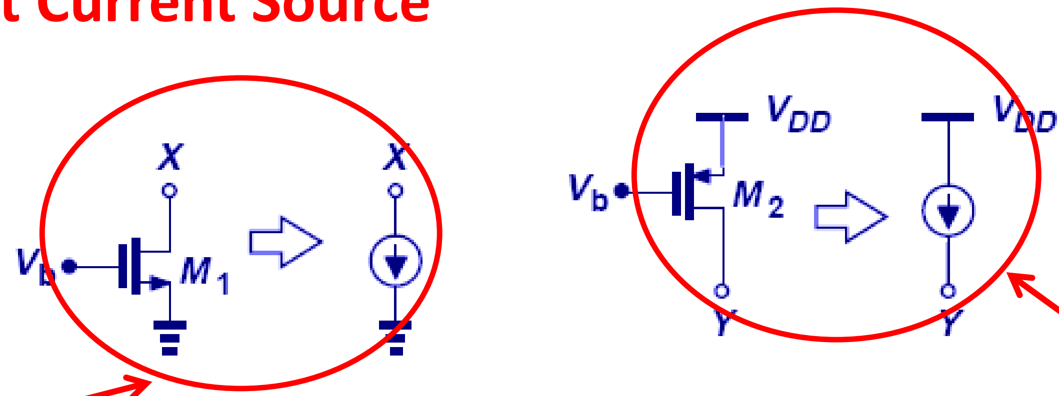
ECE315 / ECE515

Lecture – 6

Date: 29.08.2016

- CS Amplifier with Constant Current Source, Triode Load, Source Degenerated Resistor, Examples
- Common Drain Amplifier
- Examples

Constant Current Source

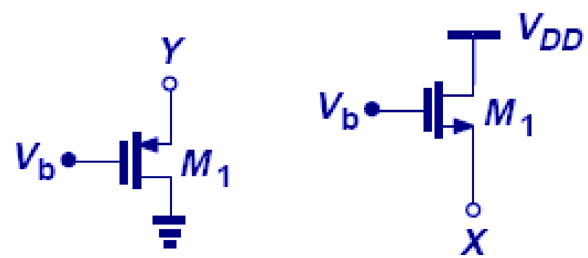


NFET ideal current source

PFET ideal current source

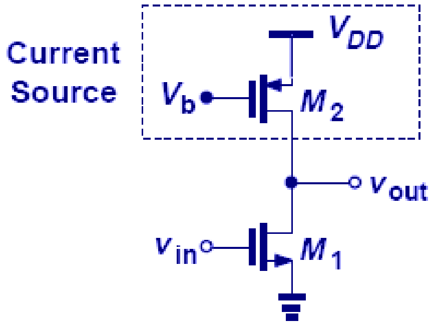
- As long as a MOS transistor is in saturation region and λ=0, the current is independent of the drain voltage and it behaves as an ideal current source seen from the drain terminal.

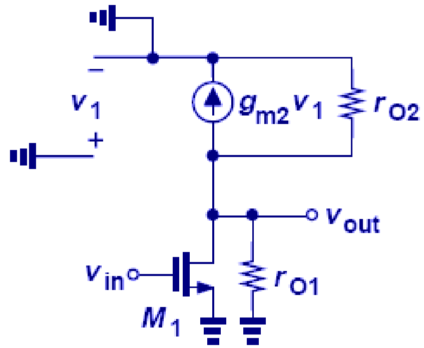
Example of poor current source



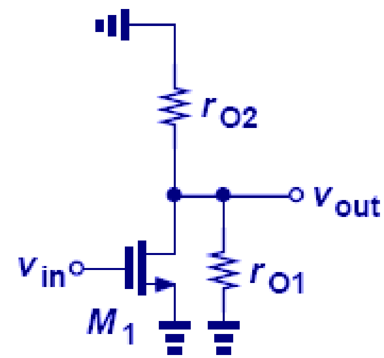
- Since the variation of the source voltage directly affects the current of a MOS transistor, it does not operate as a good current source if seen from the source terminal

CS Amplifier with Constant Current Source (contd.)





The dc voltage V_{GS2} is constant and therefore v_1 =0 → leads to $g_{m2}v_1$ =0



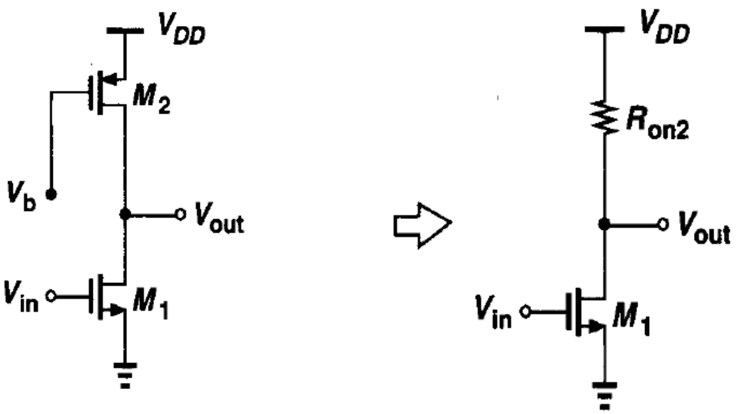
$$A_v = -g_{m1}(r_{o1} \,||\, r_{o2})$$

- Both the load and the device operates in saturation
- The gain is loosely dependent on $|V_{DS}|$ of M_2 → as it regulates r_{o2}
- The voltage $|V_{DS2,min}|=|V_{GS2}- V_{T2}|$ can be reduced → by increasing $(W/L)_2$ → increases V_{D1}→ in essence the output voltage swing
- r_{o2} can be increased → by reducing the channel length modulation effect → through increasing the length and width of M_2 → while keeping $|V_{GS2} - V_{T2}|$ constant → However, this also brings large capacitance at the output of M_2.

CS Amplifier with Constant Current Source (contd.)

- At a given drain current, W has to increase with the increasing L (r_o α L/I_D) for obtaining higher gain.
- If length of M_1 is increased by a factor → then the width has to be increased proportionally → for a given I_{D1}, $V_{GS1}–V_{T1}$ is directly proportional to $(W/L)_1$ → if W_1 is not scaled properly then it will reduce $V_{GS1}–V_{T1}$ → will effectively lead to reduced voltage swing.
- Furthermore, just scaling of L_1 leads to reduced g_{m1} → in essence possibility of reduced gain.
- However, $g_{m1}r_{o1} = \sqrt{2\left(\frac{W}{L}\right)_1 \mu_n C_{ox} I_D}\,\frac{1}{\lambda I_D}$
- The gain will increase with increasing L_1 considering that λ depends more strongly on length than g_m does.
- for M_2, increase in L_2 while keeping W_2 constant → increases r_{o2} → increases gain of the CS amplifier → but decreases $|V_{DS2}|$ → reduces the output voltage swing.

