Lecture 12: Diode-Connected Load

ECE3110J, Electronic Circuits

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Recap of Last Lecture

- MOSFET Circuits

Topic to Be Covered

- MOSFET Circuits

Common-Source

$$I_D = \mu_n C_{ox} \frac{W}{L_{eff}} [(V_{GS} - V_{TH}) V_{DS} - \frac{1}{2} {V_{DS}}^2] \tag{1}$$

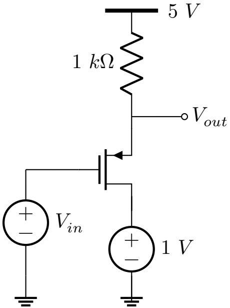
$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L_{eff}} (V_{GS} - V_{TH})^2 (1 + \lambda V_{DS}) \tag{2}$$

$$g_m = \frac{\partial I_D}{\partial V_{GS}} = \mu_n C_{ox} \frac{W}{L'} (V_{GS} - V_{TH}) = \sqrt{2 \mu_n C_{ox} \frac{W}{L'} I_D} = \frac{2 I_D}{V_{GS} - V_{TH}} \tag{3}$$

$$r_o = \frac{\partial V_{DS}}{\partial I_D} = 1 \Big/ \frac{\partial I_D}{\partial V_{DS}} \approx \frac{1}{I_D \cdot \lambda} \tag{4}$$

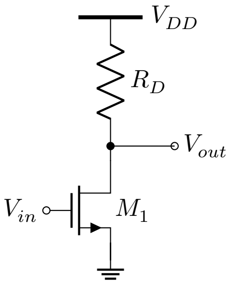
$$V_{TH} = V_{TH0} + \gamma (|\sqrt{2\Phi_F + V_{SB}}| - \sqrt{|2\Phi_F|}) \tag{5}$$

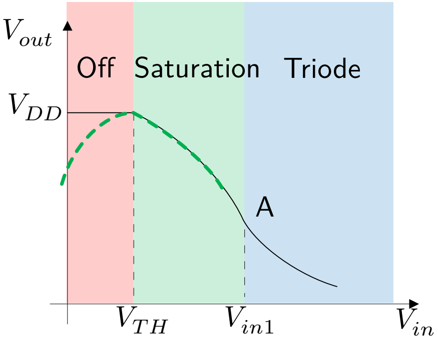
A PMOS Small-Signal Example ($\lambda \neq 0$, $\gamma \neq 0$)



$$V_{in} = 1.8 + 0.001 \sin(2\pi \cdot 100t) \quad (6)$$

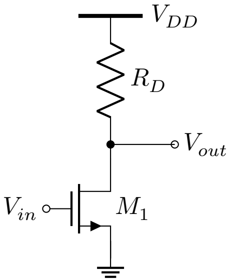
Common-Source with Resistive Load ($\lambda = 0$, $\gamma = 0$)

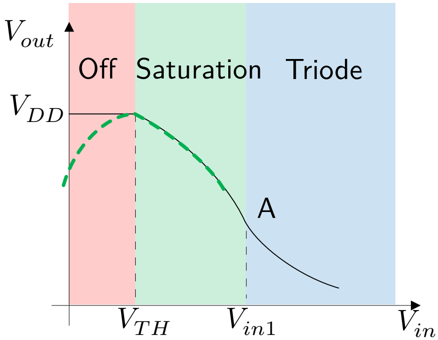




- $V_{in} < V_{TH} \rightarrow M_1$ off
- $V_{out} = V_{DD}$
- Reading: Razavi Chapter 3

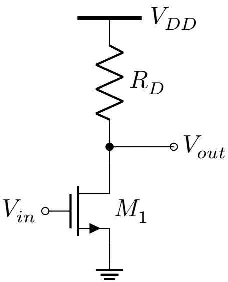
Common-Source with Resistive Load ($\lambda = 0$, $\gamma = 0$)

