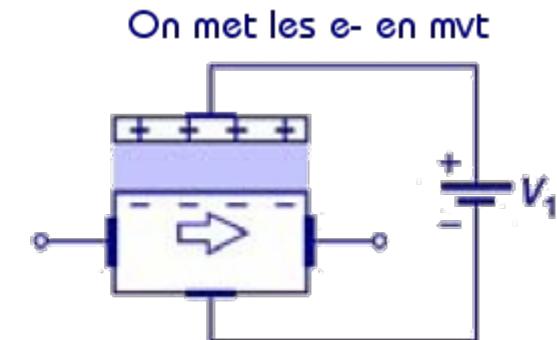
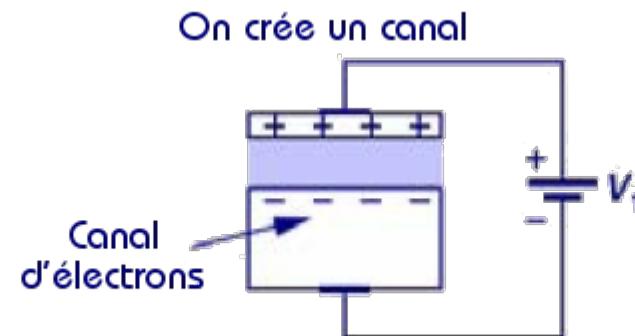
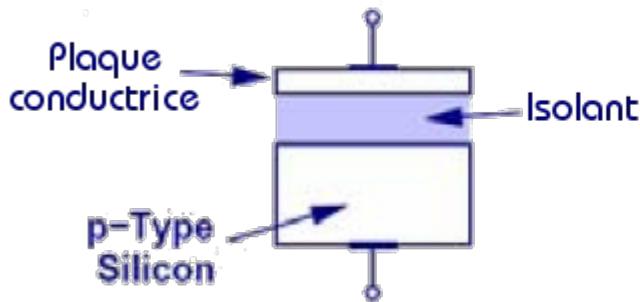


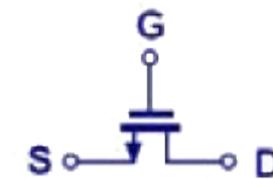
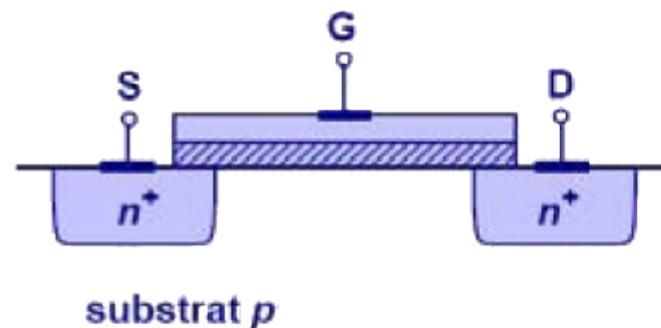
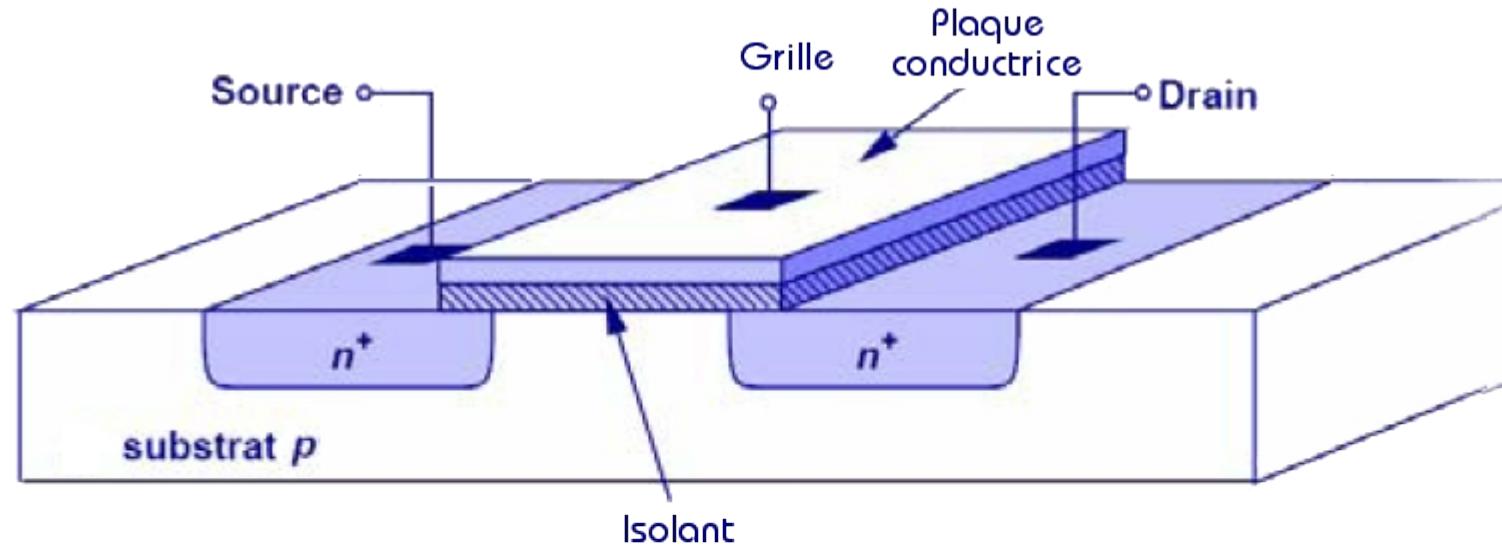
# Tout sur le MOS : brique de base

# Le transistor MOS ? Une capacité



- Fonctionnement basé sur l'électrostatique
  - On attire des électrons
  - On les met en mouvement
  - Si on complique? Tension d'inversion, canal non homogène

# Structure du MOS

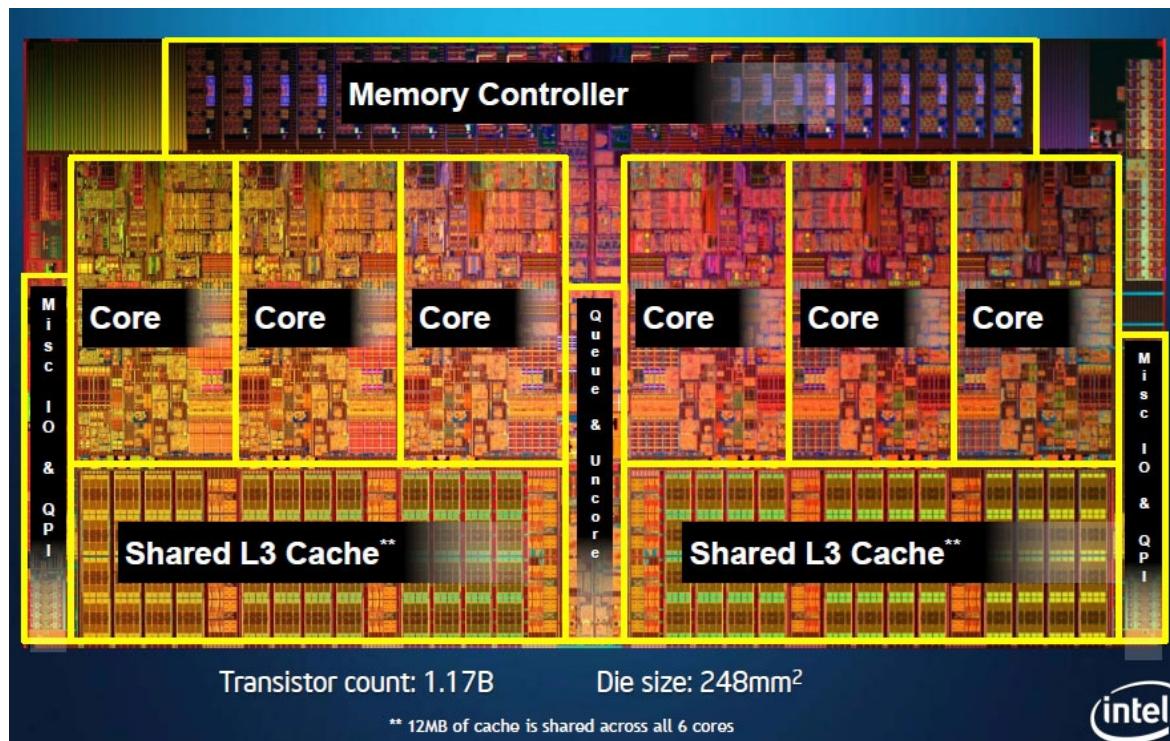
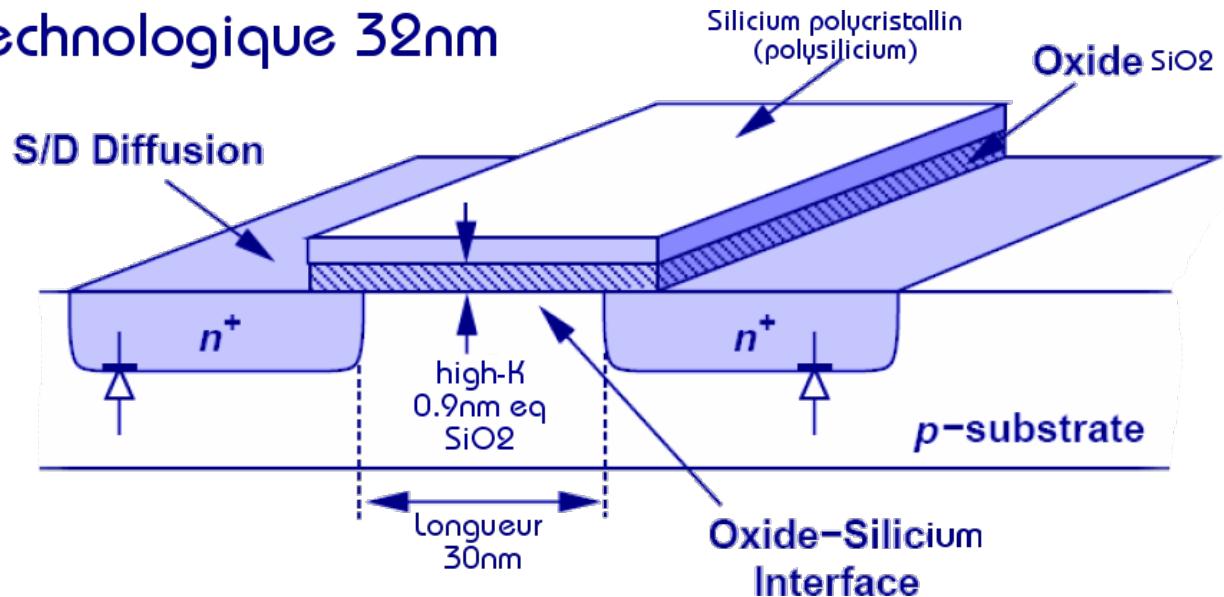


- Une structure symétrique : drain e(s)t source

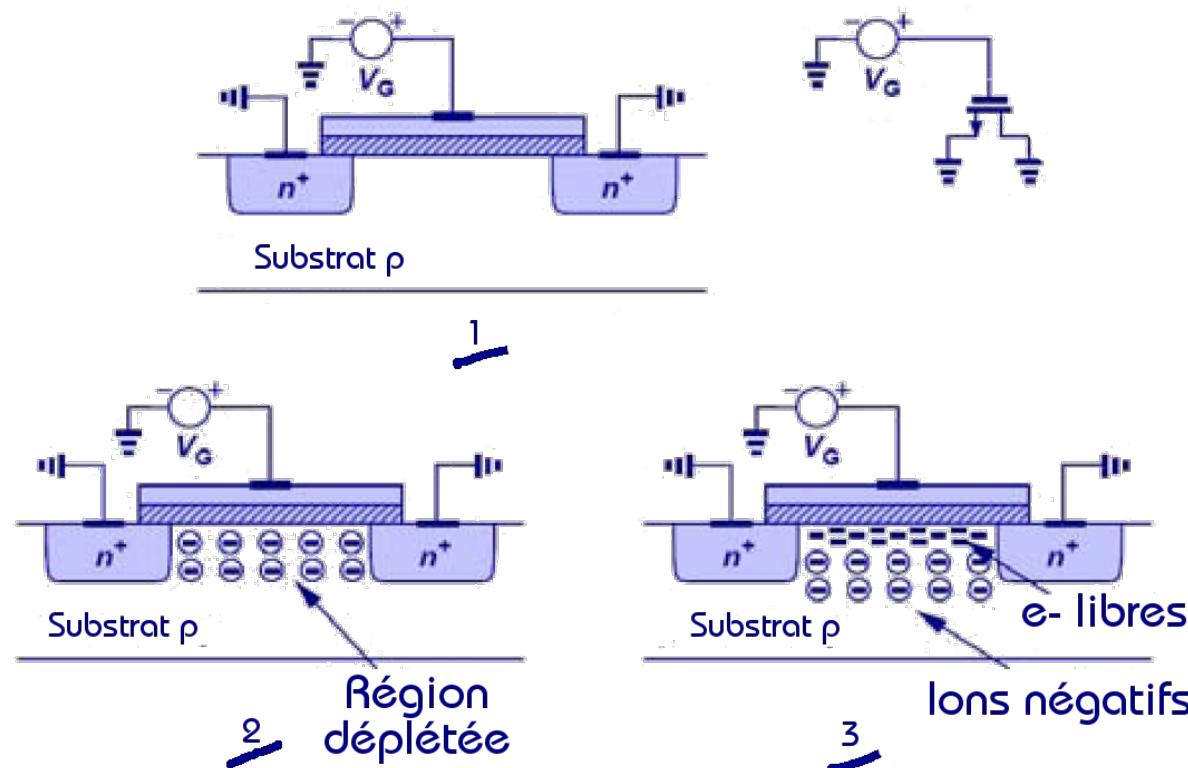
# MOS

## État de l'art

### Noeud technologique 32nm



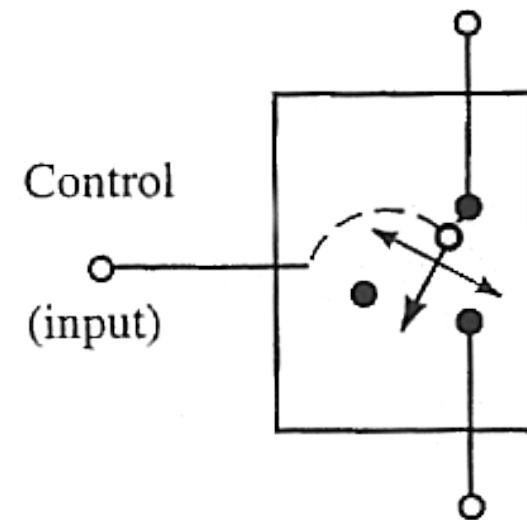
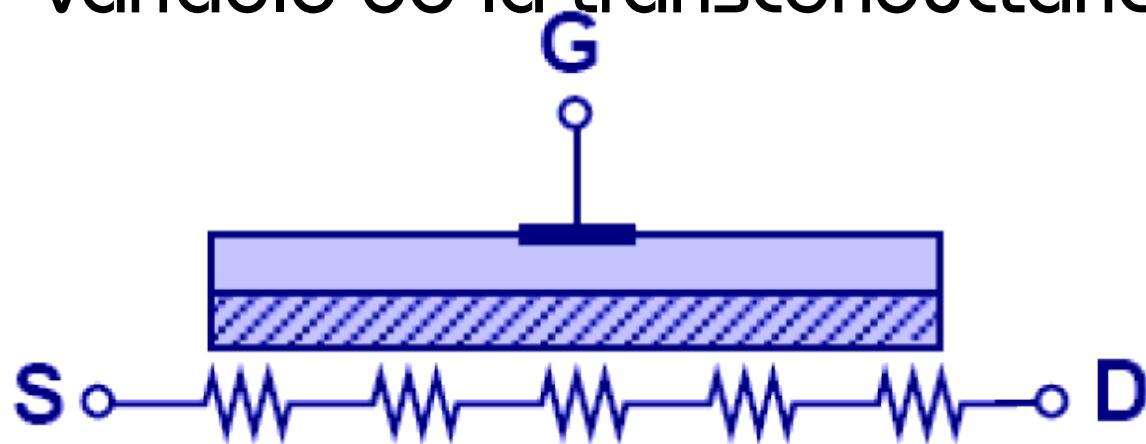
# Principe de fonctionnement