CS Amplifier with Triode Load

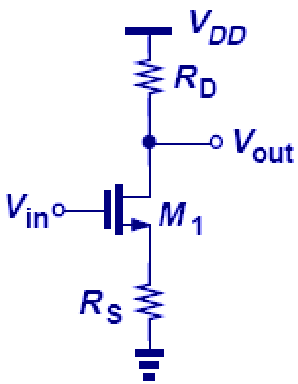


$$R_{on2} = \frac{1}{\mu_p C_{ox}(W/L)_2 (V_{DD} - V_b - |V_{TP}|)}$$

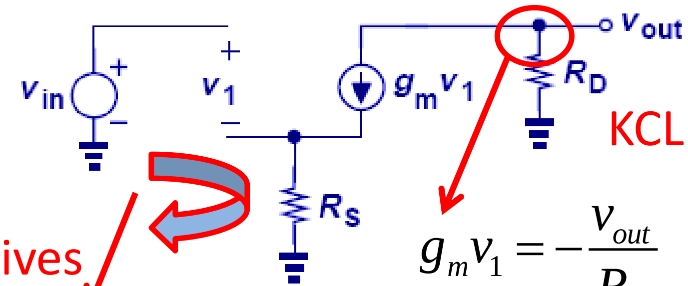
$$A_v = -g_{m1} R_{on2} \qquad A_v = -g_{m1}(r_{o1} \| R_{on2})$$

- The main limitation of this technique is the dependence of gain on the process parameters → because R_{on} is dependent on these parameters.
- Process parameters are temperature dependent → makes gain dependent on temperature.
- Triode loads consume less voltage headroom as compared to diode-connected load → Here, $V_{out,max}=V_{DD}$.

CS Amplifier with Source Degeneration



small signal model



KVL gives

$$v_{in} = v_1 + g_m v_1 R_S$$

KCL gives

$$g_m v_1 = -\frac{v_{out}}{R_D} \Rightarrow v_1 = -\frac{v_{out}}{g_m R_D}$$

$$\therefore v_{in} = -\frac{v_{out}}{g_m R_D}(1 + g_m R_S)$$

- Therefore the voltage gain: $A_v = \frac{v_{out}}{v_{in}} = -\frac{g_m R_D}{(1 + g_m R_S)}$
- The input resistance: $R_{in} = \infty$
- The output resistance: $R_{out} = R_D$
- For large R_S: $A_v = -\frac{R_D}{R_S}$ Linear

Valid as long as M_1 is in saturation

$$V_{DD} - V_{in} + V_T > I_D R_D \rightarrow V_{DD} - I_D R_D > V_{in} - V_T$$

CS Amplifier with Source Degeneration (contd.)

- A_v drops when: $V_{DD} - V_{in} + V_T < I_D R_D$ ← M_1 goes in triode

Even with all the supposed benefits of this configuration, the major drawback is the reduced small-signal gain

$$A_v = \frac{v_{out}}{v_{in}} = -\frac{g_m}{(1 + g_m R_S)} R_D$$

$$G_m = \frac{g_m}{1 + g_m R_S} = \frac{1}{(1/g_m) + R_S}$$ ← Equivalent Circuit Transconductance

$$A_v = -\frac{R_D}{\left(\frac{1}{g_m} + R_S\right)}$$

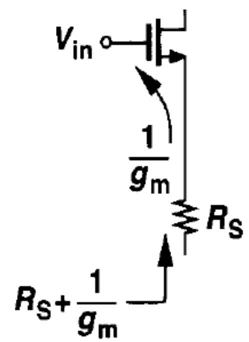
For large V_{in} (while M_1 still in saturation) → g_m is high → G_m approaches $1/R_S$

$$\Rightarrow A_v = -\frac{R_D}{R_S}$$

Reduced Gain

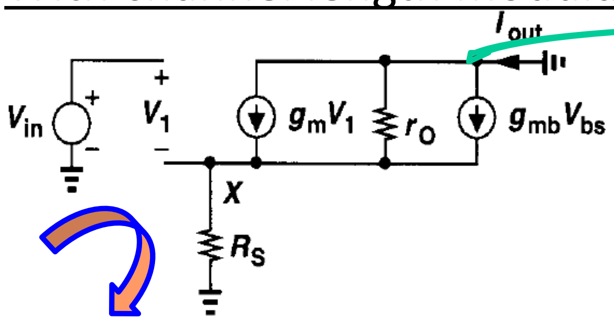
Linear

Ratio of impedances in the drain and source path →



CS Amplifier with Source Degeneration (contd.)

With channel length modulation and body effect



KCL at output:

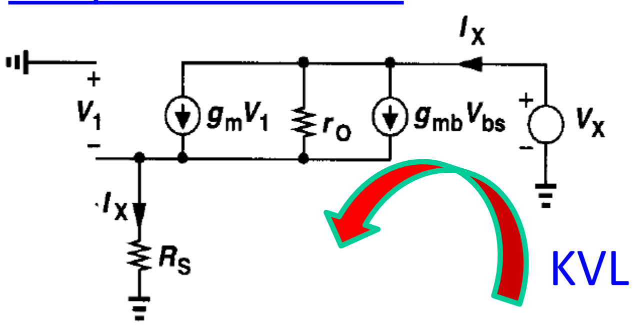
$$I_{out} = g_m V_1 - g_{mb} V_x - \frac{I_{out} R_S}{r_o}$$

$$\Rightarrow I_{out} = g_m (V_{in} - I_{out} R_S) + g_{mb}(-I_{out} R_S) - \frac{I_{out} R_S}{r_o}$$

KVL at input: $V_{in} = V_1 + I_{out} R_S$

$$\therefore G_m = \frac{I_{out}}{V_{in}} = \frac{g_m r_o}{R_S + [1 + (g_m + g_{mb}) R_S] r_o}$$

Output Resistance



Current through R_S is I_X

$$\Rightarrow V_1 = -I_X R_S$$

Current through r_o is:

$$\Rightarrow I_{r_o} = I_X - (g_m + g_{mb}) V_1$$

KVL at the output: $V_X = r_o [I_X + (g_m + g_{mb}) R_S I_X] + I_X R_S$

$$\Rightarrow R_{out} = \frac{V_X}{I_X} = r_o [1 + (g_m + g_{mb}) R_S] + R_S = [1 + (g_m + g_{mb}) r_o] R_S + r_o$$

CS Amplifier with Source Degeneration (contd.)

