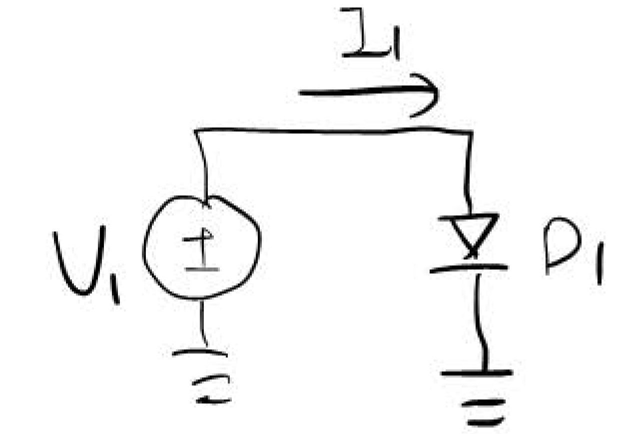
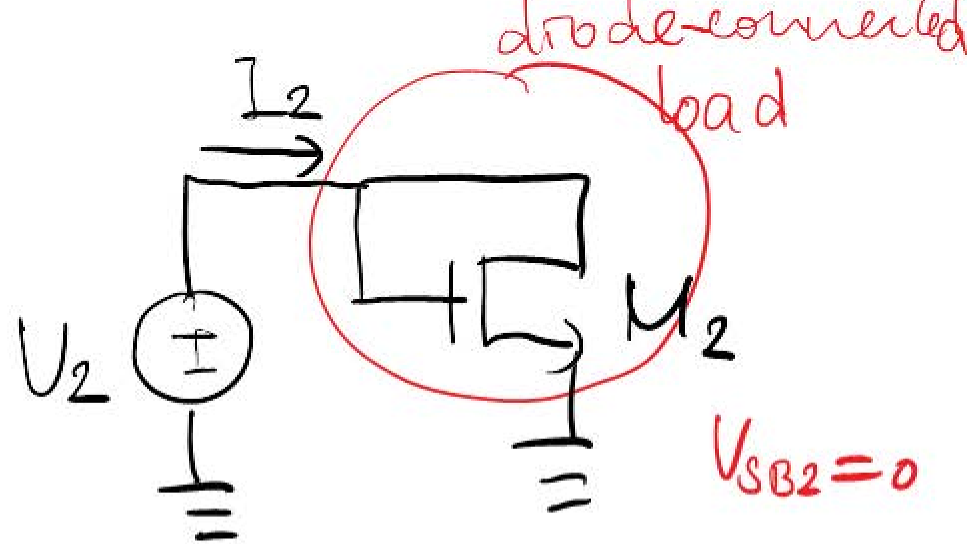
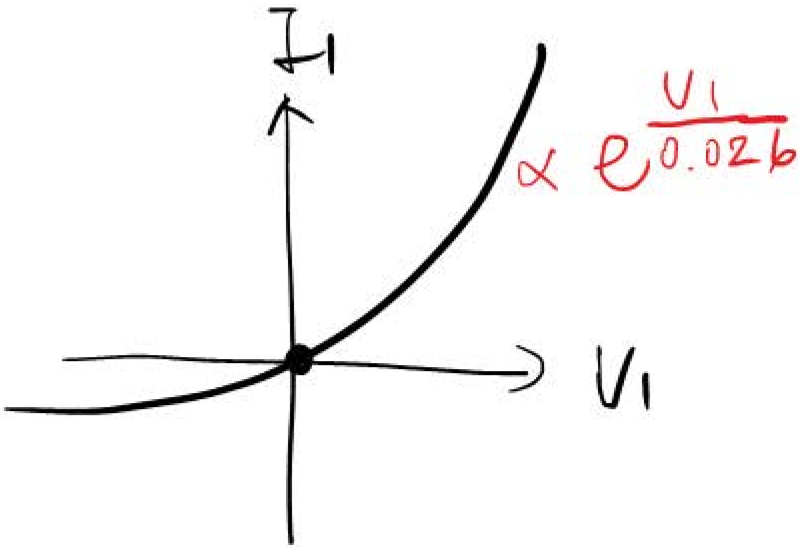
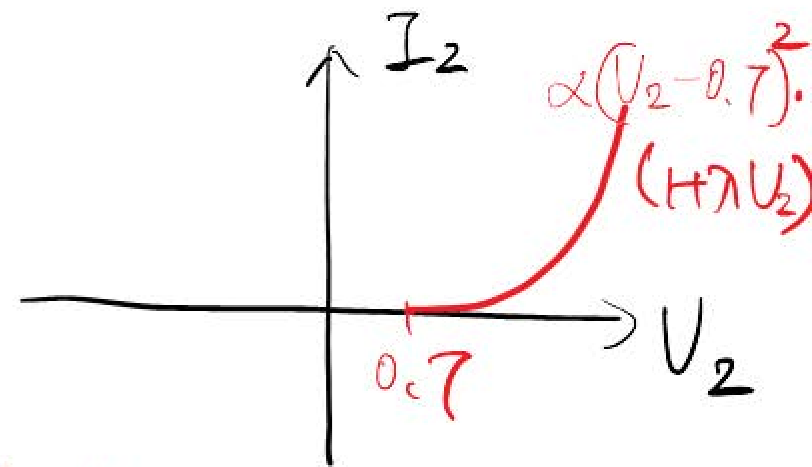
Common-Source with Diode-Connected Load





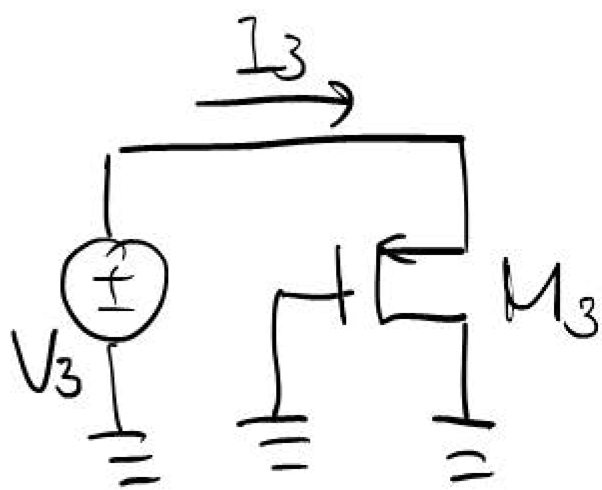
$V_{SB2} = 0$





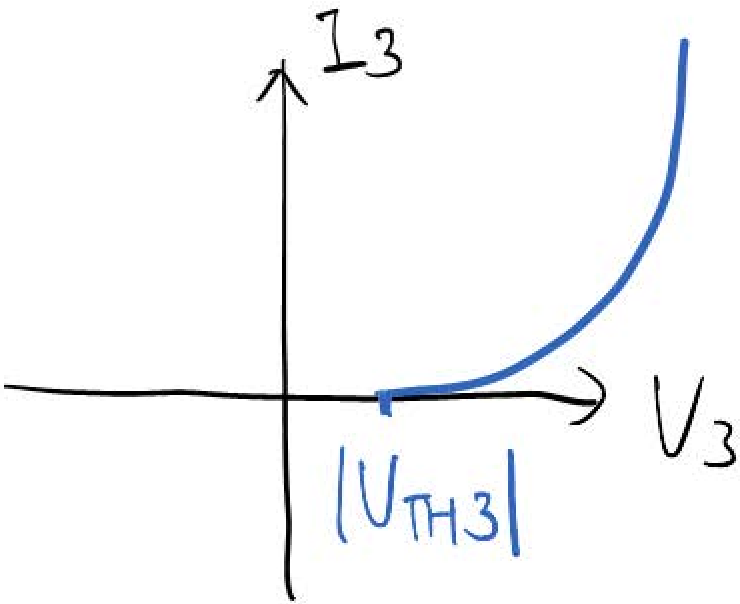
M_2 always in sat.

$$I_2 = \frac{1}{2}\mu_n C_{ox}\frac{W}{L_{eff}}(V_2 - 0.7)^2(1+\lambda V_2)$$

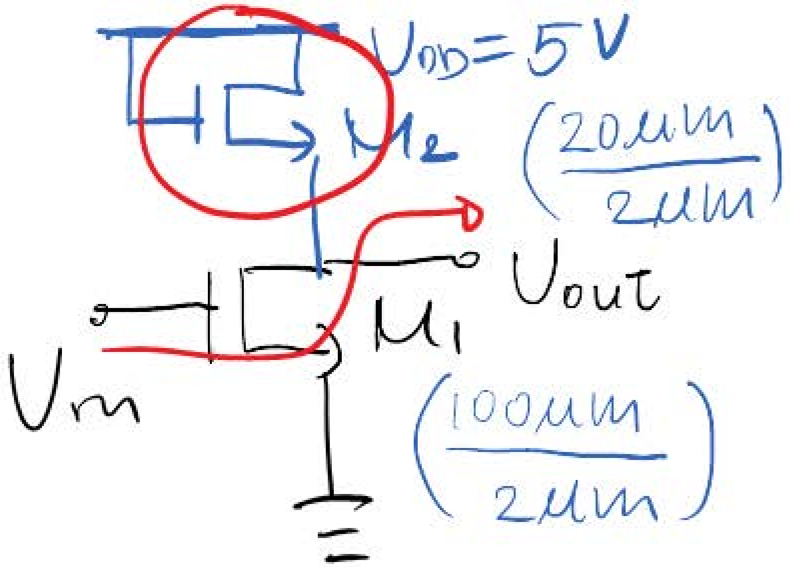


M_3 always in Sat.

