

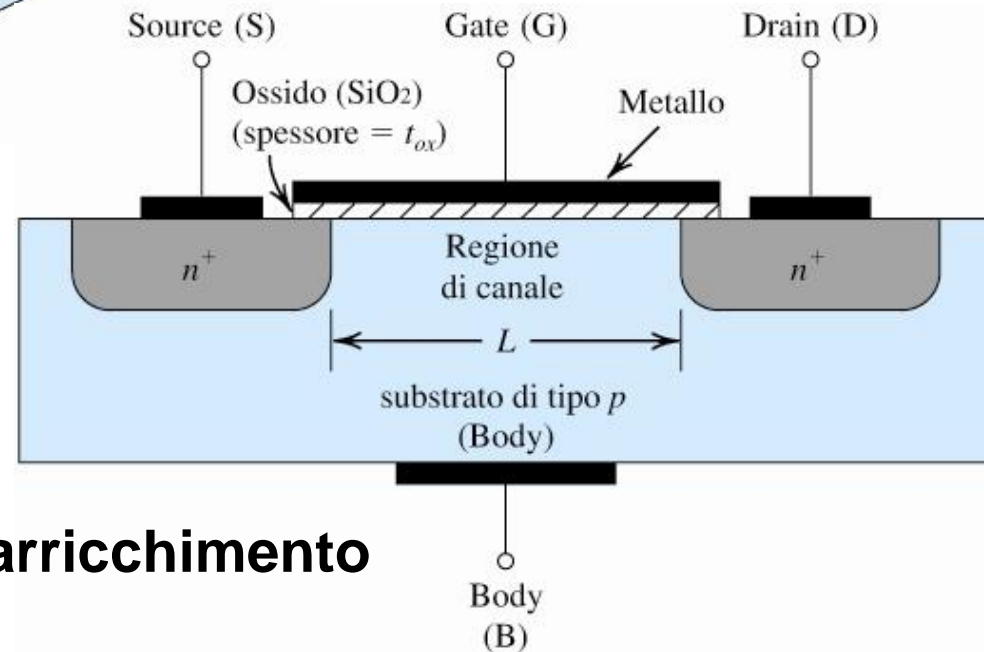
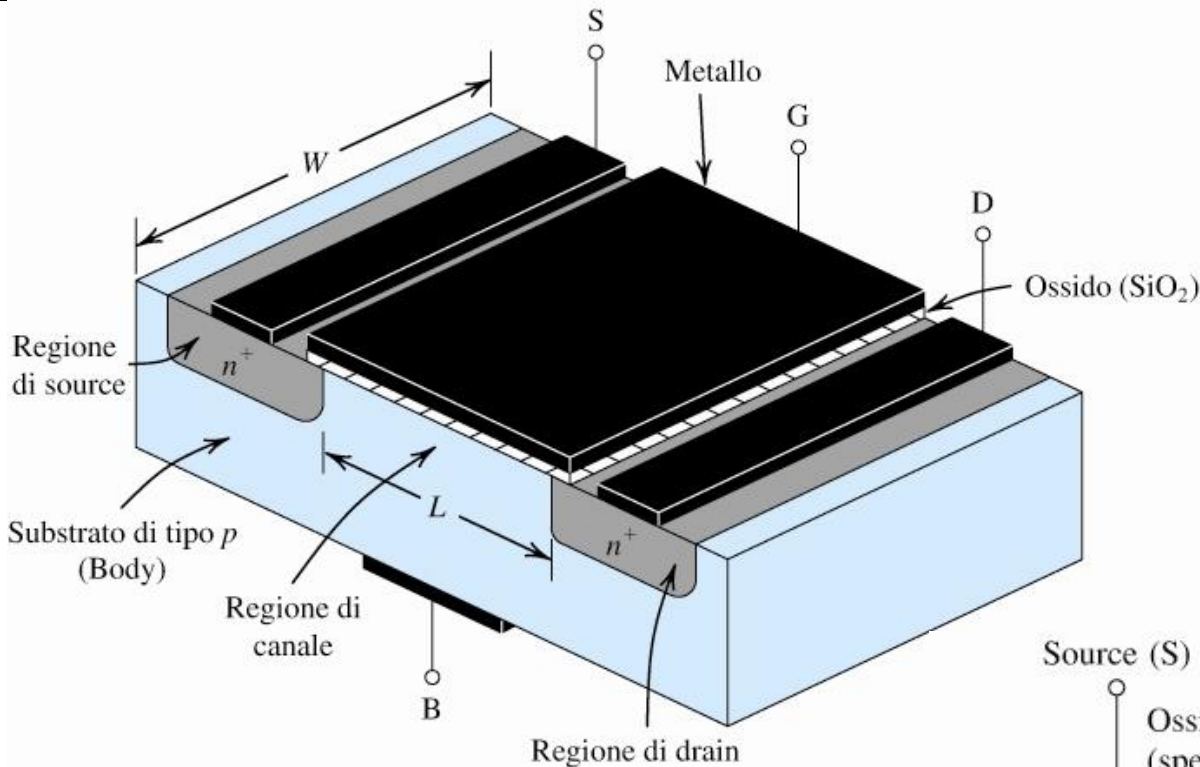
A.A. 2021-2022

Elementi di Elettronica (INF)

Prof. Paolo Crippa

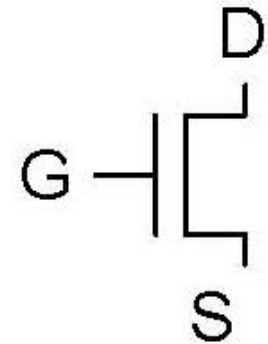
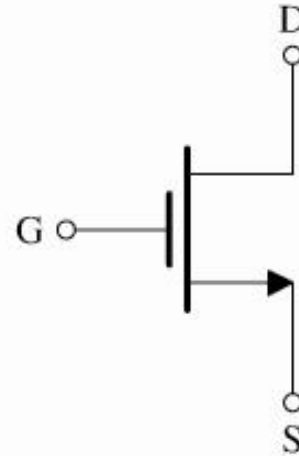
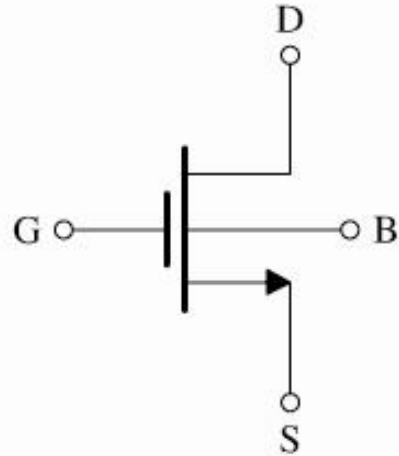
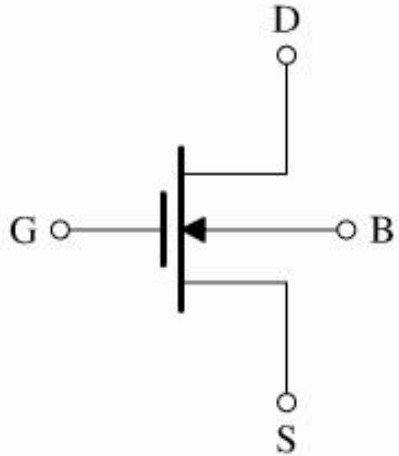
Transistore MOS

Il Transistore MOS



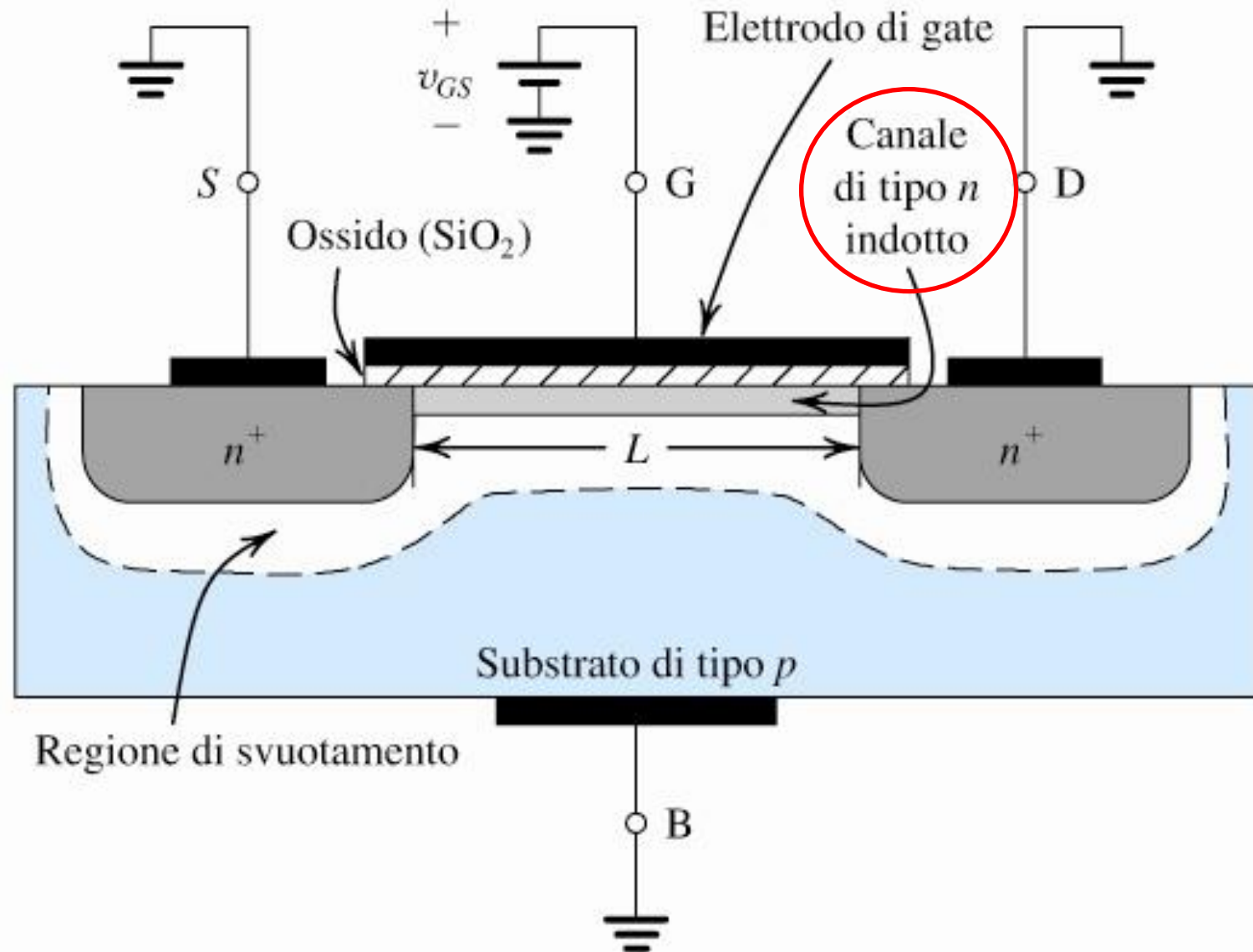
Transistore MOS a canale n ad arricchimento

Il Transistore nMOS: Simboli Grafici



Il Transistore nMOS: Funzionamento

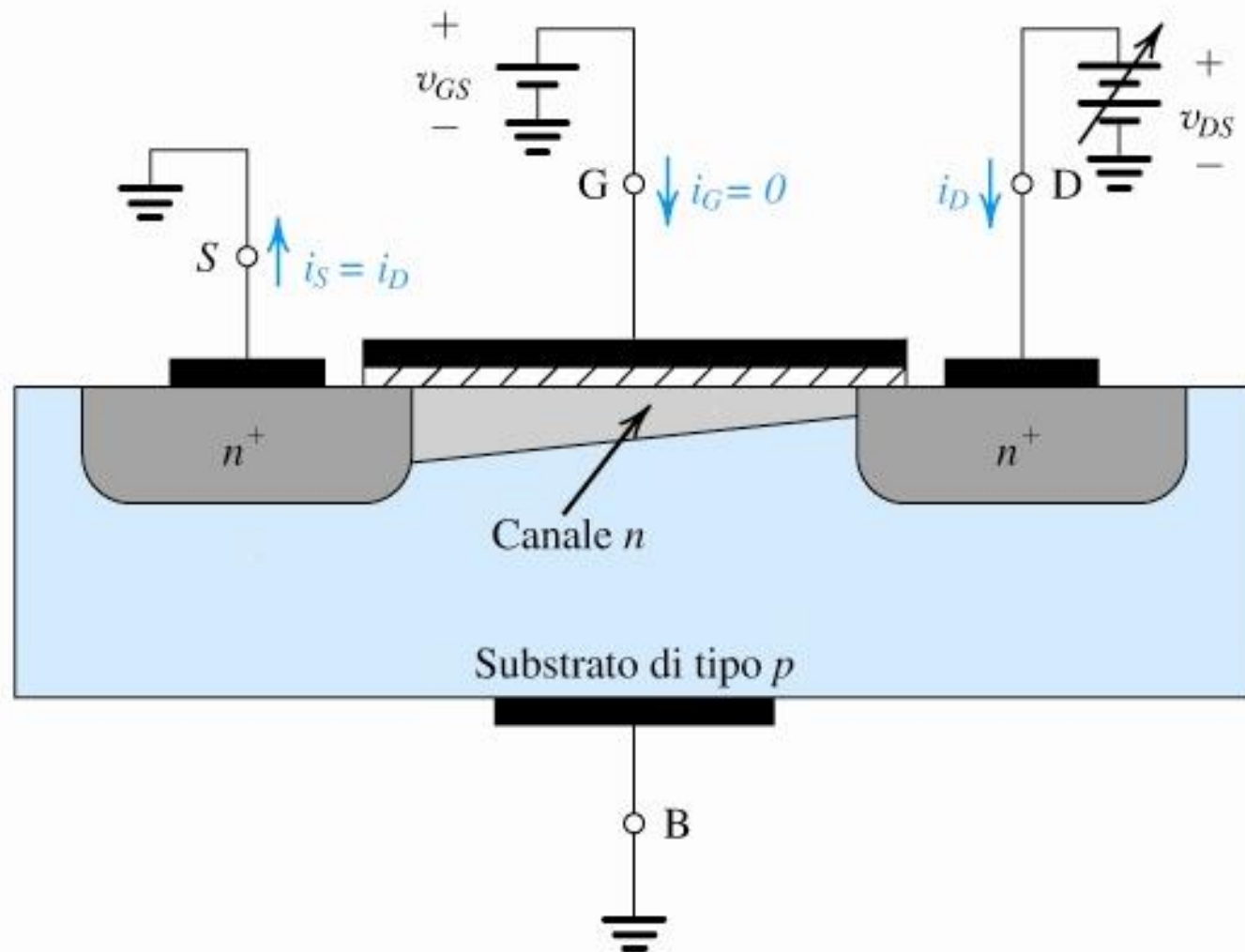
Per $V_{GS} > V_{th}$ si crea sotto il Gate un canale conduttivo tra il Source e il Drain



Il Transistore nMOS: Funzionamento

Funzionamento dell'NMOS ad arricchimento al variare della V_{ds} .

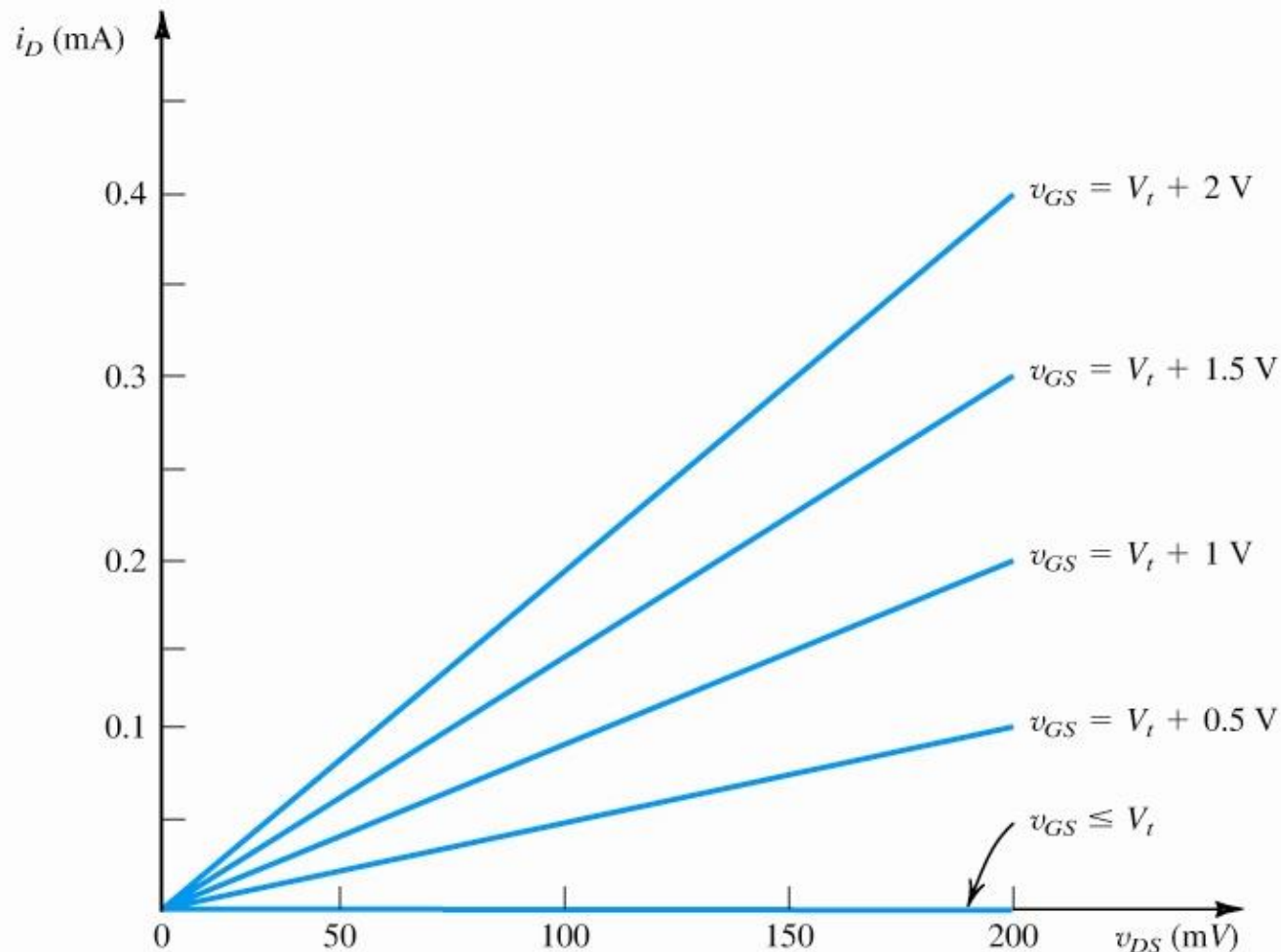
Il canale viene rastremato e la sua resistività aumenta al crescere della V_{ds} .
In questo caso la V_{gs} è mantenuta costante ad un valore $>$ di V_{th} .



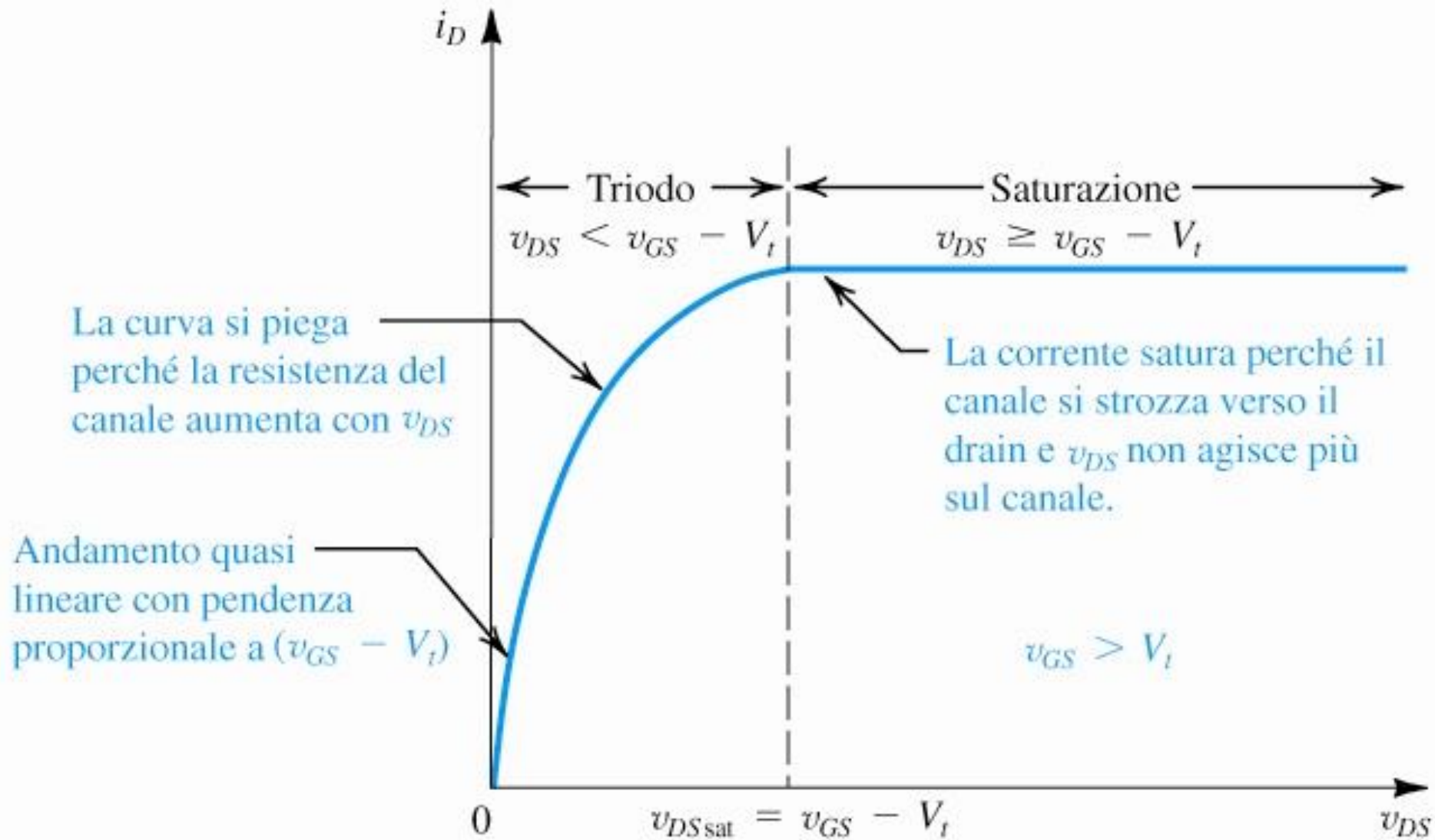
nMOSFET: Funzionamento in Regione Lineare

Caratteristica I_D - V_{DS} per piccoli valori di V_{DS}

Il dispositivo funziona come un resistore lineare il cui valore è controllato tramite V_{GS}



nMOSFET: Caratteristica $I_D - V_{DS}$

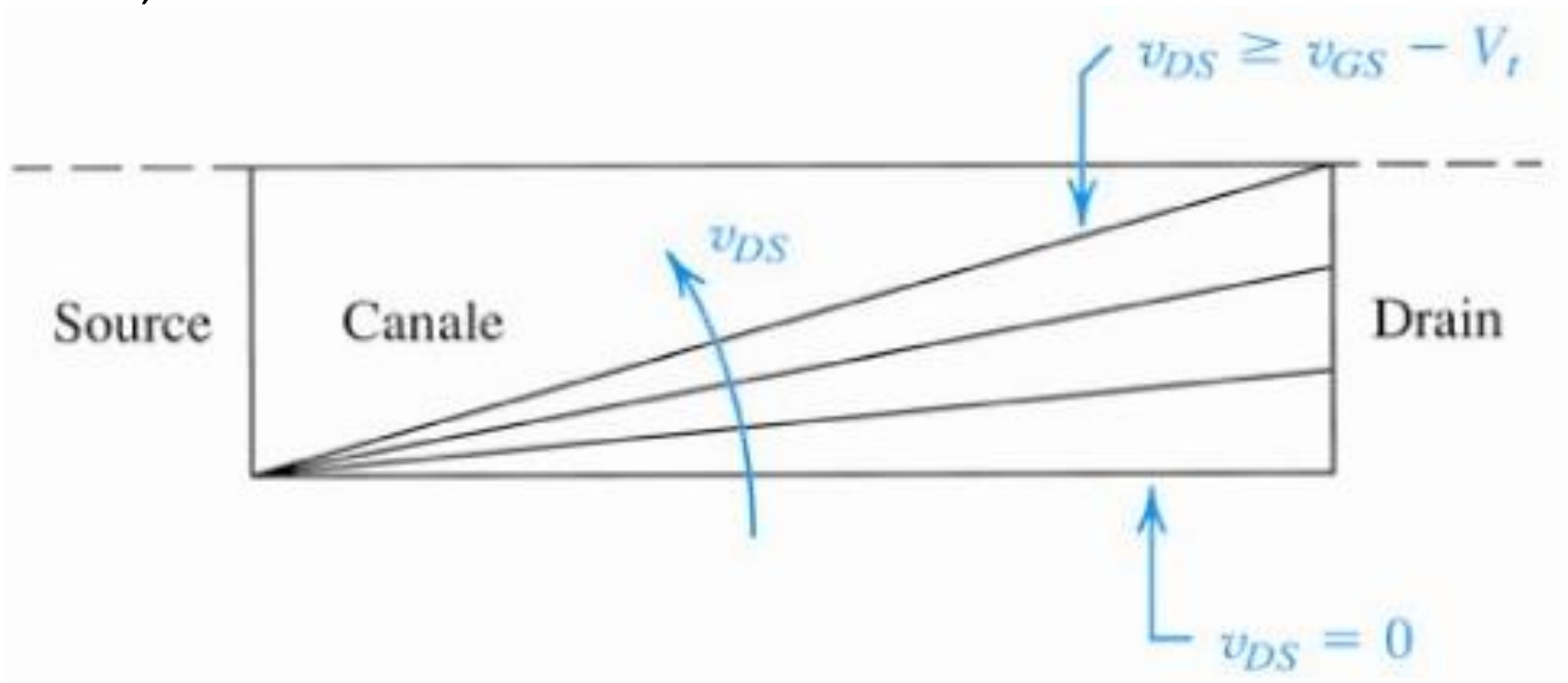


nMOSFET: La Modulazione di Canale

Al crescere di V_{ds} il canale viene rastremato.