Usually, $(g_m + g_{mb})r_o >> 1$ $\quad \therefore R_{out} \approx (g_m + g_{mb})r_o R_S + r_o$

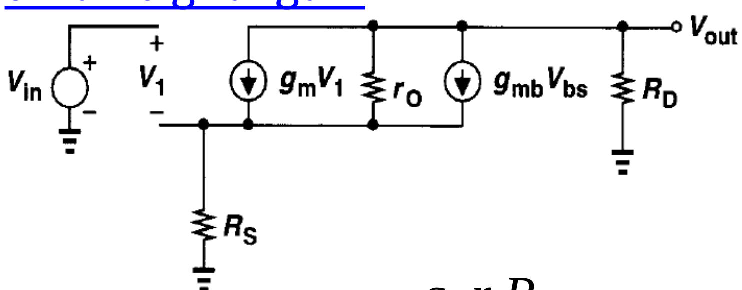
$$\Rightarrow R_{out} \approx [1 + (g_m + g_{mb})R_S]r_o$$

Output impedance has increased by this factor

Definitely a good prospect for applications requiring higher output impedance

Yes! It comes with a price → reduced gain

Small-signal gain



$$A_v = -\frac{V_{out}}{V_{in}} = -\frac{g_m r_o R_D}{R_D + R_S + [1 + (g_m + g_{mb})R_S]r_o}$$

R_{out}

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

For Simplification

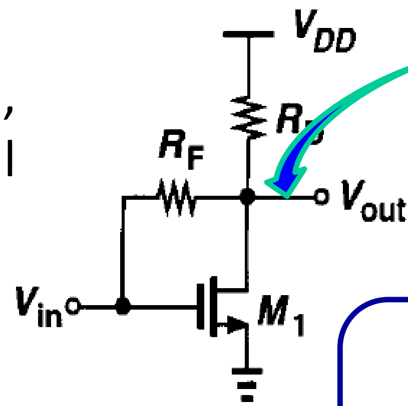
G_m

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

$R_D || R_{out}$

Example – 1

- Assuming M_1 in saturation, calculate the small signal voltage gain of the following:



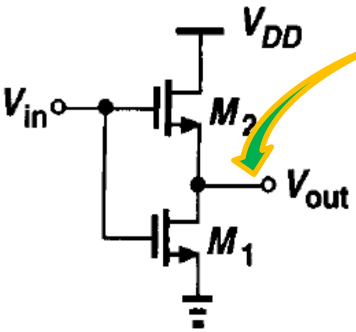
KCL at the output node:

$$\frac{v_{out}-v_{in}}{R_F}+g_{m1}v_{in}+\frac{v_{out}}{r_{o1}}+\frac{v_{out}}{R_D}=0$$

$$A_v=\frac{v_{out}}{v_{in}}=-\frac{g_{m1}-\frac{1}{R_F}}{\frac{1}{R_F}+\frac{1}{r_{o1}}+\frac{1}{R_D}}$$

Example – 2

- Assuming both M_1 and M_2 in saturation, calculate the small signal **voltage** gain of the following:



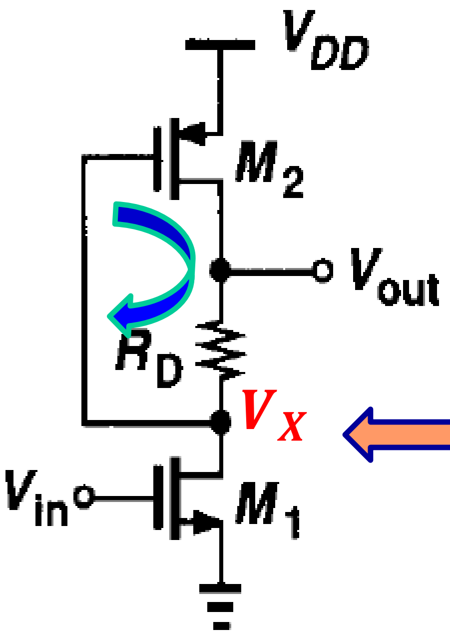
KCL at the output node:

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

$$A_v=\frac{v_{out}}{v_{in}}=-\frac{g_{m1}-g_{m2}}{g_{m2}+\frac{1}{r_{o2}}+\frac{1}{r_{o1}}}$$

Example – 3

- Assuming both M_1 and M_2 in saturation, calculate the small signal voltage gain of the following:



KVL in the mesh created by M_2: $\left(g_{m1}v_{in} + \frac{v_x}{r_{o1}}\right)R_D + v_x = v_{out}$

KCL at this node:

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

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

$$\therefore v_x = -\frac{g_{m1}v_{in} + \frac{v_{out}}{r_{o2}}}{g_{m2} + \frac{1}{r_{o1}}}$$

Example – 3 (contd.)

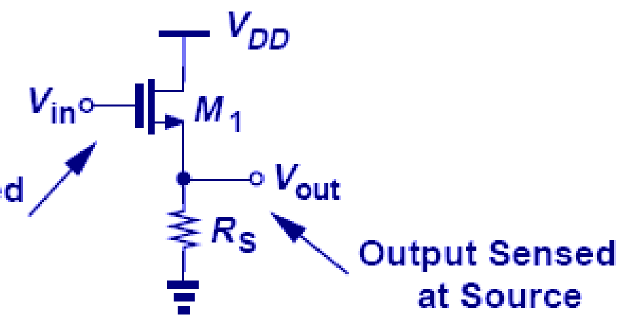
$$\left(g_{m1}v_{in}+\frac{v_x}{r_{o1}}\right)R_D+v_x=v_{out} \quad \Longrightarrow \quad g_{m1}R_Dv_{in}+\left(1+\frac{R_D}{r_{o1}}\right)v_x=v_{out}$$

- Simplification of the expressions gives:

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

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

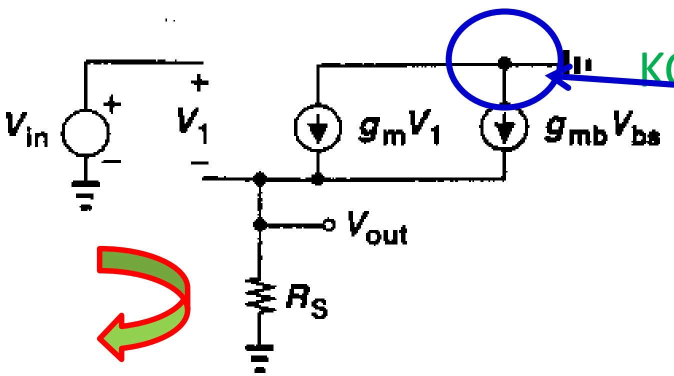
CD Amplifier (Source Follower)



It senses the input at the gate and produces the output at the source

CS-stage can achieve high voltage gain if the load impedance is large → if CS-stage is to be succeeded by a low impedance circuitry then a buffer is needed → CD-stage works as a buffer

Let us look at the small-signal voltage gain of CD-stage:



KCL at drain

$$g_m V_1 + g_{mb} V_{bs} = \frac{V_{out}}{R_S}$$

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

KVL at input: $V_{in} - V_1 = V_{out}$

- Simplification gives: $A_v = \frac{V_{out}}{V_{in}} = \frac{g_m R_S}{[1 + (g_m + g_{mb}) R_S]}$

Non-inverting action

Can you derive A_v without explicitly using the small signal model ?

CD Amplifier (Source Follower) – contd.

