Design of Analog CMOS Integrated Circuits

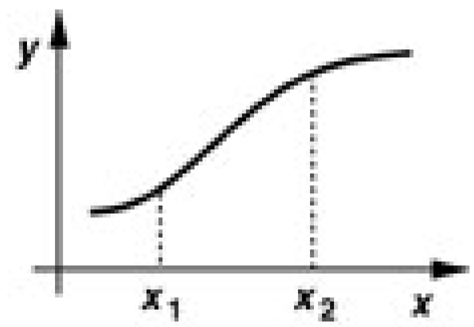
<Chapter 3>

Single Stage Amplifier

양병도

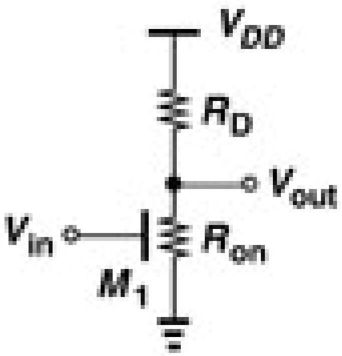
3.1 Basic concepts

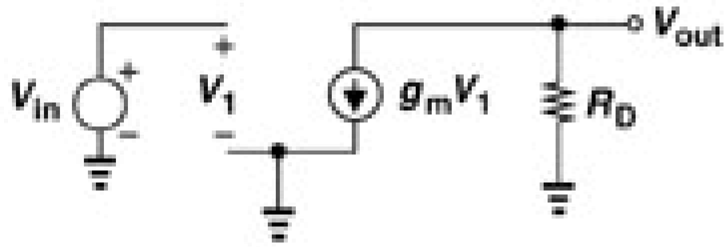
- MOSFET은 non-linear 함수 → small signal은 linear 함수로 사용
  - ✓ $y(t) \approx \alpha_0 + \alpha_1 x(t) + \alpha_2 x^2(t) + \ldots + \alpha_n x^n(t)$
  - ✓ where $x(t)$ and $y(t)$ may be current or voltage.
  - ✓ For a sufficiently narrow range of x,
  - ✓ $y(t) \approx \alpha_0 + \alpha_1 x(t)$
  - ✓ where α_0 can be considered the operating (bias) point and α_1 the small signal gain.



Non-linear system

3.2 Common Source





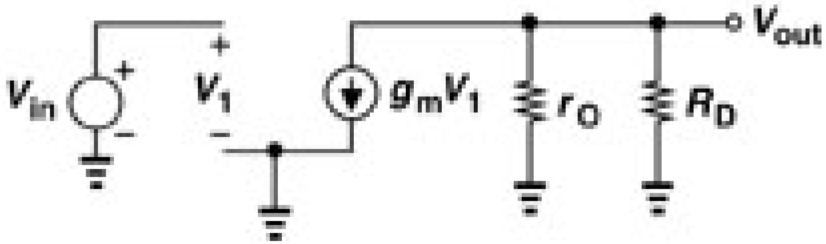
$$V_{out} = V_{DD} - R_D \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{in} - V_{TH})^2$$

$$A_v = \frac{\partial V_{out}}{\partial V_{in}} = -R_D \mu_n C_{ox} \frac{W}{L} (V_{in} - V_{TH}) = -g_m R_D$$

$$A_v = -g_m R_D$$

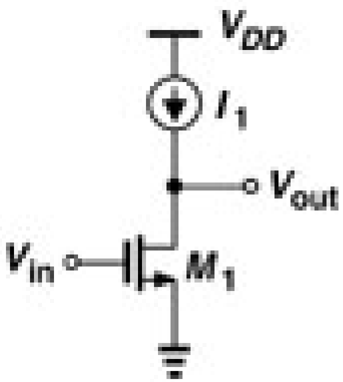
Common Source (cont.)

- Channel length modulation 고려시



$$A_v = -g_m r_o \parallel R_D$$

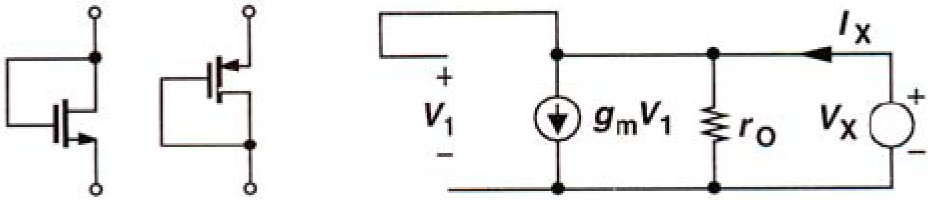
- Ex 2.5



$$A_v = -g_m r_o = -g_m \frac{1}{\lambda I_D}$$

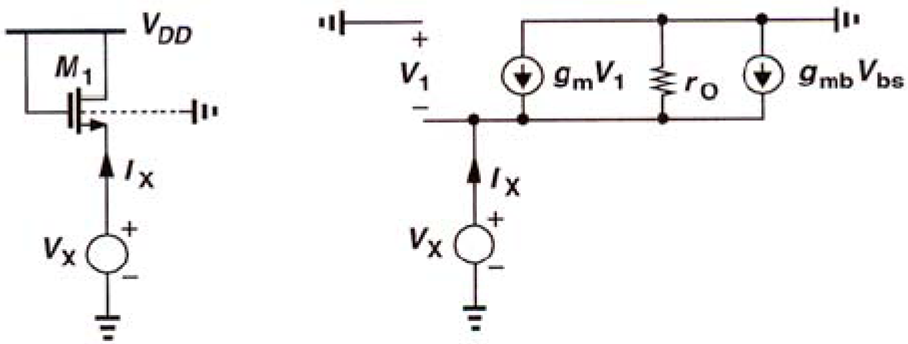
Common Source with Diode-Connected Load

- R_D 대신 MOS diode로 저항 사용



$$R_X = \frac{V_X}{I_X} = \frac{1}{g_m} \| r_O \approx \frac{1}{g_m}$$

- Body-effect 고려 → g_{mb} 추가

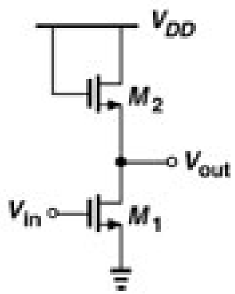


$$R_X = \frac{V_X}{I_X} = \frac{1}{g_m + g_{mb}} \| r_O$$

$$\approx \frac{1}{g_m + g_{mb}}$$

CS with Diode-Connected Load (cont.)