- Création du canal en trois temps : vaincre le potentiel de surface, repousser les trous pour créer une zone de déplétion puis attirer les électrons

# Une résistance variable

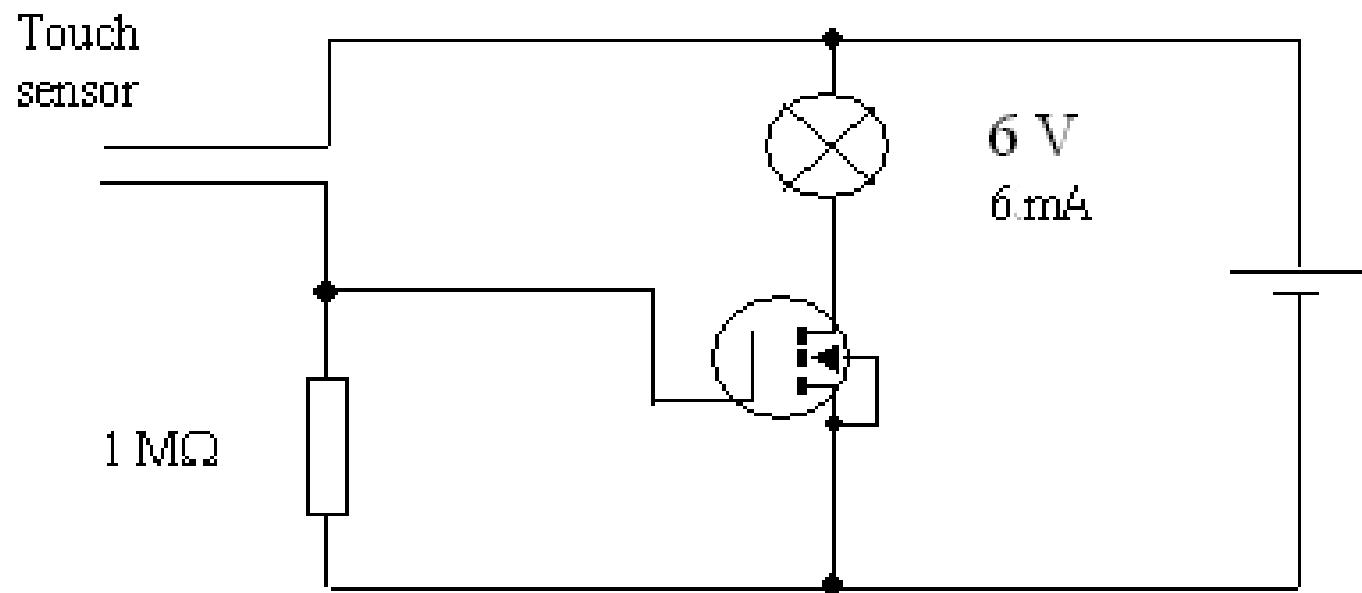
- Transistor : transconductance varistor (résistance variable de la transconductance)



- Puisque la densité de charge dépend de la tension de grille, la résistance dépend aussi de cette même tension!!

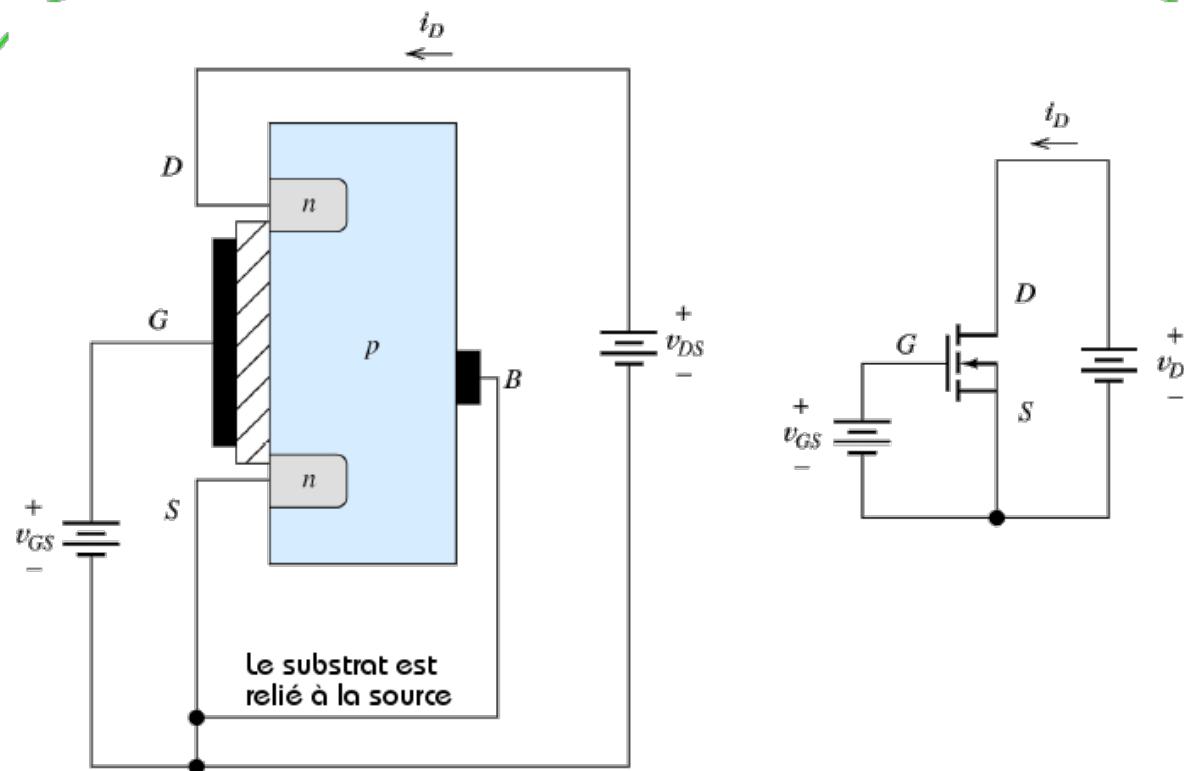
# Le MOS : un interrupteur

- On se sert du fait de disposer ou non d'un canal d'électrons
- Exemple : une commande tactile d'allumage de lampe

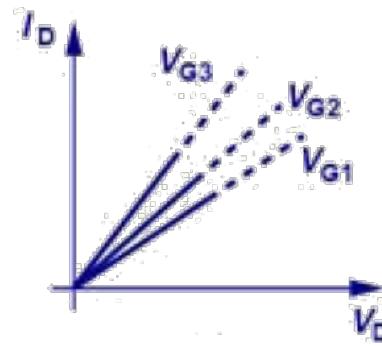
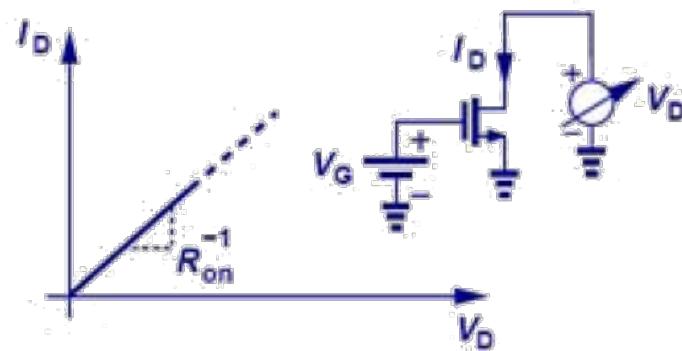
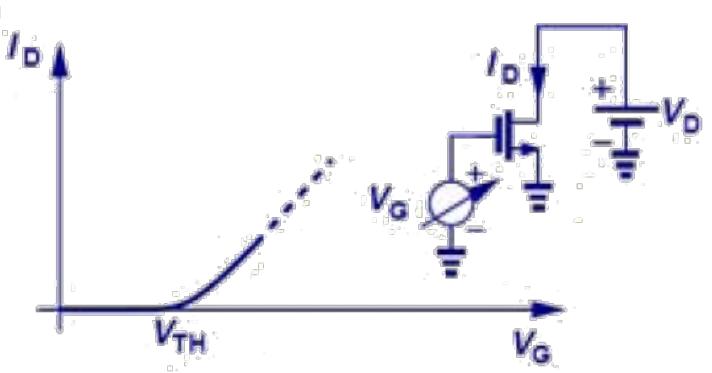
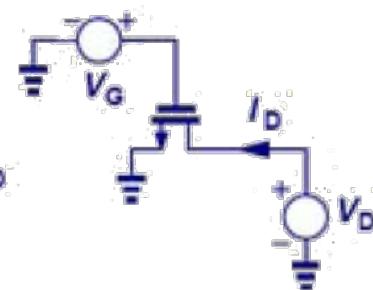
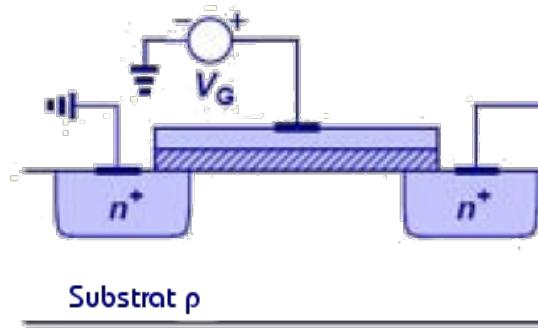


# Observation d'un MOS : montage

- Deux tensions à faire varier : celle du drain et celle de la source



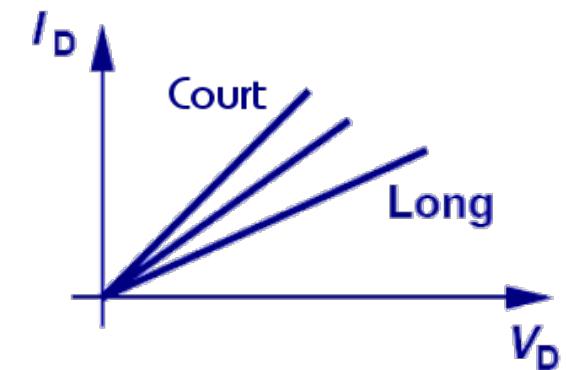
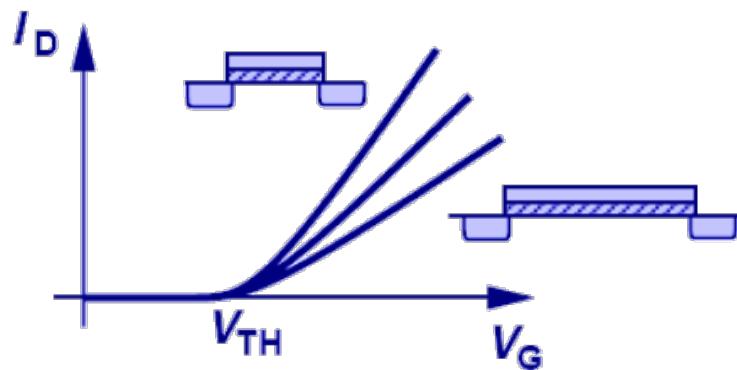
# Avec les mains



# Influence des paramètres : $L$ , $t_{ox}$

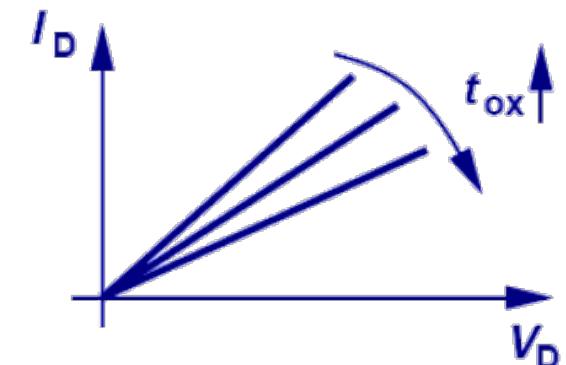
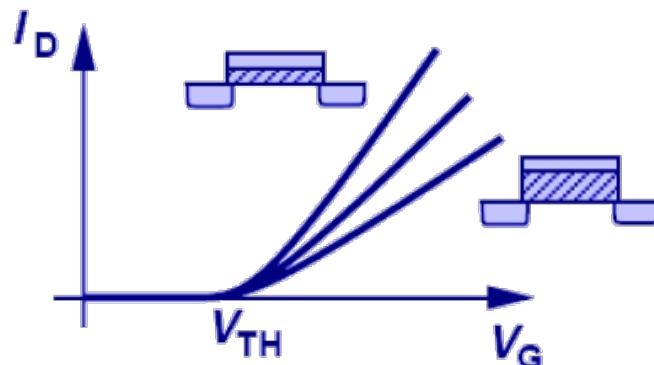
## Influence de $L$

- Réduction du chemin à parcourir
- Champ électrique plus fort à tension équivalente



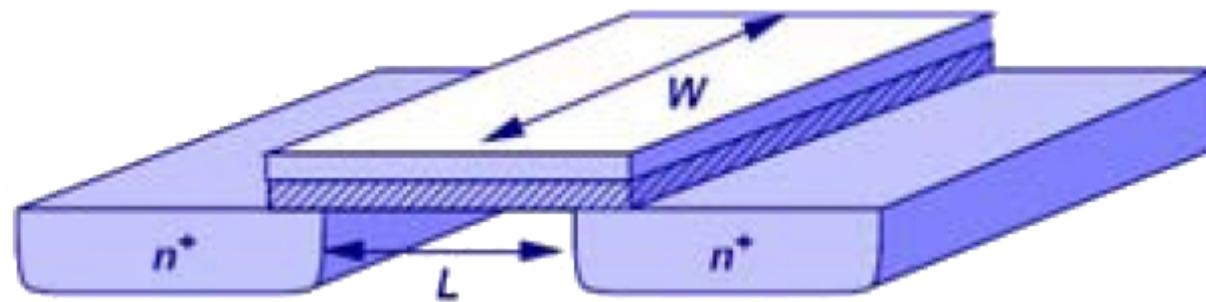
## Influence de $t_{ox}$

- Réduction de la capacité

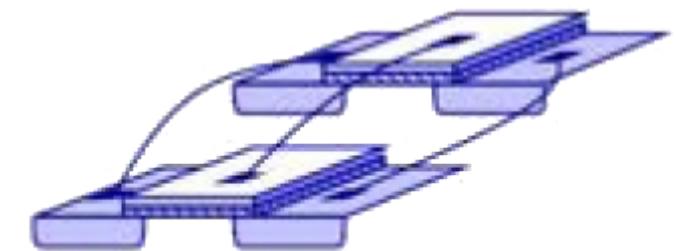
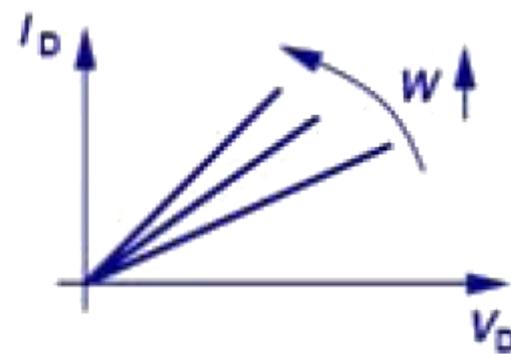
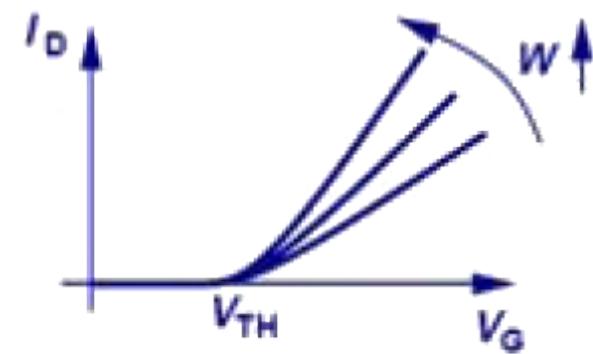


- On joue sur la densité de courant!