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

Observations

- For $V_{in} = V_T$, the transconductance $g_m = 0$ and therefore $A_v = 0$.
- V_{in} increases → I_D increases → leads to increase in g_m → A_v increases and approaches:

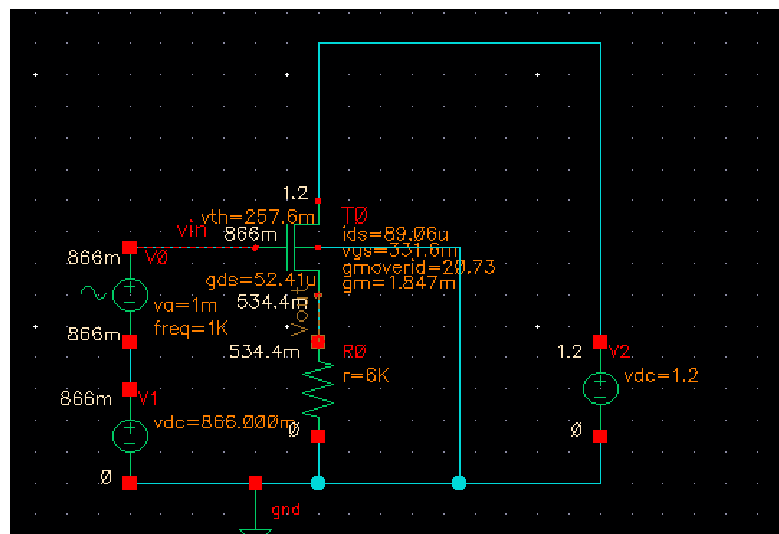
$$A_v = \frac{g_m}{g_m+g_{mb}} = \frac{1}{1+\eta}$$

η decreases with increase in V_{out} → leads to increase in A_v → η is typically 0.2 and therefore $A_v < 1$

Even for $R_S = \infty$, the small signal voltage gain $A_v < 1$

Example: g_m=2 mS
g_{mb}=0.328 mS
R_S=6 kΩ

Calculated A_v= 0.801



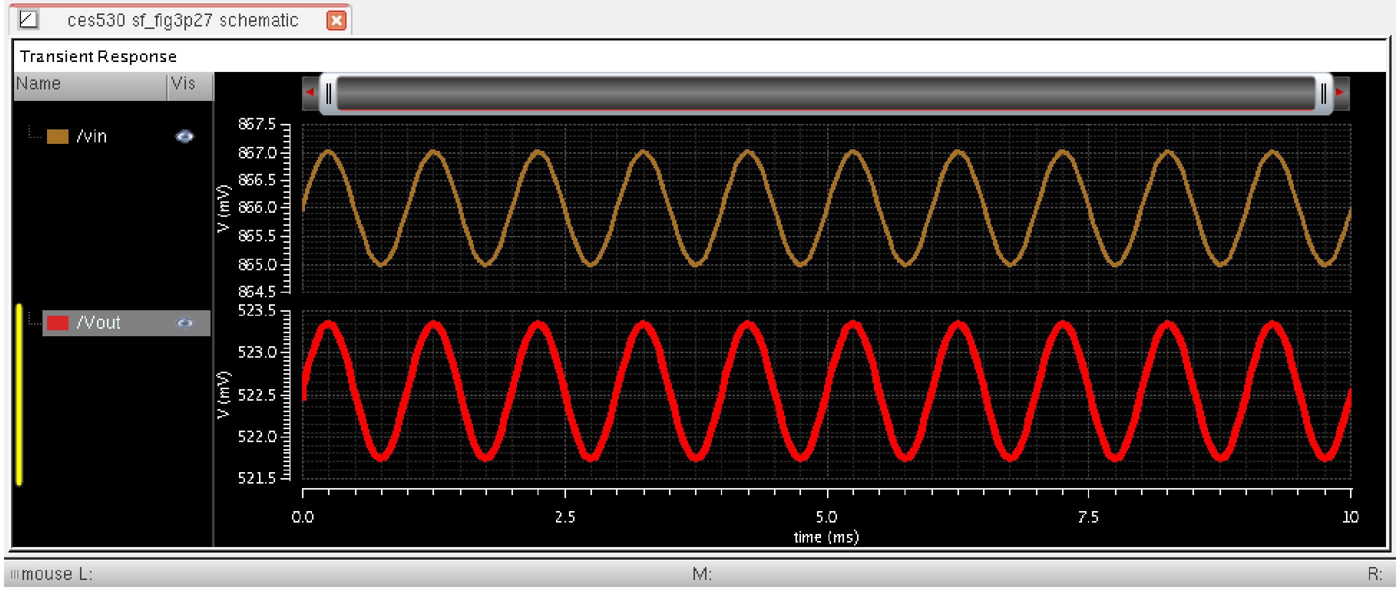
CD Amplifier (Source Follower) – contd.

Example (contd.):

$V_{in,\,pp}$=2 mV

$V_{out,\,pp}$=1.596 mV

Simulated: $A_v = 0.798$



$A_v < 1$ ← Definitely not an amplifier

- In the best case scenario when R_S is extremely high and body effect is ignored then: $A_v = 1$ ← Usefulness as buffer
- How can you ignore body effect?

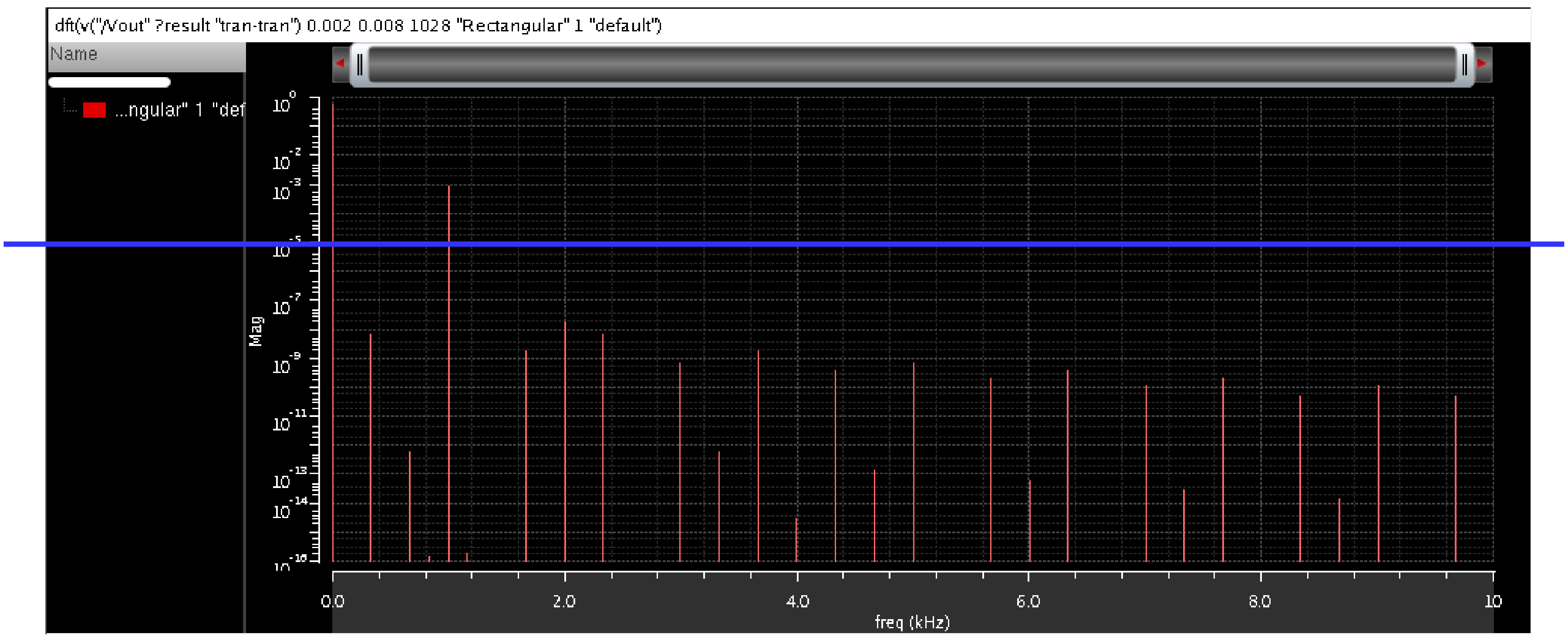
Definitely not for NMOS

By employing a PMOS and with appropriate biasing

CD Amplifier (Source Follower) – contd.

