Design of Analog CMOS Integrated Circuits

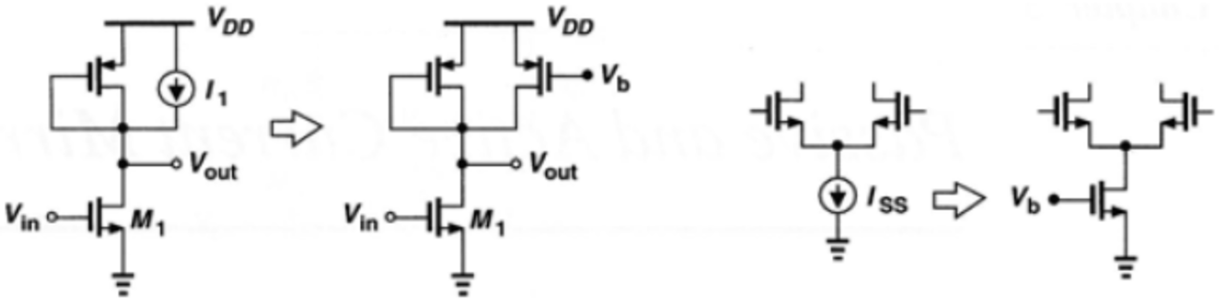
<Chapter 5>

Passive and Active Current Mirrors

양병도

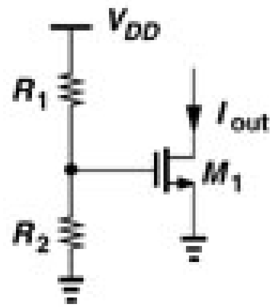
5.1 Basic current mirrors

- Application



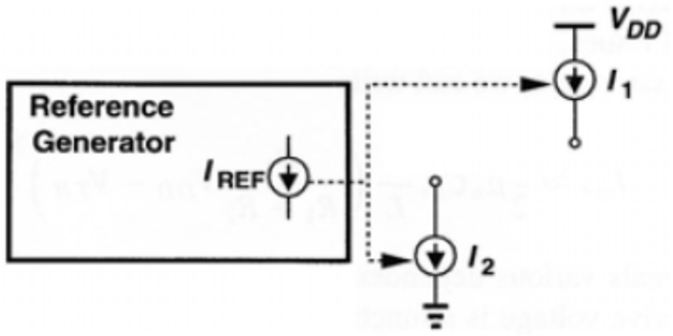
- resistive divider 를 사용한 current source
  - ✓ 단점: I_{out}이 power supply, process, temperature에 영향 받음 → 사용하기 어렵다.
    - ➢ V_{DD}, V_{TH} ~100mV 변함 → I_{out} 변함
    - ➢ μ_n, V_{TH} 는 온도에 따라 변함 → I_{out} 변함

$$I_{OUT} \approx \frac{u_n C_{ox}}{2}\frac{W}{L}\left(\frac{R_2}{R_2+R_1}V_{DD}-V_{TH}\right)^2$$

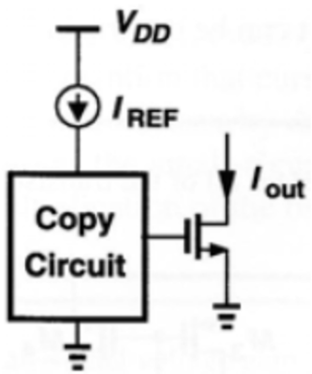


❑ Basic current mirrors

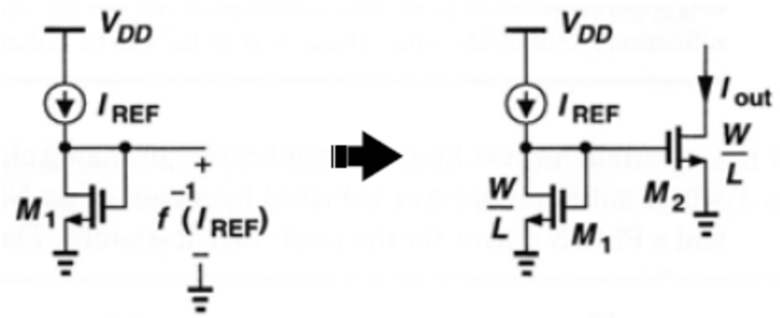
- ✓ 안정적인 reference current (I_{REF}) 를 만들고 이를 사용하여 여러 개의 current source를 복사한다.