# Influence du paramètre W

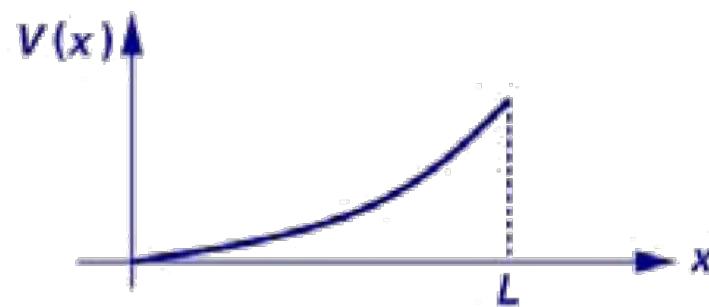
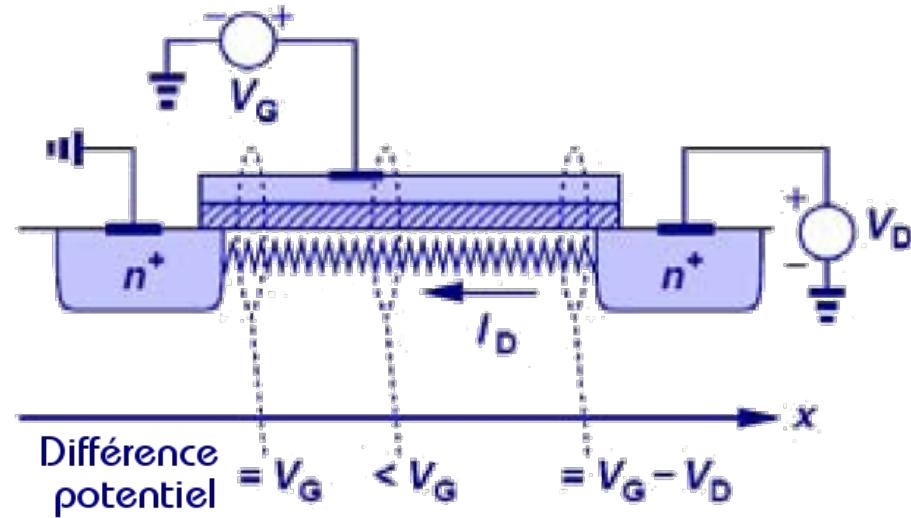


$\nearrow$  de  $W \Rightarrow$  Mise en //  
de transistors

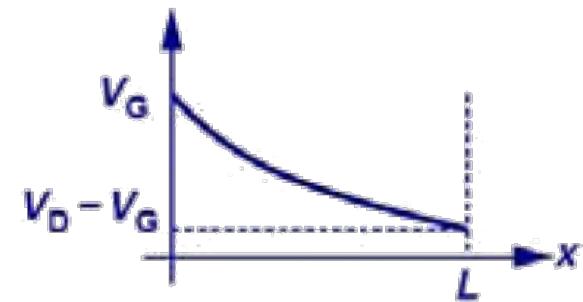


- On joue sur la surface donc sur le courant : la densité de courant reste inchangée

# Un canal non uniforme



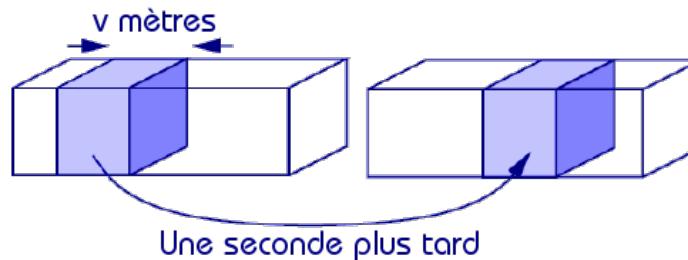
Différence de potentiel  
Grille - Sustrat



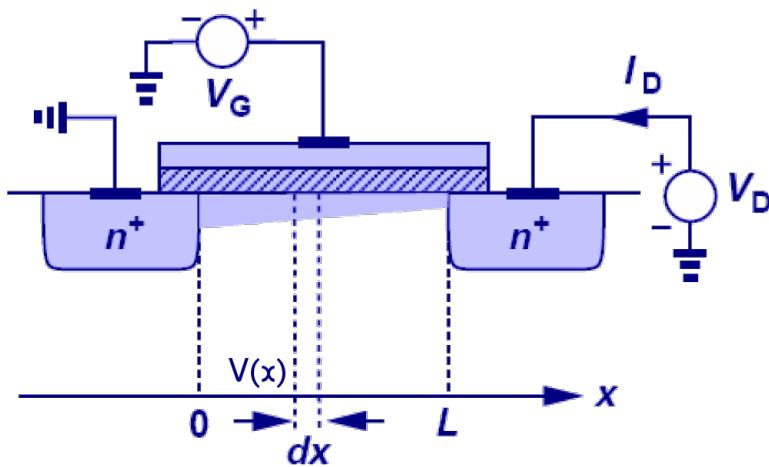
- Le canal agit comme une résistance soumis à deux potentiels (à l'équilibre) :  $V_G$  et  $V_D$

# Quel courant dans le canal?

- Le principe ? Un transfert de charge!



- Une méthode de calcul simple



- 1) Calcul de la charge unitaire
- 2) Application de la loi d'ohm
- 3) Intégration sur le canal

# Calcul du courant de canal

- **Charge unitaire**

$$Q_{I(x)} = -C_{ox} \left( \underbrace{v_G - v_S}_{v_{GS}} - v(x) - V_T \right) \text{ (coulombs/cm}^2\text{)}$$

- **Conductivité du canal**

$$\sigma_s = \mu \cdot Q_{I(x)} \left( \frac{\text{cm}^2}{\text{v} \cdot \text{s}} \right) \left( \frac{\text{coulombs}}{\text{cm}^2} \right) = \frac{A}{V} = \frac{1}{\Omega \cdot m} = S \cdot m^{-1}$$

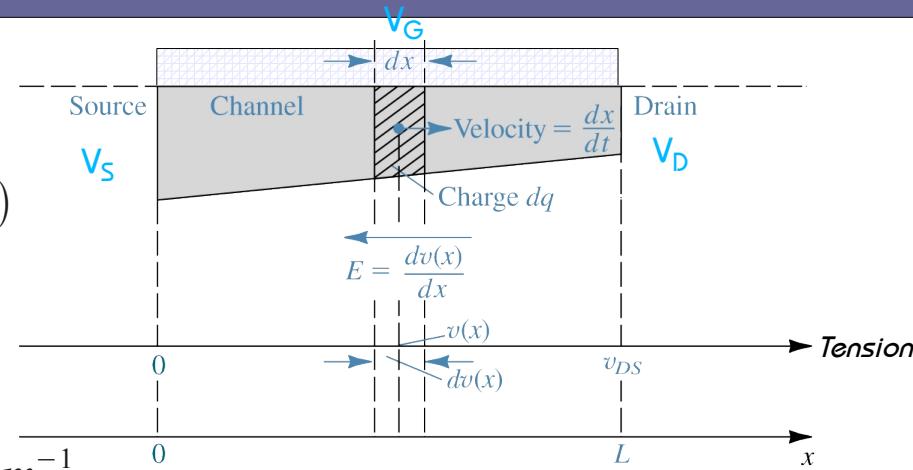
- **Loi d'Ohm**

$$J_s = \frac{i_D}{W} = -\sigma_s \cdot E_x = -\frac{\sigma_s \cdot dv}{dx} \rightarrow dv = \frac{-i_D}{\sigma_s W} dx = \frac{-i_D dx}{\mu Q_{I(x)} W} \rightarrow i_D dx = -W \mu Q_{I(x)} dv$$

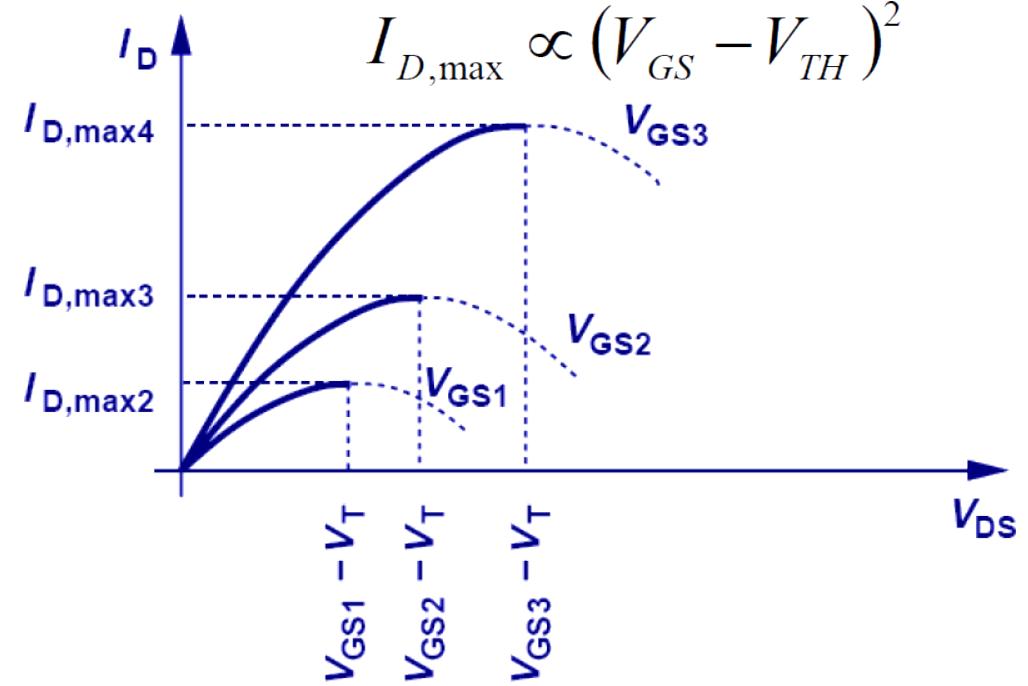
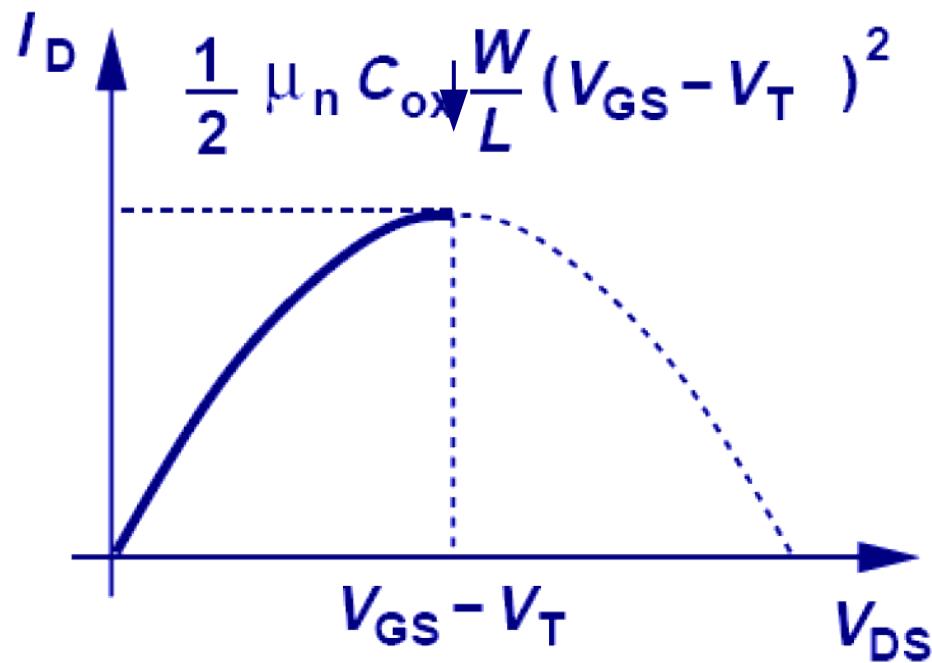
- **Intégrale**

$$\int_0^L i_D \cdot dx = - \int_0^{V_{DS}} W \mu_0 Q_{I(x)} dv = - \int_0^{V_{DS}} W \mu_0 C_{ox} (v_{GS} - v(x) - V_T) dv \quad \text{avec } v(x) \propto v$$

Aux limites  $i_D = \frac{W \mu C_{ox}}{L} \left[ (v_{GS} - V_T) v(x) - \frac{v^2(x)}{2} \right]_0^{V_{DS}} \rightarrow i_D = \mu C_{ox} \frac{W}{L} \left[ (v_{GS} - V_T) v_{DS} - \frac{v_{DS}^2}{2} \right]$



