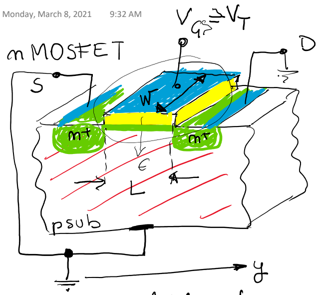
Transistore MOS

Monday, March 8, 2021 9:32 AM

n MOSFET

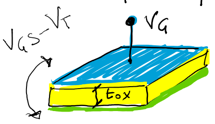


$V_{GS} \triangleq V_G - V_S$

G: GATE
D: DRAIN
S: SOURCE

V_T : TENSIONE DI SOGLIA (THRESHOLD VOLTAGE)
tensione per la quale la concentrazione di elettroni mobili nel canale (portatori minoritari) raggiunge la concentrazione di lacune mobili nel substrato non svuotato

CONDIZIONE DI INVERSIONE



CONDENSATORE MOSFET

Area dell'elettrodo di gate $= W \cdot L$

$\varepsilon_{Si} = 10^{-12}$ F/cm

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} \quad \leftarrow \varepsilon_{rox}\,\varepsilon_0 \qquad [F/cm^2]$$

capacità per unità di area dell'elettrodo di gate

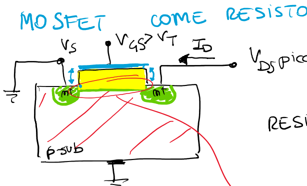
$$C_{GATE} = C_{ox}\, Area_{gate} = \frac{\varepsilon_{ox}}{t_{ox}}\, W \cdot L \qquad [F]$$

CAPACITÀ DI GATE

$$Q_n = C_{ox}\,(V_{GS} - V_T)$$

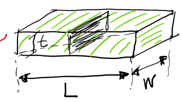
CARICA per unità di area nel canale conduttore

MOSFET COME RESISTORE VARIABILE



V_{DS} piccola (poche centinaia di mV) $\quad V_{DS} \ll V_{GS} - V_T$

RESISTENZA DEL CANALE CONDUTTIVO



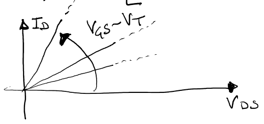
$$R_{CH} = \rho \frac{L}{Area} = \rho \frac{L}{W \cdot t} = \frac{1}{q \mu_n n t} \frac{L}{W} = \frac{1}{\mu_n Q_n} \frac{L}{W}$$

$$\rho = \frac{1}{q \mu_n n}$$

concentrazione volumetrica di elettroni

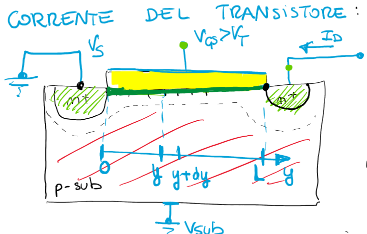
conc. di elettroni per unità di area

$$I_D = \frac{V_{DS}}{R_{CH}} = \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_T)\, V_{DS}$$



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

CORRENTE DEL TRANSISTORE: approssimazione a canale graduale

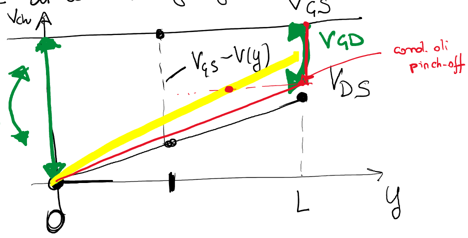


carica per unità di area nel canale alla coordinata y

$$Q(y) = C_{ox}\left[V_{GS} - V(y) - V_T\right]$$

$$dR = \frac{dy}{\mu_n Q(y)\, W}$$

resistenza del tratto di canale lungo dy



caduta di tensione ai capi del trattino dy

$$dV = I_D\, dR = \frac{I_D\, dy}{\mu_n C_{ox}\left[V_{GS} - V(y) - V_T\right] W}$$

Separando le variabili e integrando:

$$\int_0^L I_D\, dy = \int_0^{V_{DS}} \mu_n C_{ox} \left[V_{GS} - V - V_T\right] W\, dV$$

$$I_D \cdot L = \mu_n C_{ox} W \int_0^{V_{DS}} \left[V_{GS} - V - V_T\right] dV$$