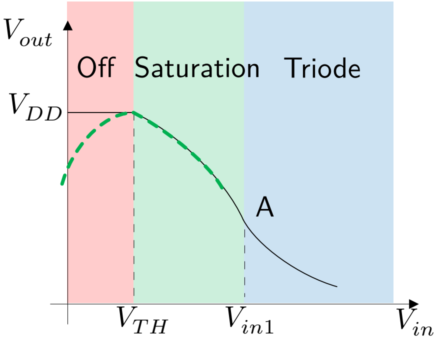




- $V_{in1} > V_{in} > V_{TH} \rightarrow$
- M_1 in Saturation
- $V_{out} = V_{DD} - R_D \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{in} - V_{TH})^2$

Common-Source with Resistive Load($\lambda = 0,\ \gamma = 0$)





- $V_{in} > V_{in1} \rightarrow M_1$ in Triode

$$V_{out} = V_{DD} - R_D \mu_n C_{ox} \frac{W}{L}((V_{in} - V_{TH})V_{out} - \frac{1}{2}{V_{out}}^2) \quad (7)$$

Common-Source with Resistive Load ($\lambda = 0$, $\gamma = 0$)

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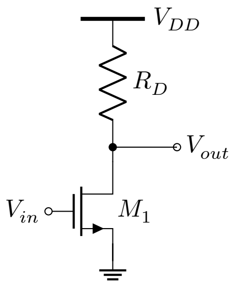

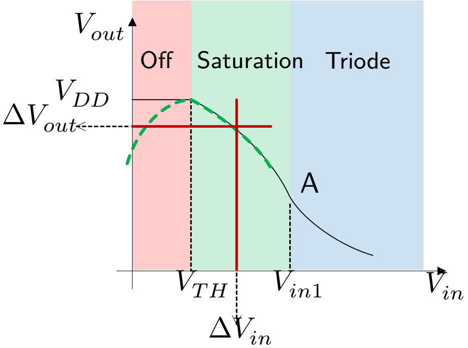

- $A_V = \frac{\partial V_{out}}{\partial V_{in}} = -R_D \mu_n C_{ox} \frac{W}{L}(V_{in} - V_{TH}) = -g_m \cdot R_D$

V_{gs} increases by $\partial V_{in} \rightarrow I_d$ increases by $\partial V_{in} \cdot g_m \rightarrow V_{out}$ decreases by $\partial V_{in} \cdot (g_m \cdot R_D)$

Common-Source with Resistive Load ($\lambda = 0$, $\gamma = 0$)

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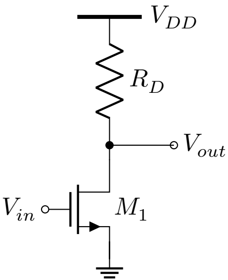
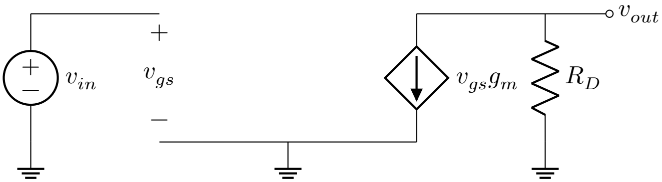
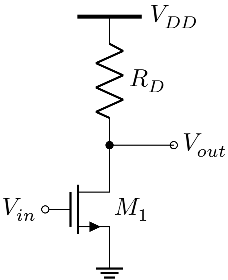


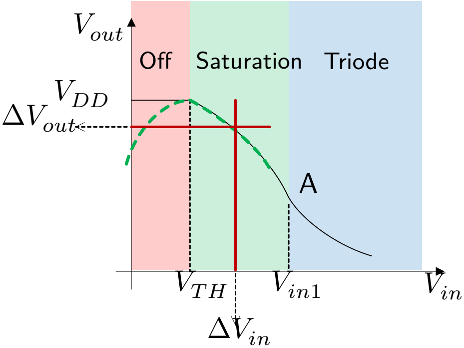


$$A_v = \frac{v_{out}}{v_{in}} = -g_m \cdot R_D \tag{8}$$

- Small-signal analysis leads to the same result.

