PAB

# PHYSIQUE DES COMPOSANTS SEMI-CONDUCTEURS

## XIII) Circuits analogiques en CMOS

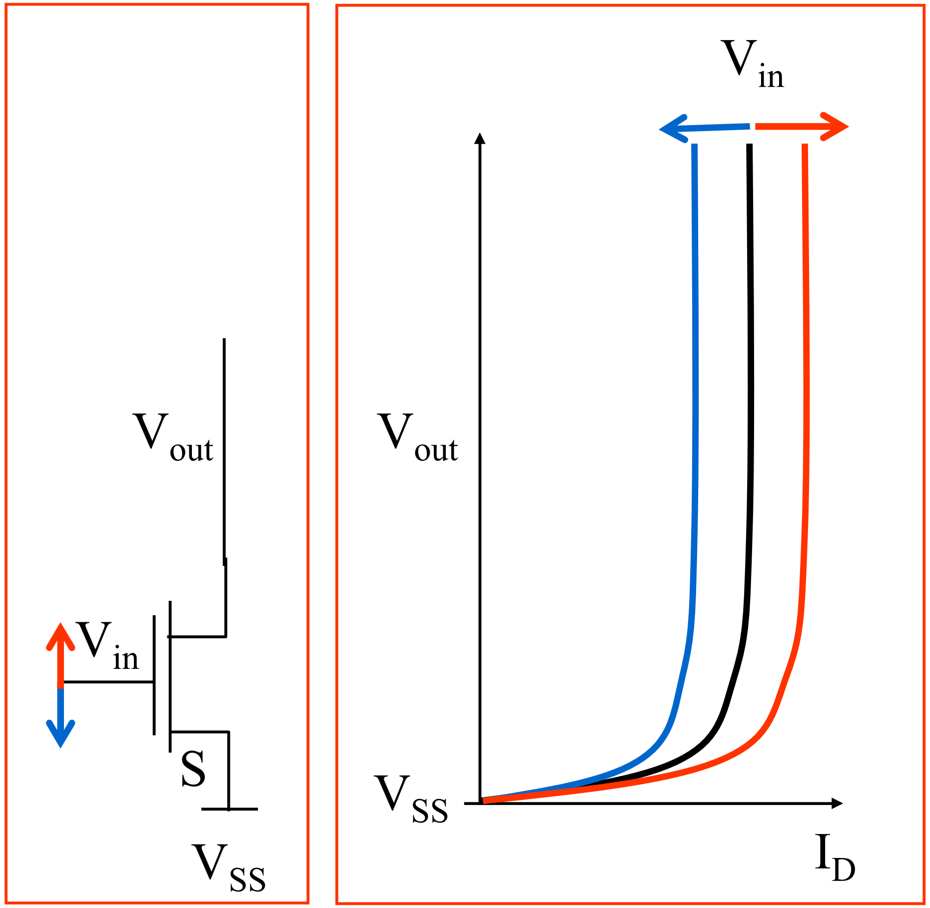
P.A. Besse

EPFL

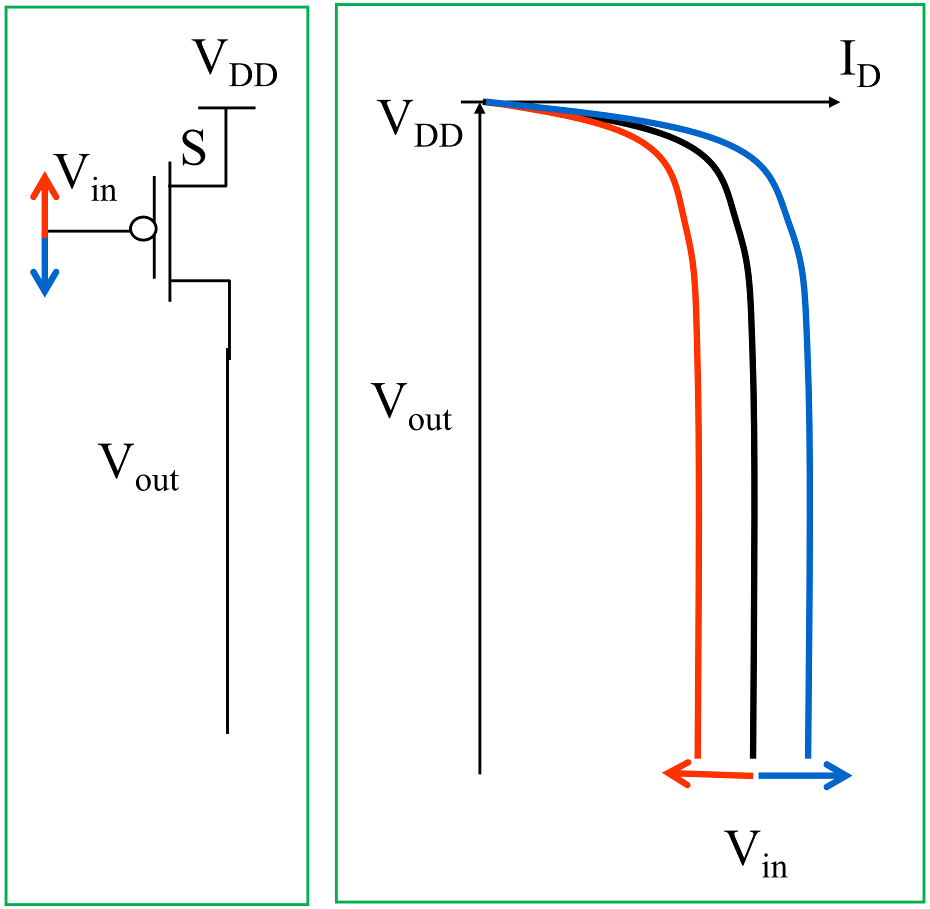
# Résumé
# des courbes caractéristiques
# des MOS

# Caractéristiques (1)

## N-MOS

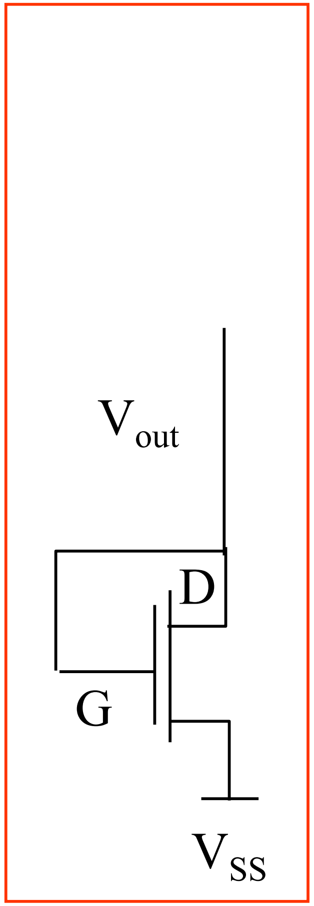


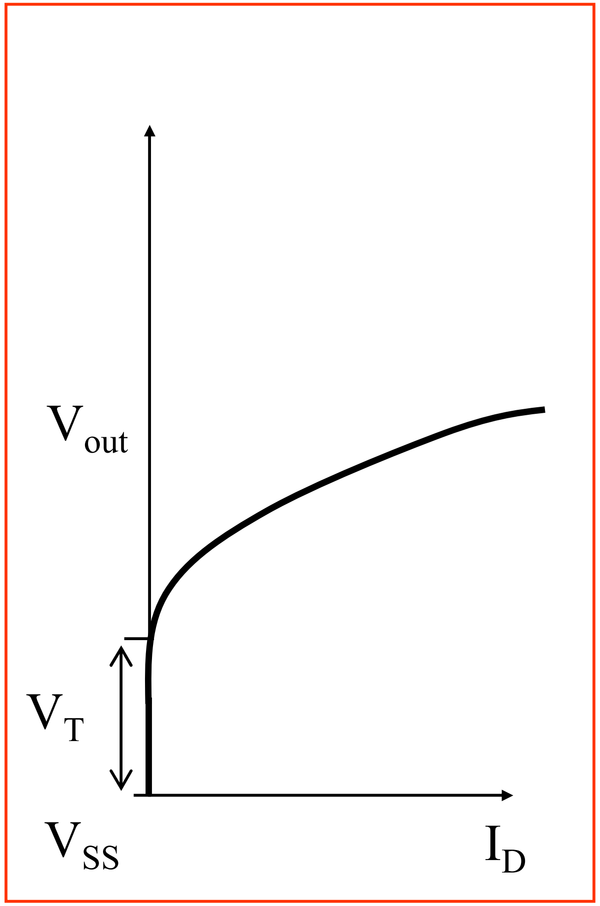
## P-MOS

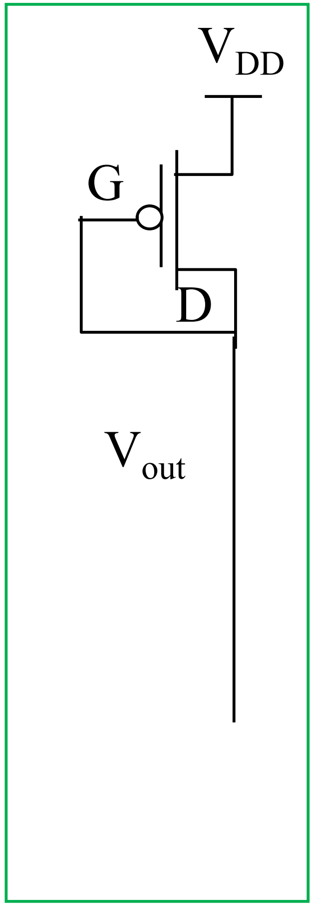


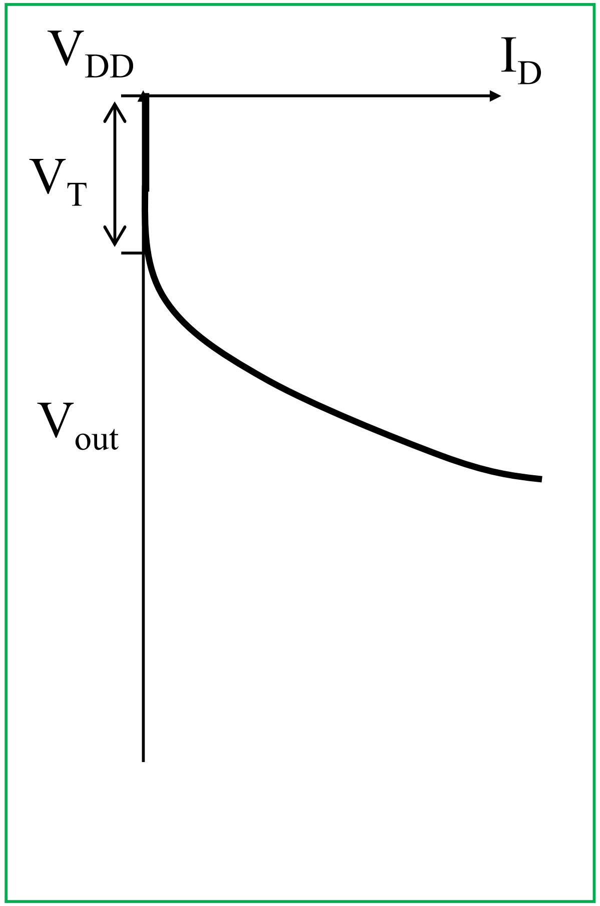
# Caractéristiques (2)

**N-MOS** **« gate – drain reliés »** **P-MOS**



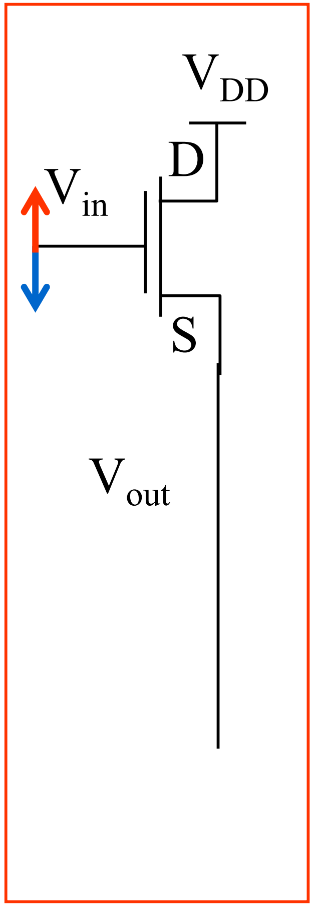


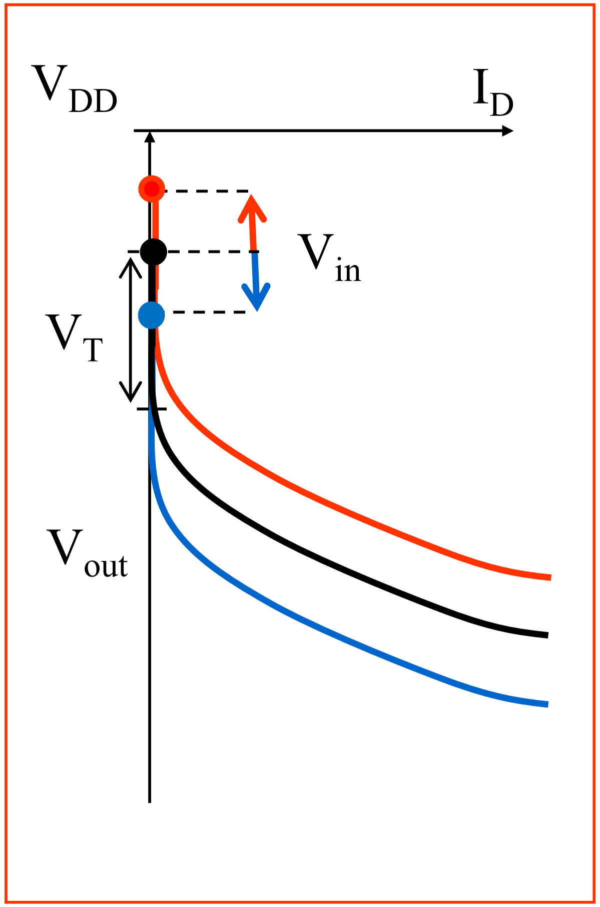




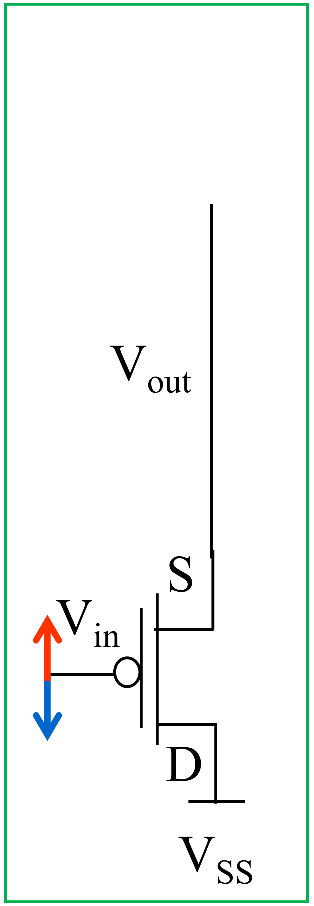
# Caractéristiques (3)