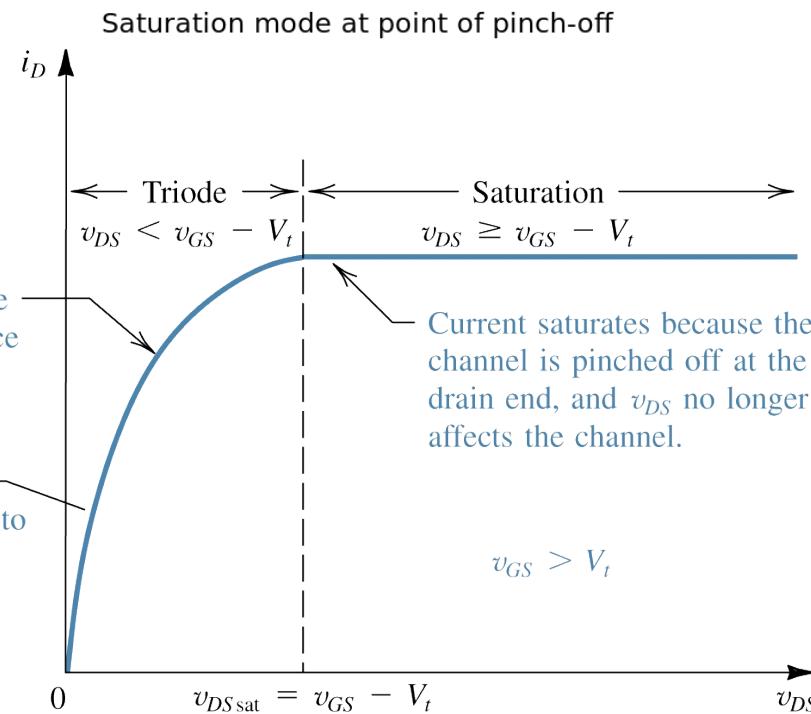
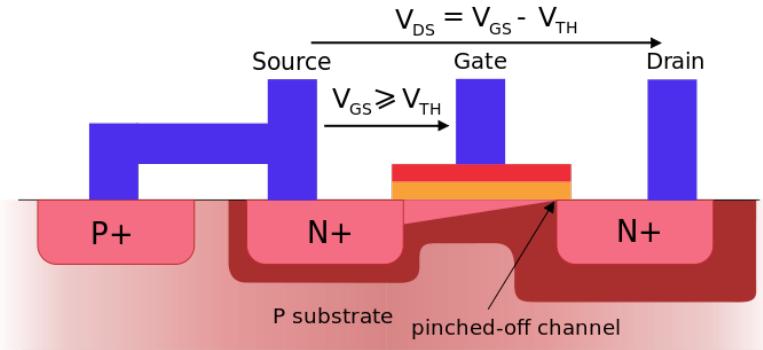
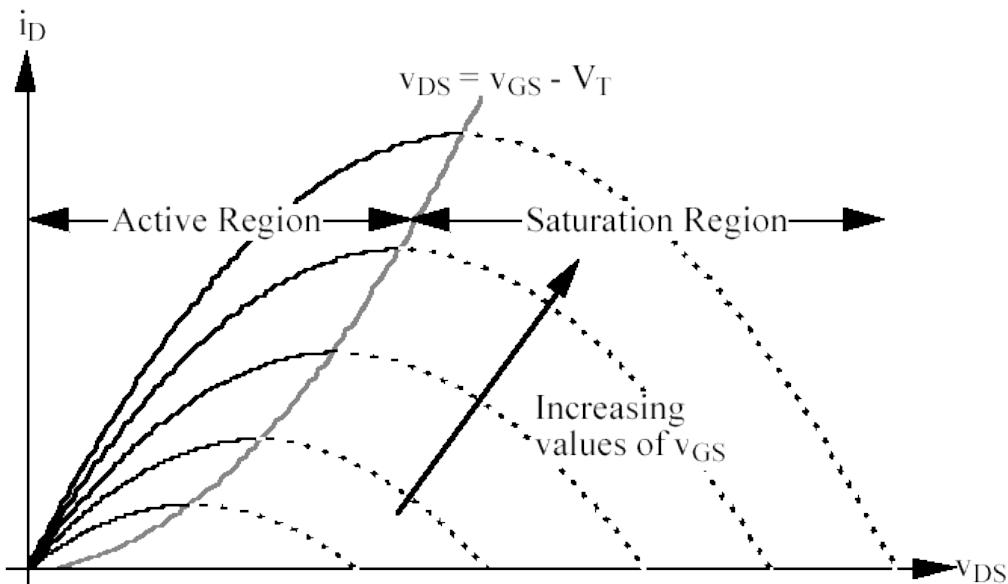
# Une relation $I_D$ - $V_{DS}$ parabolique



- À  $V_{GS}$  constant
  - Maximum atteint pour  $V_{DS}=V_{GS}-V_T$

- Si on fait varier  $V_{GS}$ 
  - Le courant maximum est proportionnel à  $(V_{GS}-V_T)^2$  ( $V_{DS}$  constant)

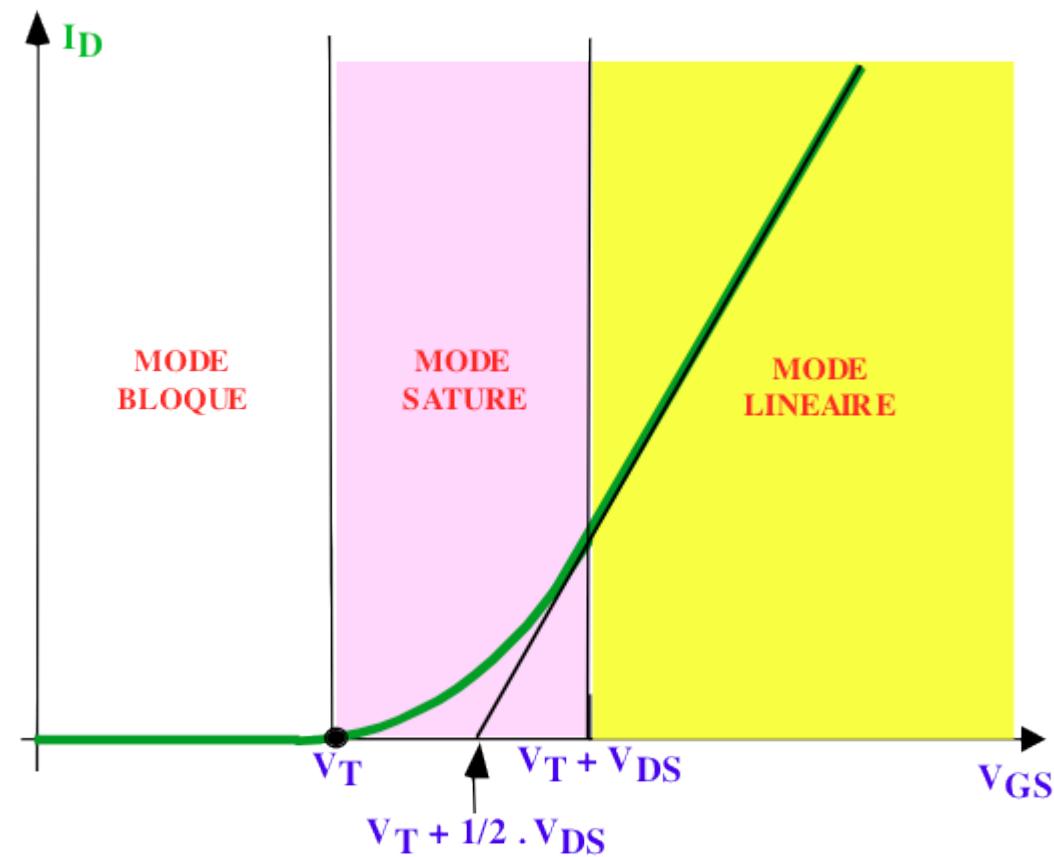
# Et au-delà?



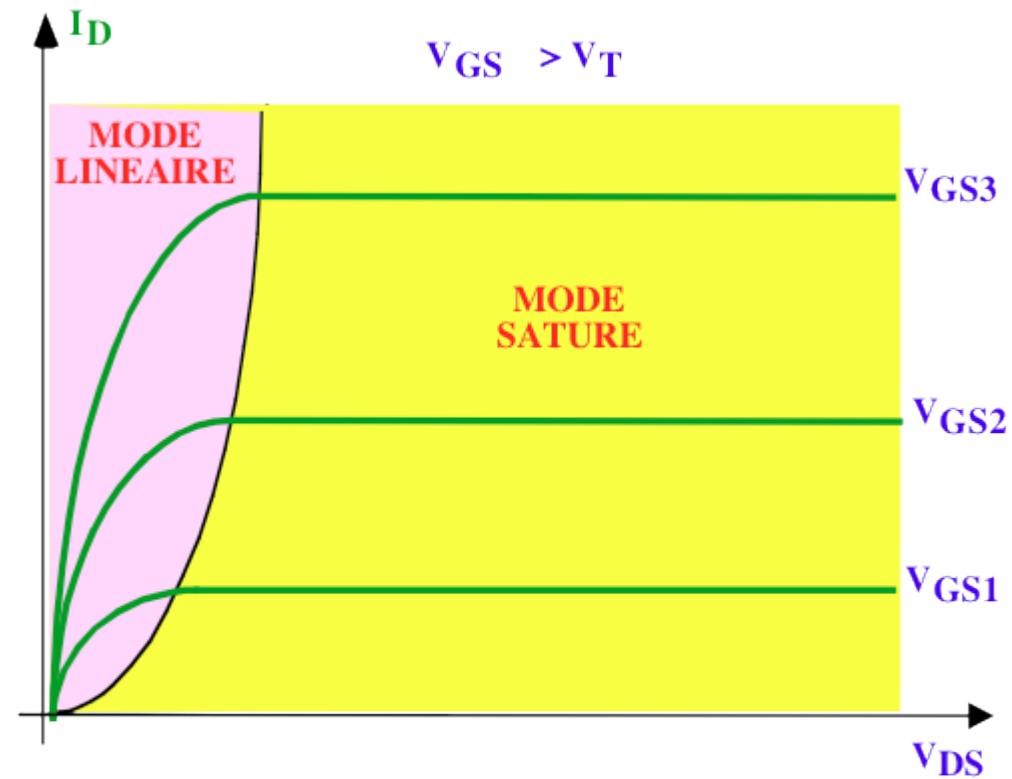
- Le point  $V_{DS}=V_{GS}-V_T$  est particulier puisqu'il représente l'annulation du potentiel en D!!
- À partir de ce point le courant reste constant

$$i_{DSat} = \mu C_{ox} \frac{W}{2 \cdot L} (v_{GS} - V_T)^2 \quad \text{avec} \quad V_{DSat} = V_{GS} - V_T$$

# Les caractéristiques



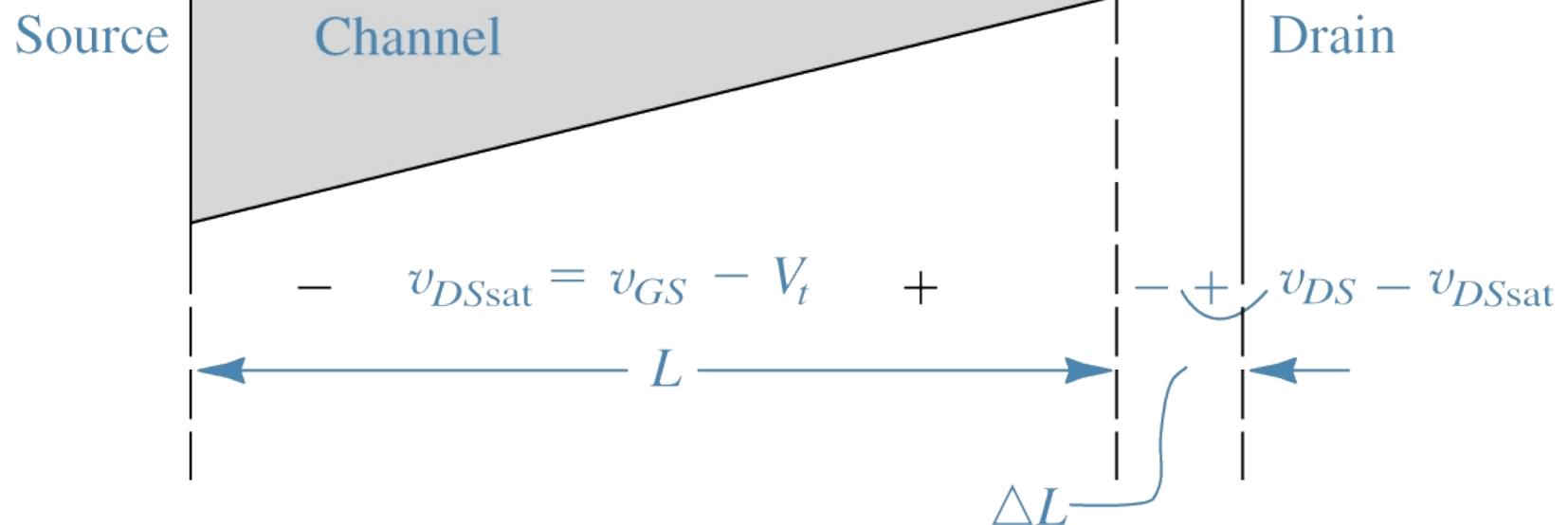
Caractéristiques de transfert



Caractéristiques de sortie

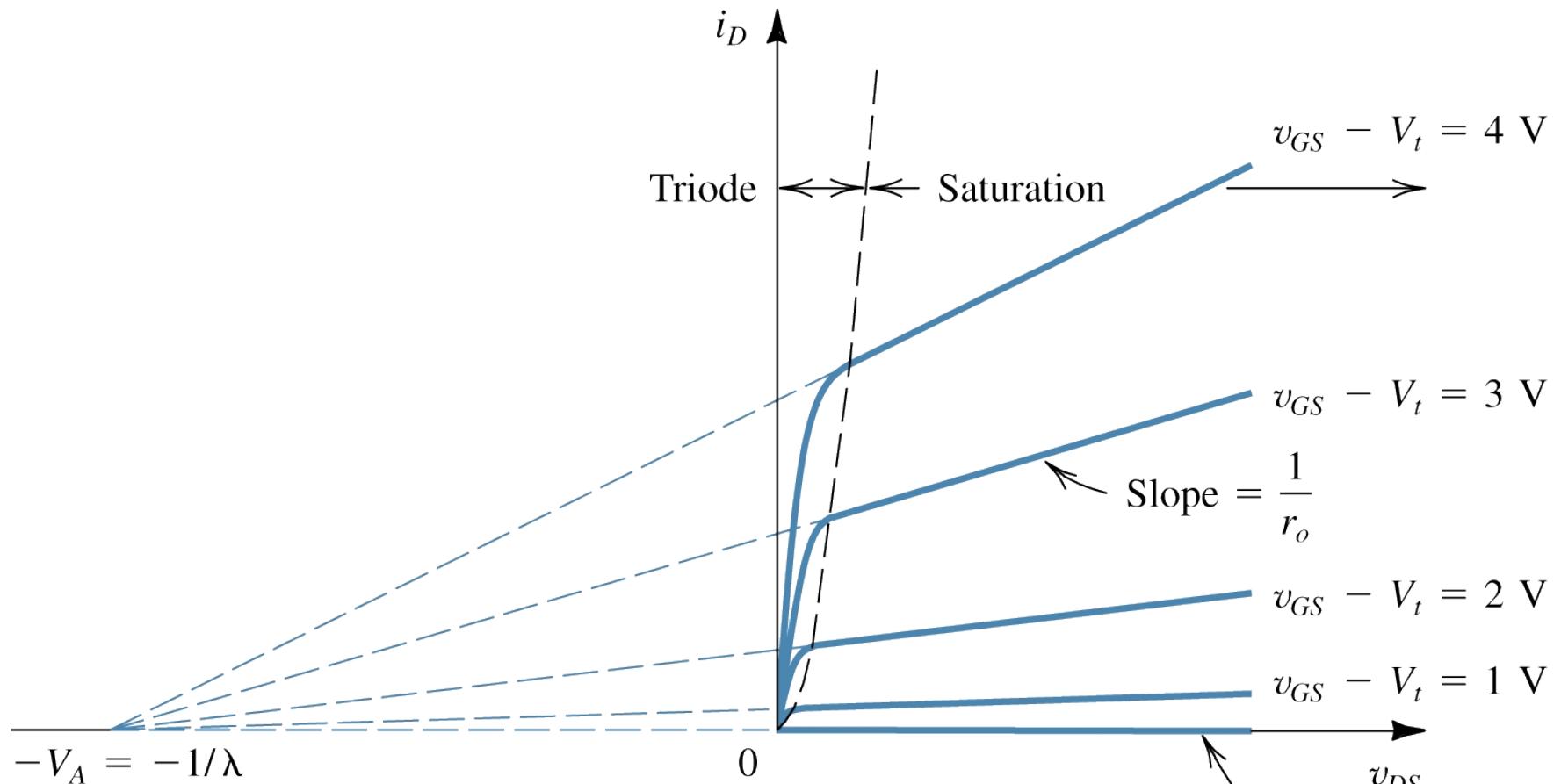


# Mais en réalité...



- Le canal est modulé
  - La zone autour du point de pincement n'est plus inversée
  - Création d'une charge d'espace autour du drain
  - On parle de longueur effective du canal qui module le courant  $I_{DSat}$  d'un facteur  $(1+\lambda \cdot V_{DS})$  ( $\lambda$  lié directement à la largeur de ZCE)
  - Discontinuité entre les deux domaines?