Per $V_{ds} = V_{gs} - V_{th}$ il canale si strozza verso il Drain (pinch-off).

Al crescere di V_{ds} oltre questo valore si rileva solo un piccolo effetto sulla forma del canale (il punto di strozzamento si sposta verso il Source)



nMOSFET: Equazioni delle Correnti

$$i_G = 0$$

$$i_D = \begin{cases} 0 & \text{per } v_{GS} \leq V_{TH} & \text{Interdizione} \\ \beta \left[(v_{GS} - V_{TH}) v_{DS} - \frac{v_{DS}^2}{2} \right] & \text{per } v_{GS} > V_{TH}, v_{DS} \leq v_{GS} - V_{TH} & \text{Triodo} \\ \frac{\beta}{2} (v_{GS} - V_{TH})^2 & \text{per } v_{GS} > V_{TH}, v_{DS} \geq v_{GS} - V_{TH} & \text{Saturazione} \end{cases}$$

$$\beta = 2K = k_n \frac{W}{L} = \mu_n C_{OX} \frac{W}{L}$$

$$C_{OX} = \frac{\epsilon_{OX}}{t_{OX}} \quad \text{valore di esempio } \beta = 20 \mu\text{A/V}^2$$

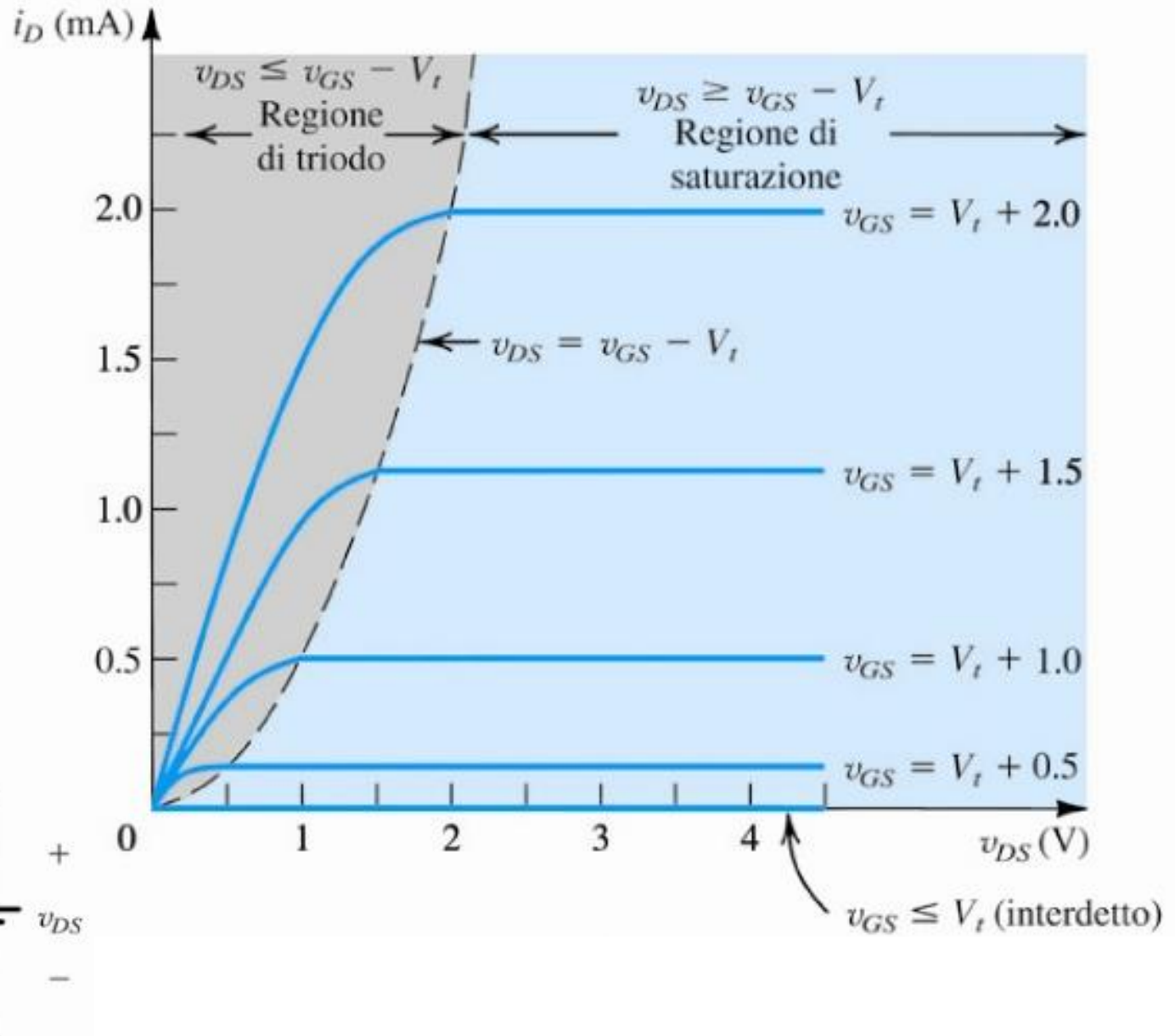
$$V_{TH} = V_{T0} + \gamma \left[\sqrt{2\phi_F - v_{BS}} - \sqrt{2\phi_F} \right] \quad \text{valore di esempio } V_{TH} = 0.5V$$

$$\gamma = \frac{\sqrt{2\epsilon_s q N_A}}{C_{OX}}$$

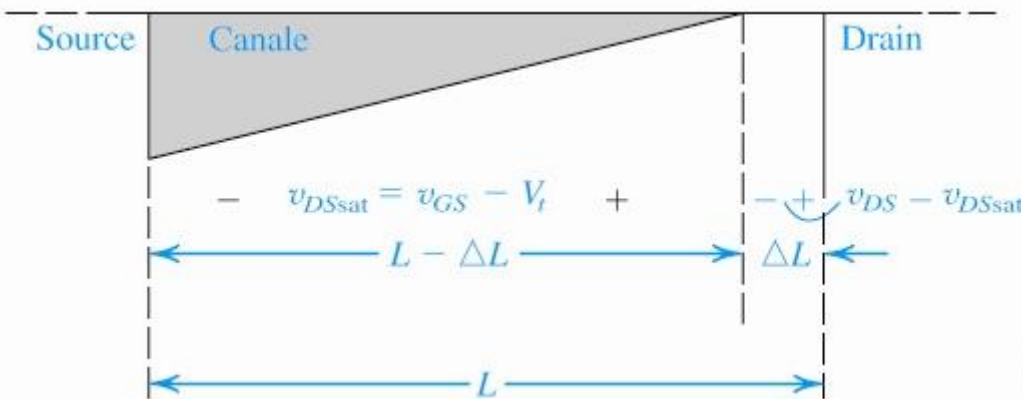
Effetto Body

Caratteristica $i_D - v_{DS}$

curve di uscita



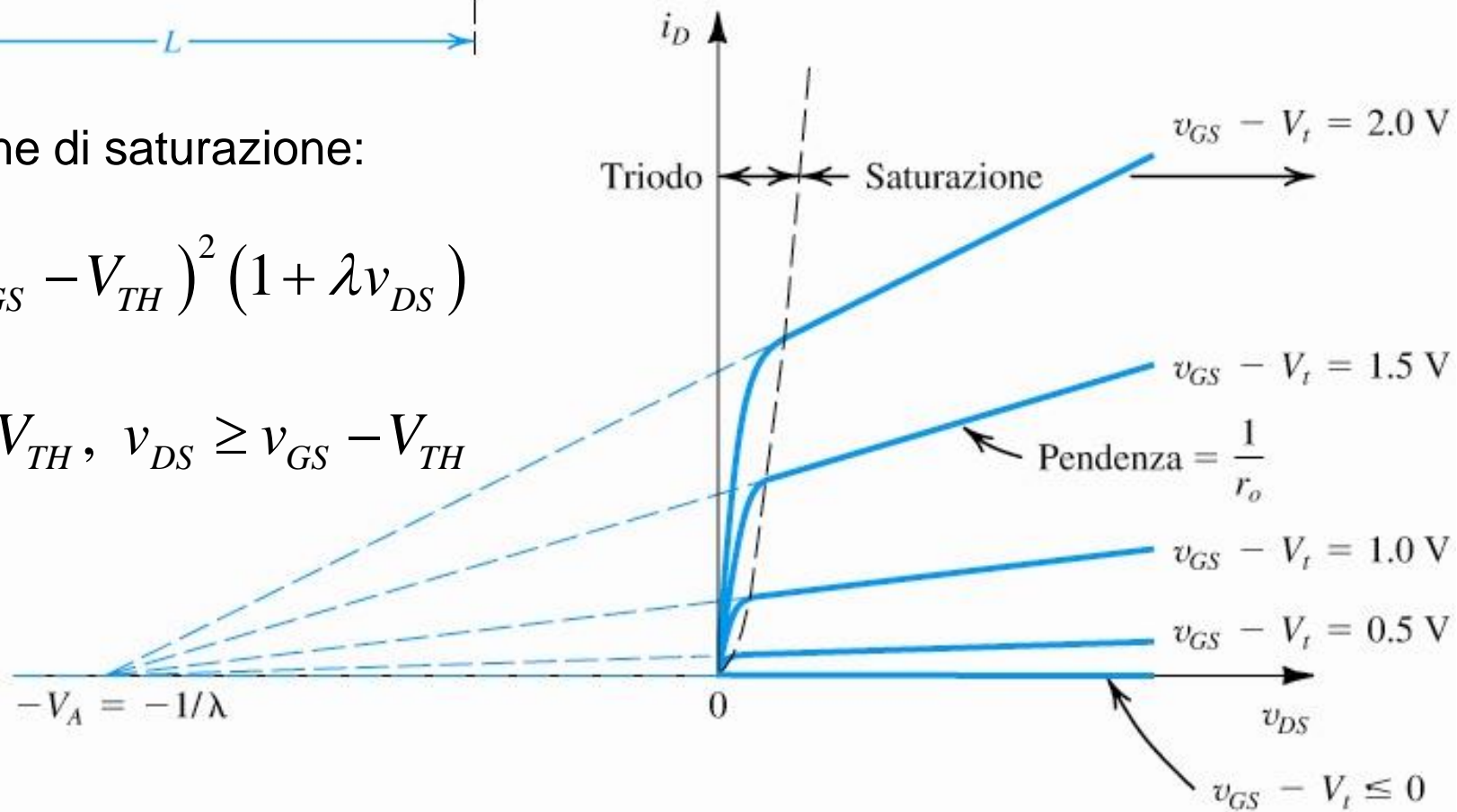
Effetto della Modulazione di Canale su $I_D - V_{DS}$



Nella regione di saturazione:

$$I_D = \frac{\beta}{2} (v_{GS} - V_{TH})^2 (1 + \lambda v_{DS})$$

per $v_{GS} > V_{TH}$, $v_{DS} \geq v_{GS} - V_{TH}$



nMOSFET: Equazioni delle Correnti

$$i_G = 0$$
$$i_D = \begin{cases} 0 & \text{per } v_{GS} \leq V_{TH} & \text{Interdizione} \\ \beta \left[(v_{GS} - V_{TH}) v_{DS} - \frac{v_{DS}^2}{2} \right] & \text{per } v_{GS} > V_{TH}, v_{DS} \leq v_{GS} - V_{TH} & \text{Triodo} \\ \frac{\beta}{2} (v_{GS} - V_{TH})^2 (1 + \lambda v_{DS}) & \text{per } v_{GS} > V_{TH}, v_{DS} \geq v_{GS} - V_{TH} & \text{Saturazione} \end{cases}$$

$$\beta = 2K = k_n \frac{W}{L} = \mu_n C_{OX} \frac{W}{L}$$

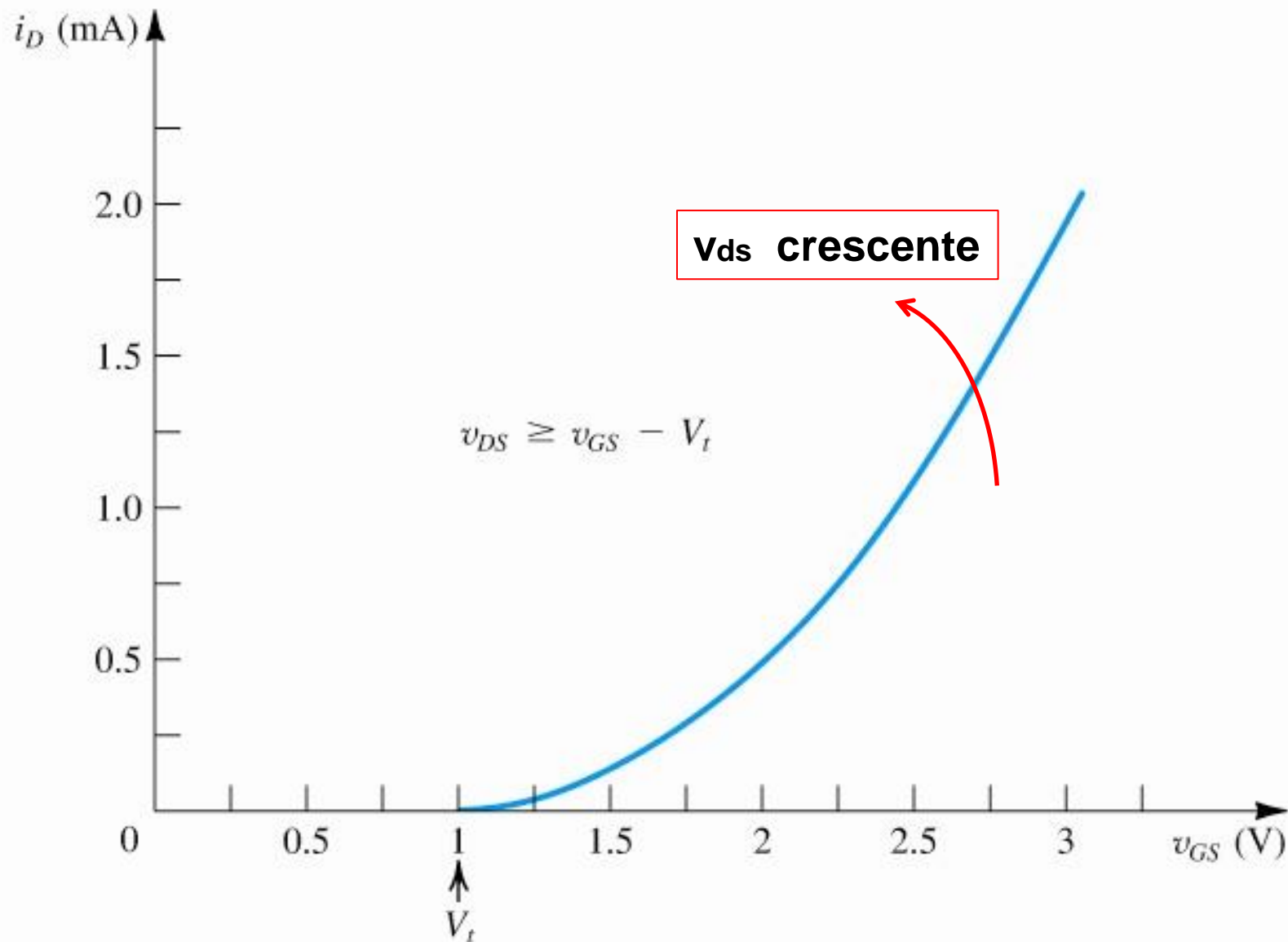
$$C_{OX} = \frac{\epsilon_{OX}}{t_{OX}} \quad \text{valore di esempio } \beta = 20 \mu\text{A/V}^2$$

$$V_{TH} = V_{T0} + \gamma \left[\sqrt{2\phi_F - v_{BS}} - \sqrt{2\phi_F} \right] \quad \text{valore di esempio } V_{TH} = 0.5V$$

$$\gamma = \frac{\sqrt{2\epsilon_s q N_A}}{C_{OX}}$$

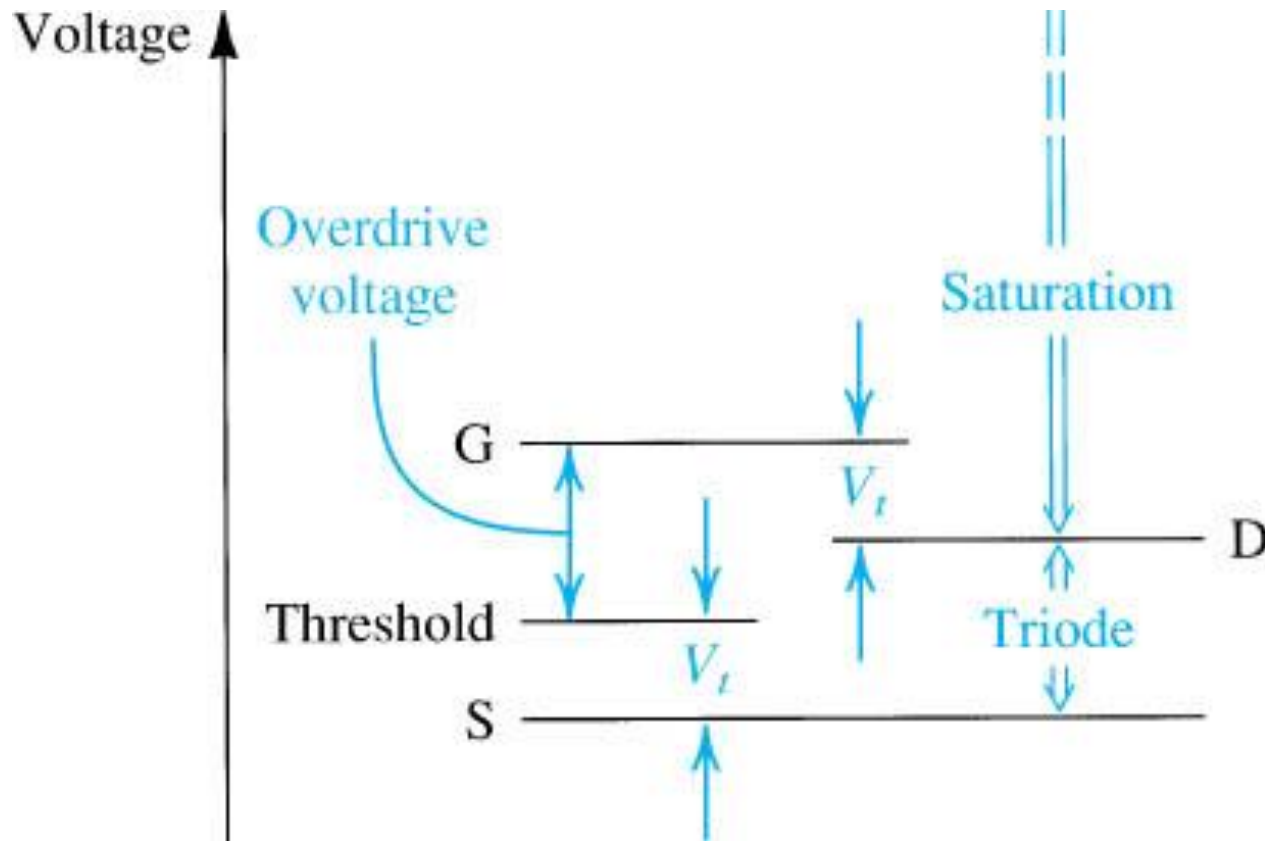
Effetto Body

Caratteristica $i_D - v_{GS}$

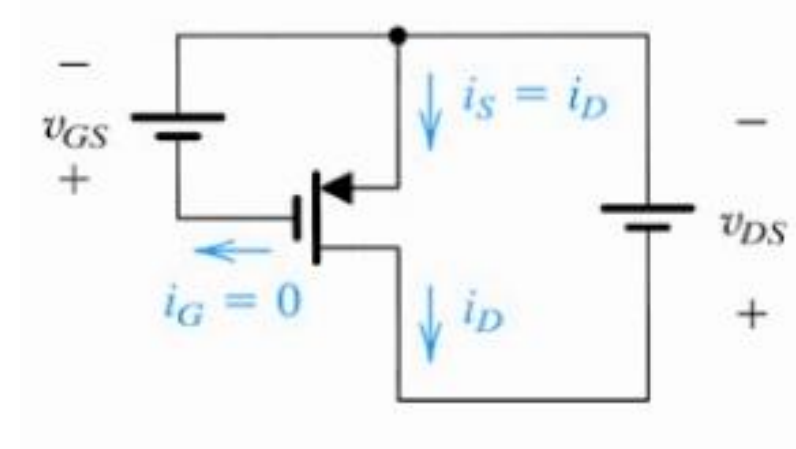
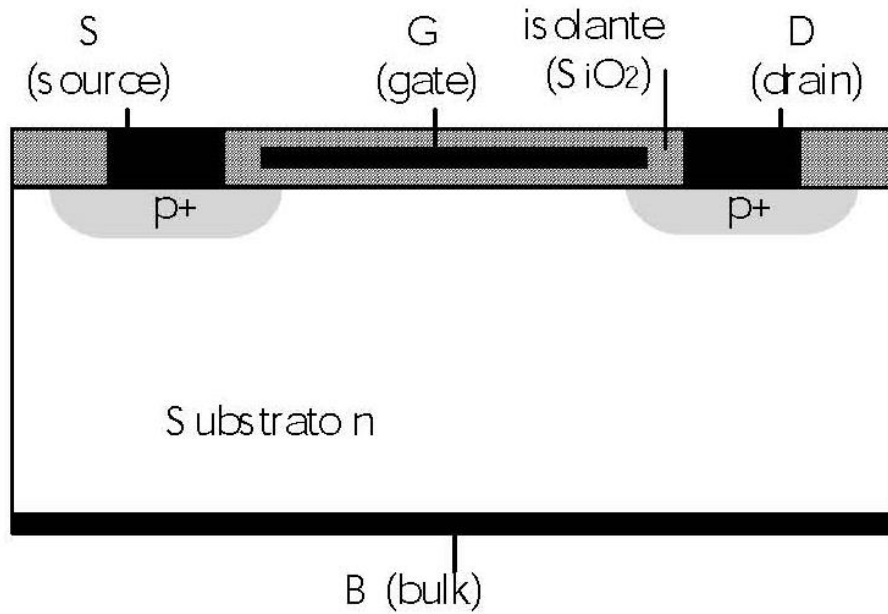


nMOSFET: Livelli di Tensione Relativi

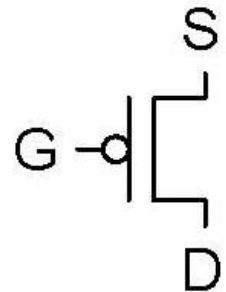
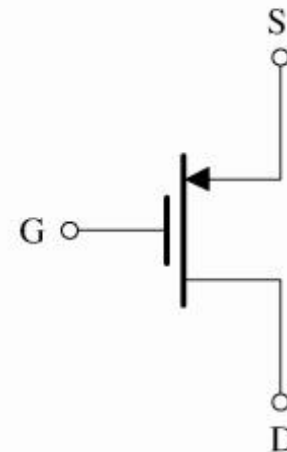
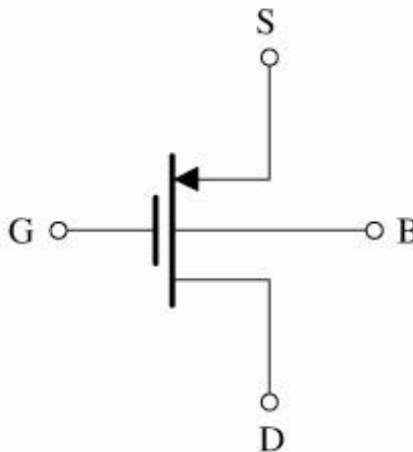
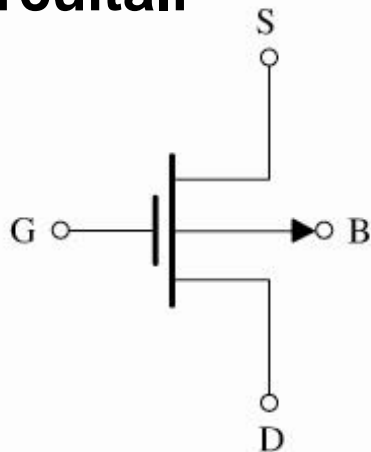
Livelli di tensione relativi dei terminali di un NMOS ad arricchimento nel funzionamento in regione di triodo e in regione di saturazione