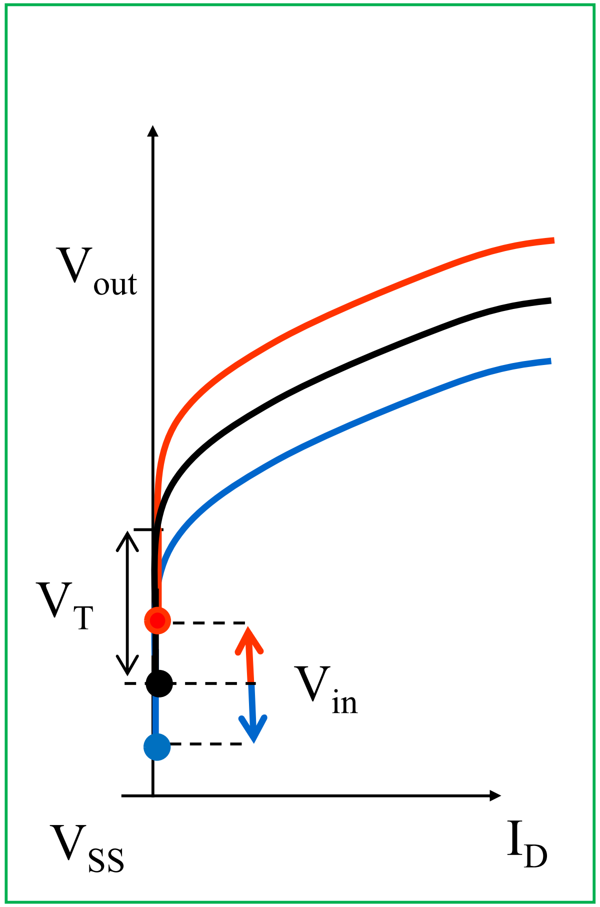
## N-MOS





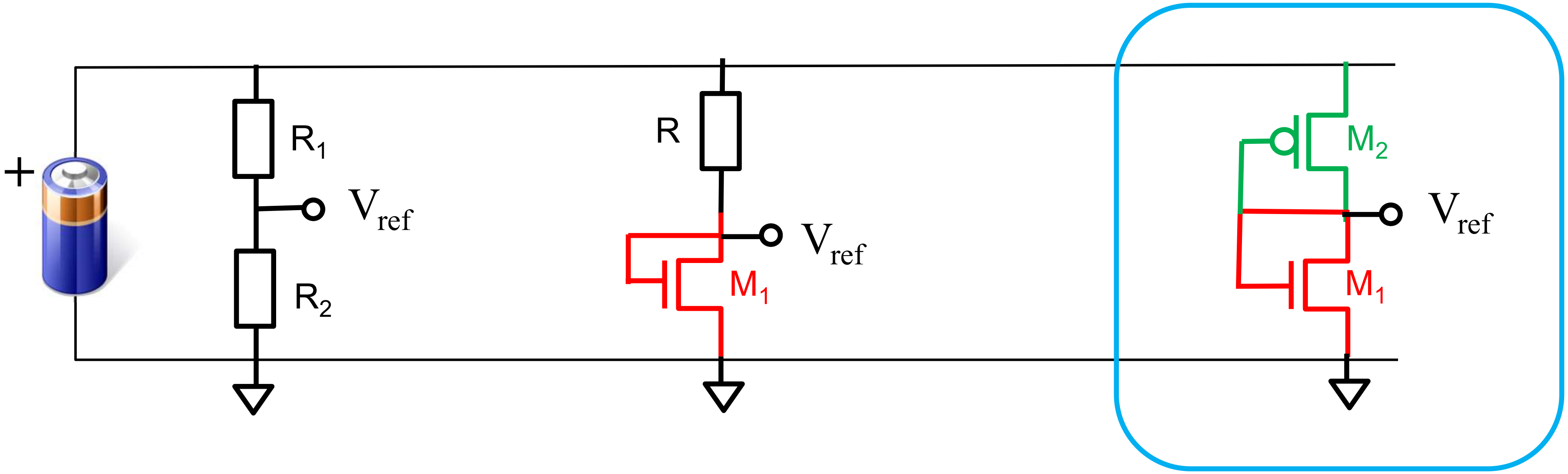
## P-MOS



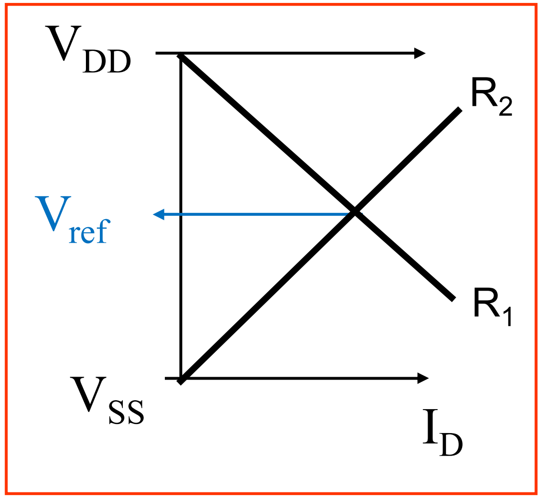


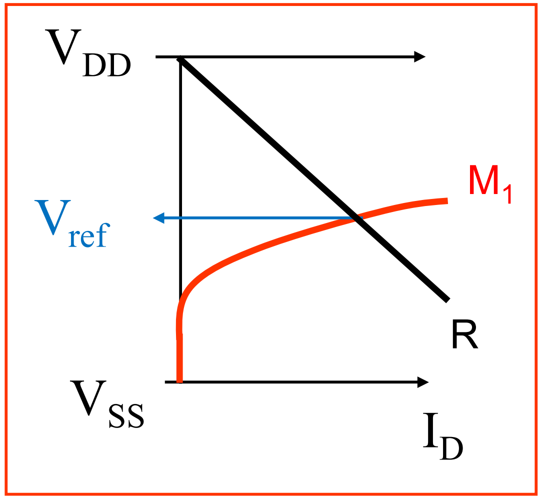
# Diviseurs de tension

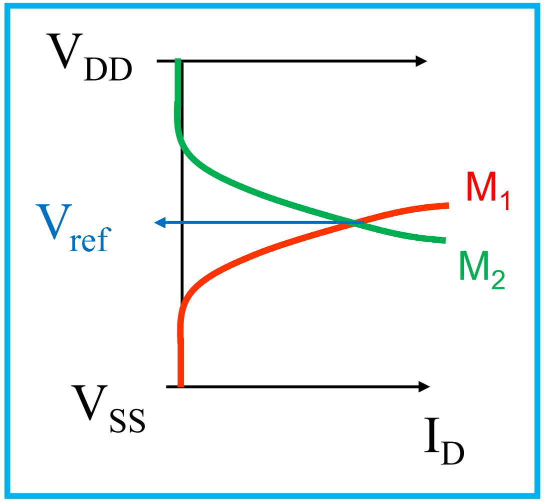
# Diviseurs de tension



**Uniquement MOSFET**

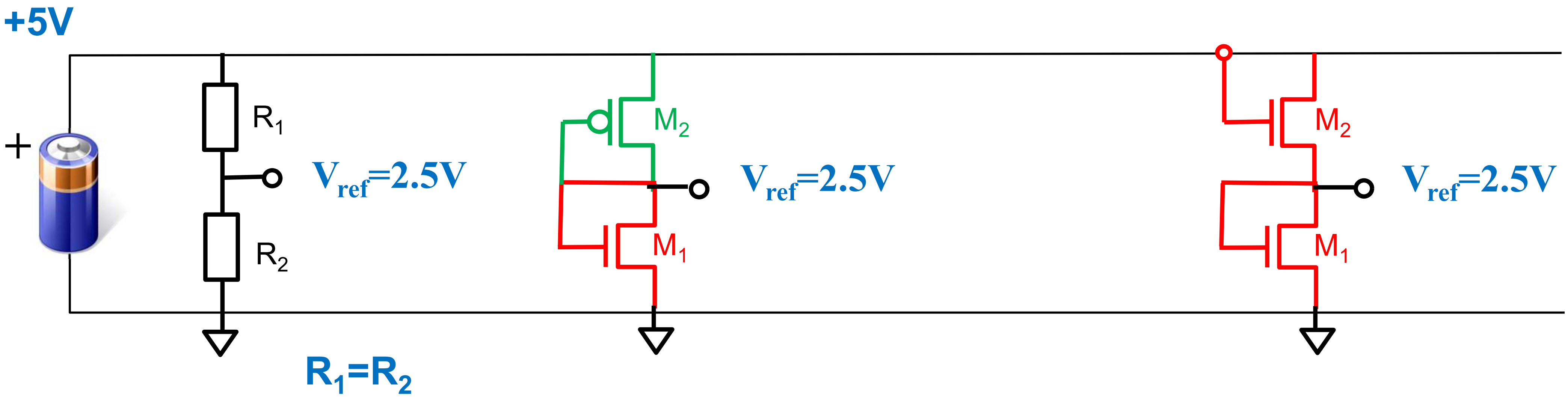


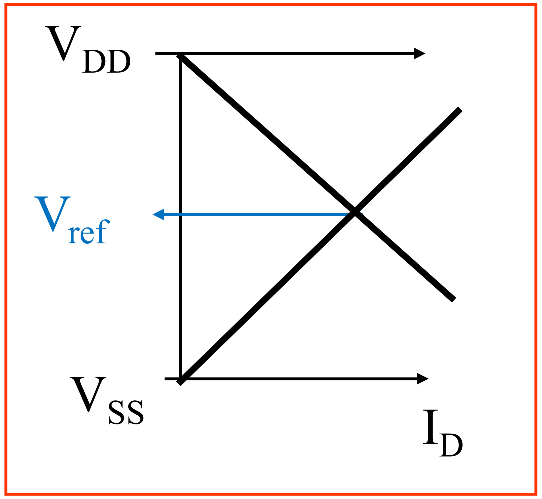


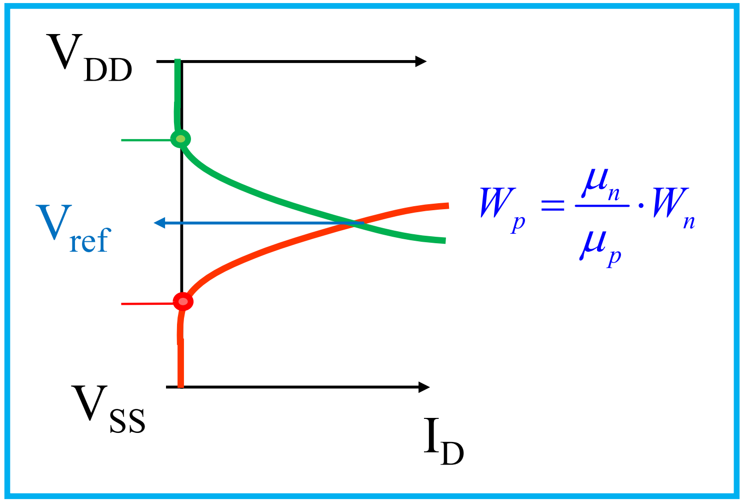


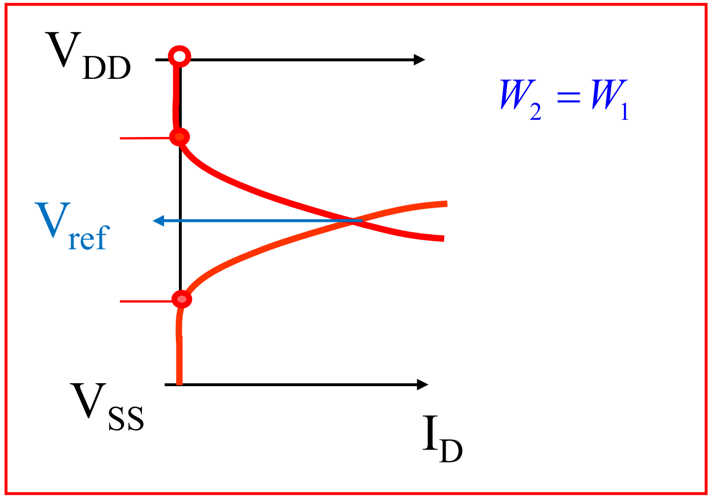
# Question:
# Diviseurs de tension

**Pile de 5V: comment obtenir 2.5V pour $V_{ref}$ ?**

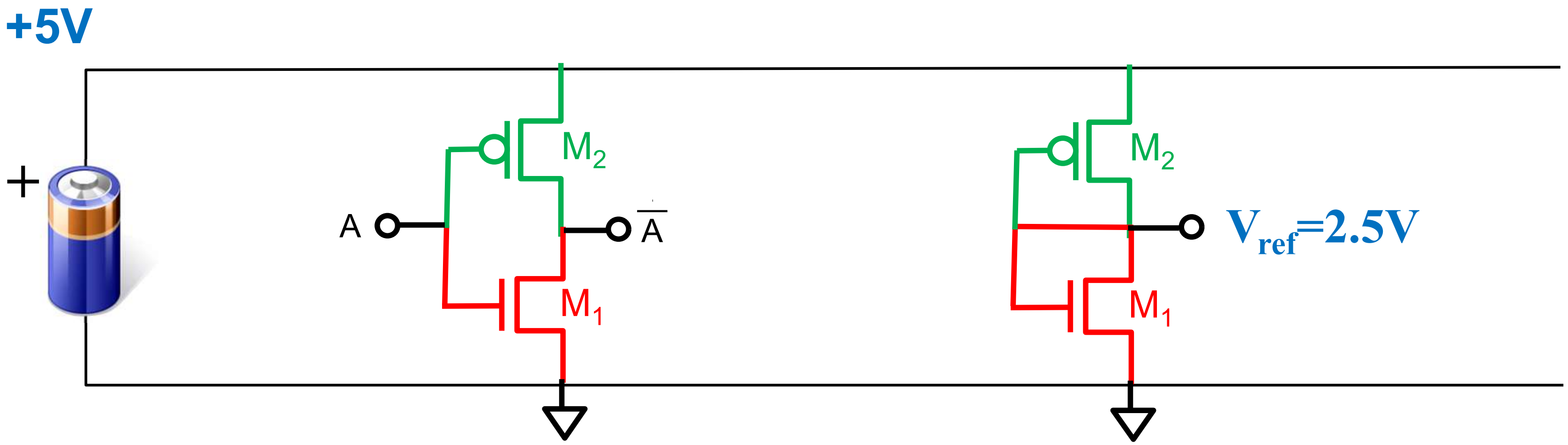






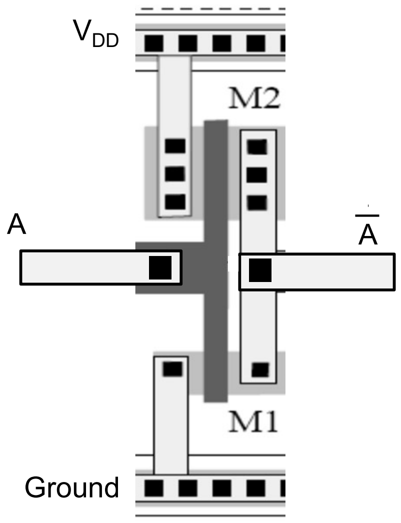


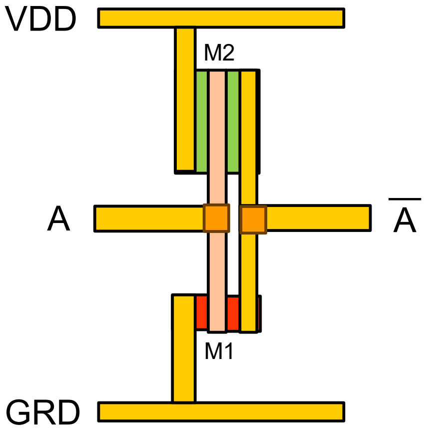
# Comparaison:
# Inverseur / Diviseurs de tension

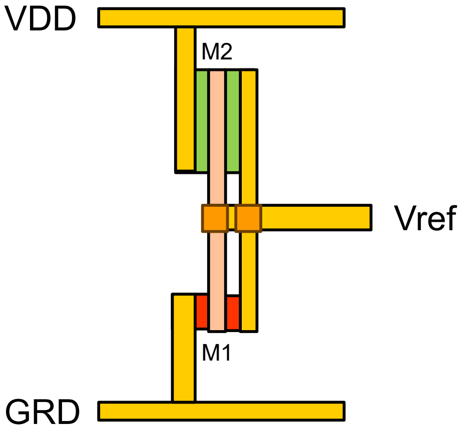


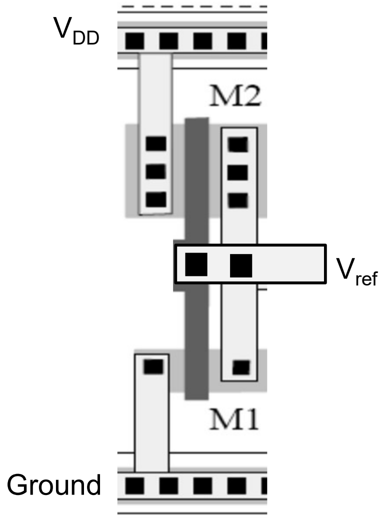
Inverseur

Diviseur de tension



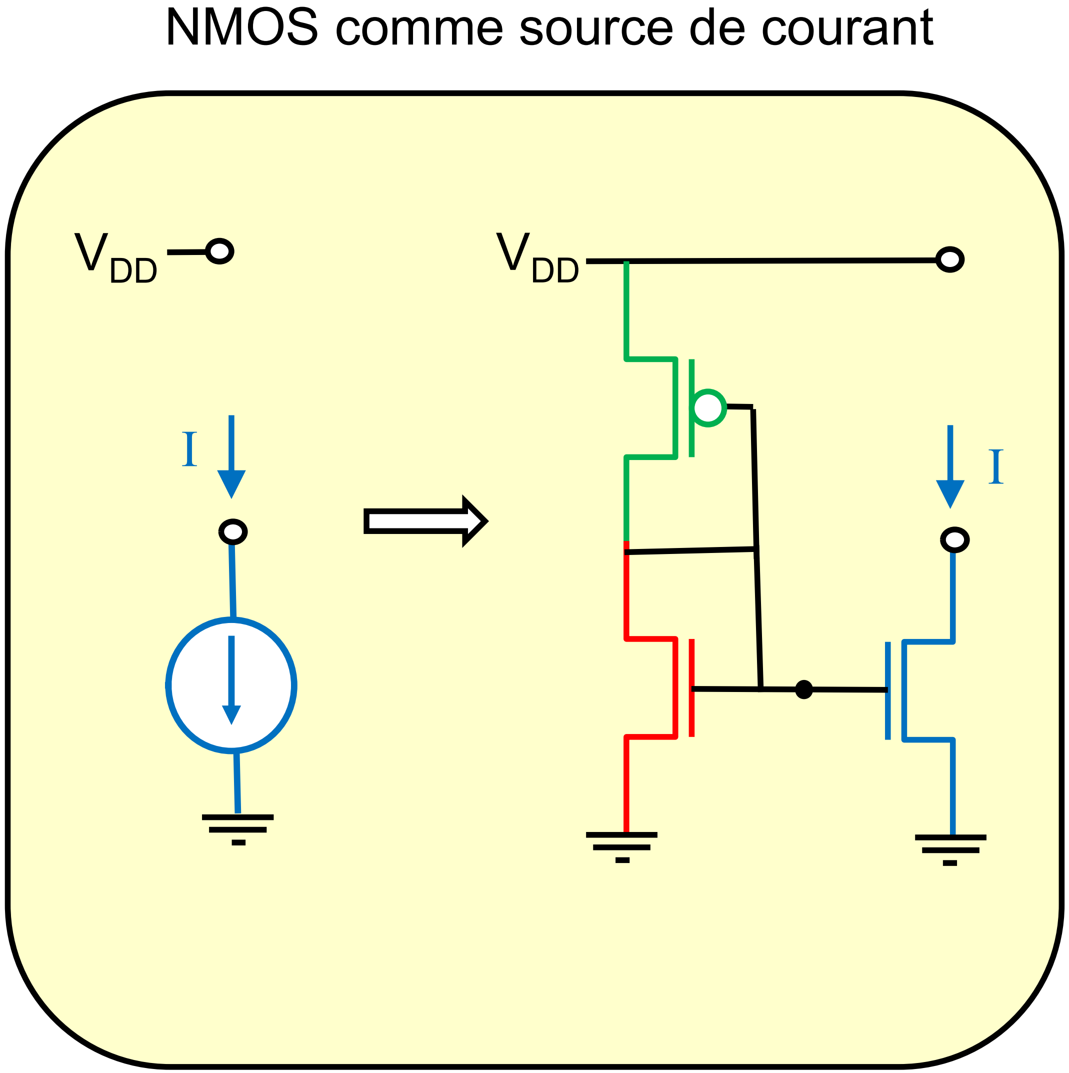




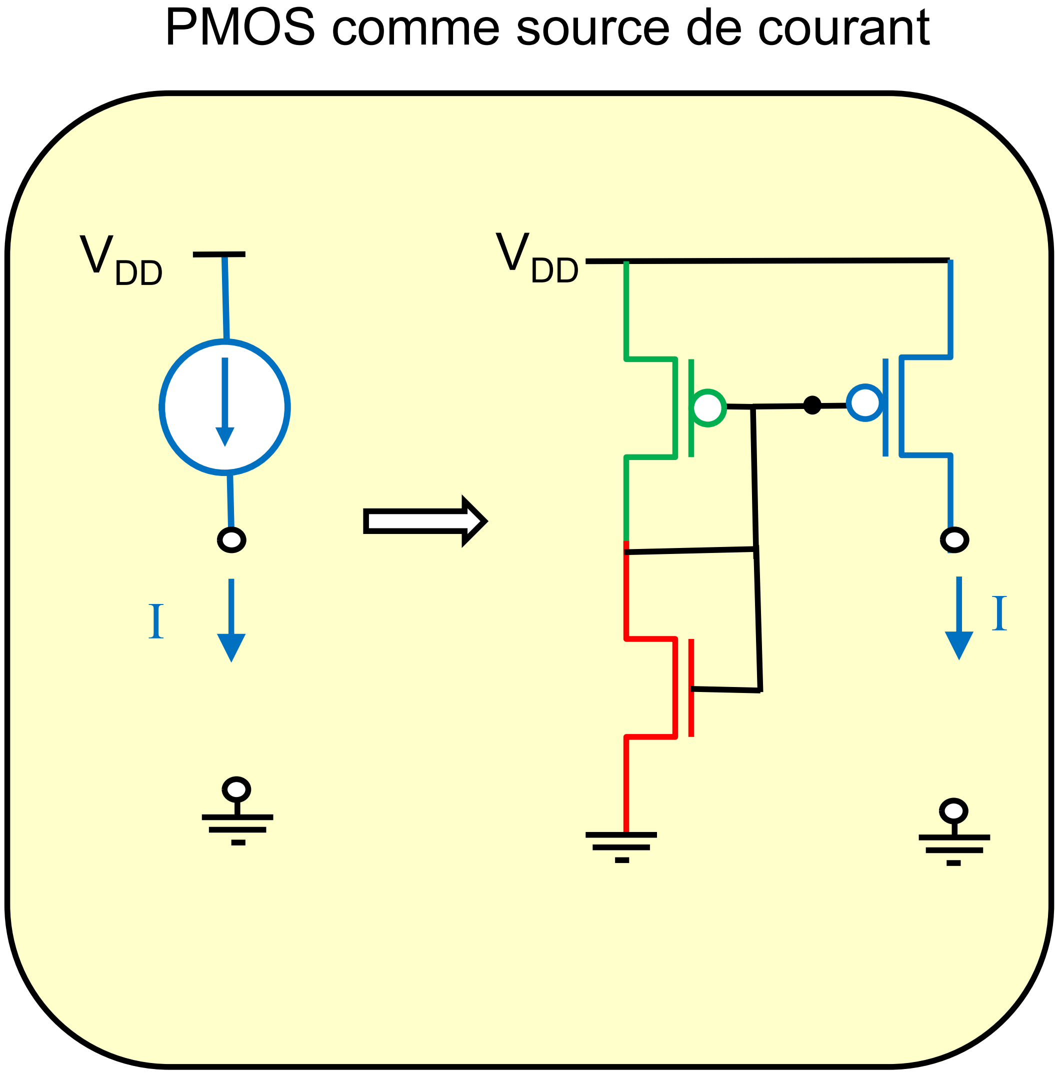


# Sources et
# miroirs de courant

# Source de courant simple (1)

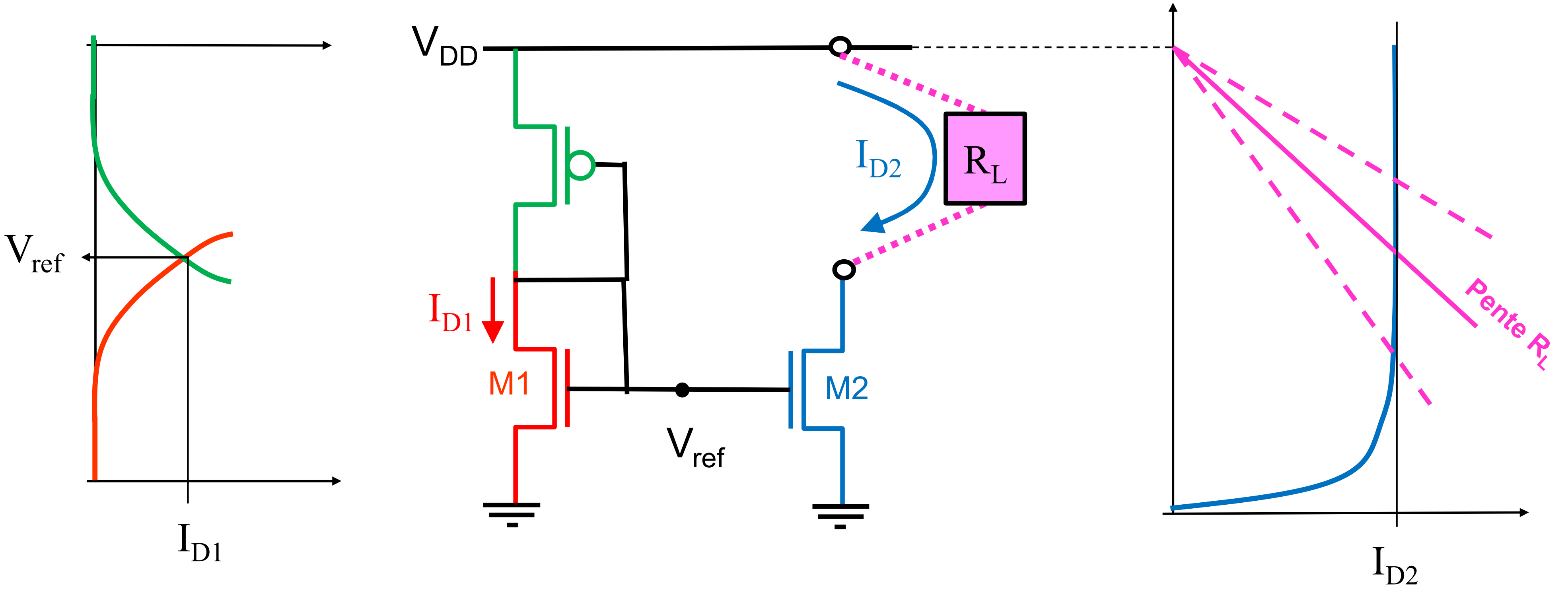


NMOS comme source de courant



PMOS comme source de courant

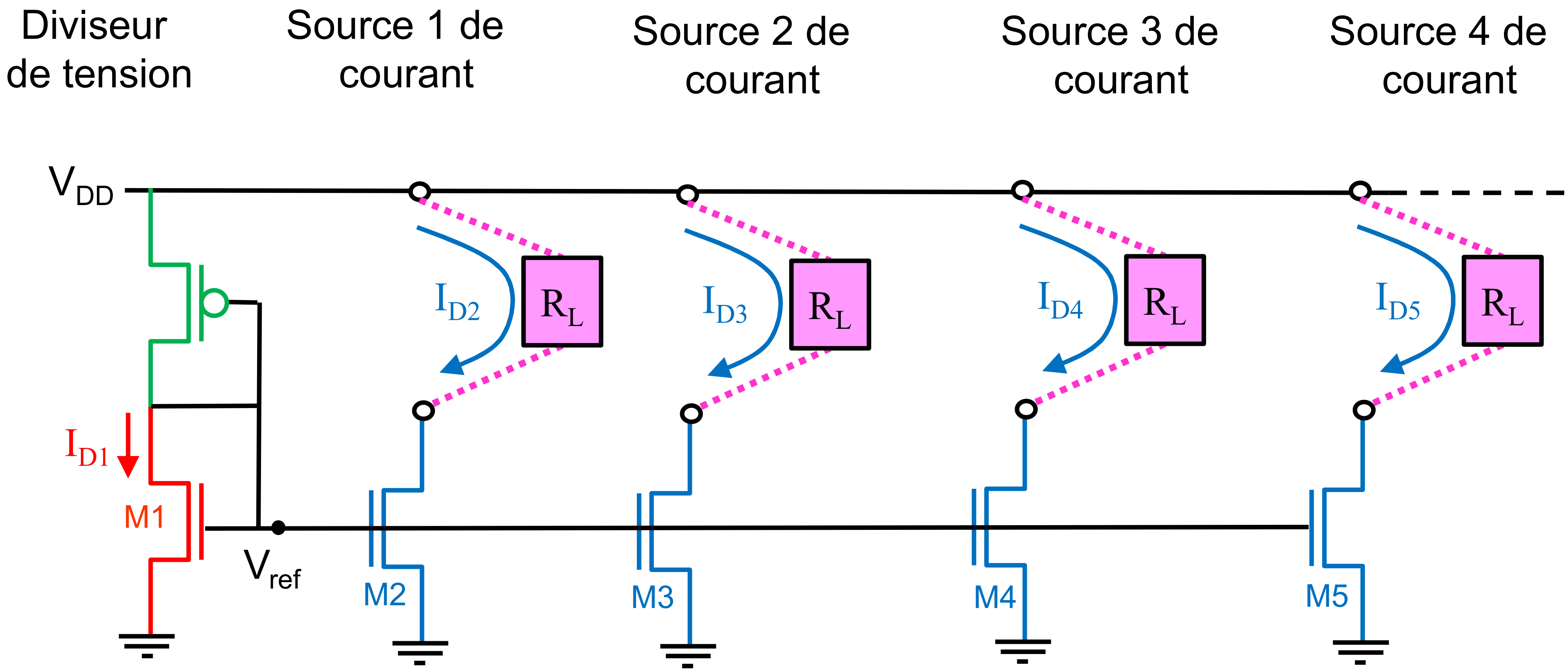
# Source de courant simple (2)



Un diviseur de tension sert à contrôler un NMOS

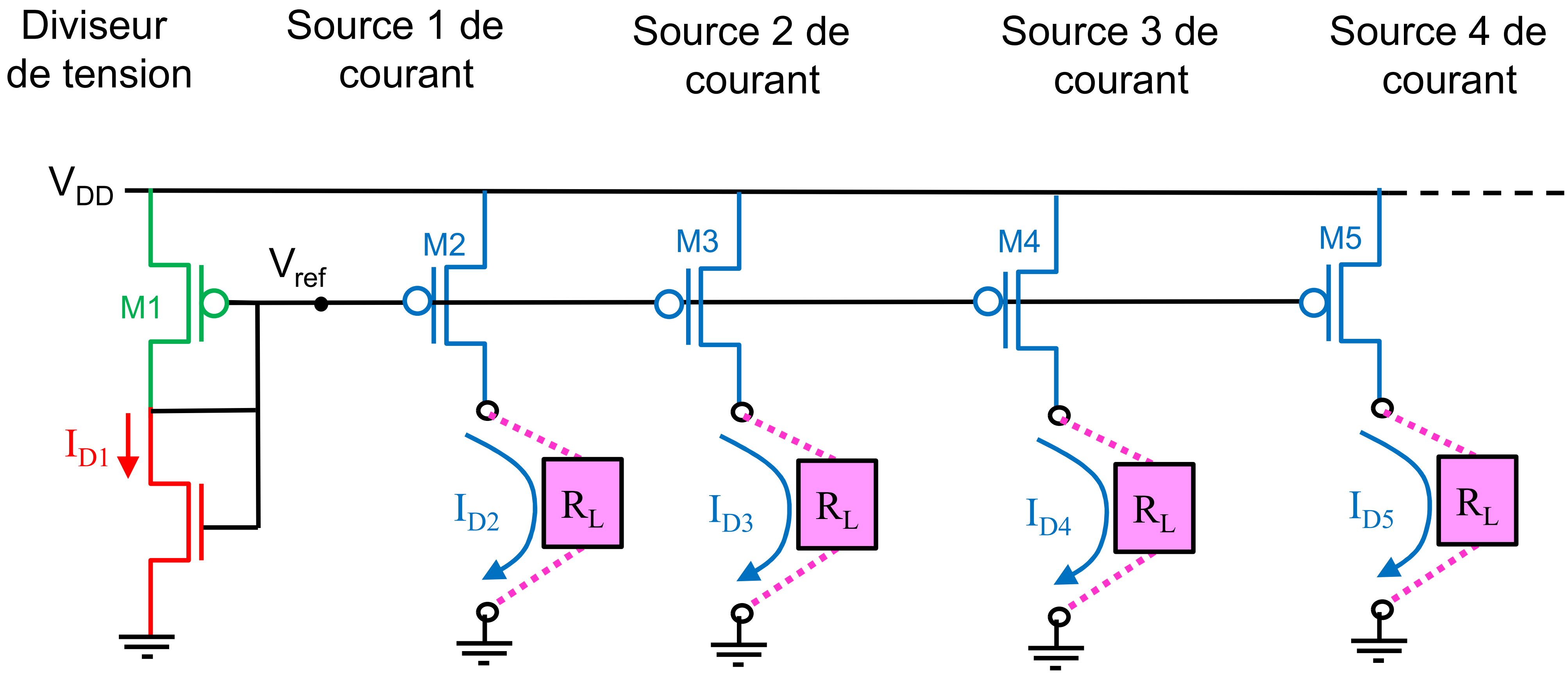
$$I_{D2} = \frac{W_2}{W_1}\frac{L_1}{L_2}\cdot I_{D1}$$