$V_{BS3} = V_{DD} - V_3 > 0$, $|V_{TH3}| > 0.8$



$$I_3 = \frac{1}{2} \mu_p C_{ox} \left(\frac{W}{L_{eff}}\right)_3 \cdot (V_3 - |V_{TH3}|)^2 (1 + \lambda V_3)$$



1° Find out $V_{OUT} = ?$

Then we make sure M_1 and M_2 in sat.

$$\frac{1}{2}\mu_n C_{ox}\left(\frac{100\mu m}{2\mu m - 2L_D}\right)(0.8-0.7)^2 \cdot (1+\lambda V_{OUT})$$

$$= \frac{1}{2}\mu_n C_{ox}\left(\frac{20\mu m}{2\mu m - 2L_D}\right) \cdot (5 - V_{OUT} - V_{TH})^2 \cdot [1+\lambda(5-V_{OUT})]$$

$V_{SB1} = 0 \rightarrow V_{TH1} = 0.7$

$V_{SB2} = V_{OUT} \rightarrow V_{TH2} > 0.7$

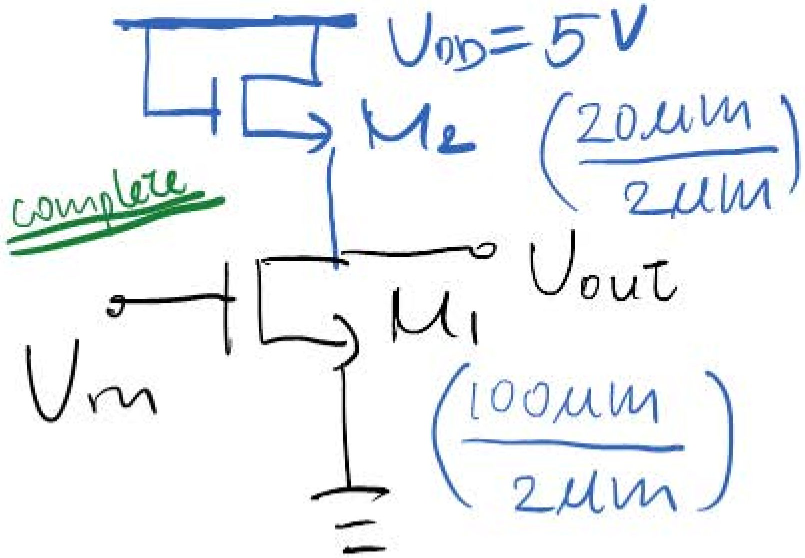
$\lambda \neq 0, \ \gamma \neq 0$

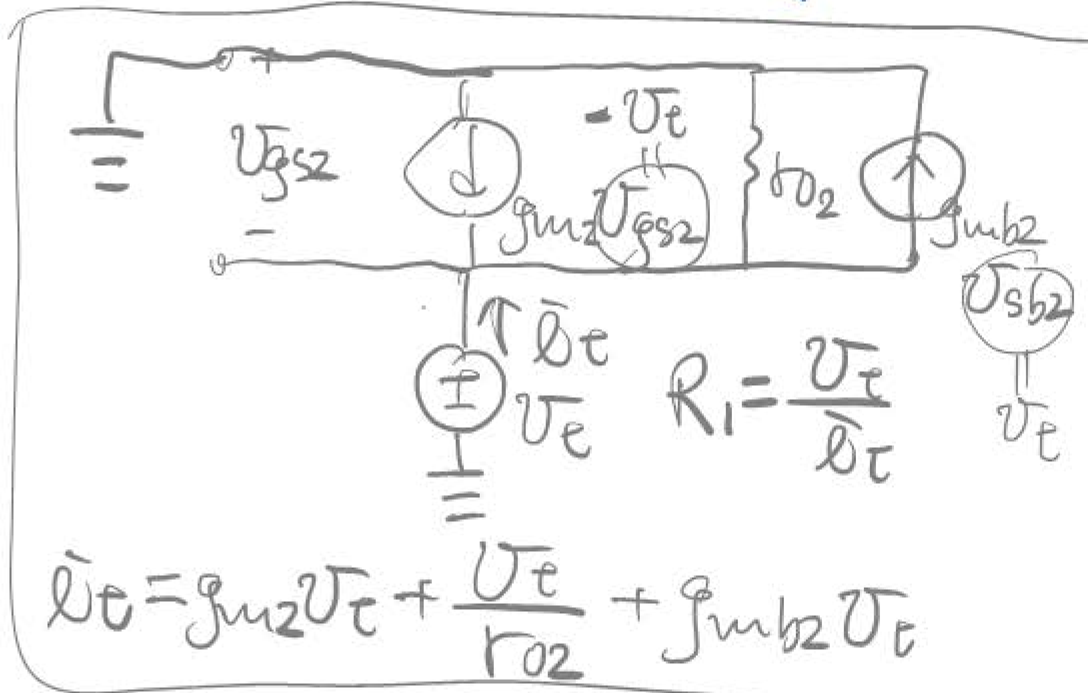
$V_{in} = 0.8 + 0.001 \sin(2\pi 100 t)$

$V_{out} = V_{OUT} + v_{out} = ?$

2° Find out $v_{out} = ?$

complete

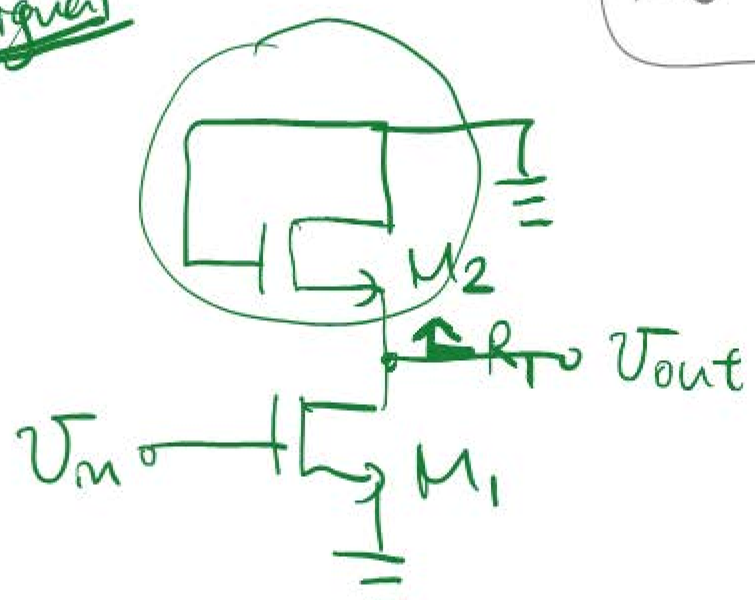




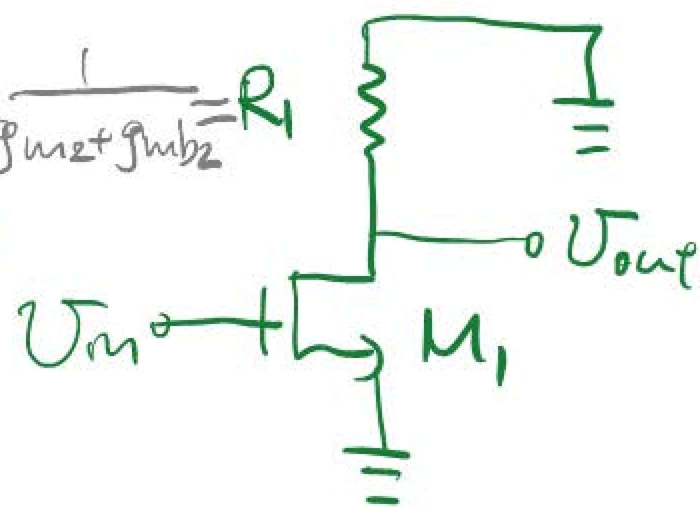
$$R_1 = \frac{v_t}{i_t}$$

$$i_t = g_{m2}v_t + \frac{v_t}{r_{o2}} + g_{mb2}v_t$$

