Body Effect for MOS Transistors

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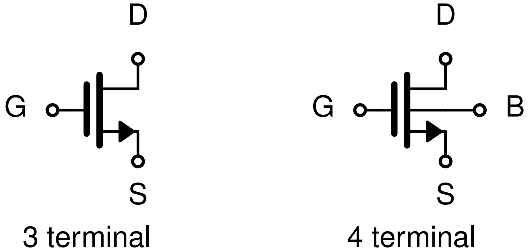
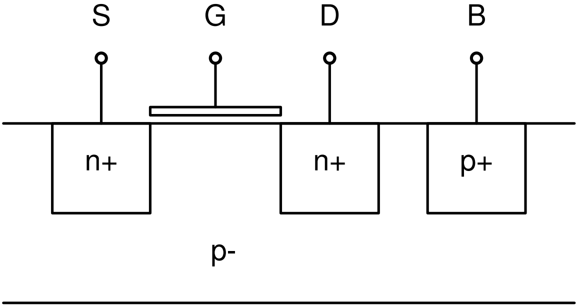
Body, or Bulk (or Substrate)

- So far, we have assumed a 3 terminal MOSFET
- Actually, a MOSFET is a 4 terminal device



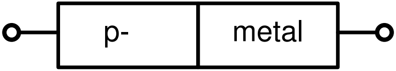
- B $\Rightarrow$ Body or Bulk (or Substrate)

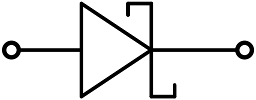
Body, or Bulk (or Substrate)



- p+ is used to connect metal to p- body
- If p+ is not used, metal direct to p- would result in a Schottky diode

Schottky Diode

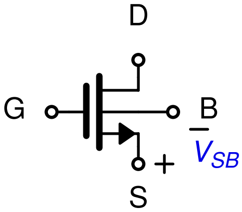




- on voltage $\approx 0.3\ \text{V}$
- We DO NOT want a Schottky diode (current only one direction and a voltage drop)
- By using metal to p+ to p-, we have an ohmic connection

Body Effect - Large Signal

- V_{SB} effect



- Effect of V_{SB} can be modelled as changing the threshold voltage, V_t.

$$V_t = V_{t0} + \gamma[\sqrt{2\Phi_f + V_{SB}} - \sqrt{2\Phi_f}] \tag{1}$$

where
  - V_{t0} is the threshold voltage with $V_{SB} = 0$
  - $2\Phi_f \approx 0.6\mathrm{V}$ (surface potential)
  - $\gamma = \sqrt{2qN_A\epsilon_S}/C_{OX}$
    (N_A - doping concentration of p-; ϵ_s - permittivity of silicon; C_{OX} is gate oxide capacitance per unit area)

Body Effect - Large Signal

- V_{SB} effect
  - As $V_{SB} \Uparrow$ then $V_t \Uparrow$
  - In other words, if the source voltage is greater than the bulk voltage, the threshold is increased.
- V_t increase due to body effect
  - Will reduce available signal swing especially for source-follower amps
- Bulk connection acts like another ”gate” if the source is held constant
  - If $V_{BS} \Uparrow$ then $V_t \Downarrow$ and $I_D \Uparrow$
- For DC analysis, V_t depends on V_{SB} and V_{SB} may depend on V_t
  - Hand analysis requires an iterative approach
  - Best left for simulation