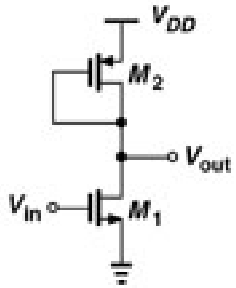
- NMOS diode로 저항 사용 → body-effect → g_{mb} 추가



$$A_v = -g_{m1}\frac{1}{g_{m2}+g_{mb2}} = -\frac{g_{m1}}{g_{m2}}\frac{1}{1+\eta}$$

$$A_v = -\sqrt{\frac{(W/L)_1}{(W/L)_2}}\frac{1}{1+\eta}$$

- PMOS diode로 저항 사용 → body-effect 없음



$$A_v = -g_{m1}\frac{1}{g_{m2}} = -\frac{g_{m1}}{g_{m2}}$$

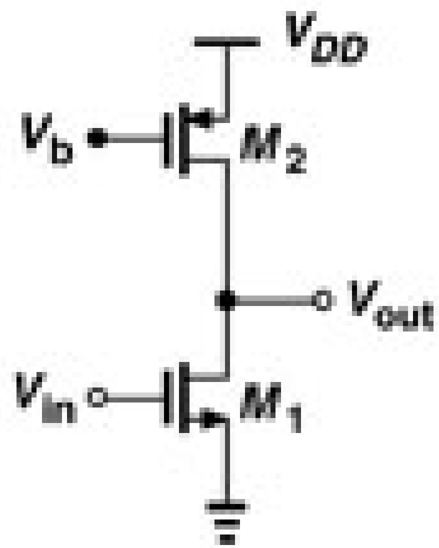
$$A_v = -\sqrt{\frac{u_n(W/L)_1}{u_p(W/L)_2}}$$

- Channel-length modulation 고려

$$A_v = -g_{m1}\left(\frac{1}{gm2}\|ro1\|ro2\right)$$

CS with Current Source Load

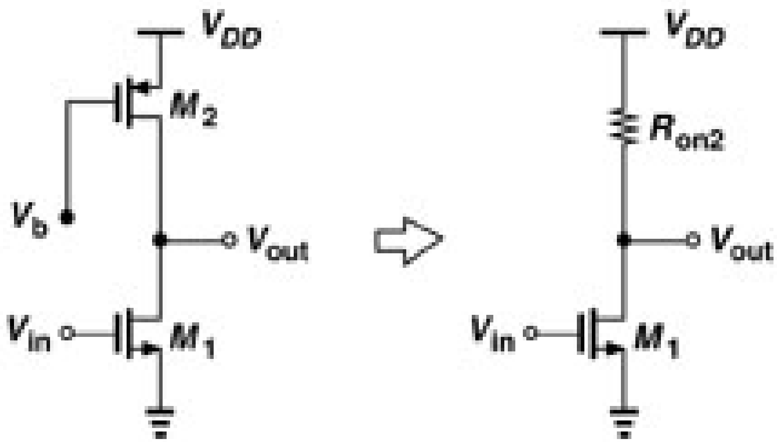
- Load의 Gate 전압이 변하지 않으므로 V_{DS}의 전압이 줄어도 동작
  → Vout swing 전압이 커진다.



$$A_v = -g_m(r_{o1} \| r_{o2})$$

CS with Triode Region Load

- Vb가 V_{DD}에 근접하면 load가 triode 동작에서 저항처럼 보인다.

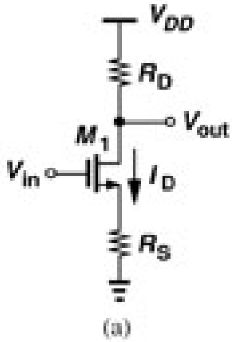


$$A_v = -g_m R_{ON2}$$

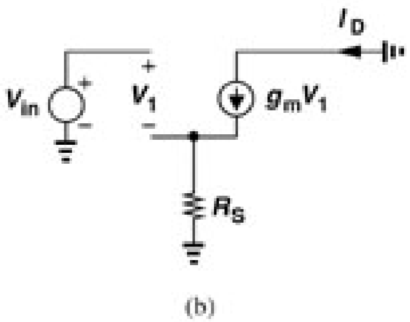
$$R_{ON2} = \frac{1}{\mu_n C_{ox} \left(\frac{W}{L}\right)_2 (V_{DD} - V_b - |V_{THP}|)}$$

CS with Source Degeneration

- 단점 → gain이 줄어든다.
- 장점 → gain이 저항으로만 이루어져 안정적이고 주파수 특성이 좋다.



(a)



(b)

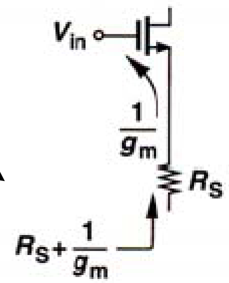
$$v_{in} = v_{gs} + R_s g_m v_{gs} = (1 + R_s g_m) v_{gs}$$

$$v_{gs} = \frac{v_{in}}{1 + R_s g_m}$$

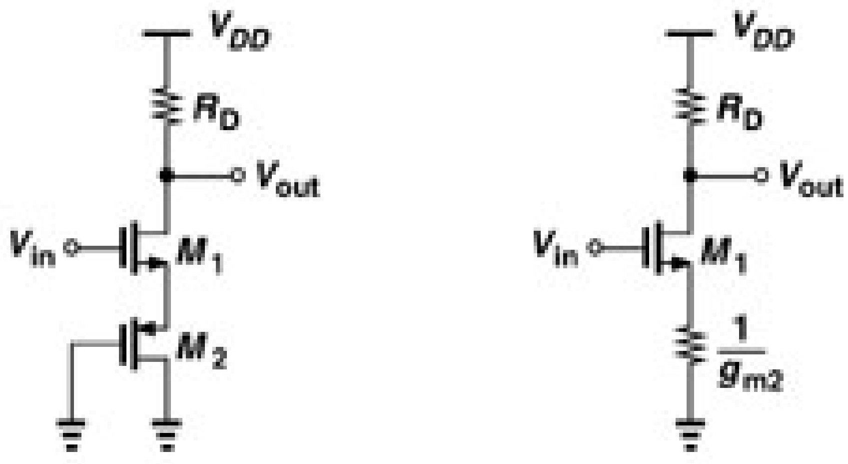
$$v_{out} = -R_D \times g_m v_{gs} = -\frac{R_D g_m}{1 + g_m R_S} v_{in}$$

