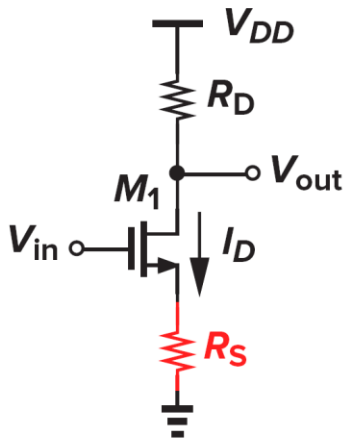
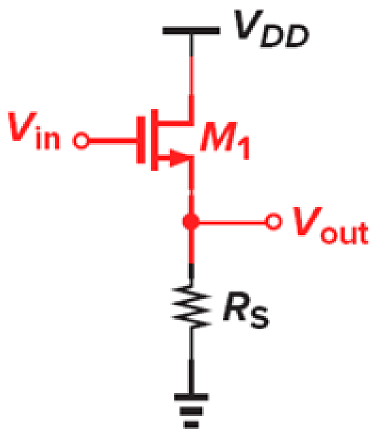
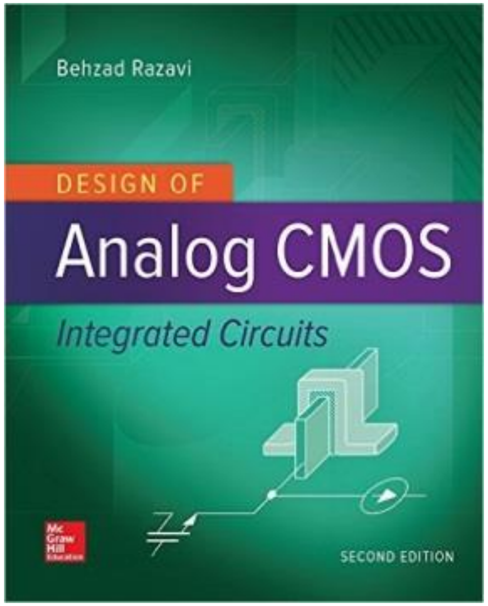
Common source with source degradation
Source follower



CS with
source degradation



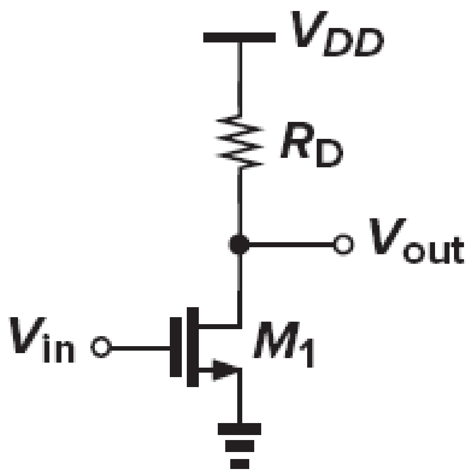
Source follower

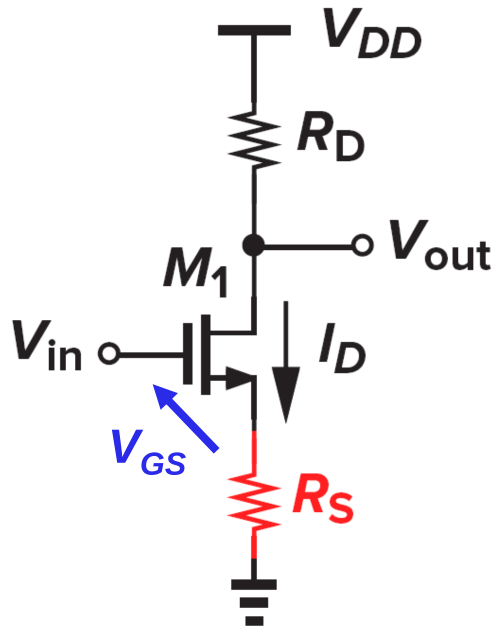


Behzad Razavi:
Design of Analog Integrated Circuit,
McGraw-Hill, 2016

Common source
with
source degradation

CS with source degradation

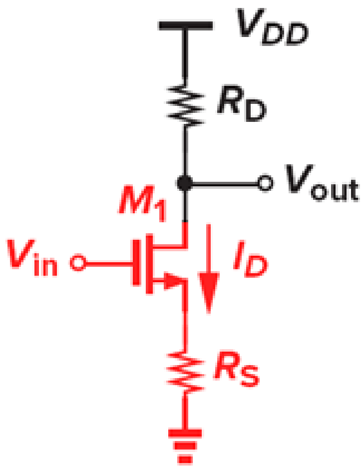


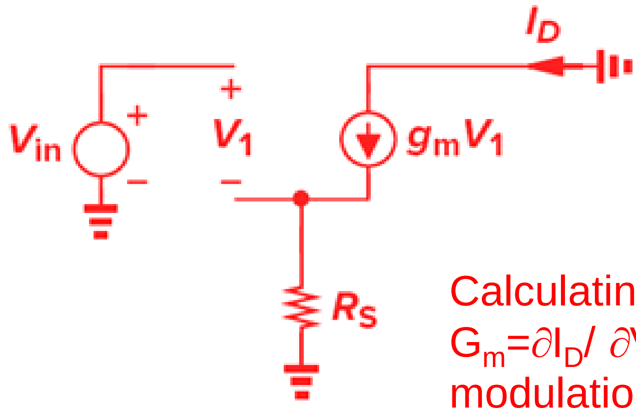


In some applications, the nonlinear dependence of the drain current upon the overdrive voltage introduces excessive nonlinearity, making it desirable to "soften" the device characteristics. As depicted in Fig. (above), this can be accomplished by placing a "degeneration" resistor in series with the source terminal so as to make the input device more linear.