Body Effect - Small Signal

- Recall the definition for g_m which relates the change in drain current to the change in V_{GS}

$$g_m \equiv \frac{\partial I_D}{\partial V_{GS}} = \frac{\partial(0.5\mu_n C_{ox}(W/L)(V_{GS} - V_t)^2)}{\partial V_{GS}}$$

$$g_m = \mu_n C_{ox}(W/L)(V_{GS} - V_t) \tag{2}$$

- Since the body also "controls" the drain current, we can also find g_{mb}

- We define

$$g_{mb} \equiv \frac{\partial I_D}{\partial V_{BS}} \tag{3}$$

$$\begin{aligned} g_{mb} &= \frac{\partial(0.5\mu_n C_{ox}(W/L)(V_{GS} - V_t)^2)}{\partial V_{BS}} \\ &= \mu_n C_{ox}(W/L)(V_{GS} - V_t)(-1)\left(\frac{\partial V_t}{\partial V_{SB}}\right)\left(\frac{\partial V_{SB}}{\partial V_{BS}}\right) \\ &= \mu_n C_{ox}(W/L)(V_{GS} - V_t)\left(\frac{\partial V_t}{\partial V_{SB}}\right) \\ &= \left(\frac{\partial V_t}{\partial V_{SB}}\right) g_m \end{aligned} \tag{4}$$

Body Effect - Small Signal

- Using (1) and defining χ as

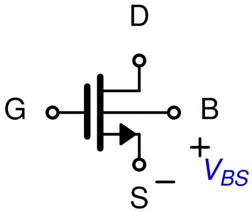
$$\chi \equiv \frac{\partial V_t}{\partial V_{SB}} = \frac{\gamma}{2\sqrt{2\phi_f + V_{SB}}} \tag{5}$$

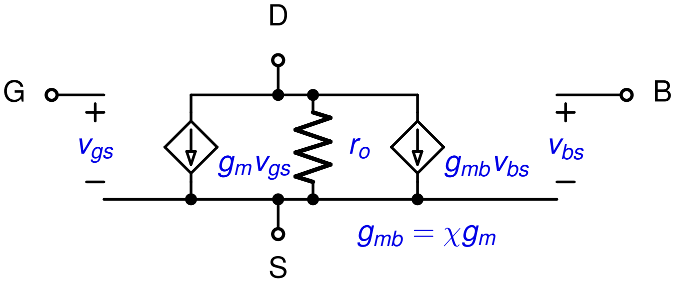
- We have that g_{mb} is related to g_m as

$$g_{mb} = \chi g_m \tag{6}$$

- Typical values for χ are 0.1 to 0.3

Body Effect - Small-Signal Model

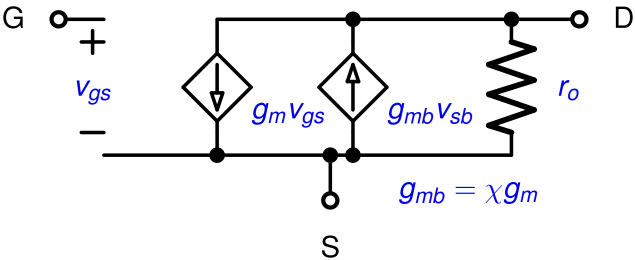




$g_{mb} = \chi g_m$

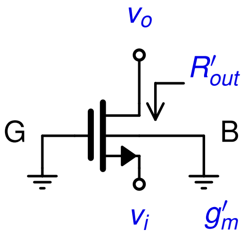
Body Effect Small-Signal Model

- In the case where the bulk is a small-signal ground



- This is common in integrated circuits
- Let's look at 3 amps with body at small-signal ground
  - Common-gate
  - Common-drain
  - Common-source

Common-Gate

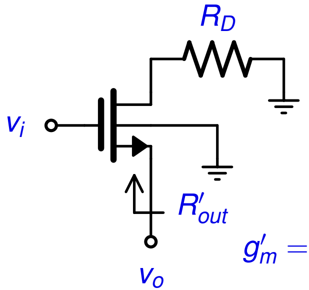


$$g'_m = (1+\chi)g_m$$

$$R'_{out} = r_o \qquad i'_{sc} = \frac{(1+g'_m r_o)}{r_o} v_i \qquad v'_{oc} = (1+g'_m r_o) v_i$$

- All results same as 3 terminal device except that g_m increased by $(1+\chi)$
- Due to $v_{sg} = v_{sb} = v_s$ since $v_g = v_b = 0$