# Comportement en saturation

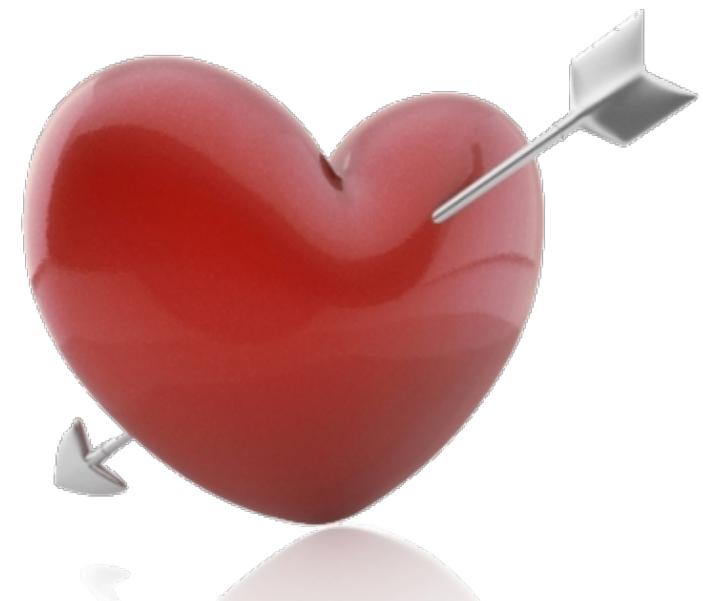


$$i_{DSat} = \mu C_{ox} \frac{W}{2 \cdot L} (v_{GS} - V_T)^2 (1 + \lambda V_{DS})$$

$$v_{GS} - V_t \leq 0$$

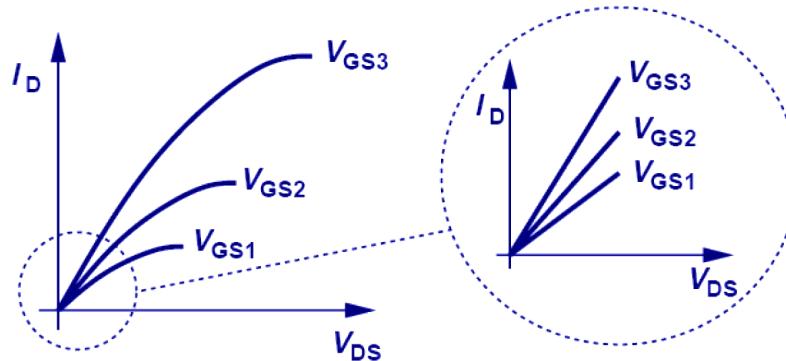
# En résumé

- Si  $V_{GS} < V_T$ 
  - Transistor bloqué :  $I_{DS} = 0$
- Si  $V_{GS} > V_T$ 
  - Régime ohmique ( $V_{DS} < V_{GS} - V_T$ )
$$I_{DS} = \mu C_{ox} \frac{W}{L} \left[ (V_{GS} - V_T) V_{DS} - \frac{V_{DS}^2}{2} \right]$$
  - Régime saturé ( $V_{DS} > V_{GS} - V_T$ )
$$I_{DS} = \underbrace{\mu C_{ox} \frac{W}{2 \cdot L} (V_{GS} - V_T)^2}_{\text{Transistor idéal}} \underbrace{(1 + \lambda V_{DS})}_{\text{Transistor réel}}$$



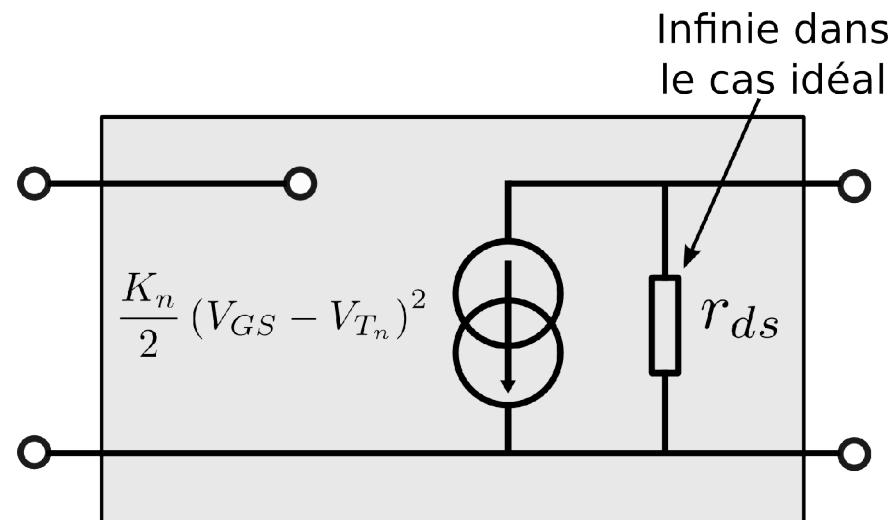
# Modèle grand signal

- En régime ohmique ? Une résistance



$$R_{on} = \frac{1}{\mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})}$$

- En régime saturé ? Une source de courant commandée en tension

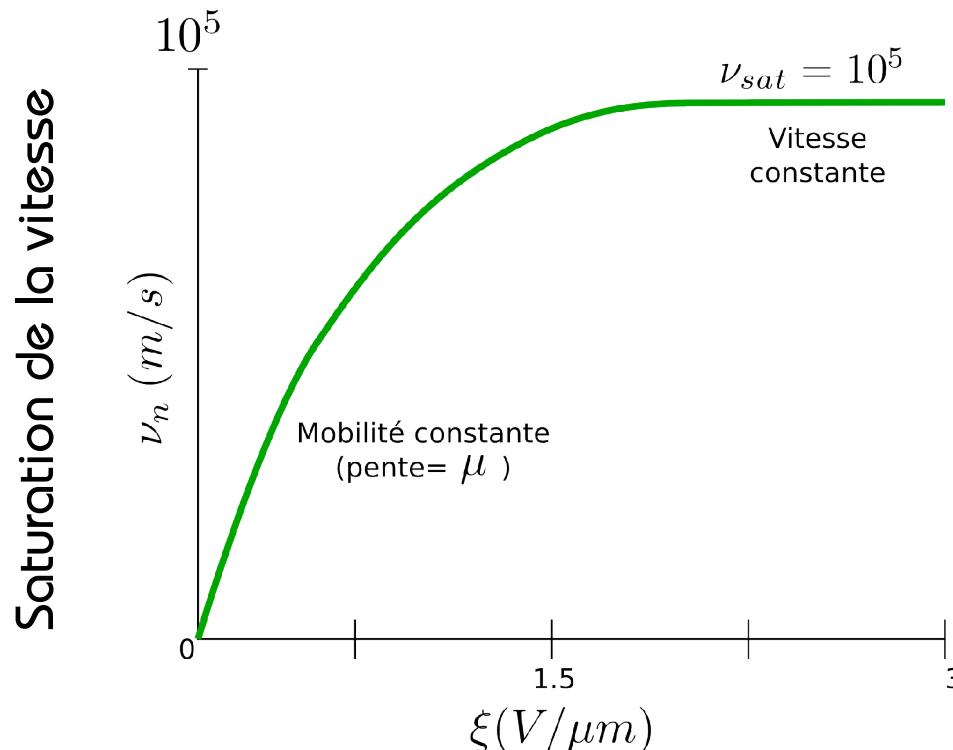


# Quelques ajouts

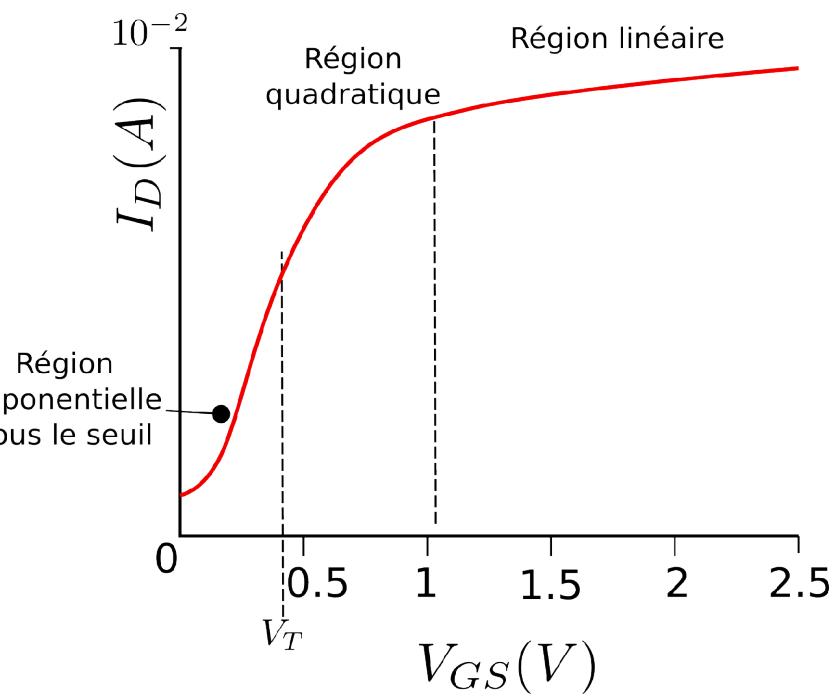
- Ordre de grandeur techno  $0.25\mu\text{m}$  TSMC

	$V_{T0}(\text{V})$	$\gamma(\text{V}^{0.5})$	$V_{DSAT}(\text{V})$	$k'(\text{A}/\text{V}^2)$	$\lambda(\text{V}^{-1})$
NMOS	0.43	0.4	0.63	$115 \times 10^{-6}$	0.06
PMOS	-0.4	-0.4	-1	$-30 \times 10^{-6}$	-0.1