# NMOS comme multiple sources de courant



$$\boxed{I_{Dn} = \frac{W_n}{W_1}\frac{L_1}{L_n}\cdot I_{D1}}$$

# PMOS comme multiple sources de courant

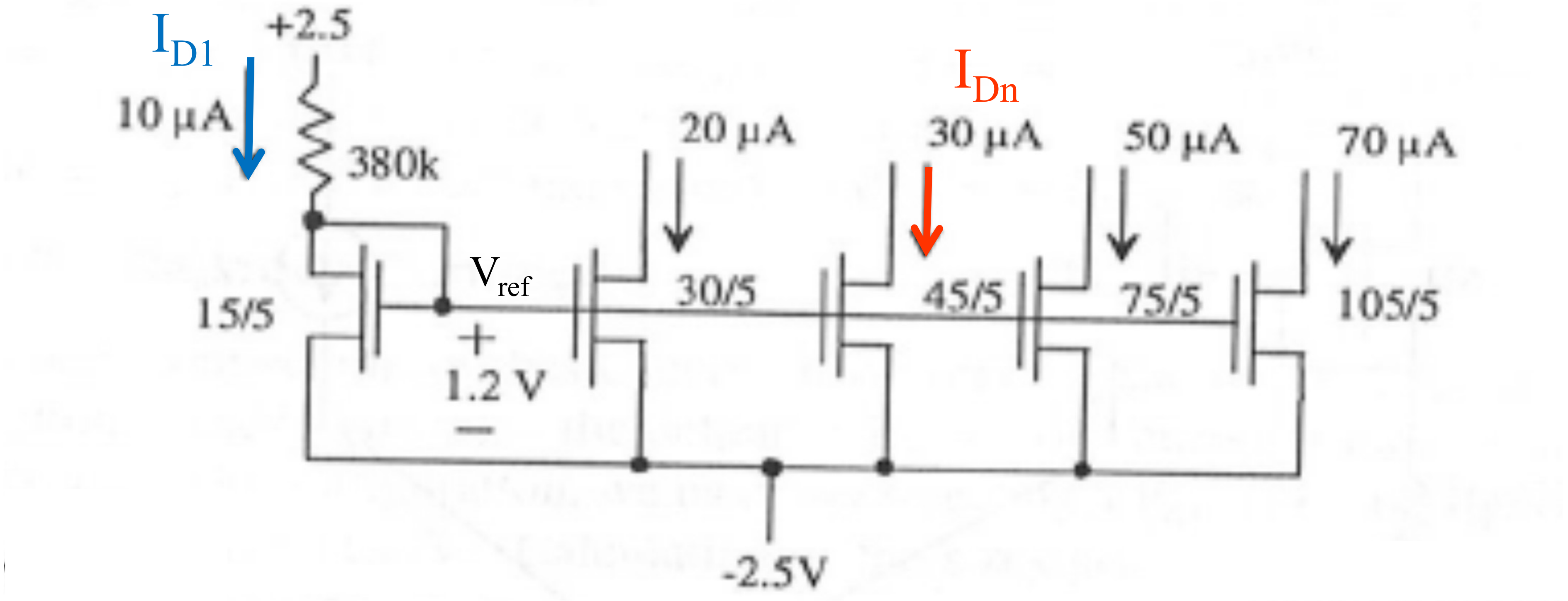


$$I_{Dn} = \frac{W_n}{W_1} \frac{L_1}{L_n} \cdot I_{D1}$$

# Exemple de multiple sources de courant

Diviseur de tension

4 sources de courant en parallèle

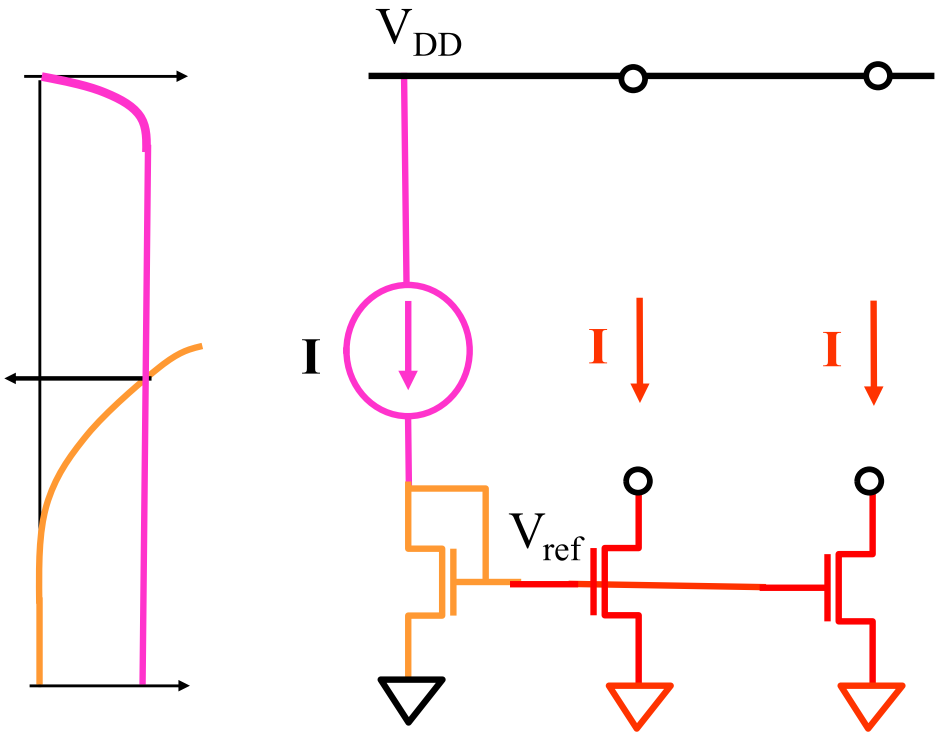


R.J. Baker, « CMOS, circuit design, layout and simulation », IEEE Press

$$\boxed{I_{Dn} = \frac{W_n}{W_1}\frac{L_1}{L_n} \cdot I_{D1}}$$

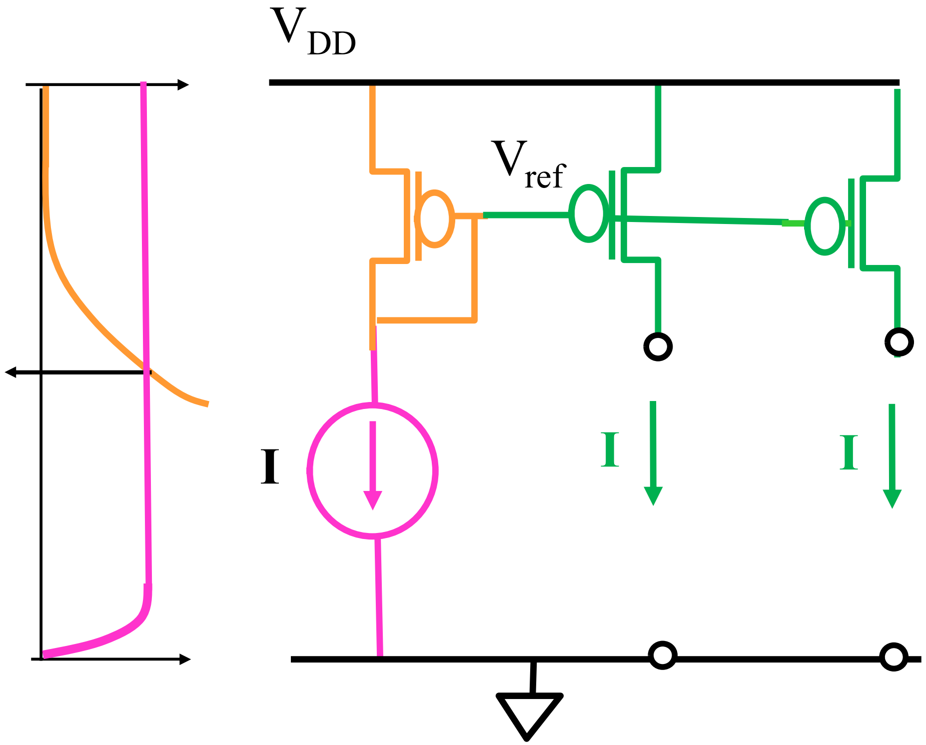
# Miroir de courant

## Basé sur NMOS



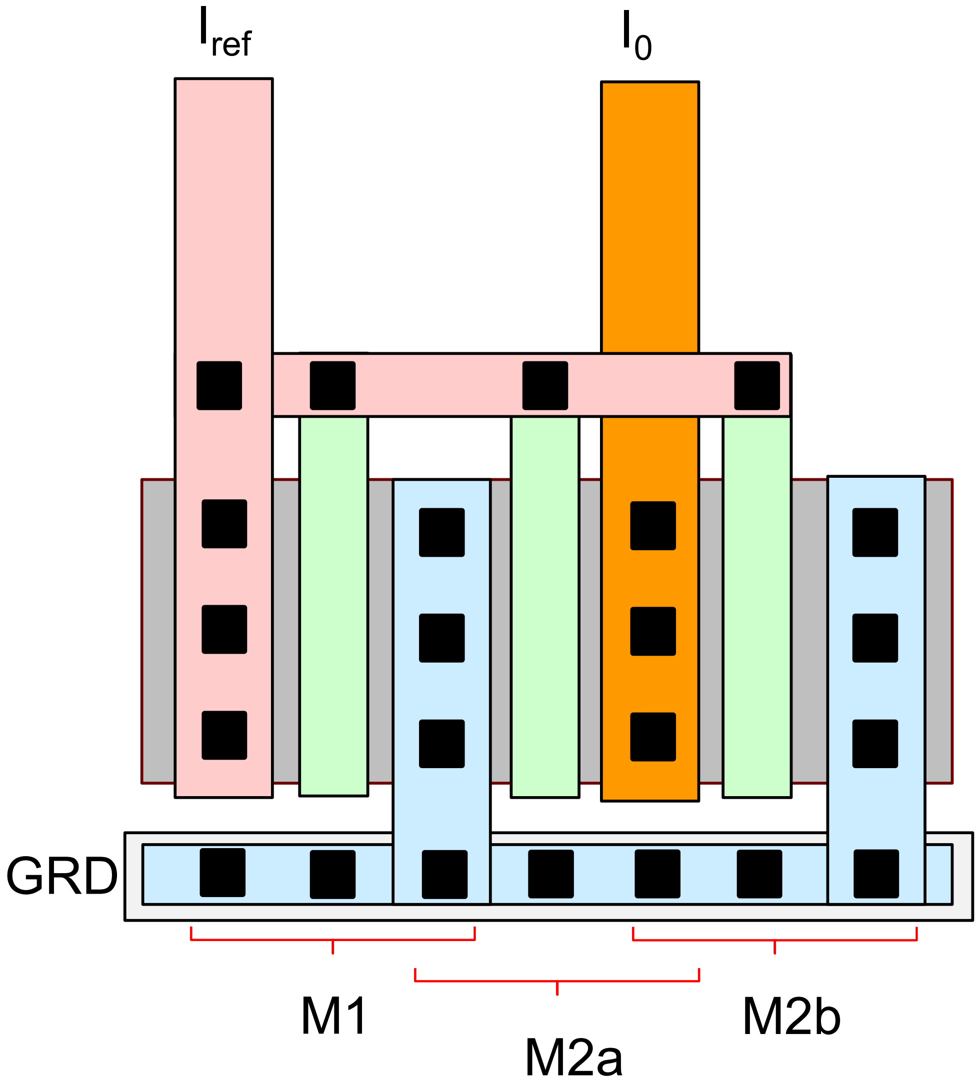
La source de courant
peut être un PMOS

## Basé sur PMOS

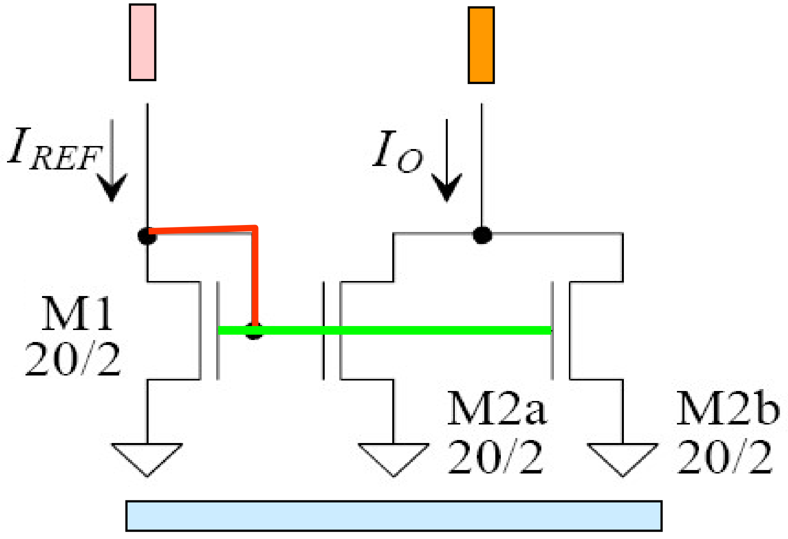


La source de courant
peut être un NMOS

# Miroir de courant: exemple de layout



R.J. Baker, « CMOS, circuit design, layout and simulation », IEEE Press



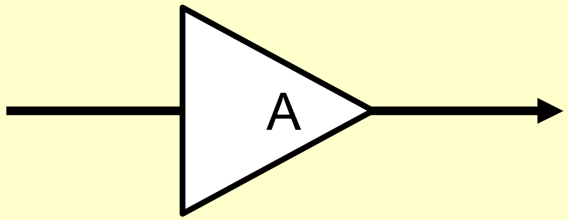
$$I_0 = 2I_{ref}$$

# Ampli de tension
# en boucle ouverte

# Ampli de tension: catégories

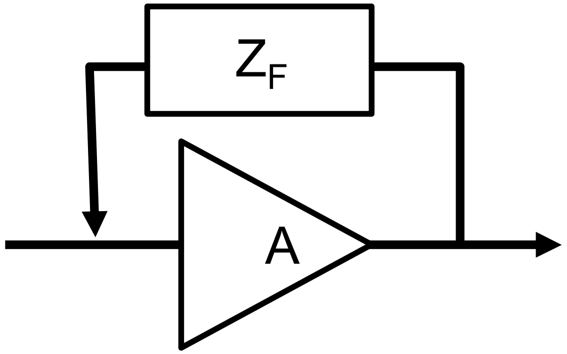
**En boucle ouverte**

- Résistance de charge
  ou
  Résistance active
- Gain modeste
- Point de travail par couplage capacitif



En boucle fermée

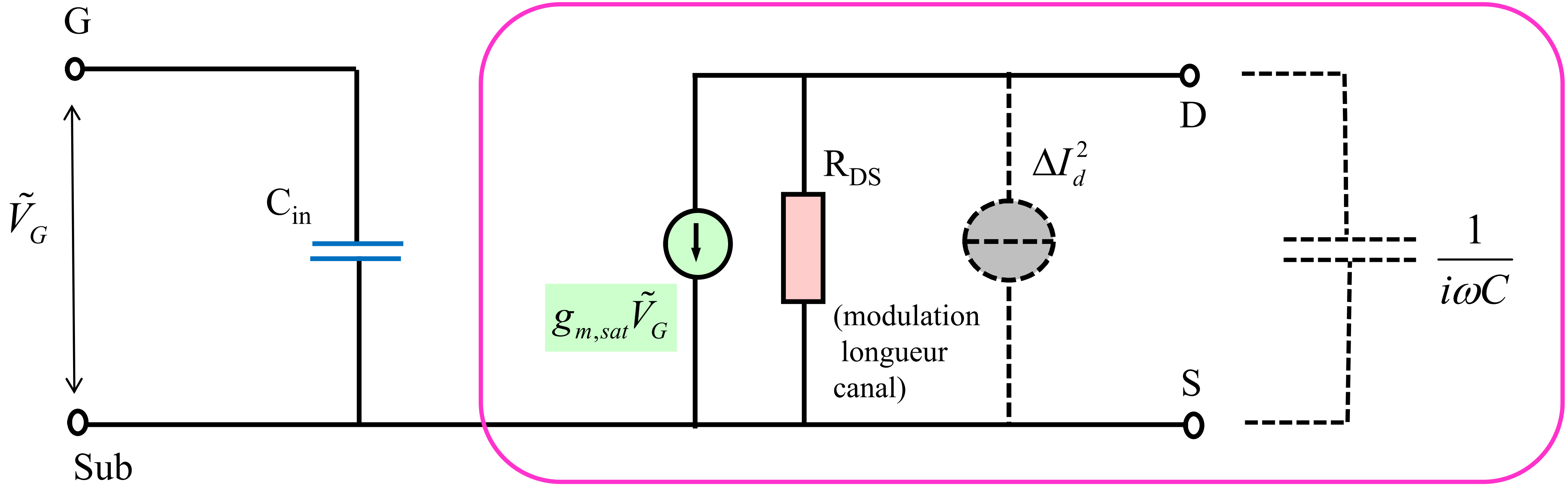
- Source de courant comme charge
- Gain en boucle ouverte
  très important
  Gain final déterminé par le feedback
- Point de travail fixé par une boucle de feedback



# Rappel: MOSFET circuit petits signaux simplifié

$$C_{in} \cong (Z \cdot L) \cdot \overline{C}_{ox}$$

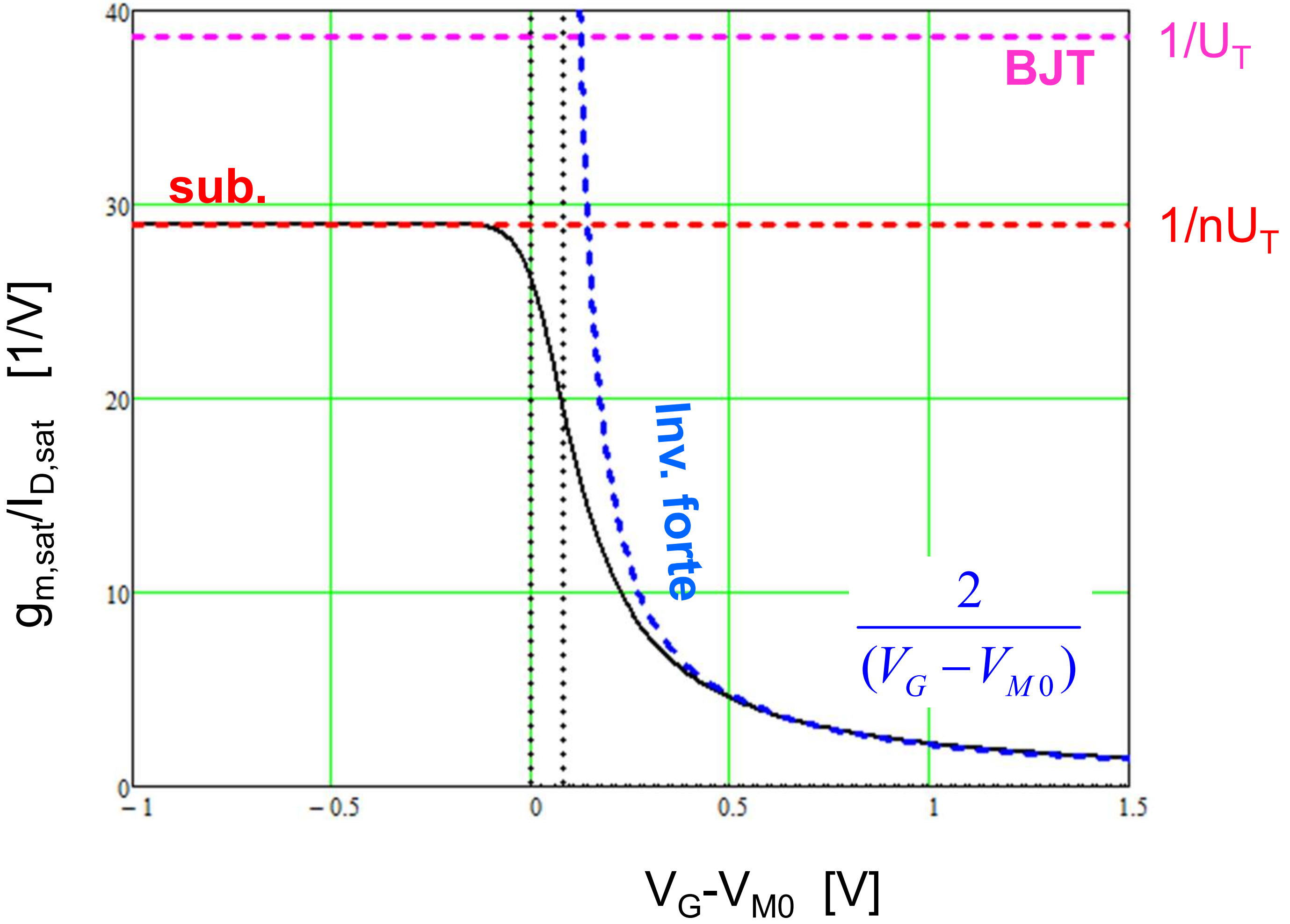
$$R_{DS} \equiv (g_{DS})^{-1} \equiv \left(\frac{\delta I_D}{\delta V_D}\right)^{-1} \cong \frac{|V_A|}{|I_{D,sat}|}$$



Inversion forte

$$\frac{g_{m,sat}}{|I_{D,sat}|} \cong \frac{2}{V_G - V_T}$$

# Comparaison: $g_m/I_D$



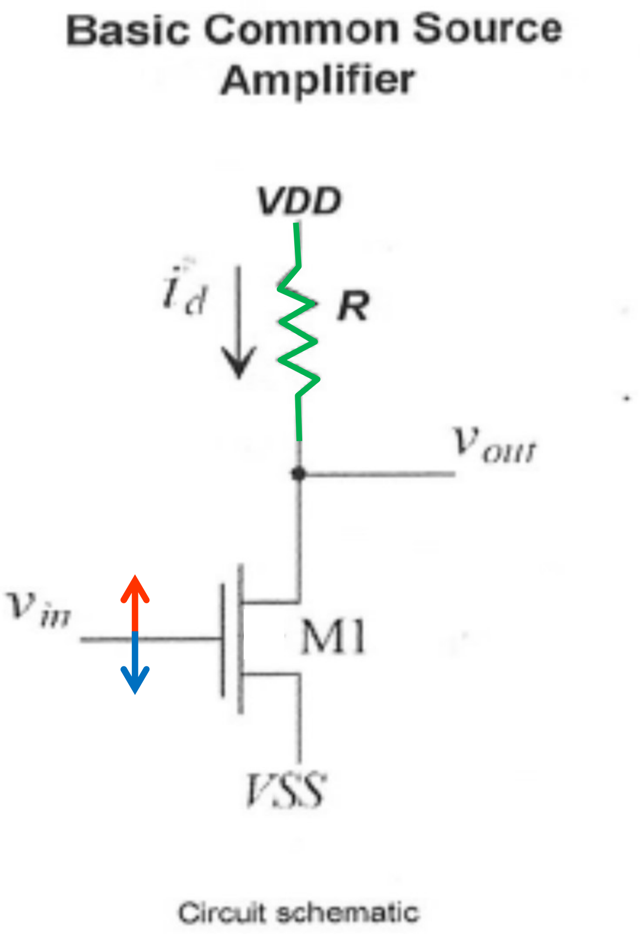
Transconductance définition

$$g_{m,sat} \equiv \frac{\partial I_{D,sat}}{\partial V_G}$$

$C_{ox}$=3fF/um$^2$
W/L=10
T=300 K

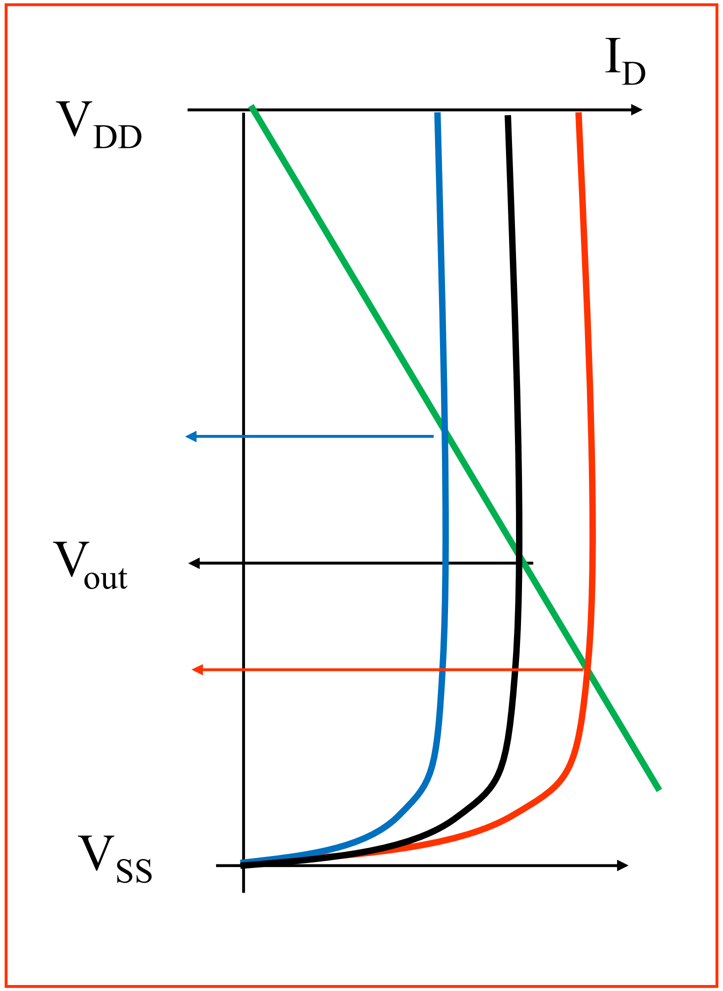
$u_n$=1000cm$^2$/V.s
n=4/3

# Ampli de tension avec résistance de charge



Basic Common Source Amplifier

Circuit schematic



## Gain

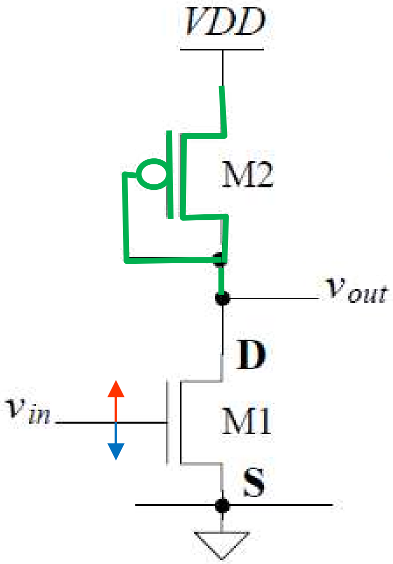
$$\frac{V_{out}}{V_{in}} = -g_{m1} \cdot R$$

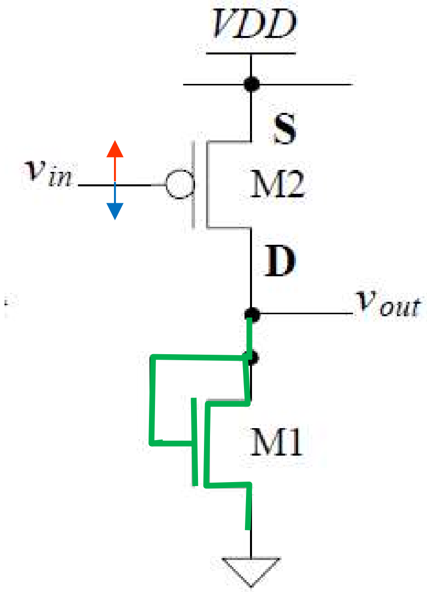
R.J. Baker, « CMOS, circuit design, layout and simulation », IEEE Press

PAB

# Ampli de tension avec résistance active

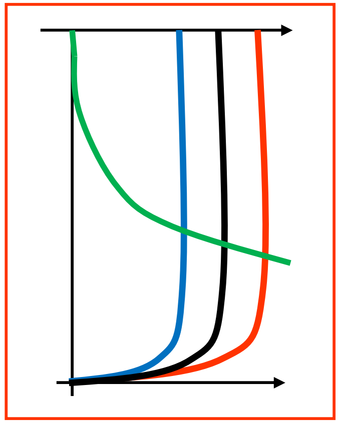
R.J. Baker, « CMOS, circuit design, layout and simulation », IEEE Press