Common-Source with Resistive Load ($\lambda \neq 0$, $\gamma \neq 0$)





$$A_v = \frac{\partial V_{out}}{\partial V_{in}} = \frac{\partial \left[V_{DD} - R_D \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{in} - V_{TH})^2(1 + \lambda V_{out})\right]}{\partial V_{in}} \tag{9}$$

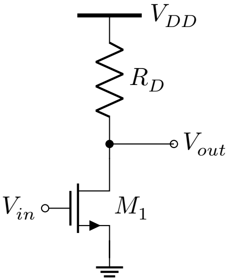
Common-Source with Resistive Load

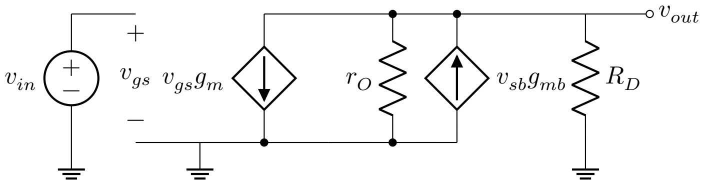
$$A_v = \frac{\partial V_{out}}{\partial V_{in}} = \frac{\partial\left[V_{DD} - R_D \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{in} - V_{TH})^2(1+\lambda V_{out})\right]}{\partial V_{in}} \tag{10}$$

$$= -R_D \mu_n C_{ox}\frac{W}{L}(V_{in} - V_{TH})(1+\lambda V_{out}) - R_D\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{in} - V_{TH})^2\lambda\frac{\partial V_{out}}{\partial V_{in}} \tag{11}$$

$$A_v = \frac{-g_m R_D}{1 + R_D I_D \lambda} = -g_m\frac{1}{\frac{1}{R_D} + \frac{1}{r_o}} = -g_m(R_D \parallel r_o) \tag{12}$$

Common-Source with Resistive Load ($\lambda \neq 0$, $\gamma \neq 0$)



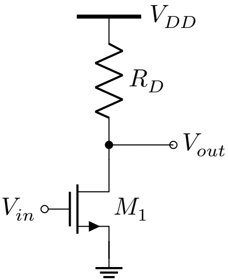


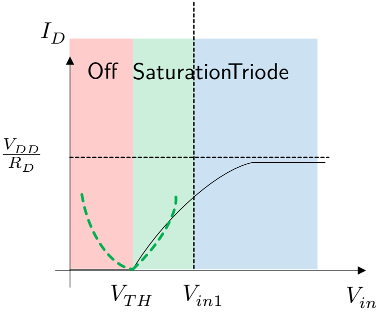
$$A_v = \frac{v_{out}}{v_{in}} = -g_m \cdot (R_D \parallel r_o) \quad (13)$$

- Small-signal analysis leads to the same result as DC analysis.
- g_m is a function of V_{GS} and V_{DS}, while r_o is a function of I_D. $\rightarrow$ **Nonlinearity**

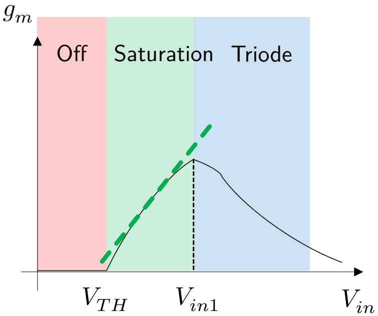
Example

Sketch the drain current and transconductance of M_1 as a function of input voltage. Assume $\lambda = \gamma = 0$.