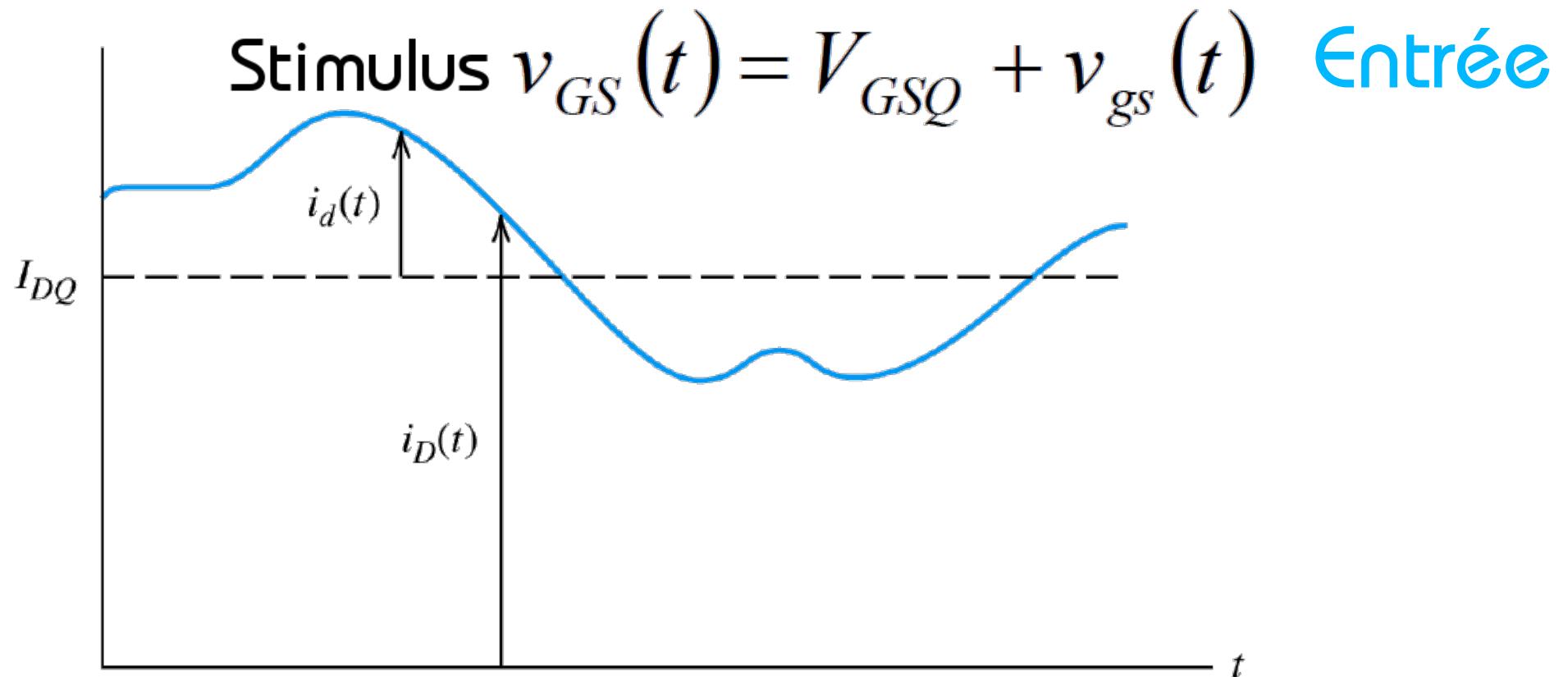
- Autres phénomènes



Courant sous le seuil

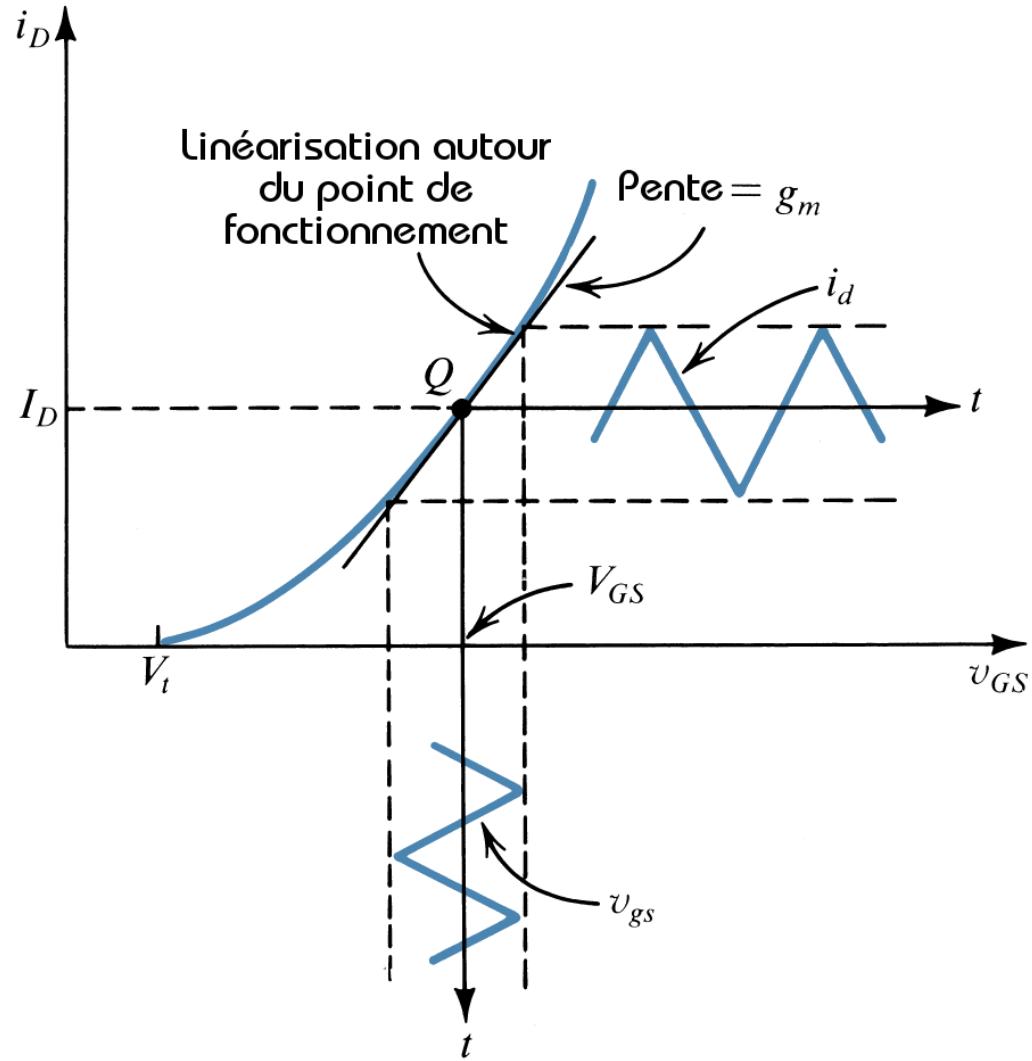


# Le MOS en dynamique



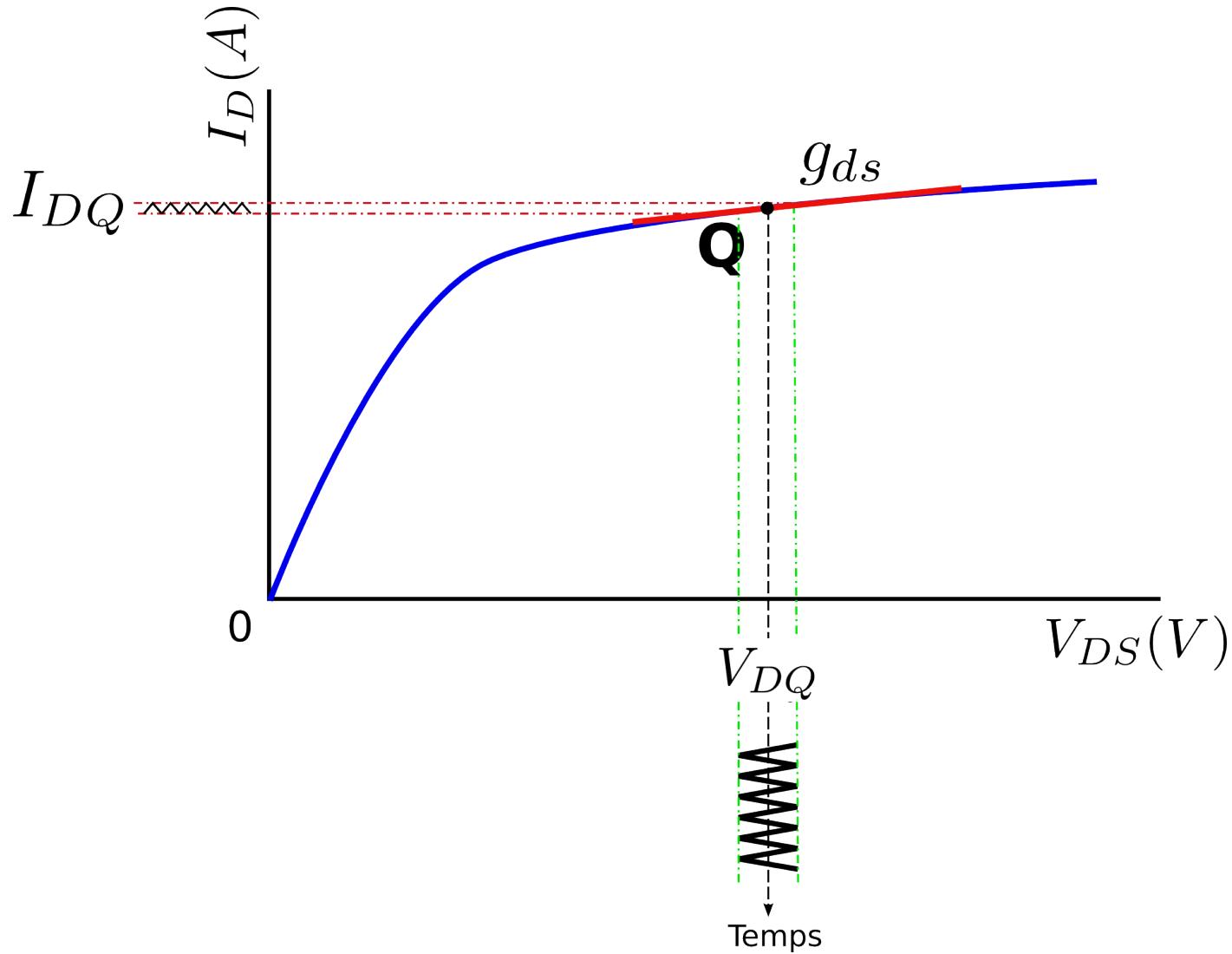
$$i_D(t) = I_{DQ} + i_d(t) \quad \text{Sortie}$$

# Transconductance



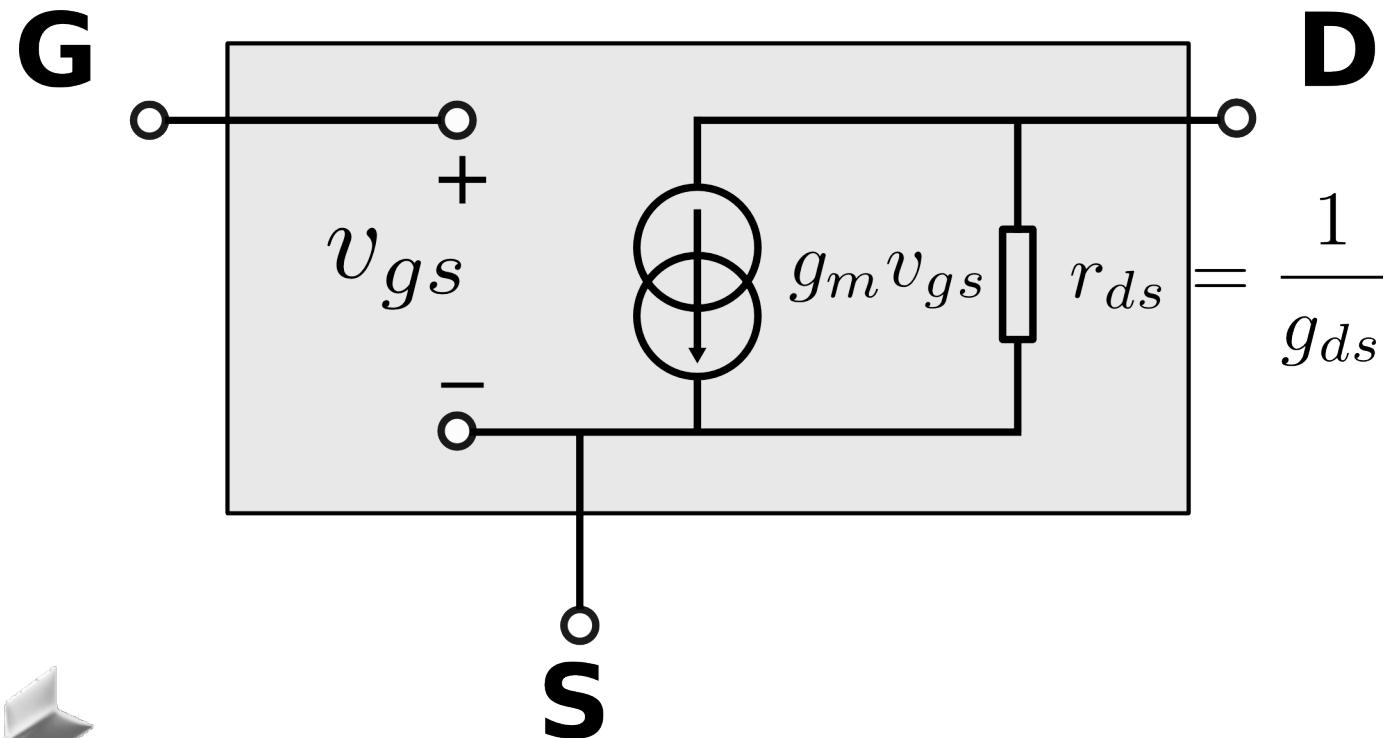
$$g_m = \frac{\partial I_{DS}}{\partial V_{GS}} \Big|_{Q \text{ constant}, V_{DS} \text{ constant}}$$

# Influence de $V_{DS}$ ?

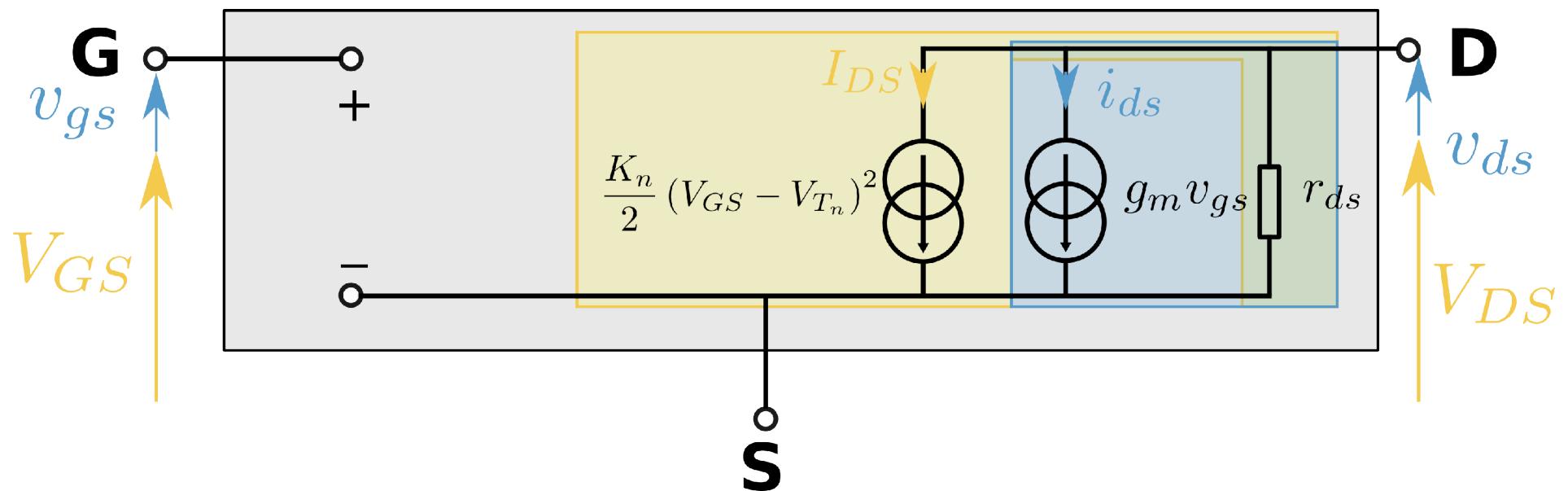


$$g_{ds} = \frac{\partial I_{DS}}{\partial V_{DS}} \Big|_{Q \text{ constant}, V_{GS} \text{ constant}}$$