❑ 어떻게 복사하는가? (I_{out}=I_{REF} ?)



❑ 어떻게 복사하는가? ($I_{out}=I_{REF}$?)



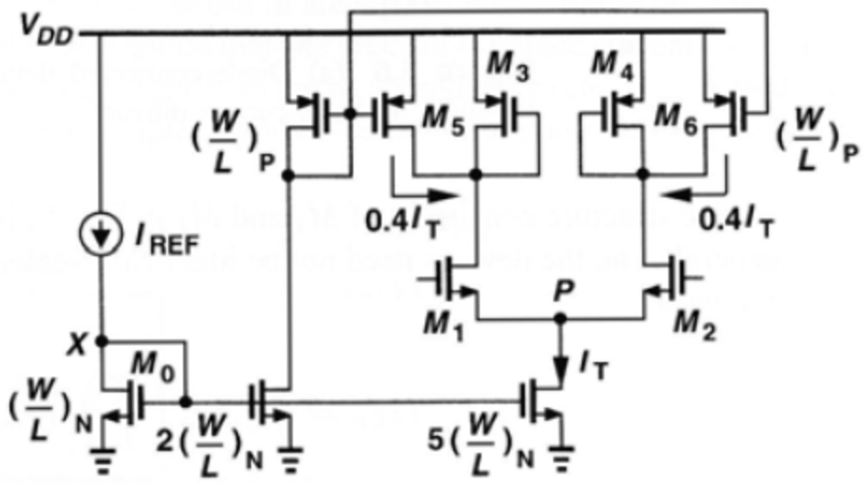
$$I_{REF} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_1 (V_{GS}-V_{TH})^2$$

$$I_{out} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_2 (V_{GS}-V_{TH})^2$$

$$I_{out} = \frac{(W/L)_2}{(W/L)_1} I_{REF}$$

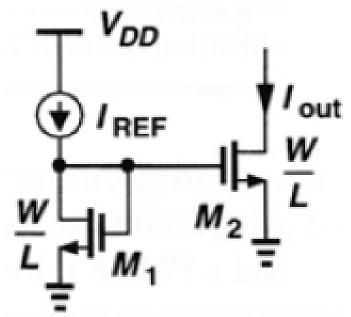
- ✓ $\lambda=0$ 가정 (channel length modulation무시)
- ✓ (1) $(W/L)_1$과 $(W/L)_2$를 조절에서 만들 수 있다.
  - ➢ $(W/L)_1$ =100= $(W/L)_2$ → $I_{out}=I_{REF}$
  - ➢ $(W/L)_1$ =100, $(W/L)_2$ =200 → $I_{out}=2I_{REF}$
- ✓ PVT (process, voltage, temperature)의 영향이 서로 상쇄된다.
  - ➢ 안정적 I_{REF} → 안정적 I_{out}
- ✓ 보통은 L은 고정하고 W만 변화시킨다.
  - ➢ L변경 → $L'=L-2L_D$ → ratio 변화가 일정하지 않음
  - ➢ V_{TH} 변경 (short channel device)

❑ current mirror 예



5.2 Cascode current mirrors

- Current mirror @ λ≠0 (channel length modulation 고려)



$$I_{D1} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_1 (V_{GS} - V_{TH})^2 (1 + \lambda V_{DS1})$$

$$I_{D2} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_2 (V_{GS} - V_{TH})^2 (1 + \lambda V_{DS2})$$