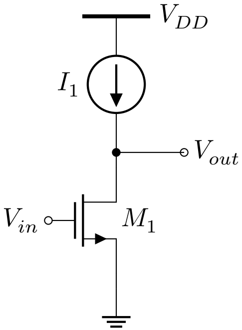
$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}\left(V_{in} - V_{TH}\right)^2$$



$$g_m = \mu_n C_{ox}\frac{W}{L}\left(V_{in} - V_{TH}\right)$$

Example

Assuming M_1 in saturation, calculate its small-signal gain.



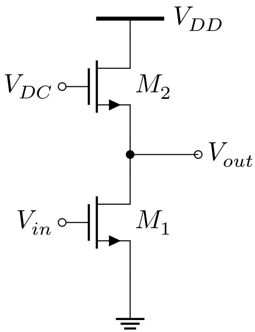
- Small-signal Analysis:

$$A_V = \frac{V_{out}}{V_{in}} = -g_{m1} r_{o1} \tag{14}$$

- DC Analysis:

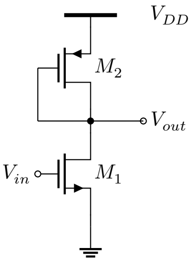
$$I_1 = \frac{1}{2}\mu_n C_{ox} \frac{W}{L}(V_{in} - V_{TH})^2(1 + \lambda V_{out}) \tag{15}$$

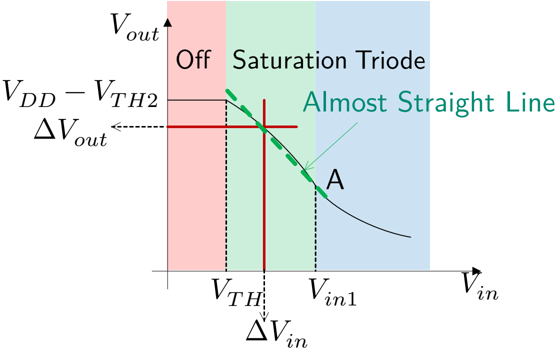
Example



- How to choose $V_{in,DC}$?

Diode-Connected Load ($\lambda = 0$, $\gamma \neq 0$)





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

$$\frac{1}{2}\mu_n C_{ox}(\frac{W}{L})_1(V_{in} - V_{TH1})^2 = \frac{1}{2}\mu_n C_{ox}(\frac{W}{L})_2[V_{DD} - (V_{in1} - V_{TH1}) - V_{TH2}]^2 \quad (16)$$

Diode-Connected Load

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

$$\frac{1}{2}\mu_n C_{ox}(\frac{W}{L})_1(V_{in} - V_{TH1})^2 = \frac{1}{2}\mu_n C_{ox}(\frac{W}{L})_2[V_{DD} - V_{out} - V_{TH2}]^2 \tag{17}$$

$$\sqrt{(\frac{W}{L})_1}(V_{in} - V_{TH1}) = \sqrt{(\frac{W}{L})_2}(V_{DD} - V_{out} - V_{TH2}) \tag{18}$$

$$\sqrt{(\frac{W}{L})_1} = \sqrt{(\frac{W}{L})_2}(-\frac{\partial V_{out}}{\partial V_{in}} - \frac{\partial V_{TH2}}{\partial V_{in}}) \tag{19}$$

Diode-Connected Load ($\lambda = 0$, $\gamma \neq 0$)

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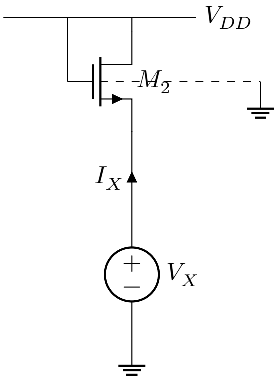
$$\sqrt{(\frac{W}{L})_1} = \sqrt{(\frac{W}{L})_2}(-\frac{\partial V_{out}}{\partial V_{in}} - \boxed{\frac{\partial V_{TH2}}{\partial V_{out}}}\frac{\partial V_{out}}{\partial V_{in}})$$