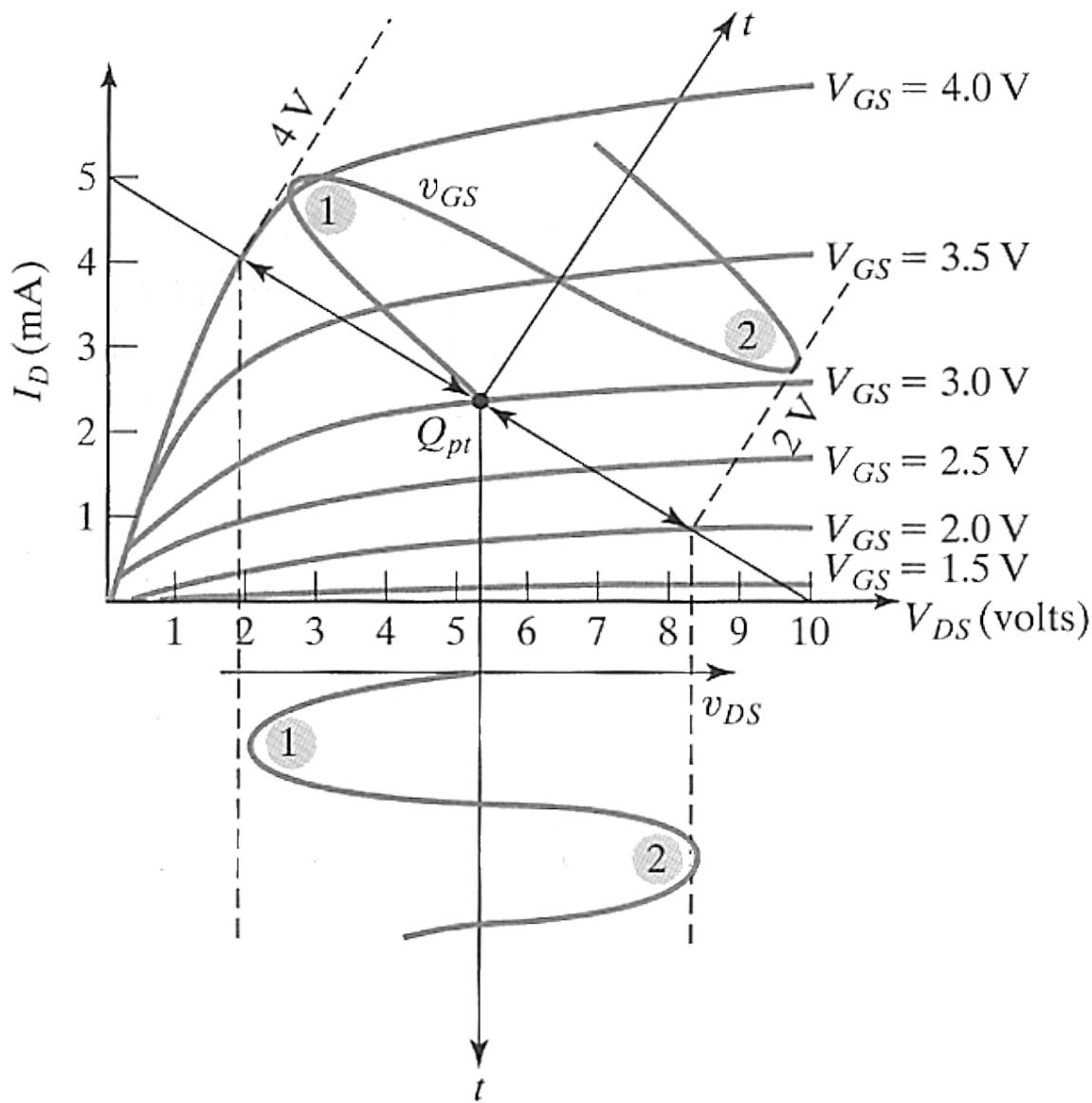
# MOS : modèle petit signal



# MOS : modèle complet

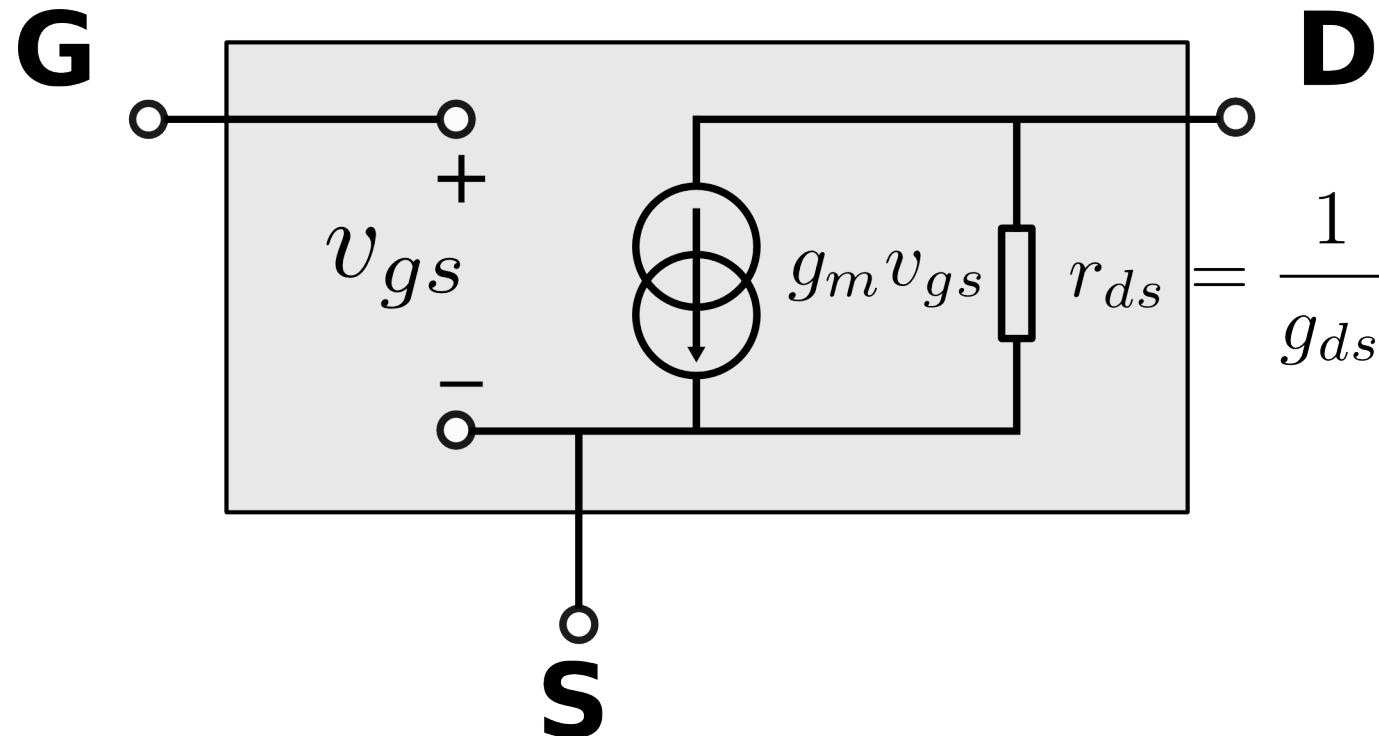


# Les deux ensemble



- Représentation graphique du comportement du circuit autour du point de repos

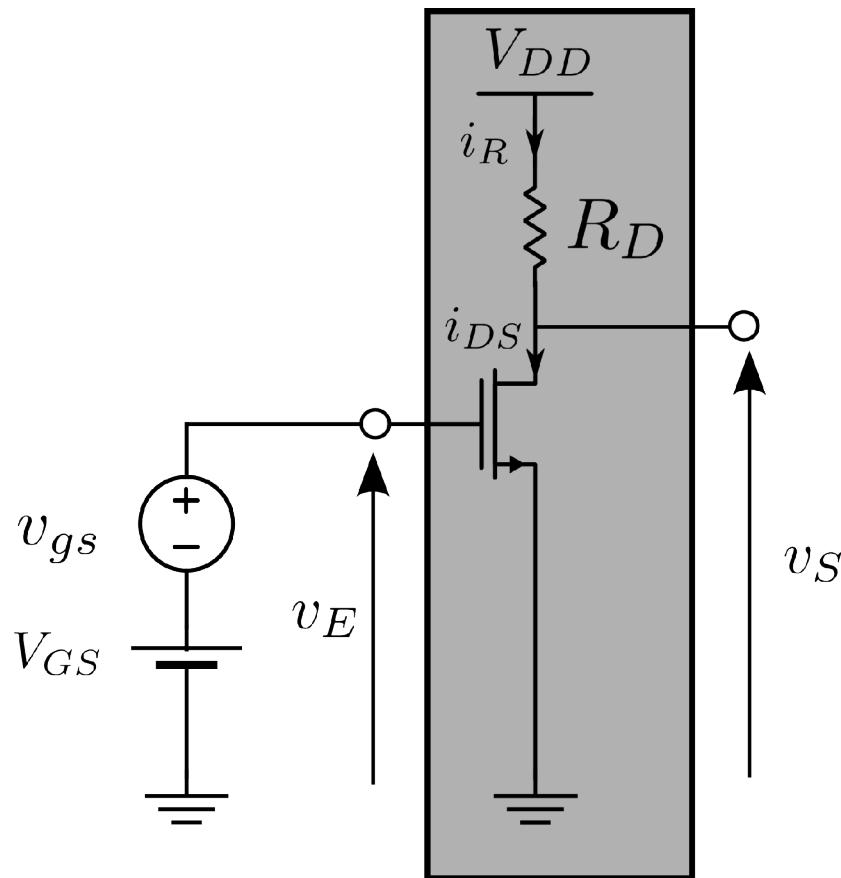
# MOS petit signal BF: résumé



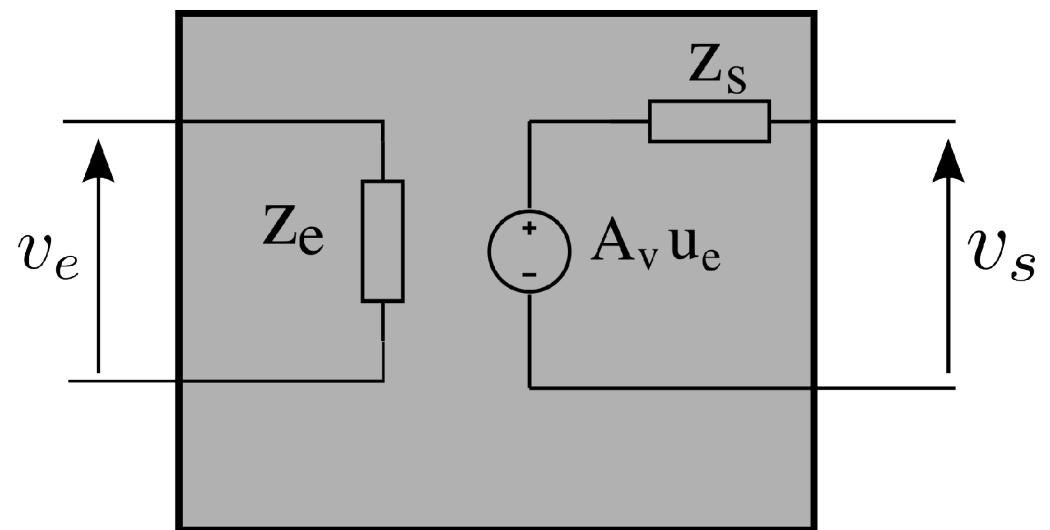
$$g_m = \sqrt{2 \cdot K_n \cdot I_{DQ}} \quad g_{ds} \simeq \lambda I_{DQ}$$

$$g_m \approx 100 \cdot g_{ds}$$

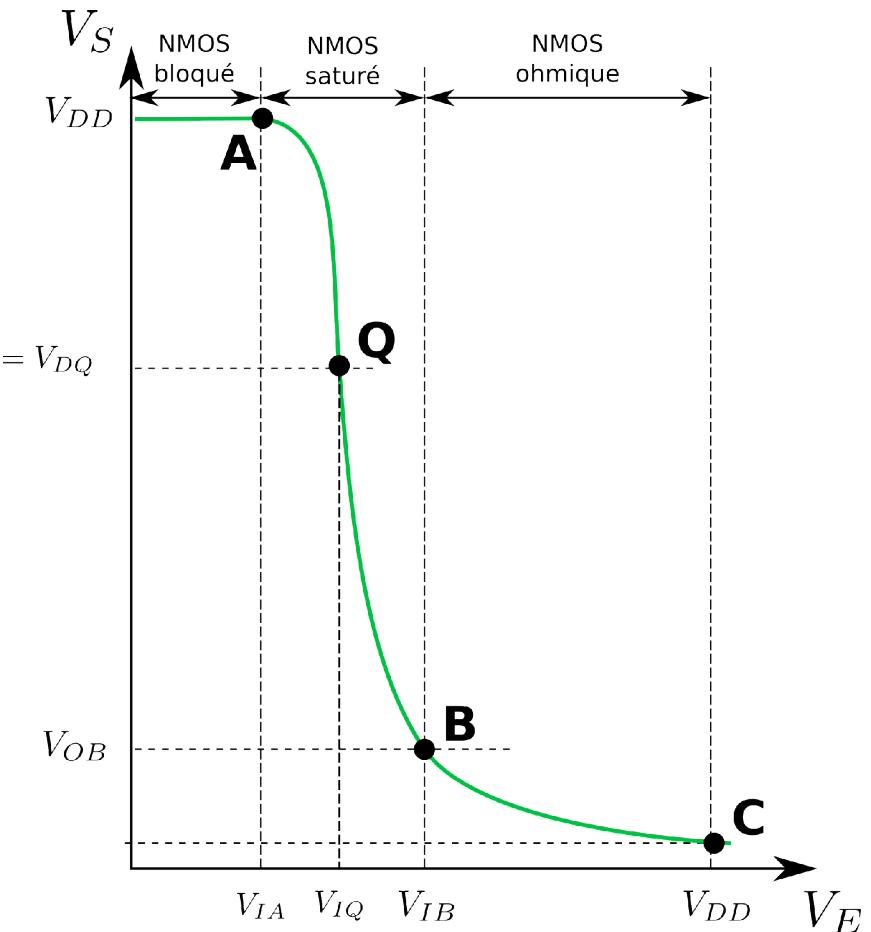
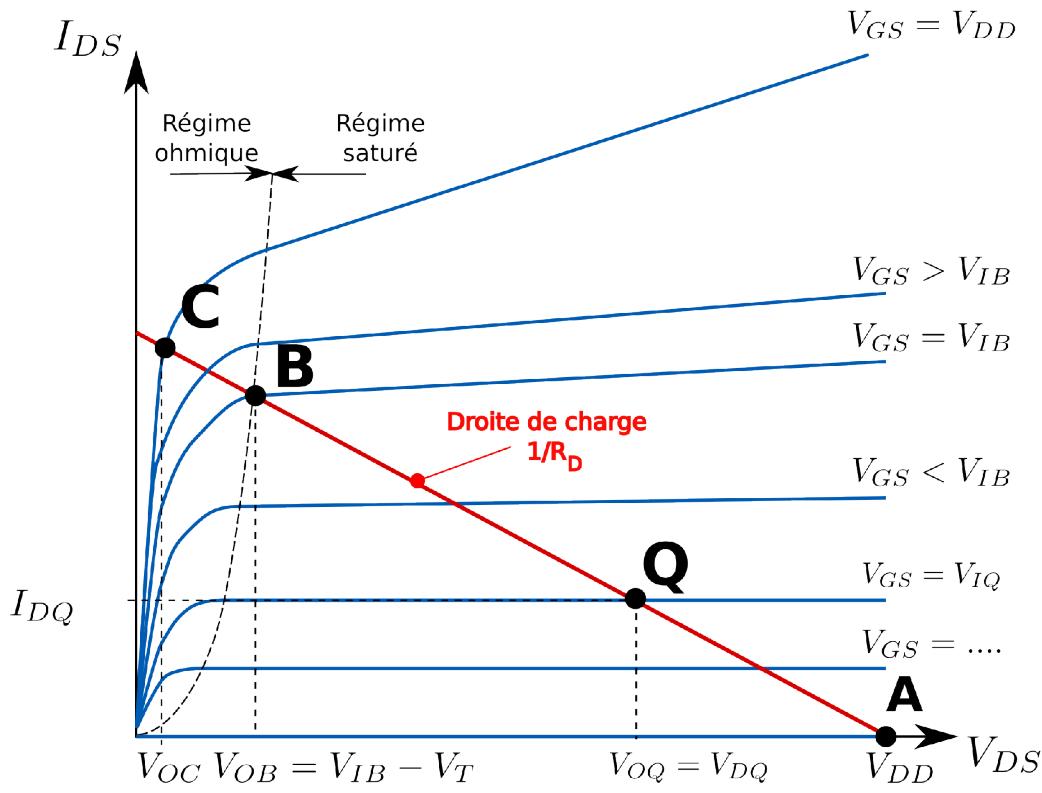
# Un exemple MOS = Amplificateur