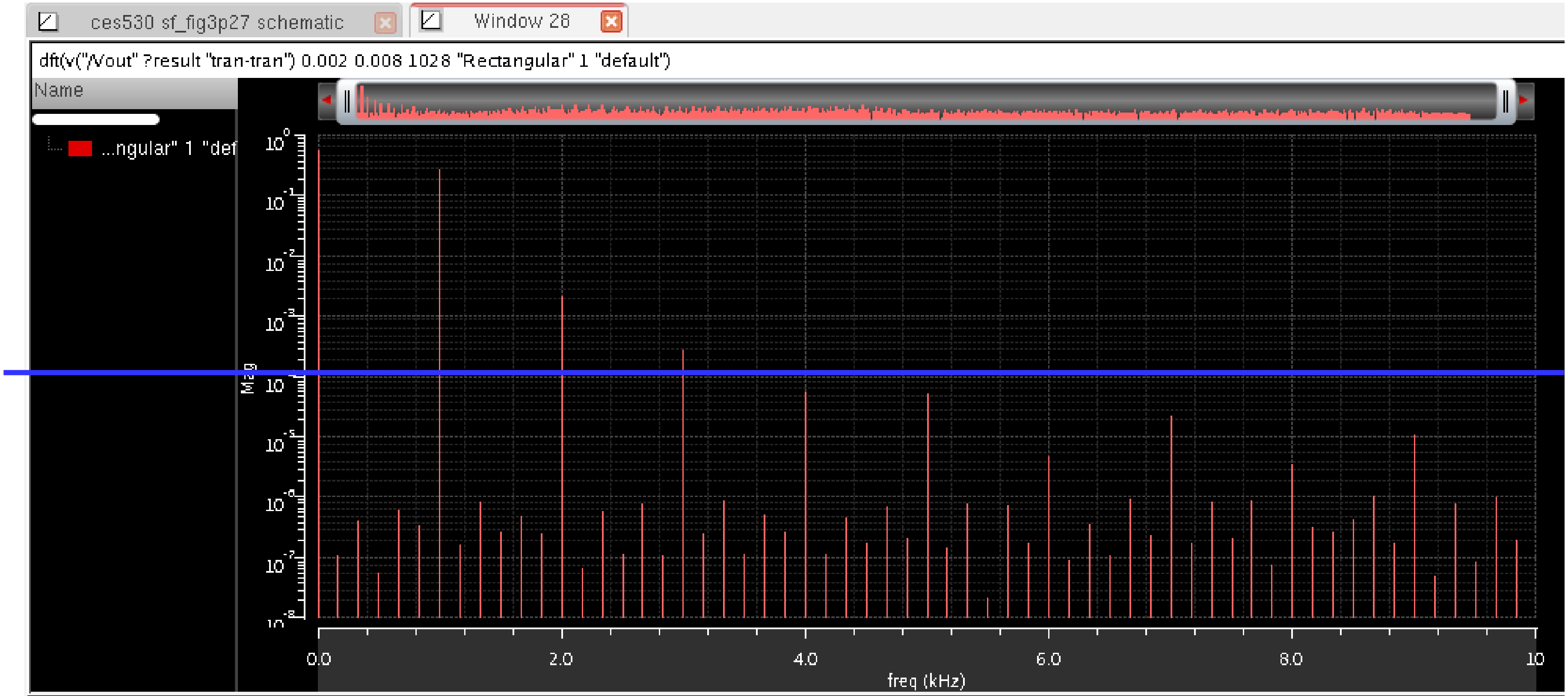
- Furthermore, the strong dependence of A_v on the input voltage makes it a nonlinear configuration → Its due to strong dependence of I_D and therefore g_m on the input voltage V_{in}

V_{in} = 1mV



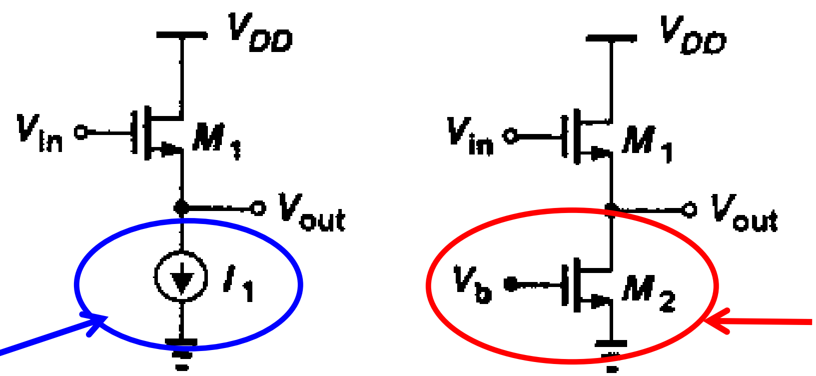
CD Amplifier (Source Follower) – contd.

V_{in} = 330mV



CD Amplifier (Source Follower) – contd.

- To mitigate this dependence → resistor R_S is replaced by a current source → the current source is realized using an NMOS operating in saturation mode

