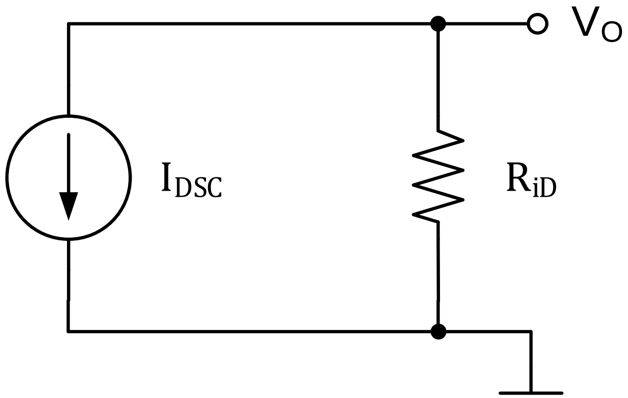
$1/gm2 << ro2$

$1/gm2 << ro1 \quad \rightarrow$

$ID_{SC} \approx Vi.gm1$

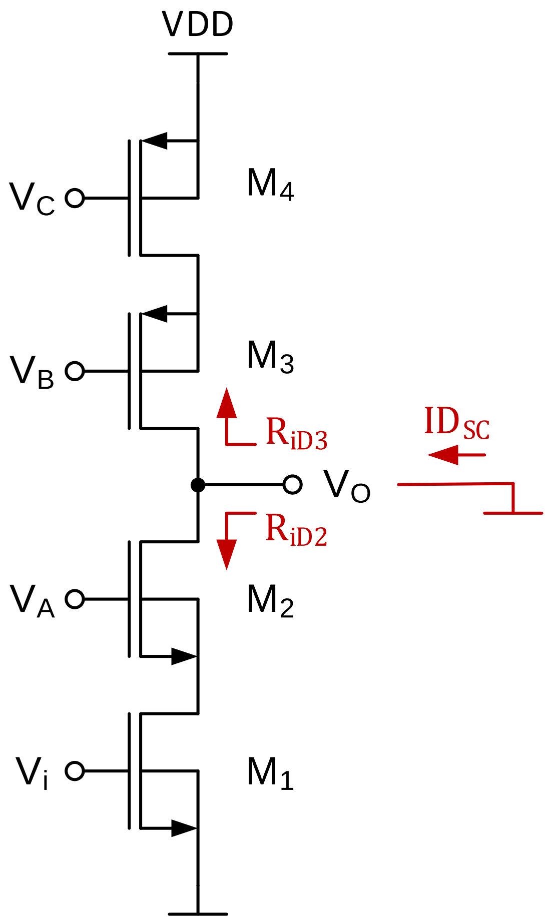


$$R_{iD} = gm2.ro2.ro1 + ro2 + ro1 \approx gm2.ro2.ro1$$



$$\boxed{Vo = - Vi.gm1.ro1.gm2.ro2}$$

1.4.6 Cascode con carga activa



$$ID_{SC} = Vi.gm1$$

$$R_{iD2} = gm2.ro2.ro1$$

$$R_{iD3} = gm3.ro3.ro4$$

$$\boxed{Vo = -\ Vi.gm1.(gm2.ro2.ro1)//(gm3.ro3.ro4)}$$