$$A_v = \frac{-g_m R_D}{1 + g_m R_S} = \frac{-R_D}{1/g_m + R_S}$$

$$A_v \approx -\frac{R_D}{R_S} \quad (g_m << R_S)$$



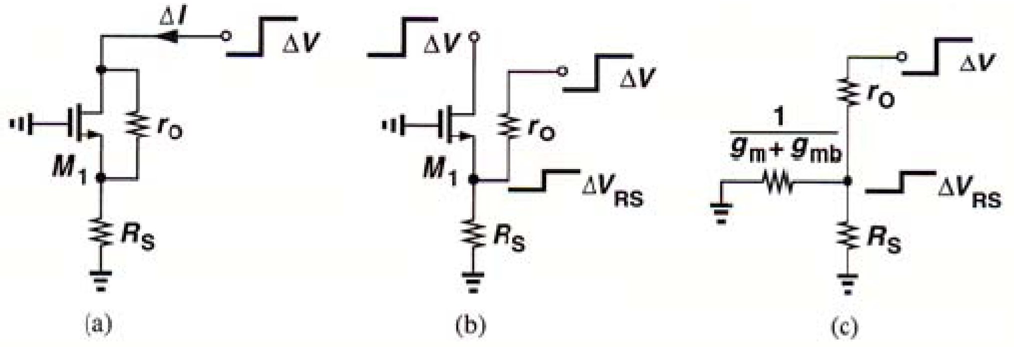
CS with Source Degeneration



(a) (b)

- Ex. 3.5
  - ✓ M_2 is “diode-connected” → 저항 $1/g_{m2}$ 으로 보인다.
  - ✓ $A_V = -R_D/(1/g_{m1}+1/g_{m2})$

CS Output Resistance

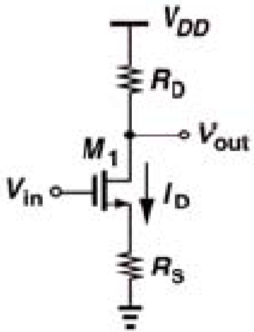


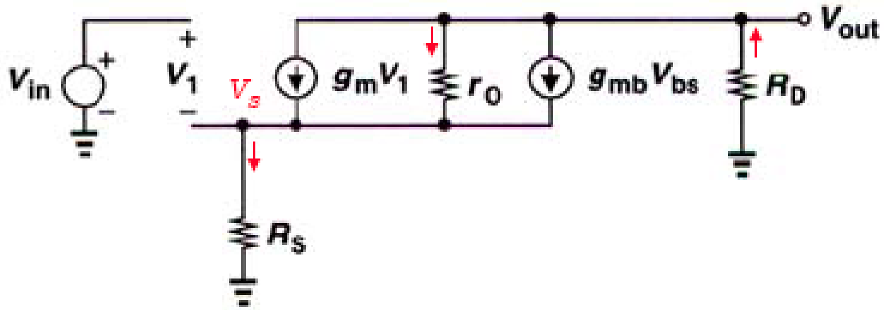
$$\Delta V_{RS} = \Delta V \frac{\frac{1}{g_m + g_{mb}} // R_S}{\frac{1}{g_m + g_{mb}} // R_S + r_o}$$

$$\Delta I = \frac{\Delta V_{RS}}{R_S} = \Delta V \frac{1}{[1 + (g_m + g_{mb})R_S]r_o + R_S}$$

$$\frac{\Delta V}{\Delta I} = [1 + (g_m + g_{mb})R_S]r_o + R_S = R_{out}$$

CS with Source Denegeneration (cont.)





$$I_{ro} = -\frac{V_{out}}{R_D} - \left(g_m V_1 + g_{mb} V_{bs}\right) = -\frac{V_{out}}{R_D} - \left[g_m\left(V_{in} + V_{out}\frac{R_S}{R_D}\right) + g_{mb}V_{out}\frac{R_S}{R_D}\right]$$

$$V_{out} = I_{ro} r_o - \frac{V_{out}}{R_D}R_S = -\frac{V_{out}}{R_D} r_o - \left[g_m\left(V_{in} + V_{out}\frac{R_S}{R_D}\right) + g_{mb}V_{out}\frac{R_S}{R_D}\right] r_o - V_{out}\frac{R_S}{R_D}$$

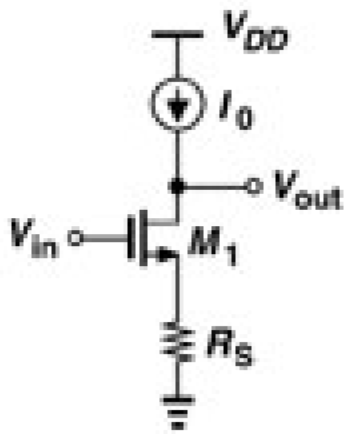
It follows that $\dfrac{V_{out}}{V_{in}} = \dfrac{-g_m r_o R_D}{R_D + R_S + r_o + (g_m + g_{mb})R_S r_o} = \dfrac{-g_m r_o R_D}{R_D + R_{out}}$

Let us rewrite as $A_v = -\dfrac{g_m r_o}{R_S + r_o + (g_m + g_{mb})R_S r_o} \cdot \dfrac{R_D\left[R_S + r_o + (g_m + g_{mb})R_S r_o\right]}{R_D + R_S + r_o + (g_m + g_{mb})R_S r_o}$

$$= -G_m (R_D // R_{out})$$

CS Gain Example

- Ex. 3.6



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

$$= -\frac{g_m r_o}{R_{out}} R_{out}$$

$$= -g_m r_o$$

3.3 Source Follower (Common-Drain)

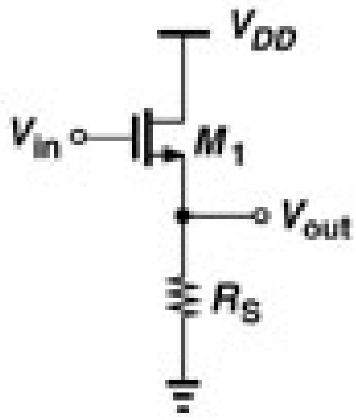
Buffering Action

- ✓ Common Source 는 high gain을 얻기 위해 R_L이 커야 한다.
- ✓ R_L이 낮은 load를 drive 하기 위해 buffer 필요

