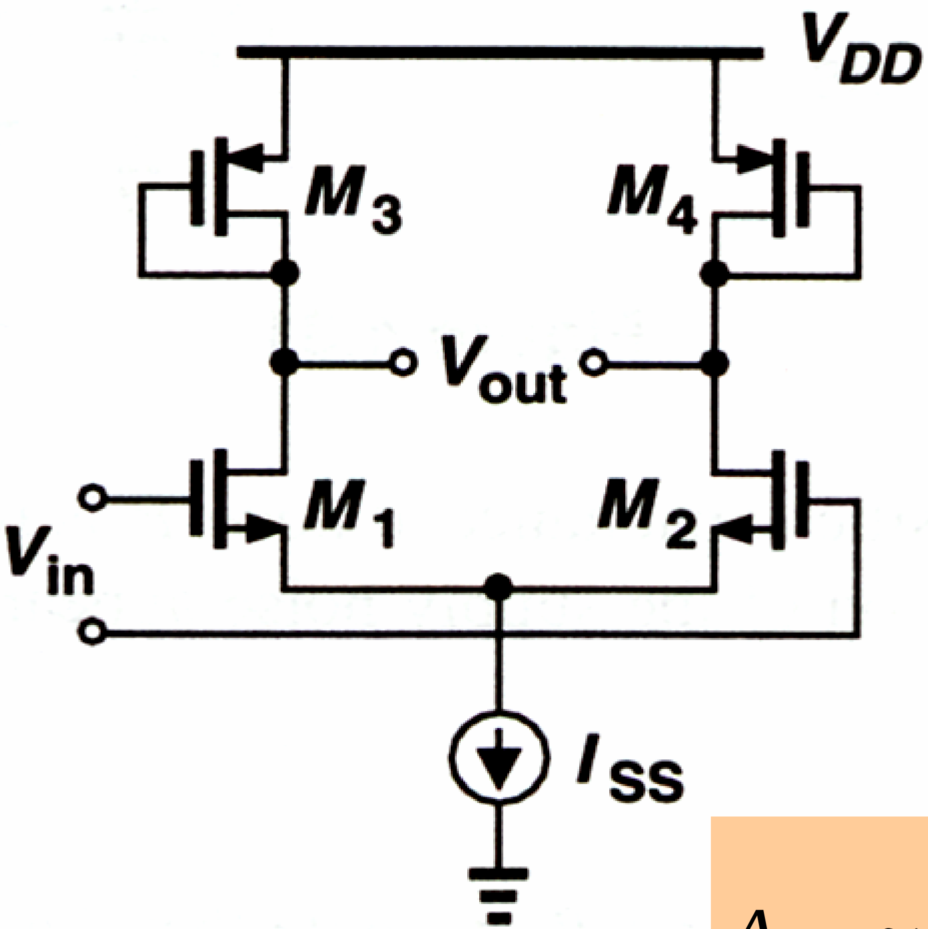
Diff pair with MOS diode load



$$A_v = -g_{mN}\left(g_{mP}^{-1} \| r_{ON} \| r_{OP}\right)$$

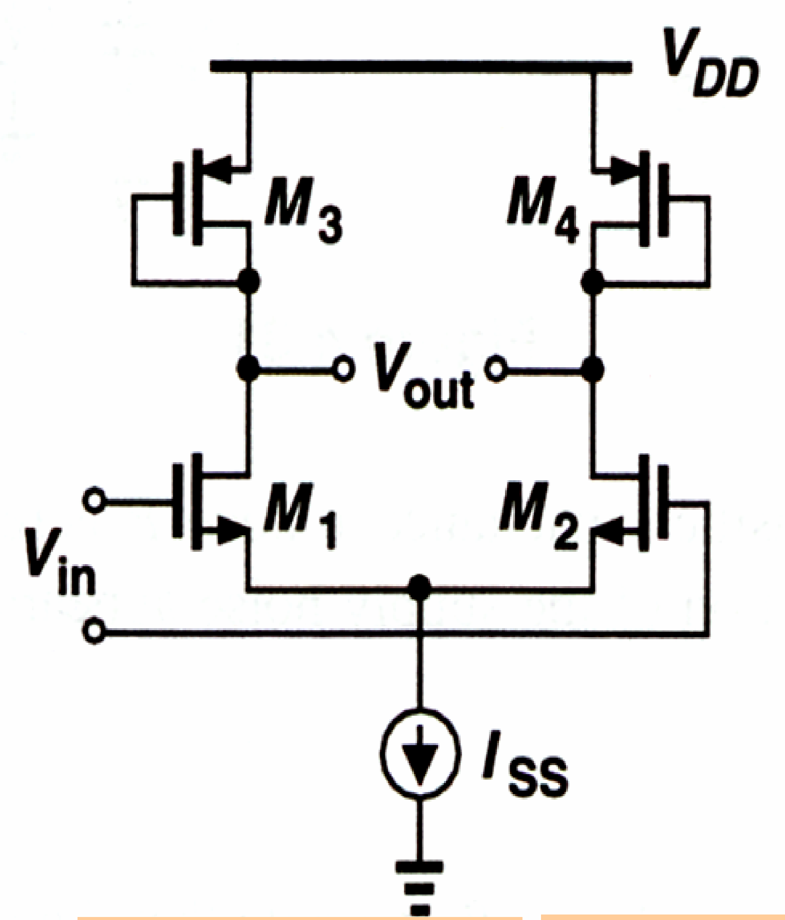
$$\approx -\frac{g_{mN}}{g_{mP}}$$

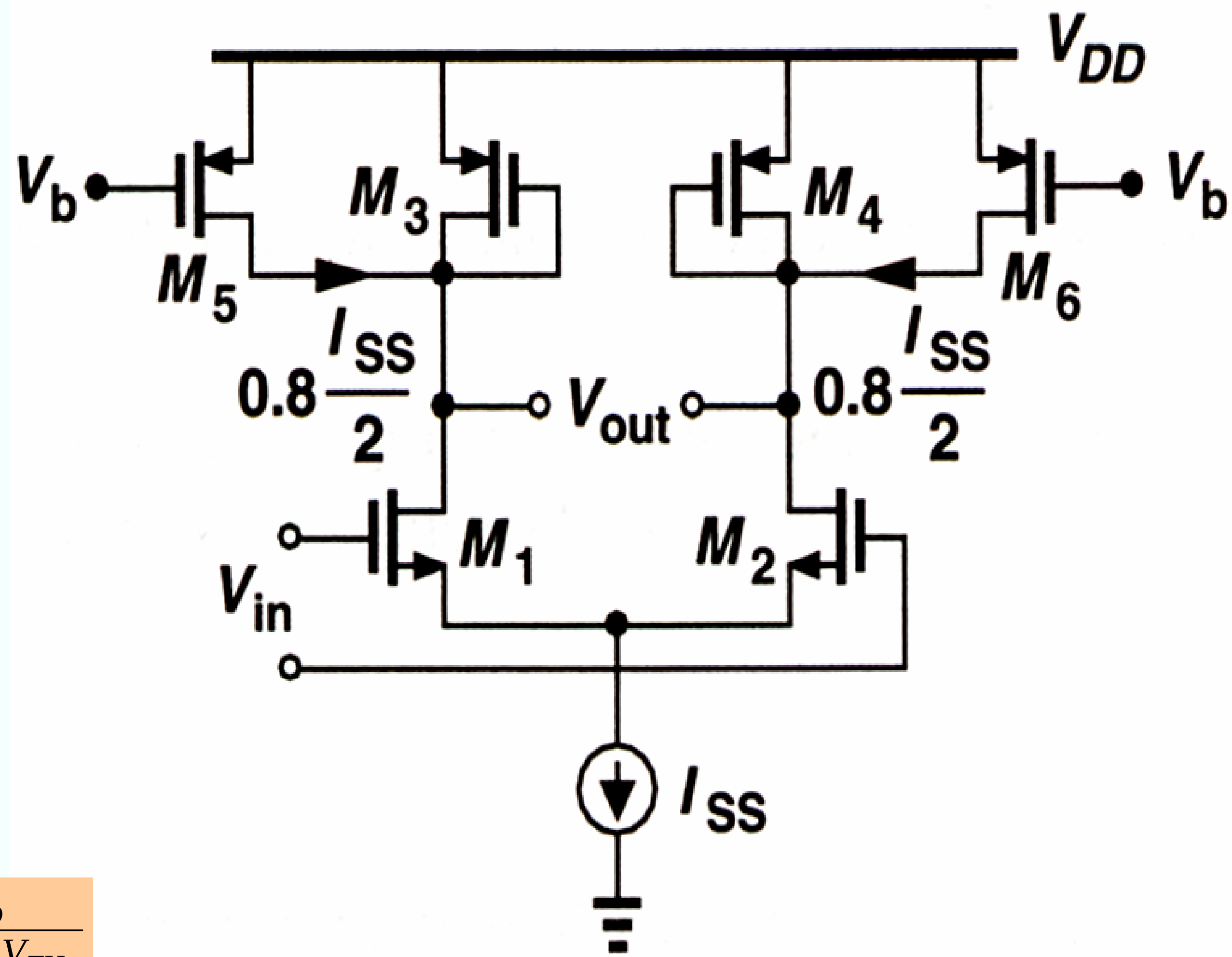
$$g_m = \sqrt{2\mu C_{ox}\cdot\frac{W}{L}\cdot I_D} = \frac{I_D}{\frac{V_{GS}-V_{TH}}{2}}$$

$$A_v \approx -\sqrt{\frac{\mu_N (W/L)_N}{\mu_P (W/L)_P}} = \frac{(V_{GS}-V_{TH})_P}{(V_{GS}-V_{TH})_N}$$

Trade-off between gain and Vout range

Diff pair with MOS diode load





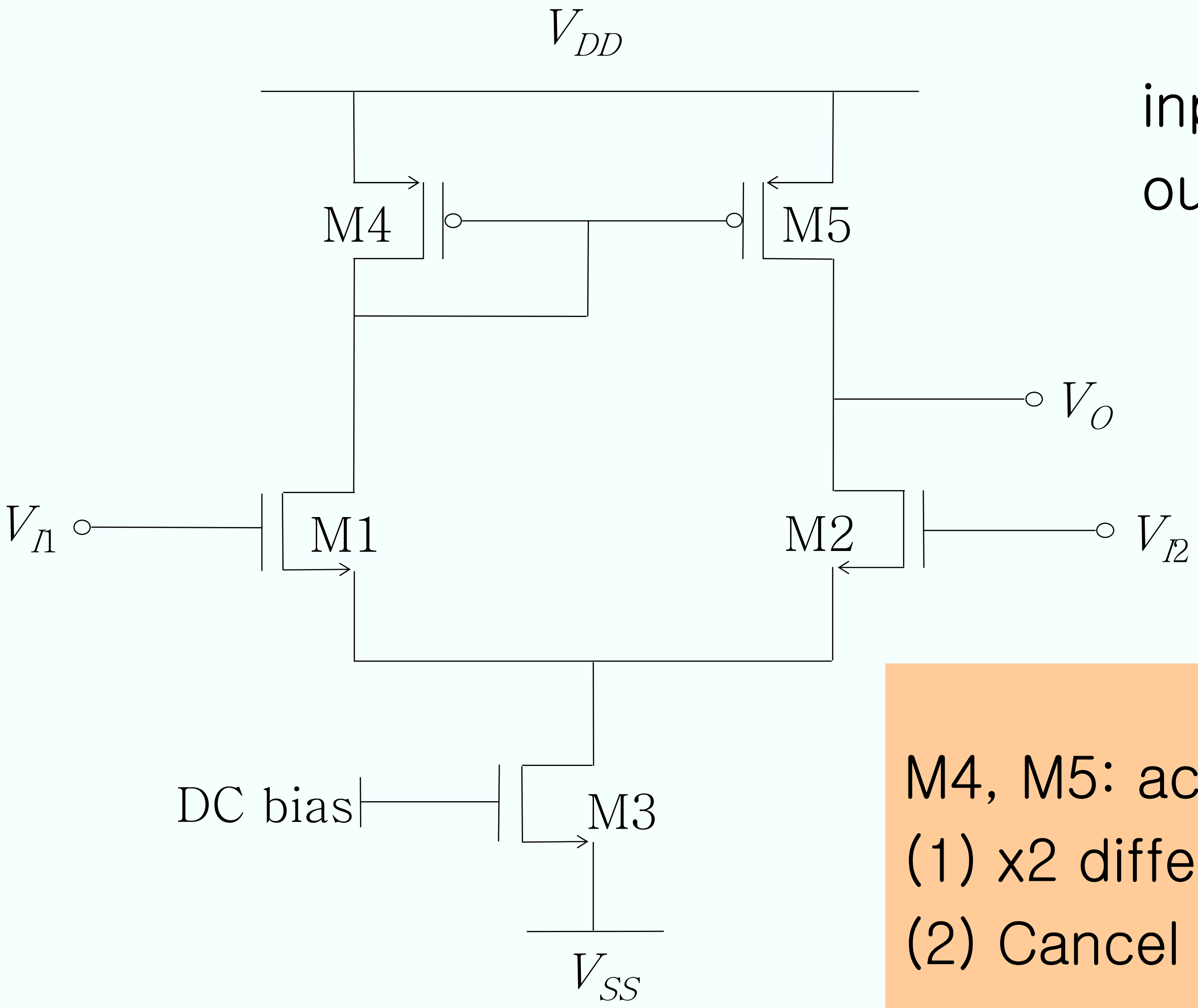
$$g_m = \sqrt{2\,\mu C_{ox} \cdot \frac{W}{L} \cdot I_D} = \frac{I_D}{\frac{V_{GS} - V_{TH}}{2}}$$

5x reduction of ID (M3, M4) => gmP reduced 5x =>

5x gain increased with the same Vout range (Vgs−Vth fixed)

Razavi

5.2 Active load NMOS differential pair



input: differential signal

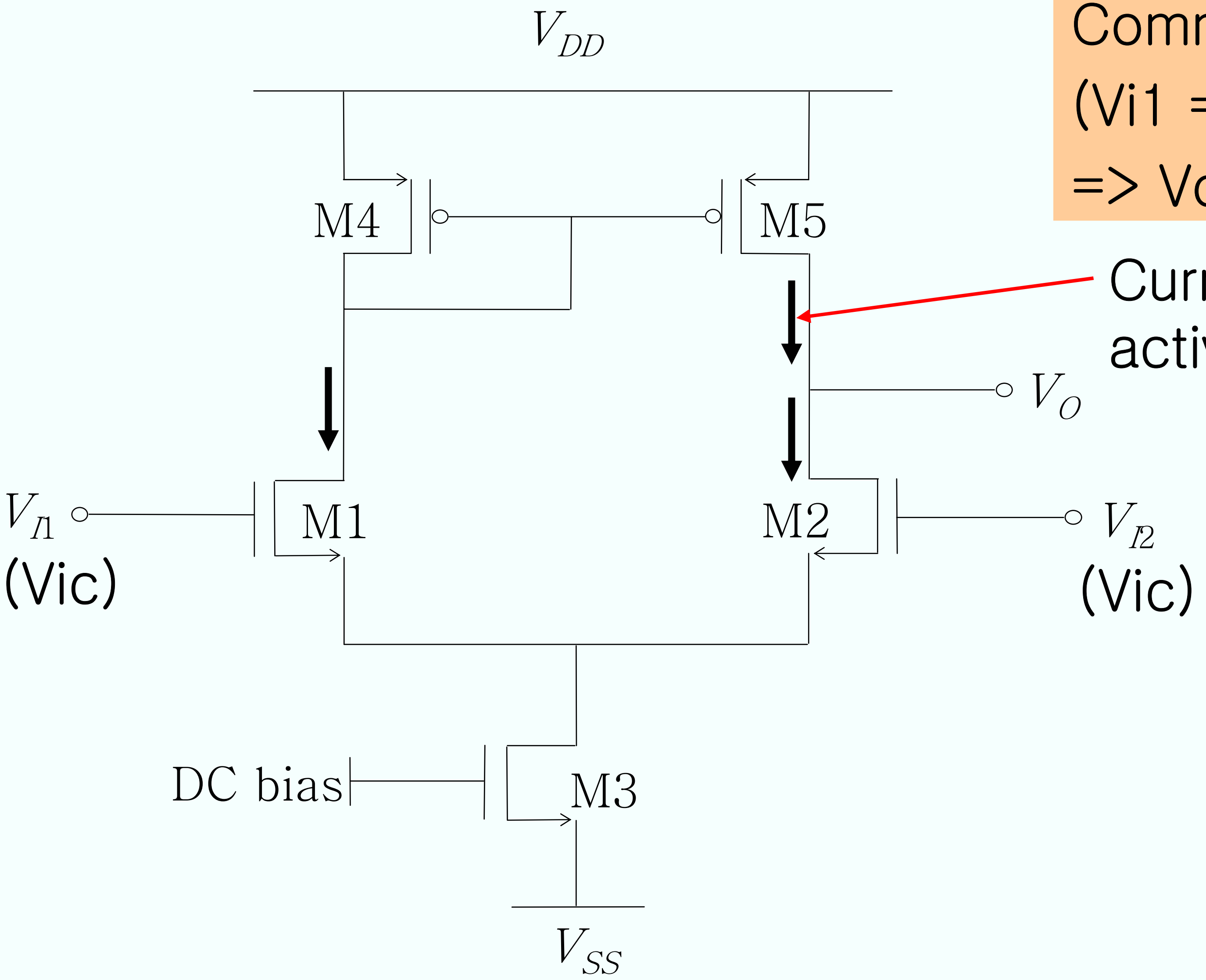
output: single-ended

M4, M5: active load

(1) x2 differential mode signal

(2) Cancel common mode signal

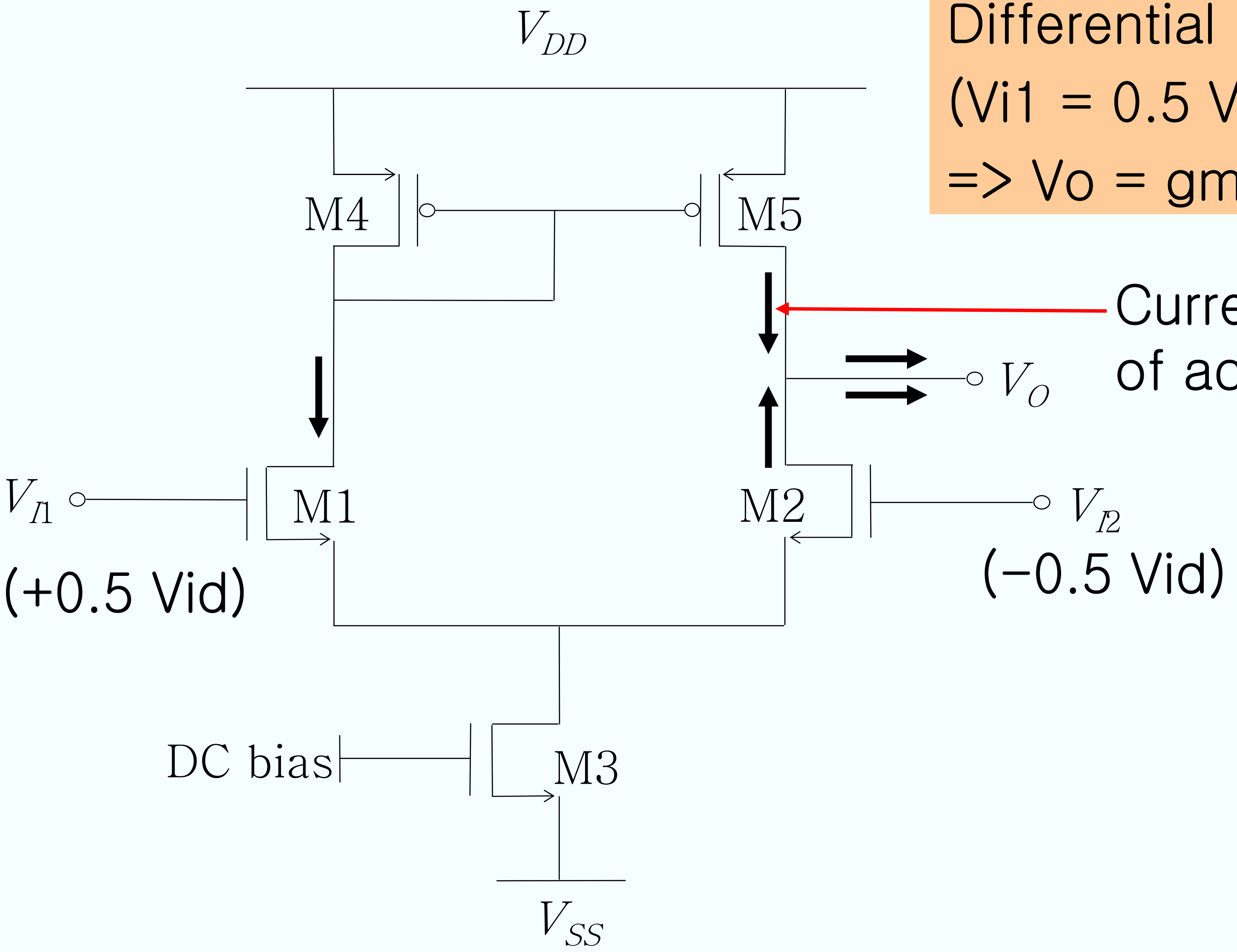
5.2 Active load NMOS differential pair



Common mode input
(Vi1 = Vi2 = Vic)
=> Vo = 0

Current mirror operation of active load(M4, M5)
~= Vic / (2 x ro3)