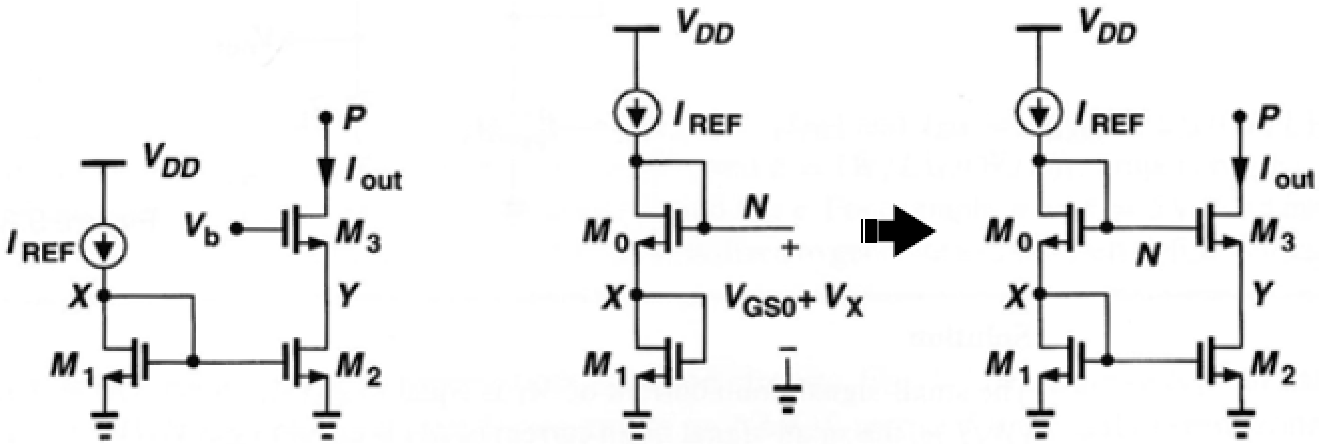
$V_{DS1} = V_{GS1} = V_{GS2} \neq V_{DS2}$

$$\frac{I_{D2}}{I_{D1}} = \frac{(W/L)_2}{(W/L)_1} \cdot \frac{1 + \lambda V_{DS2}}{1 + \lambda V_{DS1}}$$

→ λ≠0의 문제 해결 방법?

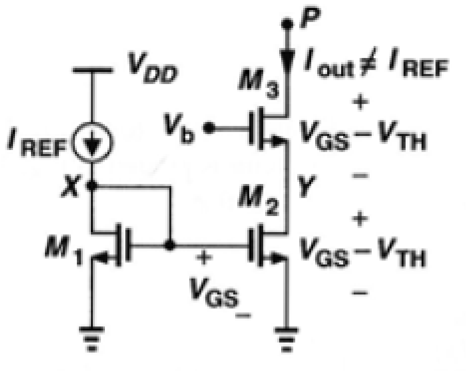
❑ Cascode current source

- ✓ channel-length modulation 영향을 줄일 수 있다.



- ✓ $V_Y = V_X$ 가 되도록 하는 V_b?
- ✓ If $\frac{(W/L)_3}{(W/L)_0} = \frac{(W/L)_2}{(W/L)_1}$
- ✓ → $V_{GS3} = V_{GS0}$ and $V_X = V_Y$.

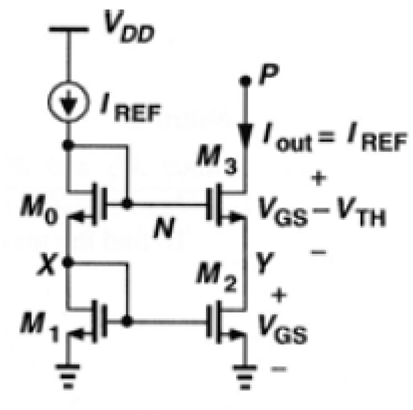
❑ Cascode mirror 에서의 voltage headroom



(a)