Il Transistore MOS a canale P



Simboli circuitali



pMOSFET: Equazioni delle Correnti

$$i_G = 0$$
$$i_D = \begin{cases} 0 & \text{per } v_{SG} \leq -V_{TH} & \text{Interdizione} \\ \beta \left[(v_{SG} + V_{TH}) v_{SD} - \frac{v_{SD}^2}{2} \right] & \text{per } v_{SG} > -V_{TH}, v_{SD} \leq v_{SG} + V_{TH} & \text{Triodo} \\ \frac{\beta}{2} (v_{SG} + V_{TH})^2 (1 + \lambda v_{SD}) & \text{per } v_{SG} > -V_{TH}, v_{SD} \geq v_{SG} + V_{TH} & \text{Saturazione} \end{cases}$$

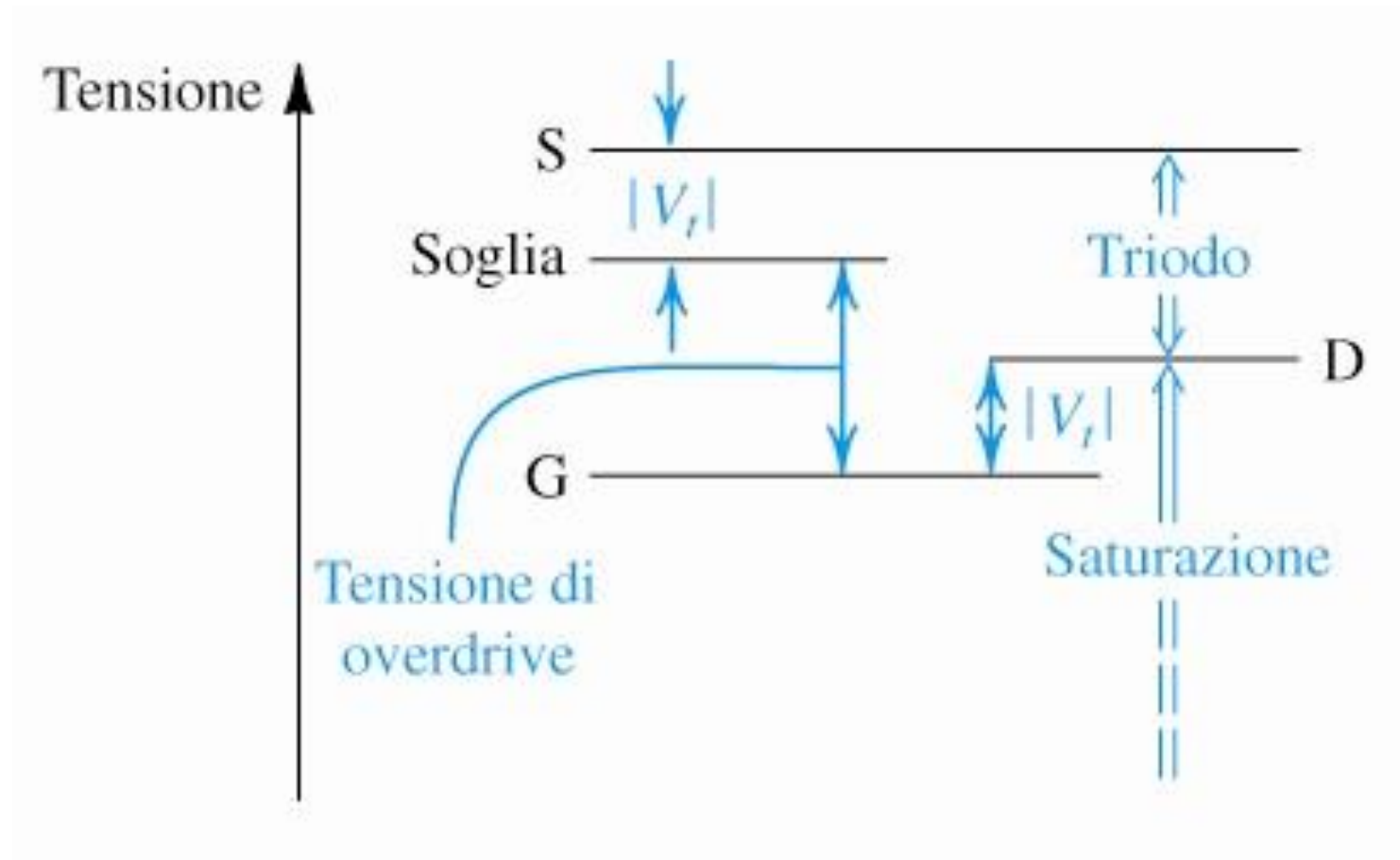
$$\beta = 2K = k_p \frac{W}{L} = \mu_p C_{OX} \frac{W}{L} \quad C_{OX} = \frac{\epsilon_{OX}}{t_{OX}} \quad \text{valore di esempio } \beta = 20 \mu\text{A/V}^2$$

$$V_{TH} = V_{T0} - \gamma \left[\sqrt{2\phi_F - v_{SB}} - \sqrt{2\phi_F} \right] \quad \text{valore di esempio } V_{TH} = -0.5V$$

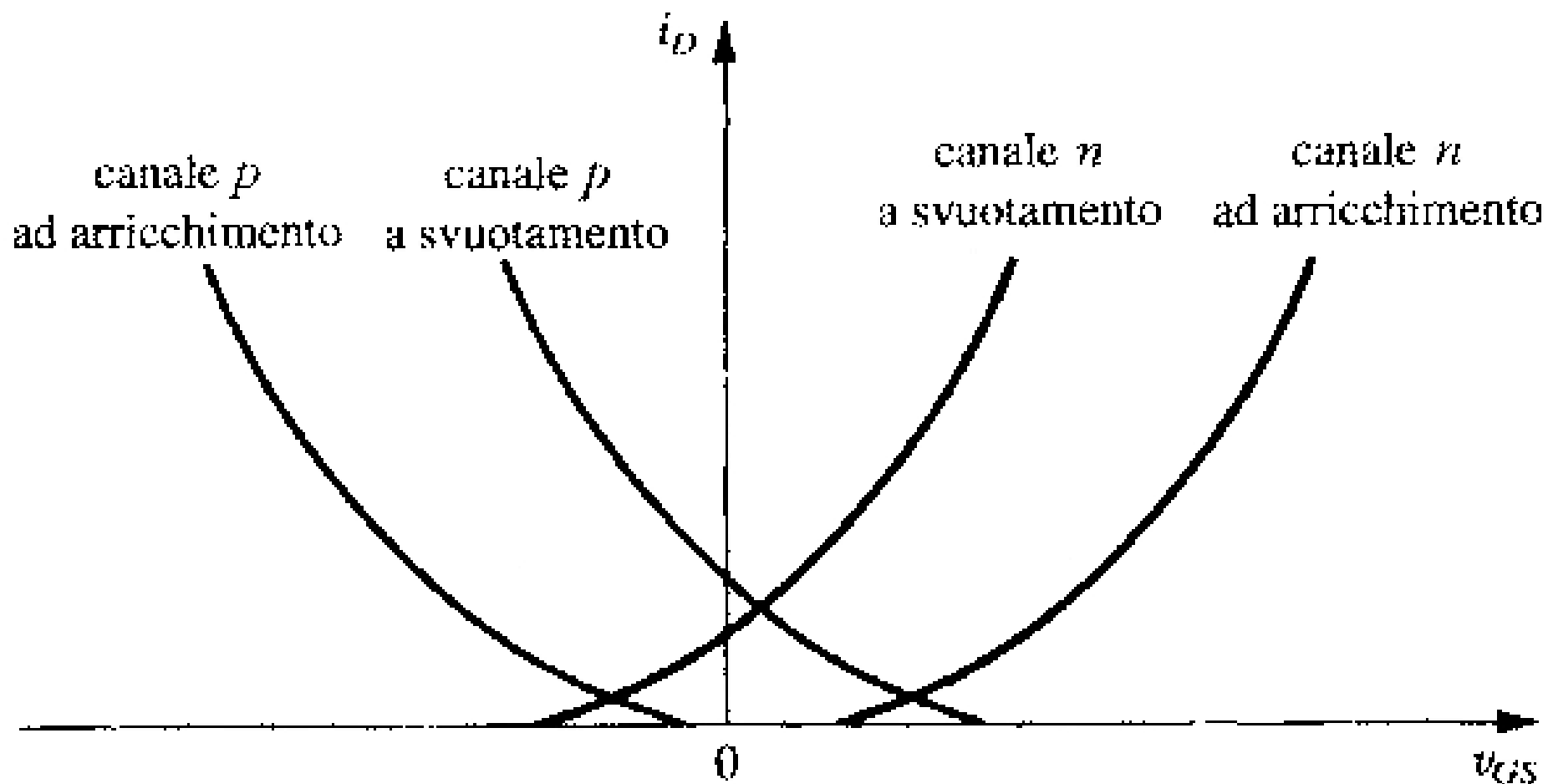
$$\gamma = \frac{\sqrt{2\epsilon_s q N_D}}{C_{OX}} \quad \text{Effetto Body}$$

pMOSFET: Livelli di Tensione Relativi

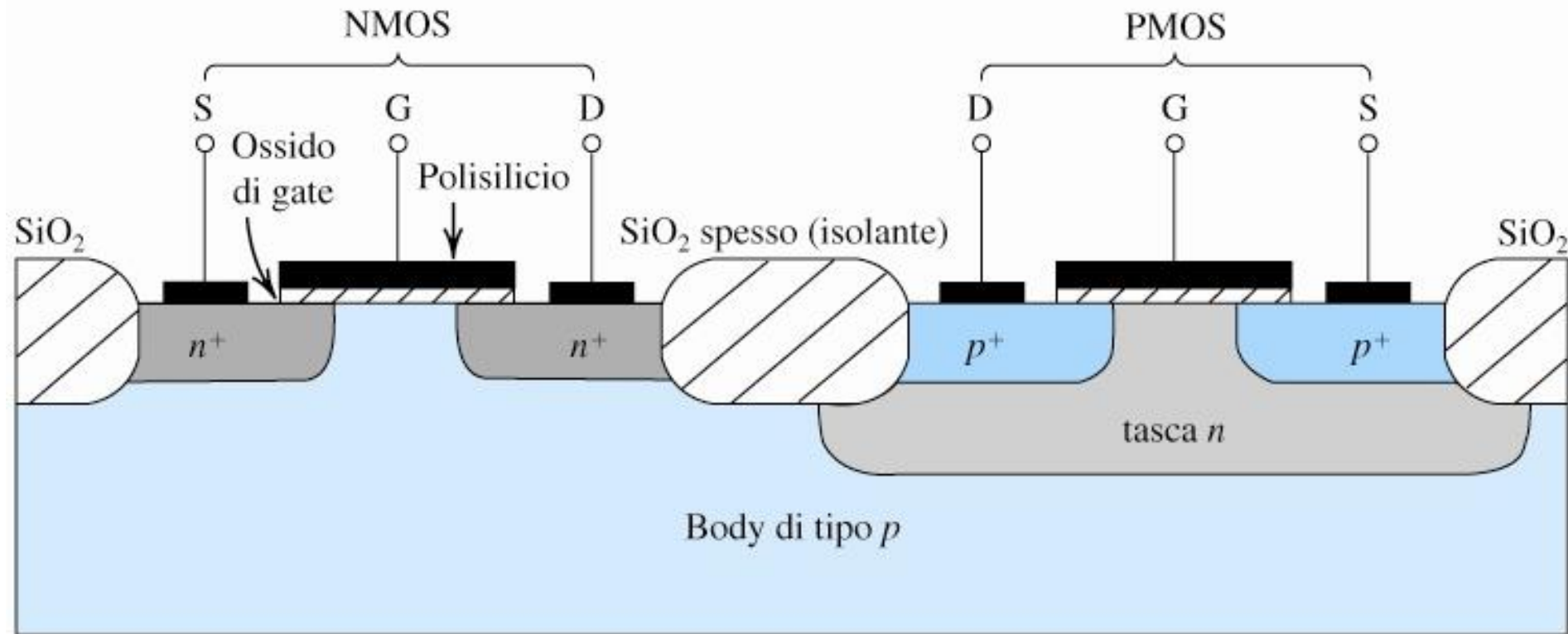
Livelli di tensione relativi dei terminali di un PMOS ad arricchimento nel funzionamento in regione di triodo e in regione di saturazione



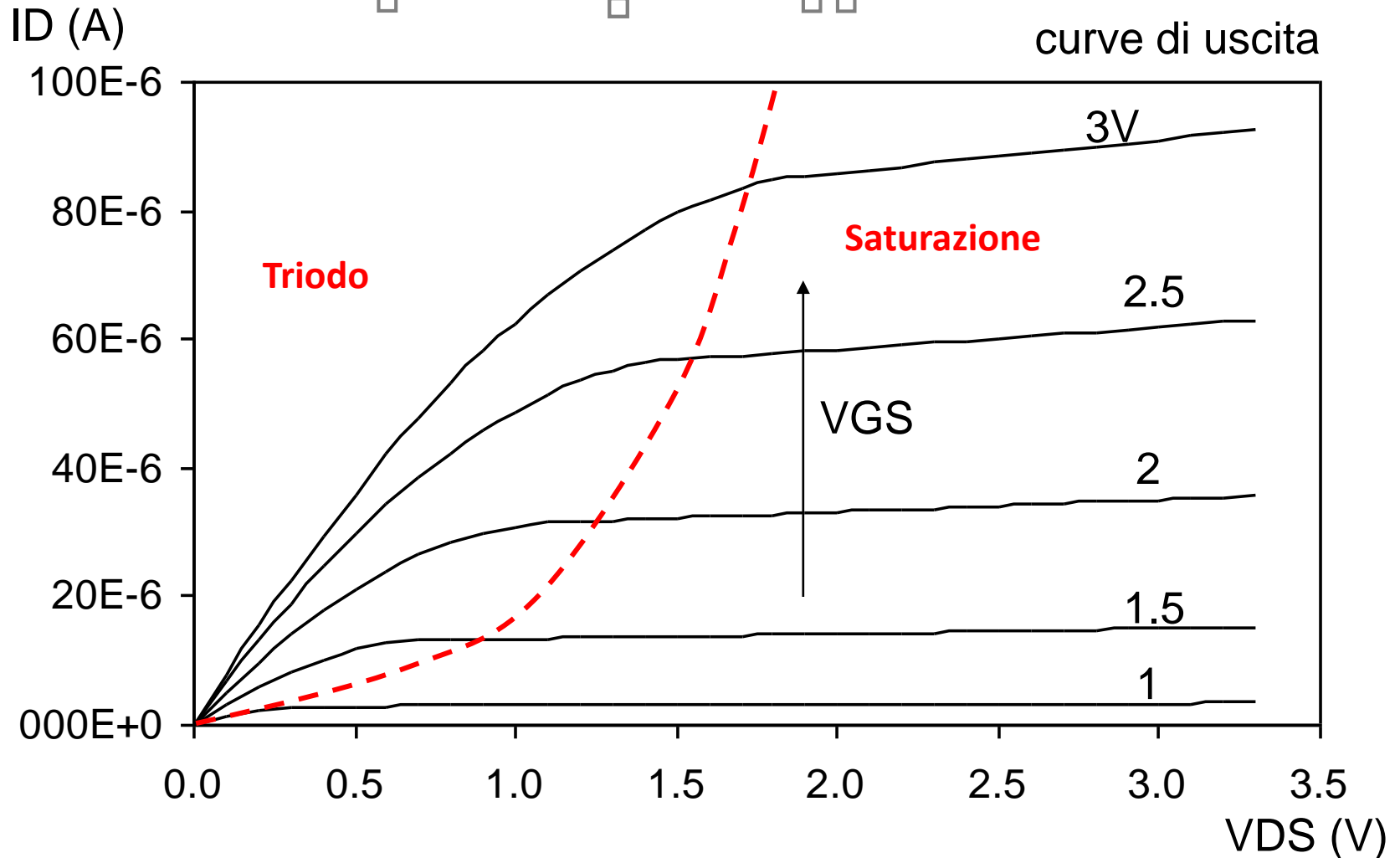
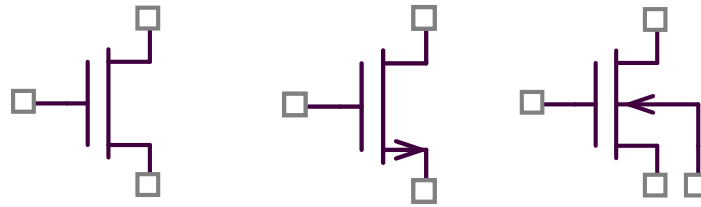
$I_D - V_{GS}$



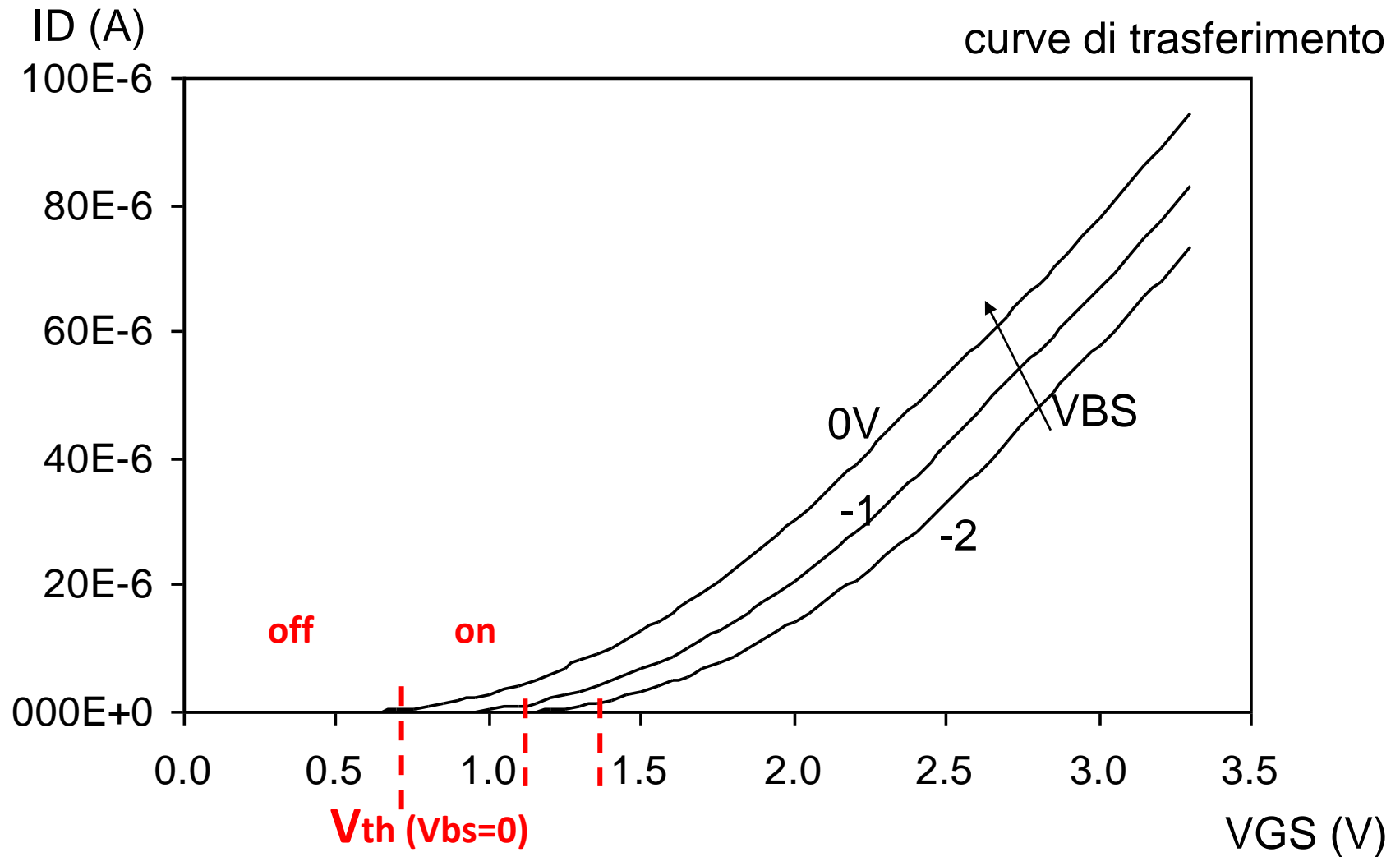
Realizzazione in tecnologia planare CMOS di un nMOSFET e di un pMOSFET