5.2 Active load NMOS differential pair



Differential mode input

(Vi1 = 0.5 Vid, Vi2 = −0.5 Vid)

=> Vo = gm x Ro x Vid

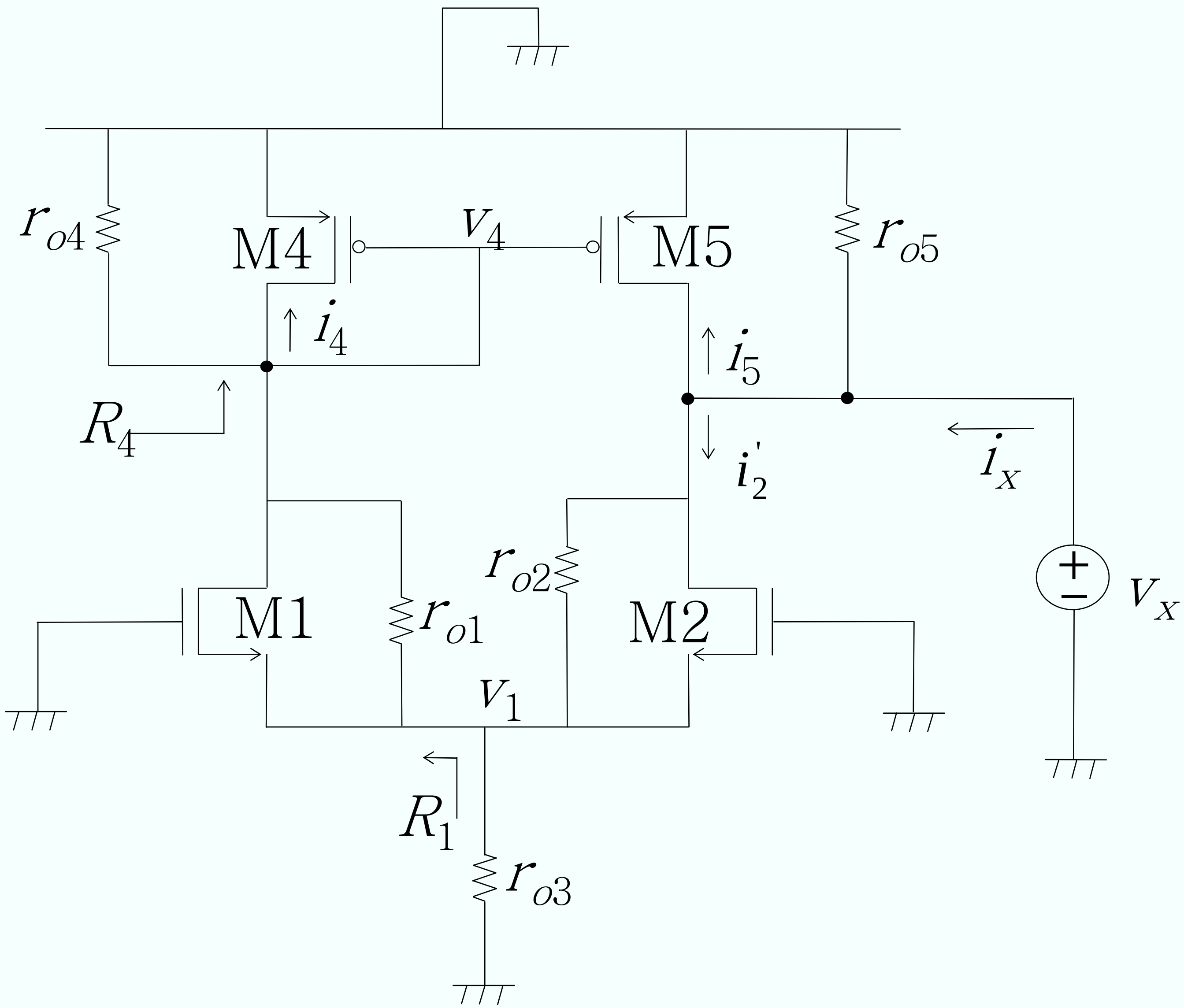
Current mirror operation of active load(M4, M5)

0.5 x gm x Vid

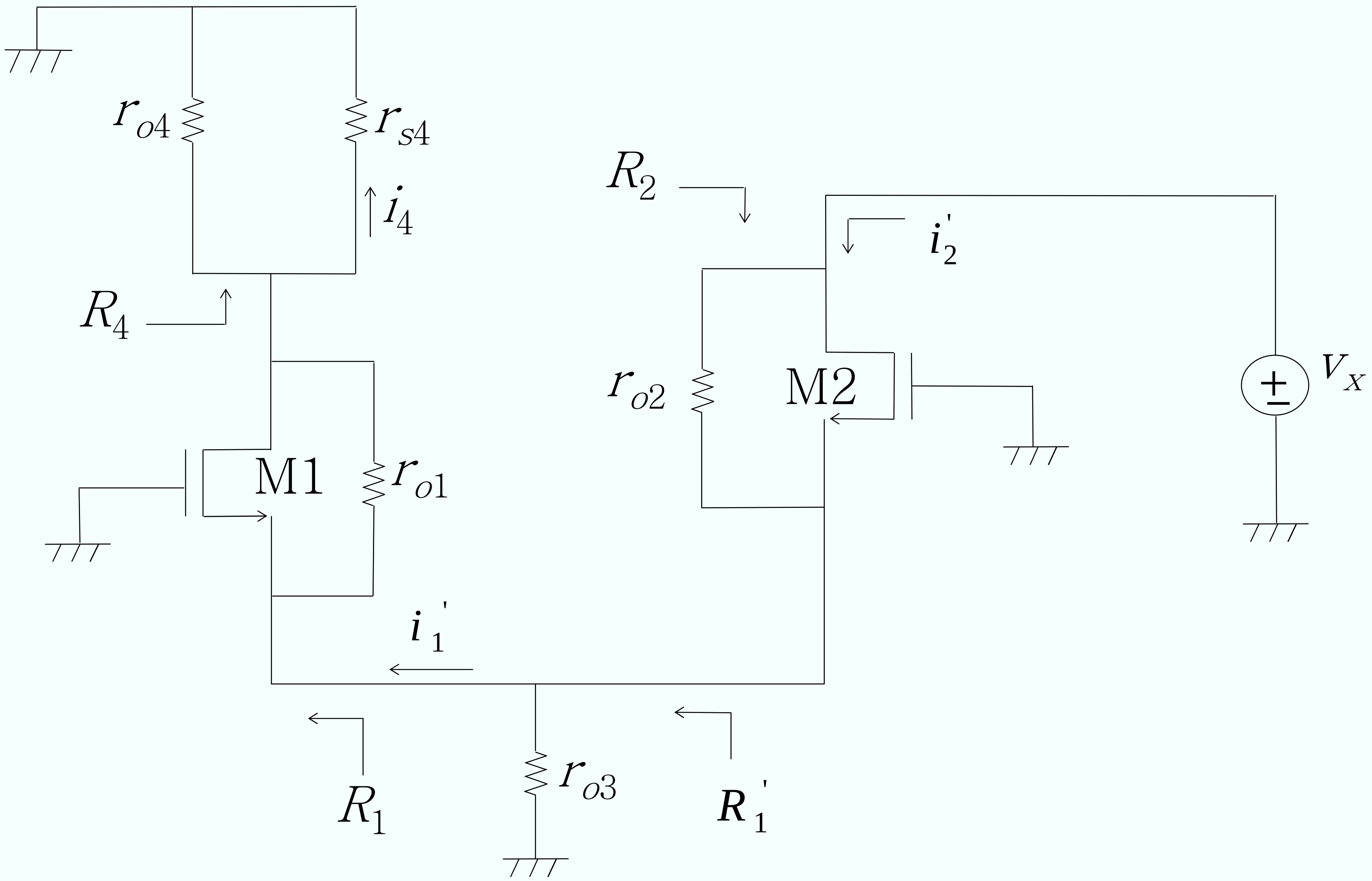
5.2 Active load NMOS differential pair

Apply the Gm Ro method

Small-signal analysis (Ro)

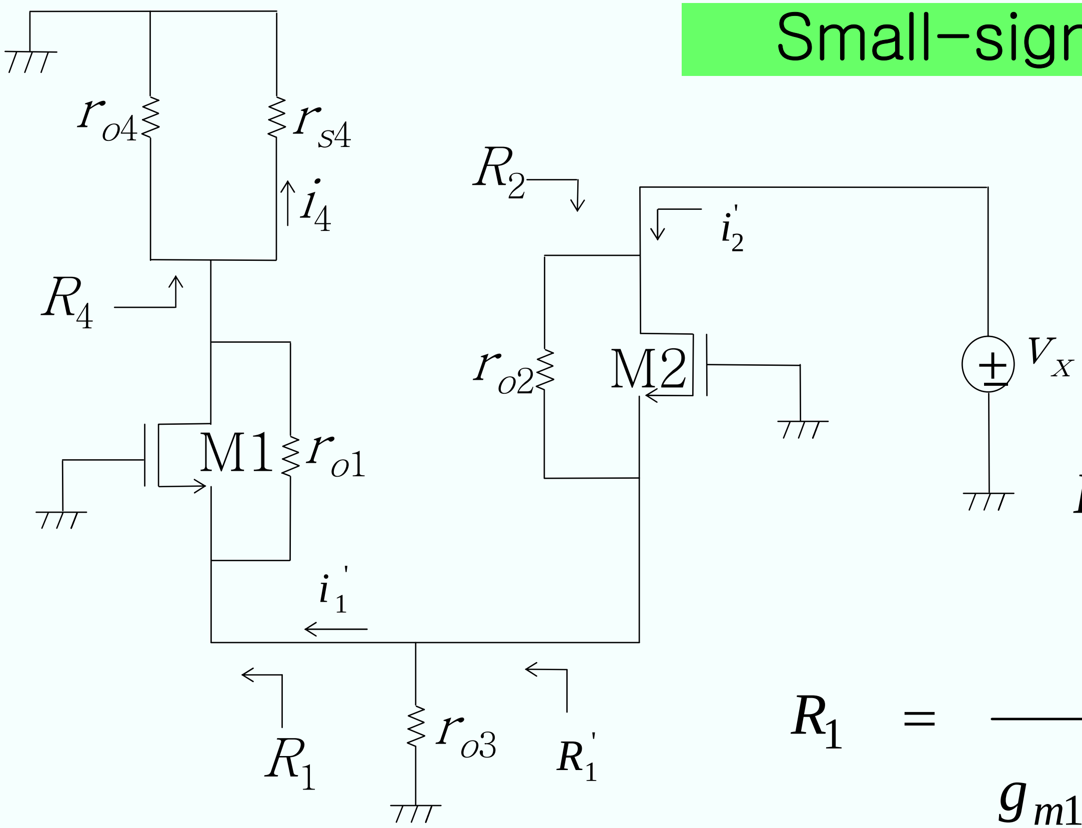


Small-signal analysis (Ro)



5.2 Active load NMOS differential pair

Small-signal analysis (Ro)



$$R_4 = r_{s4} \parallel r_{o4} \approx r_{s4} = \frac{1}{g_{m4}}$$

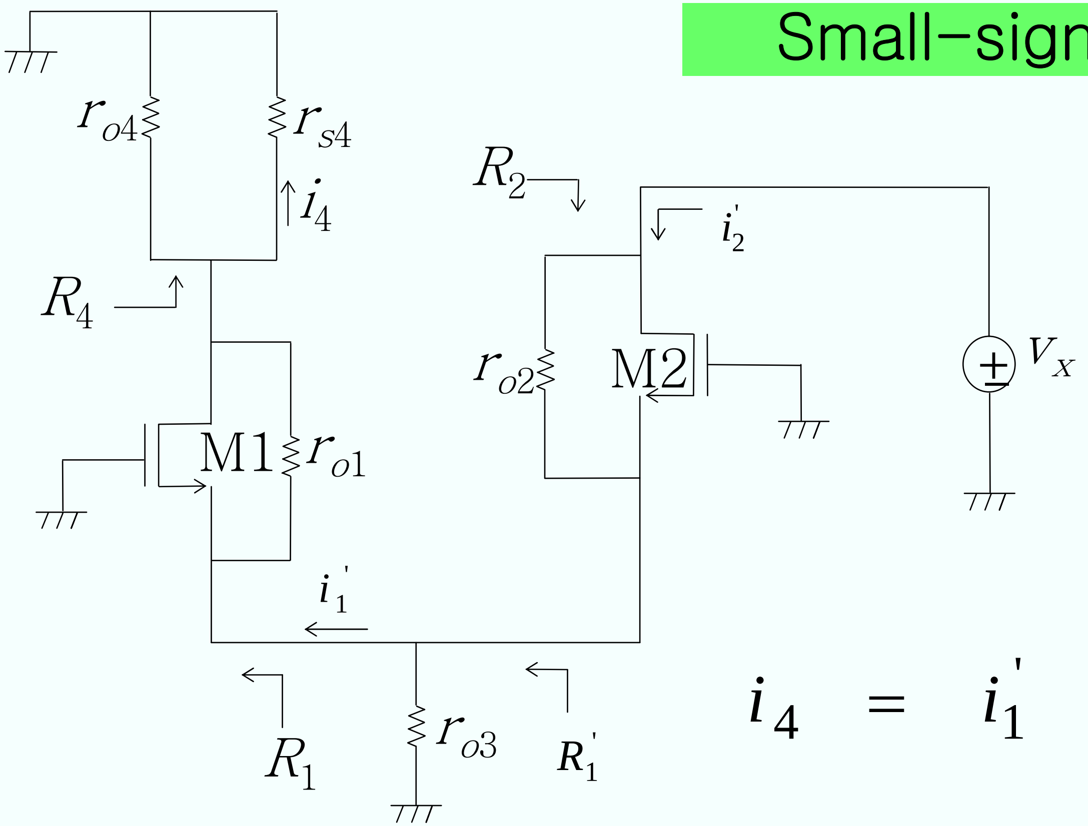
$$R_1 = \frac{1}{g_{m1} + \frac{1}{r_{o1}}} \cdot \left(1 + \frac{R_4}{r_{o1}}\right) \approx \frac{1}{g_{m1}} = r_{s1}$$

$$R_1^{'} = r_{o3} \parallel R_1 = r_{o3} \parallel r_{s1} \approx r_{s1}$$

$$i_1^{'} \approx i_2^{'}$$

5.2 Active load NMOS differential pair

Small-signal analysis (Ro)



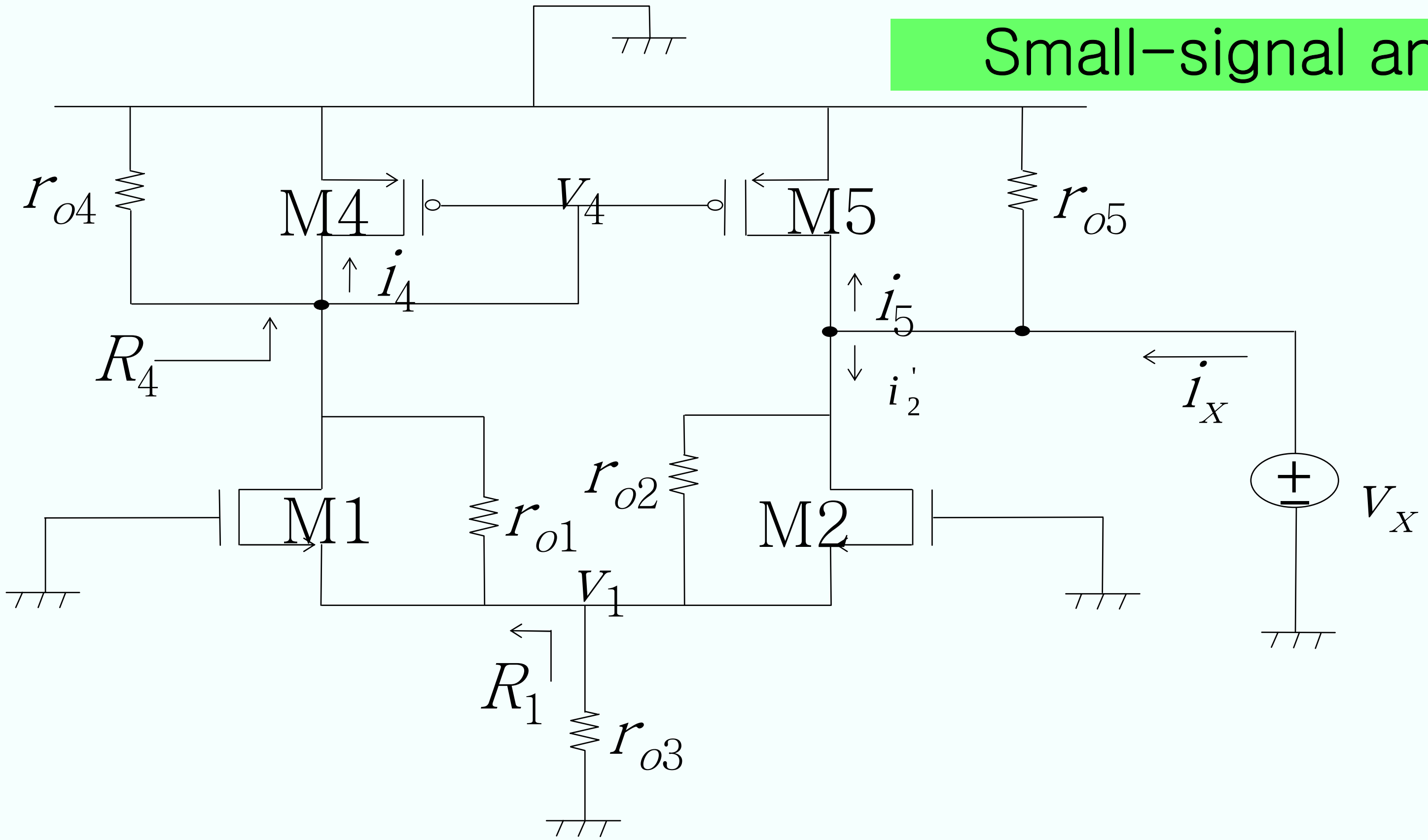
$$i_4 = i_1' \cdot \frac{r_{o4}}{r_{s4} + r_{o4}} \approx i_1' \approx i_2'$$

$$R_2 = g_{m2} r_{o2} \cdot R_1' + r_{o2} + R_1' = g_{m2} r_{o2} \cdot r_{s1} + r_{o2} + r_{s1} \approx 2 r_{o2}$$

$$i_2' = \frac{v_x}{R_2} = \frac{v_x}{2 r_{o2}}$$

5.2 Active load NMOS differential pair

Small-signal analysis (Ro)

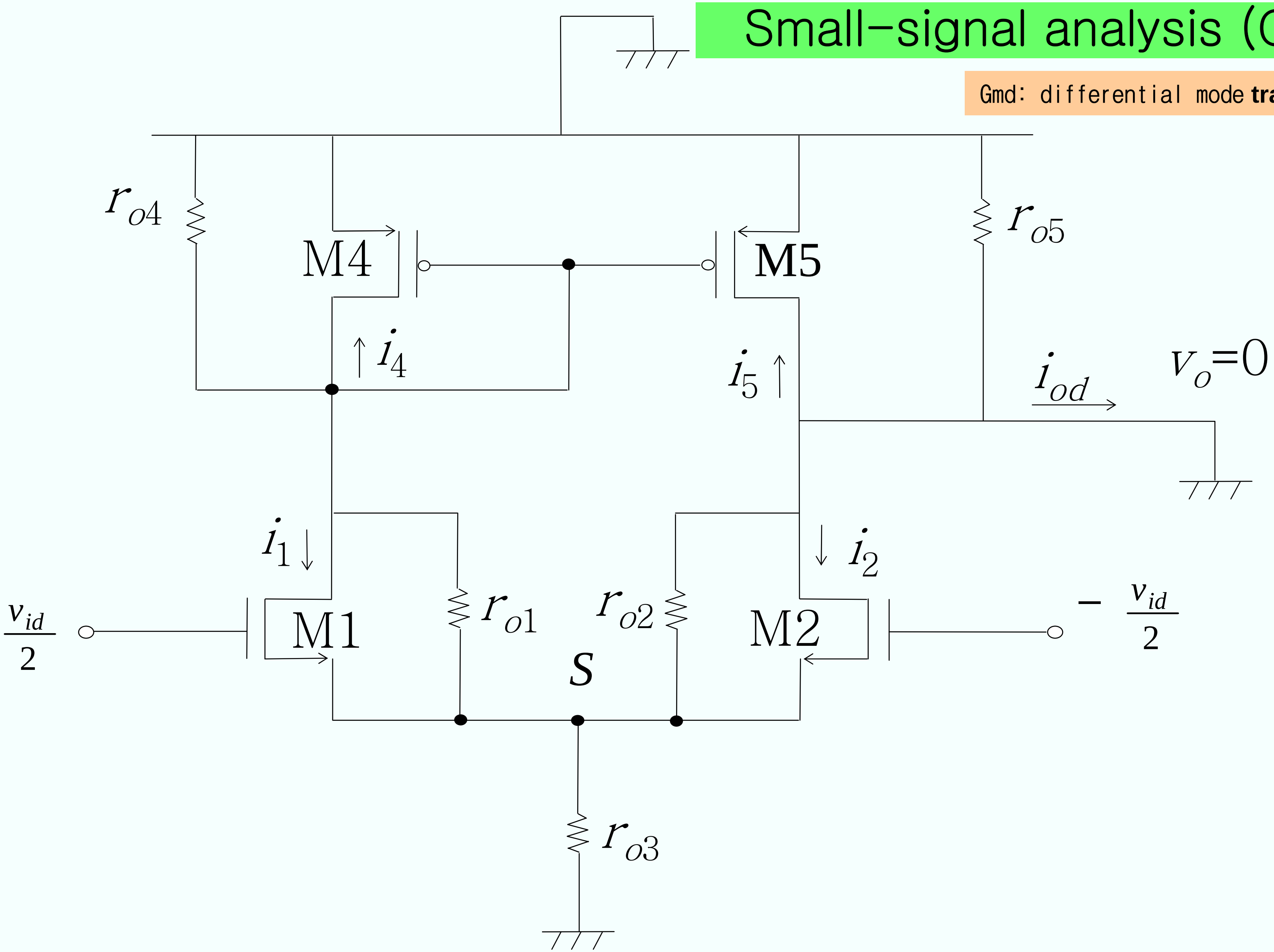


$$i_x = i_5 + i_2' + \frac{v_x}{r_{o5}} = i_2' + i_2' + \frac{v_x}{r_{o5}} = v_x \cdot \left(\frac{1}{r_{o2}} + \frac{1}{r_{o5}} \right)$$

$$R_o = \frac{v_x}{i_x} = \left(\frac{1}{r_{o2}} + \frac{1}{r_{o5}} \right)^{-1} = r_{o2} \parallel r_{o5}$$