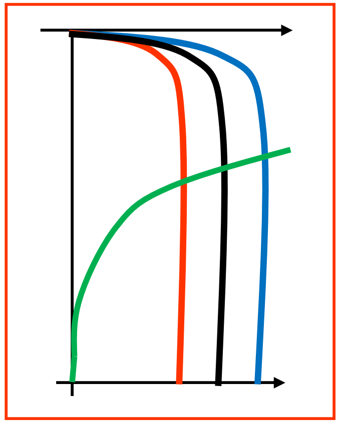
$$V_{out} = -\frac{g_{m1}}{g_{m2}} \cdot V_{in}$$

$$\frac{V_{out}}{V_{in}} = -\frac{g_{m1}/I_D}{g_{m2}/I_D}$$



$$V_{out} = -\frac{g_{m2}}{g_{m1}} \cdot V_{in}$$

$$\frac{V_{out}}{V_{in}} = -\frac{g_{m2}/I_D}{g_{m1}/I_D}$$

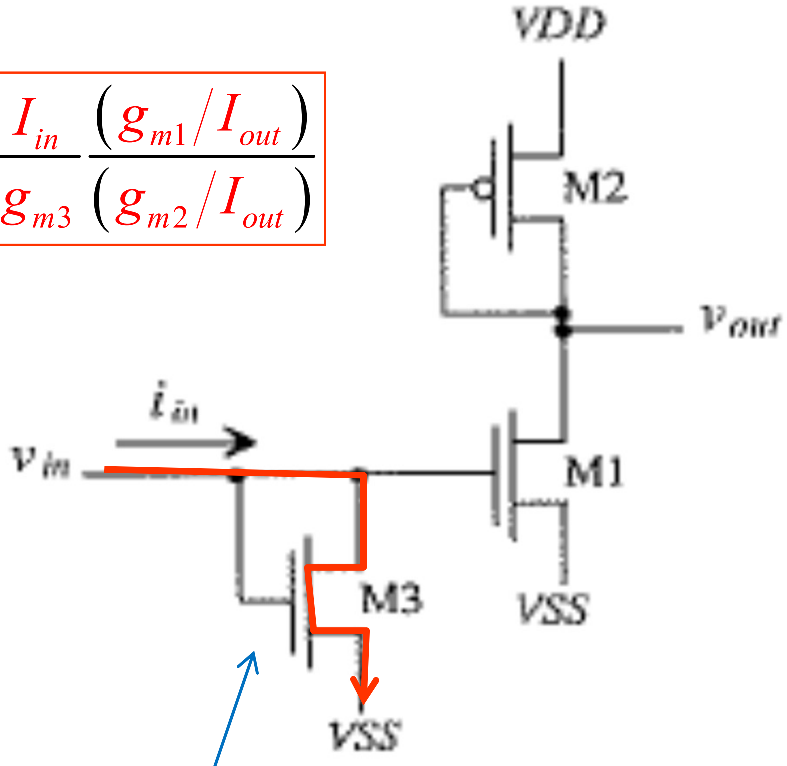


# Transimpédance amplifiers

R.J. Baker, « CMOS, circuit design, layout and simulation », IEEE Press

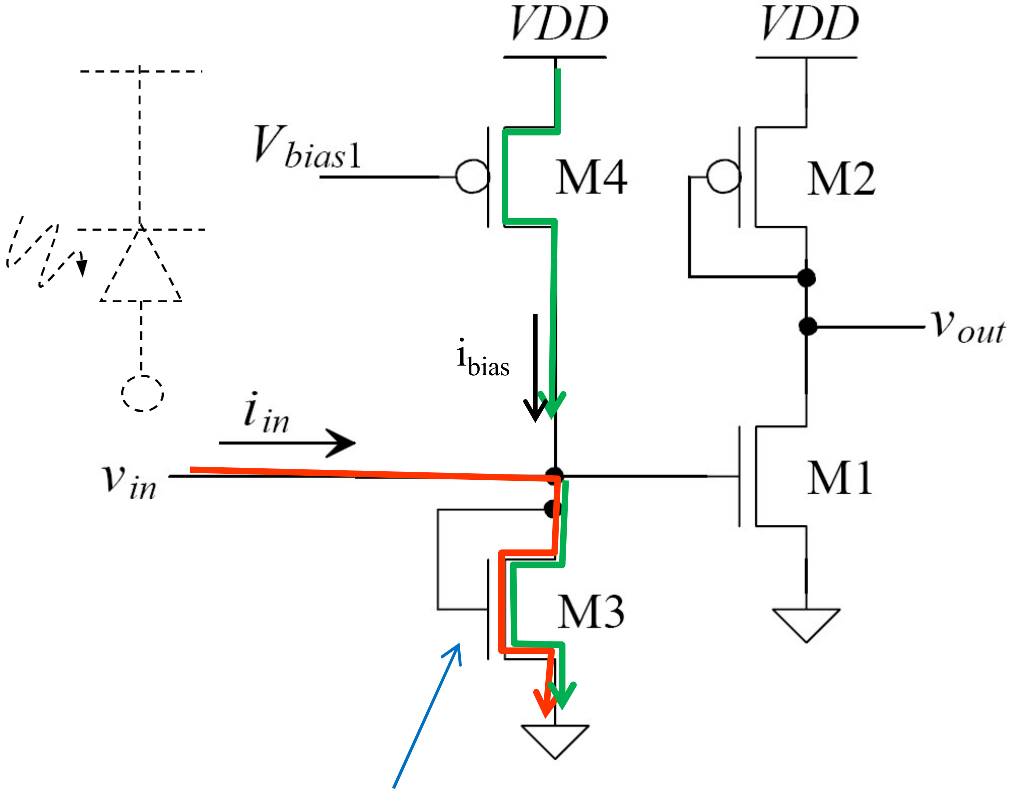
## Principe

$$V_{out} = -\frac{I_{in}}{g_{m3}}\,\frac{\left(g_{m1}/I_{out}\right)}{\left(g_{m2}/I_{out}\right)}$$



Résistance → convertit le courant en tension

## Biasing

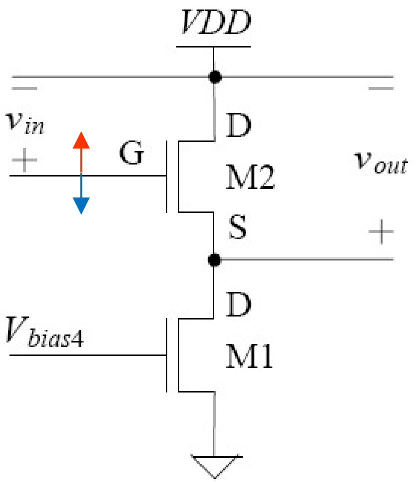


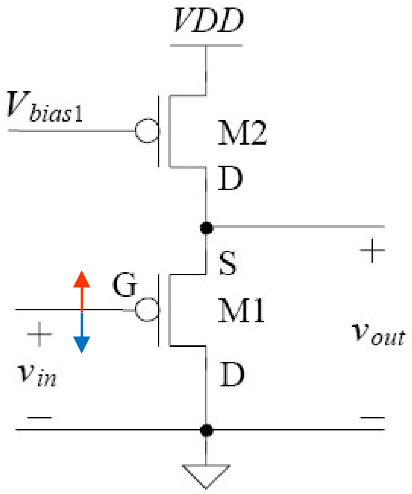
Résistance → convertit le courant en tension

# Source follower: current source load

R.J. Baker, « CMOS, circuit design, layout and simulation », IEEE Press

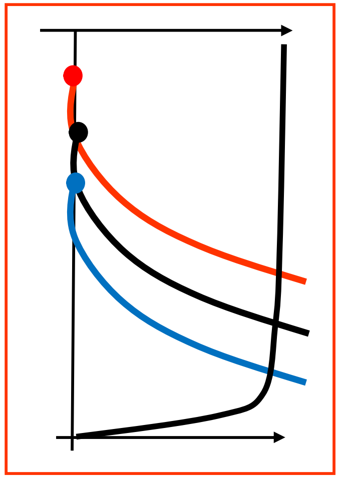
Seulement
NMOS

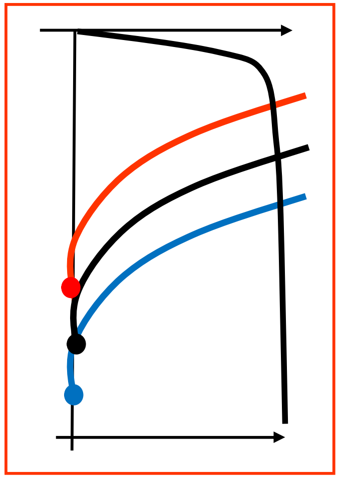




Seulement
PMOS

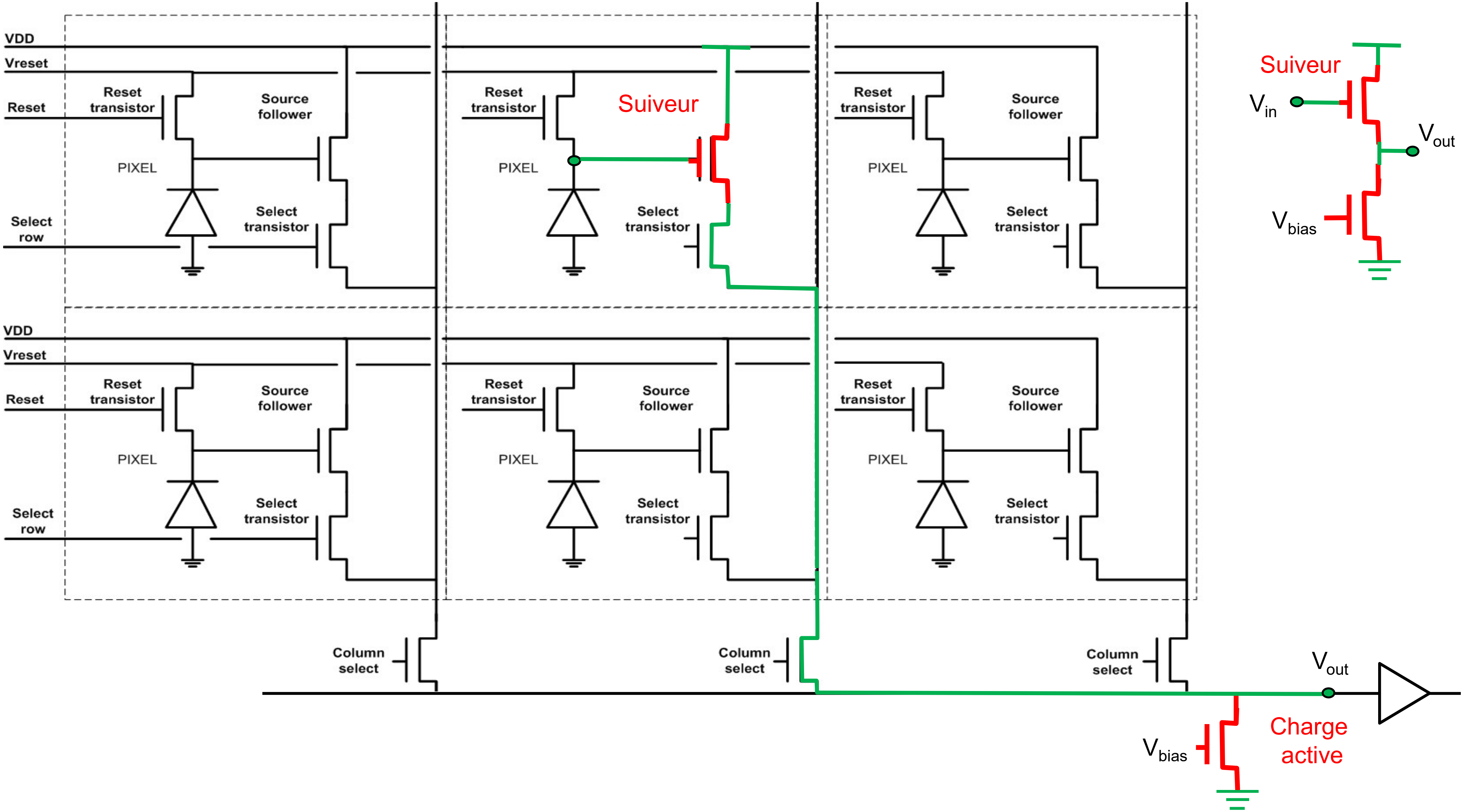
$$\frac{V_{out}}{V_{in}} \cong 1$$





$$\frac{V_{out}}{V_{in}} \cong 1$$

# Exemple d'utilization du suiveur NMOS: Standard 3T APS CMOS camera

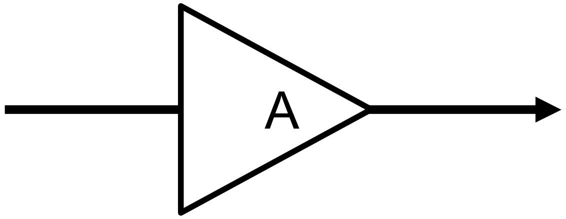


# Ampli de tension
# en boucle fermée

# Ampli de tension: catégories

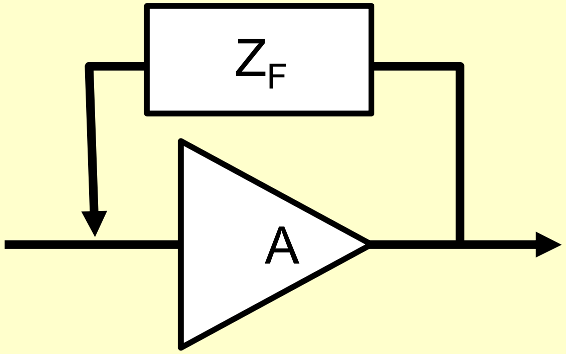
En boucle ouverte

- Résistance de charge
  ou
  Résistance active
- Gain modeste
- Point de travail par couplage capacitif

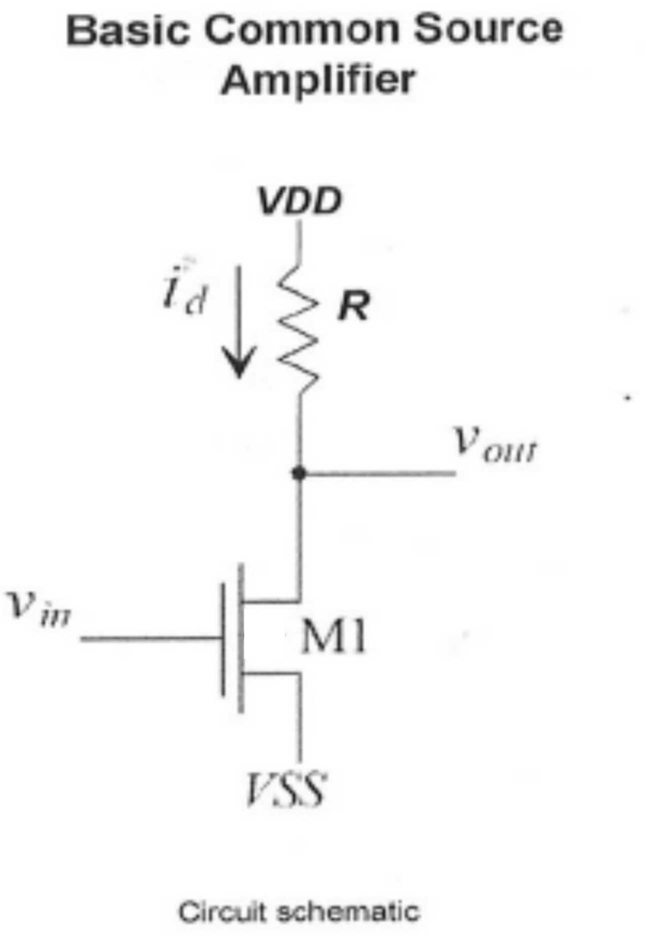


**En boucle fermée**

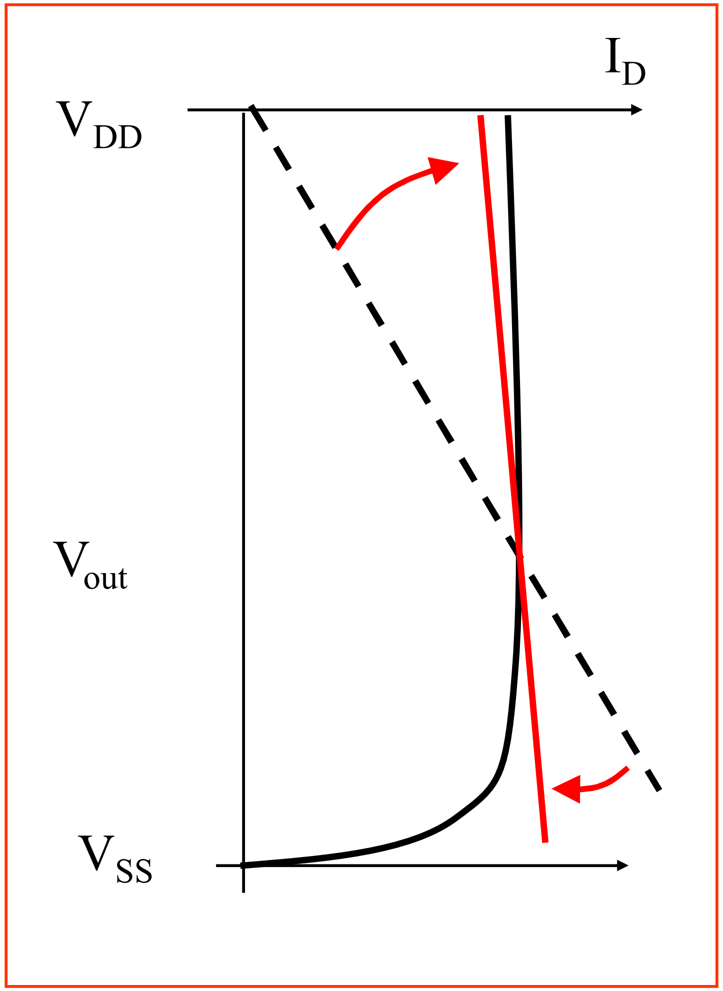
- Source de courant comme charge
- Gain en boucle ouverte
  très important
  Gain final déterminé par le feedback
- Point de travail fixé par une boucle de feedback



# Ampli de tension avec charge idéale


Basic Common Source Amplifier

Circuit schematic

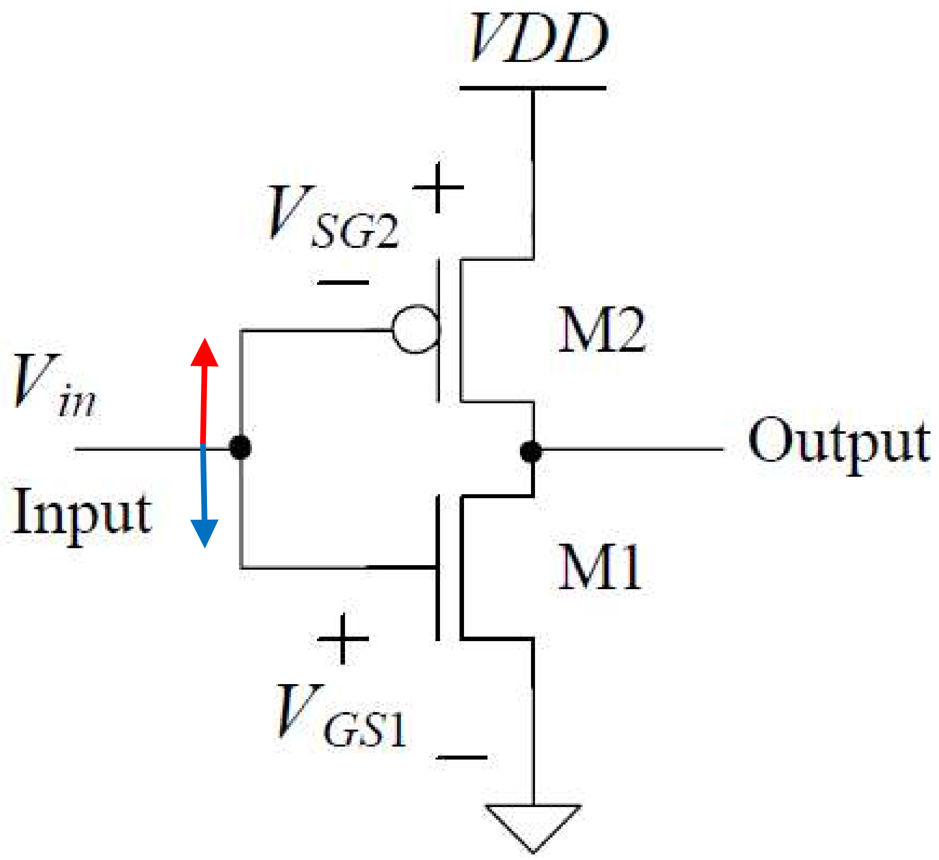


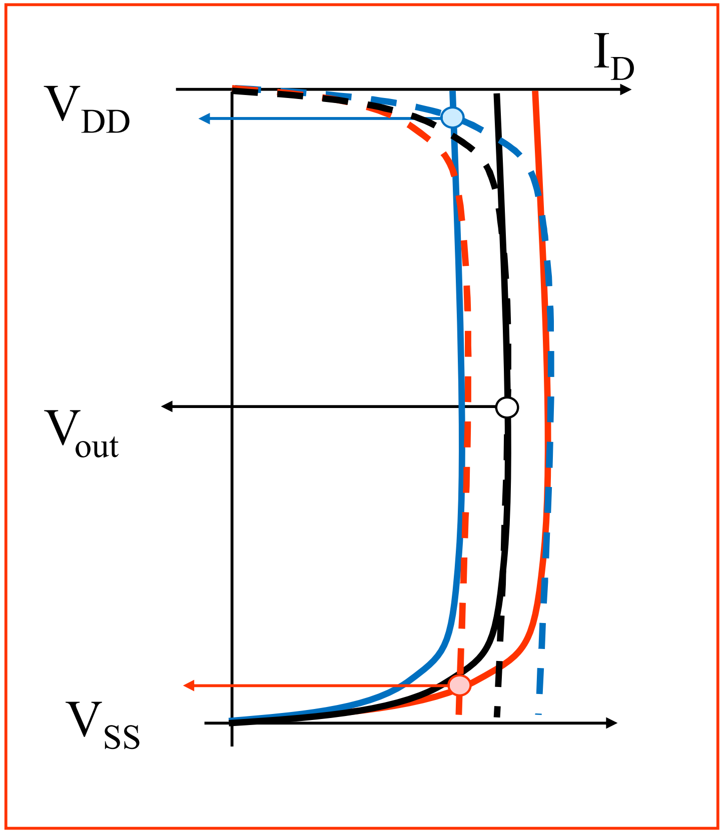
R.J. Baker, « CMOS, circuit design, layout and simulation », IEEE Press

**Gain**

$$\frac{V_{out}}{V_{in}} = -g_{m1} \cdot R$$

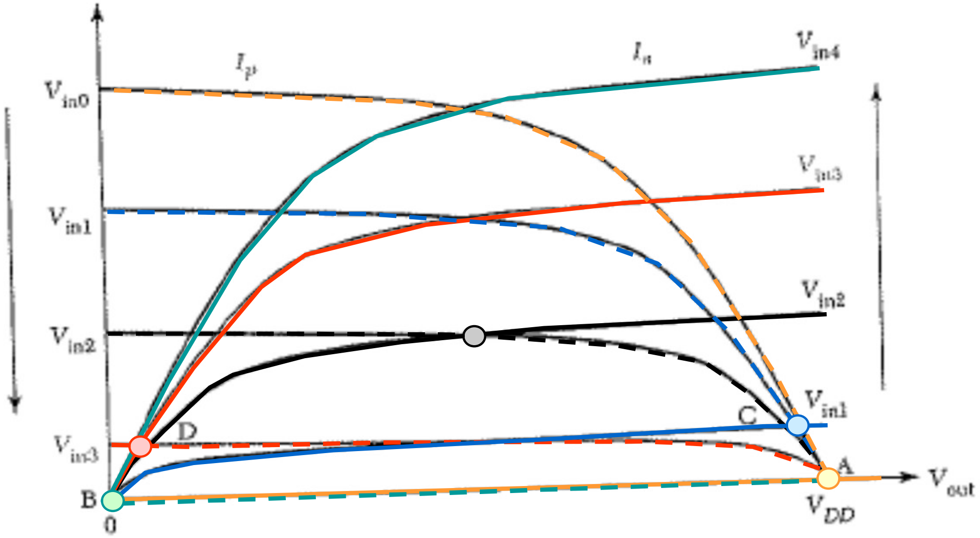
# Inverseur CMOS comme ampli de tension (1)