Common-Drain



$$g'_m = (1+\chi)g_m$$

$$R'_{out} = \frac{r_o + R_D}{1 + g'_m r_o} \qquad i'_{sc} = \frac{g_m r_o}{r_o + R_D} v_i \qquad v'_{oc} = \frac{g_m r_o}{1 + g'_m r_o} v_i$$

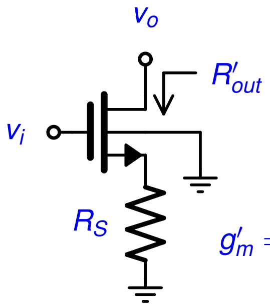
- R_{out} same as 3 terminal device except larger g_m
- i_{sc} same as 3 terminal device since output shorted so $v_{sb} = 0$

- For $g_m r_o \gg 1$

$$v'_{oc} \approx \frac{g_m}{g'_m} v_i = \frac{1}{1+\chi} v_i \tag{7}$$

- v_{oc} is reduced
- R_{out} also reduced but usually overall gain is reduced by body effect.

Common-Source



$$g'_m = (1+\chi)g_m$$

$R'_{out} = r_o + (1 + g'_m r_o)R_S$ $\quad i'_{sc} = \frac{-g_m r_o}{r_o + (1+g'_m r_o)R_S} v_i$ $\quad v'_{oc} = -g_m r_o v_i$

- R_{out} same as 3 terminal device but larger g_m
- v_{oc} same as 3 terminal device since when drain open, no current through R_S so $v_s = 0$ so $v_{sb} = 0$

Common-Source

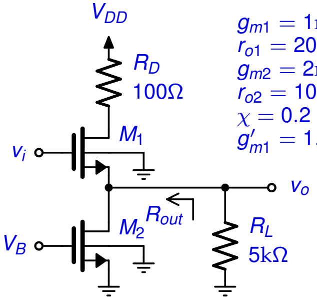
- For $g_m r_o \gg 1$

$$i'_{sc} \approx \frac{-g_m r_o v_i}{r_o + g'_m r_o R_S} = \frac{-g_m v_i}{1 + g'_m R_S} \approx \frac{-v_i}{(1/g_m) + (1+\chi) R_S} \tag{8}$$

- Body effect:
  - i_{sc} reduced
  - R_{out} increased

Example 1

- Common-drain



- M_1 has body effect since $V_B \neq V_S$
- $R_{out} = R_{S1} || R_{D2}$
- $R_o = R_{out} || R_L$
- $R_{D2} = r_{o2} = 10\mathrm{k}\Omega$; $R_{S1} = \frac{r_{o1}+R_D}{(1+g'_{m1} r_{o1})} = 804\Omega$

Example 3

- $R_{out} = R_{S1} || R_{D2} = 744\Omega$
- $R_o = R_{out} || R_L = 647\Omega$
- For i_{sc} we have $i_{sc} = G_m v_i$ where
- $G_m = (g_{m1} r_{o1})/(r_{o1} + R_D) = 995\mu\text{A}/\text{V}$
- $v_o/v_i = G_m \times R_o = 0.644\text{V}/\text{V}$
- Without body effect
  - $v_o/v_i = G_m \times R_o = 0.74\text{V}/\text{V}$
  - A gain reduction of 13% when body effect included

Example 3 - Approx Solution

- $R_{S1} = (1/g'_{m1}) + R_D/(g'_{m1} r_{o1}) = 838\Omega$
- $R_{D2} = r_{o2} = 10\text{k}\Omega$
- $v_{oc} = \frac{1}{1+\chi} v_i = 0.833 v_i$
- v_o node is a resistor divider node
- $v_o = \frac{(R_{D2}||R_L)}{(R_{D2}||R_L)+R_{S1}} v_{oc} = \frac{3.33k}{3.33k+838}(0.833)v_i$
- $vo/vi = 0.665\text{V}/\text{V}$