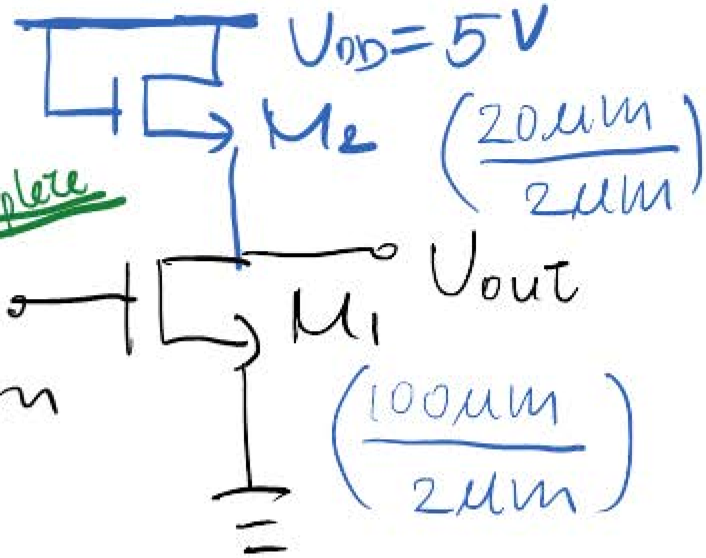
small-signal



$$r_{o2} \,\|\, \frac{1}{g_{m2}+g_{mb2}} = R_1$$



complete



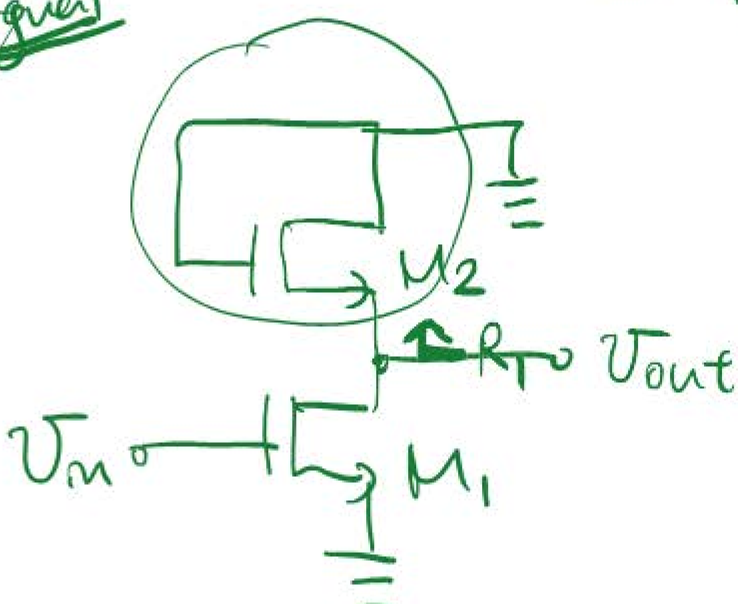
$2°$ Find out $v_{out} = ?$

$$v_{out} = -g_{m1} v_{in} (r_{o1} // R_1)$$

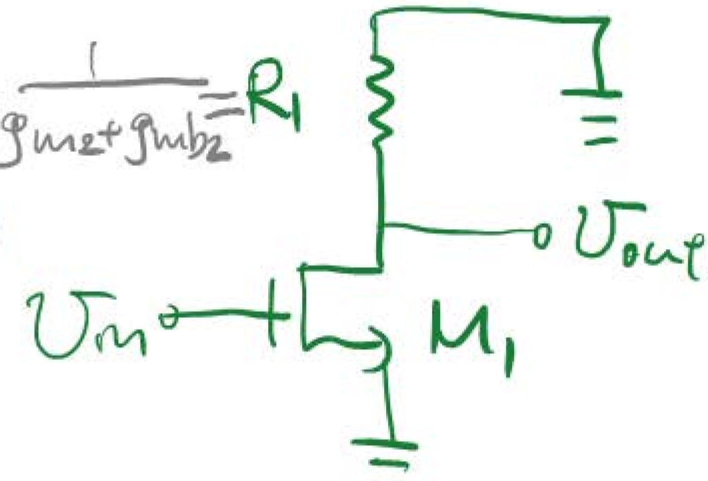
$$= -g_{m1} v_{in} \left(r_{o1} // r_{o2} // \frac{1}{g_{m2}+g_{mb2}}\right)$$

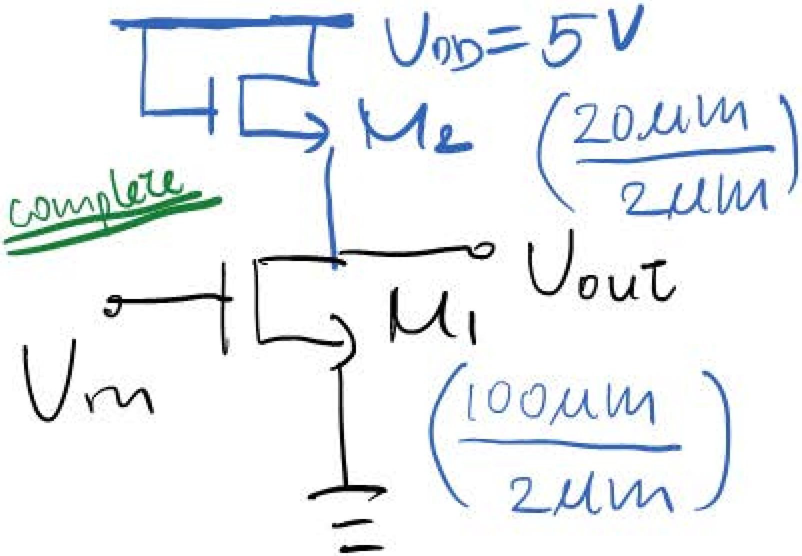
$$\cong -g_{m1} v_{in} \frac{1}{g_{m2}+g_{mb2}} \cong -v_{in} \frac{g_{m1}}{g_{m2}}$$

small-signal

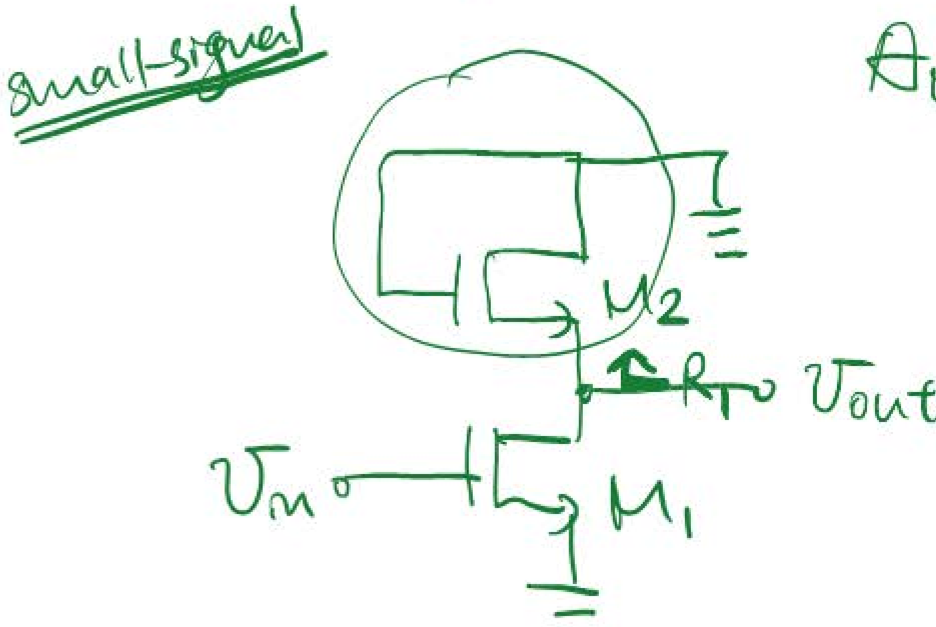


$$r_{o2} // \frac{1}{g_{m2}+g_{mb2}} = R_1$$





$\Downarrow$



2° Find out $v_{out} = ?$

$$v_{out} = -g_{m1} v_{in} (r_{o1} // R_1)$$

$$= -g_{m1} v_{in} \left(r_{o1} // r_{o2} // \frac{1}{g_{m2}+g_{mb2}}\right)$$

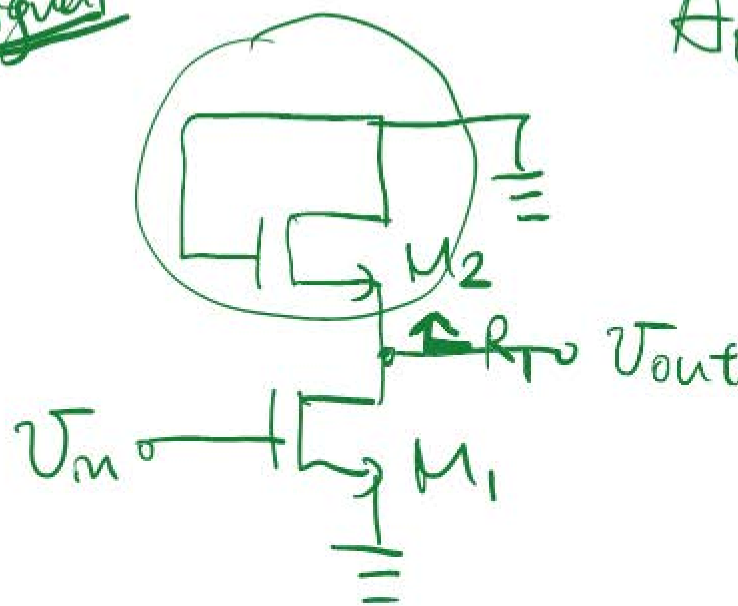
$$A_v = \frac{v_{out}}{v_{in}}$$

$$= g_{m1}\left(r_{o1} // r_{o2} // \frac{1}{g_{m2}+g_{mb2}}\right)$$

(if $\lambda = 0$, $r \neq 0$)