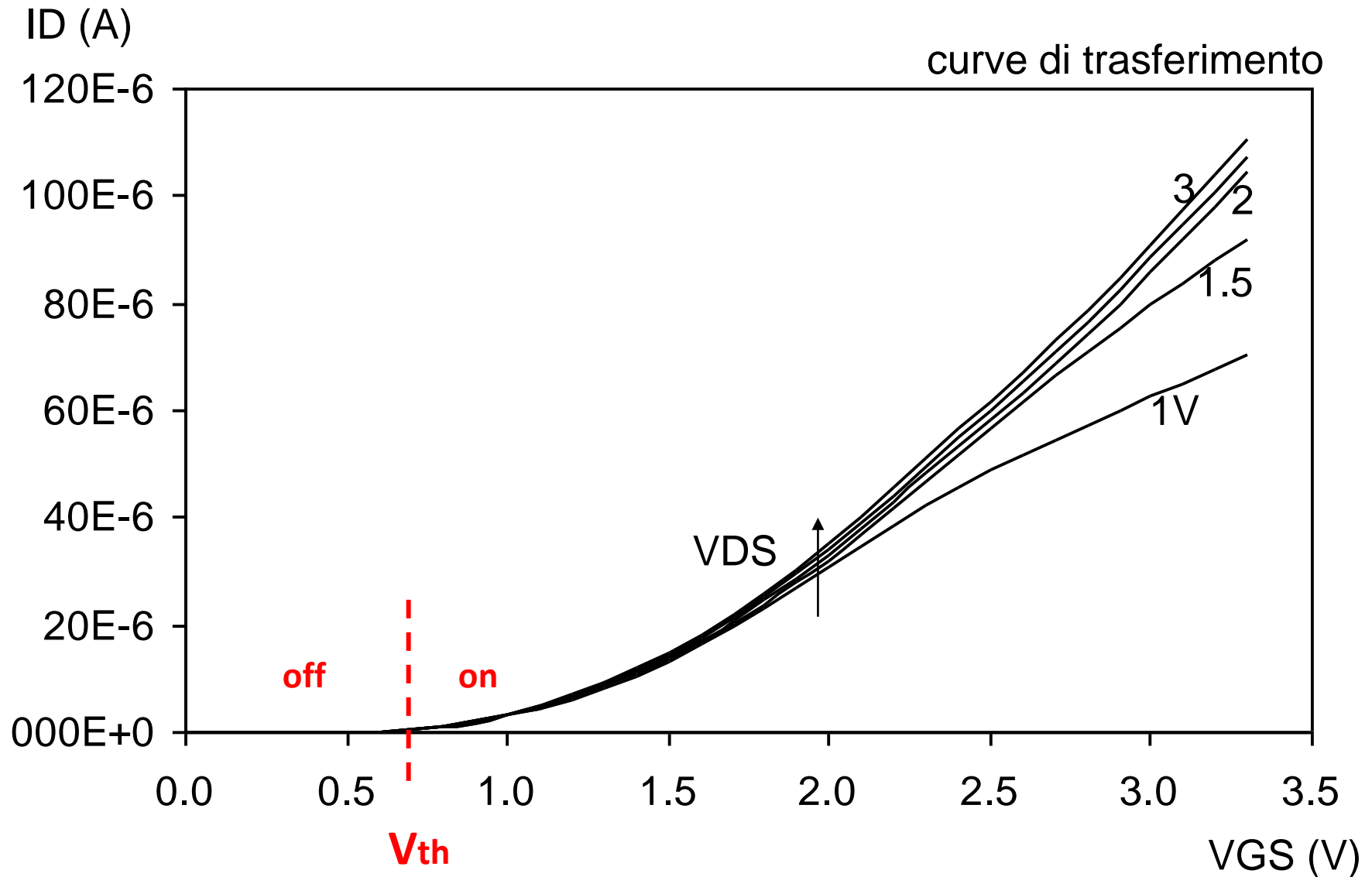
Riassumendo: nMOSFET



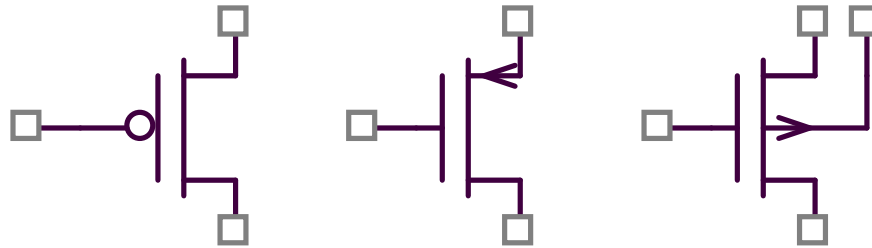
Riassumendo: nMOSFET



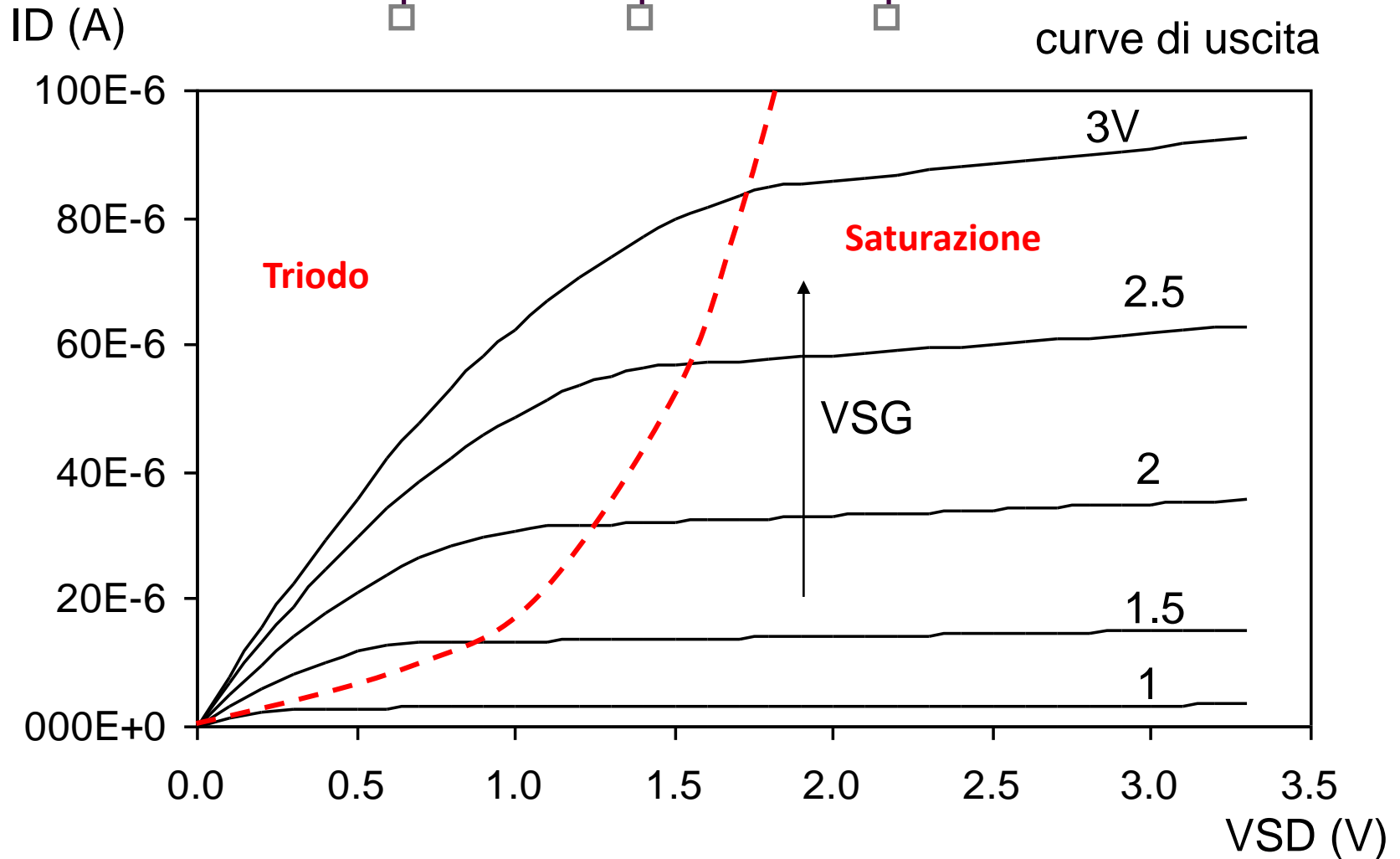
Riassumendo: nMOSFET



Riassumendo: pMOSFET



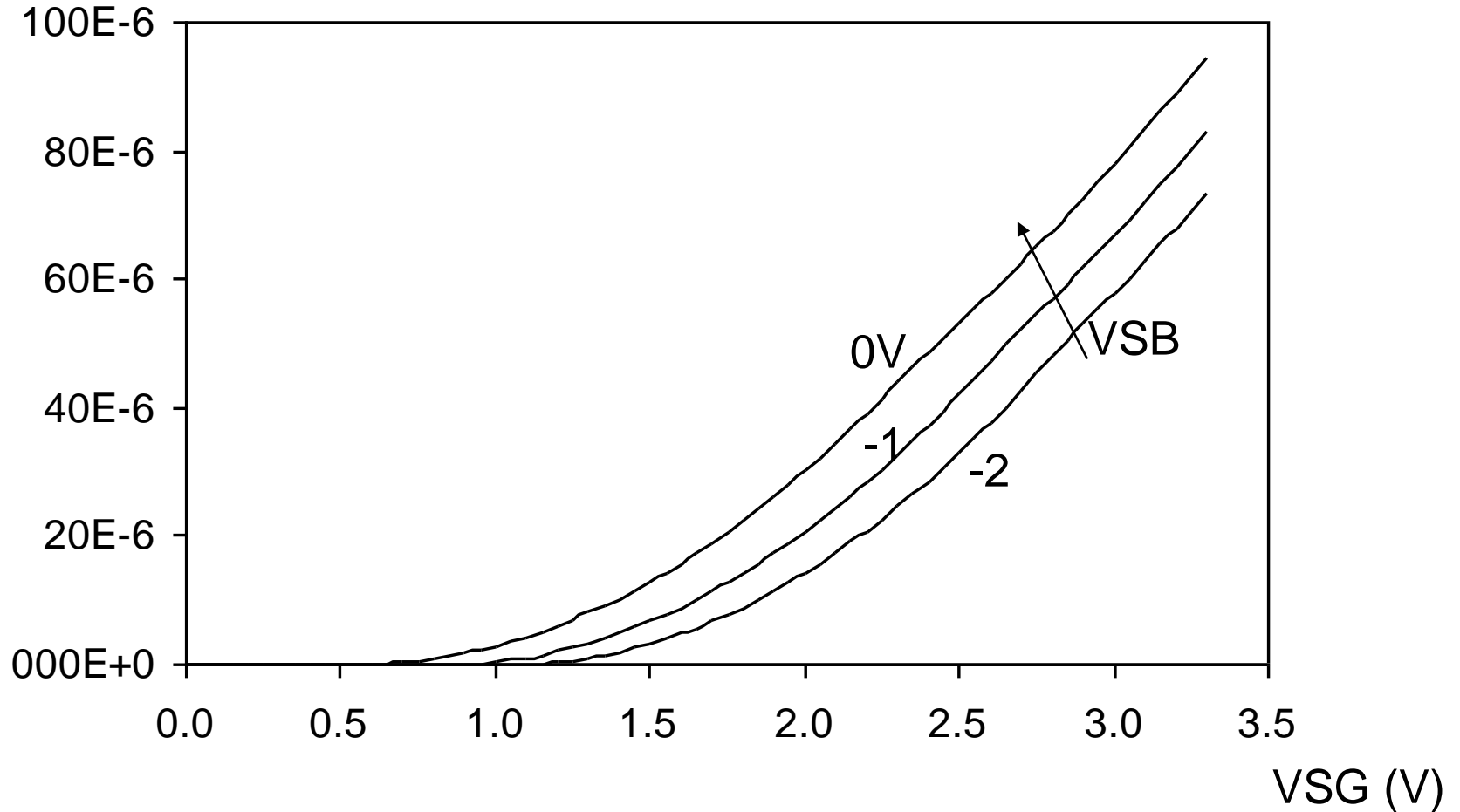
curve di uscita



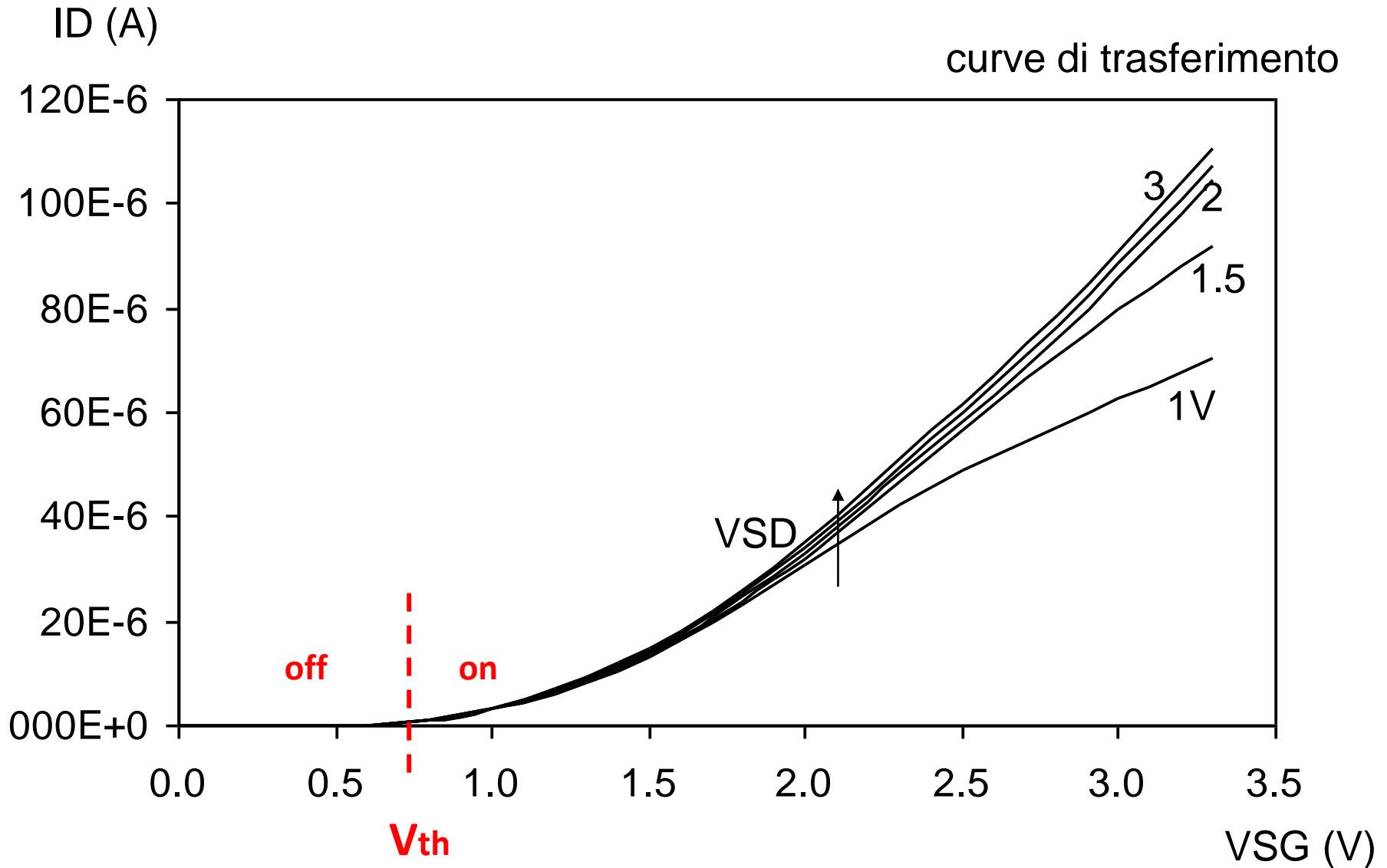
Riassumendo: pMOSFET

I_D (A)

curve di trasferimento



Riassumendo: pMOSFET



MOSFET: Equazioni per Piccoli Segnali

$$\begin{aligned}
 i_D &= i_D(v_{GS}, v_{DS}, v_{BS}) = \\
 &= i_D(v_{GS}, v_{DS}, v_{BS})|_Q + \left. \frac{\partial i_D}{\partial v_{GS}} \right|_Q \Delta v_{GS} + \left. \frac{\partial i_D}{\partial v_{DS}} \right|_Q \Delta v_{DS} + \left. \frac{\partial i_D}{\partial v_{BS}} \right|_Q \Delta v_{BS} \\
 &= i_D \Big|_{\substack{V_{GS} \\ V_{DS} \\ V_{BS}}} + \left. \frac{\partial i_D}{\partial v_{GS}} \right|_{\substack{V_{GS} \\ V_{DS} \\ V_{BS}}} (v_{GS} - V_{GS}) + \left. \frac{\partial i_D}{\partial v_{DS}} \right|_{\substack{V_{GS} \\ V_{DS} \\ V_{BS}}} (v_{DS} - V_{DS}) + \left. \frac{\partial i_D}{\partial v_{BS}} \right|_{\substack{V_{GS} \\ V_{DS} \\ V_{BS}}} (v_{BS} - V_{BS}) \\
 &= I_D + \left. \frac{\partial i_D}{\partial v_{GS}} \right|_{\substack{V_{GS} \\ V_{DS} \\ V_{BS}}} v_{gs} + \left. \frac{\partial i_D}{\partial v_{DS}} \right|_{\substack{V_{GS} \\ V_{DS} \\ V_{BS}}} v_{ds} + \left. \frac{\partial i_D}{\partial v_{BS}} \right|_{\substack{V_{GS} \\ V_{DS} \\ V_{BS}}} v_{bs} \quad i_G = 0 \quad i_B = 0
 \end{aligned}$$

$$i_d = g_m v_{gs} + g_o v_{ds} + g_{mb} v_{bs} \quad i_g = 0 \quad i_b = 0$$

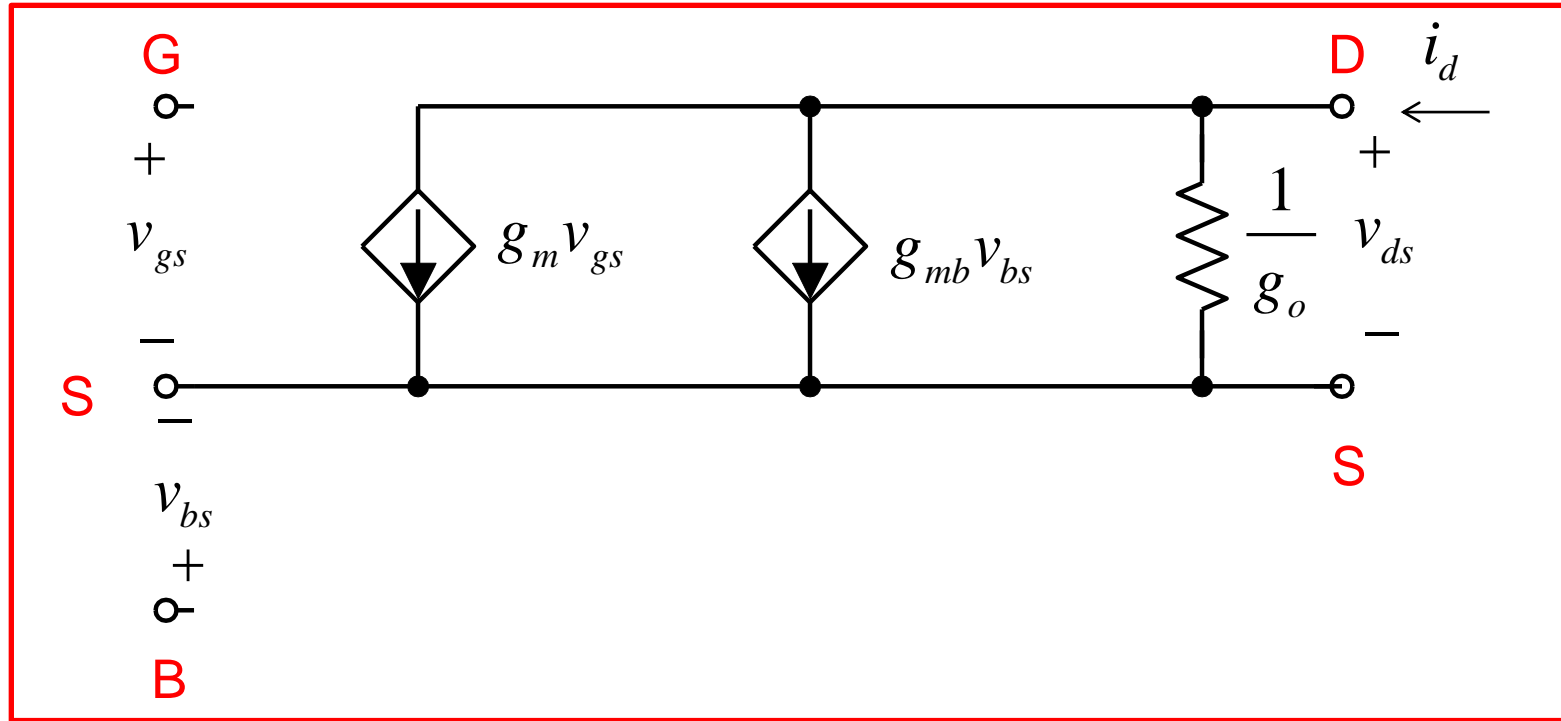
$$g_m = \left. \frac{\partial i_D}{\partial v_{GS}} \right|_{V_{GS}, V_{DS}, V_{BS}}$$

$$g_o = \left. \frac{\partial i_D}{\partial v_{DS}} \right|_{V_{GS}, V_{DS}, V_{BS}}$$

$$g_{mb} = \left. \frac{\partial i_D}{\partial v_{BS}} \right|_{V_{GS}, V_{DS}, V_{BS}}$$

nMOSFET: Circuito per Piccoli Segnali

Circuito equivalente alle variazioni del MOSFET a canale n



$$\begin{cases} i_g = 0 \\ i_b = 0 \\ i_d = g_m v_{gs} + g_o v_{ds} + g_{mb} v_{bs} \end{cases}$$

$$g_m = \left. \frac{\partial i_D}{\partial v_{GS}} \right|_{V_{GS}, V_{DS}, V_{BS}}$$

$$g_o = \left. \frac{\partial i_D}{\partial v_{DS}} \right|_{V_{GS}, V_{DS}, V_{BS}}$$

$$g_{mb} = \left. \frac{\partial i_D}{\partial v_{BS}} \right|_{V_{GS}, V_{DS}, V_{BS}}$$

Triodo

$$g_m = \beta V_{DS}$$

$$g_o = \beta (V_{GS} - V_{TH} - V_{DS})$$

$$g_{mb} = \frac{\partial i_D}{\partial V_{TH}} \frac{\partial V_{TH}}{\partial v_{BS}} = \beta V_{DS} \frac{\sqrt{2\varepsilon_s q N_A}}{C_{OX}} \left(\frac{1}{2\sqrt{2\phi_F - V_{BS}}} \right)$$

Interdizione

$$g_m = 0$$

$$g_o = 0$$

$$g_{mb} = 0$$

$$\lambda = 0$$

Saturazione

$$g_m = \beta (V_{GS} - V_{TH}) = \sqrt{2\beta I_D}$$

$$g_o = 0$$

$$g_{mb} = \frac{\partial i_D}{\partial V_{TH}} \frac{\partial V_{TH}}{\partial v_{BS}} = \beta (V_{GS} - V_{TH}) \frac{\sqrt{2\varepsilon_s q N_A}}{C_{OX}} \left(\frac{1}{2\sqrt{2\phi_F - V_{BS}}} \right)$$

nMOSFET: Parametri Differenziali

Triodo

$$g_m = \beta V_{DS}$$

$$g_o = \beta (V_{GS} - V_{TH} - V_{DS})$$

$$g_{mb} = \frac{\partial i_D}{\partial V_{TH}} \frac{\partial V_{TH}}{\partial v_{BS}} = \beta V_{DS} \frac{\sqrt{2\varepsilon_s q N_A}}{C_{OX}} \left(\frac{1}{2\sqrt{2\phi_F - V_{BS}}} \right)$$

Interdizione

$$g_m = 0$$

$$g_o = 0$$

$$g_{mb} = 0$$

$$\lambda \neq 0$$

Saturazione

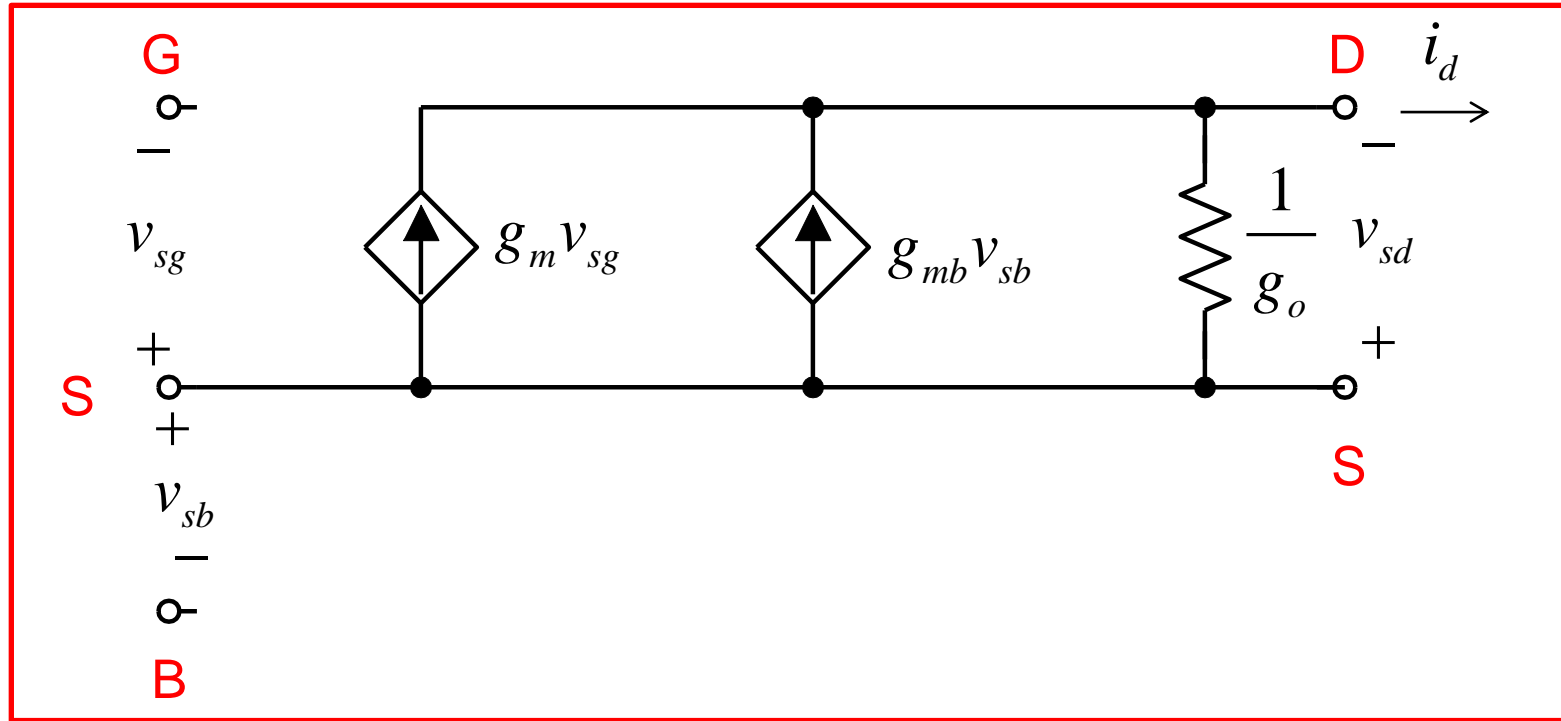
$$g_m = \beta (V_{GS} - V_{TH}) (1 + \lambda V_{DS}) = \sqrt{2\beta I_D / (1 + \lambda V_{DS})}$$

$$g_o = \lambda \frac{\beta}{2} (V_{GS} - V_{TH})^2 = I_D \frac{\lambda}{1 + \lambda V_{DS}} = \frac{I_D}{1 / \lambda + V_{DS}}$$

$$g_{mb} = \frac{\partial i_D}{\partial V_{TH}} \frac{\partial V_{TH}}{\partial v_{BS}} = \beta (V_{GS} - V_{TH}) (1 + \lambda V_{DS}) \frac{\sqrt{2\varepsilon_s q N_A}}{C_{OX}} \left(\frac{1}{2\sqrt{2\phi_F - V_{BS}}} \right)$$

pMOSFET: Circuito per Piccoli Segnali

Circuito equivalente alle variazioni del MOSFET a canale p



$$\begin{cases} i_g = 0 \\ i_b = 0 \\ i_d = g_m v_{sg} + g_o v_{sd} + g_{mb} v_{sb} \end{cases}$$

$$g_m = \left. \frac{\partial i_D}{\partial v_{SG}} \right|_{V_{SG}, V_{SD}, V_{SB}} \quad g_o = \left. \frac{\partial i_D}{\partial v_{SD}} \right|_{V_{SG}, V_{SD}, V_{SB}} \quad g_{mb} = \left. \frac{\partial i_D}{\partial v_{SB}} \right|_{V_{SG}, V_{SD}, V_{SB}}$$

pMOSFET: Parametri Differenziali

Triodo

$$g_m = \beta V_{SD}$$

$$g_o = \beta (V_{SG} + V_{TH} - V_{SD})$$

$$g_{mb} = \frac{\partial i_D}{\partial V_{TH}} \frac{\partial V_{TH}}{\partial v_{SB}} = \beta V_{SD} \frac{\sqrt{2\varepsilon_s q N_D}}{C_{OX}} \left(\frac{1}{2\sqrt{2\phi_F - V_{SB}}} \right)$$

Interdizione

$$g_m = 0$$

$$g_o = 0$$

$$g_{mb} = 0$$

$$\lambda = 0$$

Saturazione

$$g_m = \beta (V_{SG} + V_{TH}) = \sqrt{2\beta I_D}$$

$$g_o = 0$$

$$g_{mb} = \frac{\partial i_D}{\partial V_{TH}} \frac{\partial V_{TH}}{\partial v_{SB}} = \beta (V_{SG} + V_{TH}) \frac{\sqrt{2\varepsilon_s q N_D}}{C_{OX}} \left(\frac{1}{2\sqrt{2\phi_F - V_{SB}}} \right)$$

Triodo

$$g_m = \beta V_{SD}$$

$$g_o = \beta (V_{SG} + V_{TH} - V_{SD})$$

$$g_{mb} = \frac{\partial i_D}{\partial V_{TH}} \frac{\partial V_{TH}}{\partial v_{SB}} = \beta V_{SD} \frac{\sqrt{2\varepsilon_s q N_D}}{C_{OX}} \left(\frac{1}{2\sqrt{2\phi_F - V_{SB}}} \right)$$