Small-signal analysis (Gmd)

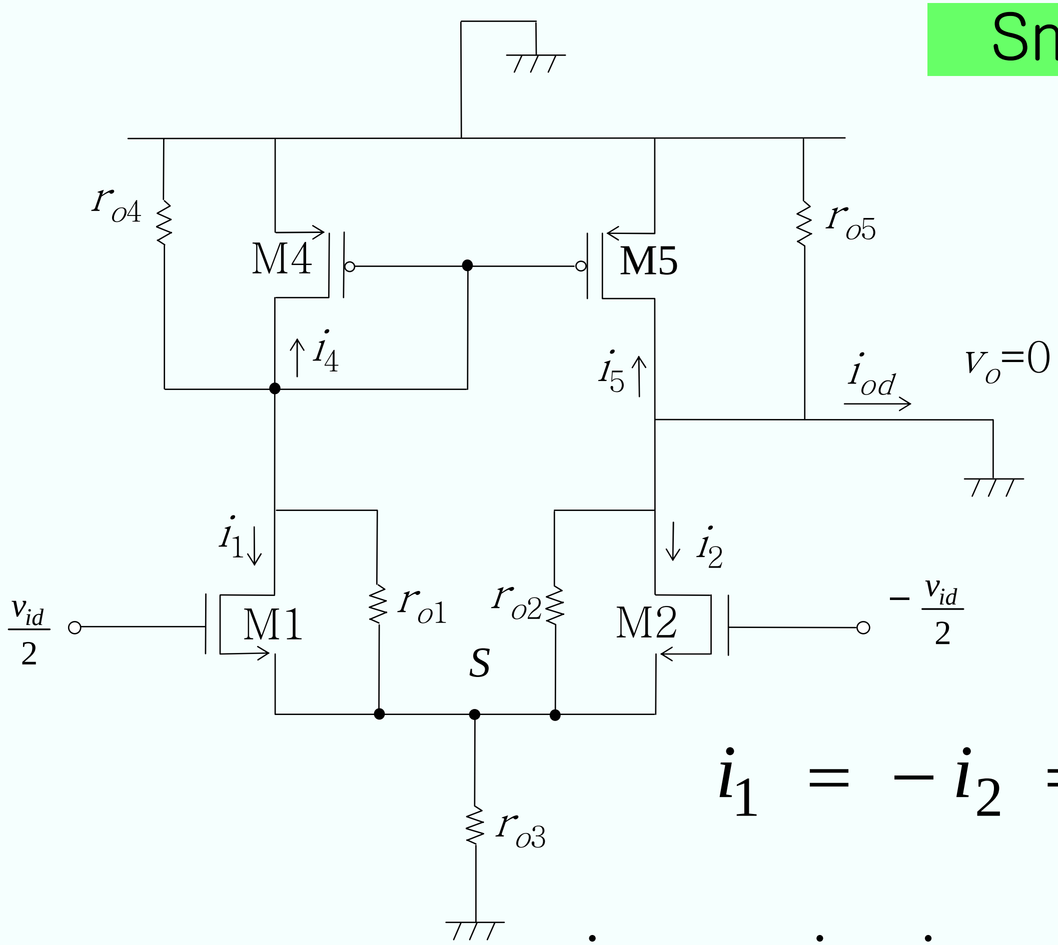
Gmd: differential mode **transconductance**



5.2 Active load NMOS differential pair

Small-signal analysis (Gmd)

Gmd: differential mode **transconductance**



$$i_1 = -i_2 = v_{id}/(r_{s1}+r_{s2}) = v_{id}/(2r_{s1})$$

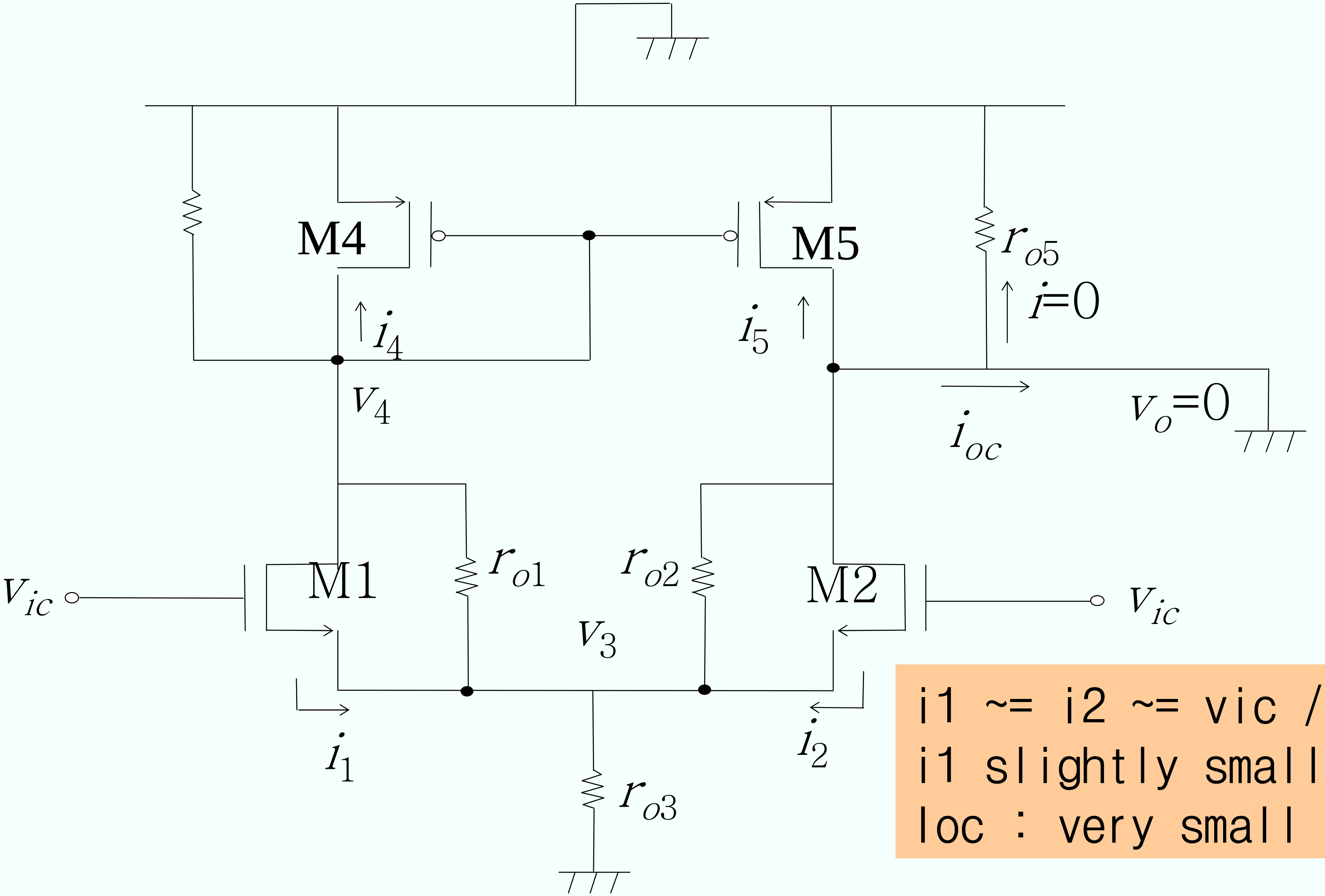
$$i_{od} = -i_5 - i_2 = -i_4 - i_2 = i_1 - i_2 = \frac{v_{id}}{r_{s1}} = g_{m1}v_{id}$$

$$G_{md} = \frac{i_{od}}{v_{id}} = g_{m1}$$

5.2 Active load NMOS differential pair

Small-signal analysis (Gmc)

Gmc : **common mode transconductance**



i1 ~= i2 ~= vic / (2 x ro3)

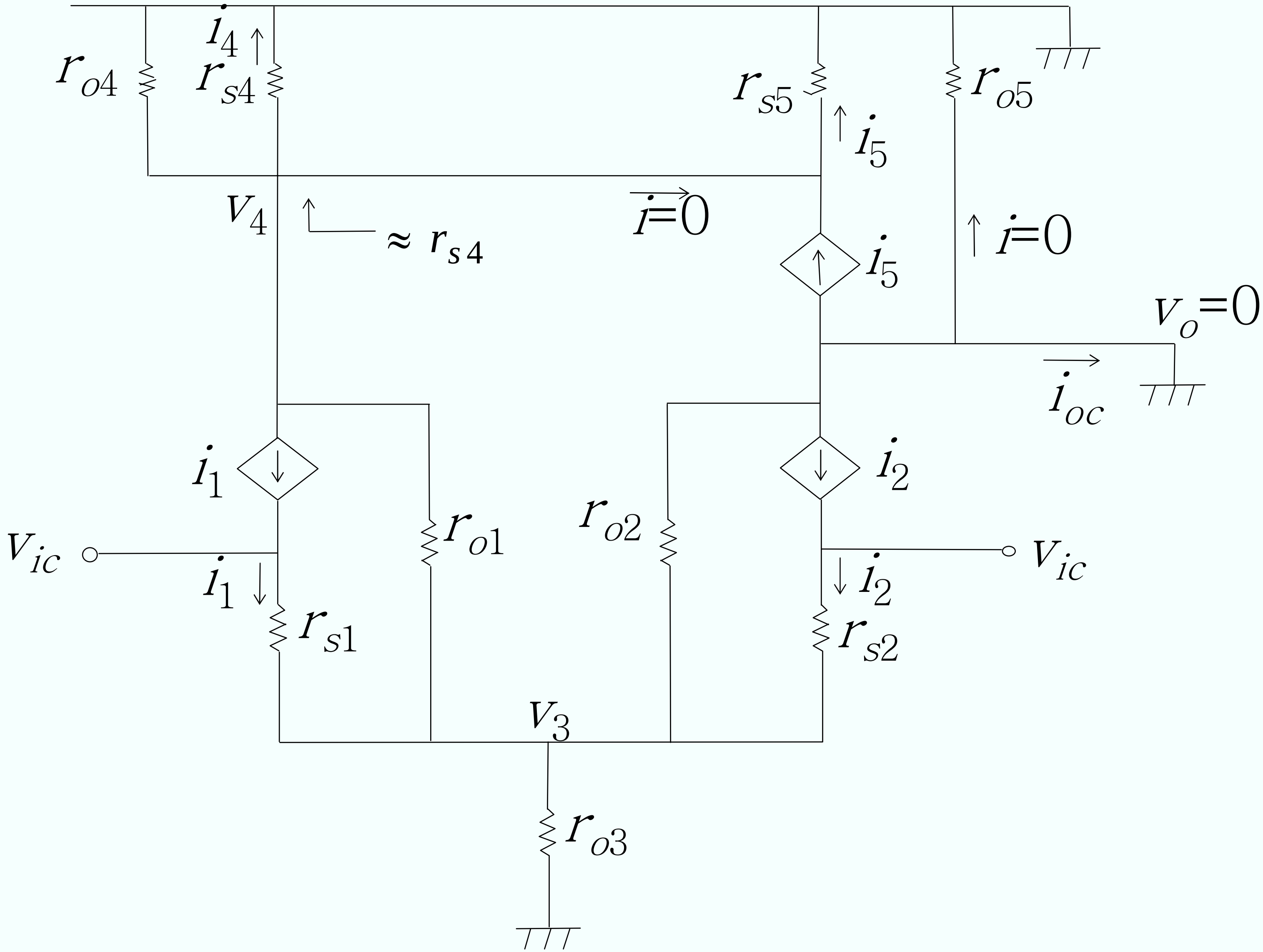
i1 slightly smaller than i2

Ioc : very small negative

5.2 Active load NMOS differential pair

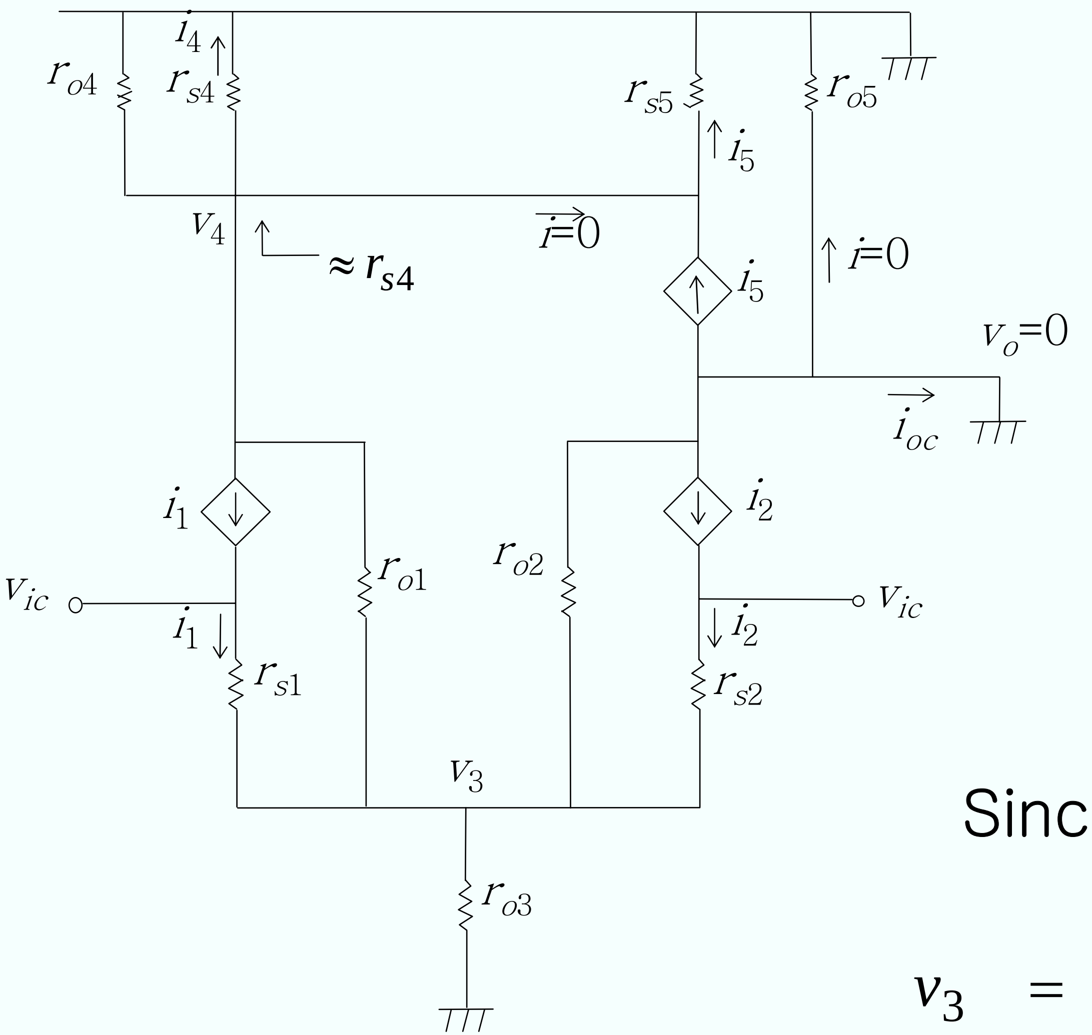
Small-signal analysis (Gmc)

Gmc : **common mode transconductance**



5.2 Active load NMOS differential pair

Small-signal analysis (Gmc)

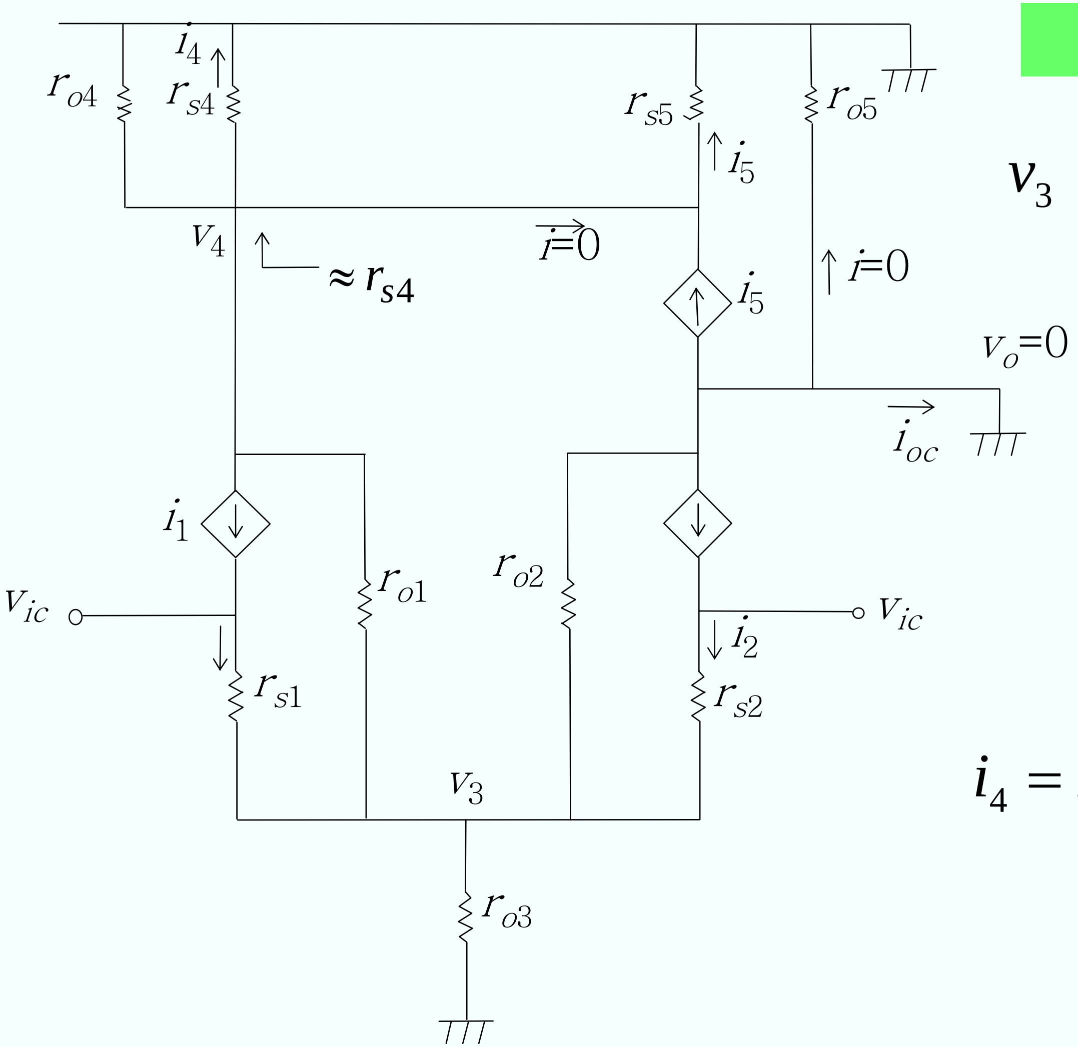


$$v_4 = \left(-i_1 + \frac{v_3 - v_4}{r_{o1}}\right) \cdot (r_{s4} \| r_{o4})$$

$$v_4 = \frac{-i_1 \cdot (r_{s4} \| r_{o4}) + \dfrac{r_{s4} \| r_{o4}}{r_{o1}} \cdot v_3}{1 + \dfrac{r_{s4} \| r_{o4}}{r_{o1}}}$$

Since v4 << v3, assume v4 ~= 0

$$v_3 = \frac{2(r_{o1} \| r_{o2} \| r_{o3})}{r_{s1} + 2(r_{o1} \| r_{o2} \| r_{o3})} \cdot v_{ic} \approx v_{ic}$$