$$= -\frac{g_{m1}}{g_{m2}+g_{m2}\eta} = -\frac{g_{m1}}{g_{m2}}\left(\frac{1}{1+\eta}\right)$$

small-signal



$$A_v = \frac{v_{out}}{v_{in}}$$

$$= g_{m1}\left(r_{o1} \parallel r_{o2} \parallel \frac{1}{g_{m2}+g_{mb2}}\right)$$

$(\text{if } \lambda = 0,\ \gamma \neq 0)$

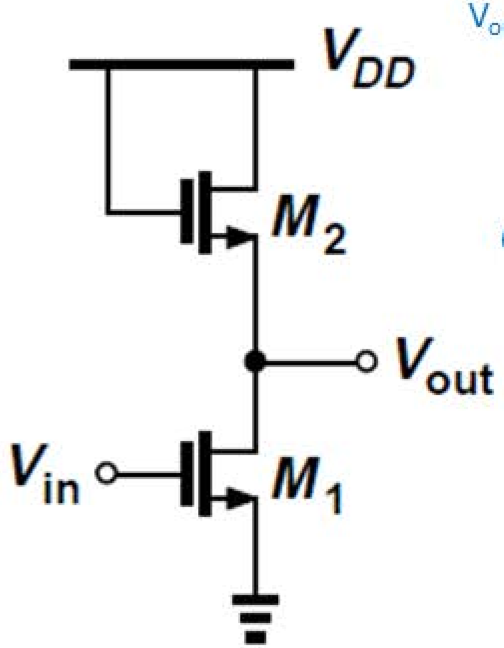
$$= -\frac{g_{m1}}{g_{m2}+g_{m2}\eta} = -\frac{g_{m1}}{g_{m2}}\left(\frac{1}{1+\eta}\right)$$

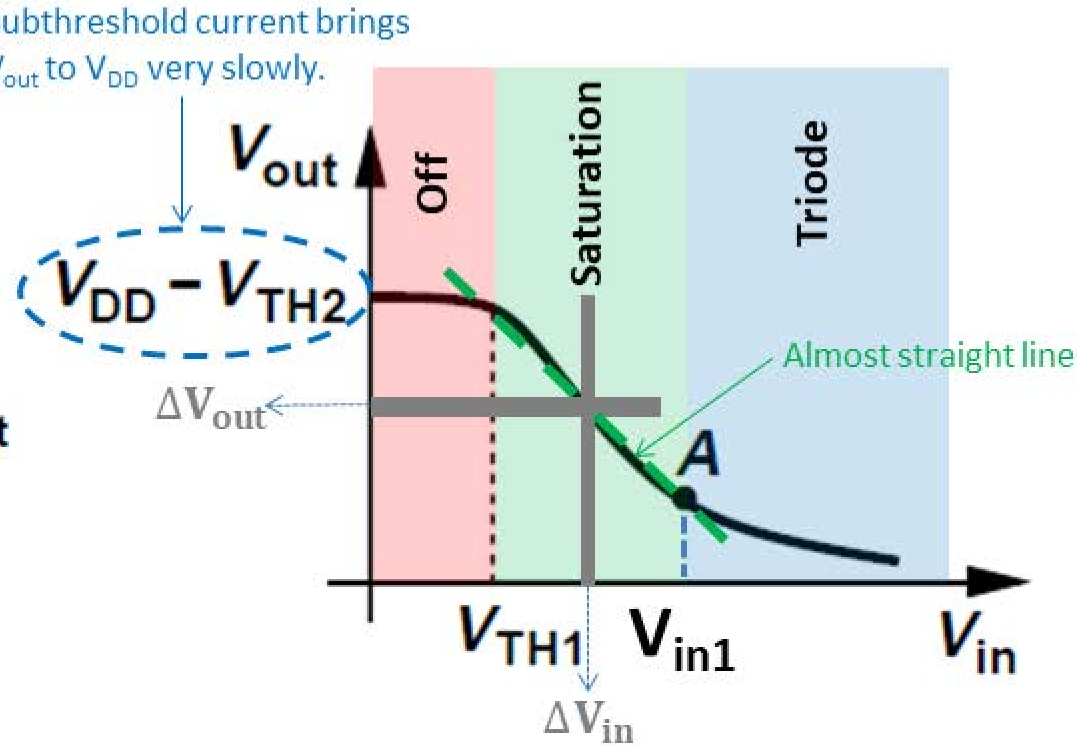
$$= -\frac{\sqrt{\cancel{2}\cancel{\mu_n}\cancel{C_{ox}}\left(W/L_{eff}\right)_1 \cancel{I_{D1}}}}{\sqrt{\cancel{2}\cancel{\mu_n}\cancel{C_{ox}}\left(W/L_{eff}\right)_2 \cancel{I_{D2}}}}\left(\frac{1}{1+\eta}\right)$$

$$= -\sqrt{\frac{\left(W/L_{eff}\right)_1}{\left(W/L_{eff}\right)_2}}\left(\frac{1}{1+\eta}\right)$$

Common-Source with Diode-Connected Load

DC Analysis $\lambda = 0 \quad \gamma \neq 0$





$$V_{out} = V_{in1} - V_{TH1}$$

$$\frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_1 (V_{in1} - V_{TH1})^2 = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_2 [V_{DD} - (V_{in1} - V_{TH1}) - V_{TH2}]^2$$

- V_{gs} increases by ΔV_{in} → I_d increases by $\Delta V_{in} \cdot gm$ → V_{out} decreases

Common-Source with Diode-Connected Load

DC Analysis $\lambda = 0 \quad \gamma \neq 0$

- $V_{in1} > V_{in} > V_{TH} \rightarrow M_1$ **in Saturation**

$$\frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_1 (V_{in} - V_{TH1})^2 = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_2 [V_{DD} - V_{out} - V_{TH2}]^2$$

$$\sqrt{\left(\frac{W}{L}\right)_1}(V_{in} - V_{TH1}) = \sqrt{\left(\frac{W}{L}\right)_2}(V_{DD} - V_{out} - V_{TH2})$$

$$\sqrt{\left(\frac{W}{L}\right)_1} = \sqrt{\left(\frac{W}{L}\right)_2}\left(-\frac{\partial V_{out}}{\partial V_{in}} - \frac{\partial V_{TH2}}{\partial V_{in}}\right)$$

$V_{out} = V_{SB2}$

$$\sqrt{\left(\frac{W}{L}\right)_1} = \sqrt{\left(\frac{W}{L}\right)_2}\left(-\frac{\partial V_{out}}{\partial V_{in}} - \frac{\partial V_{TH2}}{\partial V_{out}}\frac{\partial V_{out}}{\partial V_{in}}\right)$$

$$= \eta = \frac{\gamma}{2\sqrt{2\Phi_F + V_{SB}}}$$

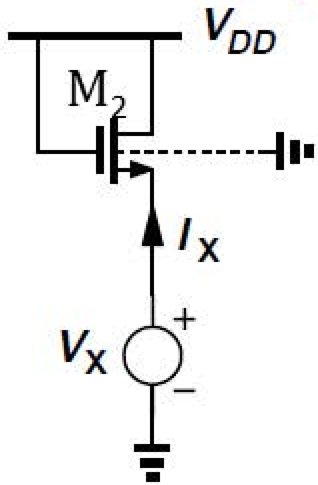
$$\boxed{A_v = \frac{\partial V_{out}}{\partial V_{in}} = -\sqrt{\frac{(W/L)_1}{(W/L)_2}}\frac{1}{1+\eta}}$$

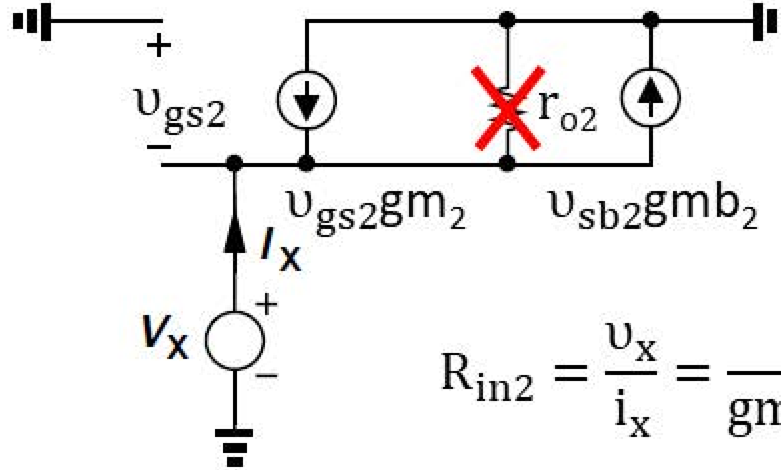
- η is a function of V_{SB}.
- A_v is almost linear for M_1 in saturation.