Let us neglect channel-length modulation and body effect. Here, as *Vin* increases, so do I_D and the voltage drop across R_S. That is, a fraction of the change in *Vin* appears across the resistor rather than as the gate-source overdrive, thus leading to a smoother variation of I_D. From another perspective, we intend to make the gain equation a weaker function of g_m. Since $Vout = V_{DD} - I_D R_D$, the nonlinearity of the circuit arises from the nonlinear dependence of I_D upon V_{in}.We note that $\partial Vout/\partial Vin = -(\partial I_D /\partial Vin)R_D$, and define the equivalent transconductance of the circuit as $Gm = \partial I_D /\partial Vin$.

CS with source degradation
(effective transconductance and gain)





Calculating effective transconductance $G_m = \partial I_D / \partial V_{in}$ neglecting channel effect modulation and body effect.

Simple equations for Gm:

$V_{in} = V_1 + R_S g_m V_1 \Rightarrow V_{in} = V_1 (1 + g_m R_S)$
$I_D = g_m V_1$

We obtain:

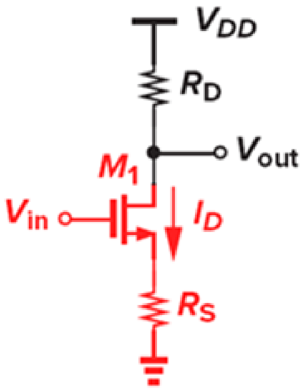
$I_D / V_{in} = g_m / (1 + g_m R_S)$

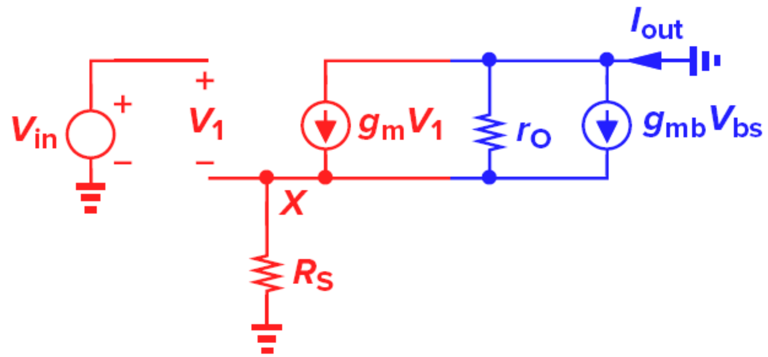
$$G_m = \frac{g_m}{1 + g_m R_S}$$

Small-signal gain:

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

CS with source degradation
(Homework: effective transconductance with r_O and g_{mb})





Calculating effective transconductance Gm with channel effect modulation and body effect.

We recognize that: $V_{in} = V_1 + R_S I_{out}$

$$I_{out} = g_m V_1 - g_{mb} V_X - \frac{I_{out} R_S}{r_O}$$

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

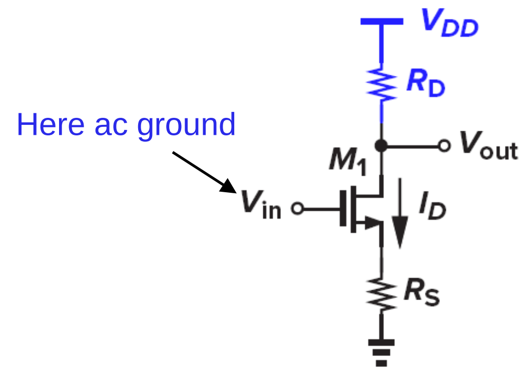
It follows that:

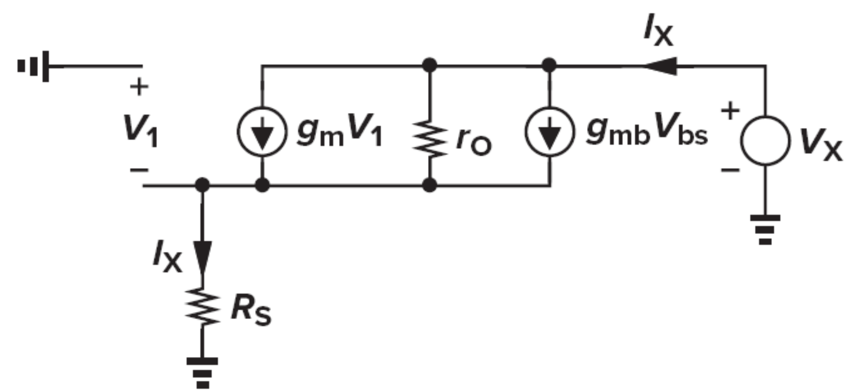
$$G_m = \frac{I_{out}}{V_{in}}$$

$$= \frac{g_m r_O}{R_S + [1 + (g_m + g_{mb}) R_S] r_O}$$

CS with source degradation – R_{out}
(similar to current source with resistor degeneration)