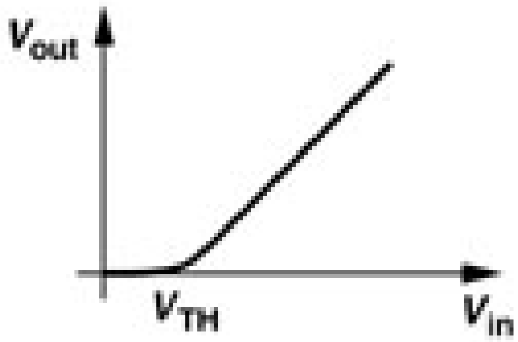
Buffer

- ✓ Av=1
- ✓ Rin=∞

Large Signal Behavior



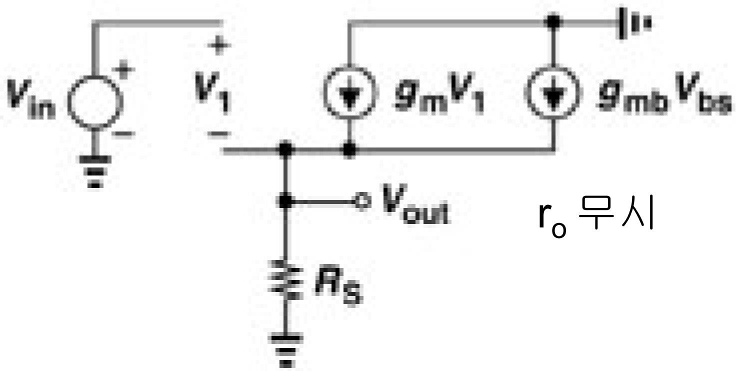
(a)



(b)

- If $V_{in}<V_{TH}$ → M_1은 off.
- If $V_{in}>V_{TH}$ → M_1은 Saturation 에서 동작
- Body Effect:
  - ✓ $I_D\uparrow$ → $V_S=I_DR_S\uparrow$ → $V_{SB}\uparrow$ → $V_{TH}\uparrow$
- $I_D \approx (V_G-V_{TH})/R_S$

Source Follower Gain



r_o 무시

$$V_{in} - V_1 = V_{out}$$

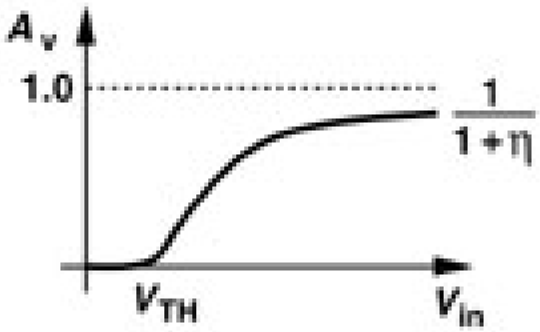
$$V_{bs} = -V_{out}$$

$$V_{out} = R_S(g_m V_1 + g_{mb} V_{bs})$$

V_{in}과 V_{bs}를 넣고 정리하면

$$A_v = \frac{V_{out}}{V_{in}} = \frac{g_m R_S}{1 + (g_m + g_{mb}) R_S}$$

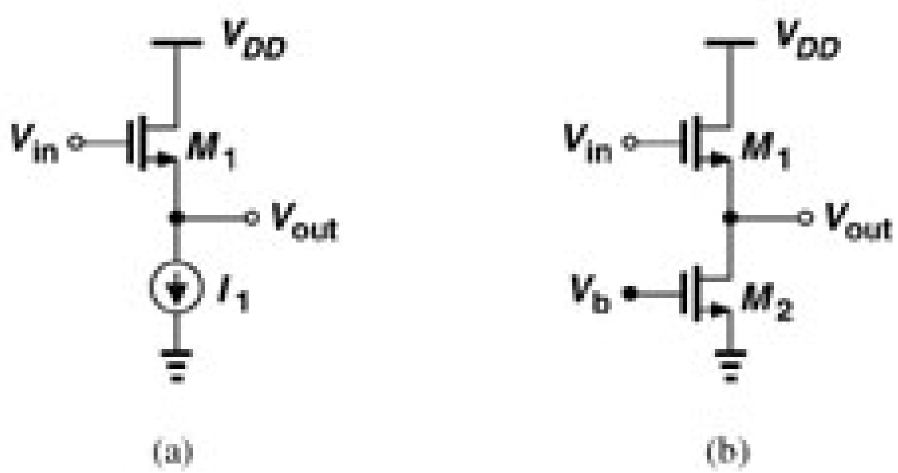
$$A_v = \frac{g_m R_S}{1 + g_m(1+\eta) R_S} \approx \frac{1}{1+\eta}$$



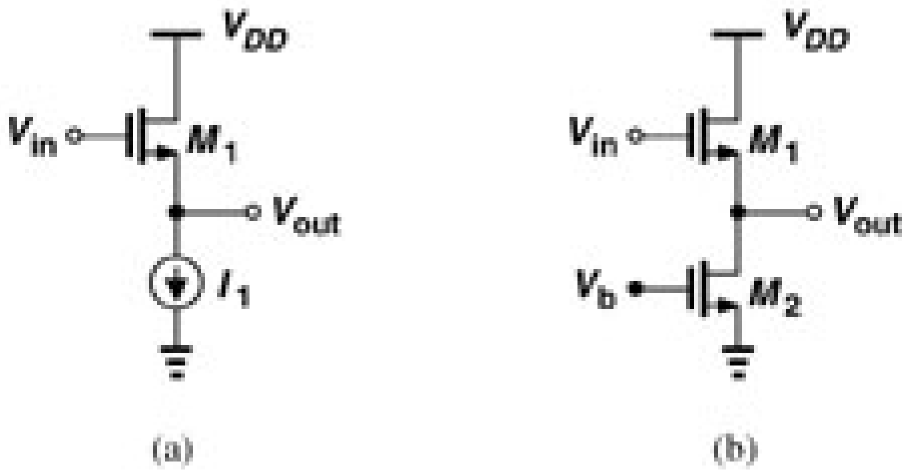
Gain Dependence on V_G

Problem with R_S

- V_{in}가 변하면 → Vs 변화 → I_D 변화 → gm 변화 → gain 변화 → nonlinearity.
- 해결: R_S → Current Source → I_D 유지