Common-Source with Diode-Connected Load

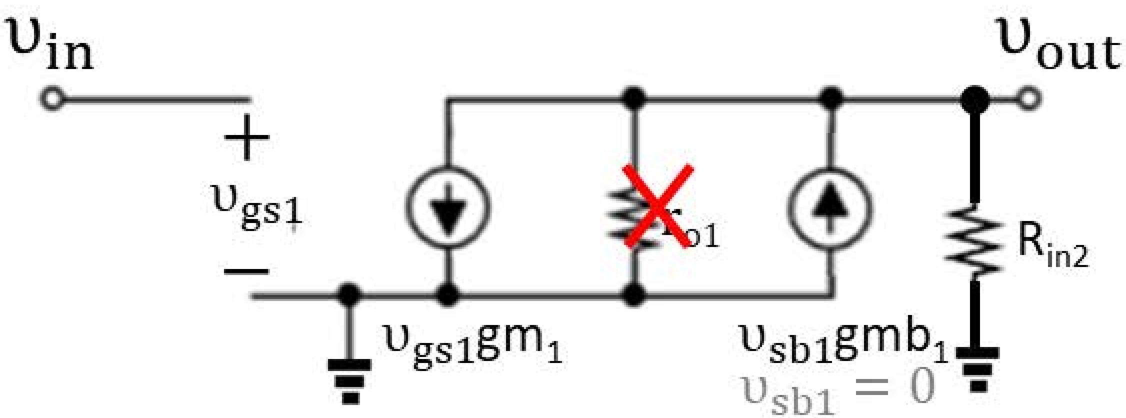
Small-signal Analysis

$\lambda = 0 \quad \gamma \neq 0$





$$R_{in2} = \frac{\upsilon_x}{i_x} = \frac{1}{gm_2 + gmb_2}$$



$$A_v = \frac{\upsilon_{out}}{\upsilon_{in}} = \frac{-gm_1}{gm_2 + gmb_2}$$

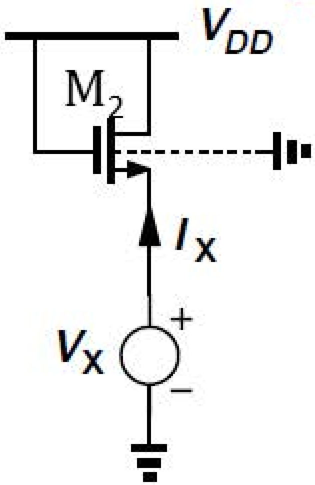
$$= -\sqrt{\frac{(W/L)_1}{(W/L)_2}}\frac{1}{1+\eta}$$

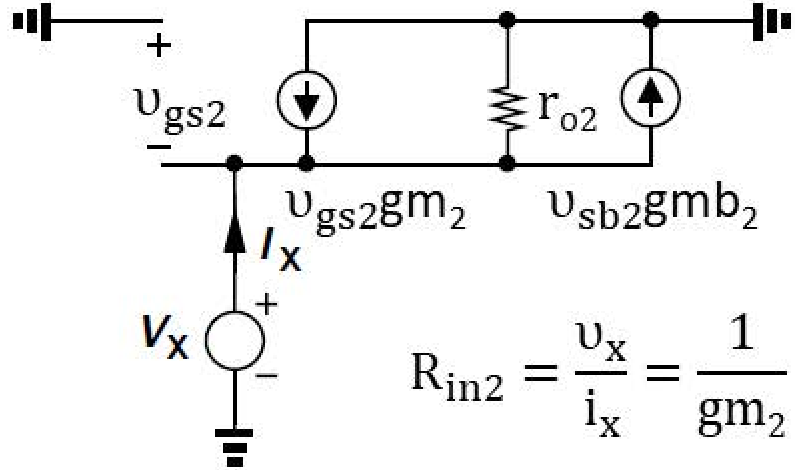
- Small-signal analysis leads to the same result as DC analysis.

Common-Source with Diode-Connected Load

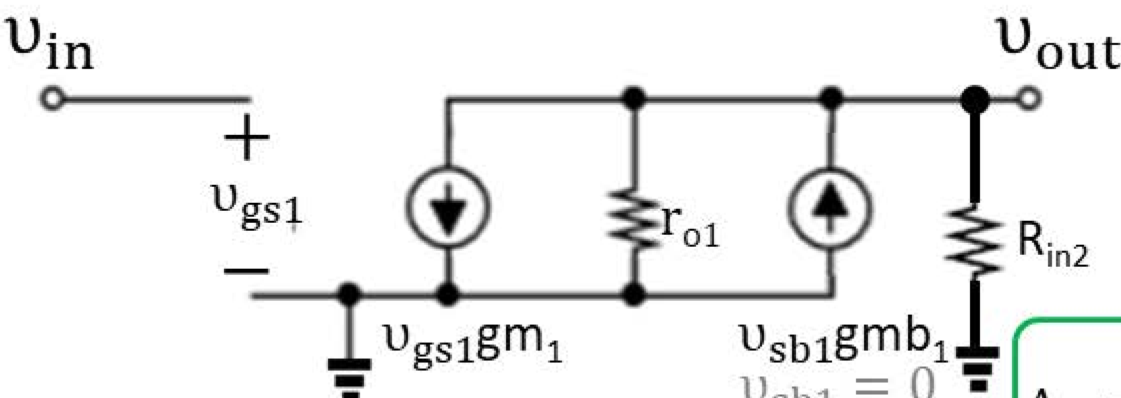
Small-signal Analysis

$\lambda \neq 0 \quad \gamma \neq 0$





$$R_{in2} = \frac{\upsilon_x}{i_x} = \frac{1}{gm_2} \parallel \frac{1}{gmb_2} \parallel r_{o2}$$



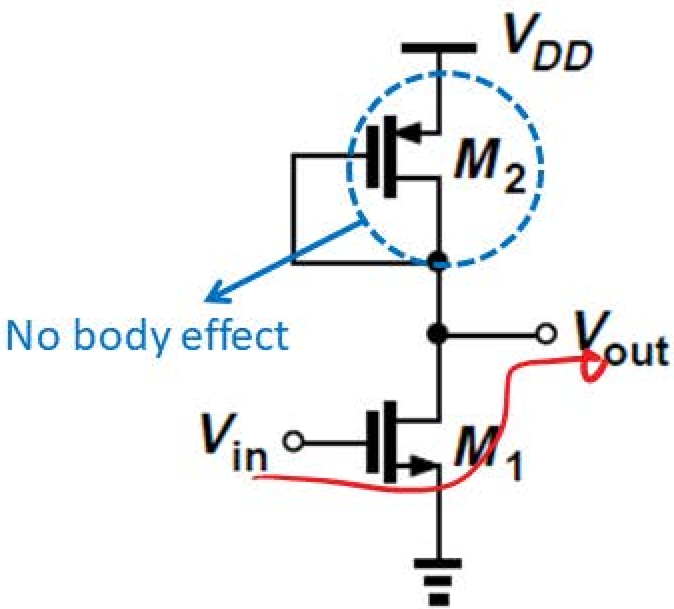
$$A_v = \frac{\upsilon_{out}}{\upsilon_{in}}$$

$$= -gm_1 \left(\frac{1}{gm_2} \parallel \frac{1}{gmb_2} \parallel r_{o2} \parallel r_{o1} \right)$$