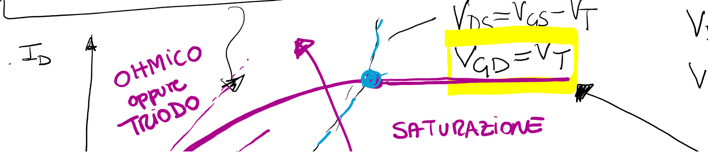
$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} \left[2 (V_{GS} - V_T) V_{DS} - V_{DS}^2\right]$$

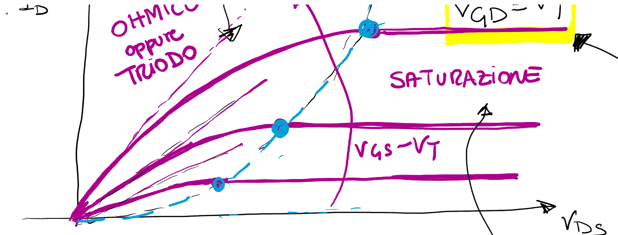
$$V_{GS} - V_{DS} = V_G - V_S - (V_D - V_S) = V_G - V_S - V_D + V_S = V_{GD}$$

$$V_{DS} < V_{GS} - V_T$$

$$V_D - V_S < V_G - V_S - V_T$$

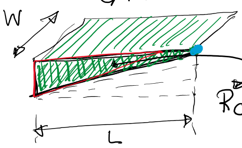
$$V_{GD} > V_T$$





$V_{G'D} > V_T$

CONDIZIONE DI PINCH-OFF DEL CANALE



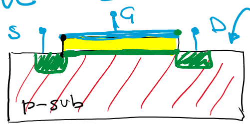
$R_{CH\,pinch\text{-}off} = 2 R_{CH\,ohmic}$

CORRENTE IN ZONA DI SATURAZIONE

$$I_D = \frac{1}{2} \mu_m C_{ox} \frac{W}{L} (V_{GS} - V_T)^2$$

ZONE DI FUNZIONAMENTO DI UN nMOSFET

V_{Tn} = tensione di soglia dell'nMOS



- $V_{GS} < V_{Tn}$ nMOSFET spento $I_D = 0$
- $V_{GS} > V_{Tn}$ nMOSFET acceso
  - * $V_{GD} > V_{Tn}$ zona ohmica o triodo { canale lato source, canale lato drain

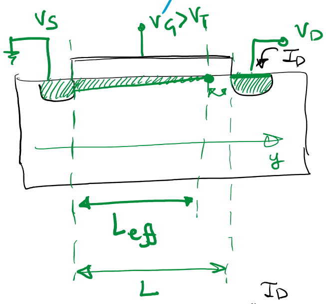
    $$I_D = \frac{1}{2} \mu_m C_{ox} \frac{W}{L} \left[2(V_{GS} - V_T) V_{DS} - V_{DS}^2 \right] \simeq$$

    $$\simeq \mu_m C_{ox} \frac{W}{L} (V_{GS} - V_T) V_{DS}$$

    V_{DS} piccole
  - * $V_{GD} < V_{Tn}$ zona di saturazione { canale lato source, pinch-off lato drain

    $$I_D = \frac{1}{2} \mu_m C_{ox} \frac{W}{L} (V_{GS} - V_T)^2$$

EFFETTO EARLY



arretramento del punto di pinchoff

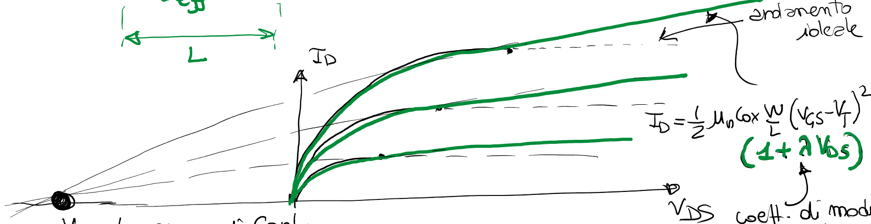
$L_{eff} < L$

⇓

resistenza di canale diminuisce

⇓

corrente I_D aumenta



$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_T)^2 (1 + \lambda V_{DS})$$