Interdizione

$$g_m = 0$$

$$g_o = 0$$

$$g_{mb} = 0$$

$$\lambda \neq 0$$

Saturazione

$$g_m = \beta (V_{SG} + V_{TH}) (1 + \lambda V_{SD}) = \sqrt{2\beta I_D / (1 + \lambda V_{SD})}$$

$$g_o = I_D \frac{\lambda}{1 + \lambda V_{SD}} = \frac{I_D}{1 / \lambda + V_{SD}}$$

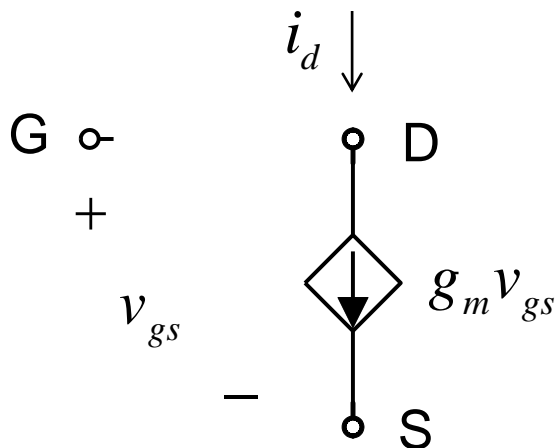
$$g_{mb} = \frac{\partial i_D}{\partial V_{TH}} \frac{\partial V_{TH}}{\partial v_{SB}} = \beta (V_{SG} + V_{TH}) (1 + \lambda V_{SD}) \frac{\sqrt{2\varepsilon_s q N_D}}{C_{OX}} \left(\frac{1}{2\sqrt{2\phi_F - V_{SB}}} \right)$$

nMOSFET: Circuito per Piccoli Segnali (Casi Particolari)

- Esempio: NMOSFET a tre terminali (B=S) in saturazione

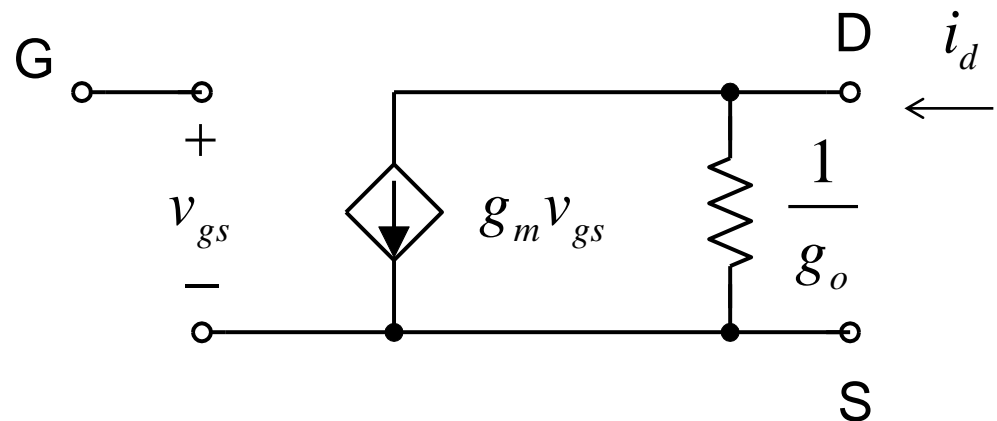
senza l'effetto di modulazione di canale

$$\lambda = 0$$



con l'effetto di modulazione di canale

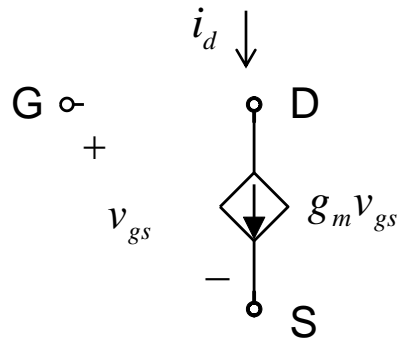
$$\lambda \neq 0$$



nMOSFET: Circuito per Piccoli Segnali (Casi Particolari)

- Esempio: NMOSFET a tre terminali (B=S) senza effetto di modulazione di canale ($\lambda = 0$)

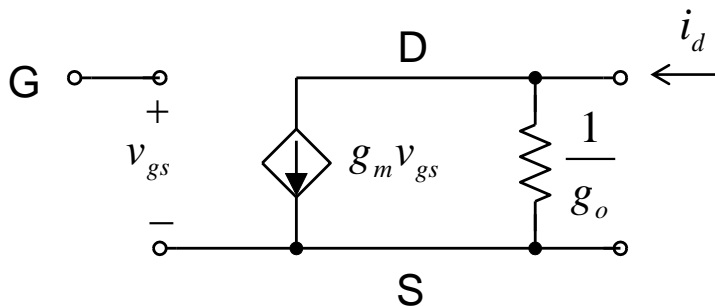
$$g_{mb} = 0$$



Saturazione

$$g_m = \beta (V_{GS} - V_{TH}) = \sqrt{2\beta I_D}$$

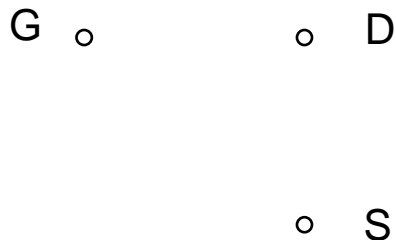
$$g_o = 0$$



Triodo

$$g_m = \beta V_{DS}$$

$$g_o = \beta (V_{GS} - V_{TH} - V_{DS})$$



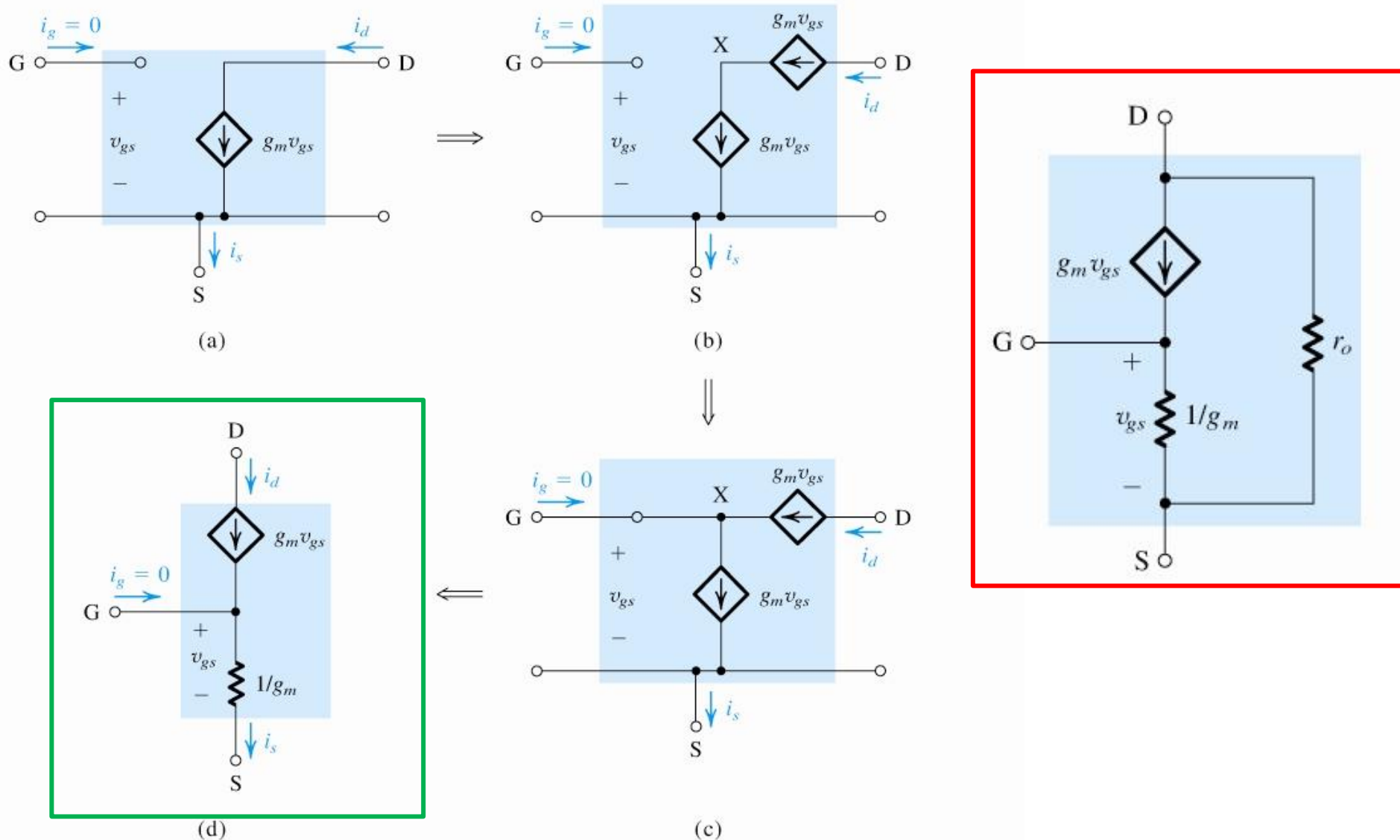
Interdizione

$$g_m = 0$$

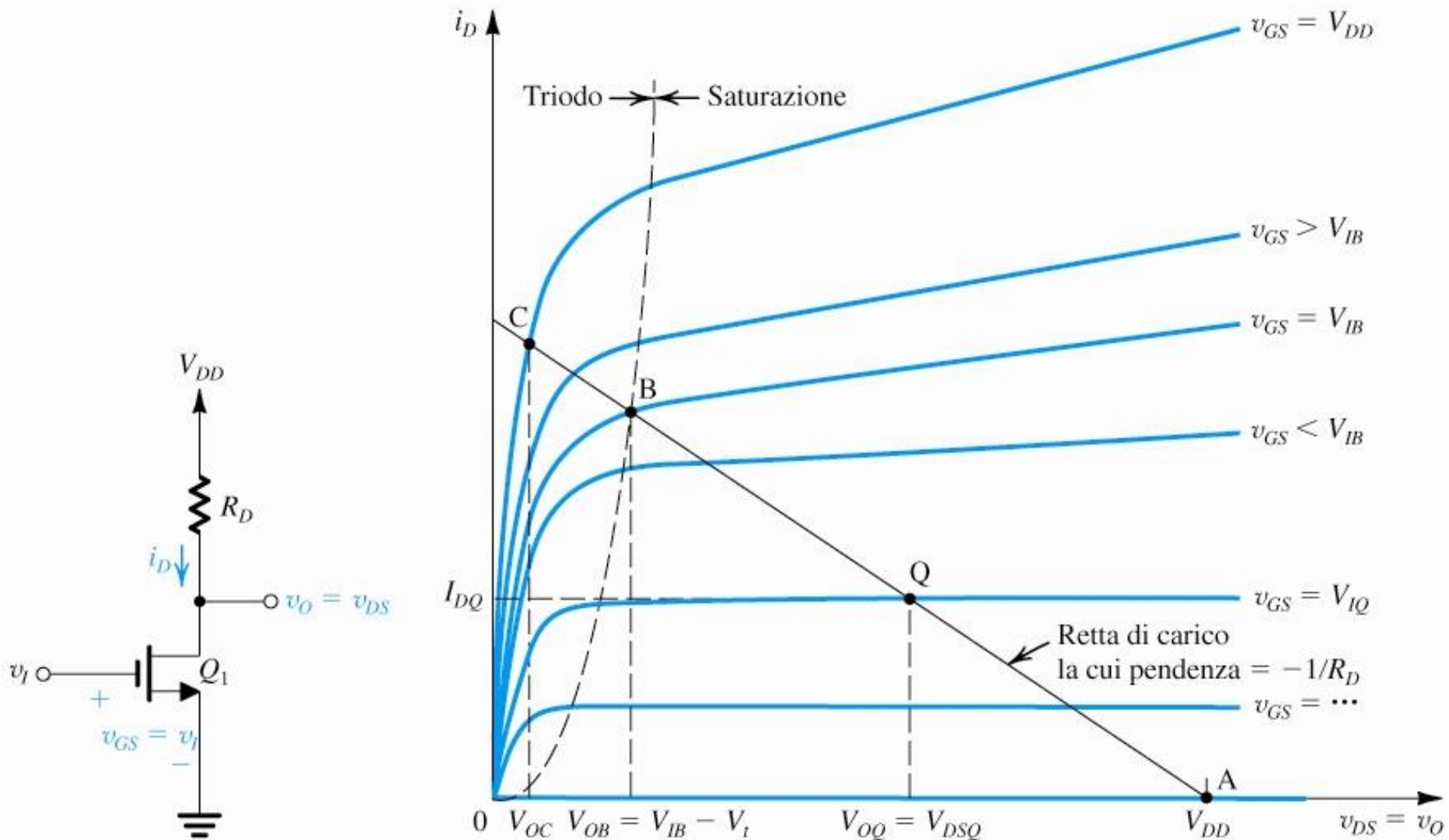
$$g_o = 0$$

nMOSFET: Circuito per Piccoli Segnali Modello a T

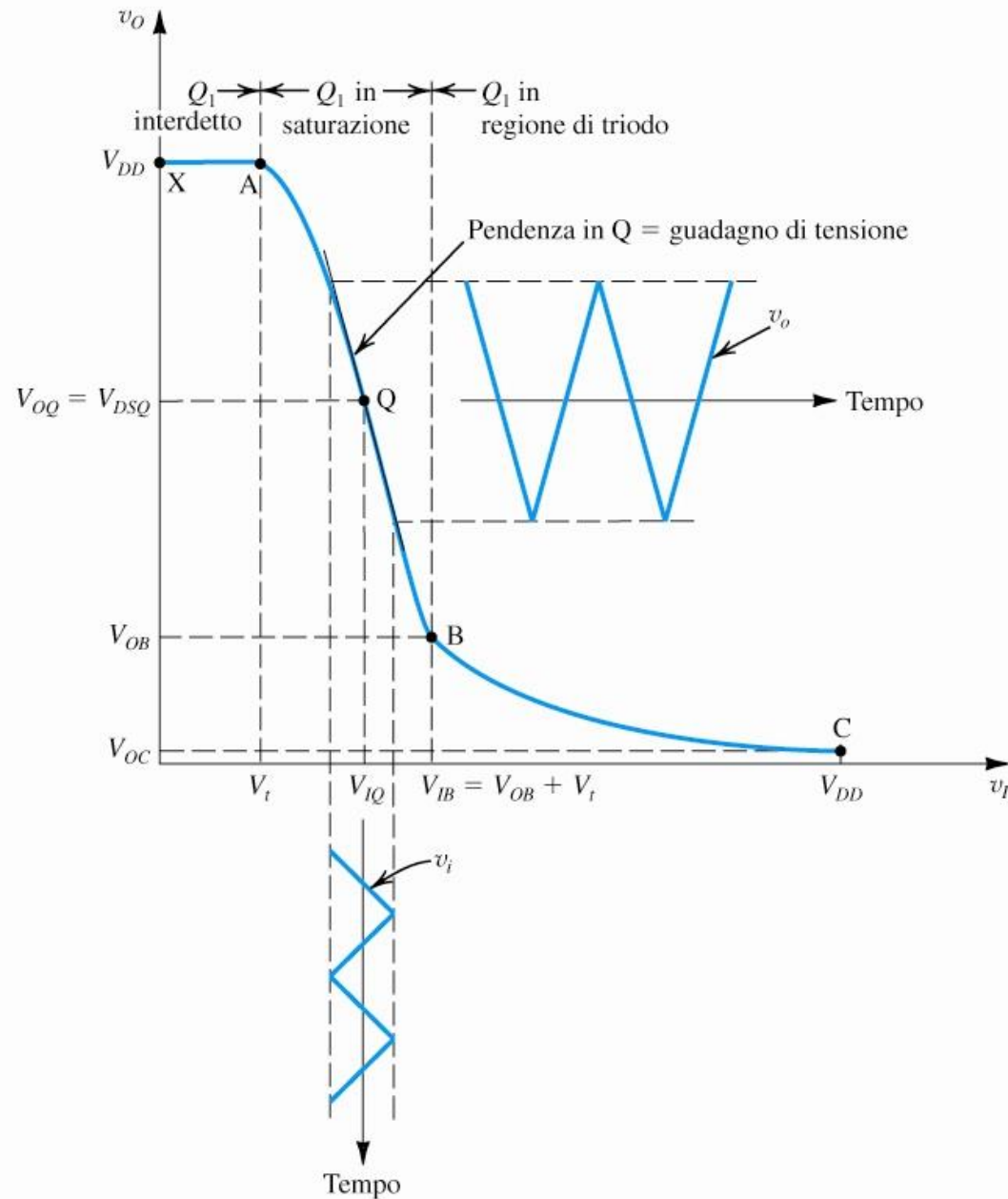
Modello a T: nMOSFET in saturazione (senza e con r_o)



Il MOSFET come Amplificatore



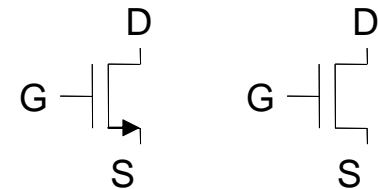
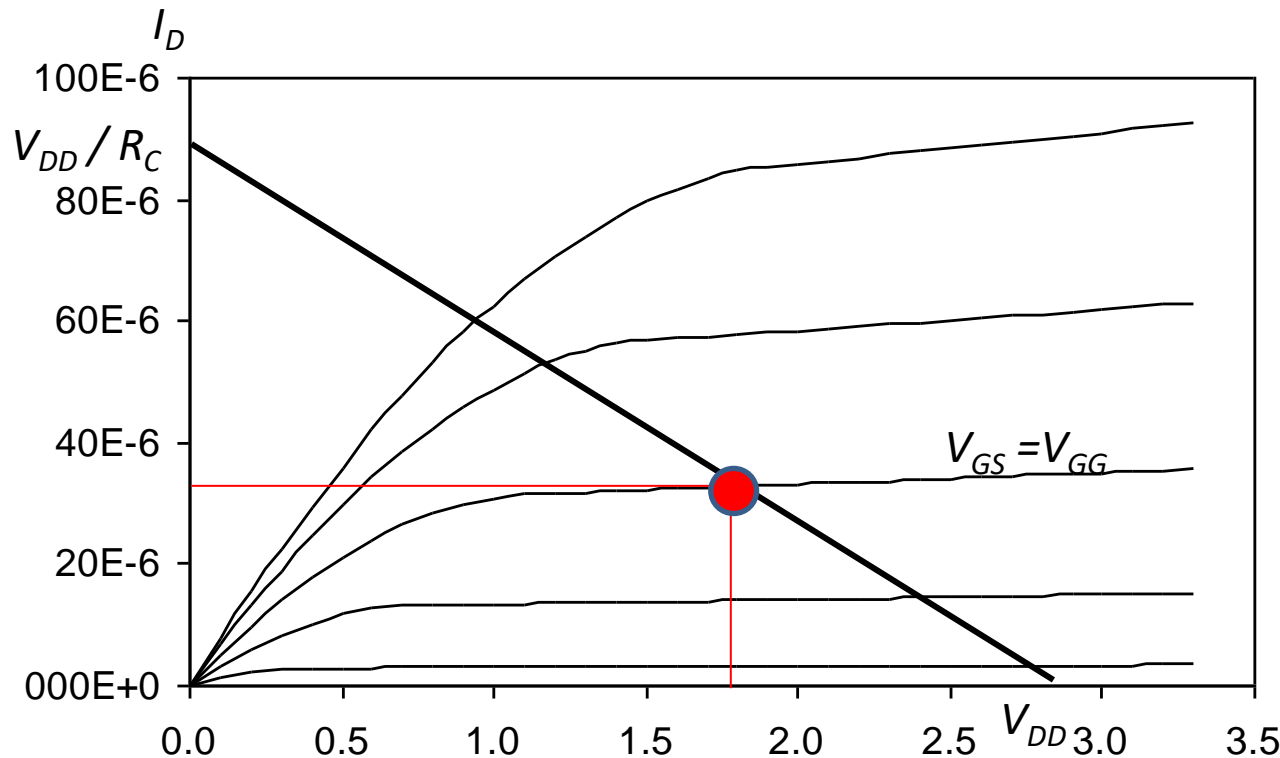
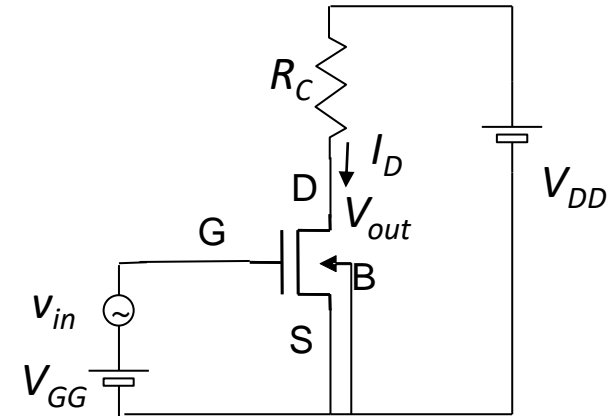
Il MOSFET come Amplificatore



Esempio di Soluzione Grafica di Circuito con MOSFET

Circuito in DC (determinazione del punto di lavoro)

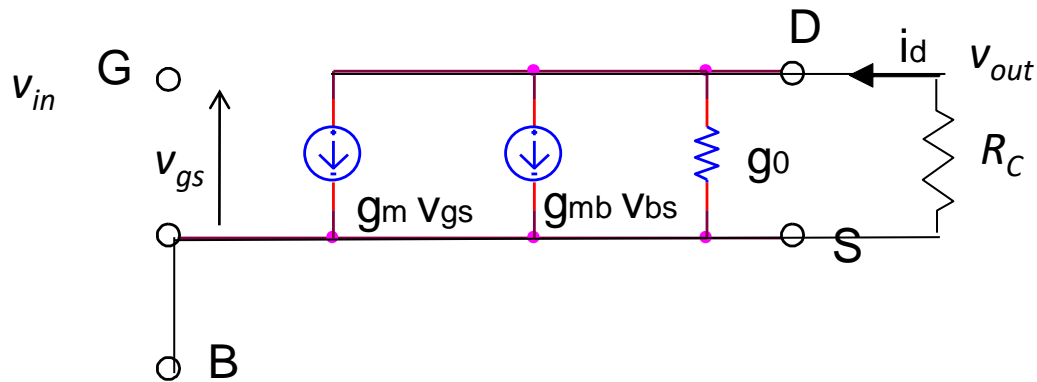
$$\frac{V_{DD} - V_{out}}{R_C} = I_D = f(V_{GS}, V_{out})$$



$$V_{DS} = V_{out}$$

Esempio di Soluzione Grafica di Circuito con MOSFET

Circuito equivalente alle variazioni



$$v_{out} = -g_m \frac{R_C 1/g_o}{R_C + 1/g_o} v_{in}$$

$$A_v = -g_m \frac{R_C 1/g_o}{R_C + 1/g_o}$$

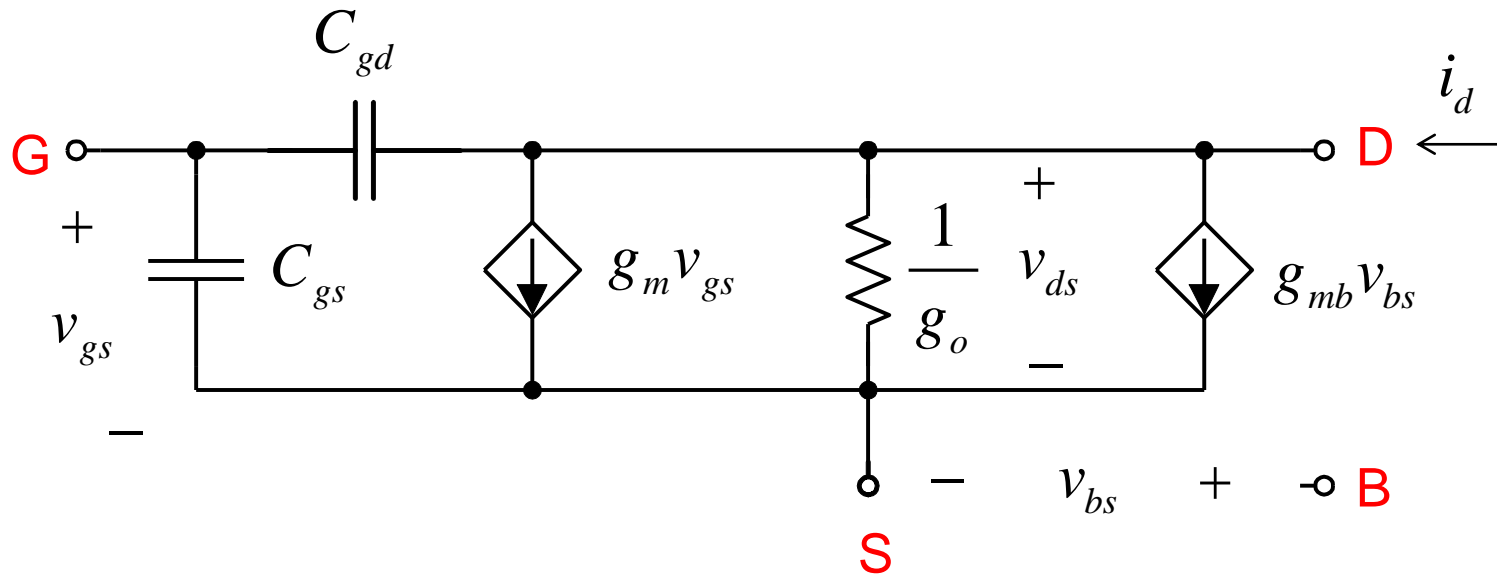
$$\text{se } g_o = 0$$

$$A_v = -g_m R_C$$

$$v_{bs} = 0$$

Circuito equivalente alle variazioni completo

Circuito equivalente alle variazioni (con capacità parassite)