Intuitive way of deriving Gmc

$$v_3 = \frac{2(r_{o1} \| r_{o2} \| r_{o3})}{r_{s1} + 2(r_{o1} \| r_{o2} \| r_{o3})} \cdot v_{ic} \approx v_{ic}$$

$$i_3 = \frac{v_{ic}}{r_{o3}}$$

$$i_{M1} \approx 0.5 \cdot i_3 \cdot (1 - 0.5 \cdot \frac{r_{s4}}{r_{o1}})$$

$$i_{M2} \approx 0.5 \cdot i_3 \cdot (1 + 0.5 \cdot \frac{r_{s4}}{r_{o1}})$$

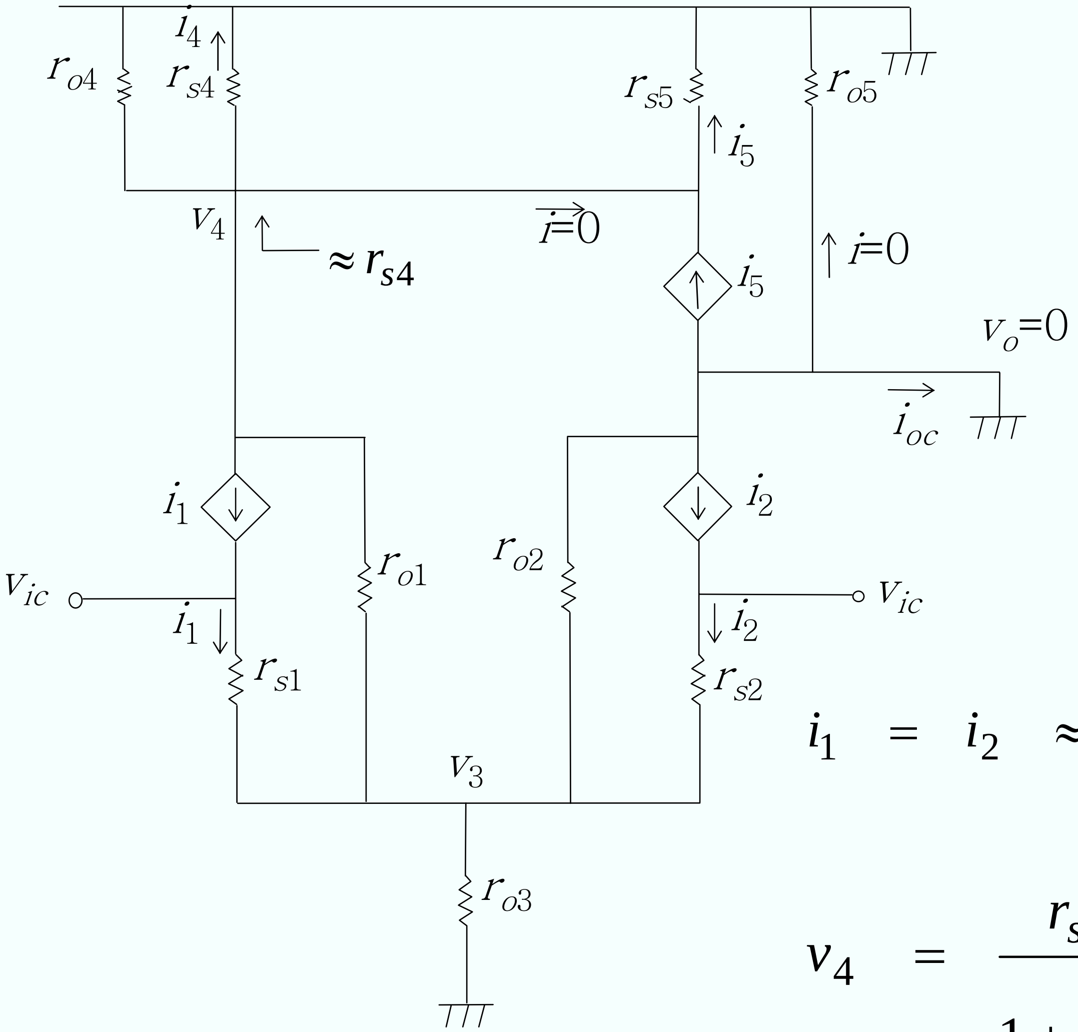
$$i_4 = i_5 = -0.5 \cdot i_3 \cdot (1 - 0.5 \cdot \frac{r_{s4}}{r_{o1}}) \cdot (1 - \frac{r_{s4}}{r_{o4}})$$

$$\approx -0.5 \cdot i_3 \cdot (1 - 0.5 \cdot \frac{r_{s4}}{r_{o1}} - \frac{r_{s4}}{r_{o4}})$$

$$i_{oc} = -i_5 - i_{M2} = -0.5\, i_3 \cdot r_{s4} \cdot (\frac{1}{r_{o1}} + \frac{1}{r_{o4}}) = \frac{-v_{ic}}{2\, r_{o3} \cdot g_{m4} \cdot (r_{o1} \| r_{o4})}$$

5.2 Active load NMOS differential pair

Details of deriving Gmc



$$v_4 = \frac{-i_1 \cdot (r_{s4} \parallel r_{o4}) + \dfrac{r_{s4} \parallel r_{o4}}{r_{o1}} \cdot v_3}{1 + \dfrac{r_{s4} \parallel r_{o4}}{r_{o1}}}$$

$$v_3 = \frac{2(r_{o1} \parallel r_{o2} \parallel r_{o3})}{r_{s1} + 2(r_{o1} \parallel r_{o2} \parallel r_{o3})} \cdot v_{ic} \approx v_{ic}$$

$$i_1 = i_2 \approx \frac{v_{ic}}{r_{s1} + 2\,(r_{o1} \parallel r_{o2} \parallel r_{o3})} \approx \frac{v_{ic}}{2\,(r_{o1} \parallel r_{o2} \parallel r_{o3})}$$

$$v_4 = \frac{r_{s4} \parallel r_{o4}}{1 + \dfrac{r_{s4} \parallel r_{o4}}{r_{o1}}} \cdot v_{ic} \cdot \left\{ \frac{1}{r_{o1}} - \frac{1}{2\,(r_{o1} \parallel r_{o2} \parallel r_{o3})} \right\}$$

5.2 Active load NMOS differential pair

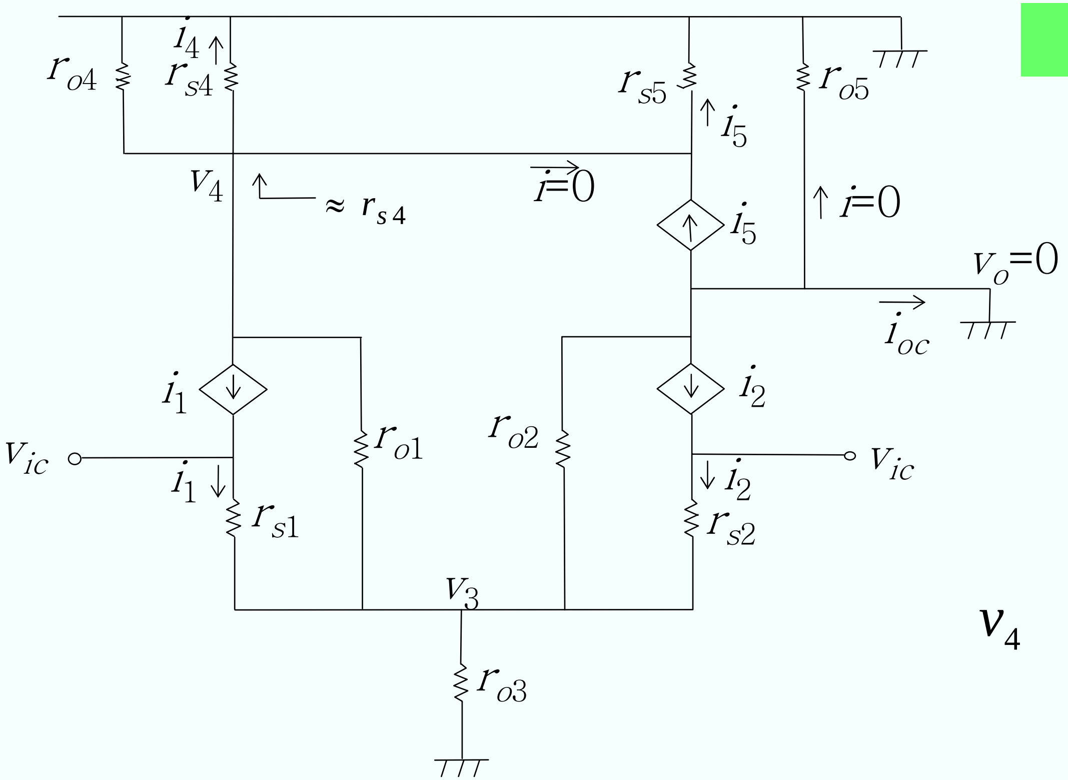
Details of deriving Gmc

$$v_4 = \frac{r_{s4} \parallel r_{o4}}{1 + \dfrac{r_{s4} \parallel r_{o4}}{r_{o1}}} \cdot v_{ic} \cdot \left\{ \frac{1}{r_{o1}} - \frac{1}{2(r_{o1} \parallel r_{o2} \parallel r_{o3})} \right\}$$

$$v_4 = \frac{r_{s4} \parallel r_{o4}}{1 + \dfrac{r_{s4} \parallel r_{o4}}{r_{o1}}} \cdot v_{ic} \cdot \left\{ -\frac{1}{2\, r_{o3}} \right\} \quad if\ r_{o1} = r_{o2}$$

5.2 Active load NMOS differential pair

Details of deriving Gmc



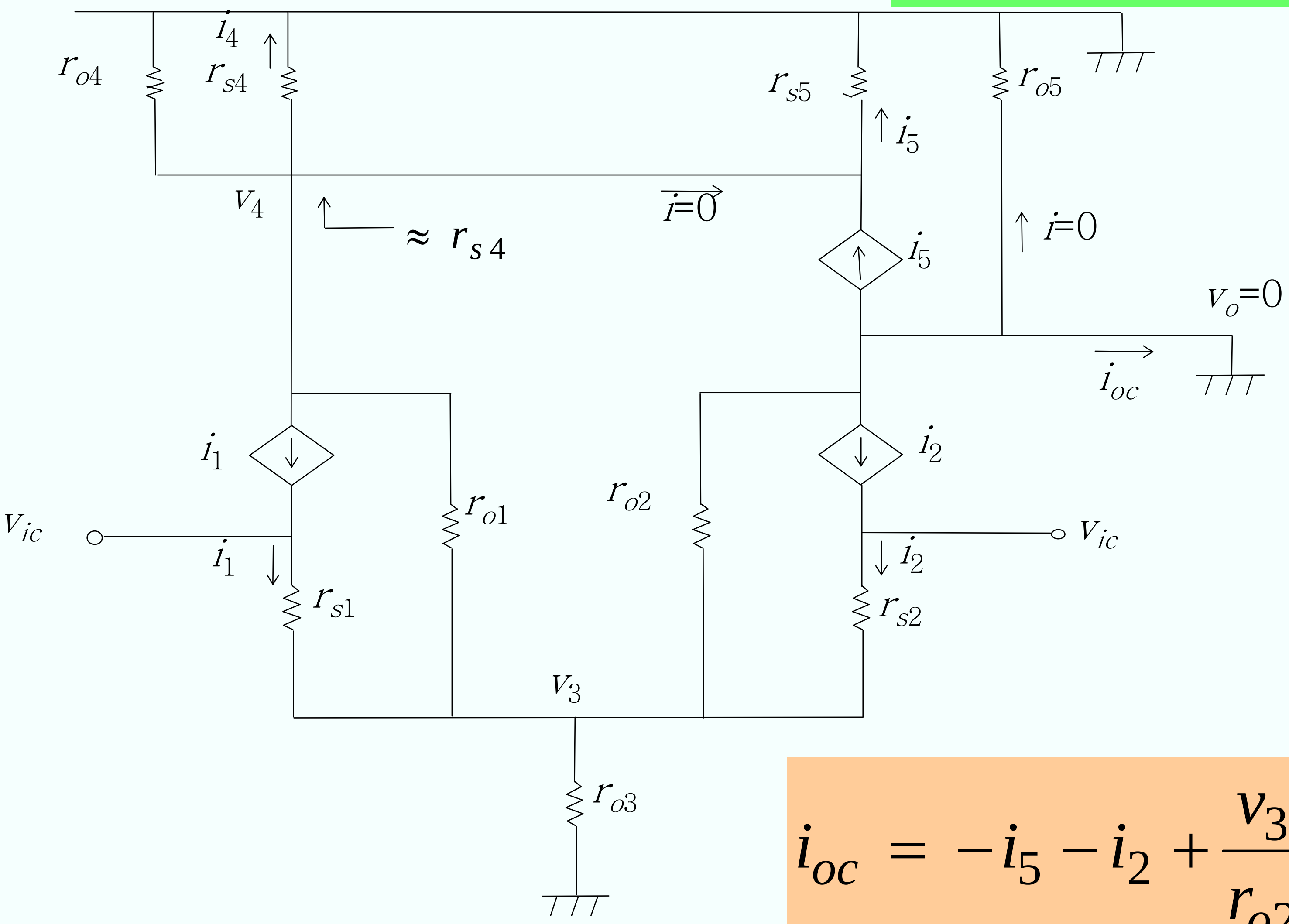
$$v_4 = \frac{r_{s4} \| r_{o4}}{1+\dfrac{r_{s4} \| r_{o4}}{r_{o1}}} \cdot v_{ic} \cdot \left\{ -\frac{1}{2\,r_{o3}} \right\} \quad if \;\; r_{o1} = r_{o2}$$

$$i_4 = \frac{v_4}{r_{s4}} = \frac{v_{ic}}{1+\dfrac{r_{s4} \| r_{o4}}{r_{o1}}} \cdot \left(-\frac{1}{2r_{o3}} \right) \cdot \frac{r_{s4} \| r_{o4}}{r_{s4}} = \frac{v_{ic}}{1+\dfrac{r_{s4} \| r_{o4}}{r_{o1}}} \cdot \left(-\frac{1}{2r_{o3}} \right) \cdot \frac{1}{1+\dfrac{r_{s4}}{r_{o4}}}$$

$$\approx \left\{ -\frac{v_{ic}}{2r_{o3}} \right\} \cdot \left(1 - \frac{r_{s4} \| r_{o4}}{r_{o1}} - \frac{r_{s4}}{r_{o4}} \right) \approx \left\{ -\frac{v_{ic}}{2r_{o3}} \right\} \cdot \left(1 - \frac{r_{s4}}{r_{o1}} - \frac{r_{s4}}{r_{o4}} \right) = \left\{ -\frac{v_{ic}}{2r_{o3}} \right\} \cdot \left\{ 1 - \frac{1}{g_{m4}(r_{o1} \| r_{o4})} \right\}$$

5.2 Active load NMOS differential pair

Details of deriving Gmc



$$i_{oc} = -i_5 - i_2 + \frac{v_3}{r_{o2}} = -i_4 - i_1 + \frac{v_{ic}}{r_{o2}}$$

Details of deriving Gmc

$$i_{oc} = -i_5 - i_2 + \frac{v_3}{r_{o2}} = -i_4 - i_1 + \frac{v_{ic}}{r_{o2}}$$

$$= v_{ic} \cdot \left(\frac{1}{2r_{o3}} \cdot \left\{ 1 - \frac{1}{g_{m4}(r_{o1} \parallel r_{o4})} \right\} - \frac{1}{2(r_{o1} \parallel r_{o2} \parallel r_{o3})} + \frac{1}{r_{o2}} \right)$$

$$\approx v_{ic} \cdot \left\{ \frac{1}{2r_{o3}} \cdot \left(1 - \frac{1}{g_{m4} \cdot (r_{o1} \parallel r_{o4})} \right) - \frac{1}{2} \left(\frac{1}{r_{o1}} + \frac{1}{r_{o2}} + \frac{1}{r_{o3}} \right) + \frac{1}{r_{o2}} \right\}$$

$$\approx v_{ic} \cdot \left\{ \frac{1}{2r_{o3}} \cdot \left(1 - \frac{1}{g_{m4} \cdot (r_{o1} \parallel r_{o4})} \right) - \frac{1}{2\, r_{o3}} \right\} \quad if \quad r_{o1} = r_{o2}$$

$$= -\frac{v_{ic}}{2r_{o3} \cdot \left\{ g_{m4}(r_{o1} \parallel r_{o4}) \right\}}$$

Small-signal analysis (Gmc)

$$i_{oc} = -\frac{v_{ic}}{2r_{o3} \cdot \{g_{m4}(r_{o1} \| r_{o4})\}}$$

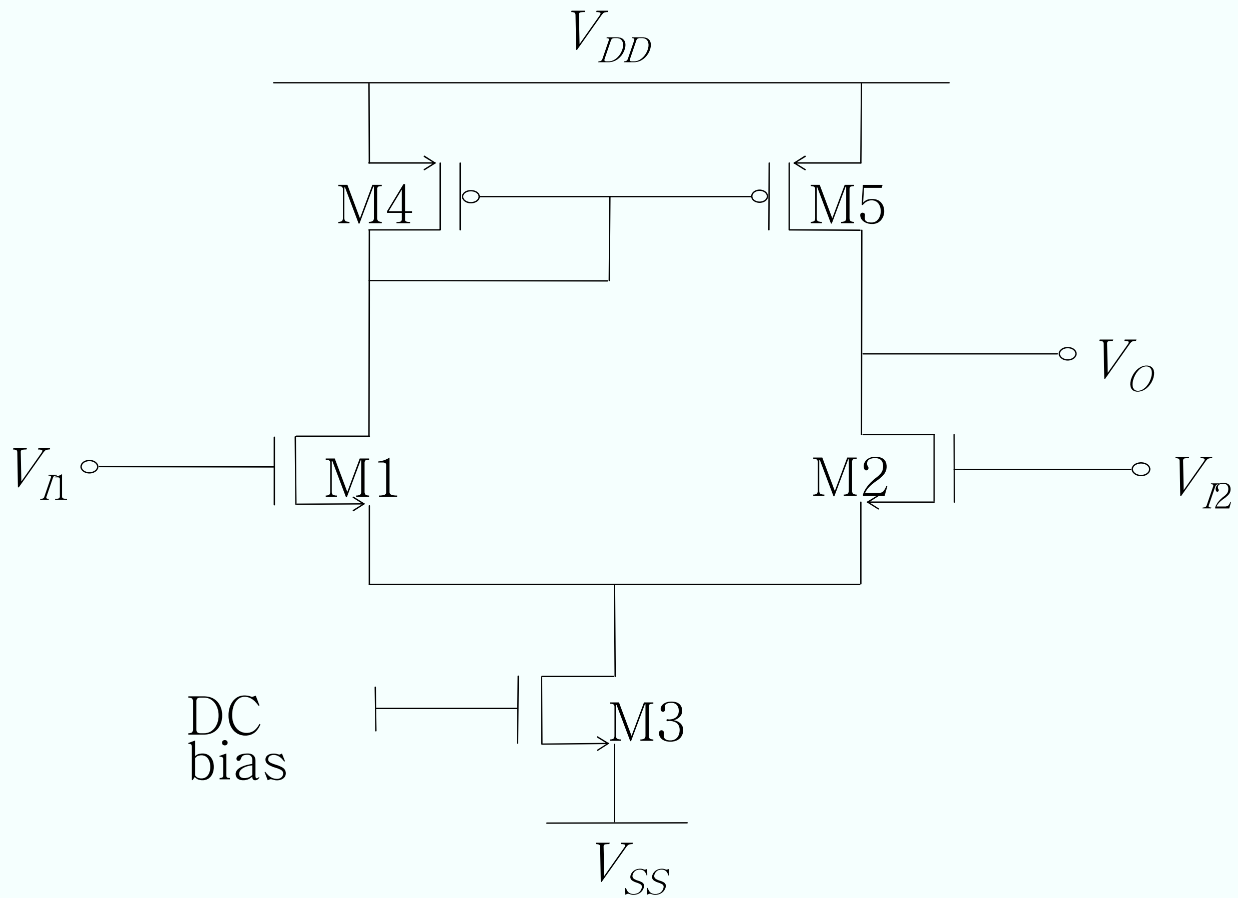
$$G_{mc} = \frac{i_{oc}}{v_{ic}} = -\frac{1}{2r_{o3} \cdot g_{m4}(r_{o1} \| r_{o4})}$$

$$CMRR = \left|\frac{A_{vd}}{A_{vc}}\right| = \left|\frac{G_{md}R_o}{G_{mc}R_o}\right| = \left|\frac{G_{md}}{G_{mc}}\right|$$

$$= (2g_{m1}r_{o3}) \cdot \{g_{m4}(r_{o1} \| r_{o4})\}$$

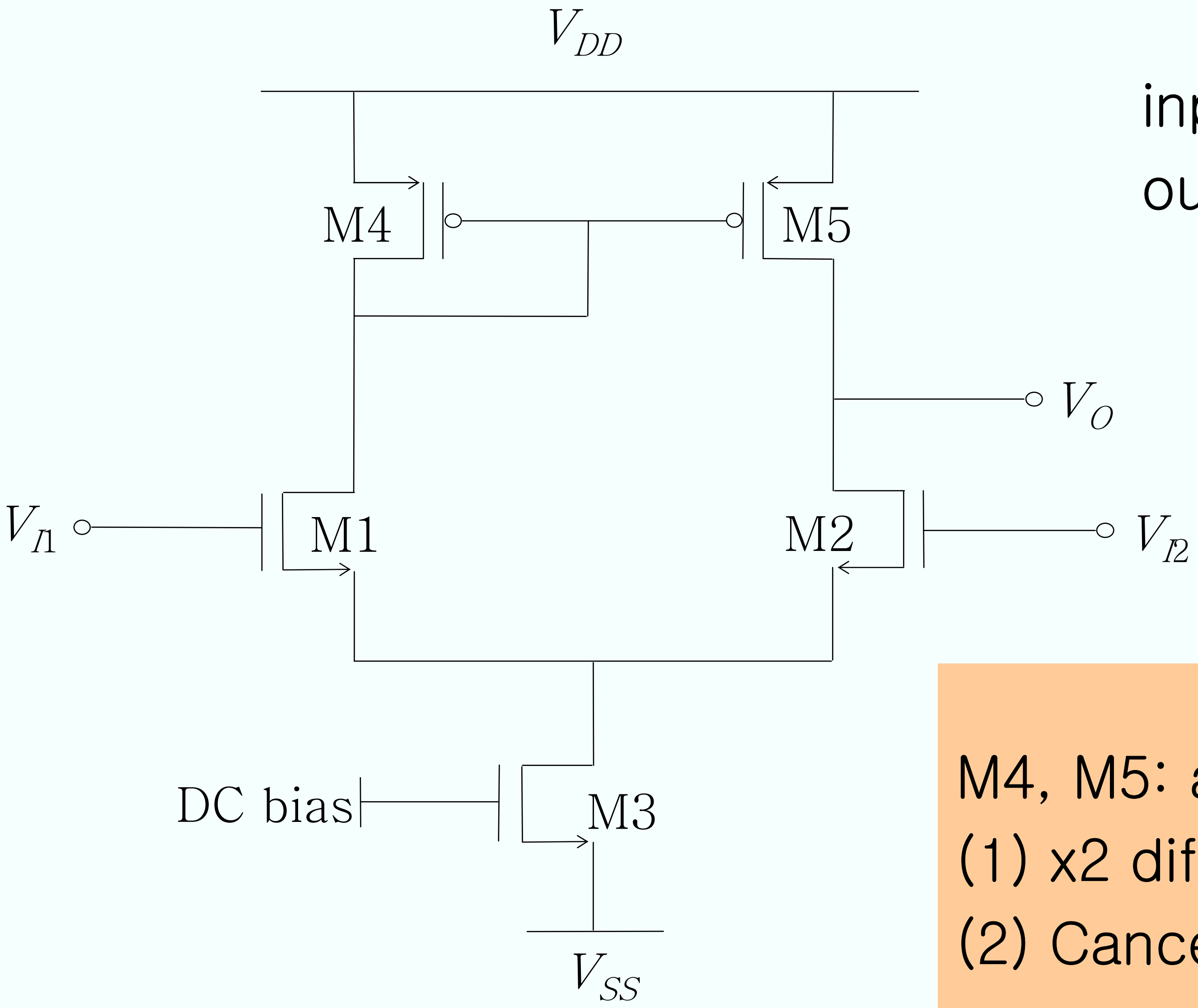
$CMRR$(active load) = $CMRR$ (R load) $\times$ $g_{m4}(r_{o1} \| r_{o4})$