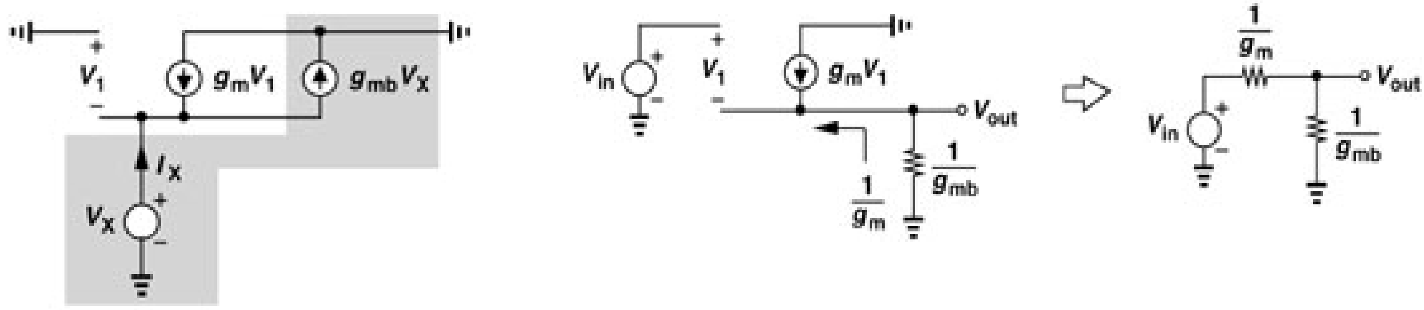


Example 3.7



- Let $(W/L)_1=20/0.5$, $I_1=200\mu A$, $V_{THO}=0.6V$, $2\Phi_F=0.7V$, $\mu_n C_{OX}=50\mu A/V^2$, $\gamma=0.4V^{1/2}$
- $V_{in}=1.2V$일 때, V_{out}?
  - ✓ Current: $(V_{in}-V_{TH}-V_{out})^2 = 2I_D/\mu_n C_{OX}(W/L)_1$ → $V_{out}\approx 0.153V$
  - ✓ 위 결과 대입 → $V_{TH}\approx V_{THO}+\gamma((2\Phi_F+V_{out})^{1/2}-(2\Phi_F)^{1/2})\approx 0.635V$
  - ✓ 위 결과를 current 계산에 다시 대입 → $V_{out}\approx 0.119V$,
- M_2 is in saturation, $(W/L)_2$의 최소 크기는?
  - ✓ $V_{out}=V_{DS2}=0.119V\geq V_b-V_{TH2}=[2I_D/\mu_n C_{OX}(W/L)_2]^{1/2}$
  - ✓ $(W/L)_2\geq 283/0.5$

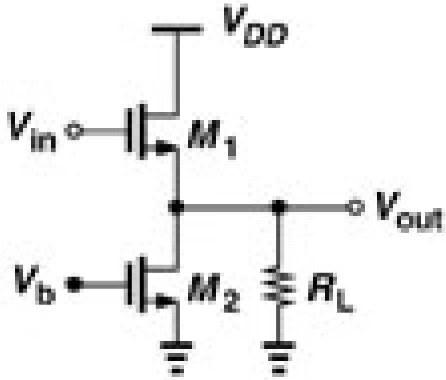
Gain of Source Follower with Current Source



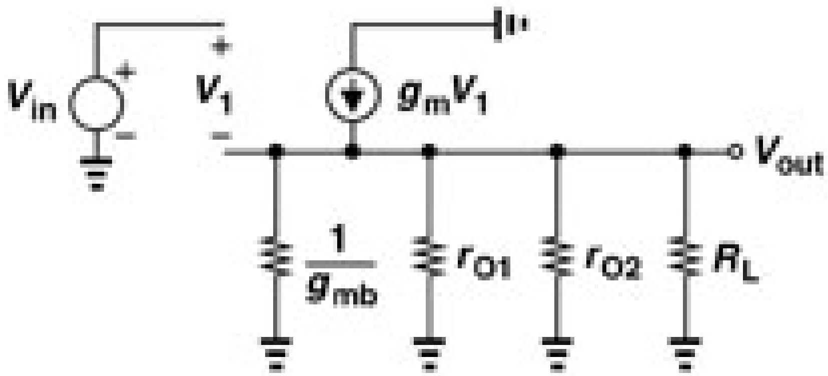
- voltage gain

$$A_V = \frac{\frac{1}{g_{mb}}}{\frac{1}{g_m} + \frac{1}{g_{mb}}} = \frac{g_m}{g_m + g_{mb}}$$

Source Follower with NMOS Current Source and R_L Loads



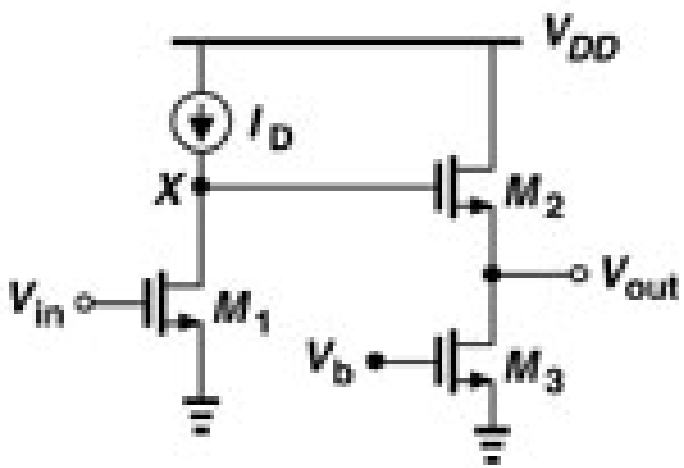
(a)



(b)

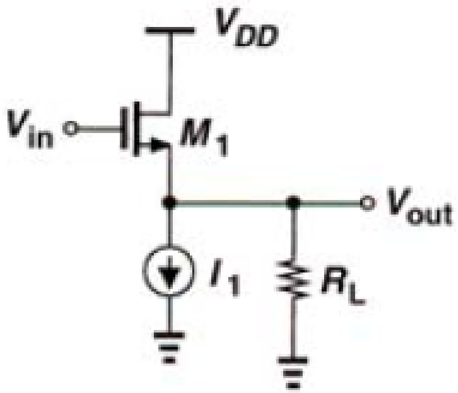
$$A_v = \frac{\frac{1}{g_{mb1}} \| r_{o1} \| r_{o2} \| R_L}{(\frac{1}{g_{mb1}} \| r_{o1} \| r_{o2} \| R_L) + \frac{1}{g_{m1}}}$$

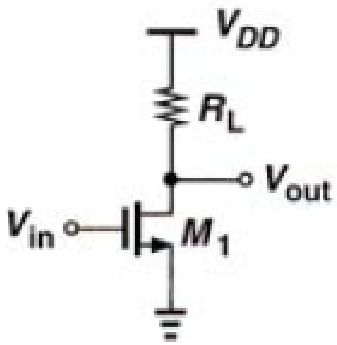
CS Amplifier + Source Follower



- Voltage headroom (swing) limitation
  - ✓ CS amp. alone: $V_X \geq V_{GS1} - V_{TH1}$ to assure that M_1 is in Saturation.
  - ✓ CS amp + Source Follower: $V_X \geq V_{GS2} + (V_{GS3} - V_{TH3})$ to assure that M_3 is in Saturation.