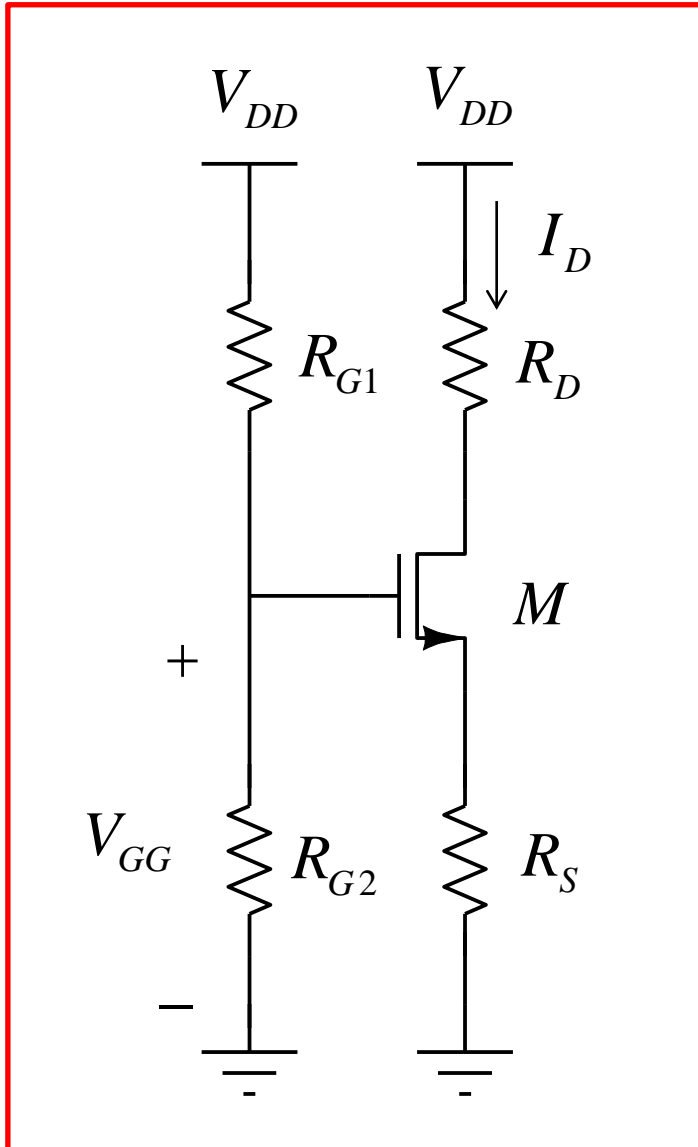


$$g_m = \left. \frac{\partial i_D}{\partial v_{GS}} \right|_{V_{GS}, V_{DS}, V_{BS}}$$

$$g_o = \left. \frac{\partial i_D}{\partial v_{DS}} \right|_{V_{GS}, V_{DS}, V_{BS}}$$

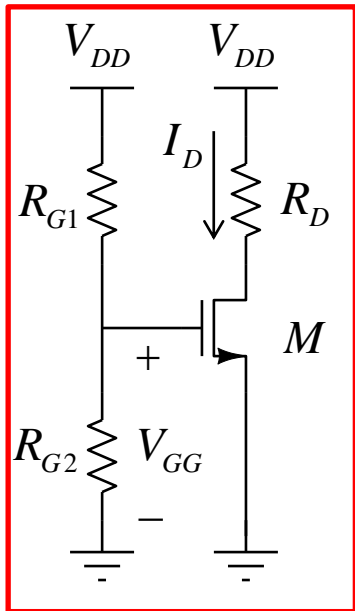
$$g_{mb} = \left. \frac{\partial i_D}{\partial v_{BS}} \right|_{V_{GS}, V_{DS}, V_{BS}}$$

Circuito a 4 resistenze



$$V_{GG} = \frac{R_{G2}}{R_{G1} + R_{G2}} V_{DD}$$

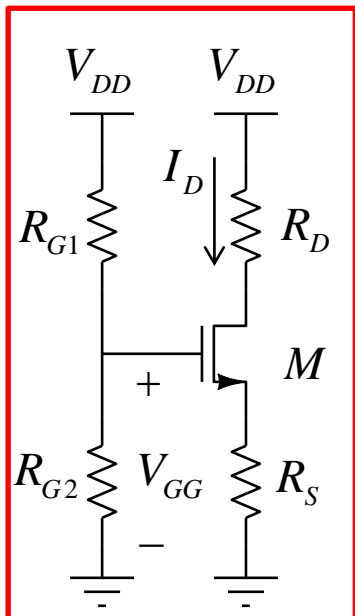
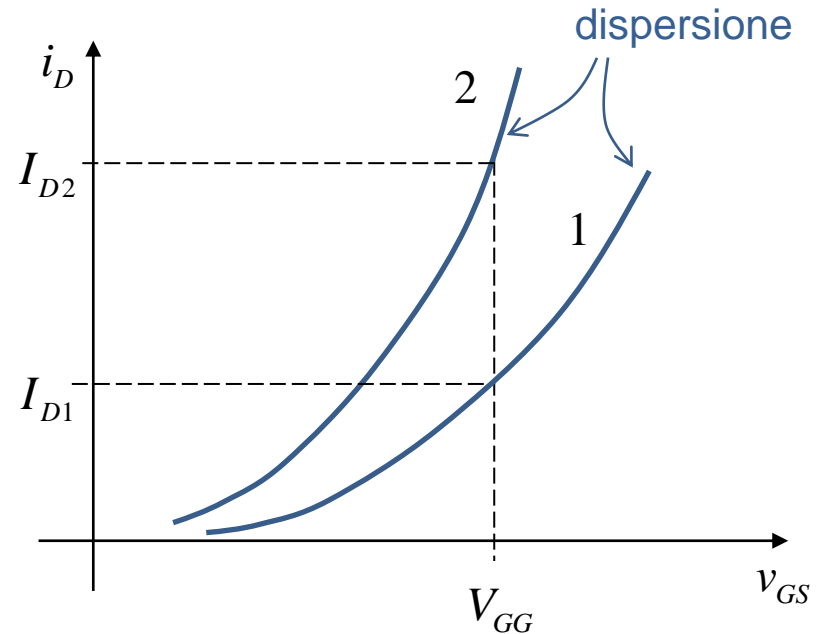
Polarizzazione nei Circuiti Discreti



Se $R_S = 0$

$$V_{GS} = V_{GG}$$

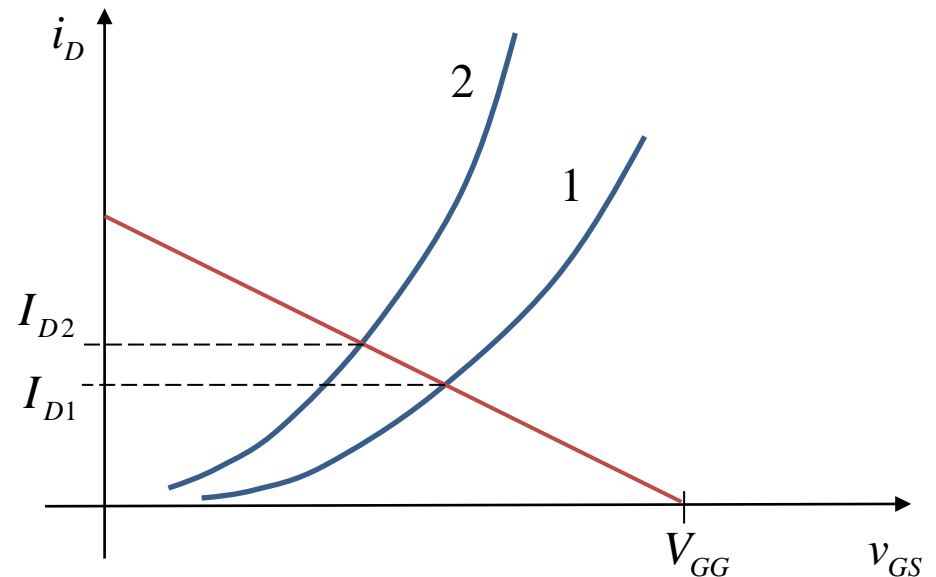
- Il punto di riposo può variare notevolmente a causa della dispersione delle caratteristiche



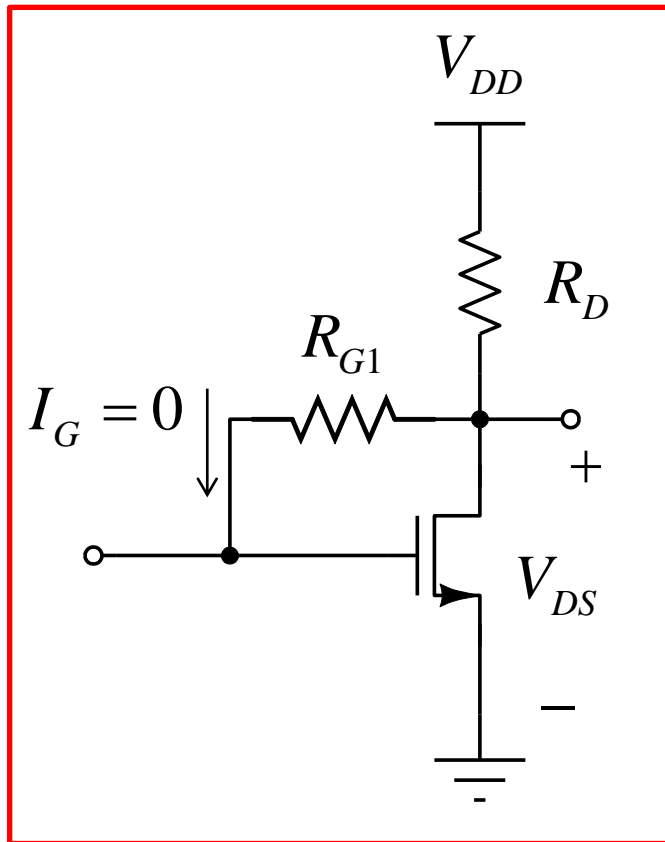
Se $R_S \neq 0$

$$V_{GG} = V_{GS} + R_S I_D$$

$$I_D = \frac{V_{GG}}{R_S} - \frac{1}{R_S} V_{GS}$$



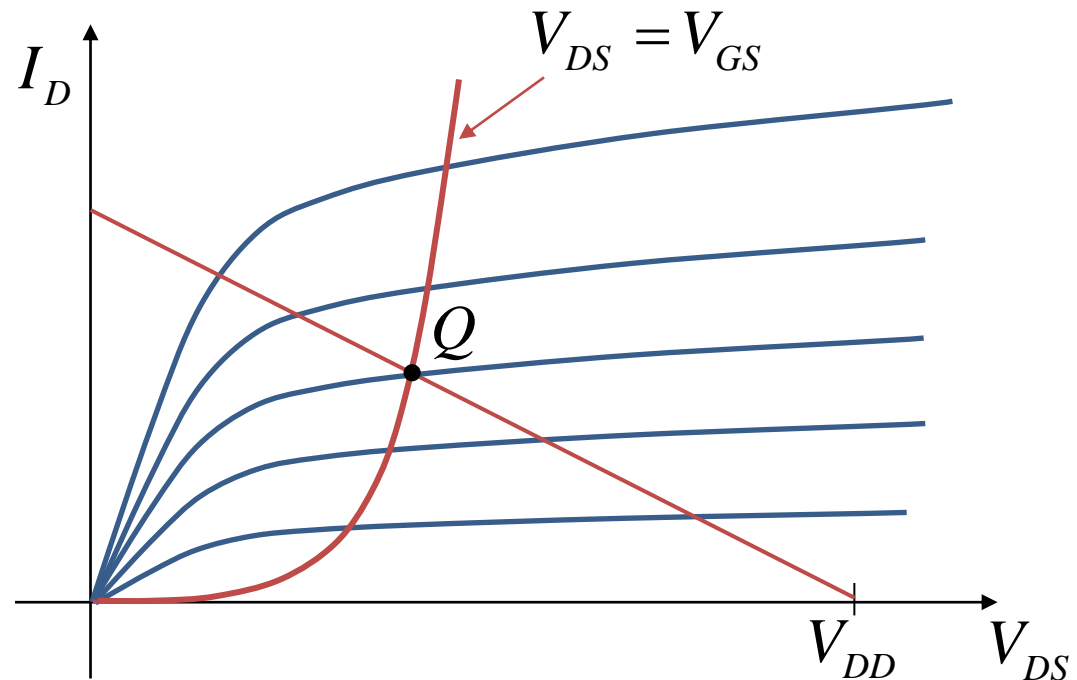
Circuito alternativo



Si ha: $V_{GS} = V_{DS} \quad (I_G = 0)$

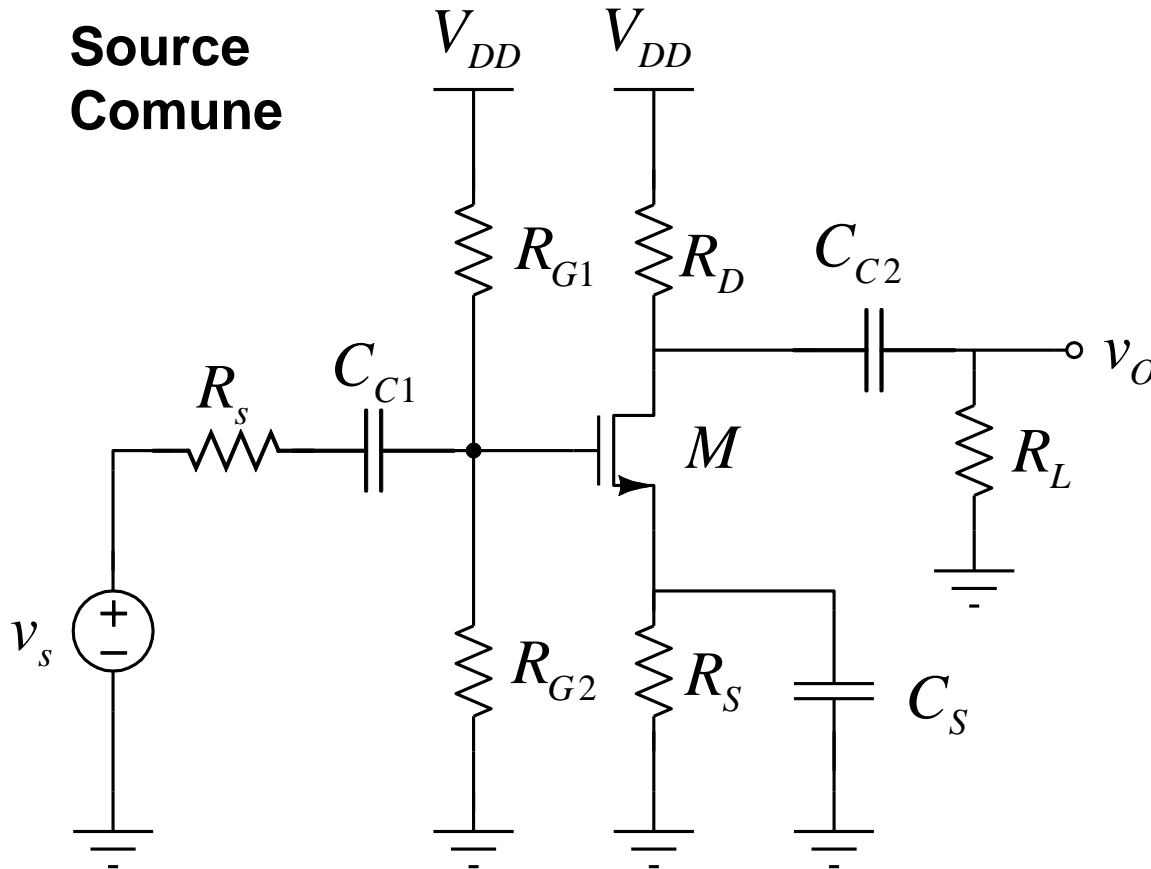
$$V_{GS} = V_{DD} - R_D I_D$$

$$I_D = \frac{V_{DD}}{R_D} - \frac{1}{R_D} V_{DS}$$



Amplificatori a Singolo Stadio: Source Comune (SC)

**Source
Comune**



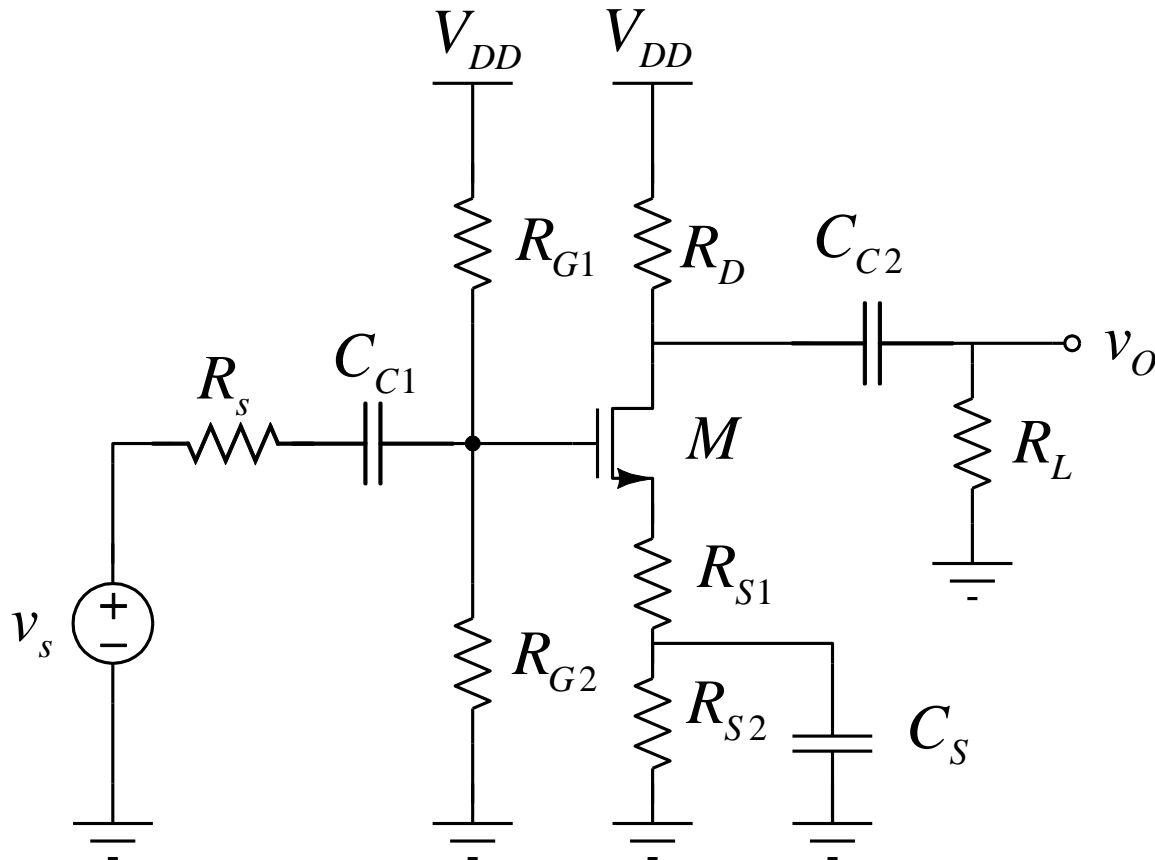
C_{C1} C_{C2} Capacità di disaccoppiamento: bloccano la componente continua cosicché il punto di lavoro non dipende dal generatore di segnale e dal carico

C_S Capacità di bypass: serve a cortocircuitare la R_S cosicché il guadagno risulta più elevato

C_{C1} C_{C2} C_S devono essere sufficientemente elevate cosicché possono essere considerate dei cortocircuiti alle frequenze di interesse (medie frequenze)

Amplificatori a Singolo Stadio: Source Comune (SC) con R_s

Source Comune (SC) con resistenza di source non cortocircuitata

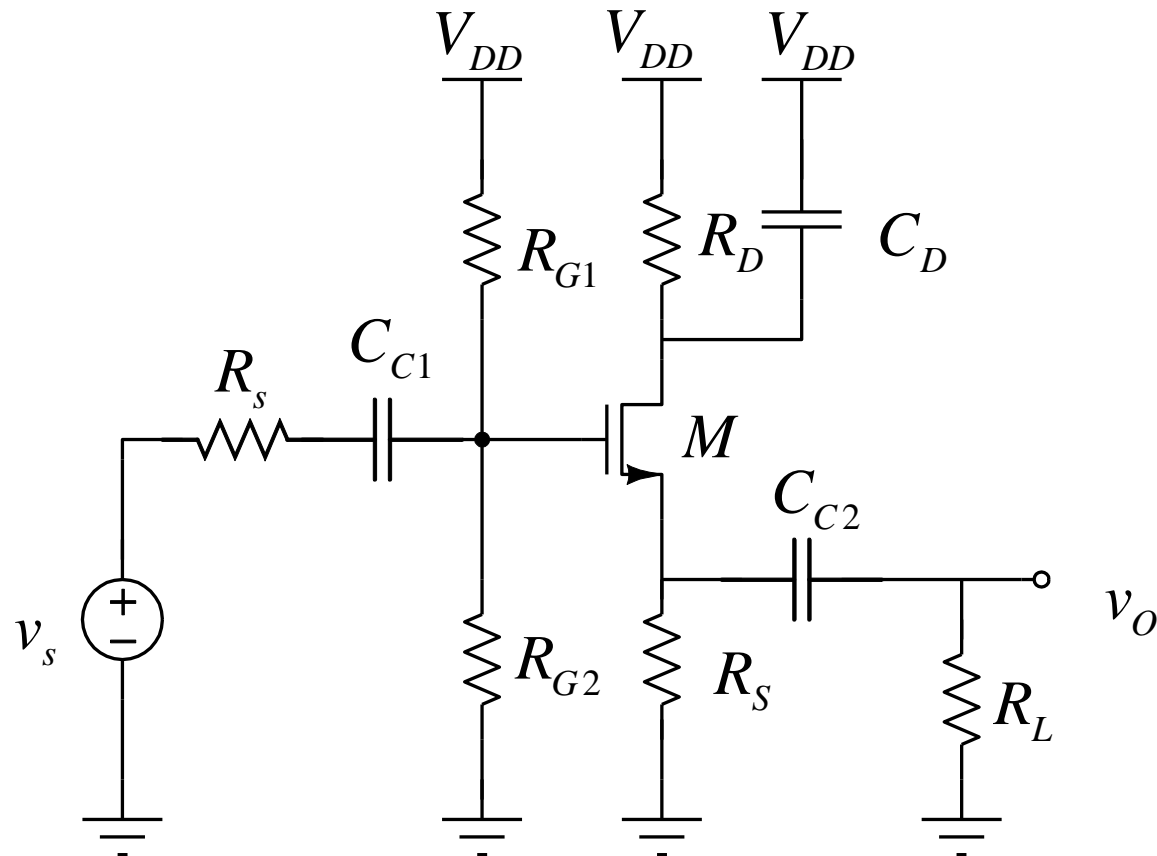


C_{C1} C_{C2} : capacità di disaccoppiamento

C_S : capacità di cortocircuito di R_{S2} al source

Amplificatori a Singolo Stadio: Drain Comune (DC) – Source Follower

Drain Comune (DC) – Source Follower

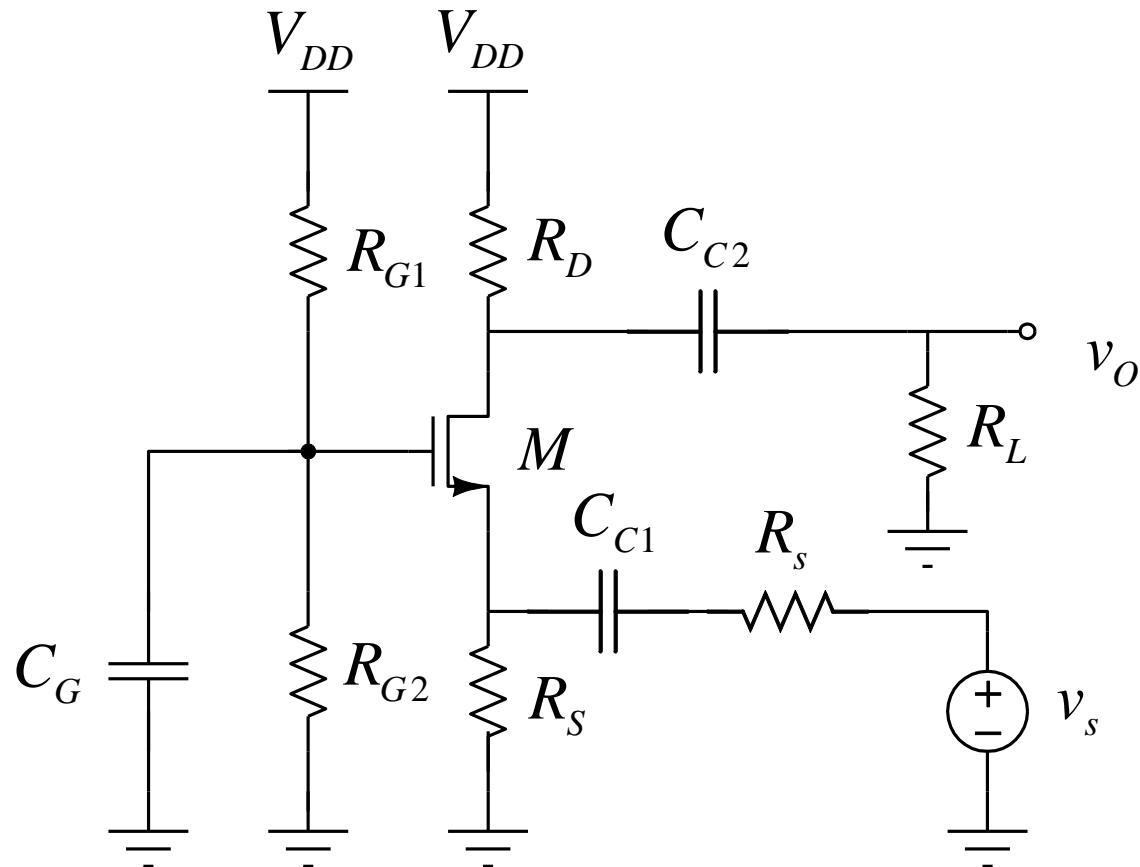


C_{C1} C_{C2} : capacità di disaccoppiamento

C_D : capacità di cortocircuito del drain

Amplificatori a Singolo Stadio: Gate Comune (GC)