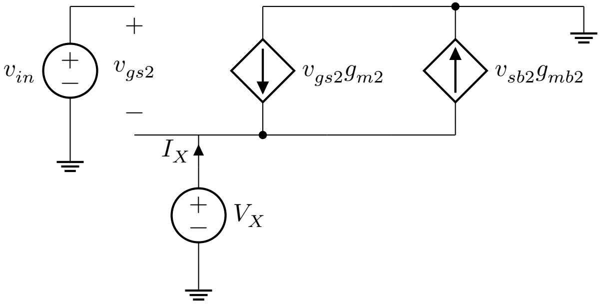
$$= \eta = \frac{\gamma}{2\sqrt{2\Phi_F + V_{SB}}}$$

$$A_V = \frac{\partial V_{out}}{\partial V_{in}} = -\sqrt{\frac{(W/L)_1}{(W/L)_2}}\frac{1}{1+\eta} \tag{20}$$

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

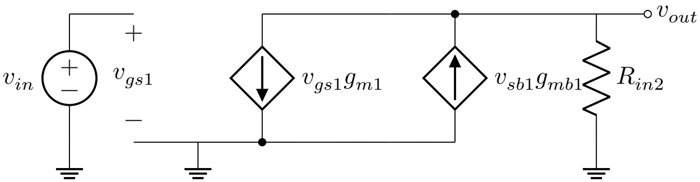
Diode-Connected Load ($\lambda = 0$, $\gamma \neq 0$)





$$R_{in2} = \frac{v_x}{i_x} = \frac{1}{g_{m2} + g_{mb2}} \tag{21}$$

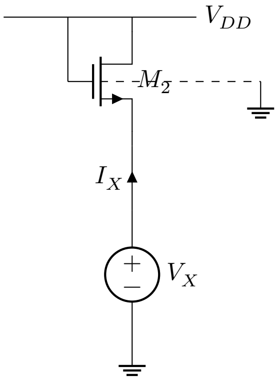
Diode-Connected Load

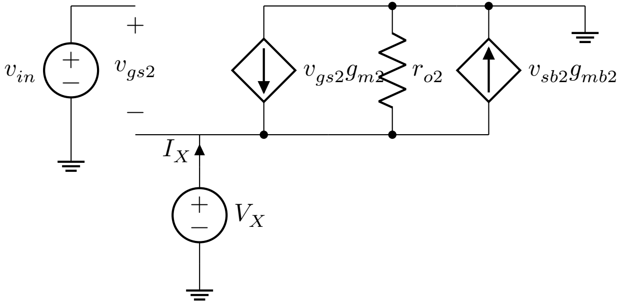


$$A_V = \frac{V_{out}}{V_{in}} = \frac{-g_{m1}}{g_{m2}+g_{mb2}} - \sqrt{\frac{(W/L)_1}{(W/L)_2}}\frac{1}{1+\eta} \tag{22}$$

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

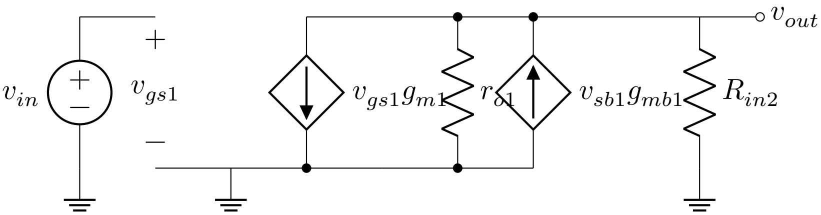
Diode-Connected Load ($\lambda \neq 0$, $\gamma \neq 0$)





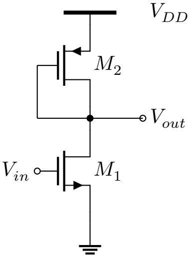
$$R_{in2} = \frac{v_x}{i_x} = \frac{1}{g_{m2}} \parallel \frac{1}{g_{mb2}} \parallel r_{o2} \tag{23}$$