Poor Driving Capability



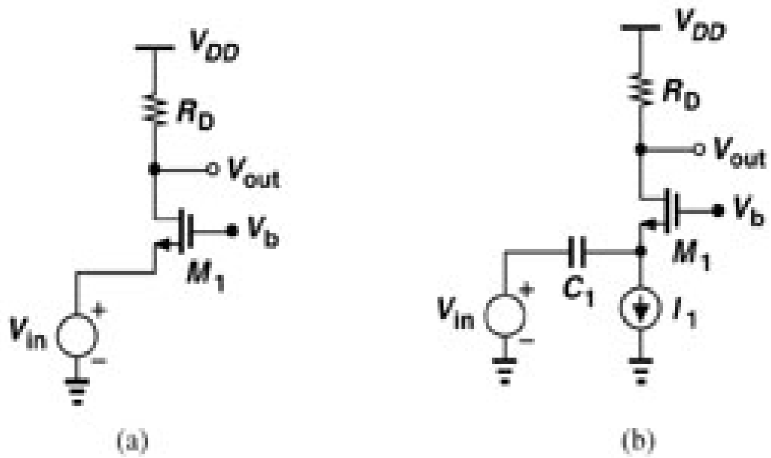


$$\left.\frac{V_{out}}{V_{in}}\right|_{SF} \approx \frac{R_L}{R_L + \dfrac{1}{g_{m1}}}$$

$$\left.\frac{V_{out}}{V_{in}}\right|_{CS} \approx g_{m1} R_L$$

- R_L이 작아지면 source follower의 gain이 크게 준다.

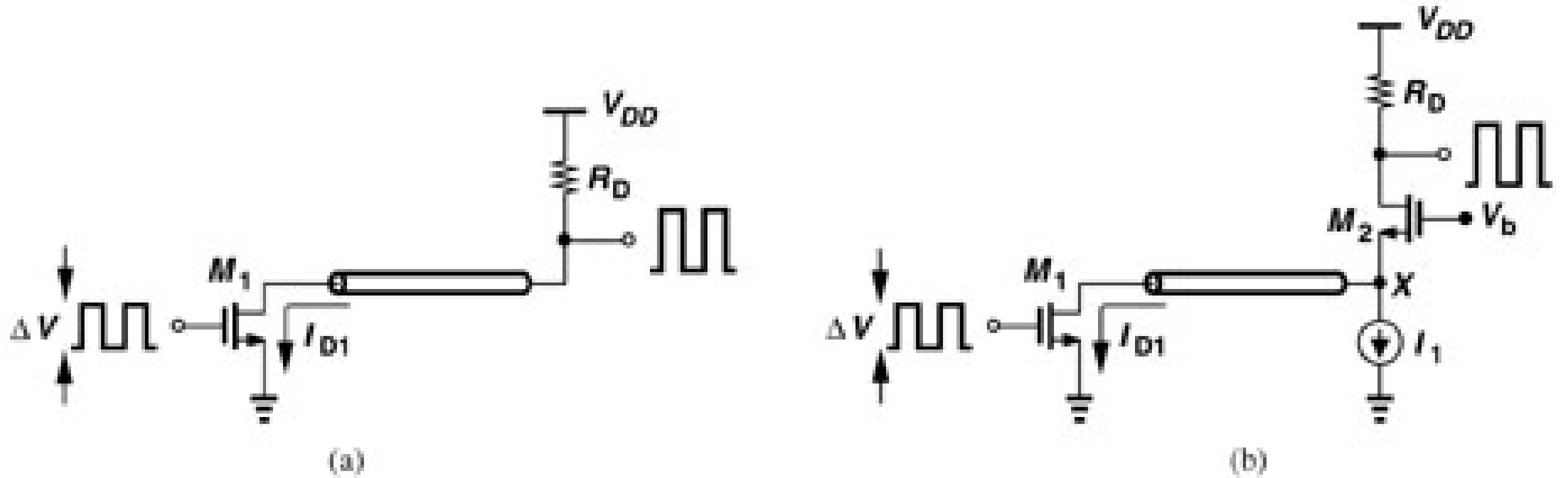
3.4 Common-Gate Amplifier



- $A_V = g_m R_D$
- $R_{in} = 1/g_m$
- $R_{out} = R_D // r_o$

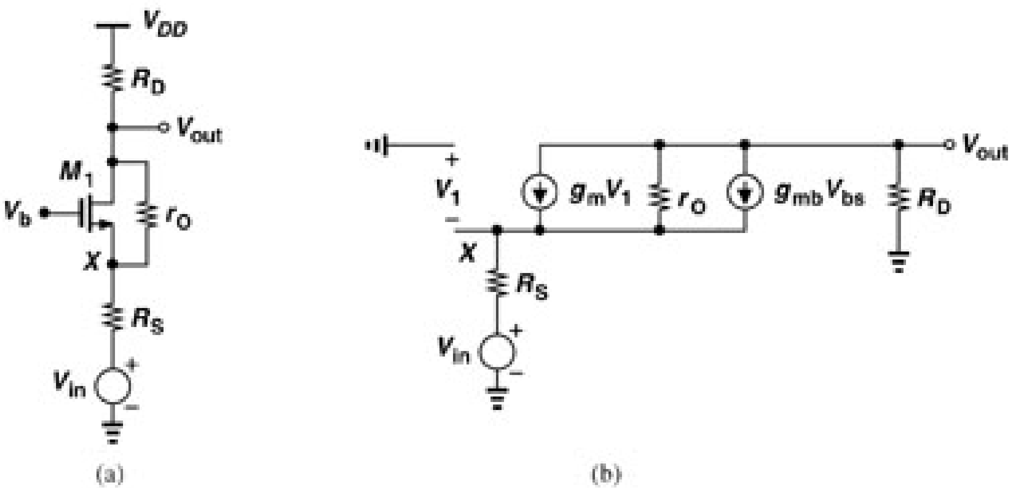
- body Effect 고려 → V_{gs}와 V_{bs}가 똑같이 V_{in}에 영향을 받음
  - ✓ $g_m \rightarrow g_m + g_{mb} = g_m(1+\eta)$
  - ✓ $A_V = g_m(1+\eta) R_D$
  - ✓ $R_{in} = 1/g_m(1+\eta)$

Low R_{in} of CG Amplifiers is useful if signal comes from a transmission line



- Assume: 50Ω transmission line
- If λ=γ=0, → 둘 회로가 같은 gain $A_V \approx -g_m R_D$.
- (a) R_D= 50Ω for no reflections → gain이 작다.
- (b) $R_{in} = 1/ g_m(1+\eta) = 50\Omega$ → R_D 를 크게 할 수 있다. → gain이 크다.