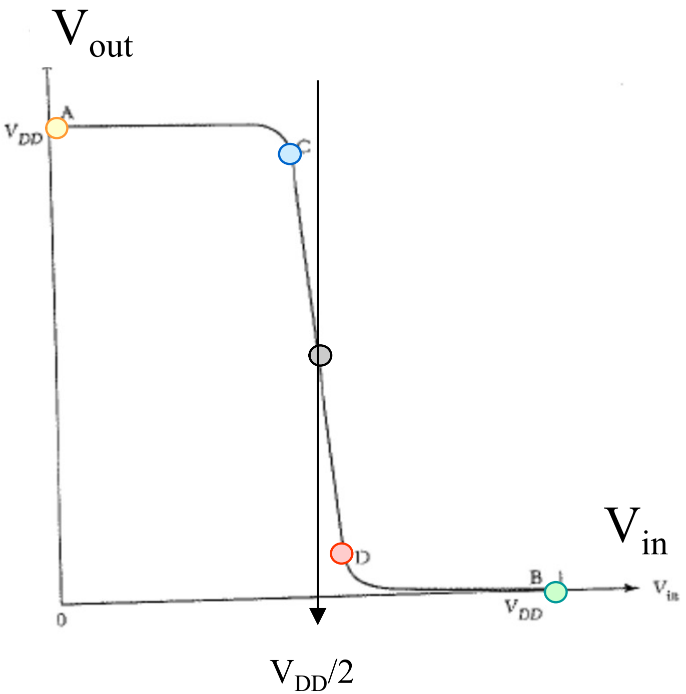




R.J. Baker, « CMOS, circuit design, layout and simulation », IEEE Press

# Inverseur CMOS comme ampli de tension (2)



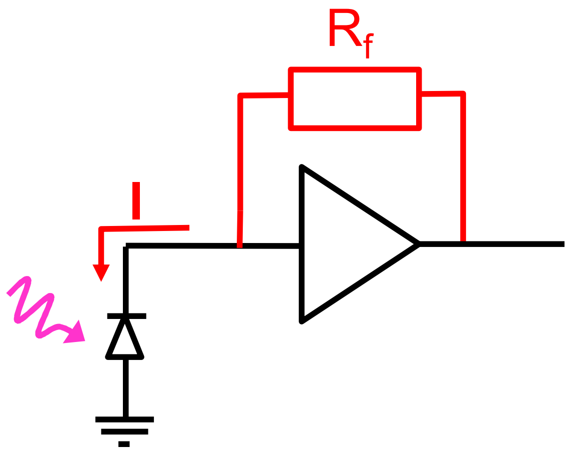


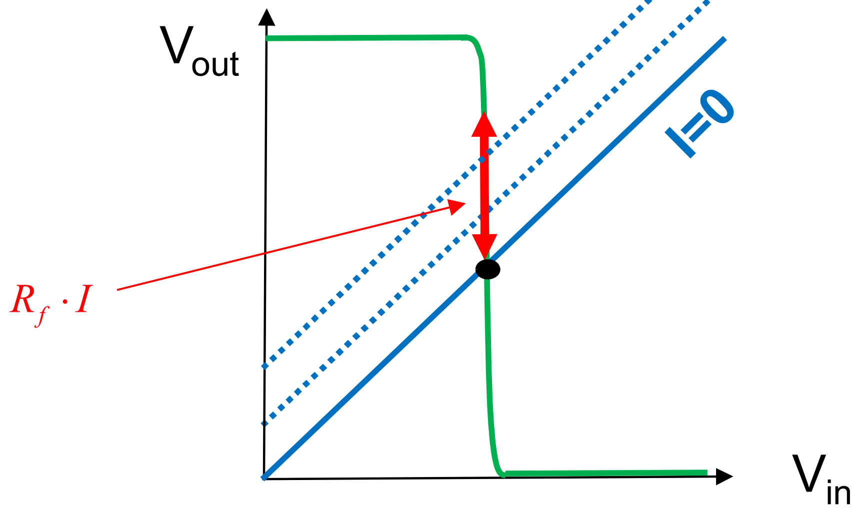
**Gain**

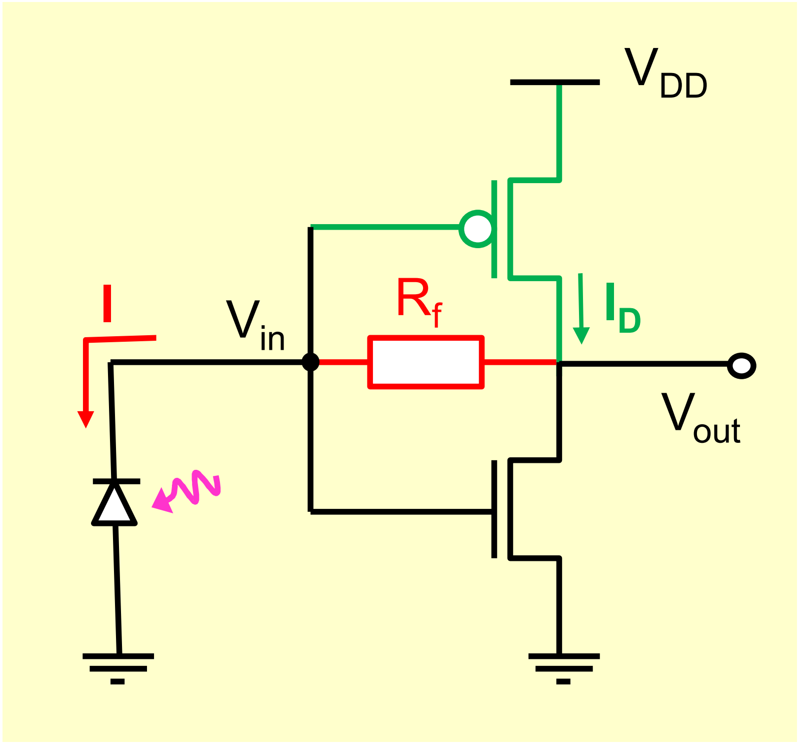
$$\frac{V_{out}}{V_{in}} = -\frac{(g_{m1}+g_{m2})}{g_{DS,1}+g_{DS,2}} = -\left[\frac{g_{m1}}{I_D}+\frac{g_{m2}}{I_D}\right]\cdot\left(\left|V_{A1}\right|^{-1}+\left|V_{A2}\right|^{-1}\right)^{-1}$$

S. Sze, « semiconductor devices, physics and technology », Wiley

# Feedback loop dans un transimpédance





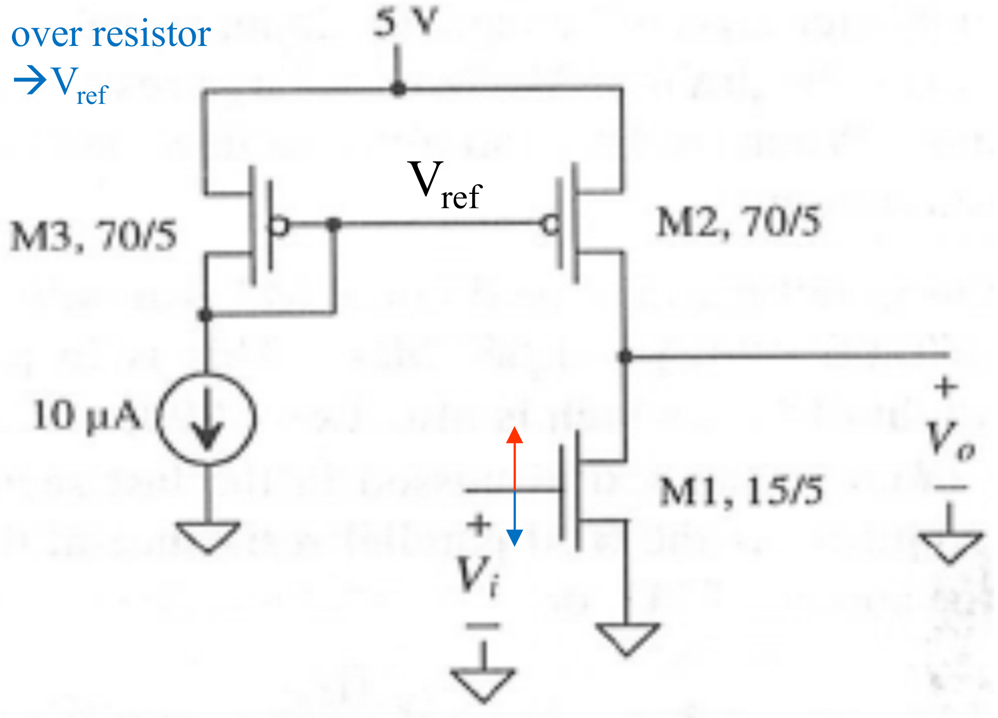


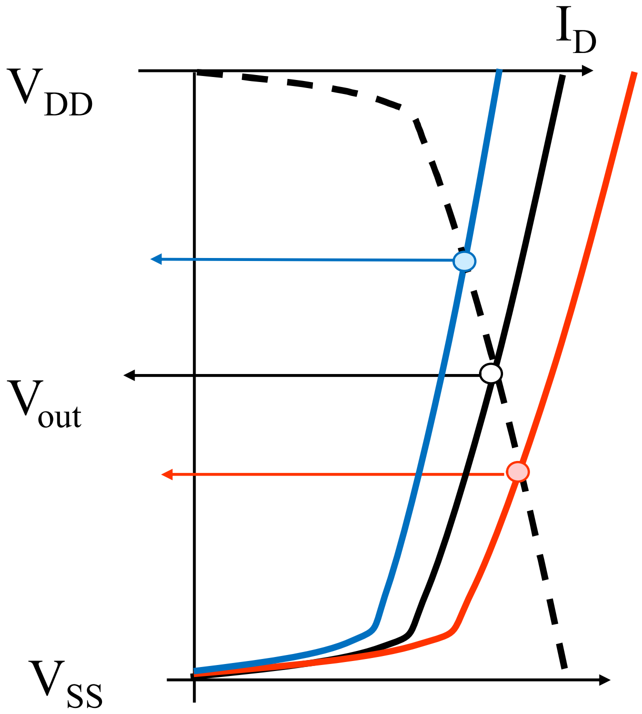
**Current source load → huge gain → feedback loop**

# Ampli de tension chargé par une source de courant

R.J. Baker, « CMOS, circuit design, layout and simulation », IEEE Press

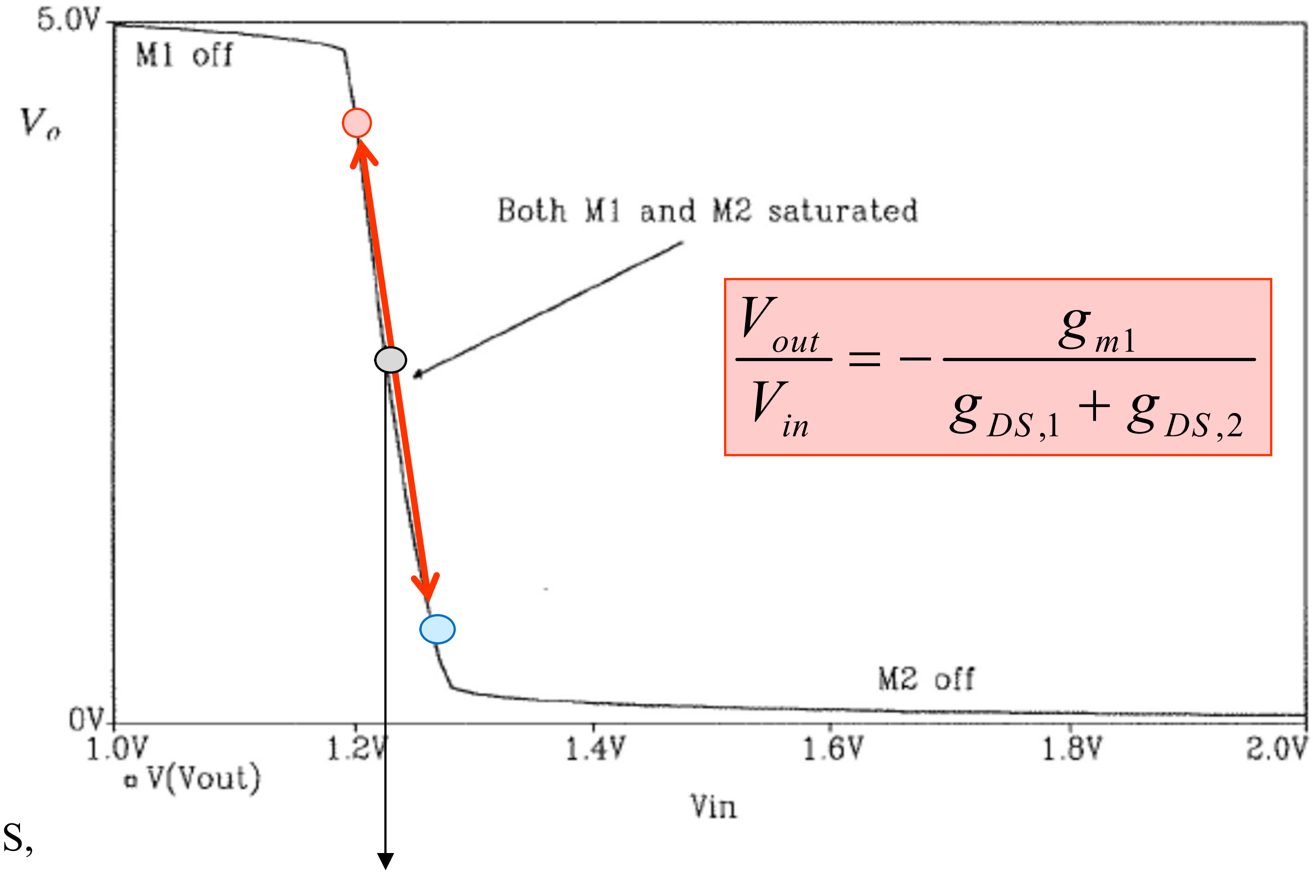
Constant current over resistor $\rightarrow V_{ref}$





$$\frac{V_{out}}{V_{in}} = -\frac{g_{m1}}{g_{DS,1}+g_{DS,2}} = -\left[\frac{g_{m1}}{I_D}\right]\cdot\left(\left|V_{A1}\right|^{-1}+\left|V_{A2}\right|^{-1}\right)^{-1}$$

# Ampli de tension chargé par une source de courant: caractéristique de transfert

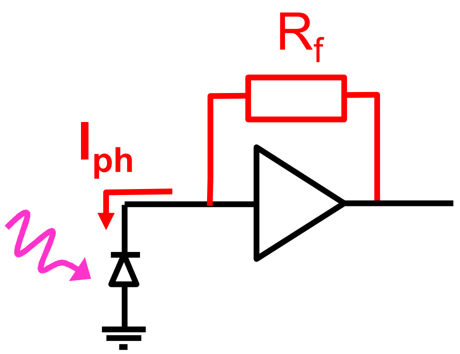


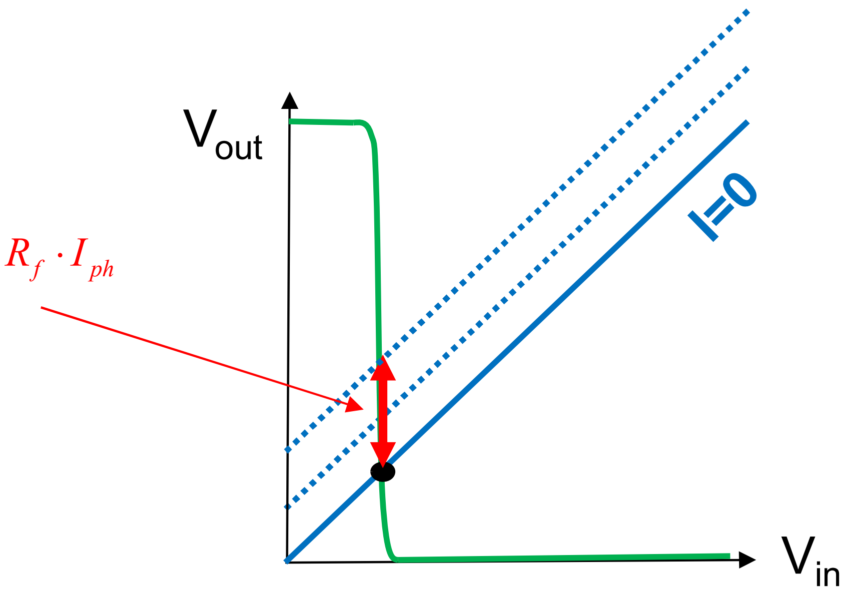
$$\frac{V_{out}}{V_{in}} = -\frac{g_{m1}}{g_{DS,1} + g_{DS,2}}$$

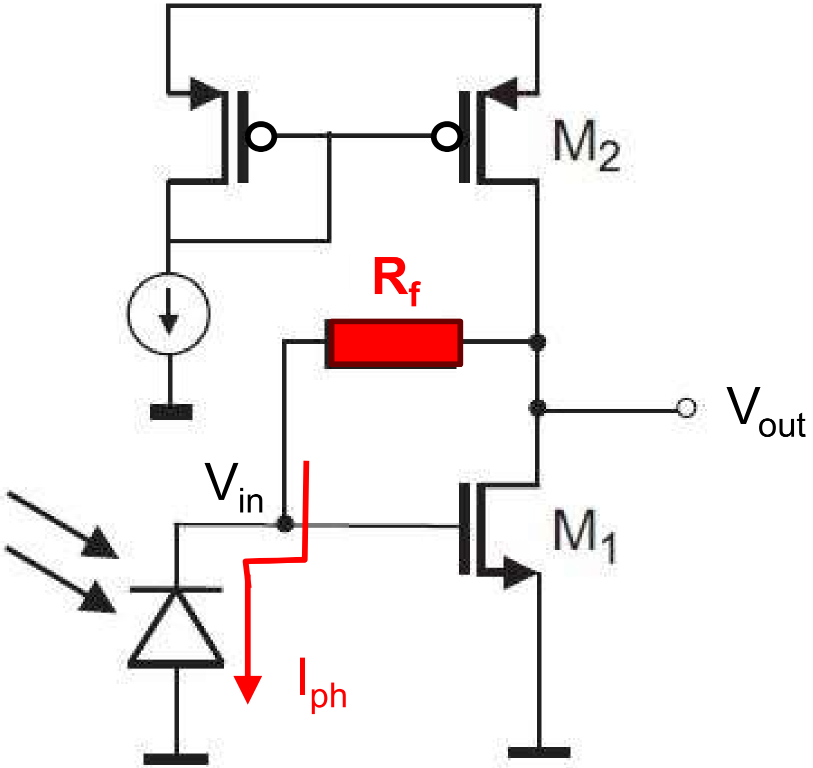
R.J. Baker, « CMOS, circuit design, layout and simulation », IEEE Press

Le point de travail peut être choisi lors du design.

# Feedback loop dans un transimpédance







Sasa Radovanovic, «HIGH-SPEED PHOTODIODES IN STANDARD CMOS TECHNOLOGY», Print Partners Ipskamp, 2004

**Current source load → huge gain → feedback loop**

# Ampli de tension

# Design de W/L

# Importance du paramètre $g_m/I_D$

## Ampli de tension

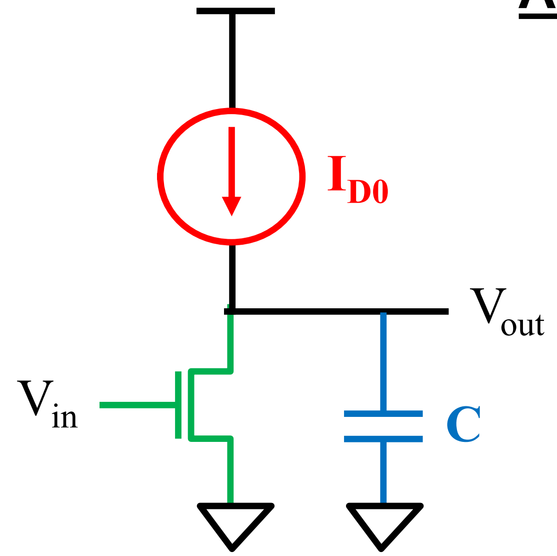
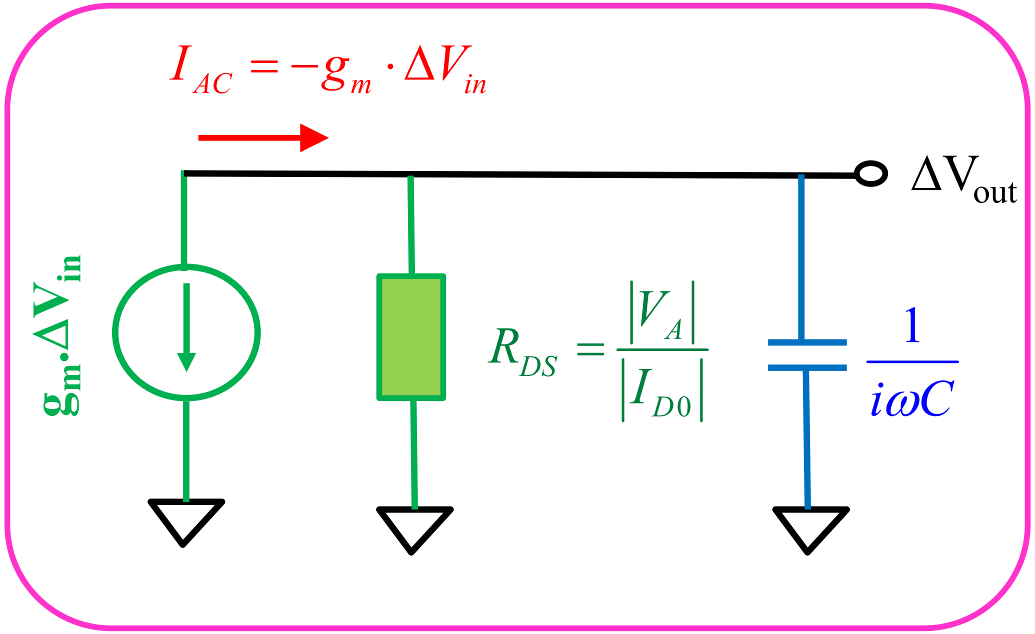


Schéma AC
petit signal



## Gain

$$A_V = -g_m \cdot R_{DS} = -|V_A| \cdot \frac{g_m}{I_{D0}}$$

$\Rightarrow$ Déterminer $V_G$-$V_{M0}$ $\Rightarrow$ Déterminer $\frac{I_{D0}}{(W/L)}$ $\Downarrow$

## Bande passante

$$2\pi\Delta f = \frac{1}{R_{DS}C} = \frac{1}{|V_A| \cdot C} \cdot |I_{D0}|$$

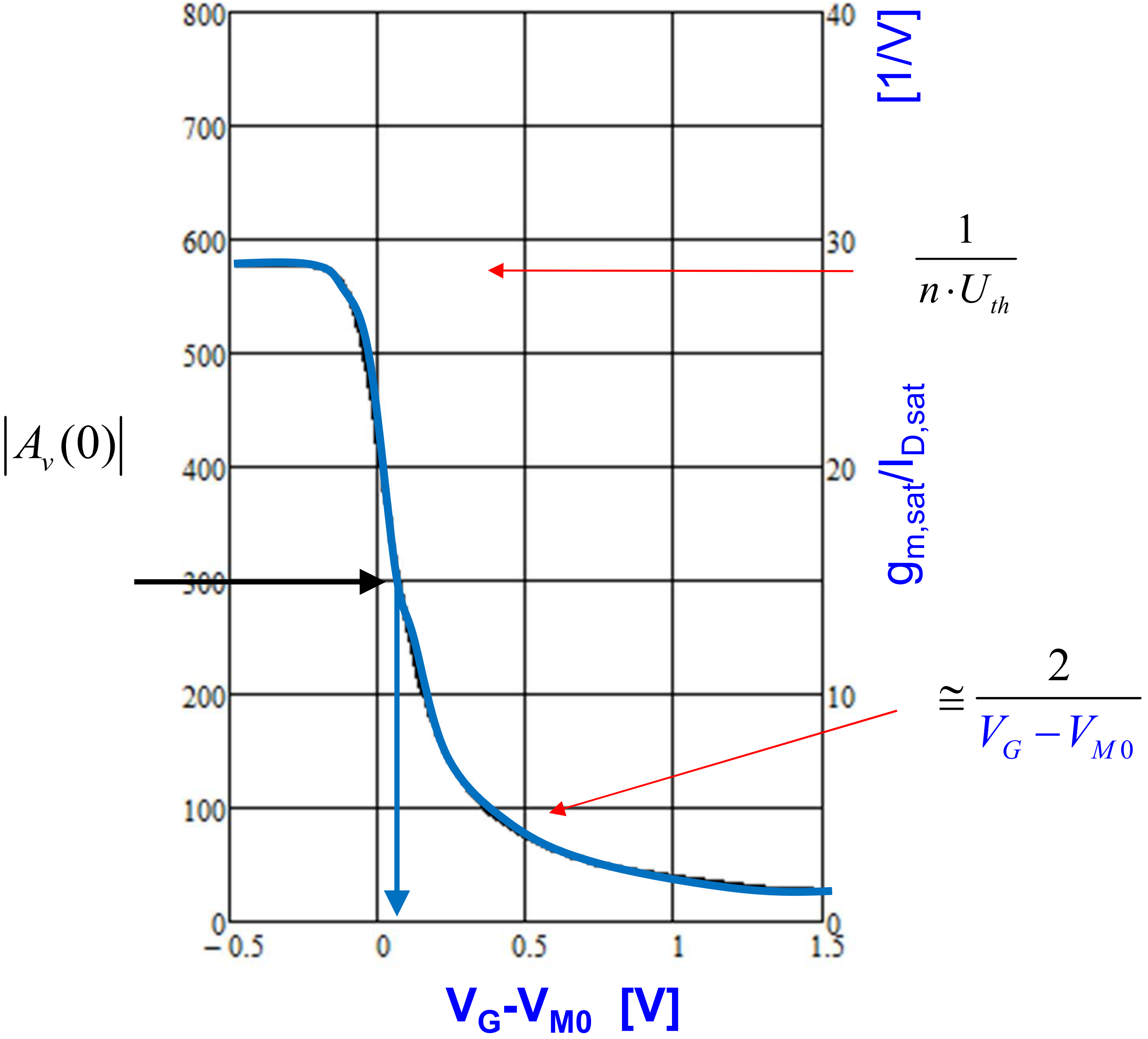
$\Rightarrow$ Déterminer $I_{D0}$ $\Rightarrow$ **W/L**

# Gain en tension et rapport $g_m/I_D$

$$\boxed{A_V = -g_m \cdot R_{DS} = -\left|V_A\right| \cdot \frac{g_m}{I_{D0}}}$$

$\Longrightarrow$ **Pour un gain donné on peut déterminer la valeur de $g_m/I_{D0}$**