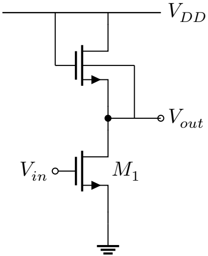
Diode-Connected Load



$$A_V = \frac{V_{out}}{V_{in}} = -g_{m1}\left(\frac{1}{g_{m2}} \parallel \frac{1}{g_{mb2}} \parallel r_{o2} \parallel r_{o1}\right) \tag{24}$$

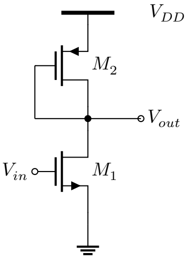
Diode-Connected Load ($\lambda \neq 0$, $\gamma \neq 0$)





Diode-Connected Load ($\lambda \neq 0$, $\gamma \neq 0$)

M_2 has no body effect

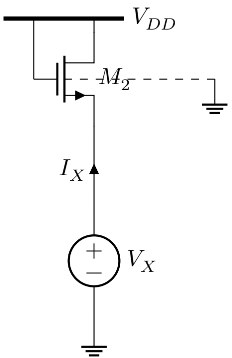


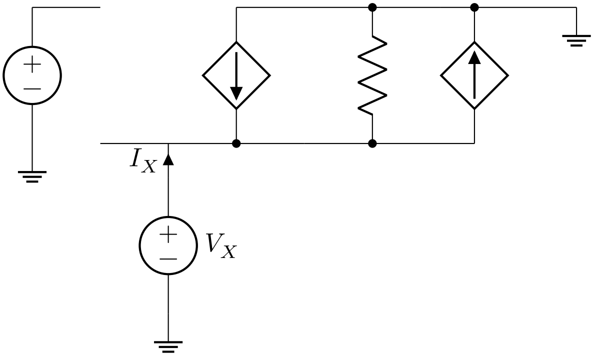
$r_o >> 1/gm$ $\uparrow$

$$\begin{aligned} A_V &= \frac{V_{out}}{V_{in}} \\ &= -g_{m1}\left(\frac{1}{g_{m2}} \parallel \boxed{r_{o2} \parallel r_{o1}}\right) \approx -\frac{g_{m1}}{g_{m2}} \\ &= -\sqrt{\frac{\mu_n (W/L)_1}{\mu_p (W/L)_2}} \\ &= -\frac{V_{SG2} - V_{TH2}}{V_{GS1} - V_{TH1}} \end{aligned} \tag{25}$$

- For $A_V = 10$, $(\frac{W}{L})_1 >> (\frac{W}{L})_2 \rightarrow$ Disproportionally large transistor
- For $A_V = 10$, $(V_{SG2} - V_{TH2}) = 10(V_{GS1} - V_{TH1}) \rightarrow$ Limited output swing

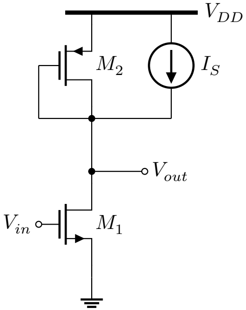
Different Load





Example

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?



Solution: Small-signal Analysis ($\lambda = 0$):

$$A_v = \frac{V_{out}}{V_{in}} = -\frac{g_{m1}}{g_{m2}} = -\frac{\sqrt{2\mu_n C_{ox}\left(\frac{W}{L}\right)_1 I_{D1}}}{\sqrt{2\mu_p C_{ox}\left(\frac{W}{L}\right)_2 I_{D2}}} \quad (26)$$

$$= -\frac{\sqrt{4\mu_n\left(\frac{W}{L}\right)_1}}{\sqrt{\mu_p\left(\frac{W}{L}\right)_2}} = \frac{4\left(V_{SG2} - V_{TH2}\right)}{\left(V_{GS1} - V_{TH1}\right)} \quad (27)$$