CG Amplifier – r_o와 R_s 고려



$$A_v = \frac{(g_m + g_{mb})r_o + 1}{r_o + (g_m + g_{mb})r_o R_S + R_S + R_D} R_D$$

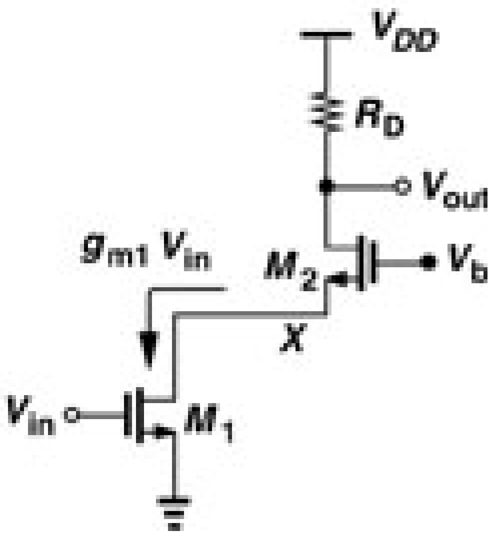
$$R_{in} = \frac{1}{g_m + g_{mb}} + \frac{R_D}{(g_m + g_{mb})r_o}$$

$$R_{out} = \{[1 + (g_m + g_{mb})r_o]R_S + r_o\} \,||\, R_D$$

CG Amplifier의 특징

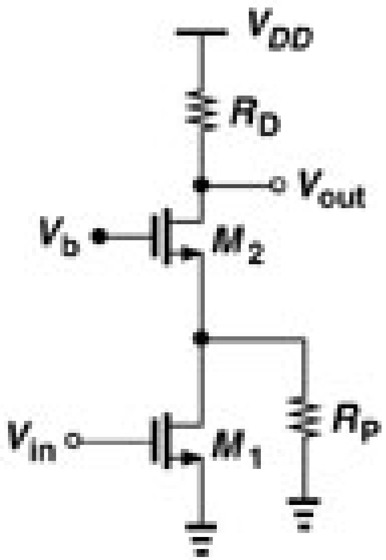
- Voltage gain = CS amplifier와 같다.
- Current gain =1 → current buffer.
- 입력 저항 작다.
- 출력 저항 크다.

3.5 Cascode stage



- CS + CG
  - ✓ Current gain은 CS에서 발생
  - ✓ CG는 current buffer
  - ✓ $A_V = -g_m R_D$ → CS와 같은 gain
- M1과 M2 saturation에서 동작
  - ✓ 출력 전압의 swing 범위가 줄어든다.
  - ✓ $V_b \geq V_{GS2} + V_{in} - V_{TH1}$
  - ✓ $V_{out} \geq V_{in} - V_{TH1} + V_{GS2} - V_{TH2}$

EX 3.14

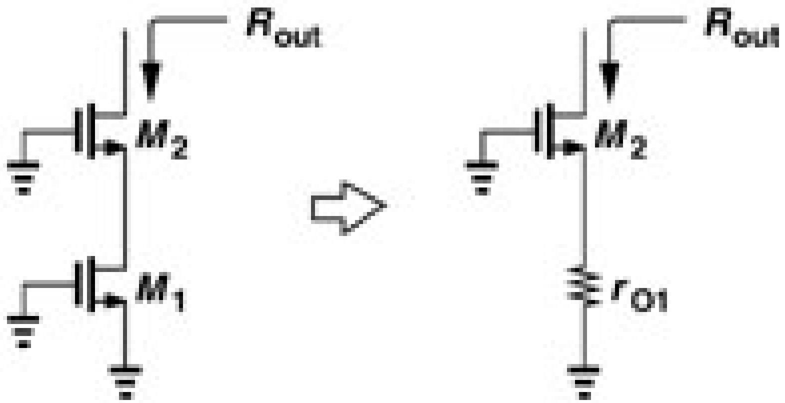


- A_v?
  - λ=0
  - $I_{D1} = g_{m1} V_{in}$
  - I_{D1}은 R_D와 I_{D2}로 전류가 나뉨.
  - → current divider
  - $A_v = I_{D2} / V_{in}$

$$I_{D2} = g_{m1} V_{in} \frac{R_P}{R_P + \frac{1}{g_{m2} + g_{mb2}}} = g_{m1} V_{in} \frac{R_P (g_{m2} + g_{mb2})}{R_P (g_{m2} + g_{mb2}) + 1}$$

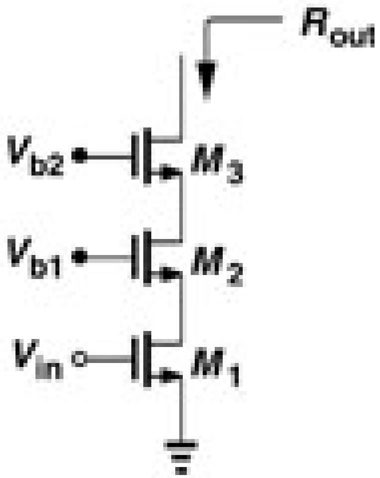
$$A_V = -g_{m1} \frac{R_P R_D (g_{m2} + g_{mb2})}{R_P (g_{m2} + g_{mb2}) + 1}$$

Output Resistance



- CS에서 degeneration 저항을 가진 경우와 같다.
- Cascode로 연결된 경우 r_{o1}이 $r_{o2}(g_{m2}+g_{mb2})$배 크게 보인다.

$$R_{out} = [1 + (g_{m2} + g_{mb2})r_{o2}]r_{o1} + r_{o2}$$
$$\approx r_{o1}r_{o2}(g_{m2} + g_{mb2})$$



- Cascode의 수를 증가시키면 지속적으로 출력 저항이 크게 보인다.