$V_X \neq V_Y$

V_b값을 잘 조절하면 $2\Delta V$까지 내려갈 수 있다.
그러나, $V_X \neq V_Y$이므로 $I_{out} \neq I_{REF}$



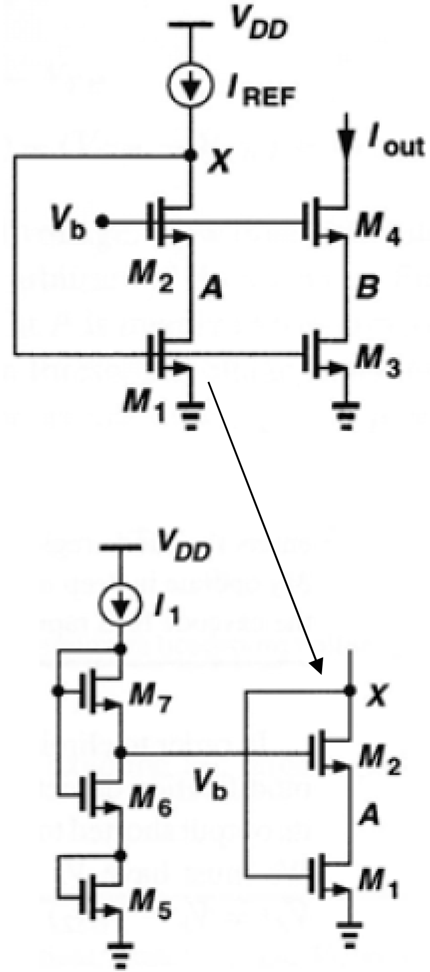
(b)

$V_X = V_Y$

$$V_{P,min} = V_N - V_{TH} = V_{GS0} + V_{GS1} - V_{TH}$$
$$= (V_{GS0} - V_{TH}) + (V_{GS1} - V_{TH}) + V_{TH}$$

$V_p = 2\Delta V + V_{TH}$
V_{TH}만큼 증가 → 해결 방법?

❑ Low-voltage cascode mirror



If $V_b = V_{GS2} + (V_{GS1} - V_{TH1}) = V_{GS4} + (V_{GS3} - V_{TH3})$

$V_{out} \geq V_b - V_{TH4}$

$= (V_{GS2} - V_{TH4}) + = (V_{GS1} - V_{TH1})$

$= 2\Delta V$

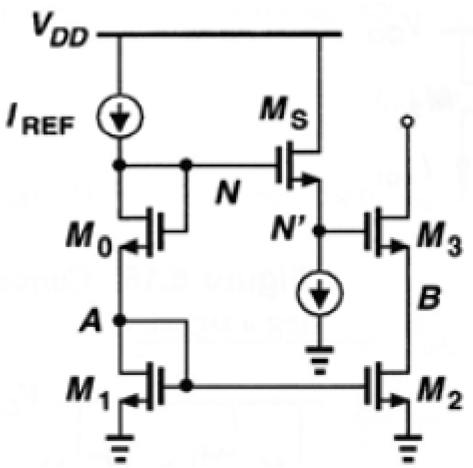
$I_1 = I_{REF}$이기 위해서는 $V_{GS5} \approx V_{GS2}$