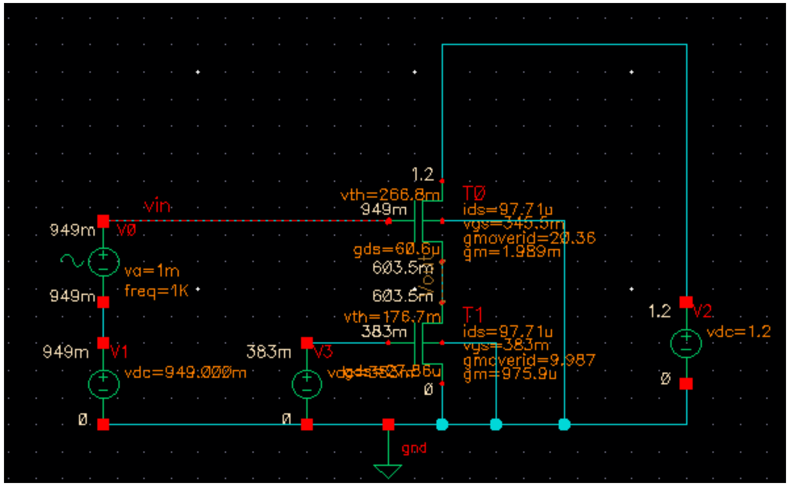


Current source providing high R_S

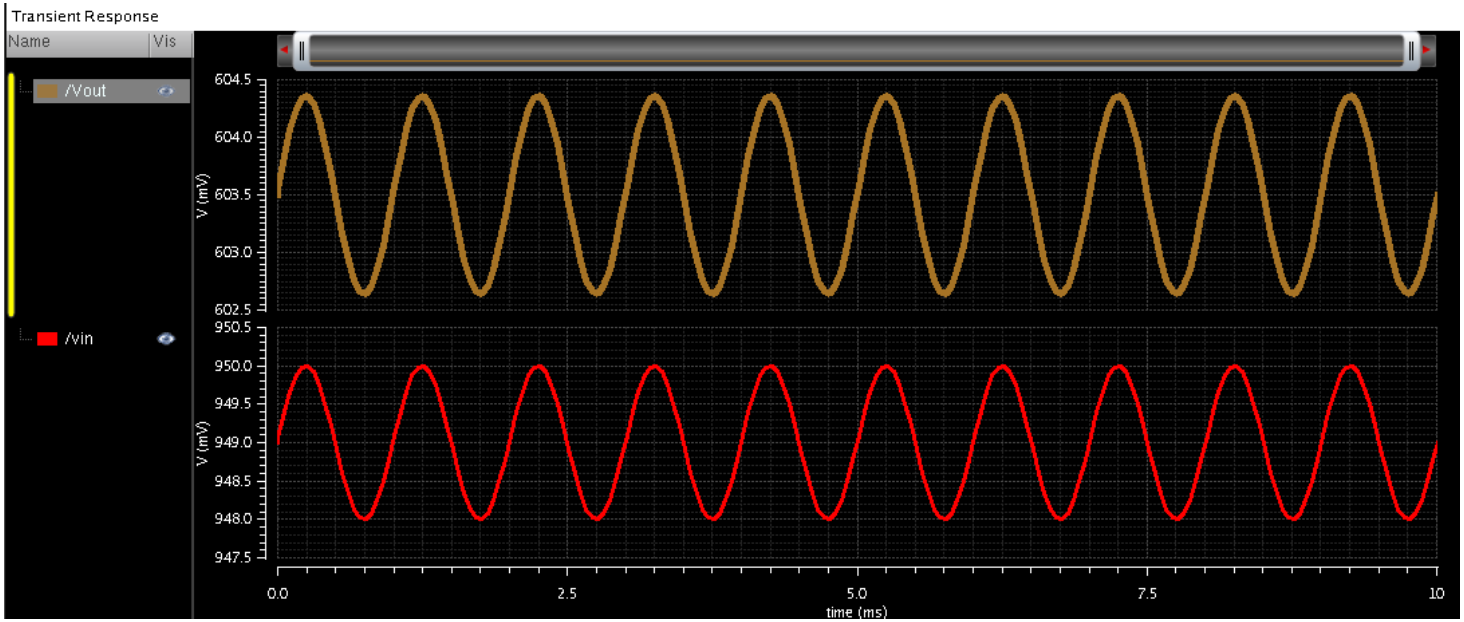
NMOS Operating in Saturation

$$A_v = \frac{\frac{1}{g_{mb1}} \| r_{01} \| r_{02}}{\frac{1}{g_{mb1}} \| r_{01} \| r_{02} + \frac{1}{g_{m1}}}$$

- Let us get back to that example:



CD Amplifier (Source Follower) – contd.

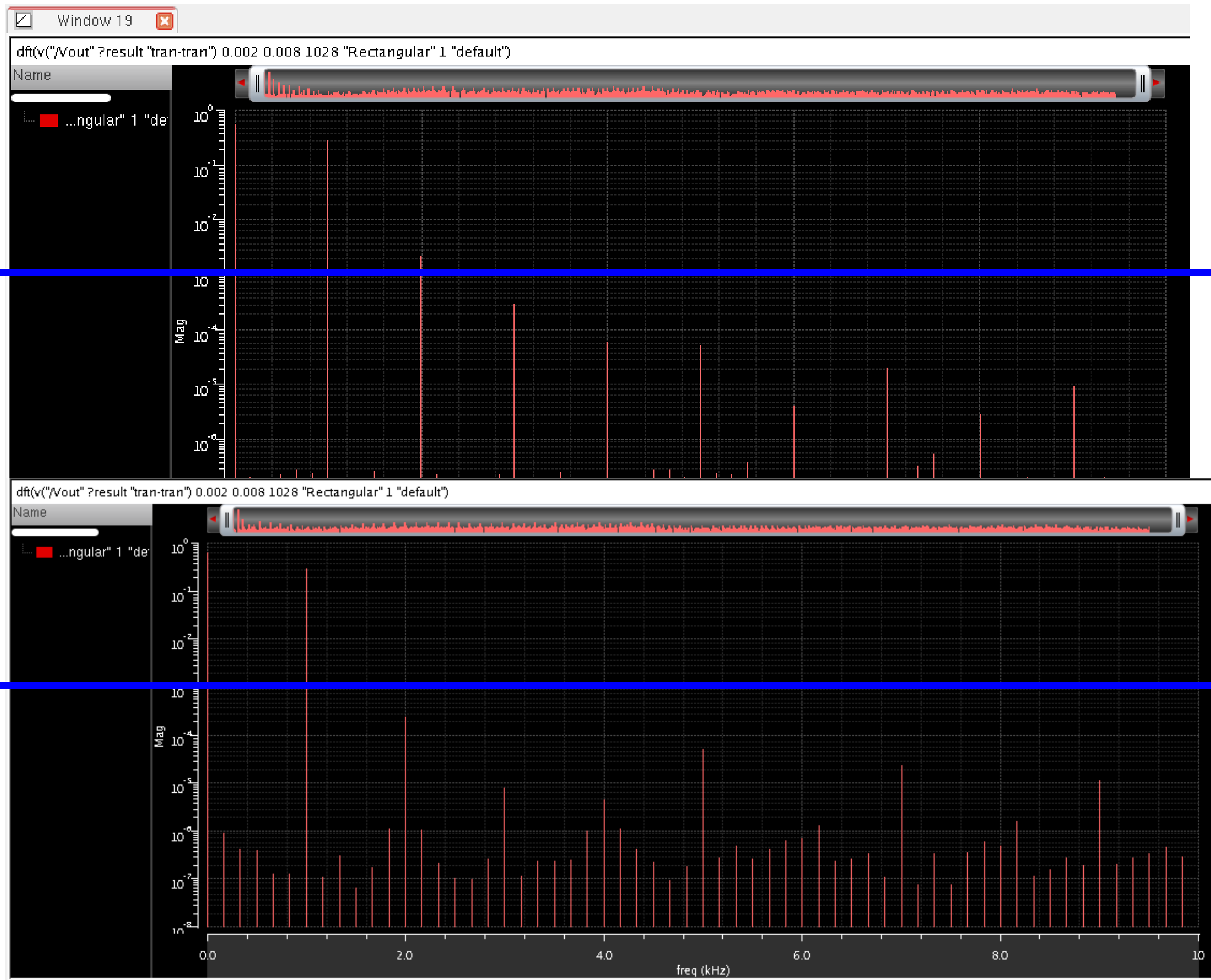


$V_{in,\,pp}$=2 mV **$V_{out,\,pp}$=1.705 mV**

Simulated: $A_v = 0.8525$

CD Amplifier (Source Follower) – contd.