EX 3.15

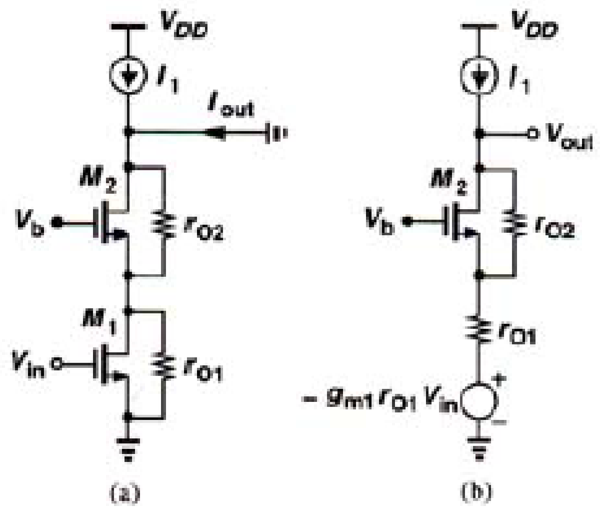
$$I_{out} = g_{m1}v_{in}\frac{r_{o1}}{r_{o1} + \frac{1}{g_{m2}+g_{mb2}}//r_{o2}}$$

$$G_m = g_{m1}\frac{r_{o1}}{r_{o1} + \frac{1}{g_{m2}+g_{mb2}}//r_{o2}} = \frac{g_{m1}r_{o1}[r_{o2}(g_{m2}+g_{mb2})+1]}{r_{o1}r_{o2}(g_{m2}+g_{mb2})+r_{o1}+r_{o2}}$$

$$A_v = -G_m R_{out} = -g_{m1}r_{o1}[r_{o2}(g_{m2}+g_{mb2})+1]$$

If we had assumed $G_m = g_{m1}$,

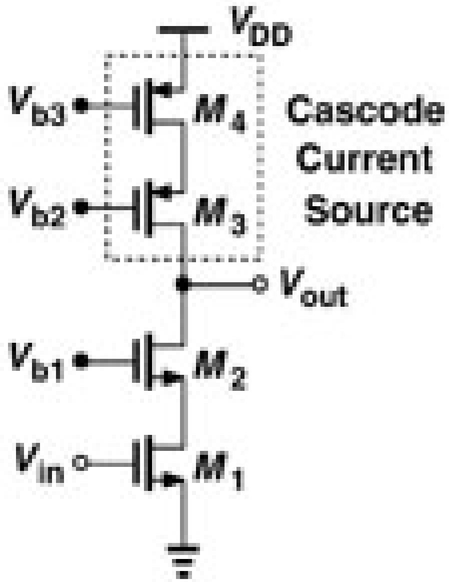
then $A_v \approx -g_{m1}\{[1+(g_{m2}+g_{mb2})r_{o2}]\ r_{o1}+r_{o2}\}$



- ❑ A_v?
  - ✓ $I_{D1} = g_{m1}V_{in}$
  - ✓ I_{D1}은 r_{o1}와 I_{out}로 전류가 나뉨. → current divider
  - ✓ $A_v = I_{out}/V_{in}$
- ❑ 쉽게 풀면, $G_m=g_m$으로 가정 후 R_{out}을 곱함.

NMOS cascode amplifier with PMOS cascode load

- PMOS current source 출력 저항 증가 → gain 증가
- 출력 전압 swing 줄어듦
  - ✓ $V_{DD} - (V_{GS1}-V_{TH1}) - (V_{GS2}-V_{TH2}) - |V_{GS3}-V_{TH3}| - |V_{GS4} - V_{TH4}|$



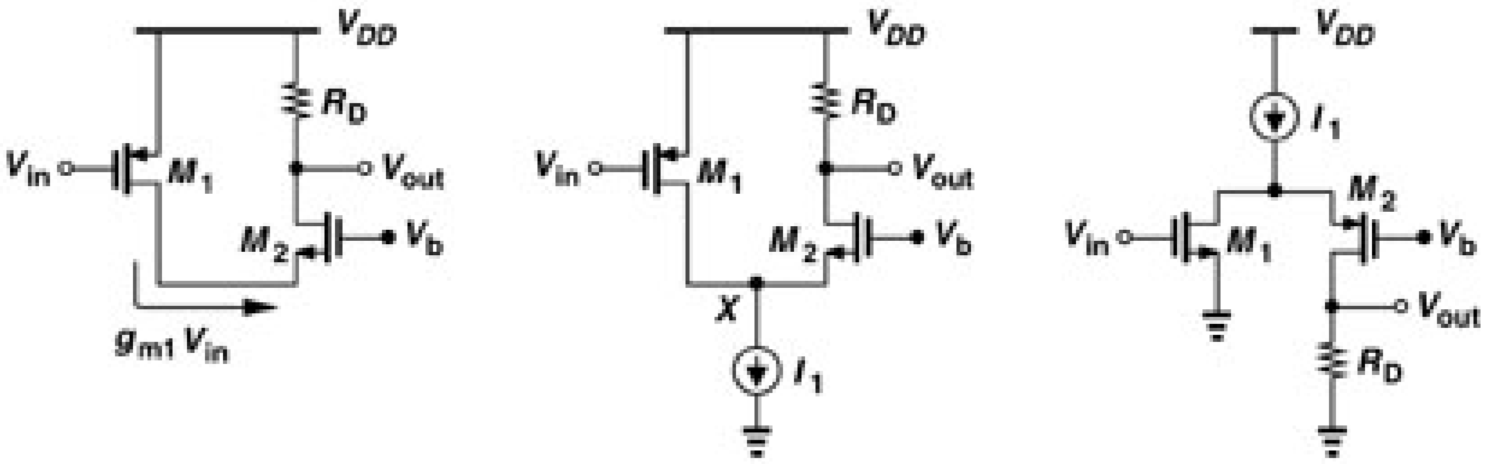
$$A_V \approx G_m R_{out}$$

$$R_{out} = \{[1+(g_{m2}+g_{mb2})r_{o2}]r_{o1} + r_{o1}\} \,||\, \{[1+(g_{m3}+g_{mb3})r_{o3}]r_{o4} + r_{o3}\}$$

$$G_m \approx g_{m1}$$

$$A_V \approx g_{m1}[(r_{o1}r_{o2}g_{m2}) \,||\, (r_{o3}r_{o4}g_{m3})]$$

Folded Cascode



(a) (b) (c)

- NMOS CS + PMOS CG or PMOS CS + NMOS CG
- Cascode 형태와 결과는 유사함
- DC current source 필요