M_7 : large $(W/L)_7$, so that $V_{GS7} \approx V_{TH7}$

$\therefore\ V_{DS6} \approx V_{GS6} - V_{TH7}$

$V_b = V_{GS5} + V_{GS6} - V_{TH7}$

❑ Low-voltage cascode using a source follower level shifter



M_S를 통해 흐르는 전류가 매우 작다면 $I_D \approx 0$

$V_{GSS} \approx V_{THS} \approx V_{TH3}$

$V_N{}' \approx V_N - V_{TH3}$

$V_B = V_{GS1} + V_{GS0} - V_{TH3} - V_{GS3}$

$\quad = V_{GS1} - V_{TH3}$

M_2 is at the edge of the triode region

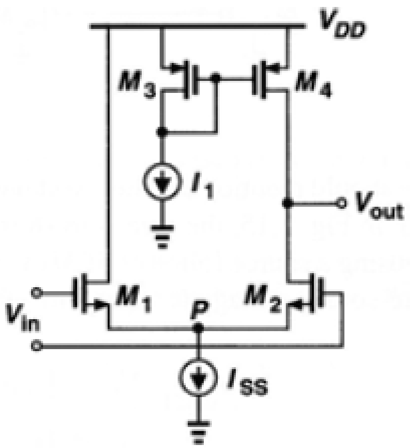
$V_{DS2} \neq V_{DS1}$

Body effect를 고려하면

M_S이 saturation에 있다고 확신하기 힘들다.