# Gain en tension $A_v$ et $(V_G\text{-}V_{M0})$



$$|A_v(0)| = |V_A| \cdot \frac{g_m}{I_D}$$

$\Longrightarrow$

**Pour un gain donné on peut déterminer la valeur de $(V_G\text{-}V_{M0})$**

$C_{ox}$=3fF/um$^2$ $u_n$=1000cm$^2$/V.s
n=4/3 VA= - 20V
$U_T$=26mV

# Rapport $I_D/(W/L)$

Le rapport $I_D/(W/L)$ ne dépend que de $(V_G-V_{M0})$ et de paramètres physiques et technologiques

Inversion faible

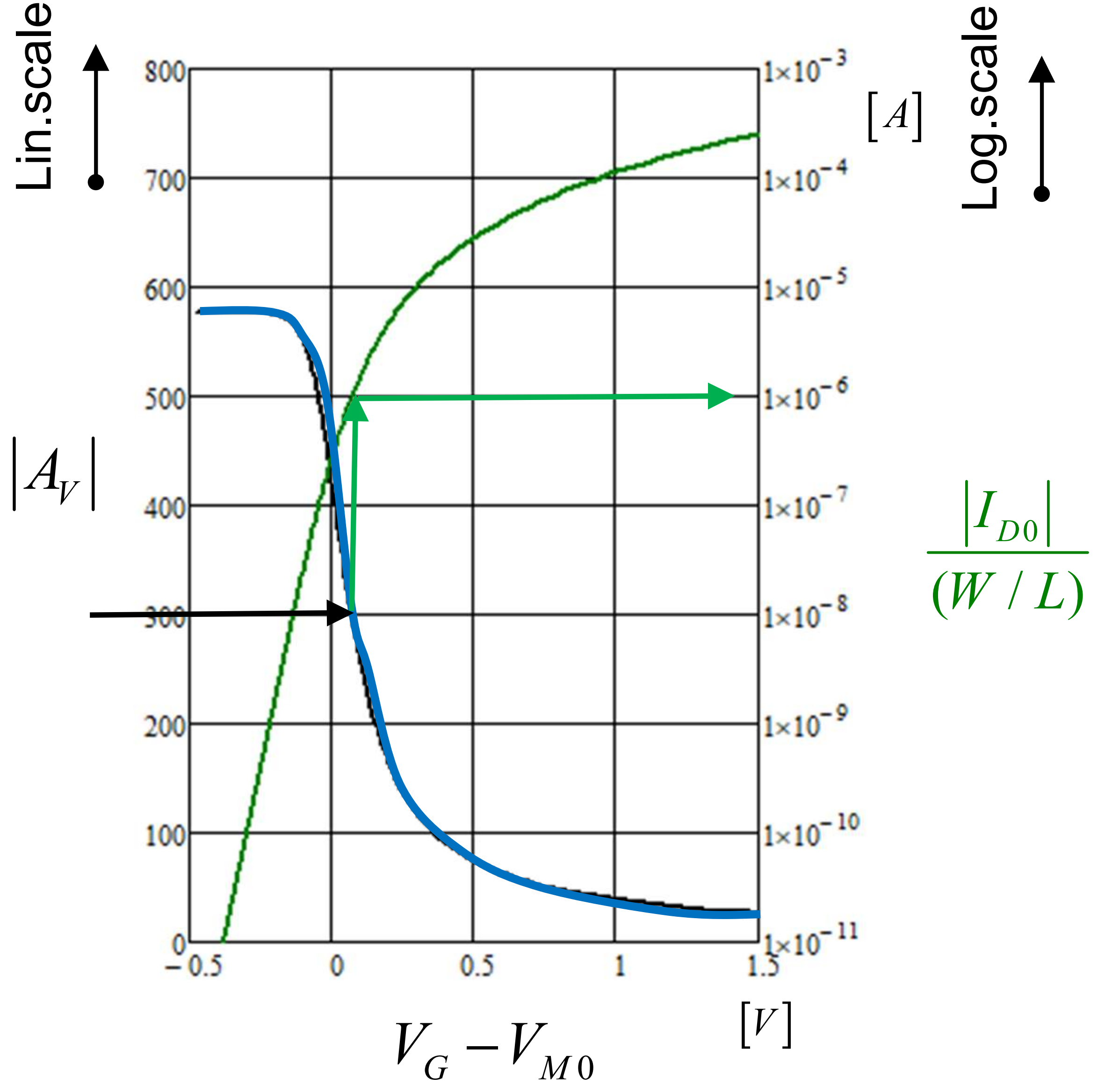
$$\frac{I_D}{(W/L)} \cong \left(2n\mu_n C_{ox} U_{th}^2\right)\cdot e^{\frac{V_G - V_{M0}}{nU_{th}}}$$

Inversion forte

$$\frac{I_D}{(W/L)} \cong \left(\frac{\mu_n C_{ox}}{2n}\right)\cdot\left(V_G - V_{M0}\right)^2$$

⟹ **Pour un gain donné on peut déterminer la valeur de** $\frac{I_D}{(W/L)}$

# Rapport $I_D/(W/L)$



$C_{ox}$=3fF/um$^2$
$V_A$= - 20V
C=1pF

$u_n$=1000cm$^2$/V.s
n=4/3
$U_T$=26mV

# Bande passante et rapport W/L

$$2\pi\Delta f = \frac{1}{R_{DS}}\frac{1}{C} = \frac{\left|I_{D0}\right|}{\left|V_A\right|}\cdot\frac{1}{C}$$

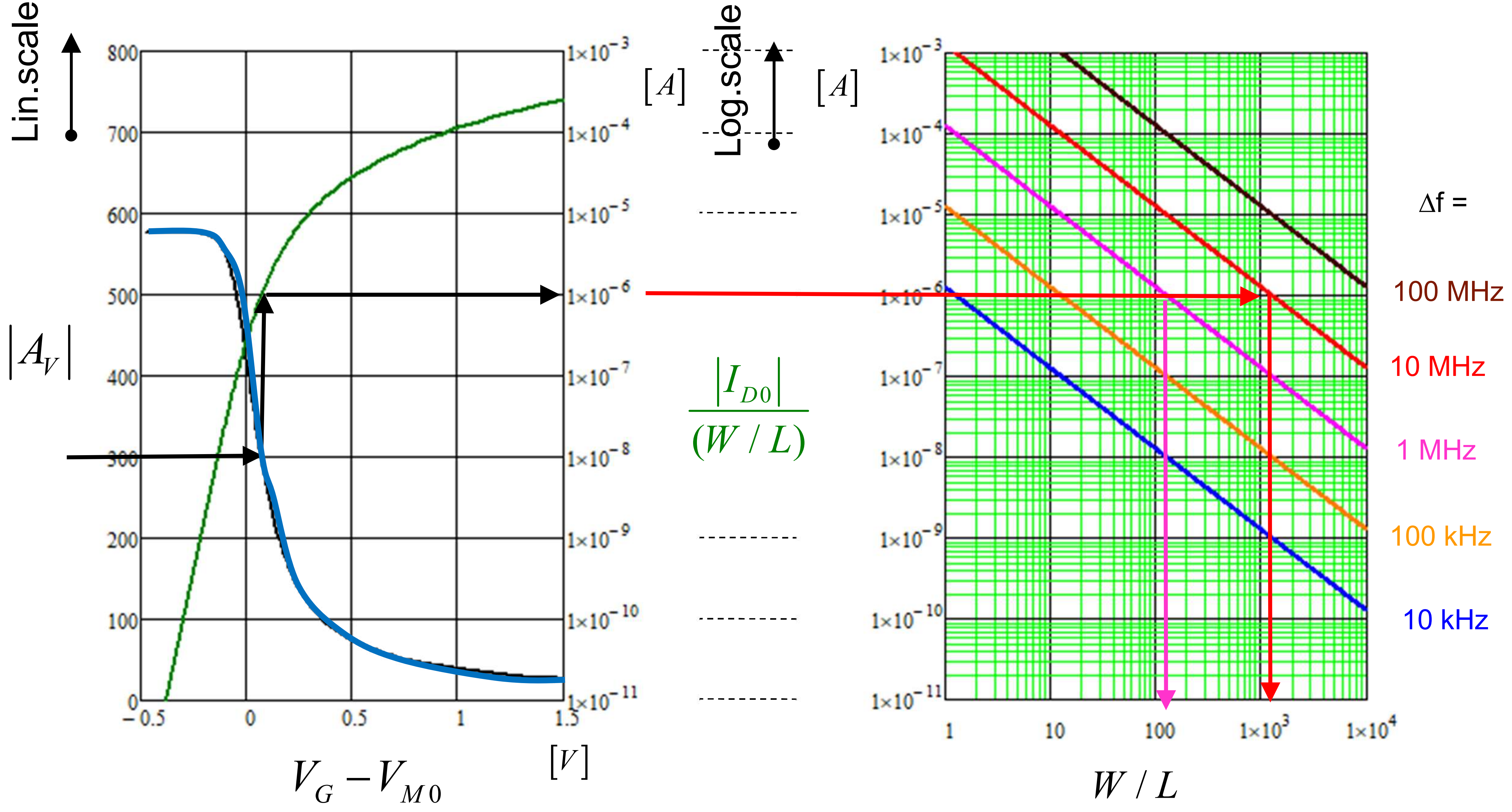
$$\Downarrow$$

$$\boxed{\frac{I_D}{(W/L)} = \left[\left(2\pi\left|V_A\right|C\right)\cdot\Delta f\right]\cdot\frac{1}{(W/L)}}$$

$\Rightarrow$ **La valeur $\frac{I_D}{(W/L)}$ et la bande passante Δf donnent le rapport W/L**

$C_{ox}$=3fF/um$^2$
$V_A$= - 20V
C=1pF

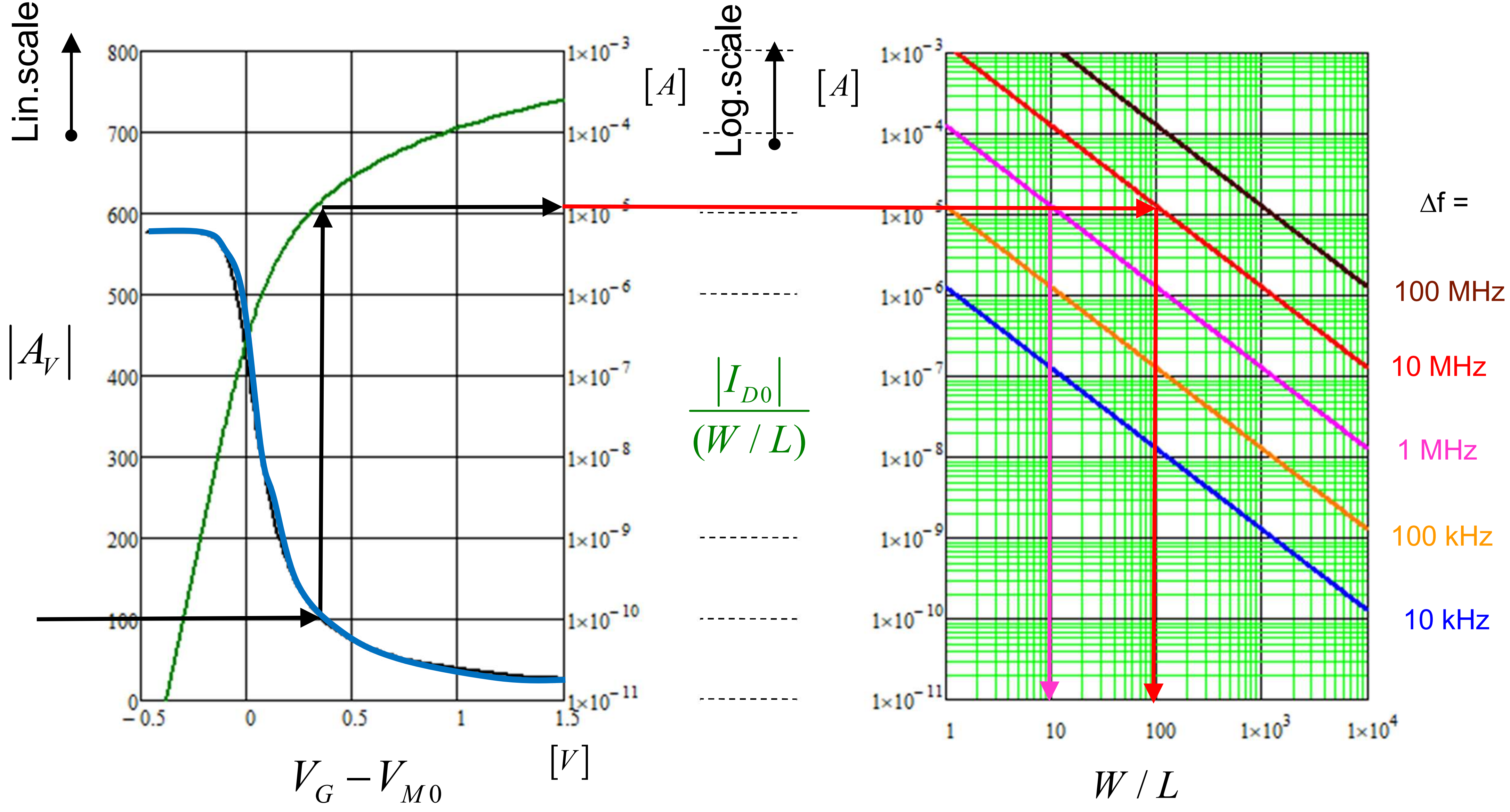
$u_n$=1000cm$^2$/V.s
n=4/3
$U_T$=26mV



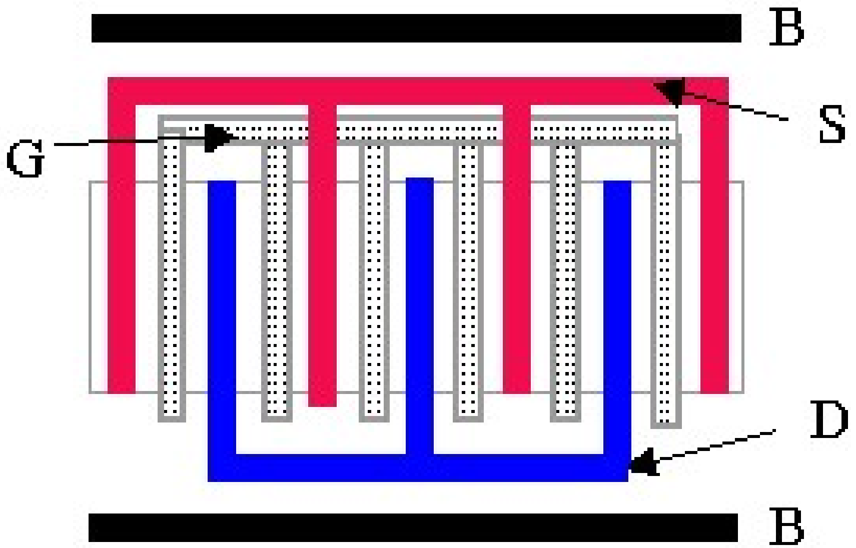
PAB

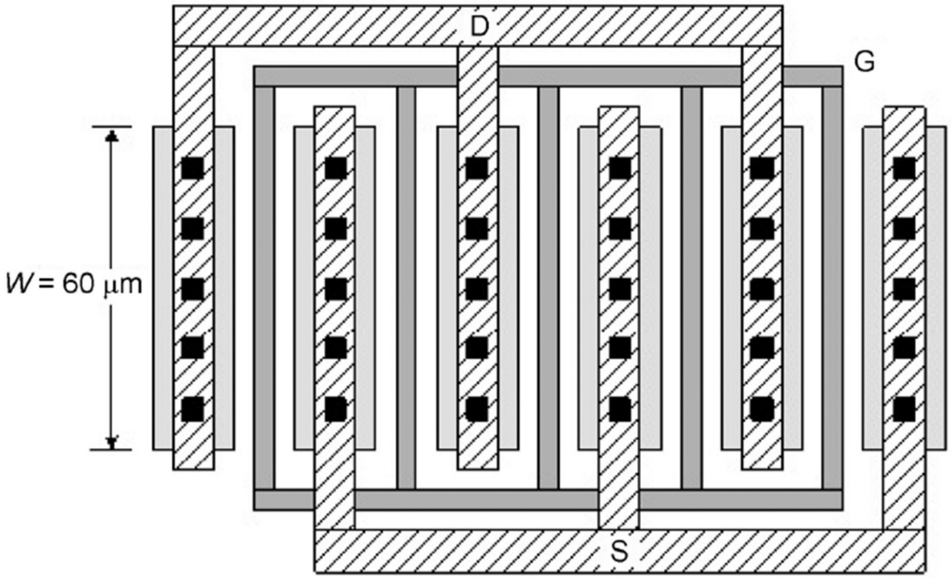
$C_{ox}$=3fF/um$^2$
$V_A$= - 20V
C=1pF

$u_n$=1000cm$^2$/V.s
n=4/3
$U_T$=26mV



# Exemples: Multi-finger MOSFET





https://www.cs.york.ac.uk/rts/docs/SIGDA-Compendium-1994-2004/papers/2004/aspdac04/pdffiles/02c_1.pdf

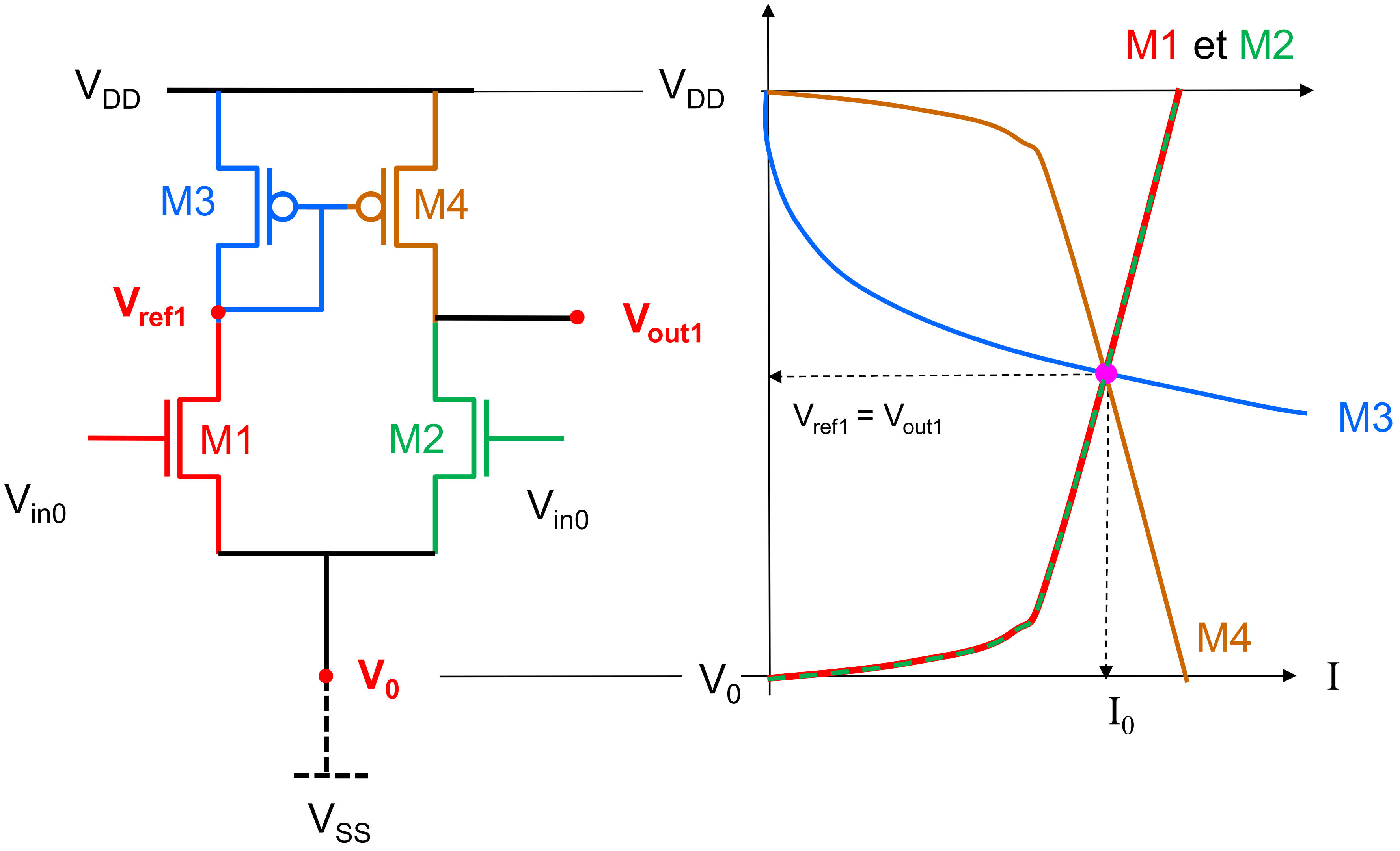
M. Dhamodaran et al., "On-Chip Spiral Inductors and On-Chip Spiral Transistors for Accurate Numerical Modeling", Journal of Magnetics, Vol. 23, No. 1, March 2018