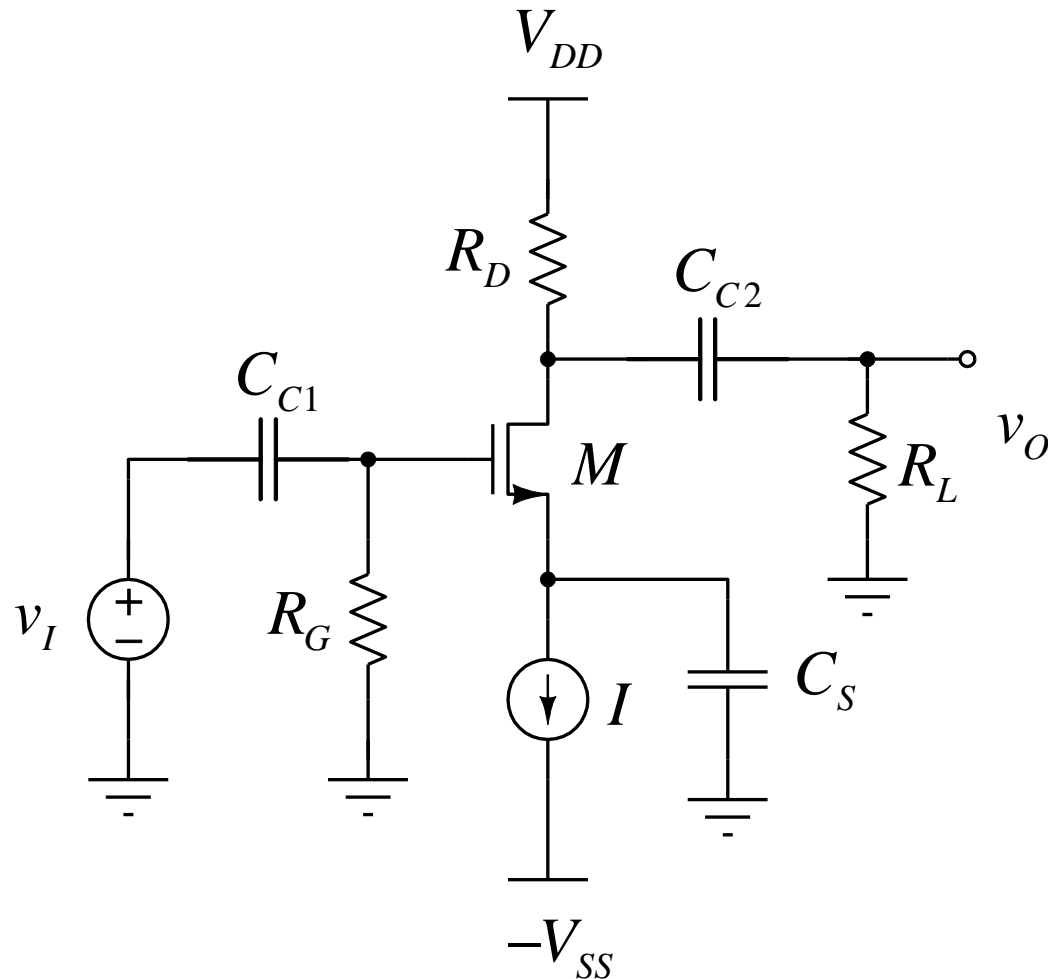
Gate Comune (GC)



C_{C1} C_{C2} : capacità di disaccoppiamento

C_G : capacità di cortocircuito del gate

Configurazione a Source Comune

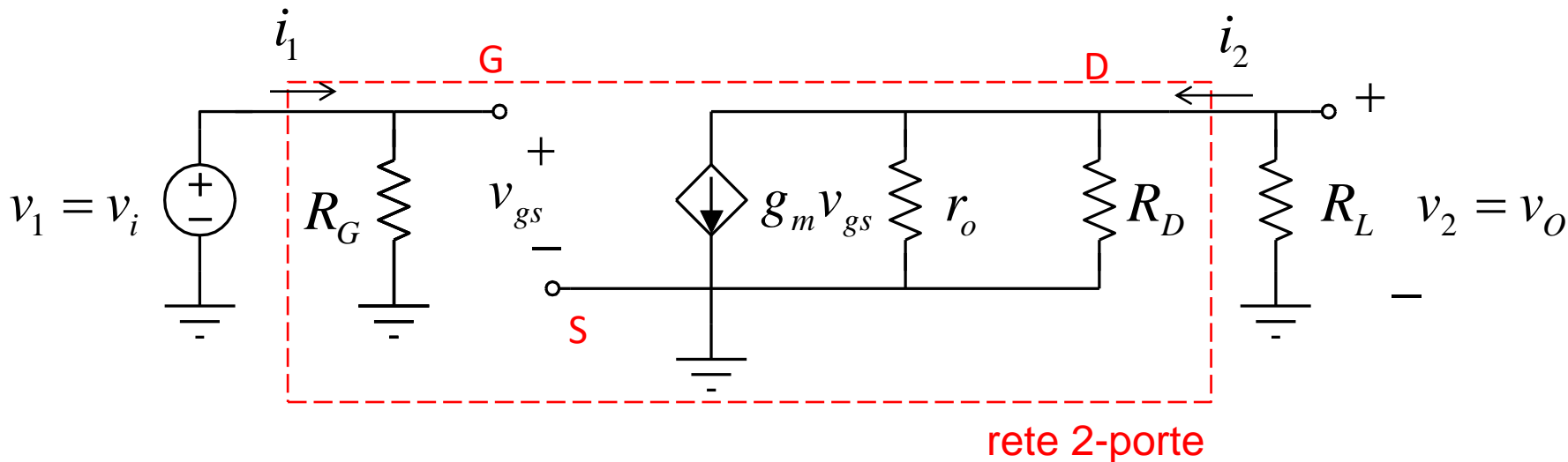


C_{C1} C_{C2} C_S devono essere sufficientemente elevate cosicché possono essere considerate dei cortocircuiti alle frequenze di interesse (medie frequenze)

La R_G evita che il gate sia flottante

Configurazione a Source Comune

Circuito equivalente alle variazioni



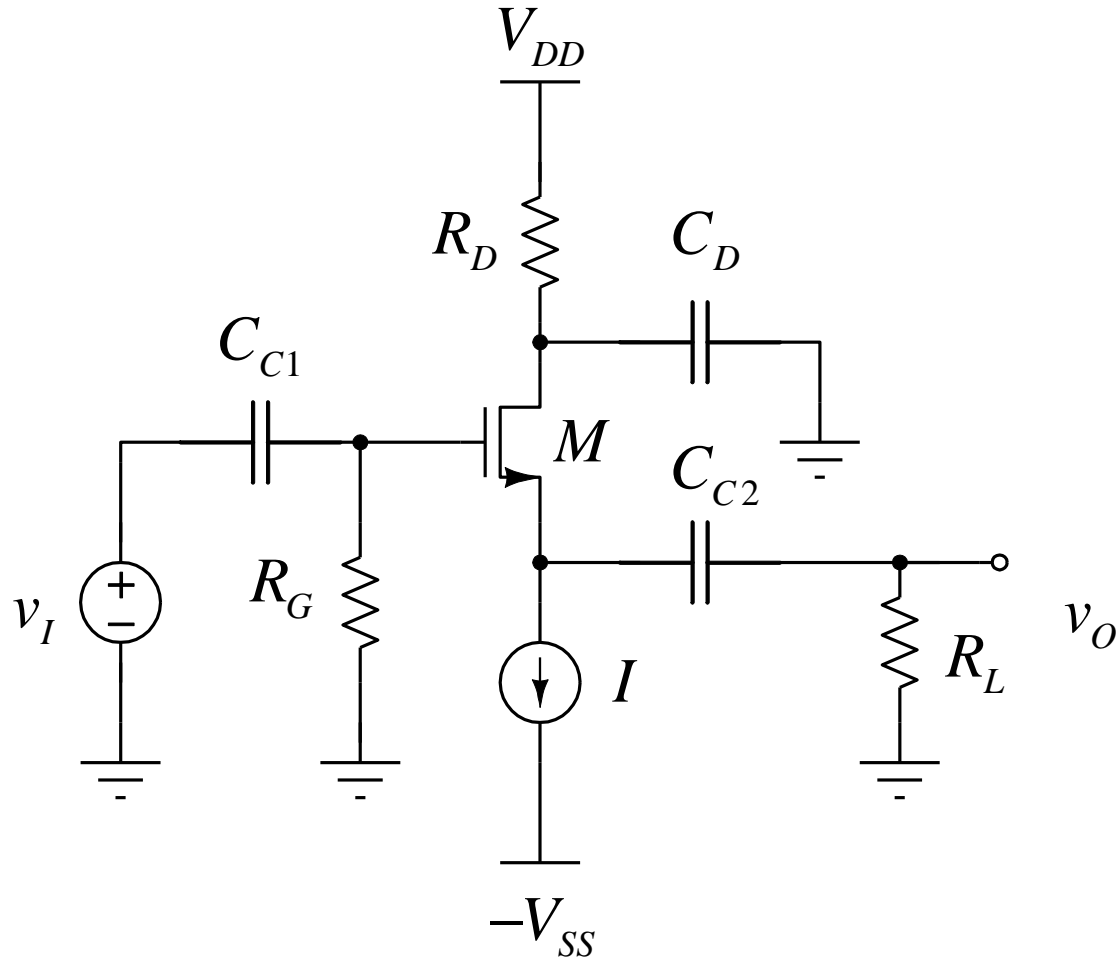
$$R_i = \frac{v_1}{i_1} = R_G$$

$$R_o' = \left. \frac{v_2}{i_2} \right|_{v_i=0} = r_o \parallel R_D$$

$$R_o = r_o \parallel R_D \parallel R_L$$

$$A_v = \frac{v_2}{v_1} = -g_m (r_o \parallel R_D \parallel R_L)$$

Configurazione a Drain Comune

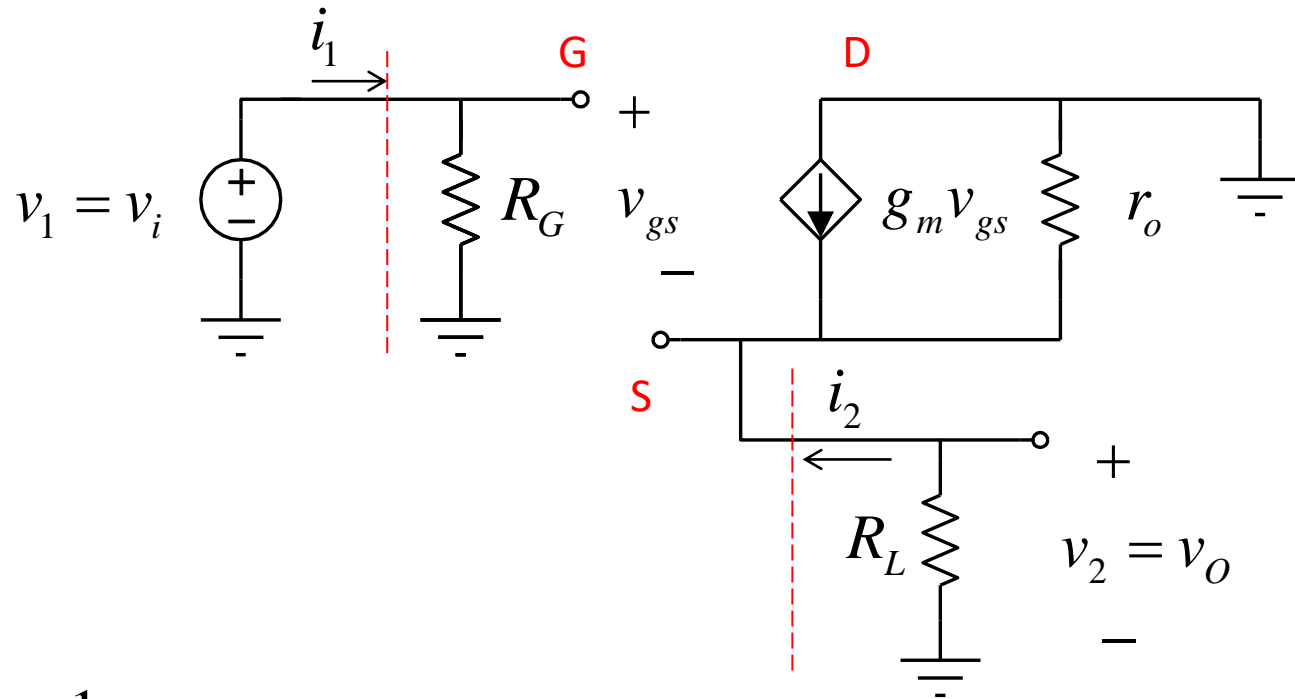


C_{C1} C_{C2} C_D devono essere sufficientemente elevate cosicché possono essere considerate dei cortocircuiti alle frequenze di interesse (medie frequenze)

La R_G evita che il gate sia flottante

Configurazione a Drain Comune

**Circuito equivalente
alle variazioni**



$$R_i = \frac{v_1}{i_1} = R_G$$

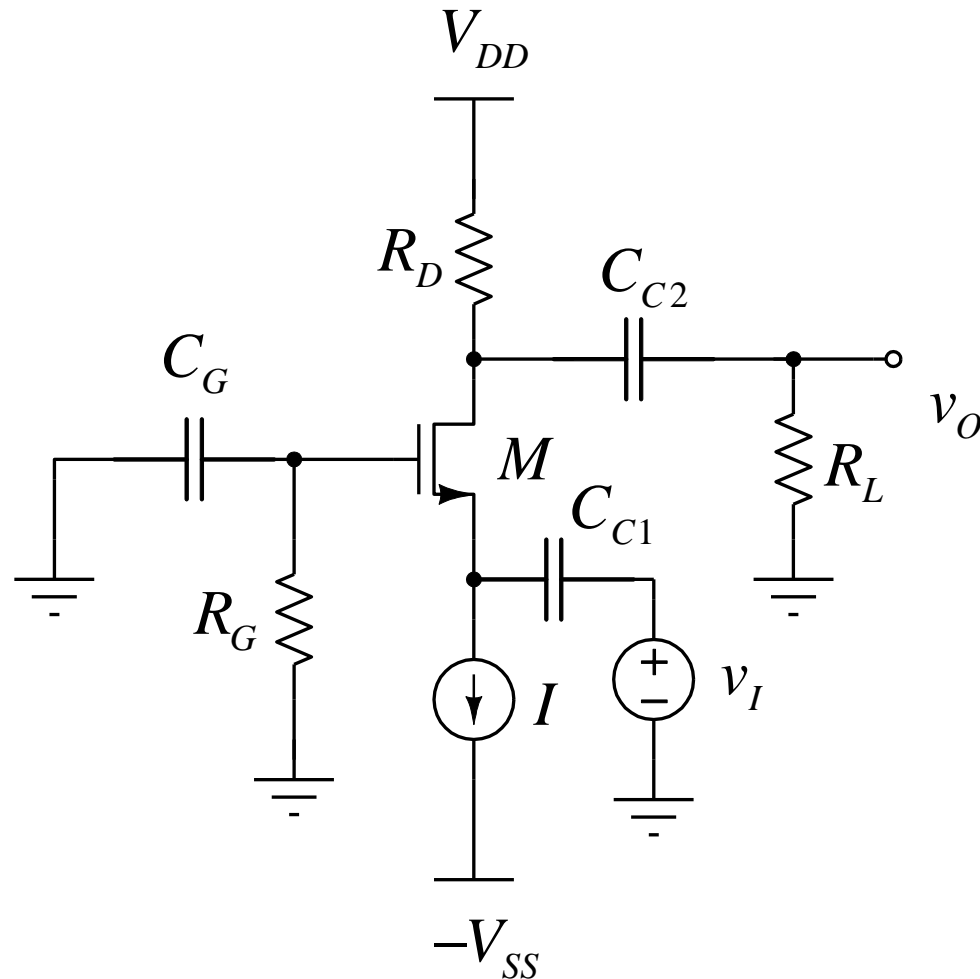
$$R_o' = \left. \frac{v_2}{i_2} \right|_{v_i=0} = \frac{1}{g_m} \parallel r_o \cong \frac{1}{g_m} \quad R_o = \frac{1}{g_m} \parallel r_o \parallel R_L \cong \frac{1}{g_m} \parallel R_L$$

$$v_o = g_m v_{gs} (r_o \parallel R_L) \quad v_i = v_{gs} + v_o \quad v_o = g_m (v_i - v_o) (r_o \parallel R_L)$$

$$v_o (1 + g_m r_o \parallel R_L) = g_m r_o \parallel R_L v_i \quad A_v = \frac{v_2}{v_1} = \frac{v_o}{v_i} = \frac{g_m r_o \parallel R_L}{1 + g_m r_o \parallel R_L} < 1$$

$$r_o \gg \frac{1}{g_m}$$

Configurazione a Gate Comune

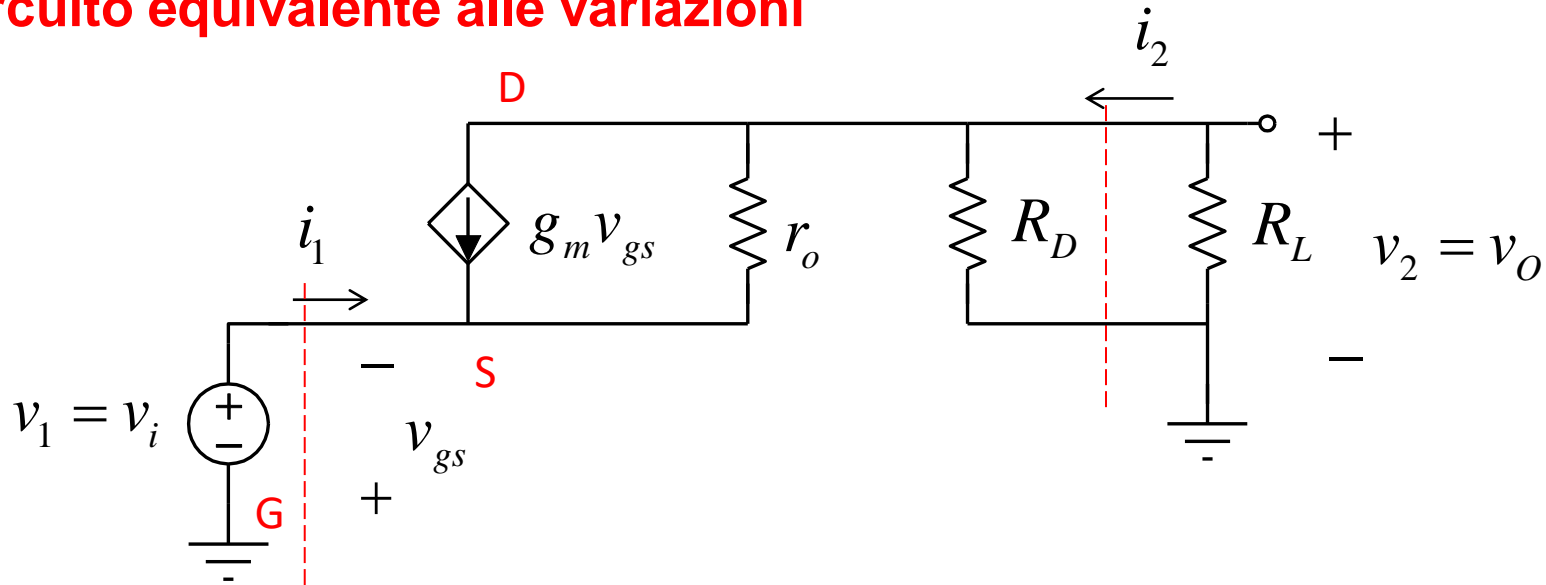


C_{C1} C_{C2} C_G devono essere sufficientemente elevate cosicché possono essere considerate dei cortocircuiti alle frequenze di interesse (medie frequenze)

La R_G evita che il gate sia flottante

Configurazione a Gate Comune

Circuito equivalente alle variazioni



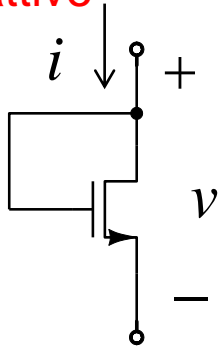
$$v_1 = v_i = -v_{gs} \quad i_1 \cong -g_m v_{gs} \quad (\text{si trascura la corrente assorbita da } r_o)$$

$$R_i = \frac{v_1}{i_1} \cong \frac{1}{g_m} \quad R_o' = \left. \frac{v_2}{i_2} \right|_{v_i=0} = R_D \quad R_o = R_D \parallel R_L$$

$$A_v = \frac{v_2}{v_1} \cong g_m (R_D \parallel R_L)$$

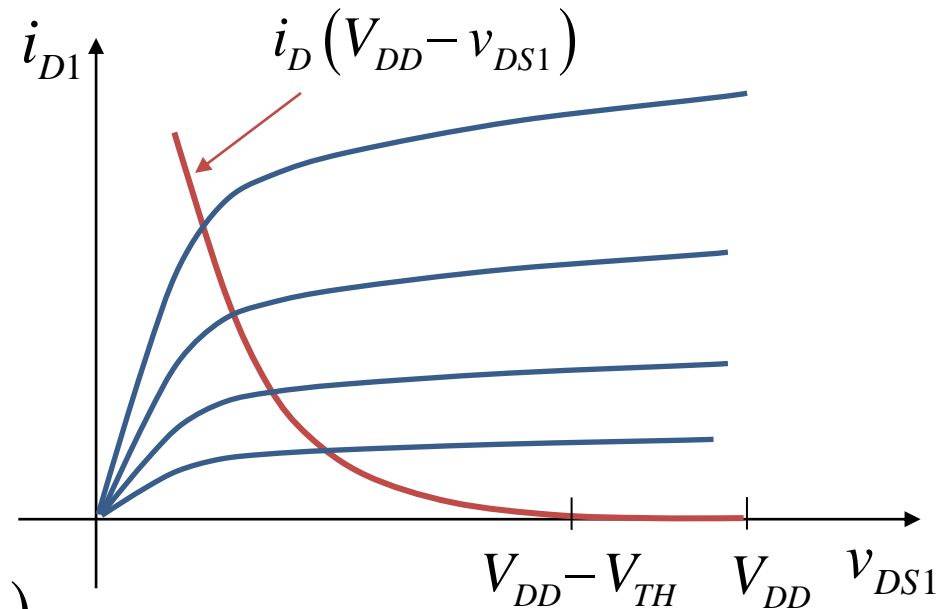
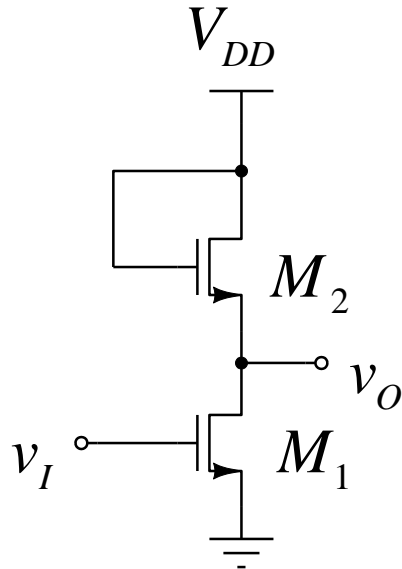
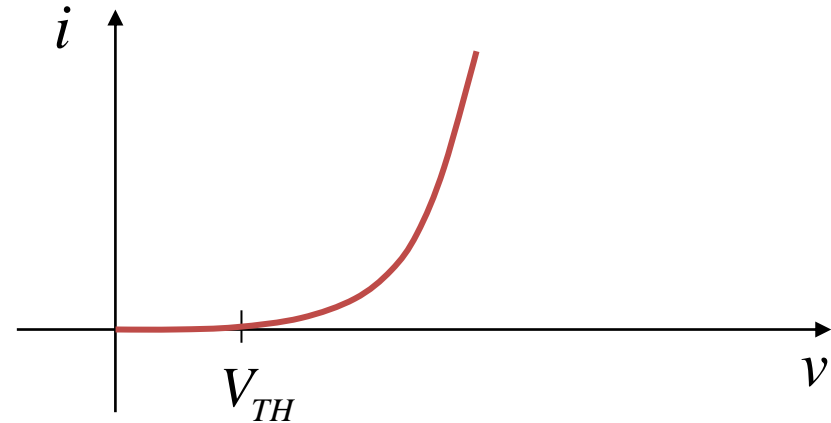
Circuiti Integrati MOS