λ: coeff. di modulazione della lunghezza di canale

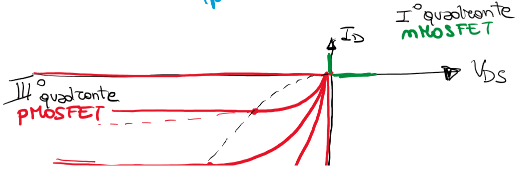
V_A = tensione di Early

$$\lambda = \frac{1}{|V_A|}$$

TRANSISTORE pMOSFET

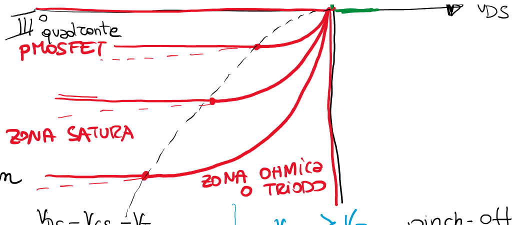
V_{Tp} : tensione di soglia pMOSFET

$V_{Tp} < 0$



- $V_{GS} > V_{Tp}$ pMOSFET off

- $V_{GS} > V_{Tp}$ pMOSFET off
  $I_D = 0$



- $V_{GS} < V_{Tp}$ pMOSFET on

$* \; V_{GD} < V_{Tp}$
pMOSFET ohmica o triodo

$$I_D = -\frac{1}{2}\mu_p C_{ox}\frac{W}{L}\left[2(V_{GS_p}-V_{Tp})V_{DS_p} - V_{DS_p}^2\right]$$

$* \; V_{GD} > V_{Tp}$ pinch-off lato drain
pMOS saturo

$$I_D = -\frac{1}{2}\mu_p C_{ox}\frac{W}{L}(V_{GS_p}-V_{Tp})^2$$

$V_{Tp} = -1$
$V_{GS_p} = -2V$

$$I_D = -\frac{1}{2}\mu_p C_{ox}\frac{W}{L}\left(-2-(-1)\right)^2 = -\frac{1}{2}\mu_p C_{ox}\frac{W}{L}\left[-1\right]^2$$

FATTORE DI TRANSCONDUTTANZA

$$k_p = -\frac{1}{2}\mu_p C_{ox}\left(\frac{W}{L}\right)_p < 0 \quad \text{pMOSFET}$$

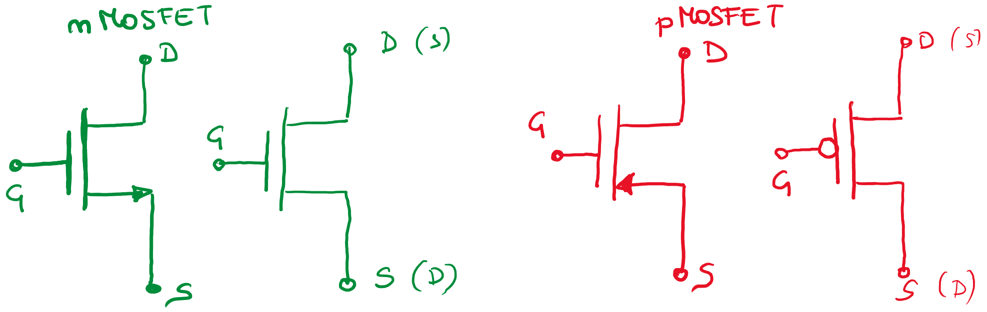
$$k_n = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_n > 0 \quad \text{nMOSFET}$$

⇓ corrente di drain in saturazione

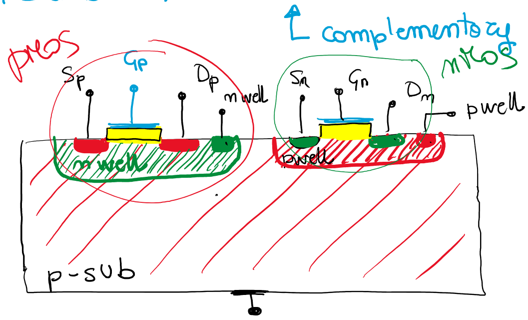
pMOS $I_{D_p} = k_p\,(V_{GS_p} - V_{Tp})^2$