# Ampli différentiel

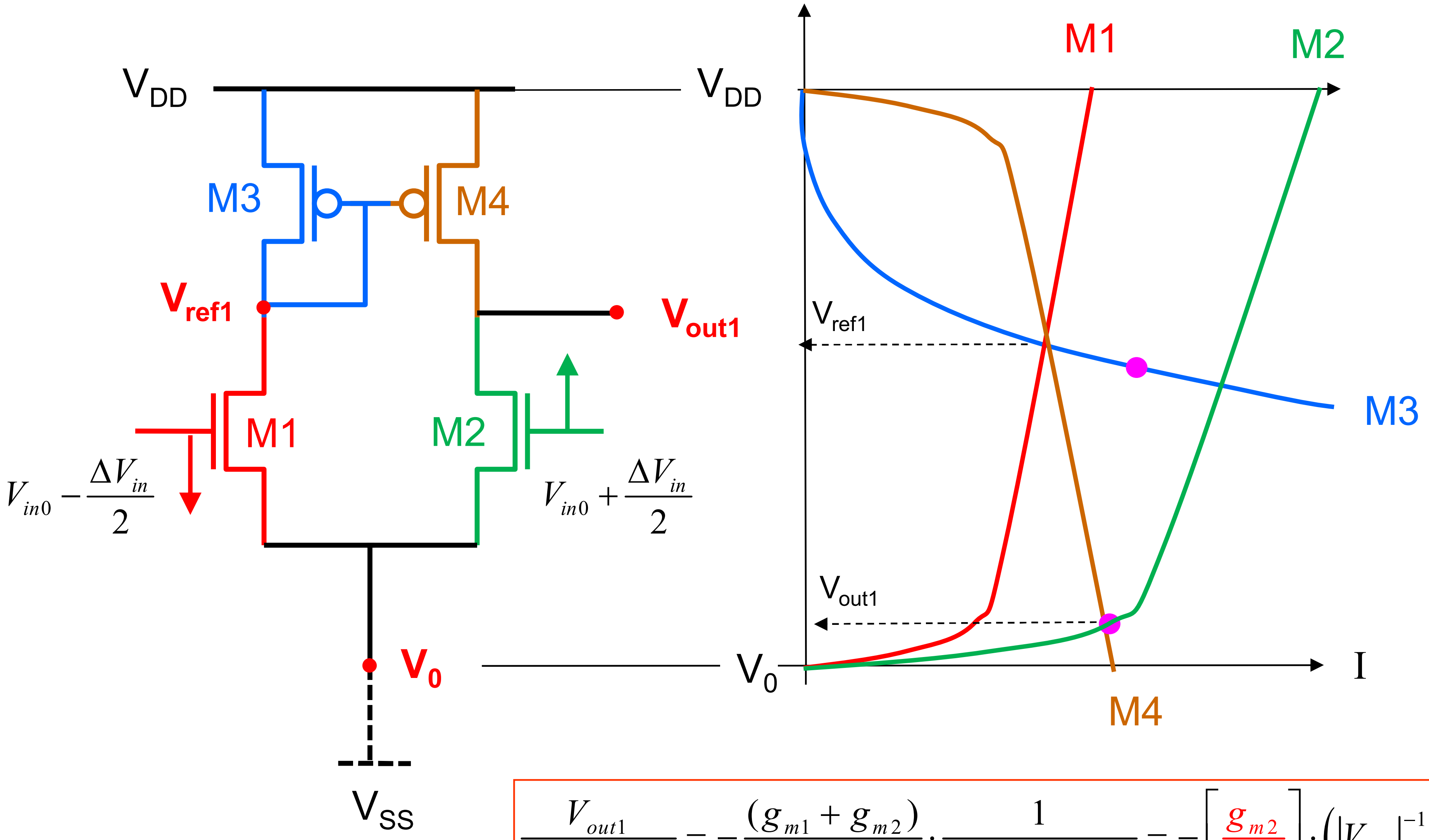
# Et Opam

PAB

# Differential amplifier: point de travail

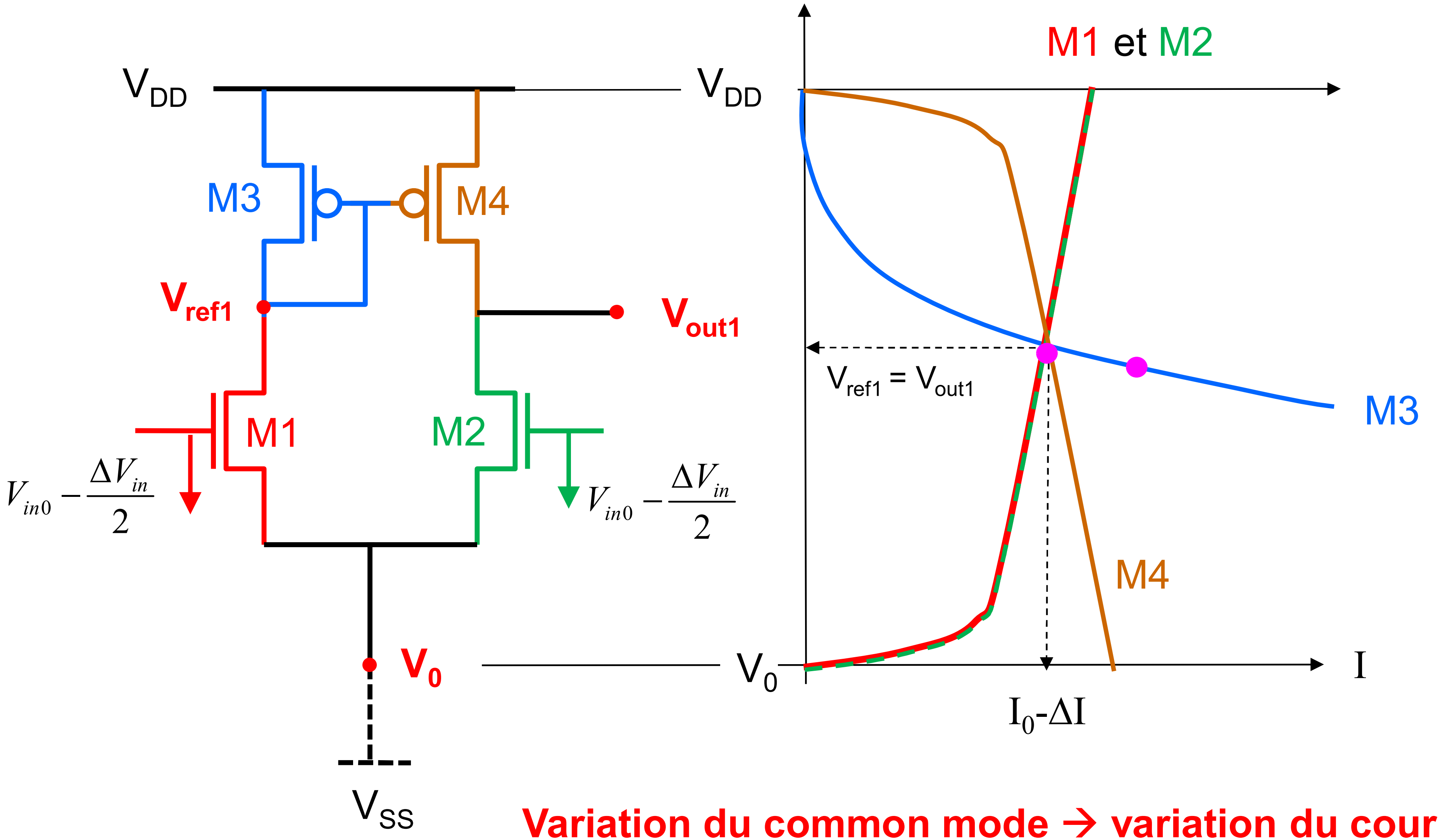


# Differential amplifier:
# analyse du mode différentiel



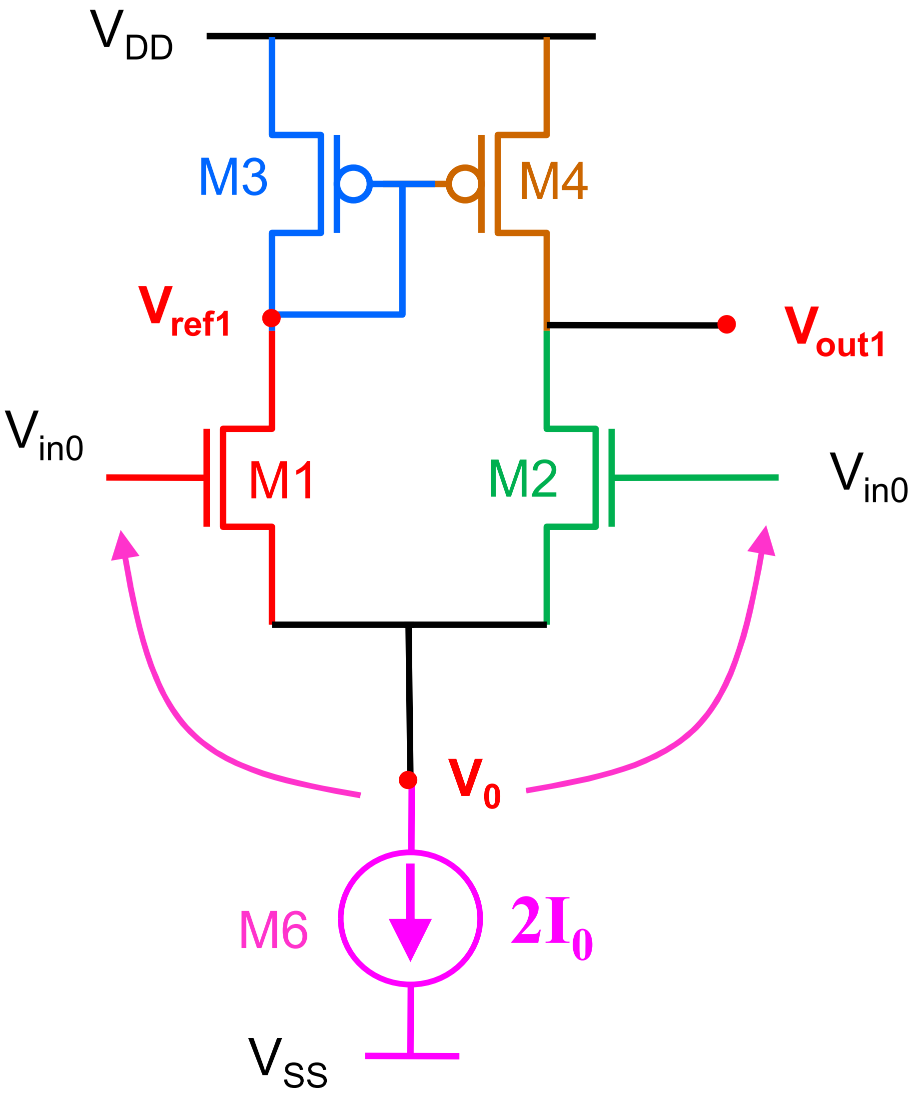
$$\frac{V_{out1}}{V_{in,2} - V_{in,1}} = -\frac{(g_{m1} + g_{m2})}{2} \cdot \frac{1}{g_{DS,4} + g_{DS,2}} = -\left[\frac{g_{m2}}{I_{D2}}\right] \cdot \left(\left|V_{A4}\right|^{-1} + \left|V_{A2}\right|^{-1}\right)^{-1}$$

# Differential amplifier: analyse du mode commun



**Variation du common mode → variation du courant**
**→ Variation du gain du mode différentiel**

# Differential amplifier: introduction d’une source de courant



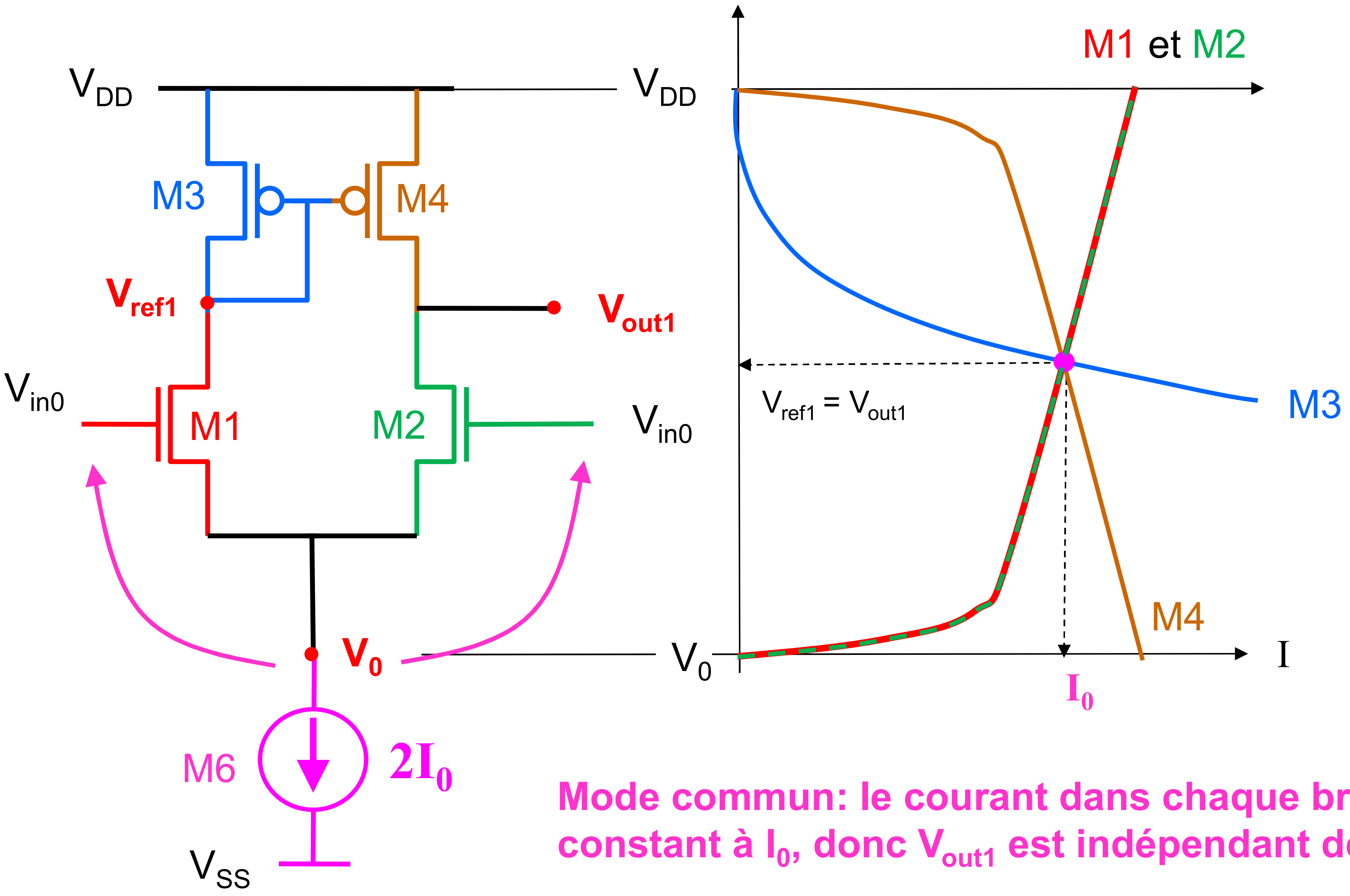
**Ajouter une source de courant**

**→ Maintenir la tension $V_{in0}$-$V_0$ constante**

**→ Le gain différentiel est fixe**

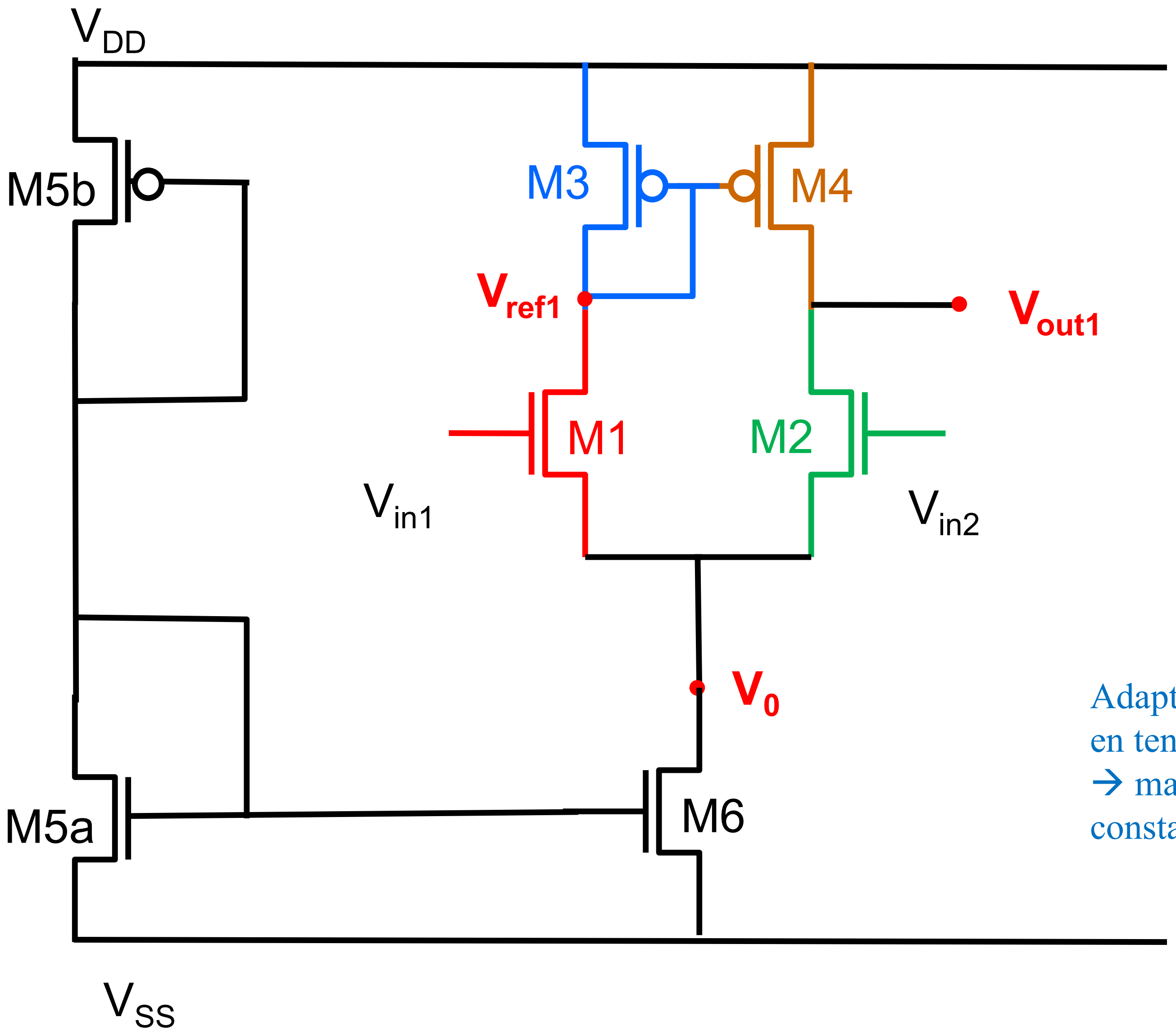
$$\frac{g_{m1,2}}{I_0} = \frac{2}{\left(V_{in0}-V_0\right)-V_{M0}} = \left(\sqrt{2\frac{W}{L}\mu_n C_{ox} n}\right)\cdot\frac{1}{\sqrt{I_0}}$$

# Differential amplifier: introduction d'une source de courant



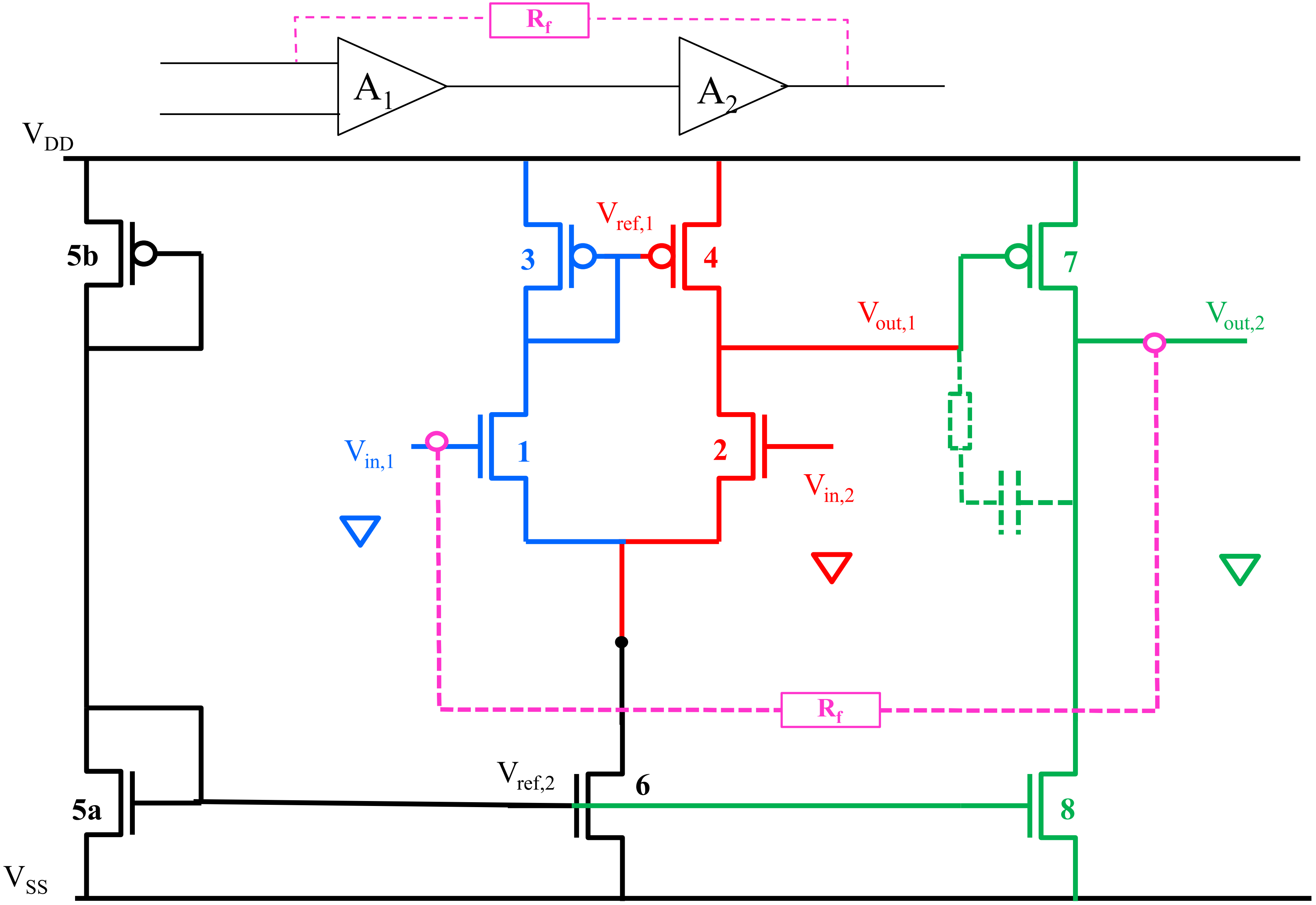
**Mode commun: le courant dans chaque branche est constant à $I_0$, donc $V_{out1}$ est indépendant de l'entrée $V_{in0}$**

# Differential amplifier:
# introduction d'une source de courant



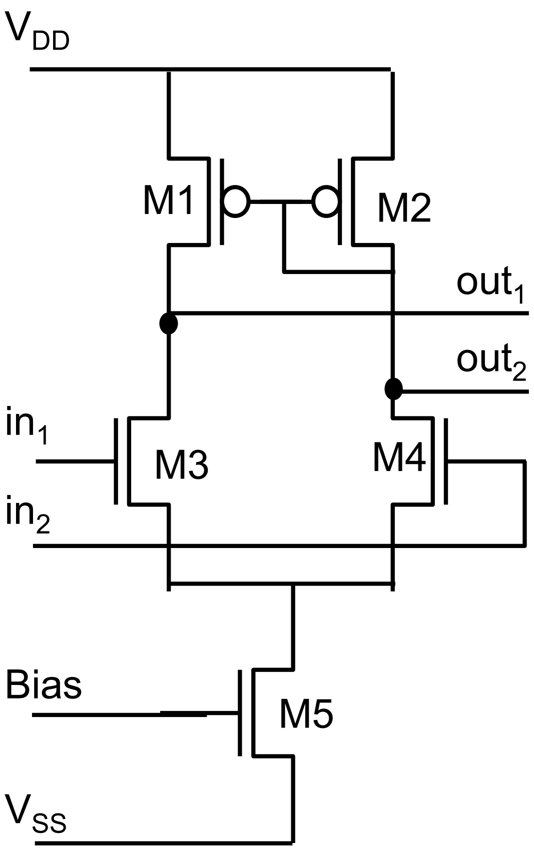
Adapter la tension en $V_0$ en tenant $I_6$ constant
→ maintenir $g_{m1}$ et $g_{m2}$ constantes.

# Op-Amp: two stages (2)

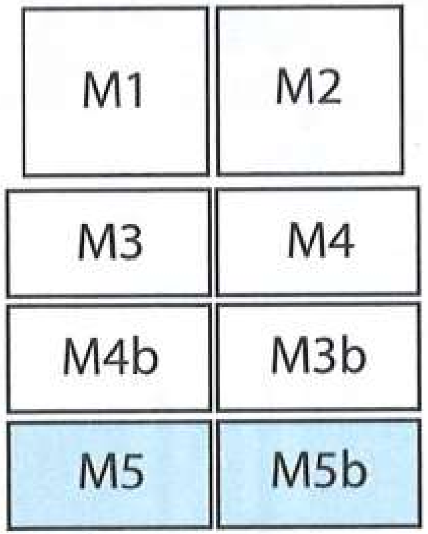


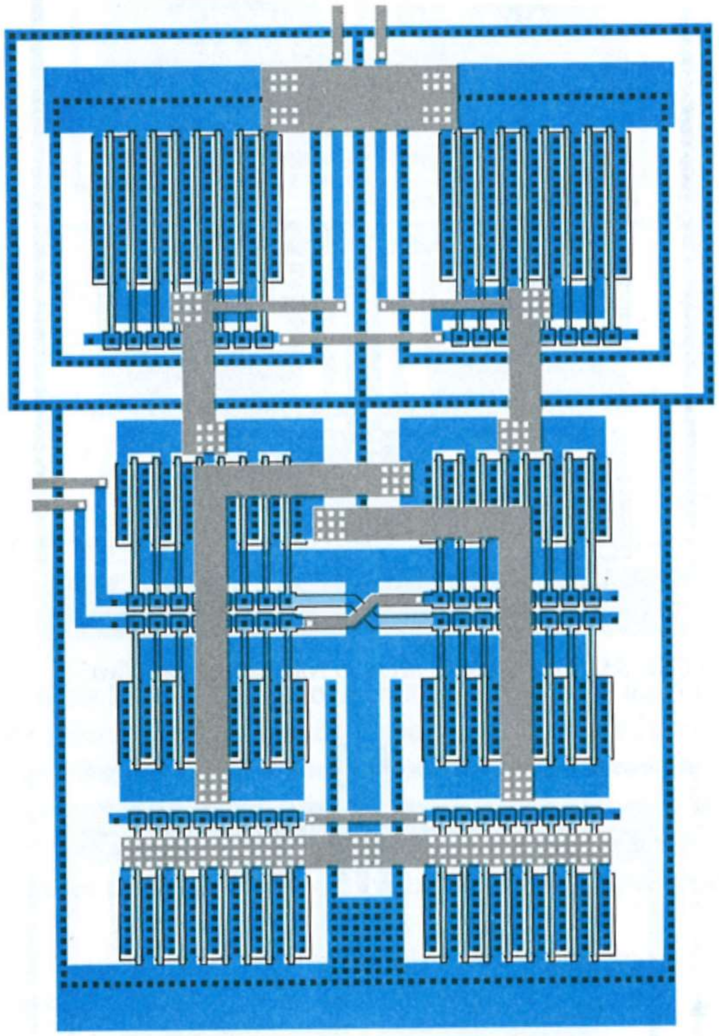
# Exemple de layout

Schématique



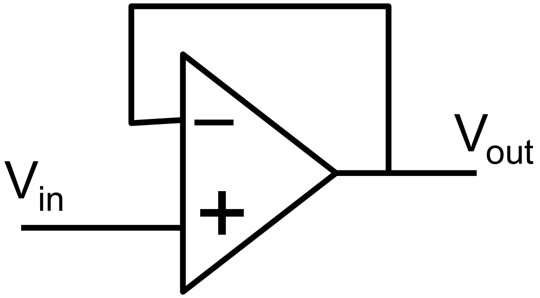
**Ampli différentiel**



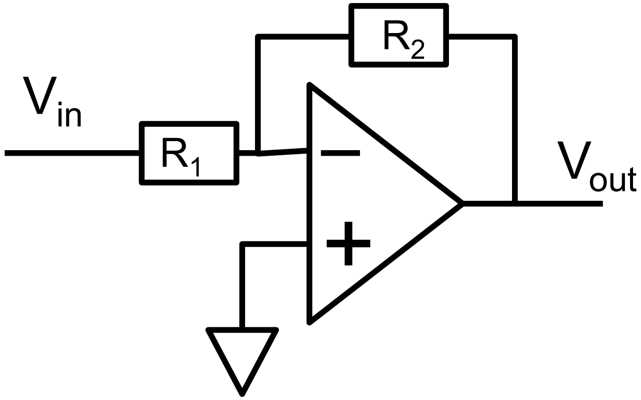


Ch. Saint, « IC mask design »,
2002 McGraw-Hill

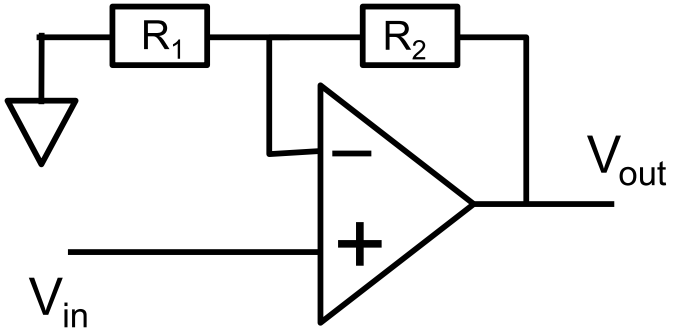
# Exemples: Opam avec boucle de feedback