Active input common mode voltage range



$$V_{SS} + V_{DSAT.3} + V_{DSAT.1} + V_{TH.1} \leq V_{IC} \leq V_{DD} - \left| V_{DSAT.4} \right| - \left| V_{TH.4} \right| + V_{TH.1}$$

Summary : Differential pair with active load



input: differential signal

output: single-ended

M4, M5: active load

(1) x2 differential mode input

(2) Cancel common mode input

Summary : Differential pair with active load

$$G_{md} = \frac{i_{od}}{v_{id}} = g_{m1}$$

$$G_{mc} = \frac{i_{oc}}{v_{ic}} = -\frac{1}{2r_{o3} \cdot g_{m4}(r_{o1} \parallel r_{o4})}$$

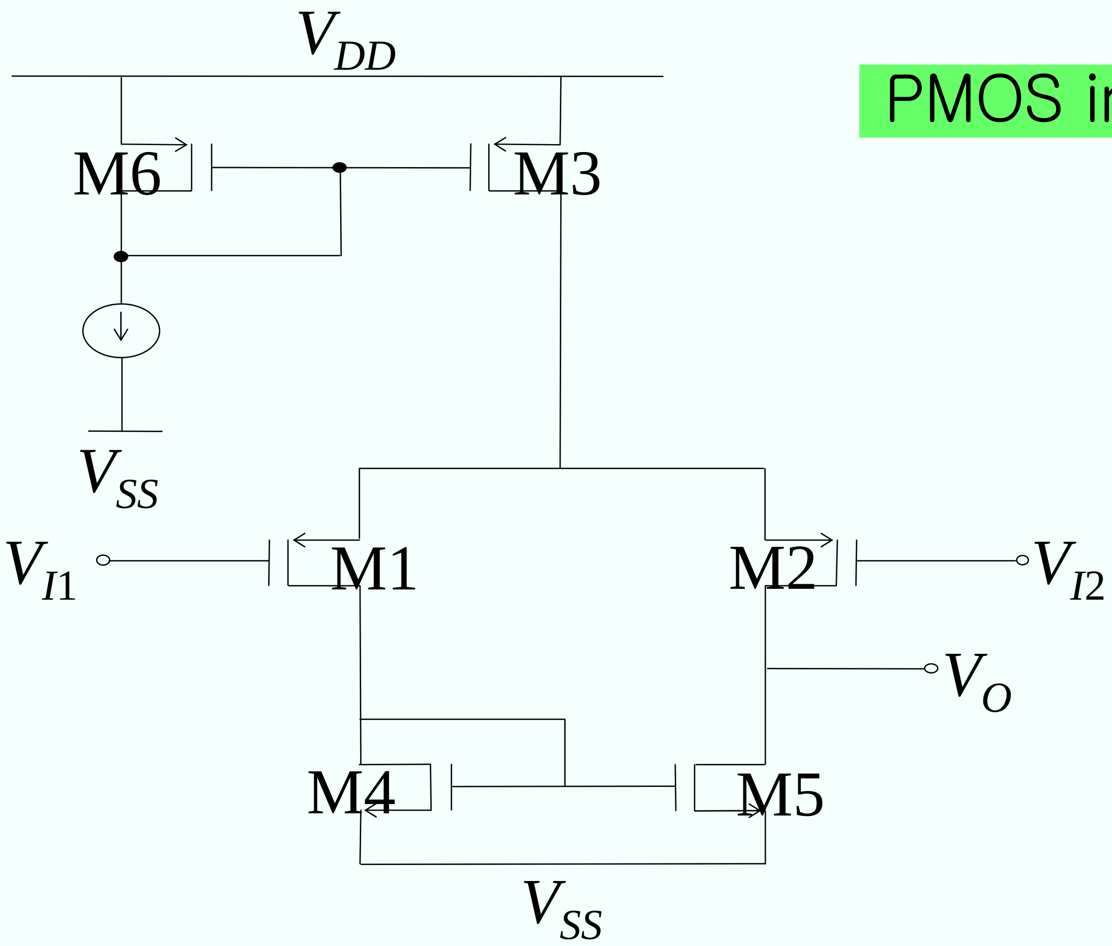
$$CMRR = \left|\frac{A_{vd}}{A_{vc}}\right| = \left|\frac{G_{md}R_o}{G_{mc}R_o}\right| = \left|\frac{G_{md}}{G_{mc}}\right|$$

$$= (2g_{m1}r_{o3}) \cdot \{g_{m4}(r_{o1} \parallel r_{o4})\}$$

$$R_o = \frac{v_x}{i_x} = \left(\frac{1}{r_{o2}} + \frac{1}{r_{o5}}\right)^{-1} = r_{o2} \parallel r_{o5}$$

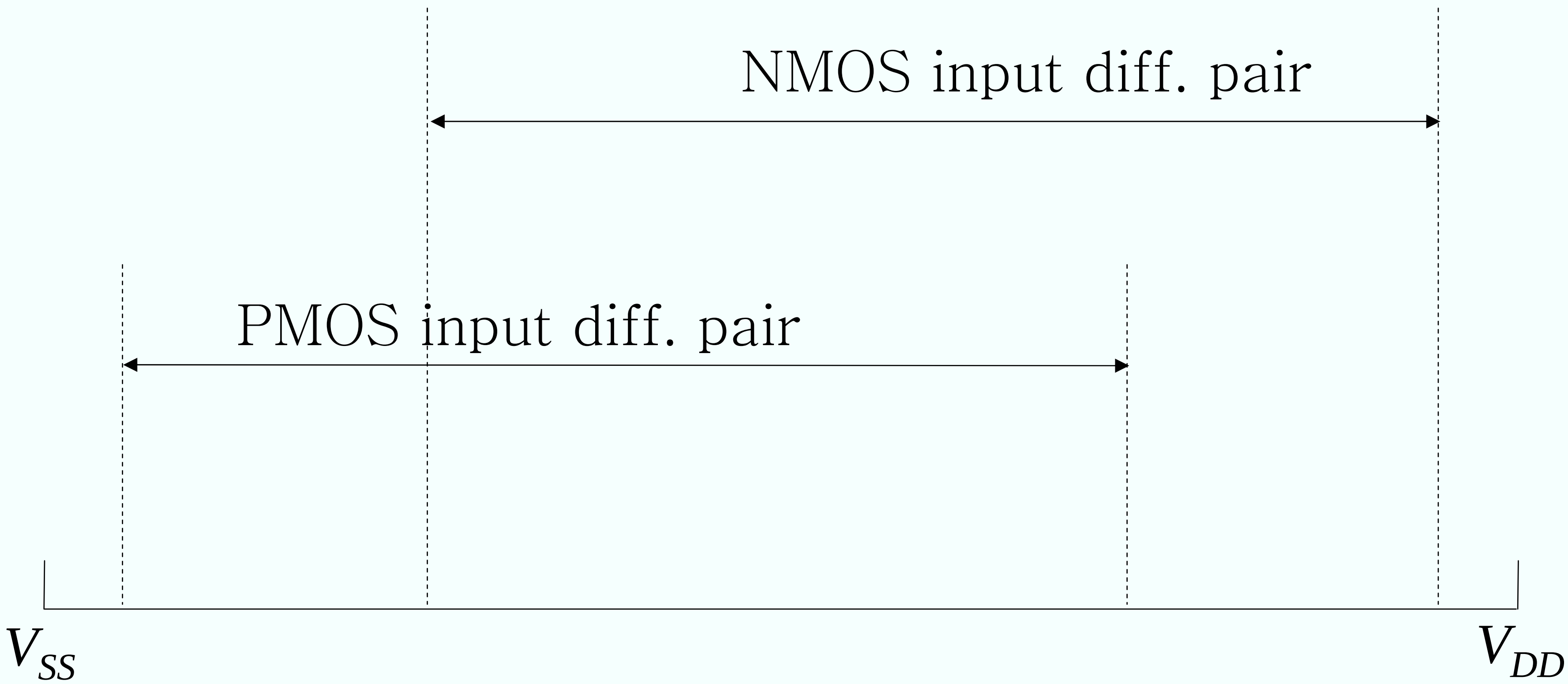
Active input common mode voltage range

PMOS input diff pair



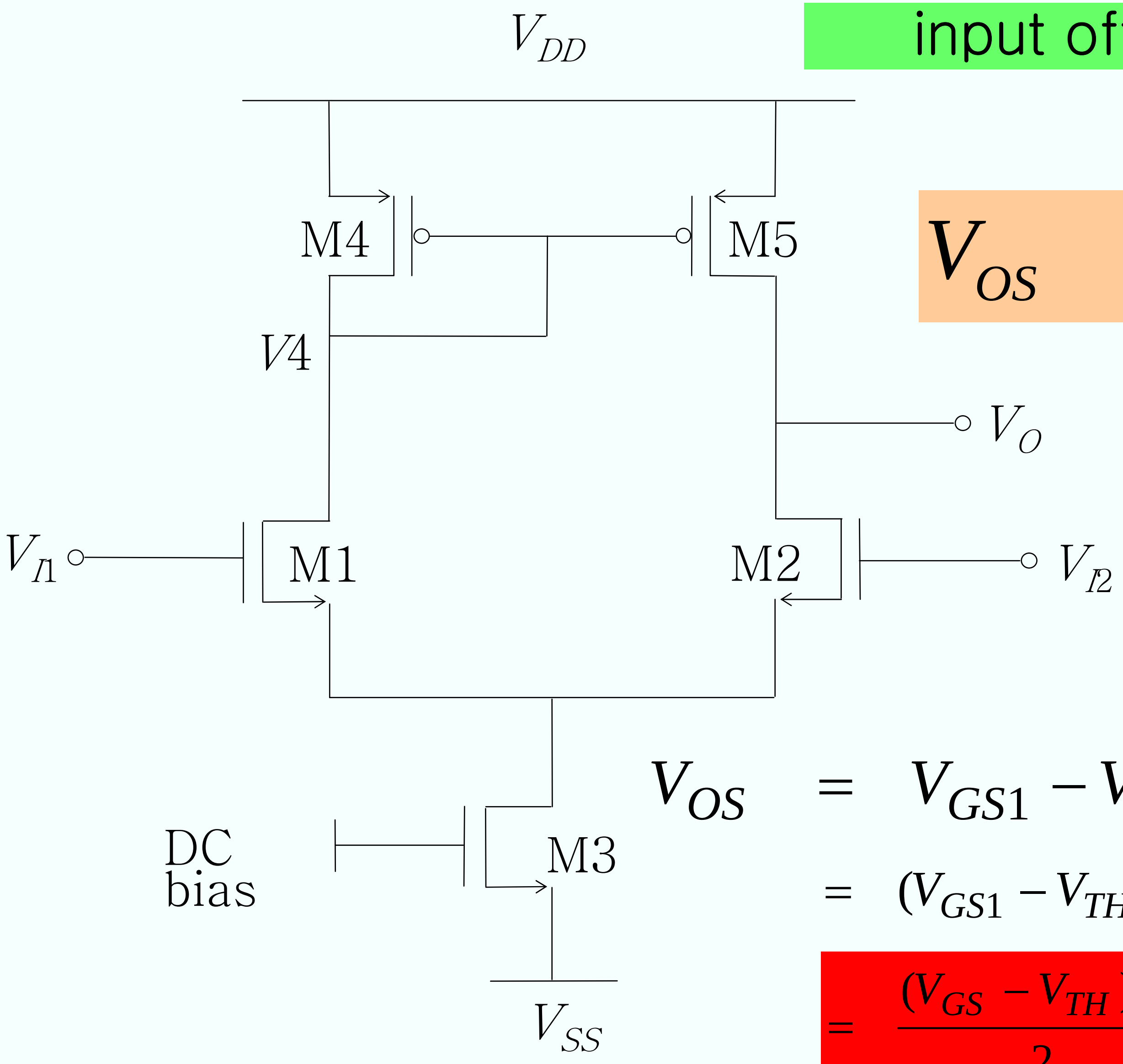
$$V_{SS} + V_{DSAT.4} + V_{TH.4} - |V_{TH.1}| \leq V_{IC} \leq V_{DD} - |V_{DSAT.3}| - |V_{DSAT.1}| - |V_{TH.1}|$$

Active input common mode voltage range



5.2 Active load NMOS differential pair

input offset voltage



$$V_{OS} = V_{I1} - V_{I2} \,|_{(V_O = V_4)}$$

$$V_{OS} = V_{GS1} - V_{GS2}$$

$$= (V_{GS1} - V_{TH1}) - (V_{GS2} - V_{TH2}) + (V_{TH1} - V_{TH2})$$

$$= \frac{(V_{GS} - V_{TH})_{1,2}}{2} \cdot \left\{ \frac{\Delta I_{D1,2}}{I_{D1,2}} - \frac{\Delta (W/L)_{1,2}}{(W/L)_{1,2}} \right\} + \Delta V_{TH1,2}$$

5.2 Active load NMOS differential pair

input offset voltage

$$V_{OS} = \frac{(V_{GS} - V_{TH})_{1,2}}{2} \cdot \left\{ \frac{\Delta I_{D1,2}}{I_{D1,2}} - \frac{\Delta (W/L)_{1,2}}{(W/L)_{1,2}} \right\} + \Delta V_{TH1,2}$$

$$I_D = \mu_p C_{ox} \cdot (W/L) \cdot (V_{GS} - V_{TH})^2 / 2$$

$$\ln I_D = \ln\left(\frac{1}{2}\mu_p C_{ox}\right) + \ln(W/L) + 2\ln(V_{GS} - V_{TH})$$

$$\frac{\Delta I_{D4,5}}{I_{D4,5}} = \frac{\Delta (W/L)_{4,5}}{(W/L)_{4,5}} + \frac{\Delta (V_{GS} - V_{TH})_{4,5}}{\left\{ \frac{(V_{GS} - V_{TH})_{4,5}}{2} \right\}}$$

input offset voltage

$$V_{OS} = \Delta V_{TH1,2} - \frac{(V_{GS} - V_{TH})_{1,2}}{(V_{GS} - V_{TH})_{4,5}} \cdot \Delta V_{TH4,5} + \frac{(V_{GS} - V_{TH})_{1,2}}{2} \cdot \left\{ -\frac{\Delta(W/L)_{1,2}}{(W/L)_{1,2}} + \frac{\Delta(W/L)_{4,5}}{(W/L)_{4,5}} \right\}$$

$$(V_{GS} - V_{TH})_{1,2} / (V_{GS} - V_{TH})_{4,5} = g_{m4,5} / g_{m1,2} = \sqrt{\mu_p (W/L)_{4,5} / \{\mu_n (W/L)_{1,2}\}}$$

$$= \Delta V_{TH1,2} + \Delta V_{TH4,5} \cdot \sqrt{\frac{\mu_p \cdot (W/L)_{4,5}}{\mu_n \cdot (W/L)_{1,2}}} + \sqrt{\frac{I_{D1,2}}{2\mu_n C_{ox} (W/L)_{1,2}}} \cdot \left\{ -\frac{\Delta(W/L)_{1,2}}{(W/L)_{1,2}} + \frac{\Delta(W/L)_{4,5}}{(W/L)_{4,5}} \right\}$$