V_{in} = 330mV

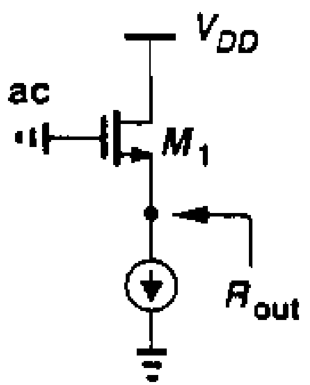


R_S= 6kΩ

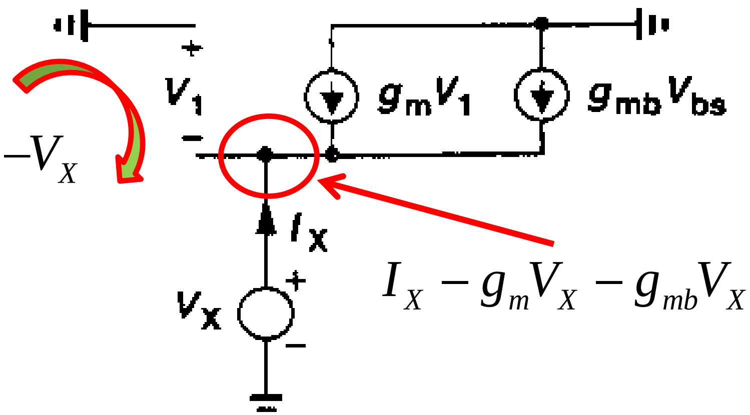
R_S=Current Source

CD Amplifier (Source Follower) – contd.

- Let us look into the small-signal output resistance:



$$V_1 = -V_X$$



$$R_{out} = \frac{1}{g_m + g_{mb}}$$

$$I_X - g_m V_X - g_{mb} V_X = 0$$

Body effect reduces the output impedance

- If channel length modulation is taken into account then:

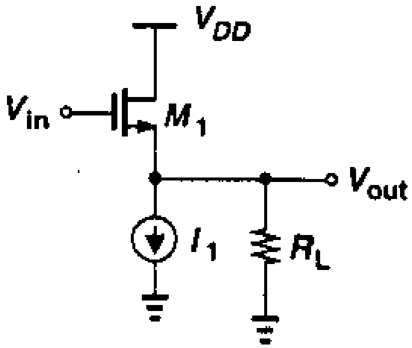
$$\therefore R_{out} = \frac{1}{g_m + g_{mb}} \| r_o$$

Further Reduction in output impedance

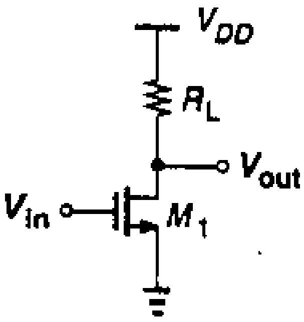
CD Amplifier (Source Follower) – contd.

- High input impedance and low output impedance with near unity gain enables CD stage to work as buffer (not always!) → useful for CS stage specially when the load impedance is raised very high to enhance the gain
- Reduced output voltage swing when used as buffer for a CS stage
- CD topology is nonlinear → due to body effect and channel length modulation → also the gain is dependent on g_m
- CD topology generates substantial noise → hence not suitable for low noise applications (beyond this course!!)

Comparison of CD and CS Stages



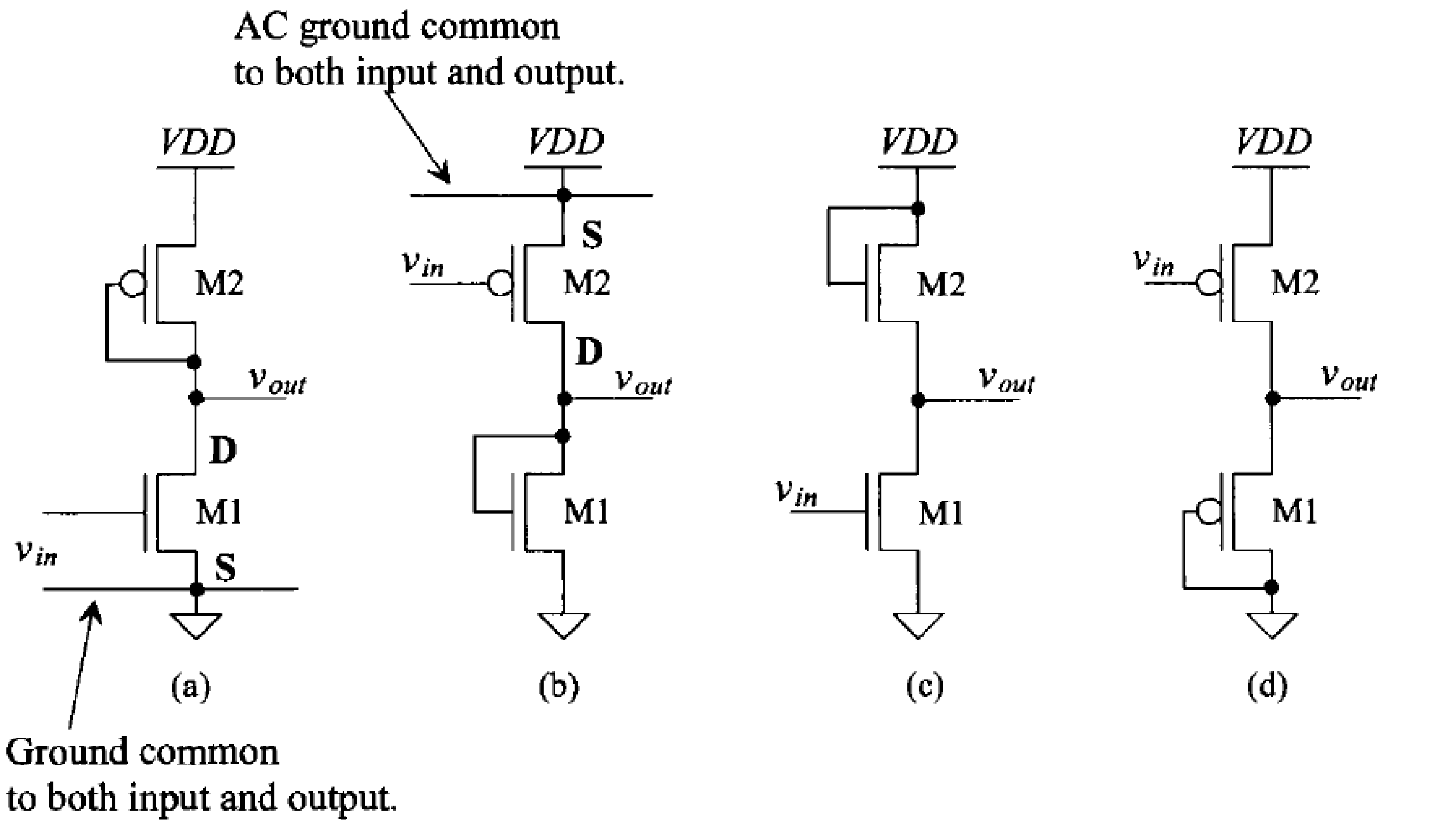
$$A_v|_{CD} \approx \frac{R_L}{R_L + \frac{1}{g_{m1}}}$$