5.3 Active current mirrors

❑ 저항 대신 current source 이용



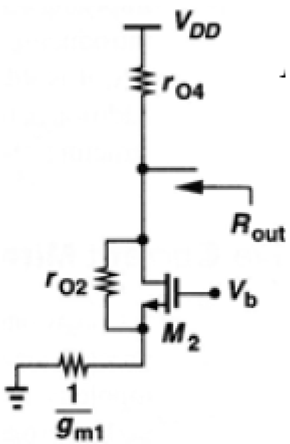
Assuming $\gamma = 0$

$$G_m = \frac{I_{out}}{V_{in}}$$

$$= \frac{g_{m1}V_{in}/2}{V_{in}}$$

$$= \frac{g_{m1}}{2}$$

$$|A_v| = G_m R_{out}$$



$$R_{out1} = (1 + g_{m2}r_{o2})(1/g_{m1}) + r_{o2}$$

$$= 2r_{o2} + 1/g_{m1}$$

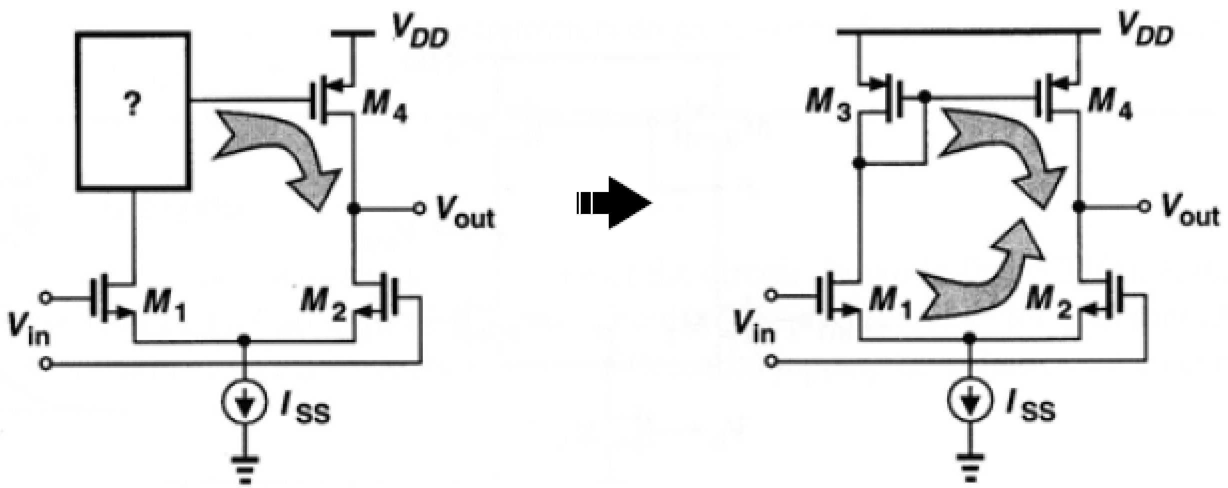
$$\approx 2r_{o2}$$

t

Thus, $R_{out} \approx (2r_{o2})\|r_{o4}$

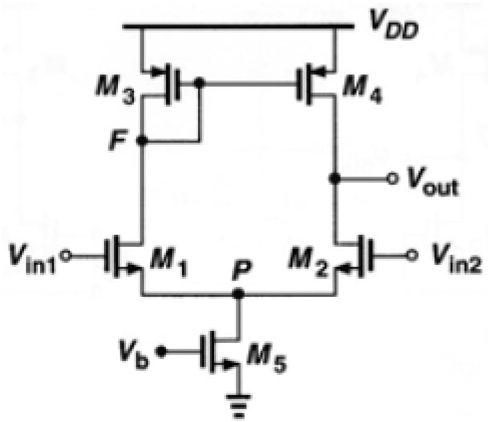
$$|A_v| \approx \frac{g_{m1}}{2}\left[(2r_{o2})\|r_{o4}\right]$$

❑ Differential pair with active current mirrors



M_3 and M_4 are identical.

❑ Large-signal analysis



(1) $V_{in1} << V_{in2}$ → M1 'off' → M3 & M4 'off'

→ M2 & M5 'on' → $V_{out} = 0$ → M2 & M5 triode

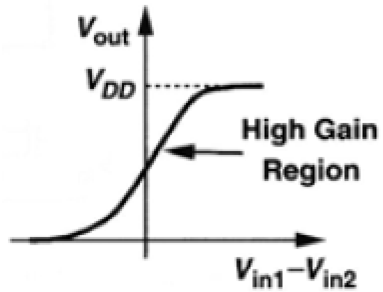
(2) $V_{in1}\uparrow$ & $V_{in2}\downarrow$ → $V_{in1} \approx V_{in2}$ → high gain

(3) $V_{in1} > V_{in2}$ → I_{D1}, I_{D3}, $I_{D4}\uparrow$, $I_{D2}\downarrow$ → $V_{out}\uparrow$

→ M4 triode

(4) $V_{in1} >> V_{in2}$ → M2 'off' → M4 deep triode $I_{D4} \approx 0$

→ $V_{out} = V_{DD}$



Input common mode 전압?

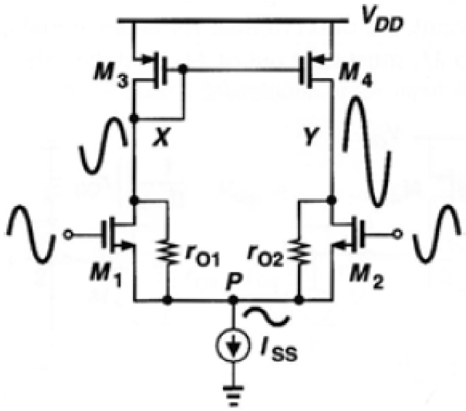
→ M2가 saturation 이려면 $V_{out} \geq V_{in,CM} - V_{TH}$

→ Output swing↑ $V_{in,CM}\downarrow$

→ $V_{in,CM,min} = V_{GS1,2} + V_{DS5,min}$

❑ Small-signal analysis (1)

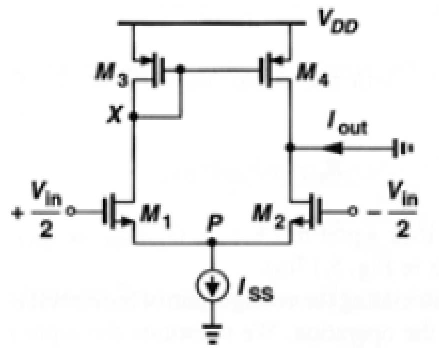
✓ Asymmetric swings, P → virtual ground.