$r_o >> 1/gm$

Common-Source with Diode-Connected Load

Small-signal Analysis $\lambda \neq 0 \quad \gamma \neq 0$



$$A_v = \frac{\upsilon_{out}}{\upsilon_{in}}$$

$$= -gm_1\left(\frac{1}{gm_2} \parallel r_{o2} \parallel r_{o1}\right)$$

$r_o >> 1/gm$

$$\approx -\frac{gm_1}{gm_2} = -\frac{\sqrt{\cancel{2}\mu_n \cancel{C_{ox}}(W/L_{eff})_1 \cancel{I_{D1}}}}{\sqrt{\cancel{2}\mu_p \cancel{C_{ox}}(W/L_{eff})_2 \cancel{I_{D2}}}}$$

$$= -\sqrt{\frac{\mu_n (W/L_{eff})_1}{\mu_p (W/L_{eff})_2}}$$

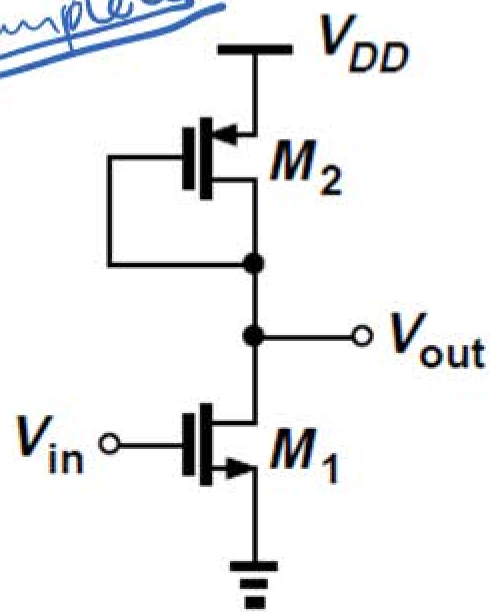
$$\parallel$$

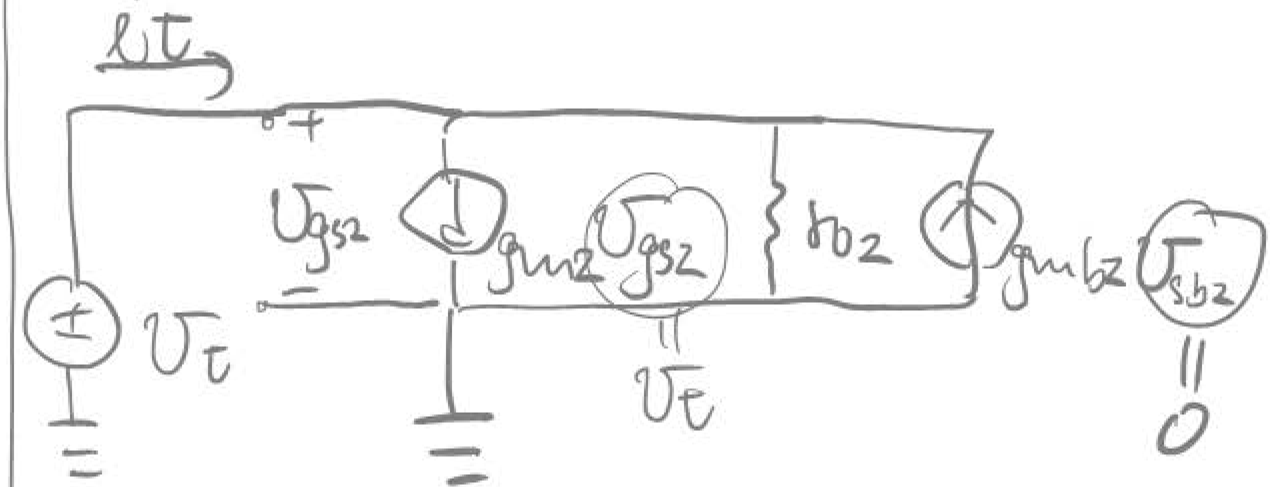
$$-\frac{\frac{2I_{D1}}{V_{GS1}-V_{TH1}}}{\frac{2I_{D2}}{V_{SG2}-|V_{TH2}|}}$$

$$= -\frac{V_{SG2} - |V_{TH2}|}{V_{GS1} - V_{TH1}}$$

- For $A_v = 10$, $(W/L)_1 >> (W/L)_2$ → **Disproportionally large transistor**
- For $A_v = 10$, $(V_{SG2} - V_{TH2}) = 10 \times (V_{GS1} - V_{TH1})$ → **Limited output swing**

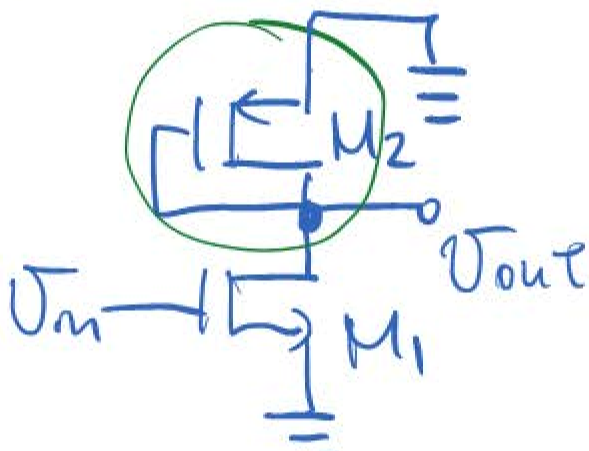
complete



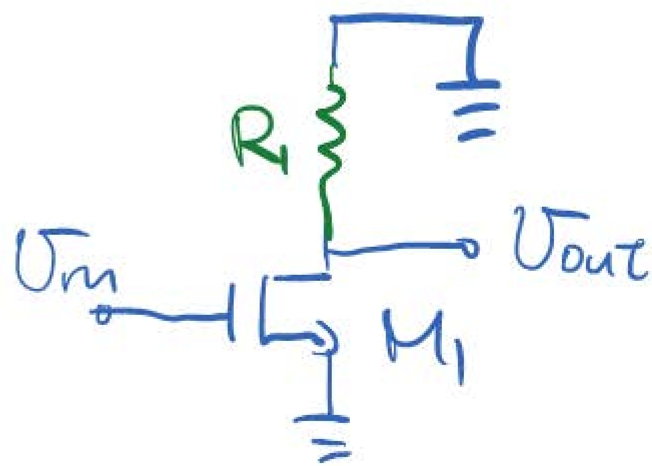


$$R_1 = \frac{v_t}{i_t} = \frac{1}{g_{m2}} // r_{o2}$$

small-signal



$\Rightarrow$



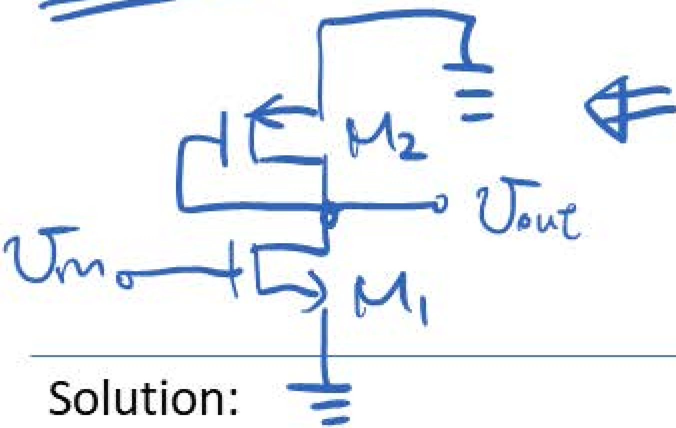
Example

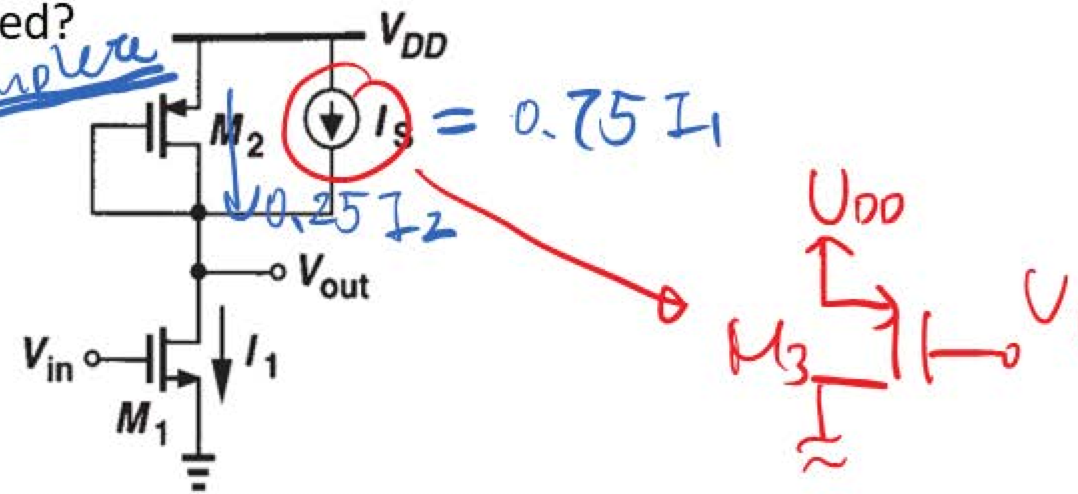
λ=0
r≠0

M_1 in saturation and $I_S = 0.75 \times I_1$. How do the disadvantages of CS stage with diode-connected load get improved?