$$A_v|_{CS} \approx -g_{m1}R_L$$

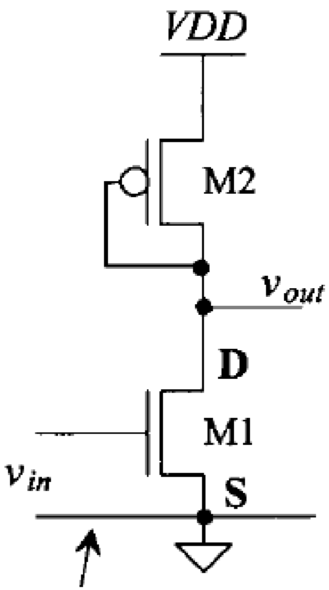
- CD is non-inverting whereas CS is inverting
- CS provides higher gain
- For example, if $1/g_{m1} = R_L$ then the gain provided by the CS stage equals 1 whereas the output of CD stage is 0.5 of the input

Intuitive Analysis - CS Stage

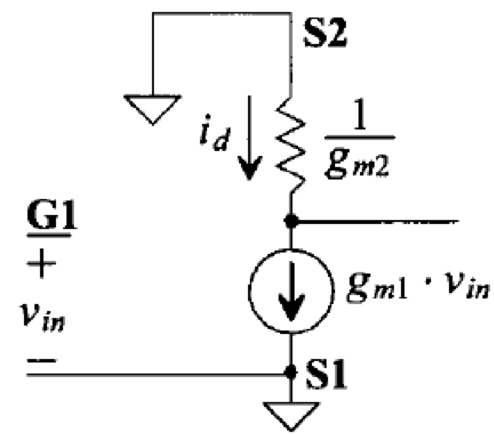


Four possible configurations of common-source amplifiers with diode-connected loads.

Intuitive Analysis - CS Stage (contd.)



To analyze the gain, begin by replacing M2 with a resistor $\frac{1}{g_{m2}}$ **[Assume $\frac{1}{g_{m2}} \ll r_{o1} || r_{o2}$]** and replacing M1 with a current source of $g_{m1} v_{in}$.



- The small-signal gain of the **CS amplifier** is given by

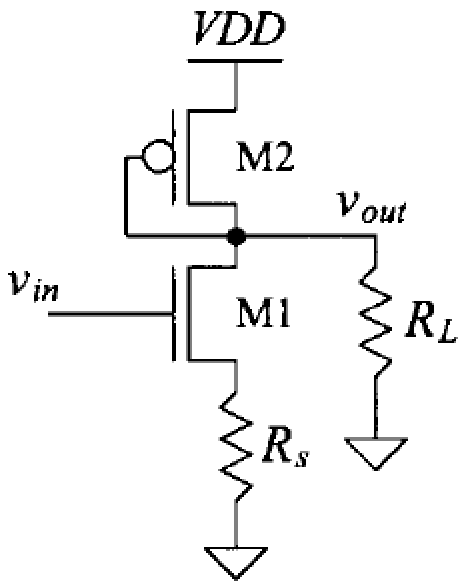
$$A_v = \frac{-i_d . \frac{1}{g_{m2}}}{i_d . \frac{1}{g_{m1}}} = -\frac{\frac{1}{g_{m2}}}{\frac{1}{g_{m1}}}$$

Ratio of the resistance in the drain of M1 divided by the resistance in the source of M1

Caution: it is assumed that r_o is much greater than $\frac{1}{g_m}$.

Example – 4

Determine the small-signal AC gain of the following circuit.



$$A_v = \frac{v_{out}}{v_{in}} = -\frac{resistance\ in\ the\ drain}{reistance\ in\ the\ source}$$

resistance in the drain: $\frac{1}{g_{m2}} || R_L$

For: $r_{o1} || r_{o2} \gg \frac{1}{g_{m2}}$

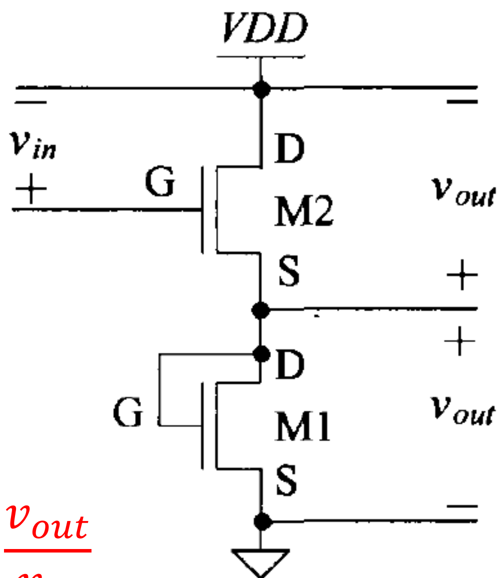
resistance in the source: $\frac{1}{g_{m1}} + R_S$

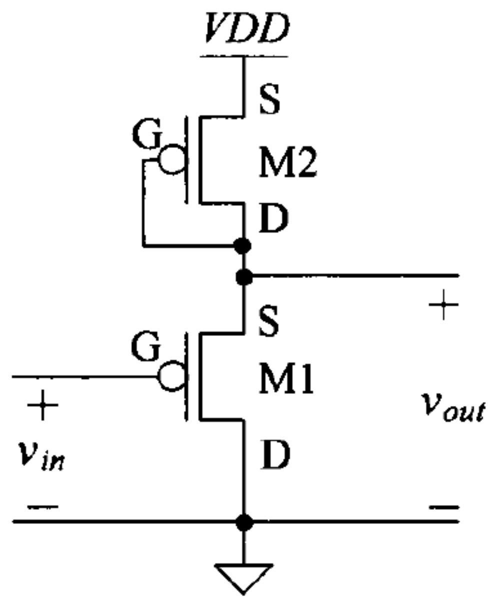
$$A_v = \frac{v_{out}}{v_{in}} = -\frac{\frac{1}{g_{m2}} || R_L}{\frac{1}{g_{m1}} + R_S}$$

$R_L \to \infty$ and $R_S \to 0$

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

Intuitive Analysis - CD Stage





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

$$= \frac{\text{resistance connected to the source}}{\text{resistance connected to the source} + \text{resistance looking into the source}}$$

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

output resistance = ??