Suiveur



Ampli inverseur



Ampli non-inverseur

$$V_{out} = V_{in}$$

$$V_{out} = -\frac{R_2}{R_1} \cdot V_{in}$$

$$V_{out} = \left( \frac{R_1 + R_2}{R_1} \right) \cdot V_{in}$$

■ ■ ■

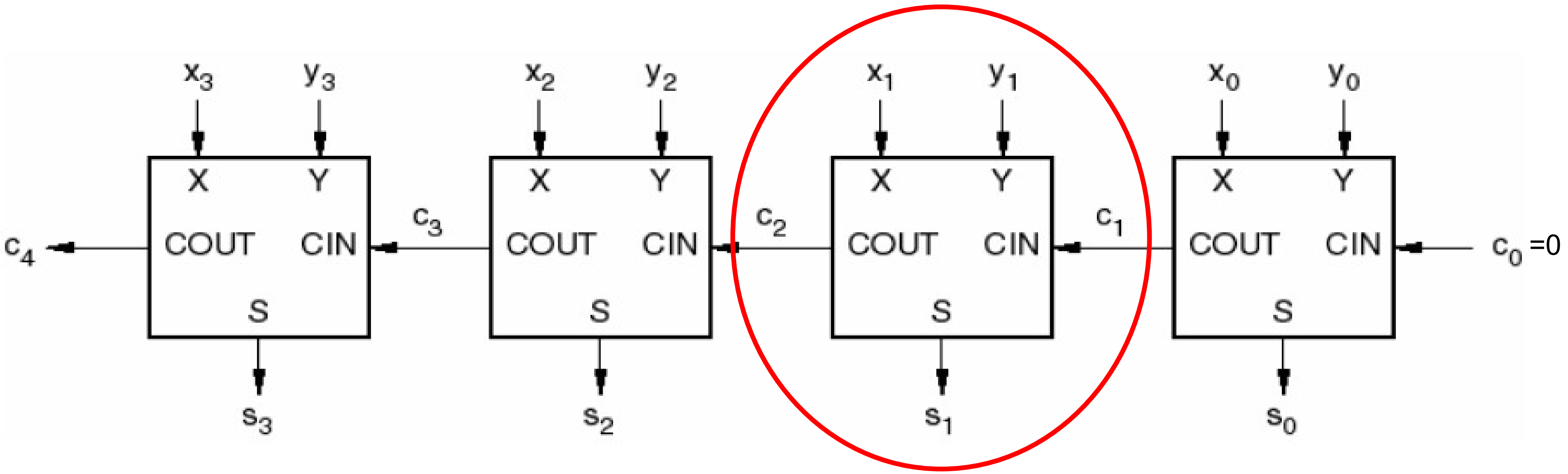
# Exercice E12.2: Addition binaire

## Principe

$$
\begin{array}{rccccc}
 & c_4 & c_3 & c_2 & c_1 & 0 \\
 & & x_3 & x_2 & x_1 & x_0 \\
+ & & y_3 & y_2 & y_1 & y_0 \\
\hline
= & c_4 & s_3 & s_2 & s_1 & s_0
\end{array}
$$

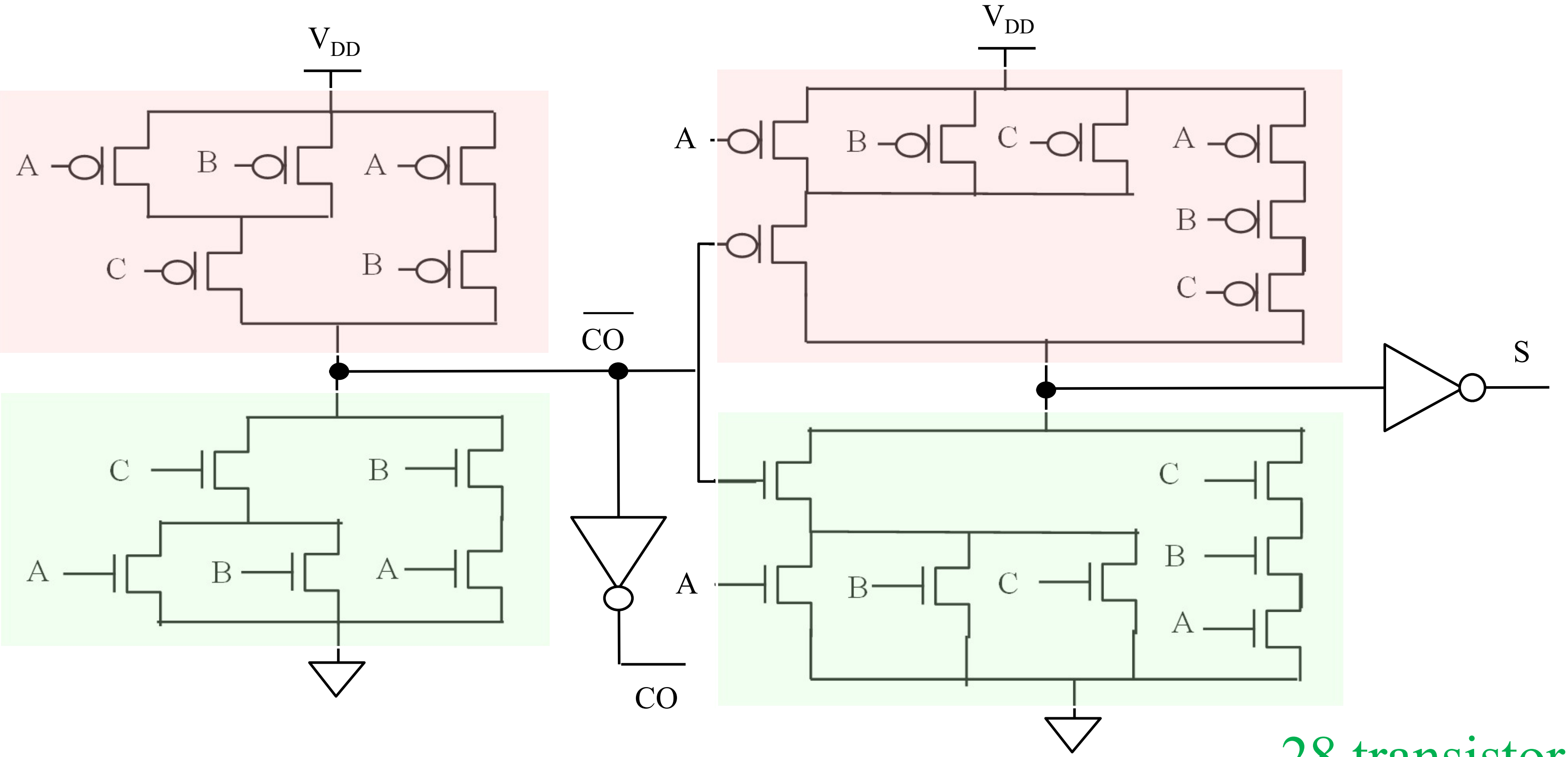
## Exemple d’addition binaire:
**1101 + 1001 = 10110**

| | | |
|---|---|---|
| | 1 0 0 1 0 | C |
| | 1 1 0 1 | A |
| + | 1 0 0 1 | B |
| = | 1 0 1 1 0 | S |



# Exercice E12.2: « Full adder »

Calculez la table de vérité et montrez qu'elle correspond à une addition binaire

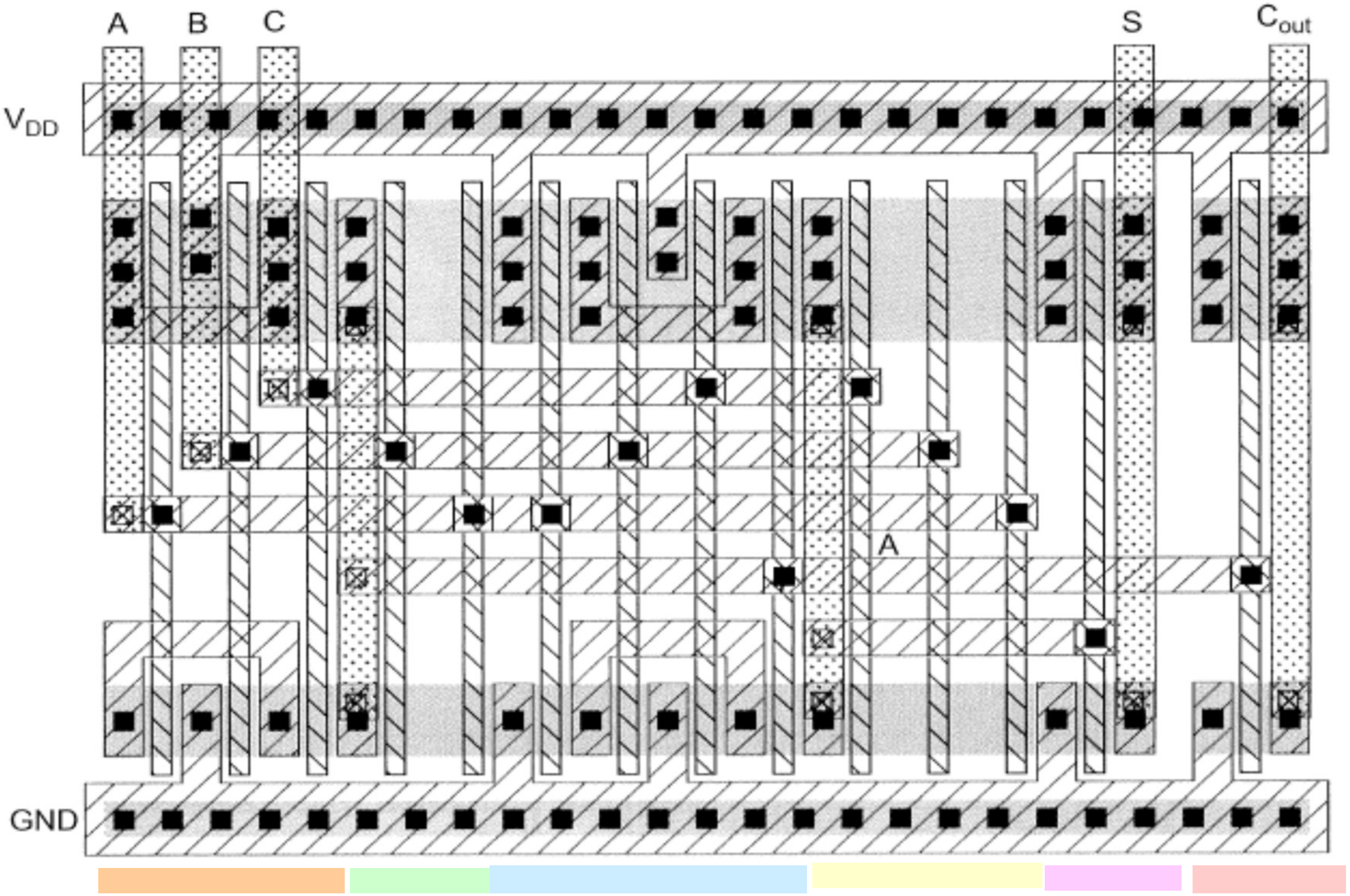


28 transistors

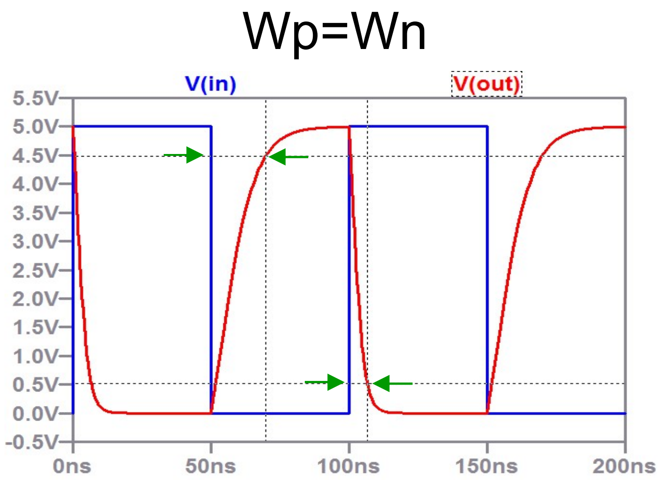
Zimmermann, Fichtner, IEEE journal of solid-state circuits, Vol. 32, No. 7, pp. 1-12.

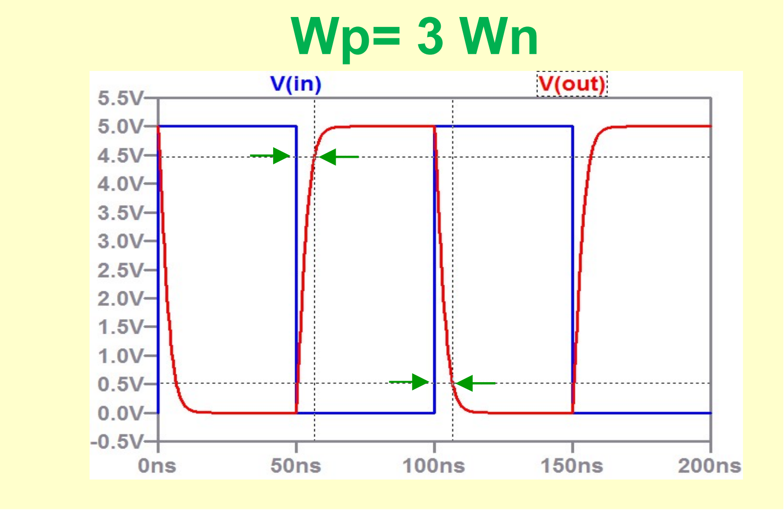
# Layout du « full adder » de l'exercice E12.2

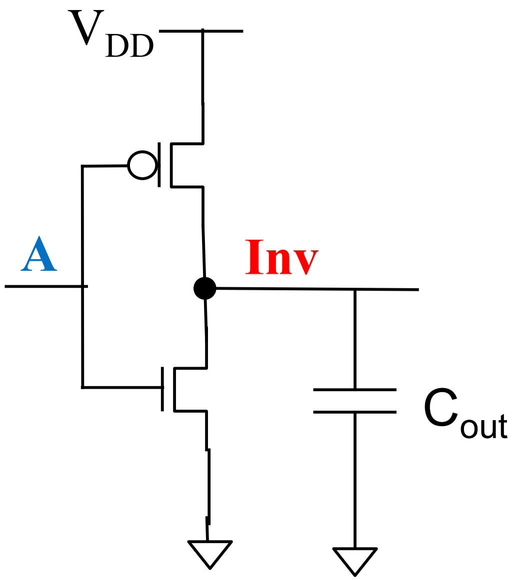
Weste/Harris, « CMOS VLSI design », Addison-Wesley



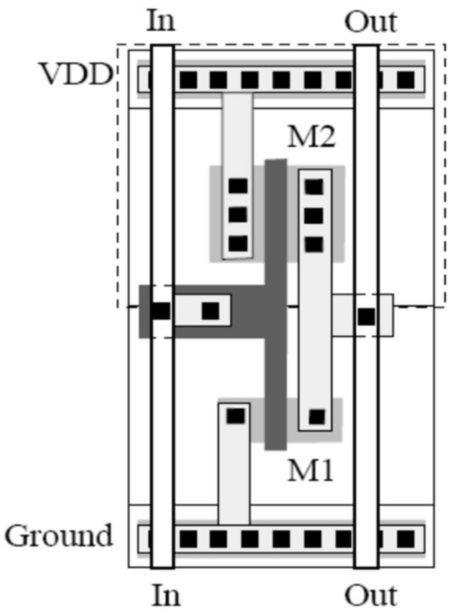
# Exercice 12.3: dimensionnement (1)







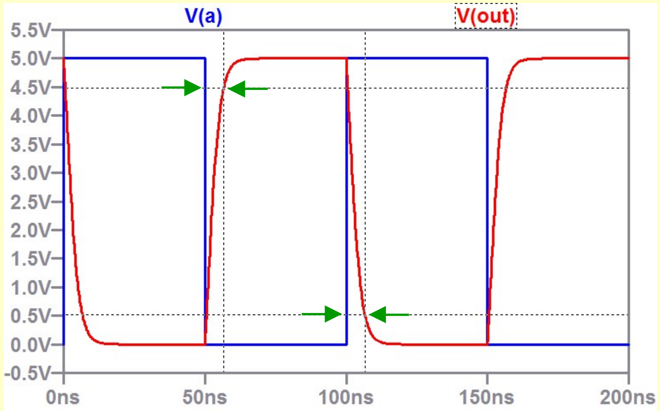
**Inverseur**



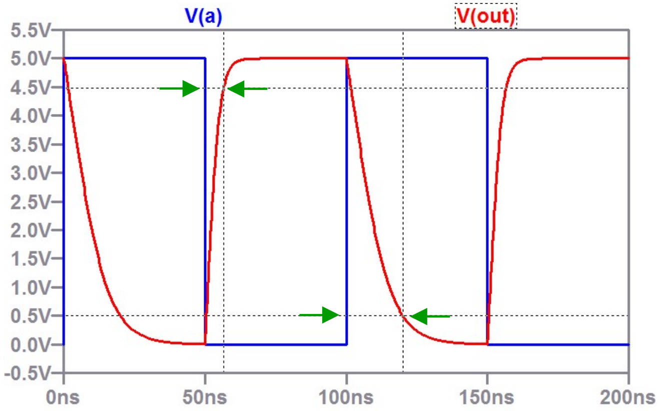
Wp= 3 Wn

# Exercice 12.3: dimensionnement (2)

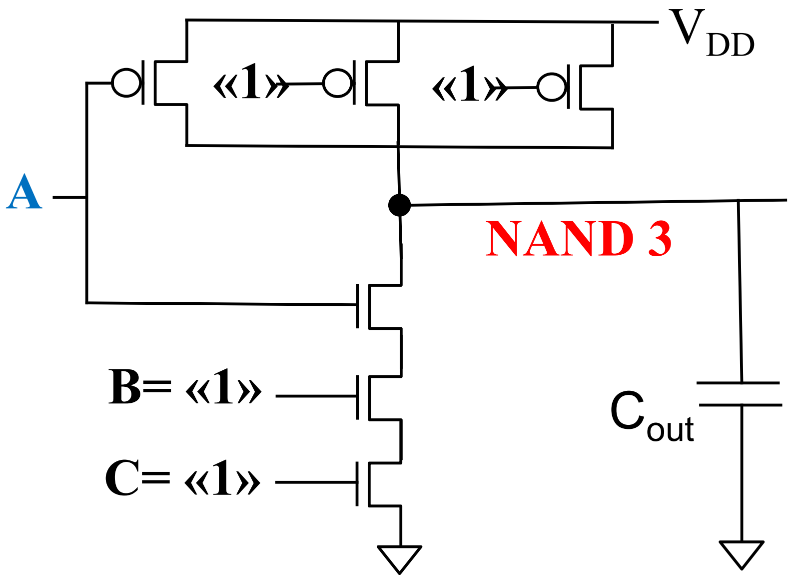
**Wp= Wn**

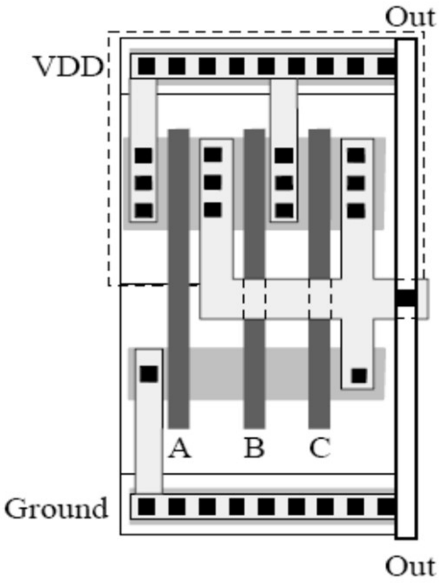


Wp= 3 Wn



**NAND 3**

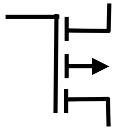




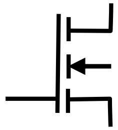
Wp= 3 Wn

**PAB**

# Exercice 13.1 A

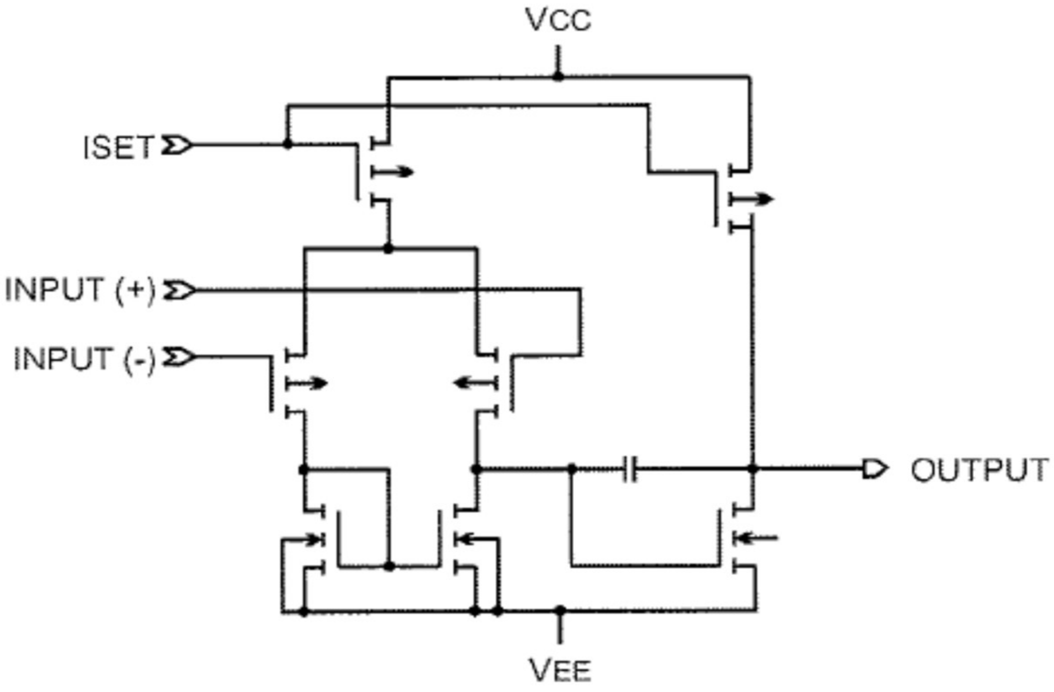


PMOS



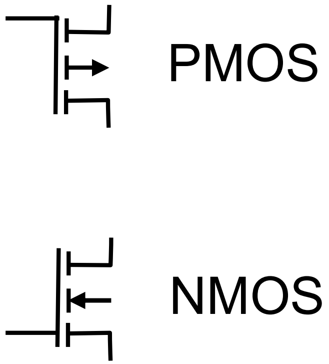
NMOS

**Interprétez ce schéma:**

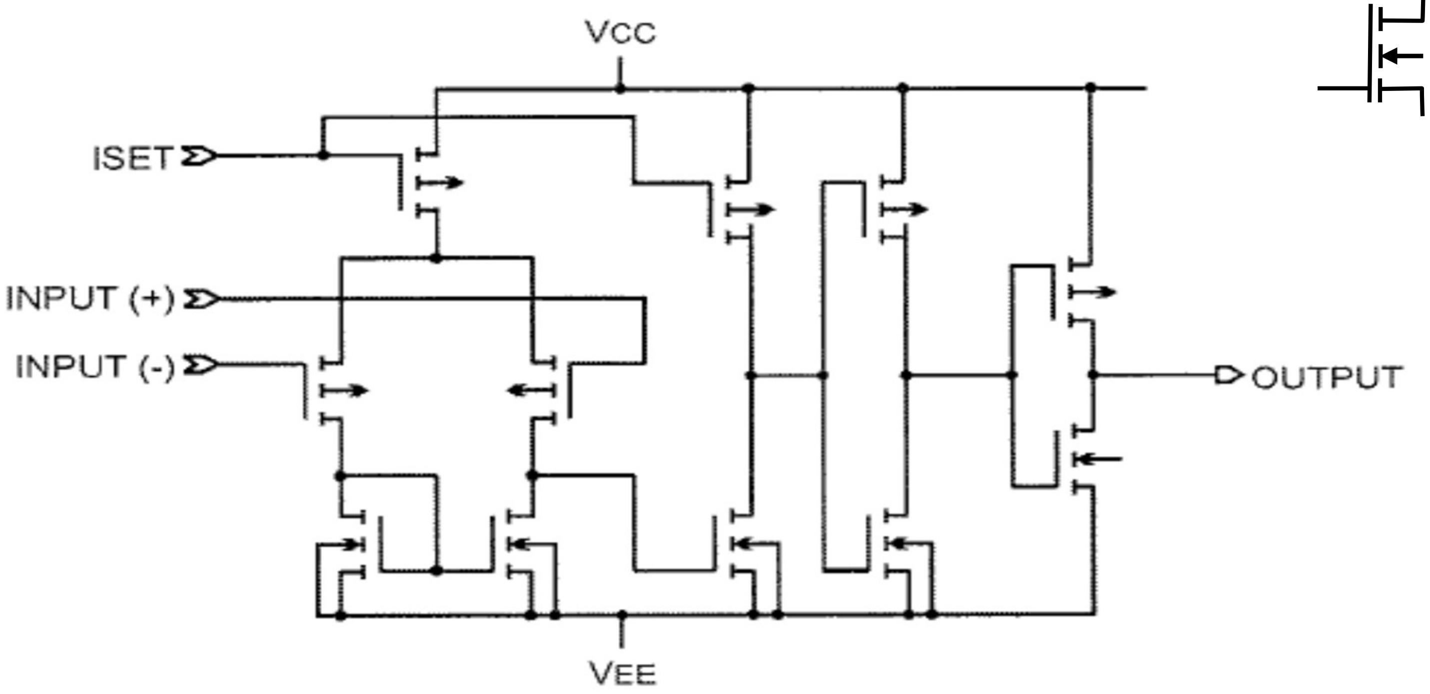


MC14573 from Motorola Semiconductor

# Exercice 13.1 B



**Interprétez ce schéma:**



MC14574 from Motorola Semiconductor

PAB

# Exercice E13.2:
# Ampli de tension avec NMOS

Utilisez un NMOS comme ampli de tension.
Inspirez-vous du chapitre 7 sur les BJT.
Remplacez le transistor bipolaire par un NMOS !