small-signal

complete

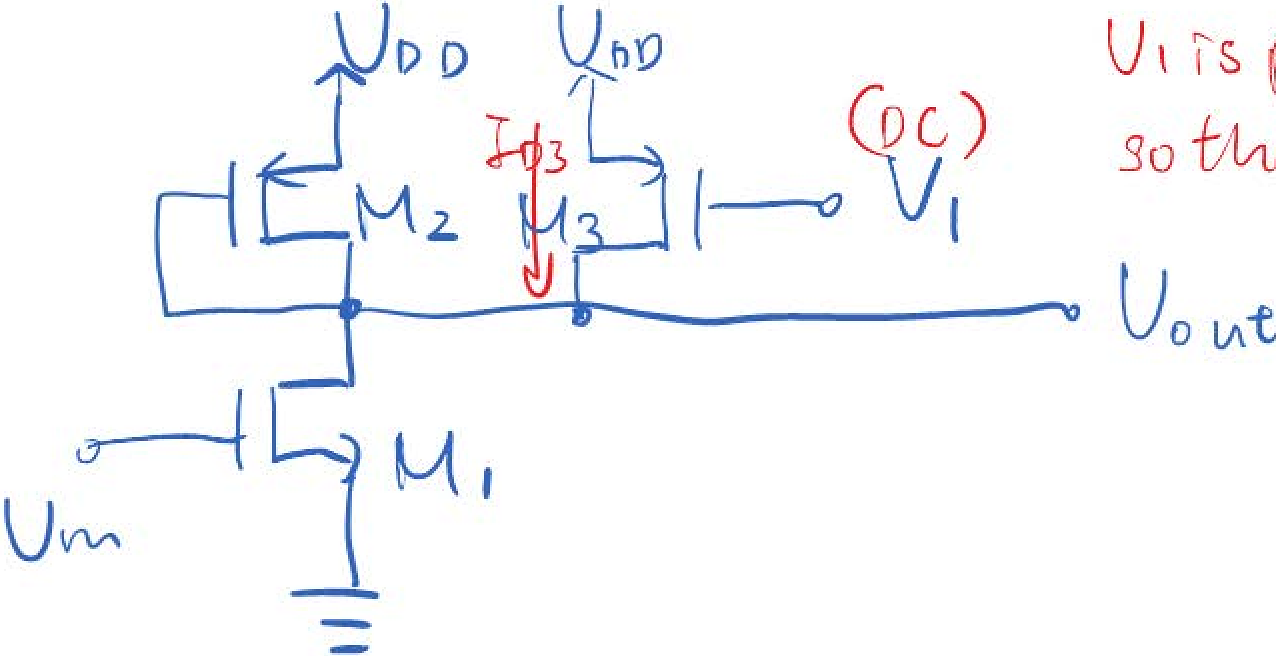




Solution:

- Small-signal Analysis (λ = 0):

$$A_v = \frac{\upsilon_{out}}{\upsilon_{in}} = -\frac{gm_1}{gm_2} = -\frac{\sqrt{2\mu_n C_{ox}\left(\frac{W}{L}\right)_1 I_{D1}}}{\sqrt{2\mu_p C_{ox}\left(\frac{W}{L}\right)_2 I_{D2}}} = -\frac{\sqrt{4\mu_n\left(\frac{W}{L}\right)_1}}{\sqrt{\mu_p\left(\frac{W}{L}\right)_2}} = -\frac{4(V_{SG2}-V_{TH2})}{(V_{GS1}-V_{TH1})}$$

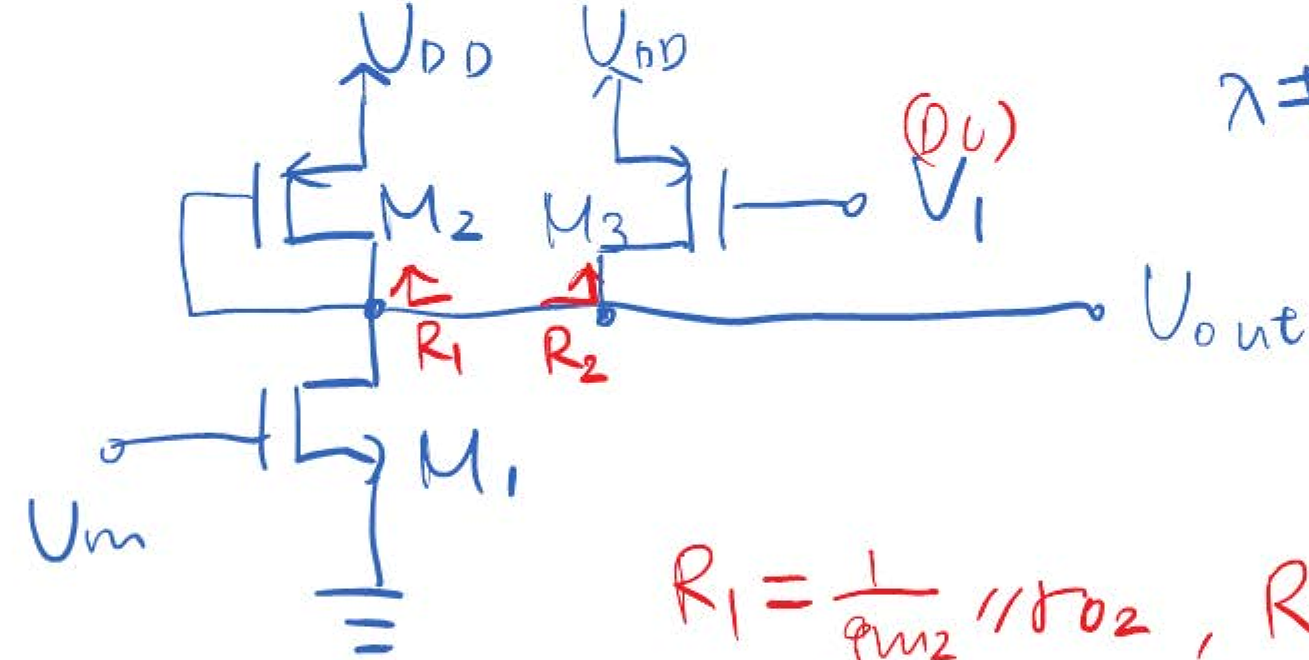


V_1 is properly chosen so that M_3 in sat.

$$I_{D3} = \frac{1}{2}\mu_p C_{ox}\left(\frac{W}{L_{eff}}\right)_3 (V_{DD}-V_1-0.8)^2\left[1+\lambda(V_{DD}-V_{OUT})\right]$$

$\Downarrow$ if $\lambda = 0$, $\gamma \neq 0$

$$I_{D3} = \boxed{\text{constant}}\,(V_{DD}-0.8-V_1)^2 = \boxed{\text{constant}}$$