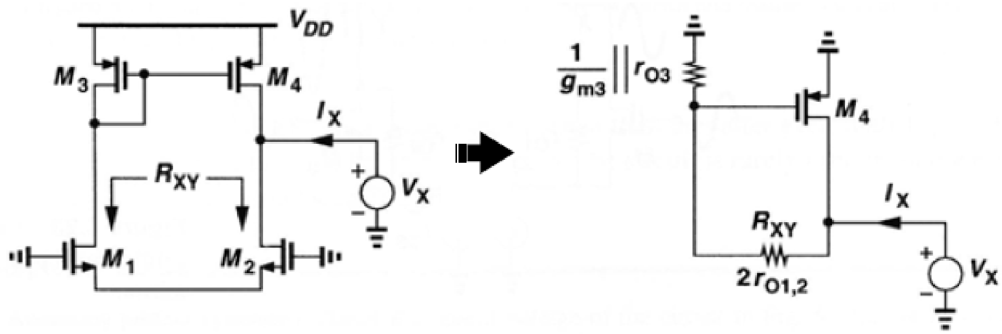


$$\begin{cases} I_{D1} = |I_{D3}| = |I_{D4}| = \dfrac{g_{m1}V_{in}}{2} \\ I_{D2} = -\dfrac{g_{m2}V_{in}}{2} \end{cases}$$

$$\Rightarrow I_{out} = I_{D2} + I_{D4} = -g_{m1,2}V_{in}$$

$$\therefore |G_m| = g_{m1,2}$$





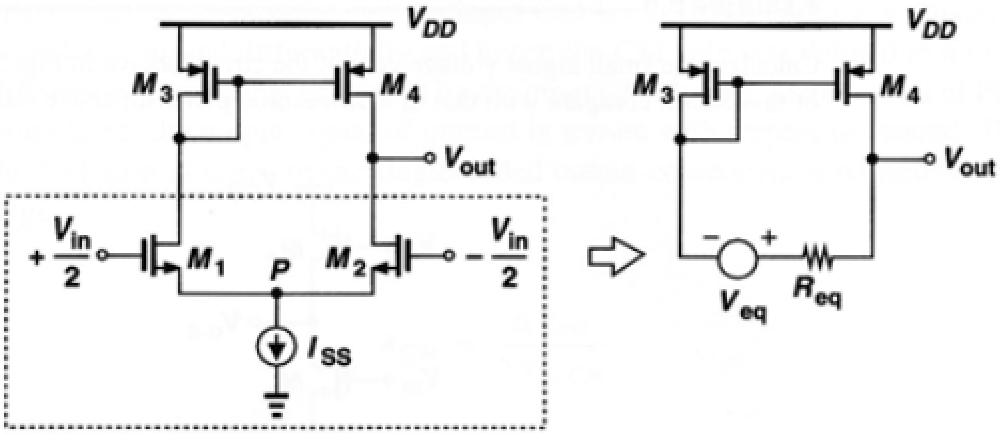
$$I_X = 2\frac{V_X}{2r_{o1,2} + \dfrac{1}{g_{m3}} \| r_{o3}} + \frac{V_X}{r_{o4}}$$

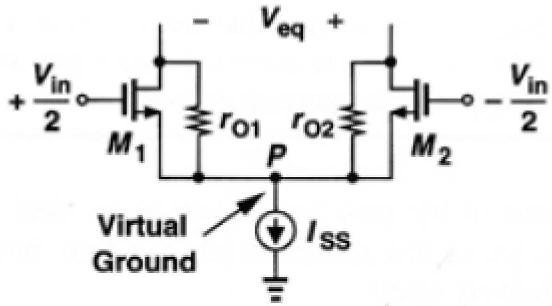
where the factor 2 accounts for current copying action of M_3 and M_4.