For small offset

$$(W/L)_{4,5} << (W/L)_{1,2}$$

5.2.6 Low frequency PSRR of CMOS active load diff. pair (*)

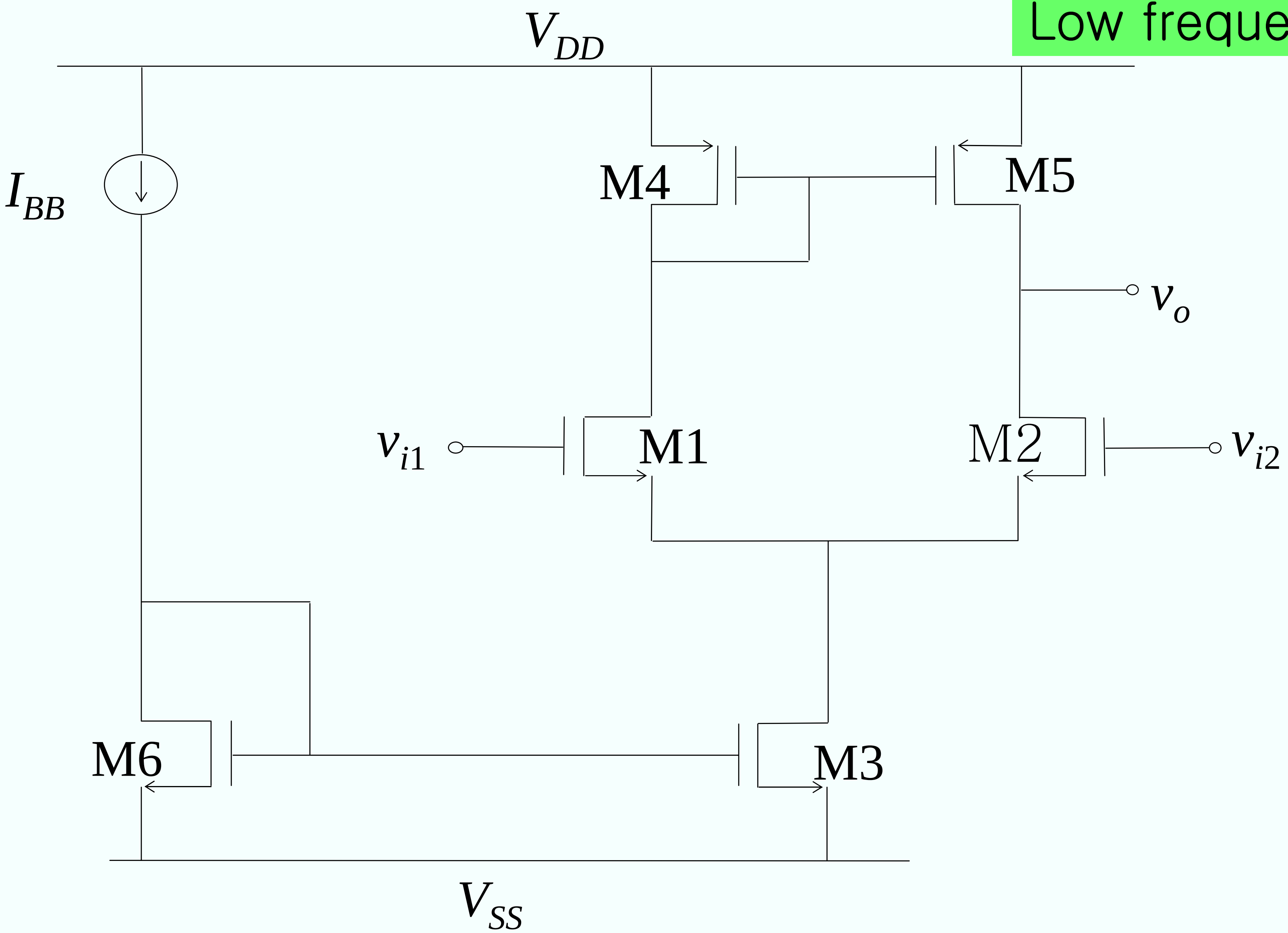
PSRR : power supply rejection ratio

$$PSRR^{+} \triangleq \left| \frac{A_{vd}}{v_o / v_{dd}} \right|$$

$$PSRR^{-} \triangleq \left| \frac{A_{vd}}{v_o / v_{ss}} \right|$$

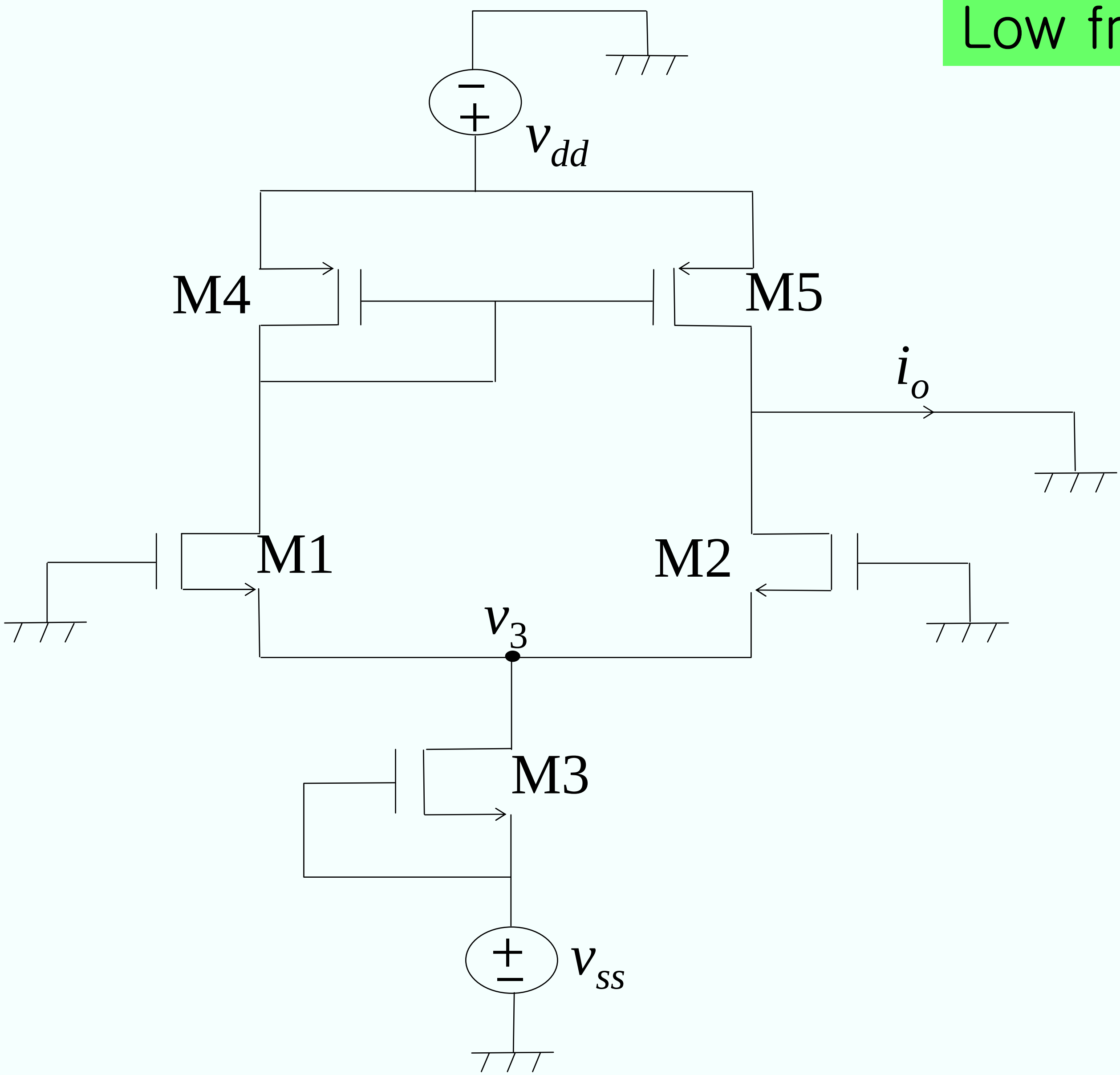
5.2 Active load NMOS differential pair

Low frequency PSRR



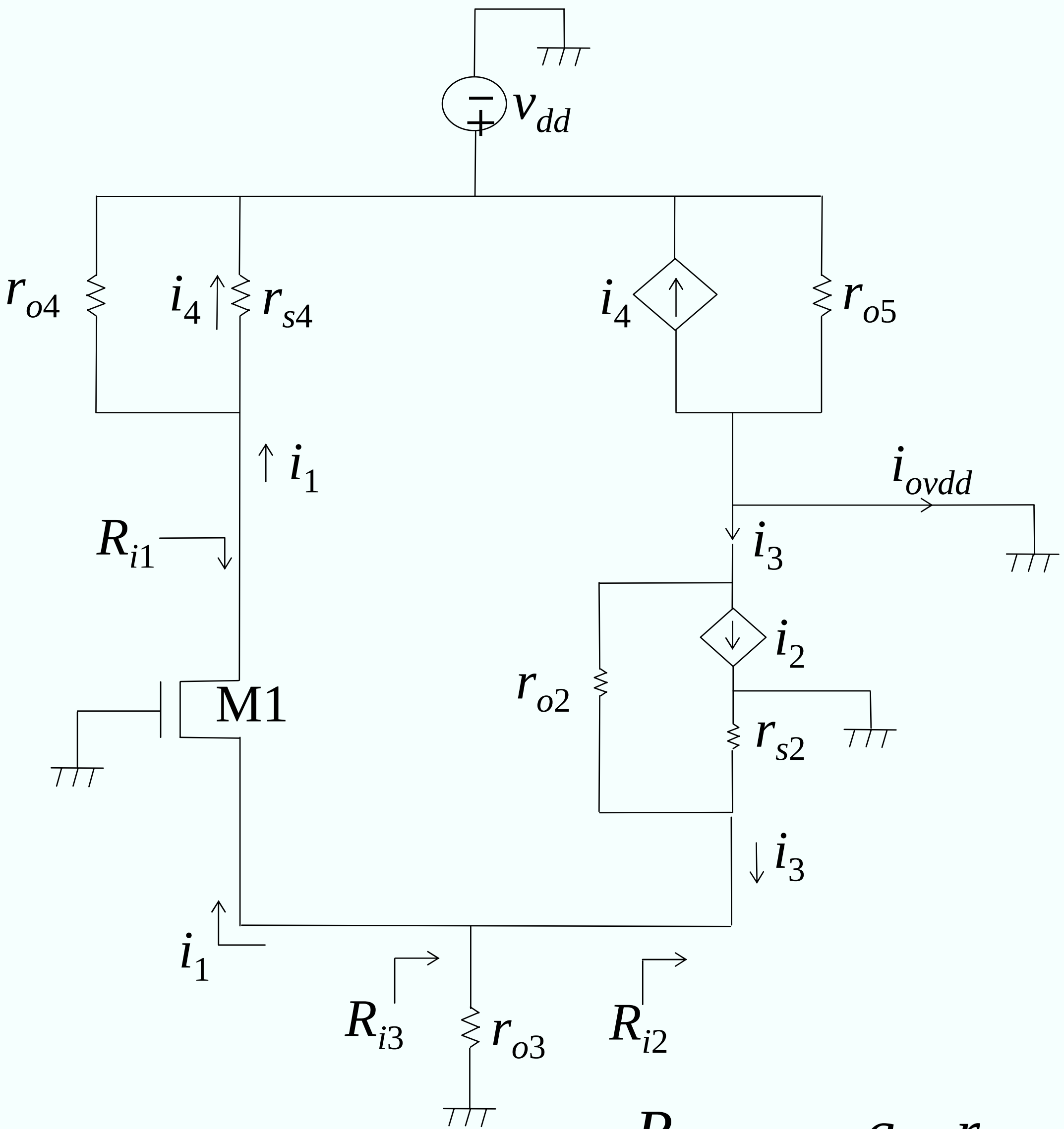
5.2 Active load NMOS differential pair

Low frequency PSRR +



5.2 Active load NMOS differential pair

Low frequency PSRR +



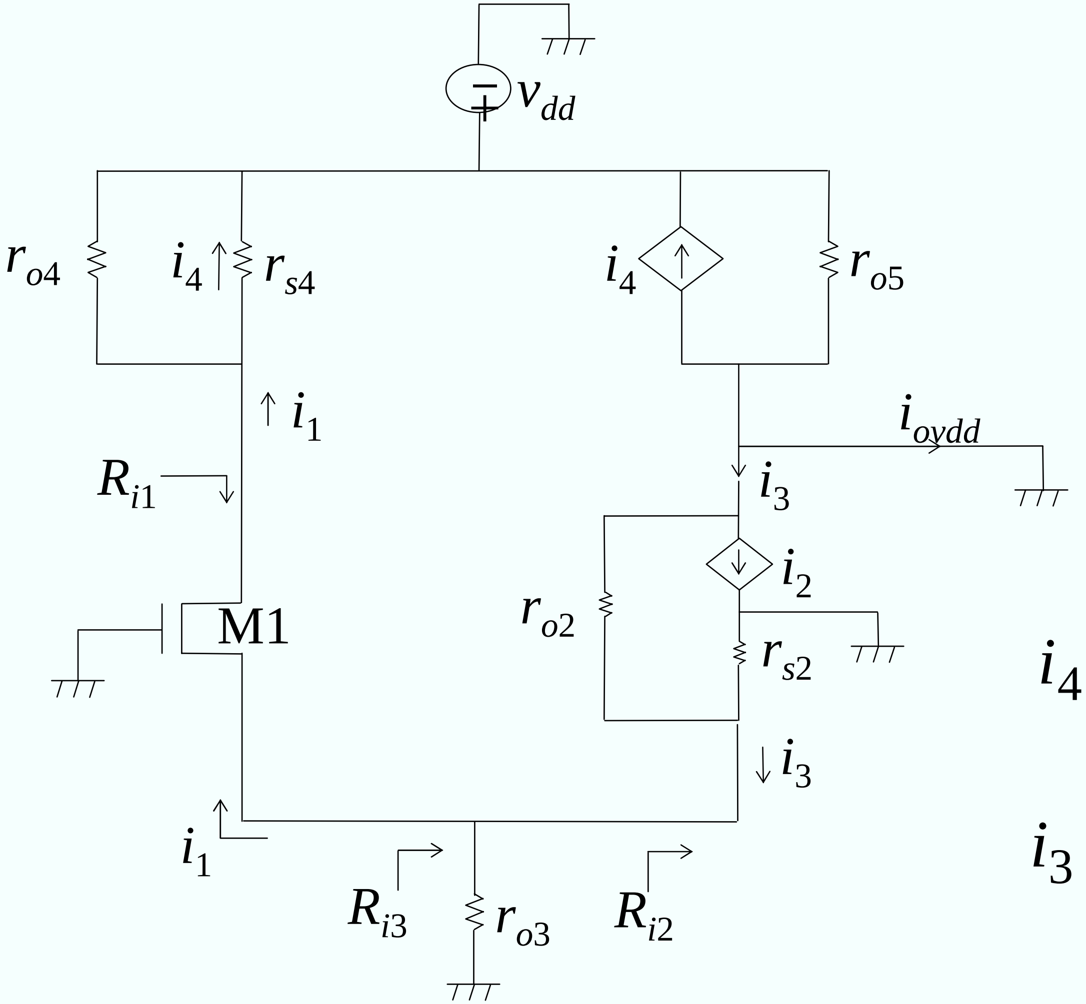
$$R_{i2} = r_{s2} \parallel r_{o2} \approx r_{s2}$$

$$R_{i3} = r_{o3} \parallel R_{i2} \approx r_{s2}$$

$$R_{i1} = g_{m1} r_{o1} \cdot R_{i3} + r_{o1} + R_{i3} = 2r_{o1} + r_{s2} \approx 2r_{o1}$$

5.2 Active load NMOS differential pair

Low frequency PSRR +



$$i_1 = -\frac{v_{dd}}{(r_{s4} \| r_{o4}) + R_{i1}} = -\frac{v_{dd}}{(r_{s4} \| r_{o4}) + 2r_{o1}}$$

$$= -\frac{v_{dd}}{r_{s4} + 2r_{o1}} = -\frac{v_{dd}}{2r_{o1}}$$

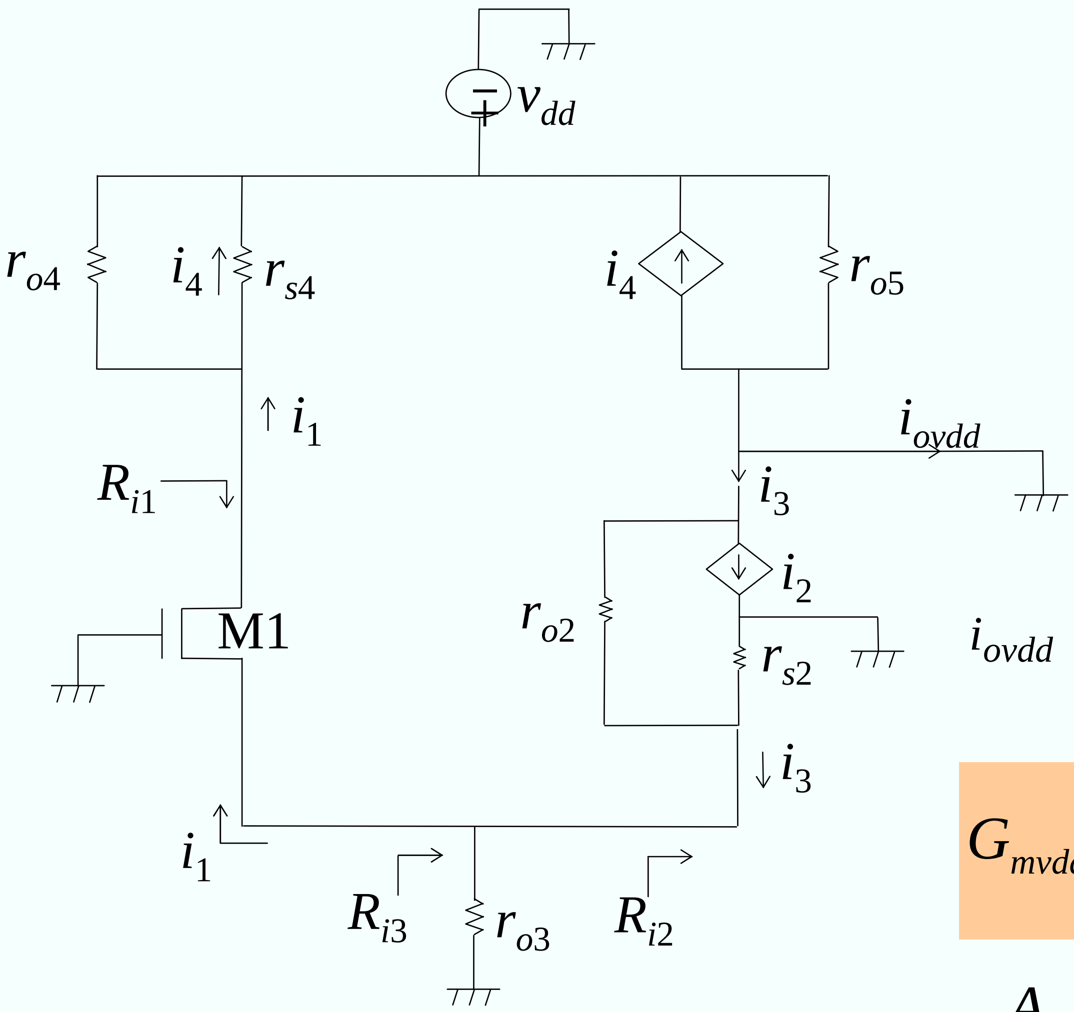
$$i_4 = i_1 \cdot \frac{r_{o4}}{r_{s4} + r_{o4}} \approx i_1$$

$$i_3 = i_1 \cdot \frac{r_{o3}}{(r_{s2} \| r_{o2}) + r_{o3}} \approx i_1$$

$$i_{ovdd} = \frac{v_{dd}}{r_{o5}} - i_4 - i_3 = \frac{v_{dd}}{r_{o5}} - 2i_1 = v_{dd} \cdot \left(\frac{1}{r_{o5}} + \frac{1}{r_{o1}} \right) = \frac{v_{dd}}{r_{o5} \| r_{o1}}$$

5.2 Active load NMOS differential pair

Low frequency PSRR +



$$i_{ovdd} \approx \frac{v_{dd}}{r_{o5}} + \frac{v_{dd}}{r_{o1}} = \frac{v_{dd}}{r_{o1} \parallel r_{o5}} = \frac{v_{dd}}{r_{o2} \parallel r_{o5}}$$

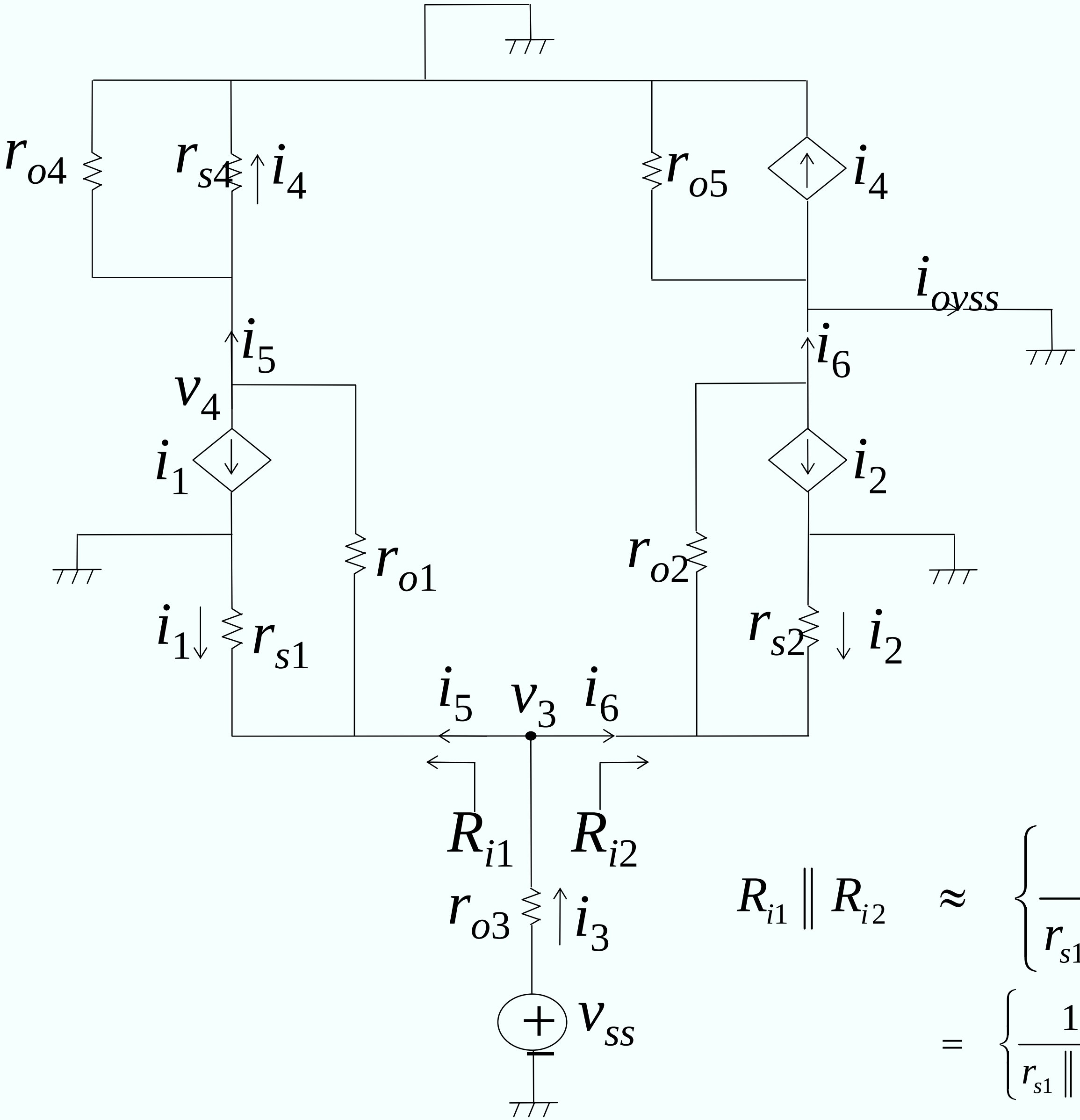
$$G_{mvdd} \triangleq \frac{i_{ovdd}}{v_{dd}} = \frac{1}{r_{o2} \parallel r_{o5}} = \frac{1}{R_o}$$