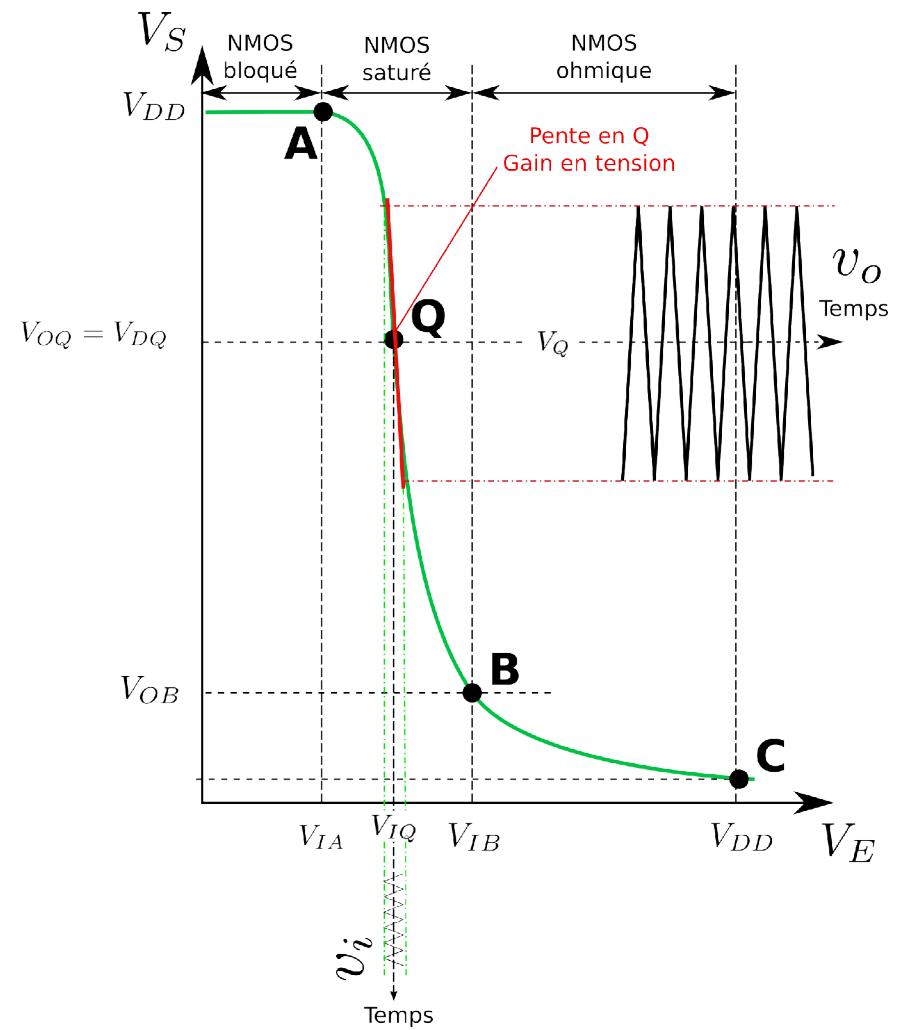
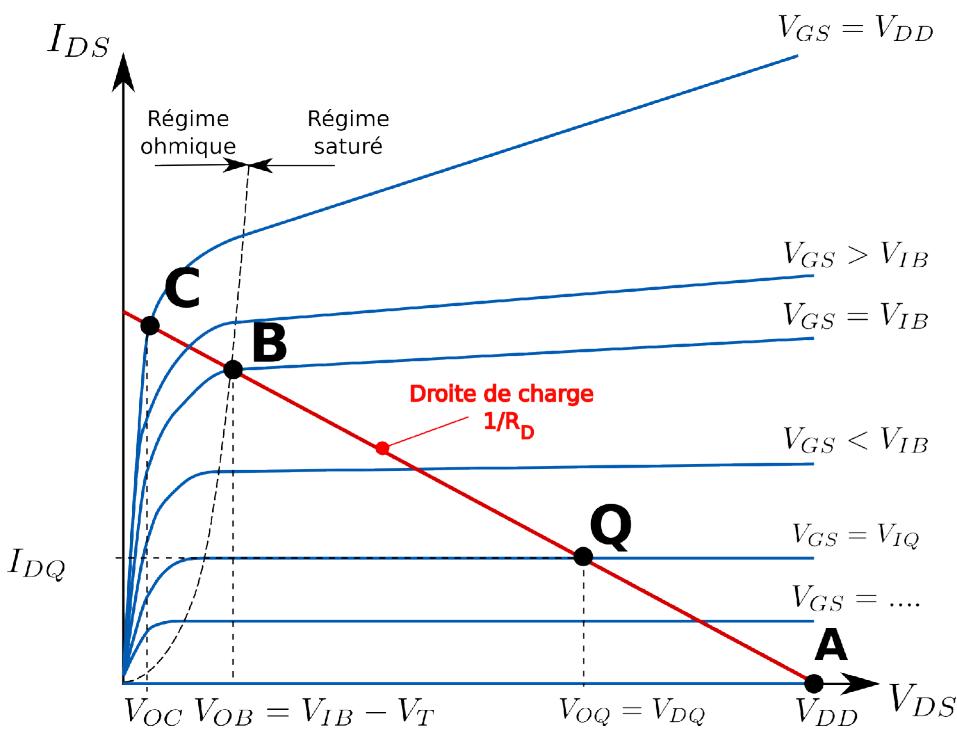
Autour d'un point  
polarisation



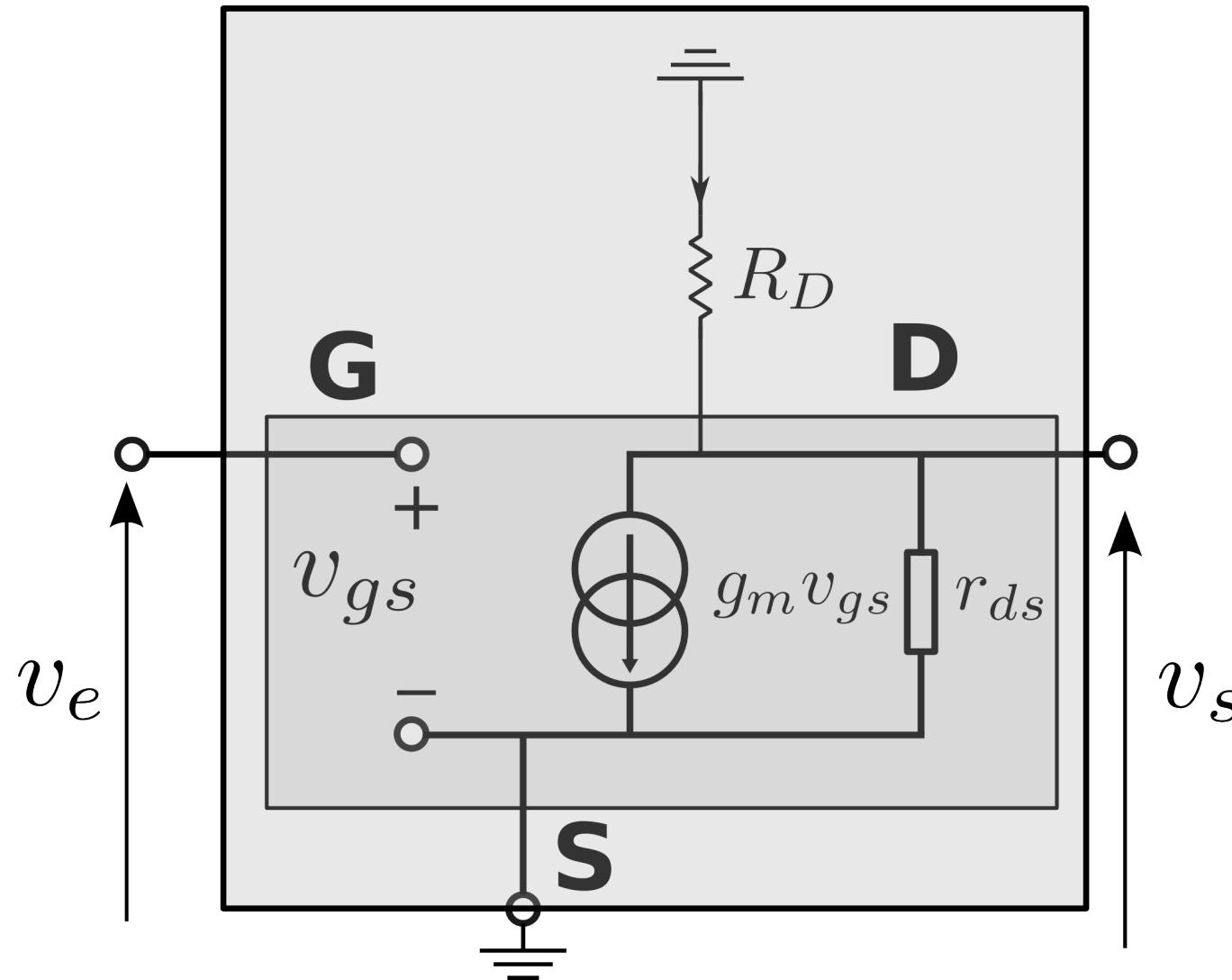
# Caractéristique $V_S = f(V_\epsilon)$



# Approche petit signal

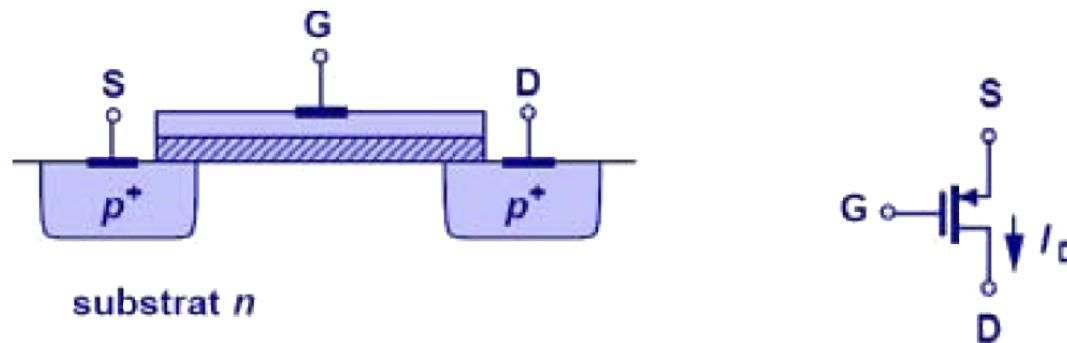


# Modèle petit signal global



# Le PMOS

- Même principe que le NMOS mais avec des trous

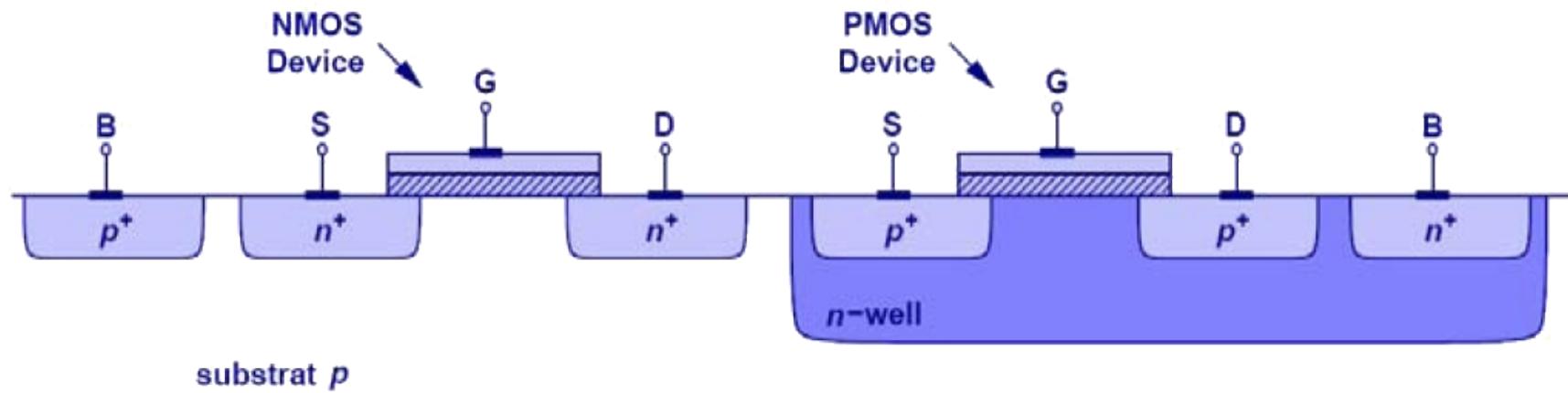


- Les formules sont les mêmes mais  $V_T$  est négatif (de même que les autres tensions)
  - Une manière simple de procéder : inverser S et D et S et G dans les formules du NMOS et prendre  $|V_T|$

$$I_{SD} = \mu_p C_{ox} \frac{W}{L} \left[ (V_{SG} - |V_{Tp}|) V_{SD} - \frac{V_{SD}^2}{2} \right] \quad I_{SDsat} = \mu_p C_{ox} \frac{W}{2 \cdot L} (V_{SG} - |V_{Tp}|)^2 (1 + \lambda V_{SD})$$

# CMOS

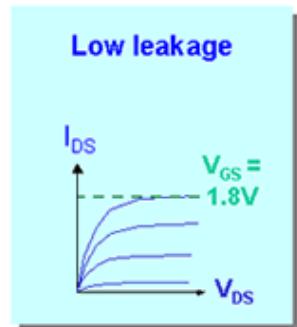
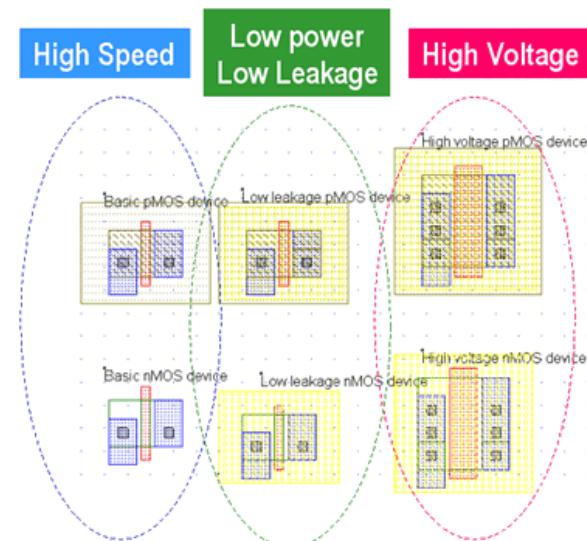
- Complémentaire : la technologie permet d'implémenter les deux types de transistors



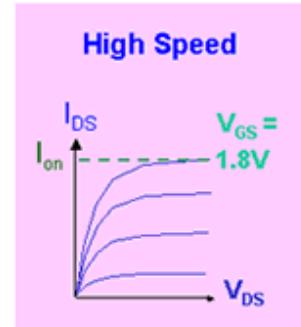
- C'est la base de tous les circuits actuels!

# Déclinaison d'une technologie

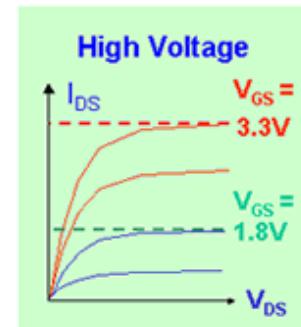
- Choix parmi trois variantes à partir de la techno  $0.18\mu\text{m}$
- low power : transistors par défaut
- High speed : circuits digitaux rapides
- High voltage : los, blocs analogiques



- $V_t$  fort
- $I_{on}$ ,  $I_{off}$  faible



- Performant
- $I_{on}$ ,  $I_{off}$  fort



- $I_{on}$ ,  $I_{off}$  très fort
- Oxyde épais, long canal

# Bibliographie

- Digital Integrated Circuits, 2nd Edition, Jan M. Rabaey  
Jan et al, Prentice Hall.
- Operation and modeling of the MOS transistor,  
Tsividis, Yannis, WCB/McGraw-Hill, 621.381 528 TSI
- Design of analog CMOS integrated circuits, Razavi  
Behzad , McGraw-Hill, Publication Boston, MA, 2001,  
621.39 RAZ
- Microelectronic circuits, Sedra Adel S. et al., Oxford  
University Press, New York Oxford, 2004, 621.381 5  
SED