For $2r_{o1,2} >> (1/g_{m3}) \| r_{o3}$, we have $R_{out} \approx r_{o2} \| r_{o4}$

$|A_v| = G_m R_{out} = g_{m1,2}\,(r_{o2} \| r_{o4})$

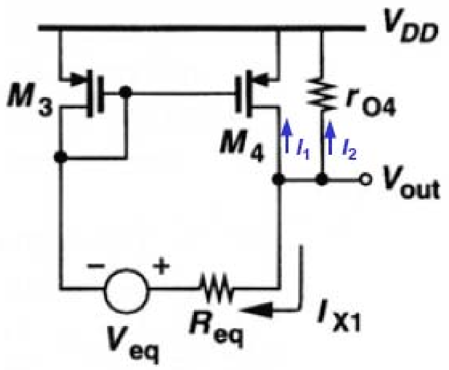
❑ Small-signal analysis (2)





$$V_{eq} = g_{m1,2}\, r_{o1,2}\, V_{in}$$

$$R_{eq} = 2\, r_{o1,2}$$



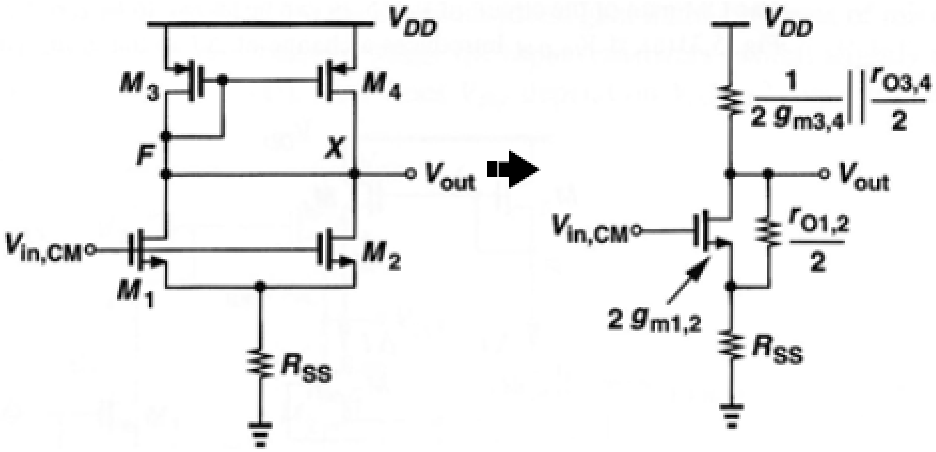
$$I_{X1} = \frac{V_{out} - g_{m1,2} r_{o1,2} V_{in}}{2r_{o1,2} + \frac{1}{g_{m3}} \| r_{o3}}$$

$$I_{X1} + \underbrace{\frac{V_{out} - g_{m1,2} r_{o1,2} V_{in}}{2r_{o1,2} + \frac{1}{g_{m3}} \| r_{o3}} \cdot \frac{r_{o3}}{r_{o3} + \frac{1}{g_{m3}}}}_{I_1} + \underbrace{\frac{V_{out}}{r_{o4}}}_{I_2} = 0$$

$$2r_{o1,2} >> (1/g_{m3,4}) \| r_{o3,4}:$$

$$\frac{V_{out}}{V_{in}} = \frac{g_{m1,2} r_{o3,4} r_{o1,2}}{r_{o1,2} + r_{o3,4}} = g_{m1,2}\left(r_{o1,2} \| r_{o3,4}\right)$$

❑ Common-mode 특성



$$A_{CM} \approx -\frac{\frac{1}{2g_{m3,4}} \left\| \frac{r_{o3,4}}{2} \right.}{\frac{1}{2g_{m1,2}} + R_{SS}}$$ ← $R_{o1,2,3,5}$를 무시

$$= -\frac{1}{1+2g_{m1,2}R_{SS}} \cdot \frac{g_{m1,2}}{g_{m3,4}}$$

$$CMRR = \left| \frac{A_{DM}}{A_{CM}} \right| = g_{m1,2}\left(r_{o1,2} // r_{o3,4}\right)\frac{g_{m3,4}\left(1+2g_{m1,2}R_{SS}\right)}{g_{m1,2}} = \left(1+2g_{m1,2}R_{SS}\right)g_{m3,4}\left(r_{o1,2} // r_{o3,4}\right)$$