$$A_{vdd} = G_{mvdd} \cdot R_o = +1$$

$$PSRR^{+} \triangleq A_{vd} / A_{vdd} = A_{vd}$$

5.2 Active load NMOS differential pair

Low frequency PSRR –



$$R_{i1} = \frac{1}{g_{m1} + \frac{1}{r_{o1}}} \cdot \left(1 + \frac{r_{s4} \| r_{o4}}{r_{o1}}\right)$$

$$= (r_{s1} \| r_{o1}) \cdot \left(1 + \frac{r_{s4} \| r_{o4}}{r_{o1}}\right)$$

$$\approx (r_{s1} \| r_{o1}) \cdot \left(1 + \frac{r_{s4}}{r_{o1}}\right)$$

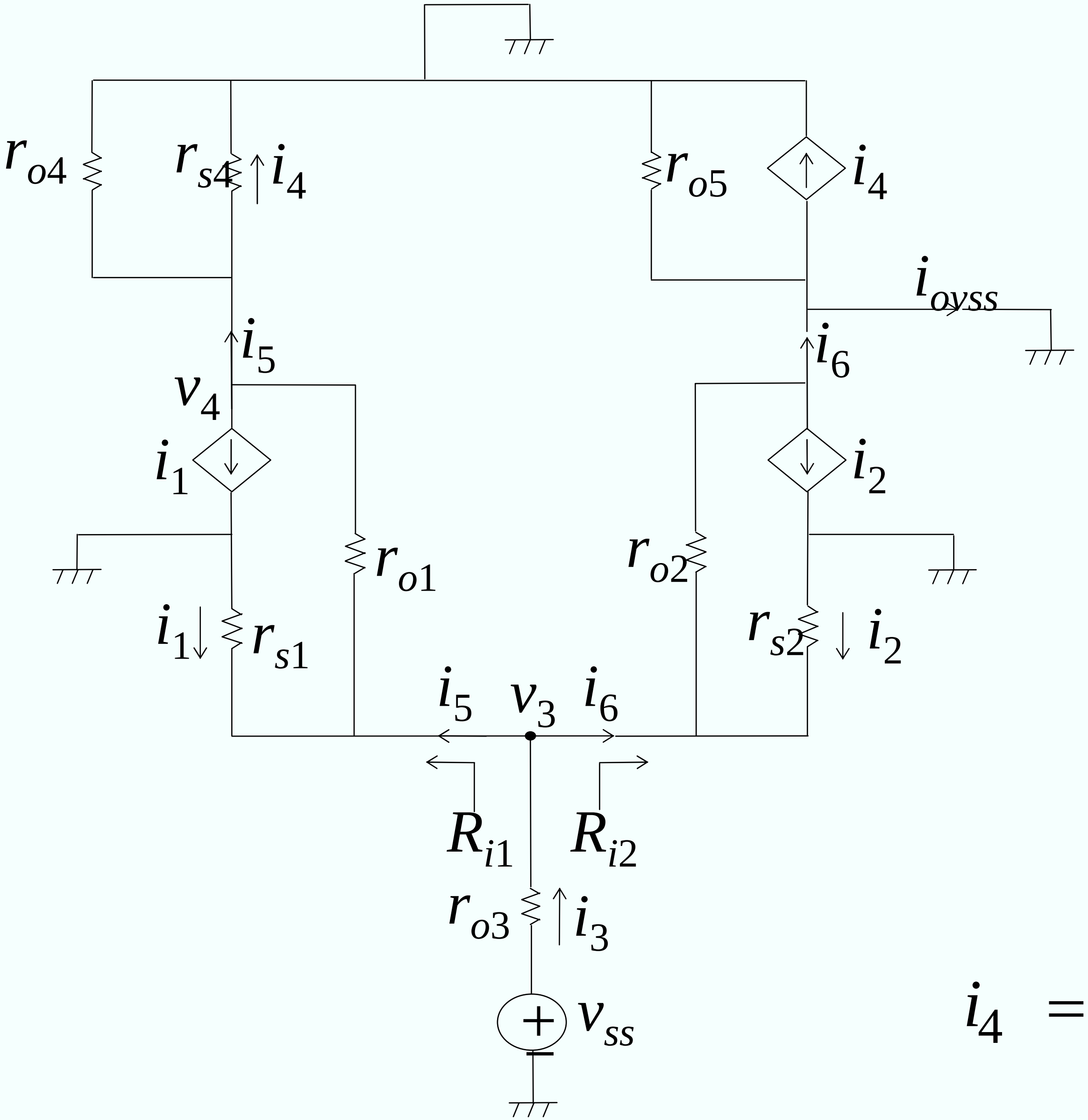
$$R_{i2} = r_{s2} \| r_{o2}$$

$$R_{i1} \| R_{i2} \approx \left\{ \frac{1}{r_{s1} \| r_{o1}} \cdot \left(1 - \frac{r_{s4}}{r_{o1}}\right) + \frac{1}{r_{s2} \| r_{o2}} \right\}^{-1}$$

$$= \left\{ \frac{1}{r_{s1} \| r_{o1}} \cdot \left(2 - \frac{r_{s4}}{r_{o1}}\right) \right\}^{-1} \approx \frac{r_{s1} \| r_{o1}}{2} \approx \frac{r_{s1}}{2}$$

5.2 Active load NMOS differential pair

Low frequency PSRR –



$$i_3 = \frac{v_{ss}}{r_{o3} + (R_{i1} \parallel R_{i2})}$$

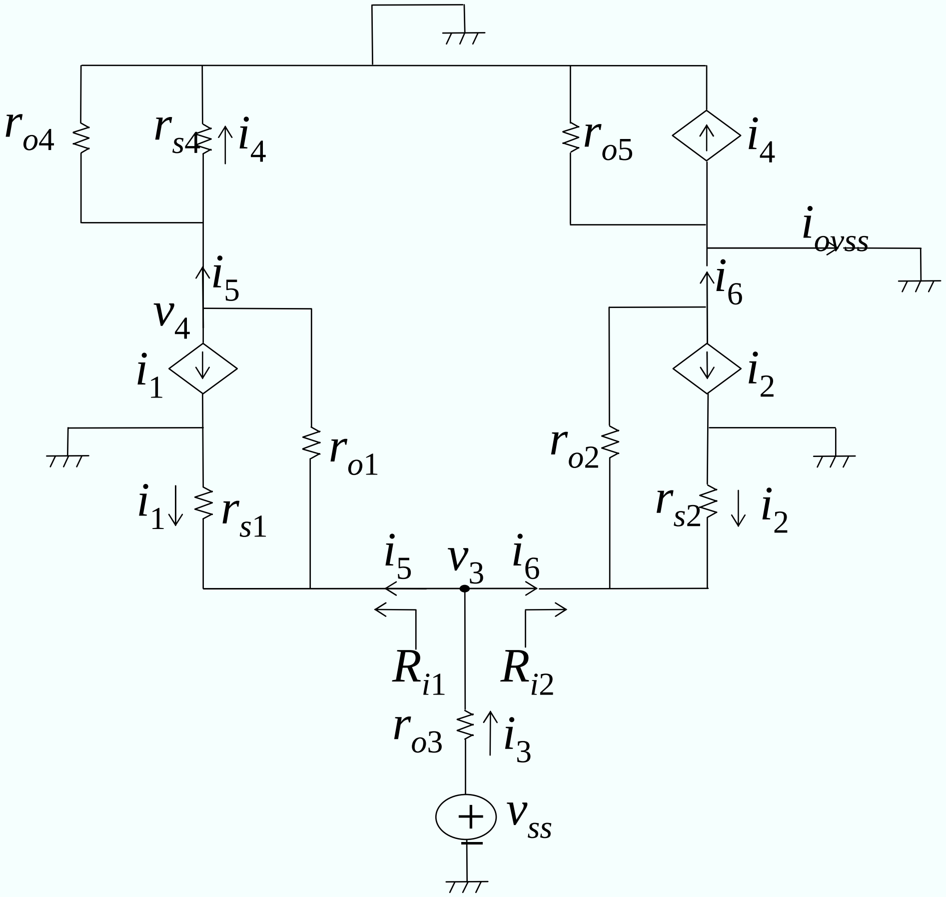
$$= \frac{v_{ss}}{r_{o3} + \left(r_{s1}/2\right)} \approx \frac{v_{ss}}{r_{o3}}$$

$$i_6 = i_3 \cdot \frac{R_{i1}}{R_{i1} + R_{i2}}$$

$$i_5 = i_3 \cdot \frac{R_{i2}}{R_{i1} + R_{i2}}$$

$$i_4 = i_5 \cdot \frac{r_{o4}}{r_{s4} + r_{o4}} \approx i_5 \cdot \left(1 - \frac{r_{s4}}{r_{o4}}\right)$$

5.2 Active load NMOS differential pair



Low frequency PSRR –

$$i_4 = i_5 \cdot \frac{r_{o4}}{r_{s4} + r_{o4}} \approx i_5 \cdot \left(1 - \frac{r_{s4}}{r_{o4}}\right)$$

$$i_{ovss} = -\ i_4 + i_6$$

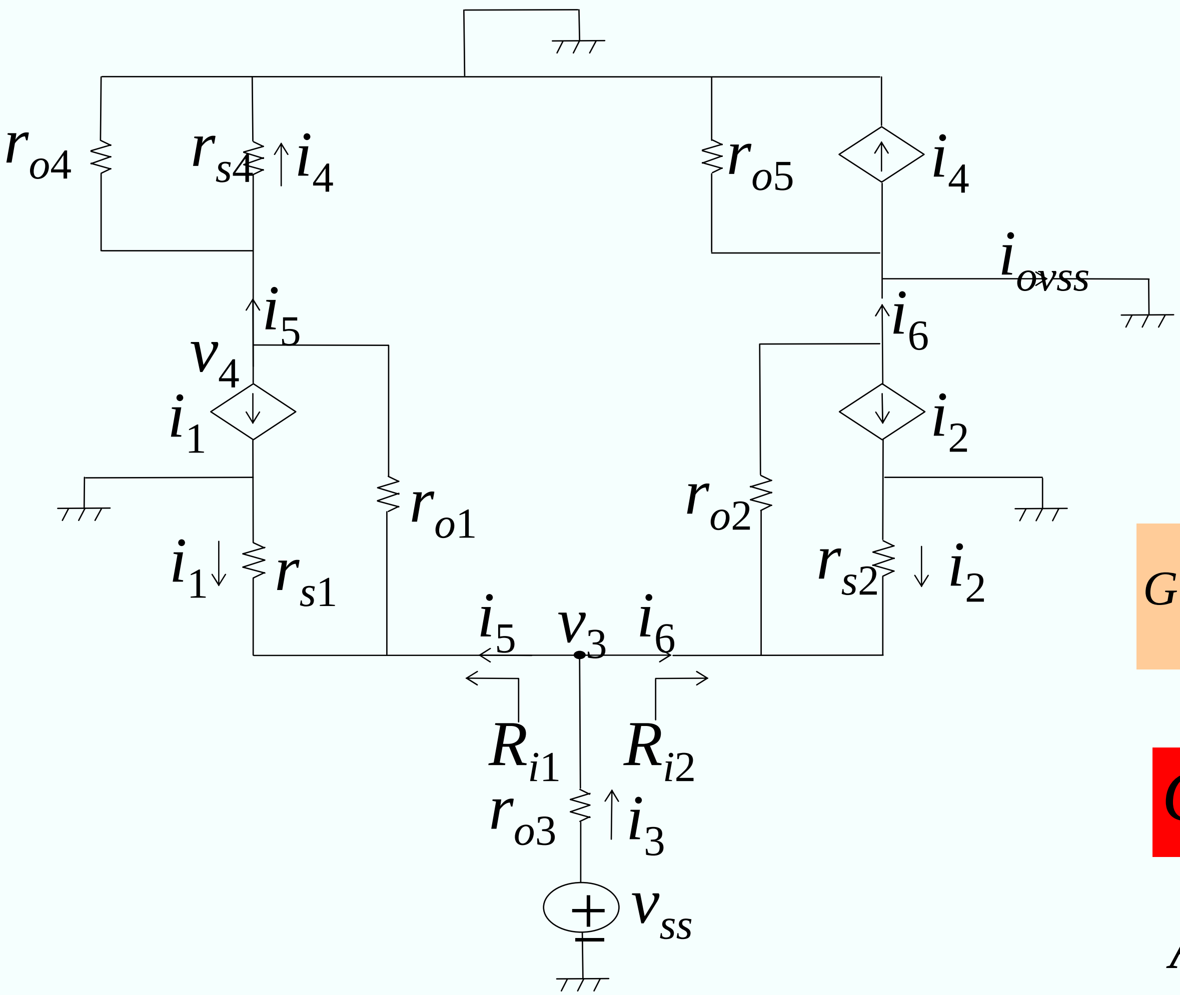
$$= \frac{i_3}{R_{i1} + R_{i2}} \cdot \left\{ R_{i1} - R_{i2} \cdot \left(1 - \frac{r_{s4}}{r_{o4}}\right) \right\}$$

$$= \frac{i_3}{R_{i1} + R_{i2}} \cdot (r_{s1} \parallel r_{o1}) \cdot \left(\frac{r_{s4}}{r_{o1}} + \frac{r_{s4}}{r_{o4}} \right)$$

$$\approx \frac{i_3}{2 \cdot (r_{s1} \parallel r_{o1})} \cdot (r_{s1} \parallel r_{o1}) \cdot \left(\frac{r_{s4}}{r_{o1}} + \frac{r_{s4}}{r_{o4}} \right)$$

$$\approx \frac{v_{ss}}{2\ r_{o3}} \cdot \frac{r_{s4}}{(r_{o1} \parallel r_{o4})} \approx \frac{v_{ss}}{2\ r_{o3} \cdot \{g_{m4}(r_{o1} \parallel r_{o4})\}}$$

5.2 Active load NMOS differential pair



Low frequency PSRR –

$$i_{ovss} \approx \frac{v_{ss}}{2\, r_{o3} \cdot \{g_{m4}(r_{o1} \| r_{o4})\}}$$

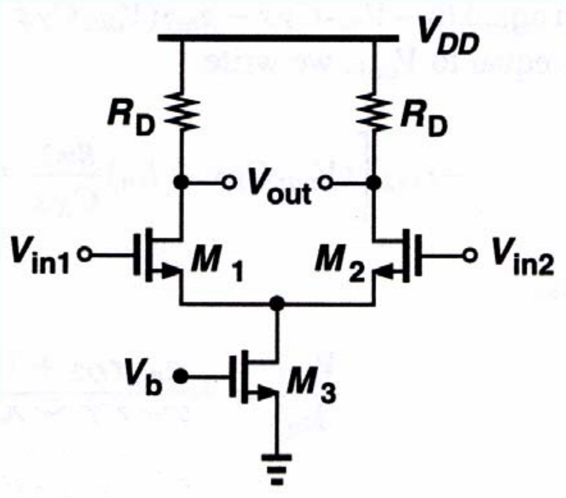
$$G_{mvss} \triangleq \frac{i_{ovss}}{v_{ss}} = \frac{1}{2\, r_{o3} \cdot \{g_{m4}(r_{o1} \| r_{o4})\}}$$

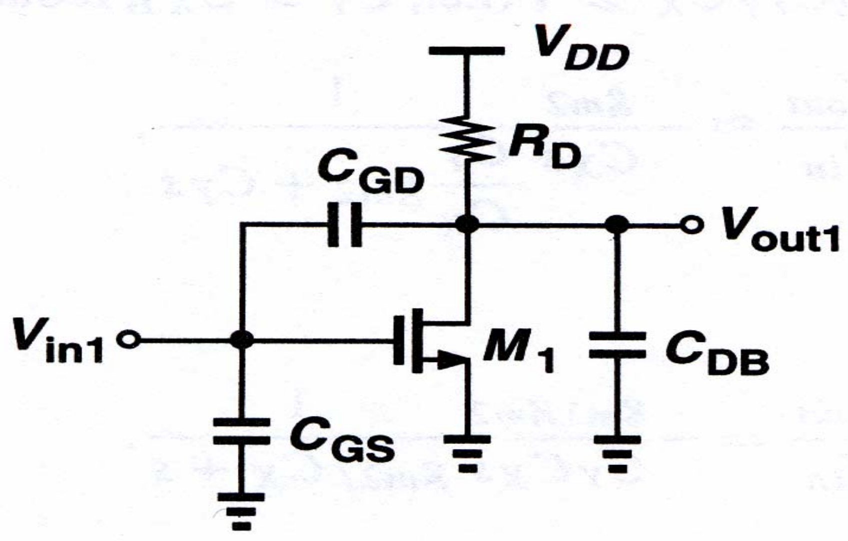
$$G_{mvss} = -G_{mc}$$

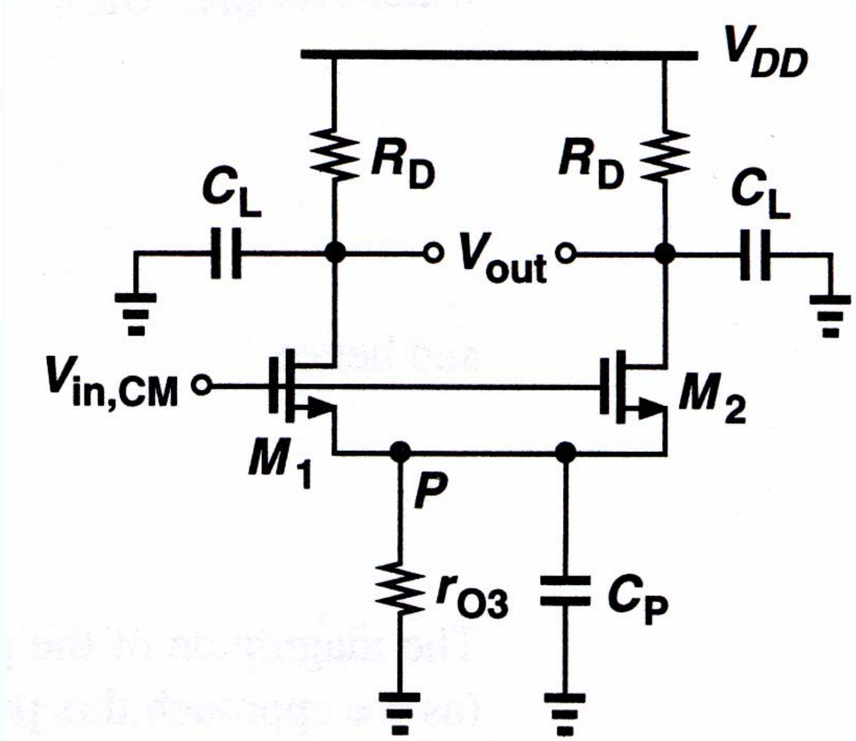
$$A_{vss} = G_{mvss} \cdot R_o = -A_{vc}$$

$$PSRR^{-} \triangleq \left| \frac{A_{vd}}{A_{vss}} \right| = \left| \frac{A_{vd}}{A_{vc}} \right| = (2g_{m1}r_{o3}) \cdot \{ g_{m4}(r_{o1} \| r_{o4}) \} = CMRR$$

Differential pair with R load





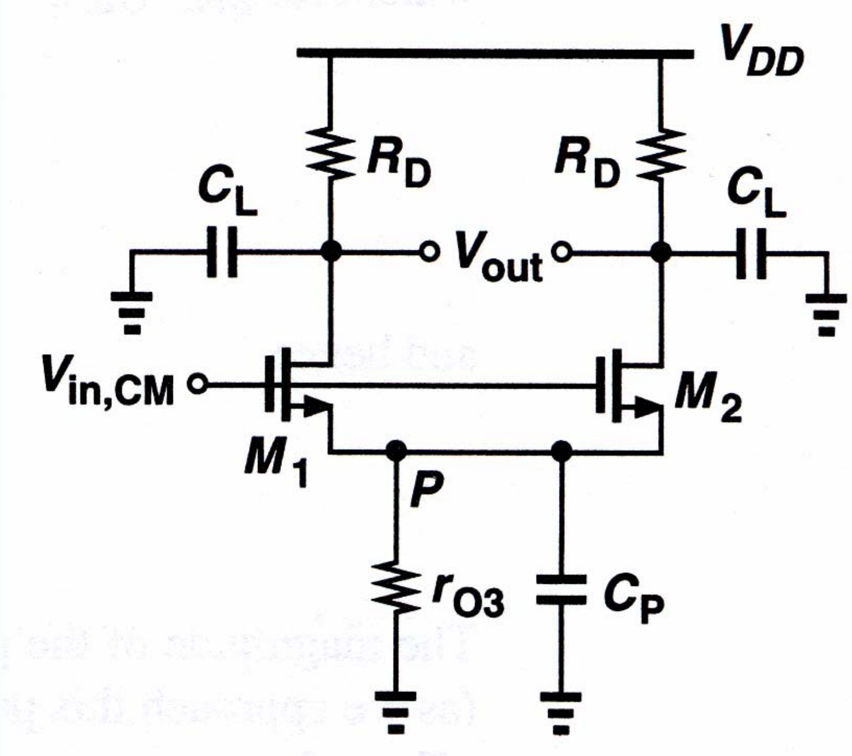


Differential mode
Same as CS amp

Common mode
Pole at P decides HF response.
If this pole << output pole
➔ Degrades HF CMRR too much

Razavi

Differential pair with R load



Common mode

Zero at node P : 1 / (ro3 * Cp)

Pole at P decides HF response.