nMOS $I_{D_n} = k_n\,(V_{GS_n} - V_{Tn})^2$

SIMBOLI CIRCUITALI

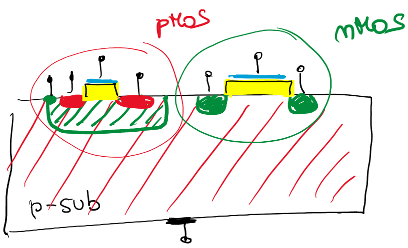


TECNOLOGIA CMOS
↑ complementary



doppia well

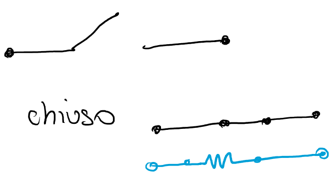
singola well



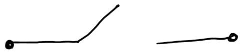
MOSFET come interruttore

nMOS off ⇒ interruttore aperto

nMOS on (ohmico) ⇒ interruttore chiuso



$R_{ds_{on}}$



circuito aperto $I_i = 0$

interruttore chiuso = cortocircuito

$$R_{ds_{on}} \triangleq \left.\frac{\partial V_{DS}}{\partial I_{D_{ohm}}}\right|_{V_{DS}=0} = \left.\left[\frac{\partial I_{D_{ohm}}}{\partial V_{DS}}\right]^{-1}\right|_{V_{DS}=0}$$

RESISTENZA TRA DRAIN E SOURCE IN ZONA OHMICA

nMOS

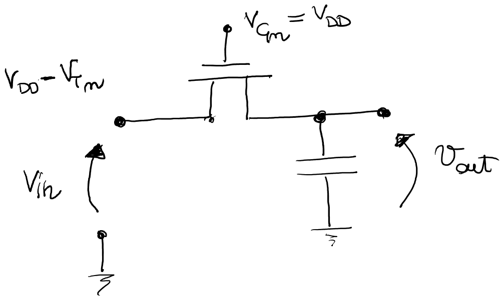
$$I_{D_{ohm}} = k_n \left[2\left(V_{GS_n} - V_{T_n}\right) V_{DS_n} - V_{DS_n}^2\right] \qquad k_n = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_n$$

$$R_{ds_{on_n}} = \left.\left[2k_n\left(V_{GS_n} - V_{T_n}\right) - 2V_{DS_n}\right]^{-1}\right|_{V_{DS}=0} = \frac{1}{2k_n\left(V_{GS_n} - V_{T_n}\right)}$$

pMOS

$$R_{ds_{on_p}} = \frac{1}{2k_p\left(V_{GS_p} - V_{T_p}\right)} > 0$$

k_p: < 0 ; $\left(V_{GS_p} - V_{T_p}\right)$: < 0



$(V_{G_n} - V_{in}) < V_{T_n}$

nMOS off $\Rightarrow$

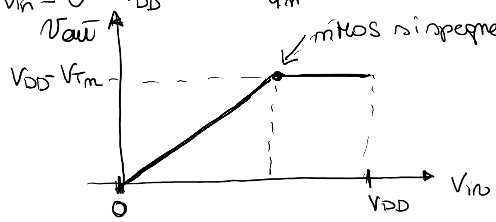
V_{out} e V_{in} sono scollegati (int. aperto)

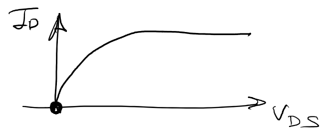
$(V_{G_n} - V_{in}) > V_{T_n}$

nMOS on

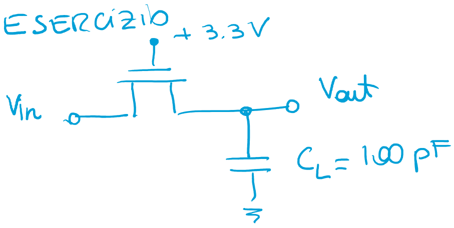
Connettiamo V_{out} a V_{in}

$V_{in} = 0 - V_{DD}$ $\quad V_{G_n} = V_{DD}$





ESERCIZIO



$V_T = 0.8$ V

(a) V_{out} ? se $V_{in} = 0$ V (esaurire i transitori)

(b) V_{out} ? se $V_{in} = +3.3$ V (esaurire i transitori)