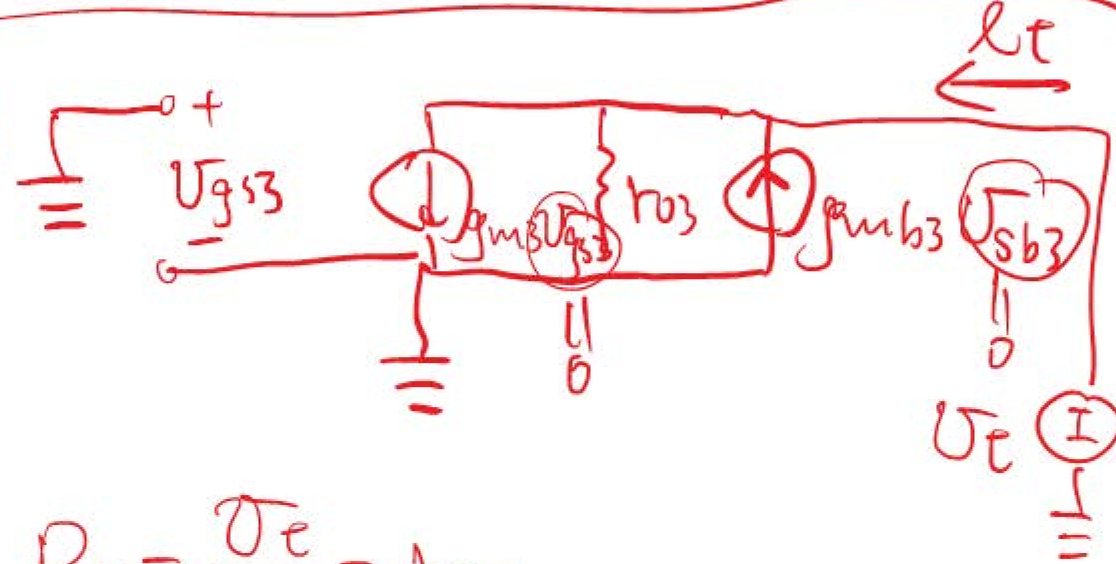
$\lambda \neq 0, \gamma \neq 0$

$A_v = ?$

$R_1 = \frac{1}{g_{m2}} // r_{o2}$, $R_2 = r_{o3}$

$A_v = -g_{m1}(r_{o1} // R_1 // R_2)$

$= -g_{m1} \cdot (r_{o1} // \frac{1}{g_{m2}} // r_{o2} // r_{o3})$



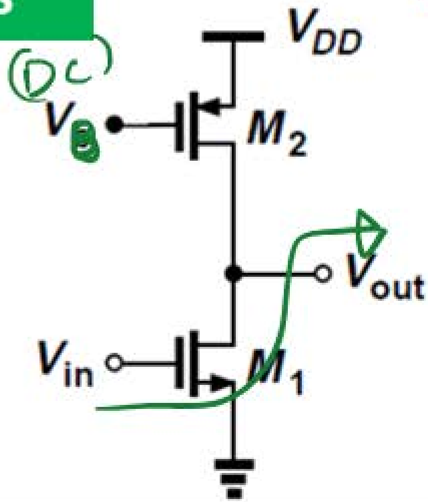
$R_2 = \frac{v_t}{i_t} = r_{o3}$

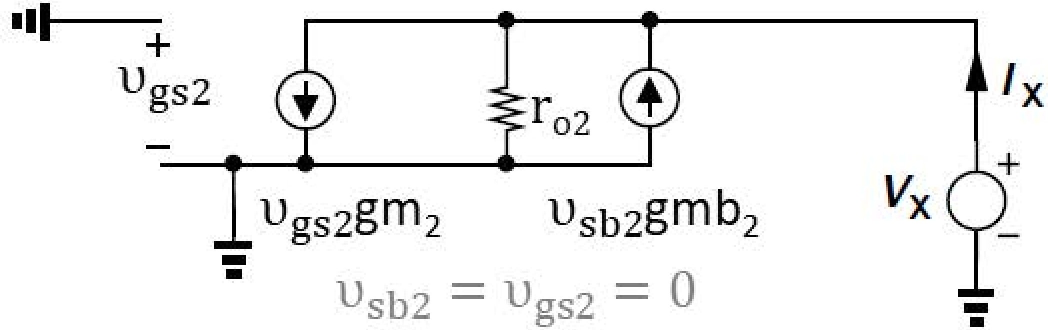
Common-Source with Current-Source Load

Common-Source with Current-Source Load

Small-signal Analysis

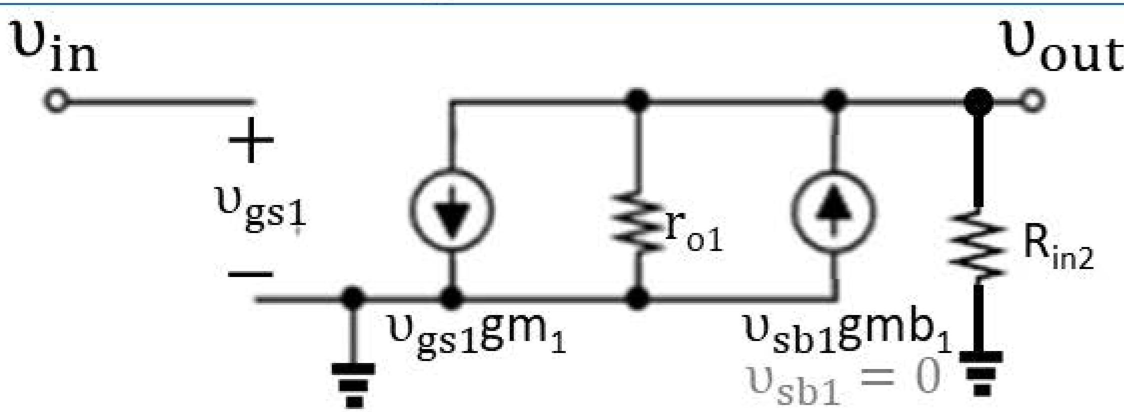
$\lambda \neq 0 \quad \gamma \neq 0$





$\upsilon_{sb2} = \upsilon_{gs2} = 0$

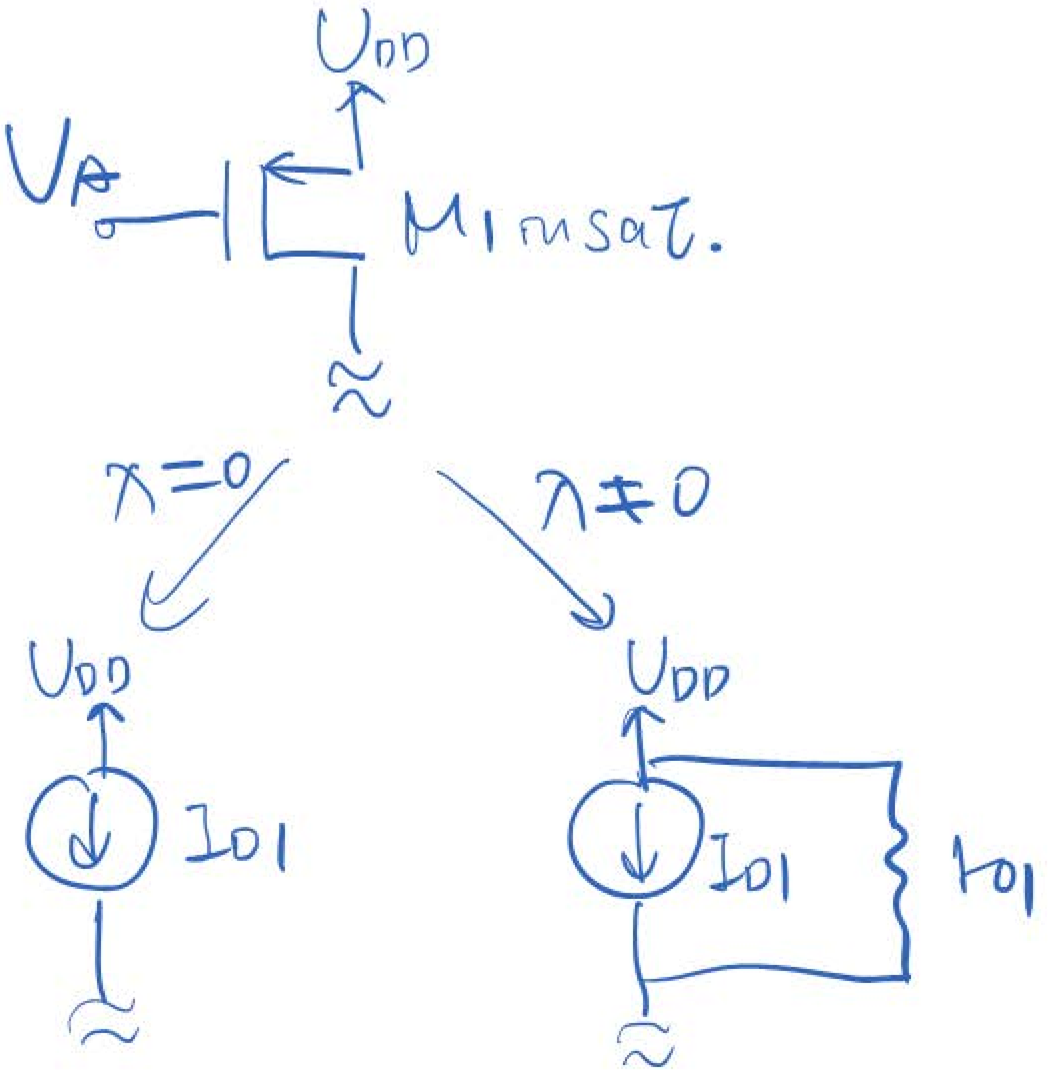
$$R_{in2} = \frac{\upsilon_x}{i_x} = r_{o2}$$



$\upsilon_{sb1} = 0$

$$A_v = \frac{\upsilon_{out}}{\upsilon_{in}} = -gm_1 (r_{o2} \parallel r_{o1})$$

- To achieve high A_v, the output swing is severely limited in the CS stages with resistive load and diode-connected load.
- Here $V_{out,\,max} = V_{DD} - (V_{SG2} - V_{TH2})$, which can be quite close to V_{DD}.


VDD
VB
M1 in sat.
λ=0
λ≠0
VDD
ID1
VDD
ID1
ro1