Carico attivo



MOSFET
enhancement

$$i = \frac{\beta}{2} (v - V_{TH})^2$$



$$i_{D1}(v_{DS1}) = i_{D2}(v_{DS2}) = i_{D2}(V_{DD} - v_{DS1})$$

$$\begin{cases} i_{D1} = \frac{\beta_1}{2} (v_{GS1} - V_{TH})^2 = \frac{\beta_1}{2} (v_I - V_{TH})^2 \\ i_{D2} = \frac{\beta_2}{2} (v_{GS2} - V_{TH})^2 = \frac{\beta_2}{2} (V_{DD} - v_O - V_{TH})^2 \end{cases}$$

$$i_{D1} = i_{D2} \quad \Rightarrow \quad \frac{\beta_1}{2} (v_I - V_{TH})^2 = \frac{\beta_2}{2} (V_{DD} - v_O - V_{TH})^2$$

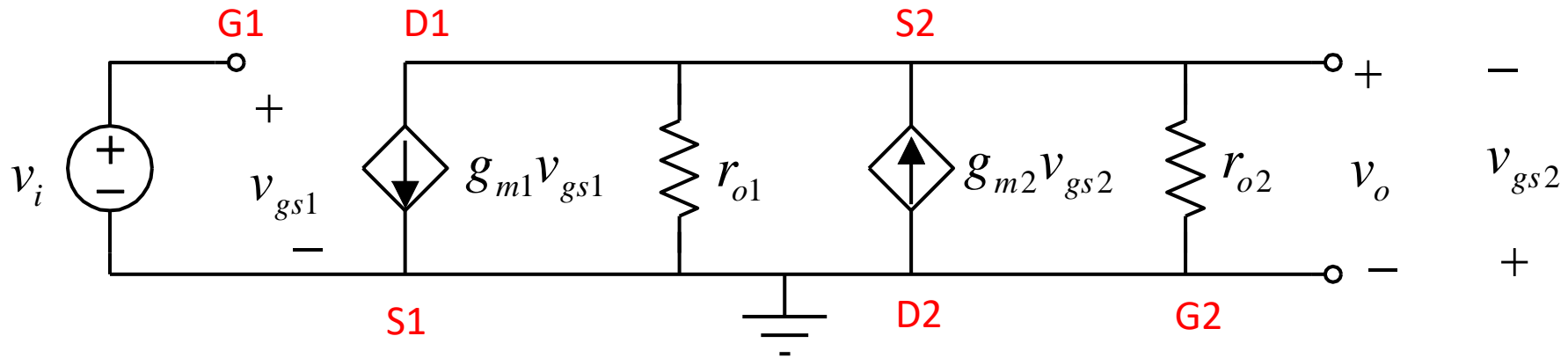
Da cui:

$$v_O = \left(V_{DD} - V_{TH} + \sqrt{\frac{\beta_1}{\beta_2}} V_{TH} \right) - \sqrt{\frac{\beta_1}{\beta_2}} v_I$$

è lineare in v_I

$$A_v = \frac{dv_O}{dv_I} = -\sqrt{\frac{\beta_1}{\beta_2}} = -\sqrt{\frac{(W/L)_1}{(W/L)_2}}$$

Circuiti Integrati MOS



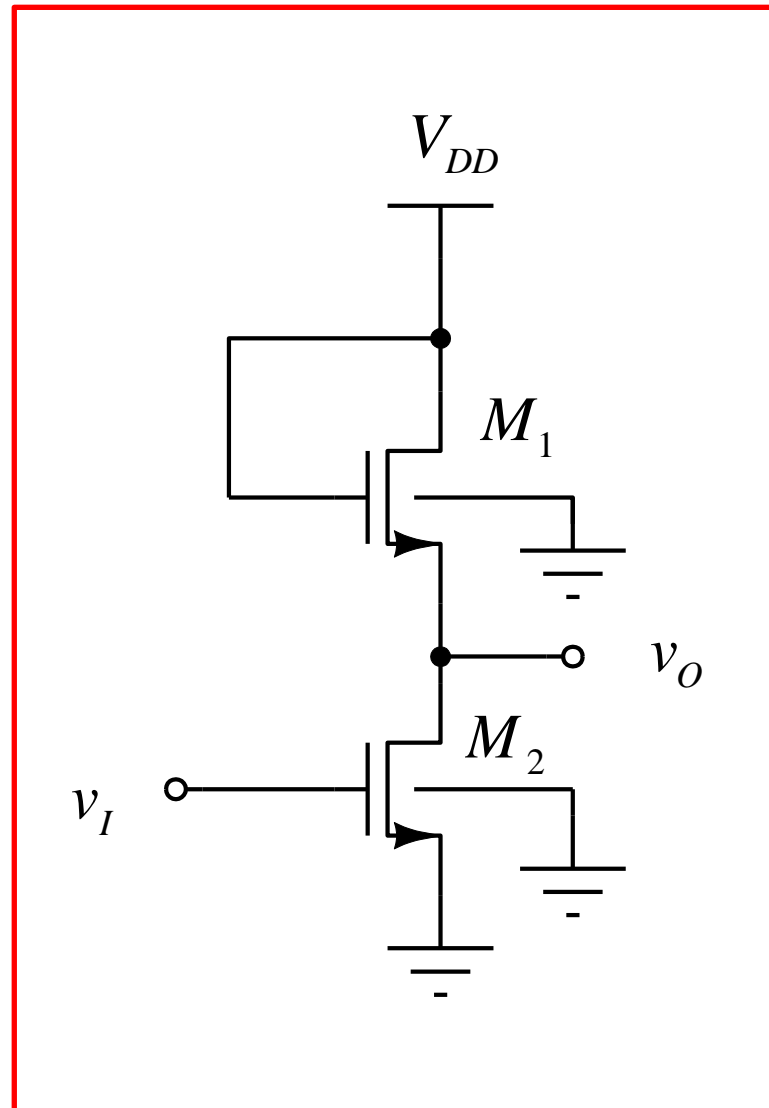
$$v_{gs2} = -v_o$$

$$v_i = v_{gs1} \quad v_o = -g_{m1}v_{gs1} \left(\frac{1}{g_{m2}} \parallel r_{o1} \parallel r_{o2} \right) = \frac{-g_{m1}v_{gs1}}{g_{m2} + \frac{1}{r_{o1}} + \frac{1}{r_{o2}}}$$

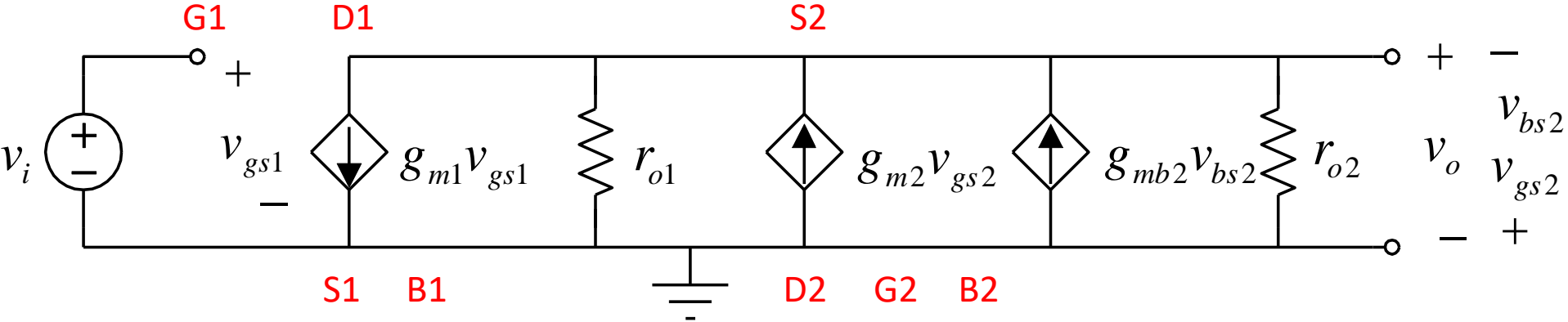
$$A_v = \frac{v_o}{v_i} = - \frac{g_{m1}}{g_{m2} + \frac{1}{r_{o1}} + \frac{1}{r_{o2}}}$$

$$A_v \cong - \frac{g_{m1}}{g_{m2}}$$

Effetto di Substrato



Effetto di Substrato



$$v_i = v_{gs1} \quad v_{gs2} = -v_o \quad v_{bs1} = 0 \quad v_{bs2} = -v_o$$

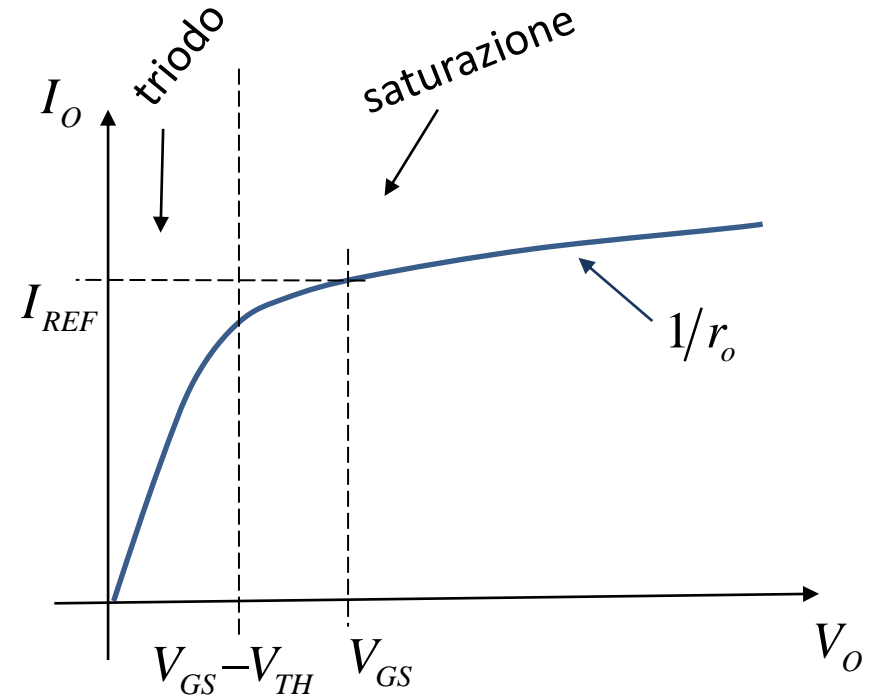
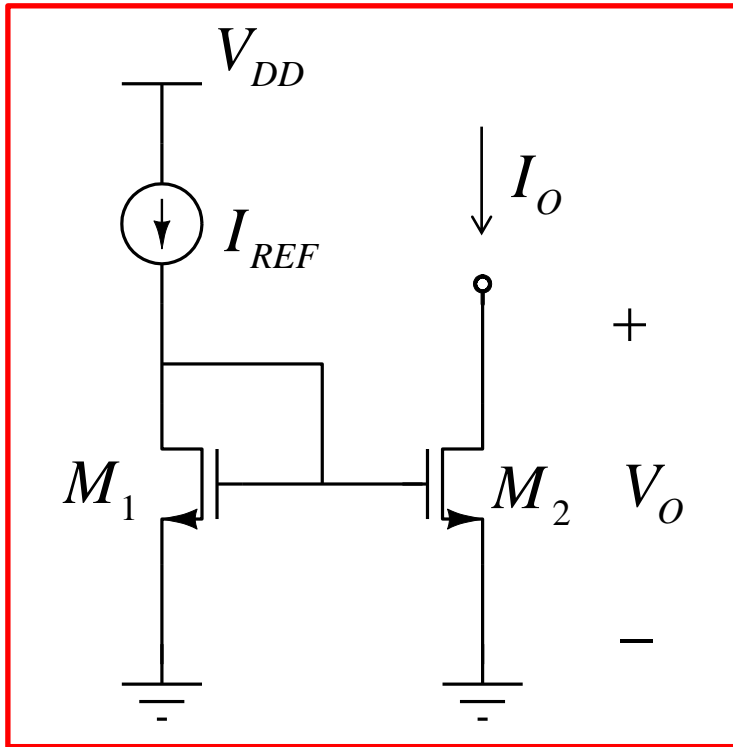
$$v_o = -g_{m1}v_{gs1} \left(\frac{1}{g_{m2}} \parallel \frac{1}{g_{mb2}} \parallel r_{o1} \parallel r_{o2} \right) = \frac{-g_{m1}v_{gs1}}{g_{m2} + g_{mb2} + \frac{1}{r_{o1}} + \frac{1}{r_{o2}}}$$

$$A_v = \frac{v_o}{v_i} = - \frac{g_{m1}}{g_{m2} + g_{mb2} + \frac{1}{r_{o1}} + \frac{1}{r_{o2}}}$$

$$A_v \cong - \frac{g_{m1}}{g_{m2} + g_{mb2}}$$

Il guadagno si riduce

Lo Specchio di Corrente



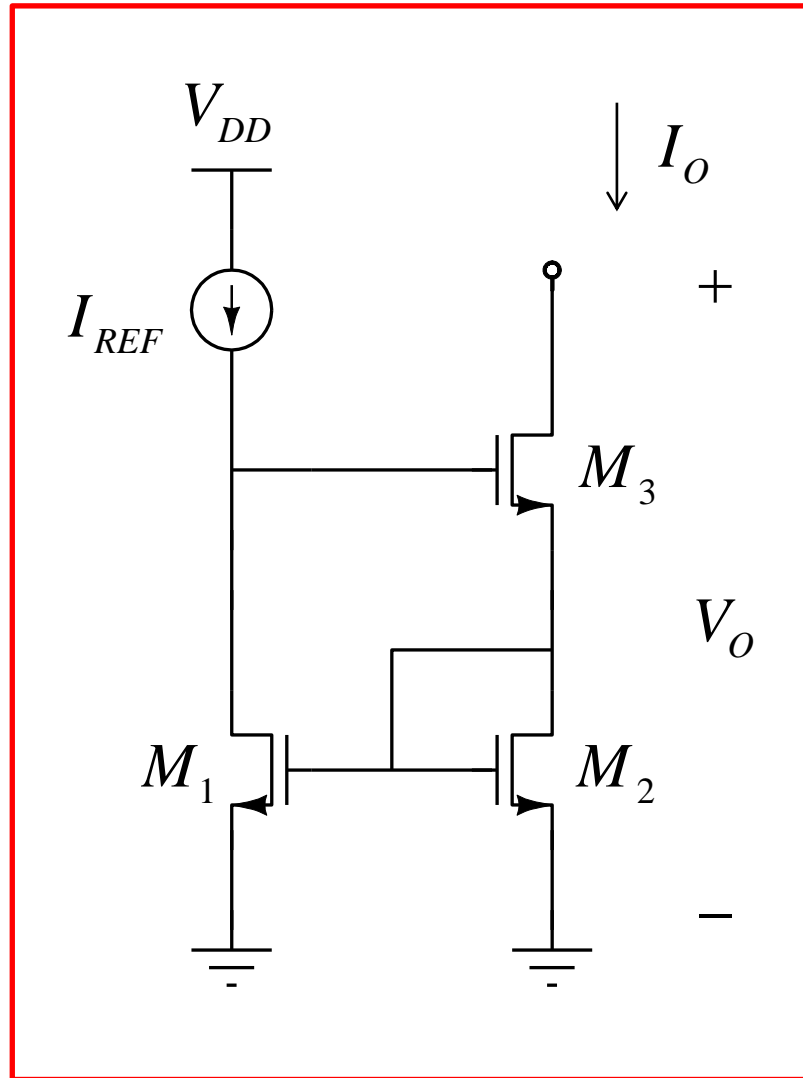
$$I_{REF} = \frac{\beta_1}{2} (V_{GS1} - V_{TH})^2$$

$$I_O = \frac{\beta_2}{2} (V_{GS2} - V_{TH})^2$$

$$\beta = 2K = k_n \frac{W}{L} = \mu_n C_{OX} \frac{W}{L}$$

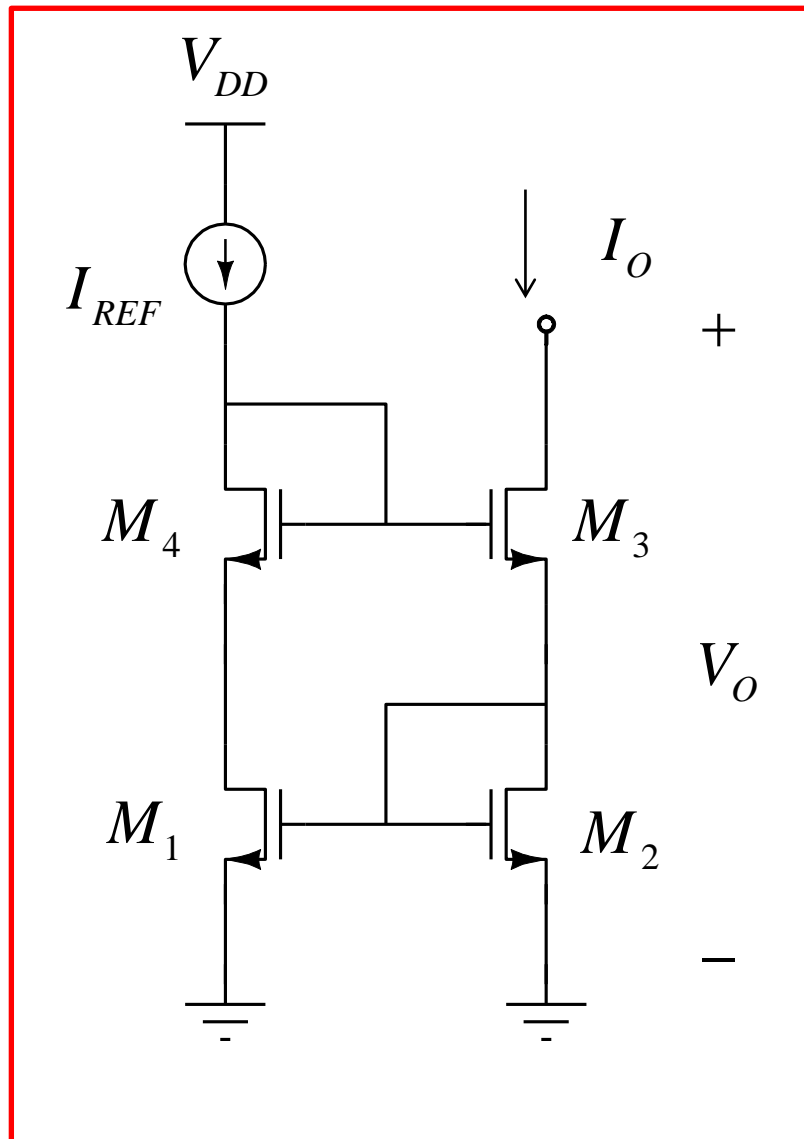
$$V_{GS} = V_{GS1} = V_{GS2} \quad \text{da cui:} \quad I_O = I_{REF} \frac{\beta_2}{\beta_1} \quad I_O = I_{REF} \frac{(W/L)_2}{(W/L)_1}$$

Generatore di Wilson

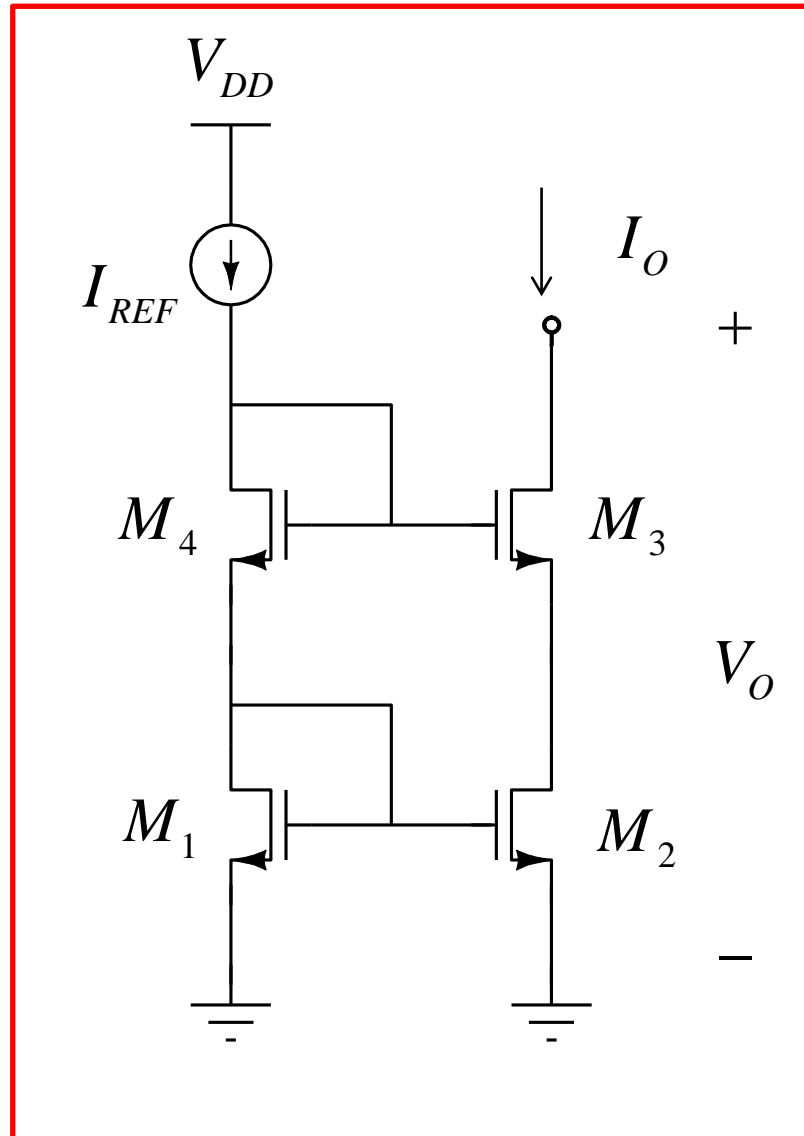


$$R_o = r_{o3} (g_{m3} r_{o1} + 2) \cong g_{m3} r_{o1} r_{o3}$$

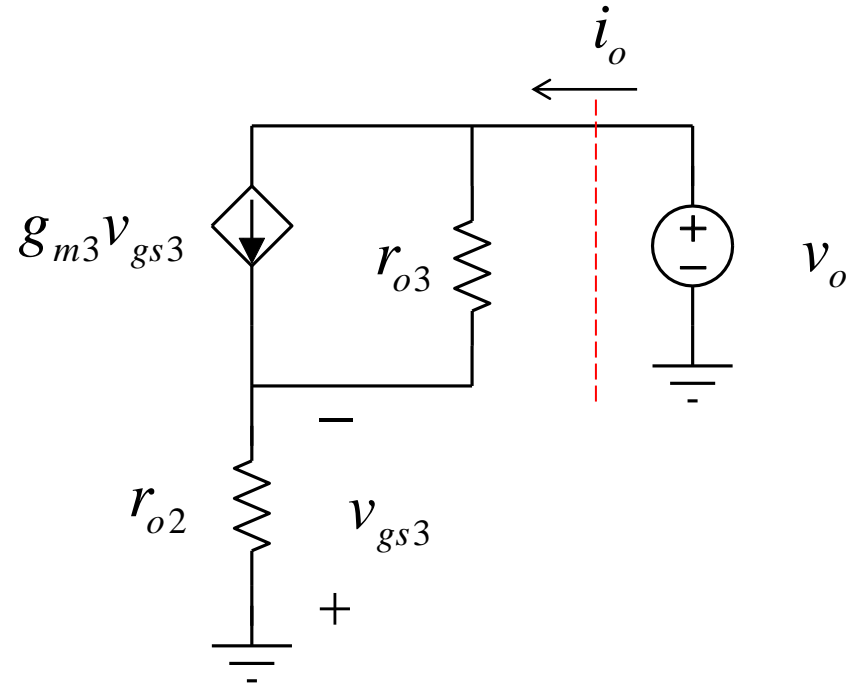
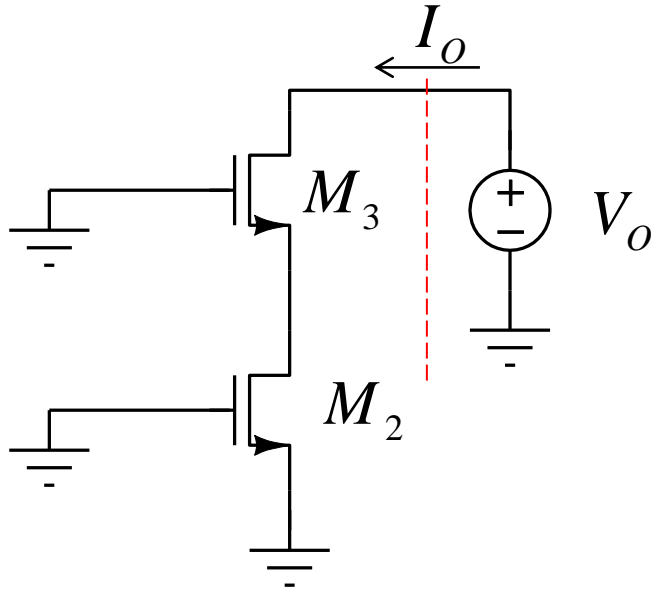
Generatore di Wilson Modificato



Generatore Cascode



Generatore Cascode: Resistenza di Uscita



$$\begin{cases} v_o = (i_o - g_{m3} v_{gs3}) r_{o3} + i_o r_{o2} \\ v_{gs3} = -i_o r_{o2} \end{cases}$$

$$v_o = i_o (r_{o3} + g_{m3} r_{o2} r_{o3} + r_{o2})$$

$$R_o = r_{o3} + g_{m3} r_{o2} r_{o3} + r_{o2}$$

molto elevata