If this pole << output pole

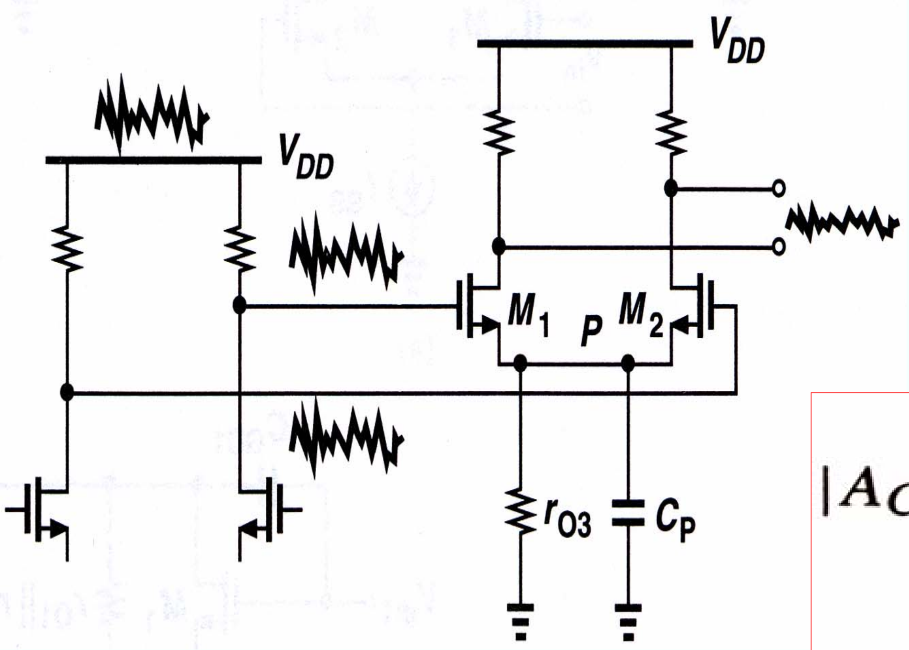
➔ Degrades HF CMRR too much

Cp : Reduction of HF CMRR ➔ Mismatch causes HF common mode noise ➔ diff mode

Razavi

Reduction of HF CMRR

➔ HF common mode noise ➔ diff mode

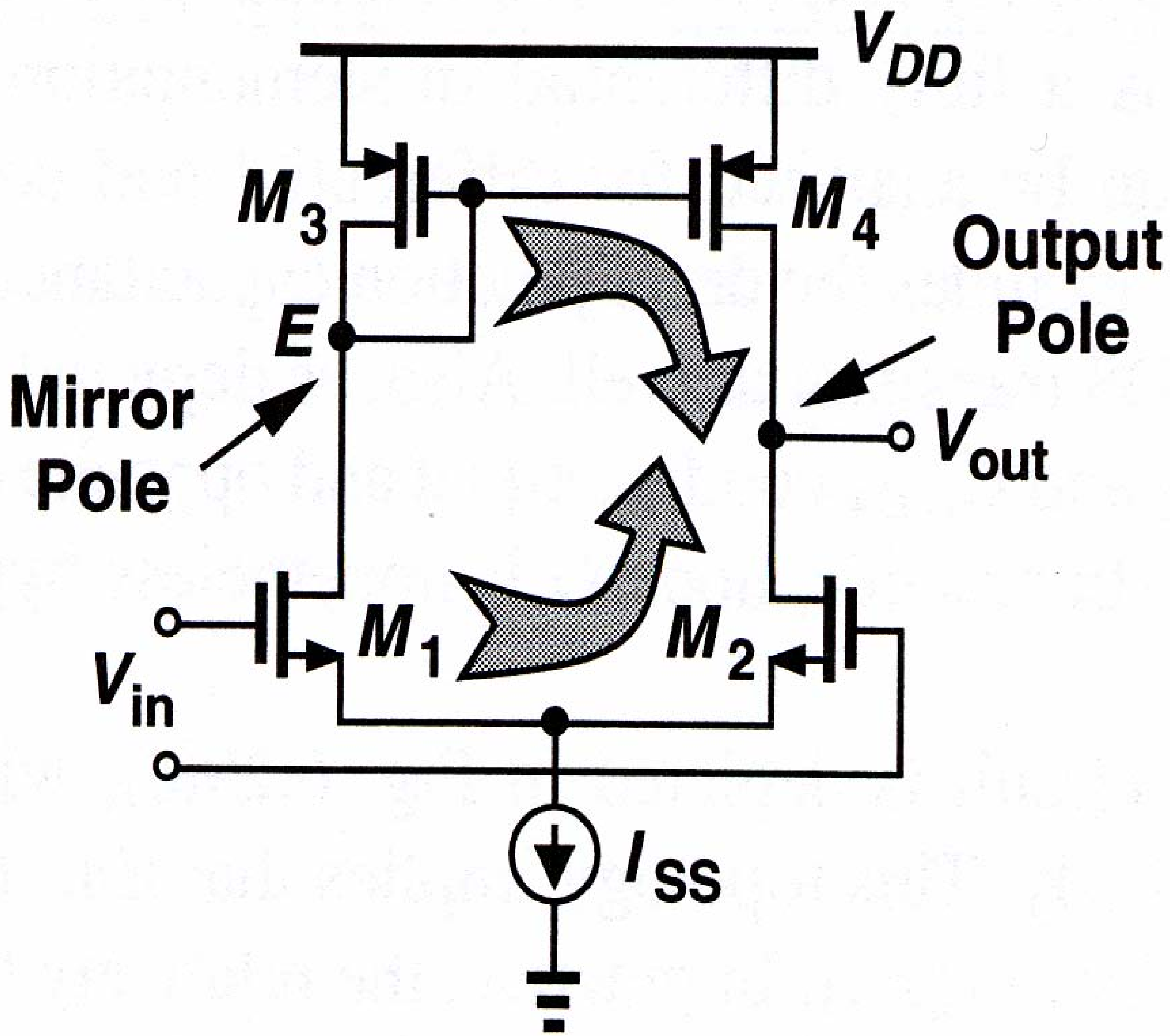


$$|A_{CM-DM}| = \frac{\Delta g_m R_D}{\sqrt{1 + (g_{m3} + g_{m4})^2 \left| \frac{1}{C_P \omega} \right|^2}}$$

Rss => 1/(s Cp)

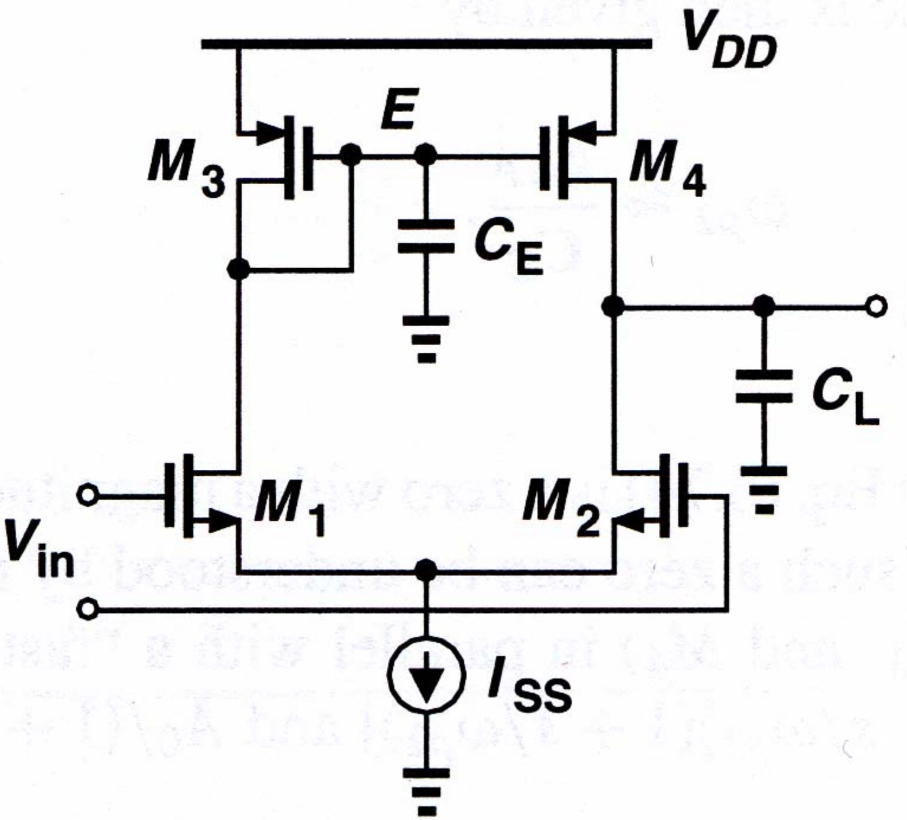
More significant at high frequency

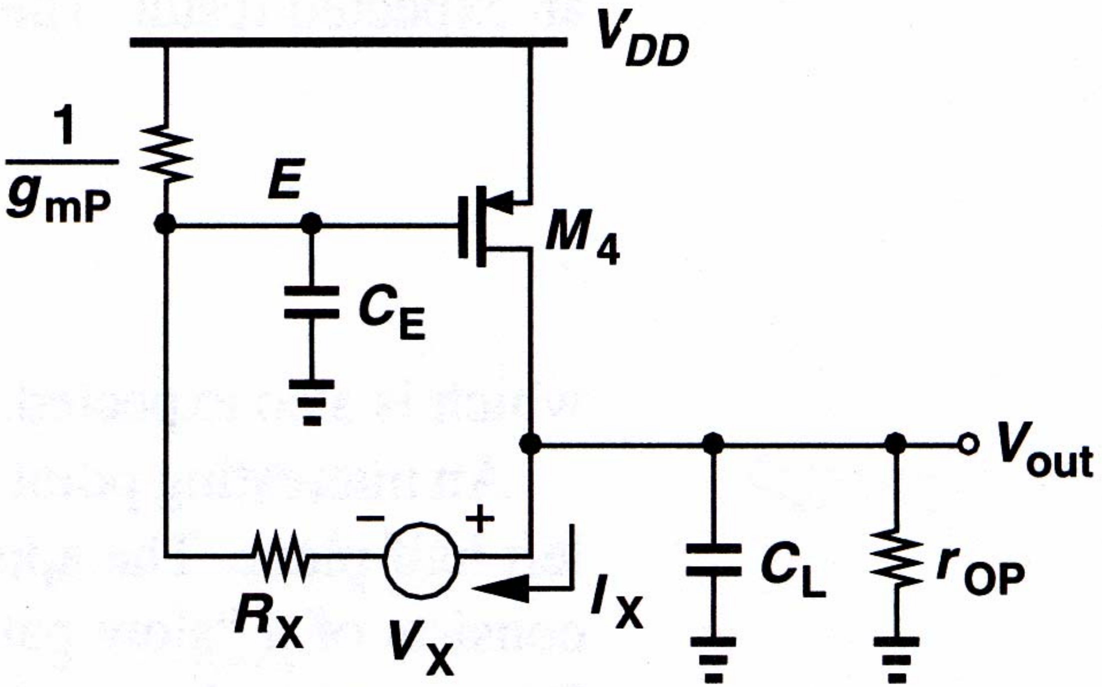
Differential pair with active load



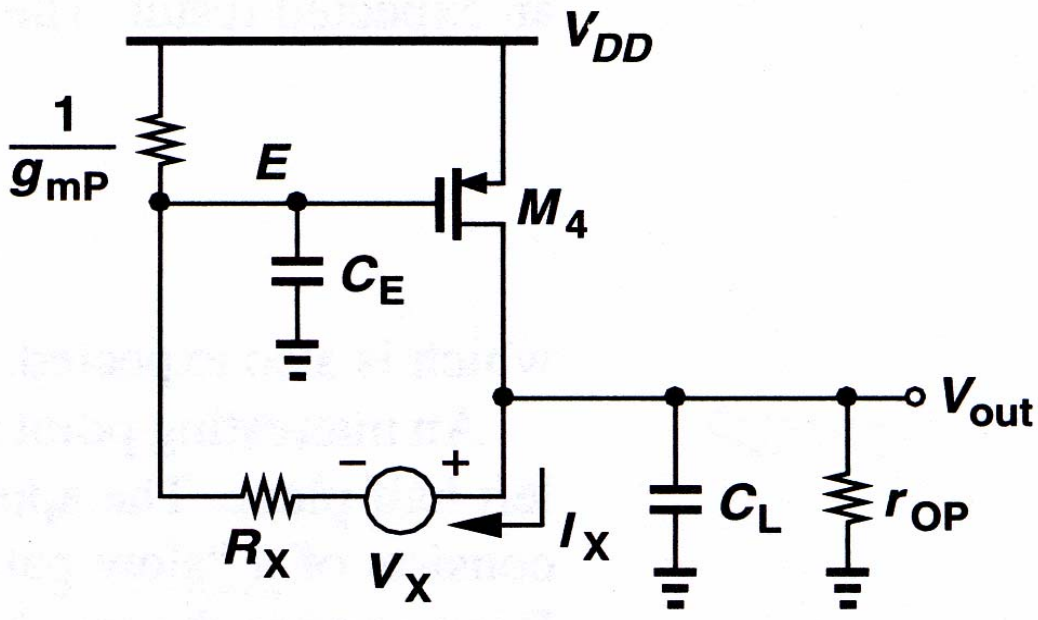
Razavi

Mirror pole (at node E)





Razavi



Mirror pole (at node E)

Thevenin equivalent ckt

$$V_X = g_{mN}\ r_{oN}\ V_{in}$$

$$R_X = 2\ r_{oN}$$

$$I_x = \frac{v_E}{\dfrac{1}{g_{mP} + s\ C_E}}$$

$$V_E = (V_{out} - V_X)\frac{\dfrac{1}{C_E s + g_{mP}}}{\dfrac{1}{C_E s + g_{mP}} + R_X}$$

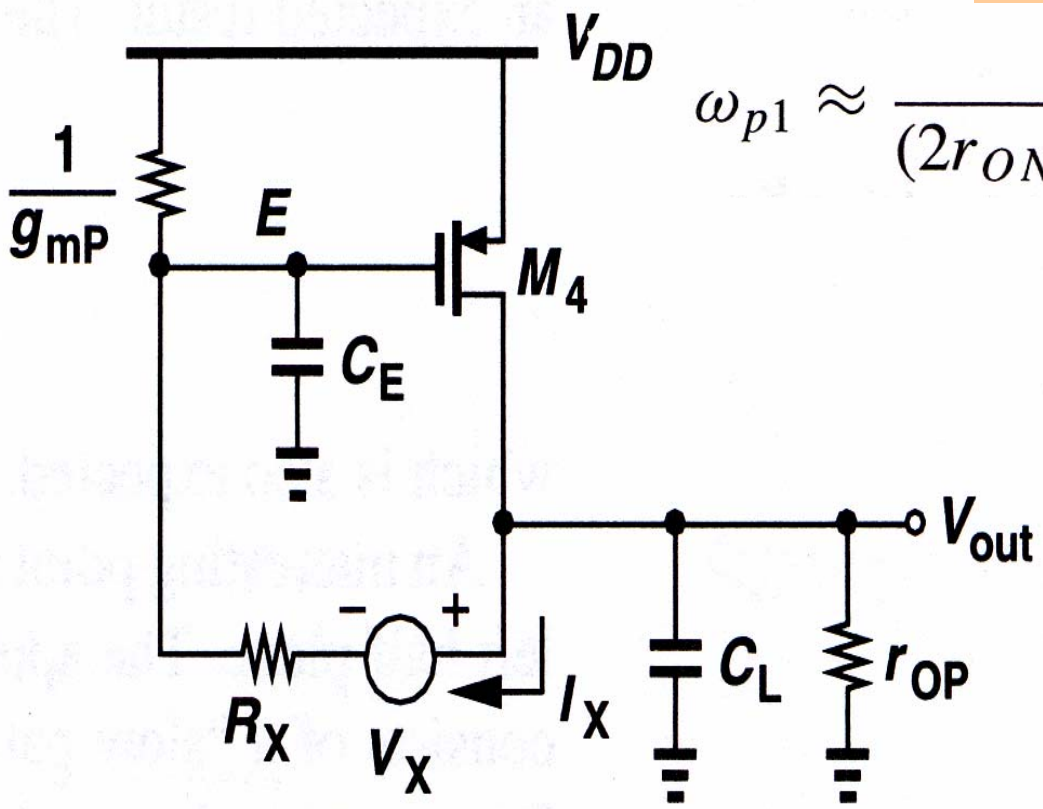
$$-g_{m4} v_E - I_x = v_{out} \cdot (sC_L + \frac{1}{r_{oP}})$$

Razavi

Differential pair with active load

r_{OP} ✓

$$\frac{V_{out}}{V_{in}} = \frac{g_{mN} r_{ON} (2g_{mP} + C_E s)}{2r_{OP} r_{ON} C_E C_L s^2 + [(2r_{ON} + r_{OP})C_E + r_{OP}(1 + 2g_{mP} r_{ON})C_L]s + 2g_{mP}(r_{ON} + r_{OP})}$$



Dominant pole

$$\omega_{p1} \approx \frac{2g_{mP}(r_{ON} + r_{OP})}{(2r_{ON} + r_{OP})C_E + r_{OP}(1 + 2g_{mP} r_{ON})C_L}$$

$$\omega_{p1} \approx \frac{1}{(r_{ON} \| r_{OP})C_L}$$

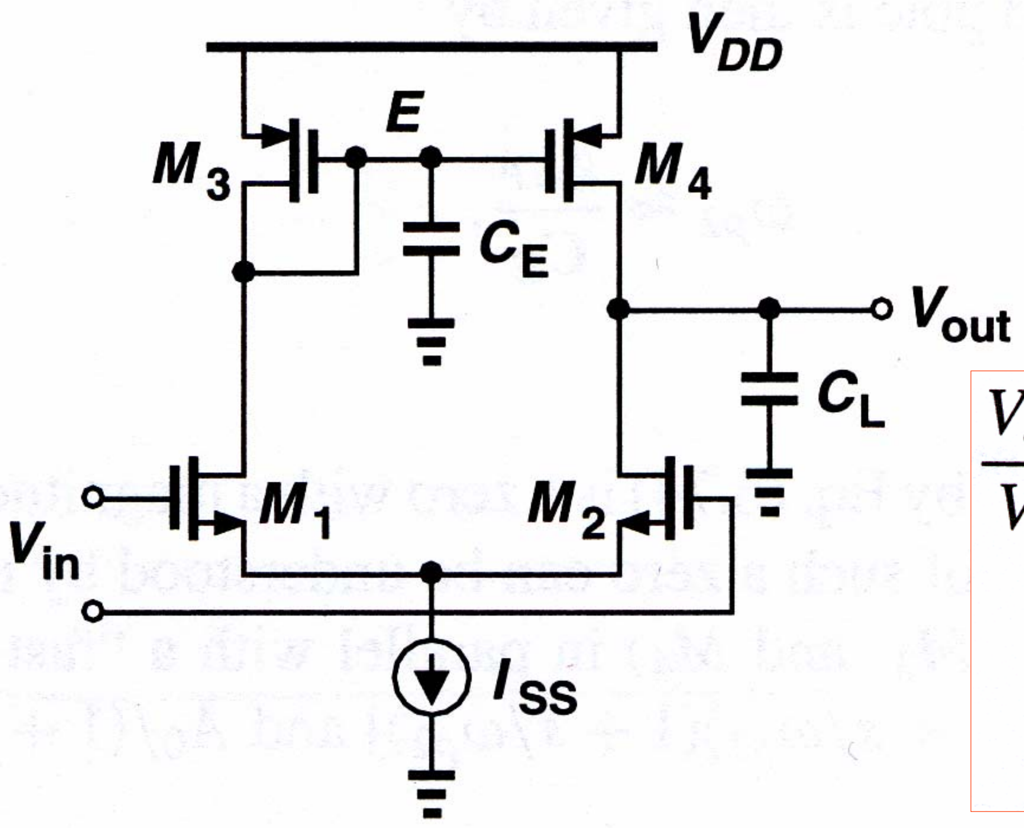
Mirror pole (at node E)

$$\omega_{p2} \approx \frac{g_{mP}}{C_E}$$

Razavi

r_{OP} ✓

$$\frac{V_{out}}{V_{in}} = \frac{g_{mN} r_{ON}(2g_{mP} + C_E s)}{2r_{OP}r_{ON}C_E C_L s^2 + [(2r_{ON} + r_{OP})C_E + r_{OP}(1 + 2g_{mP}r_{ON})C_L]s + 2g_{mP}(r_{ON} + r_{OP})}$$



Negative real zero)

Due to fast path (M1,M2) + slow path (M1, M3, M4)

Av(s) = Aslow(s) + Afast(s)

$$\frac{V_{out}}{V_{in}} = \frac{A_0}{1 + s/\omega_{p1}}\left(\frac{1}{1 + s/\omega_{p2}} + 1\right)$$

$$= \frac{A_0(2 + s/\omega_{p2})}{(1 + s/\omega_{p1})(1 + s/\omega_{p2})}$$

Razavi

Differential pair with R load

(1) Large signal transfer curve

(2) Small signal characteristic (Gmd, Gmc, Ro)

(3) Active input common mode range

(4) Input offset voltage

(5) Common mode to differential conversion due to mismatches

Differential pair with diode load

Differential pair with active load

Differential pair: frequency response