Another important consequence of source degeneration is the increase in the output resistance of the stage. We calculate the output resistance first with the aid of the equivalent circuit shown in Fig. (below), where the load resistor, R_D, is excluded for now. Note that body effect is also included to arrive at a general result. Since the current through R_S is equal to I_X , $V_1 = -I_X R_S$, and the current flowing through r_O is given by $I_X - (g_m + g_{mb})V_1 = I_X + (g_m + g_{mb})R_S I_X$. Adding the voltage drops across r_O and R_S, we obtain:





$$r_O[I_X + (g_m + g_{mb})R_S I_X] + I_X R_S = V_X$$

It follow that:

$$R_{out} = [1 + (g_m + g_{mb})R_S]r_O + R_S$$
$$= [1 + (g_m + g_{mb})r_O]R_S + r_O$$

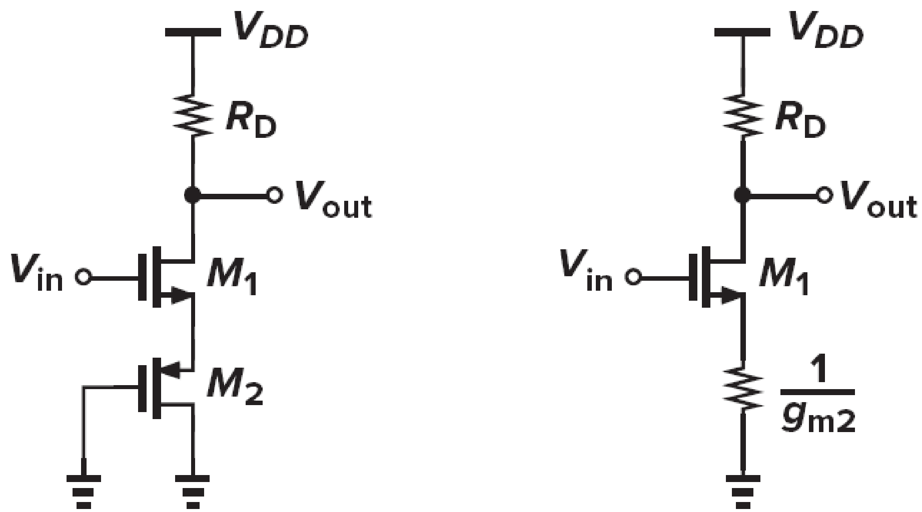
Equation R_{out} indicates that r_O is "boosted" by a factor of $1 + (g_m + g_{mb})R_S$ and then added to R_S.

As an alternative perspective, eq. suggests that R_S is boosted by a factor of $1 + (g_m + g_{mb})r_O$ (a value close to the transistor's intrinsic gain) and then added to r_O.

Both views prove useful in analyzing circuits.

CS with source degradation
(Homework: degradation as diode connected MOS)

Assuming $\lambda = \gamma = 0$, calculate the small-signal gain of the circuit shown in Fig. 3.28(a).



(a) (b) **Figure 3.28**

Solution

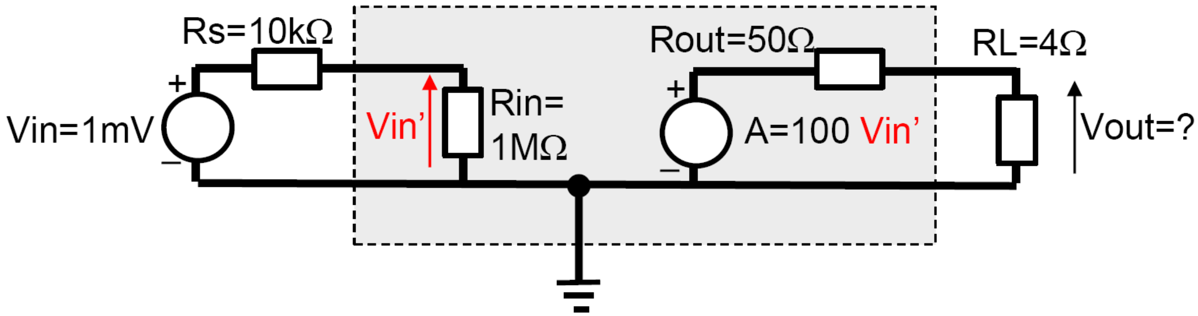
Noting that M_2 is a diode-connected device and simplifying the circuit to that shown in Fig. 3.28(b), we use the above rule to write

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

Source follower

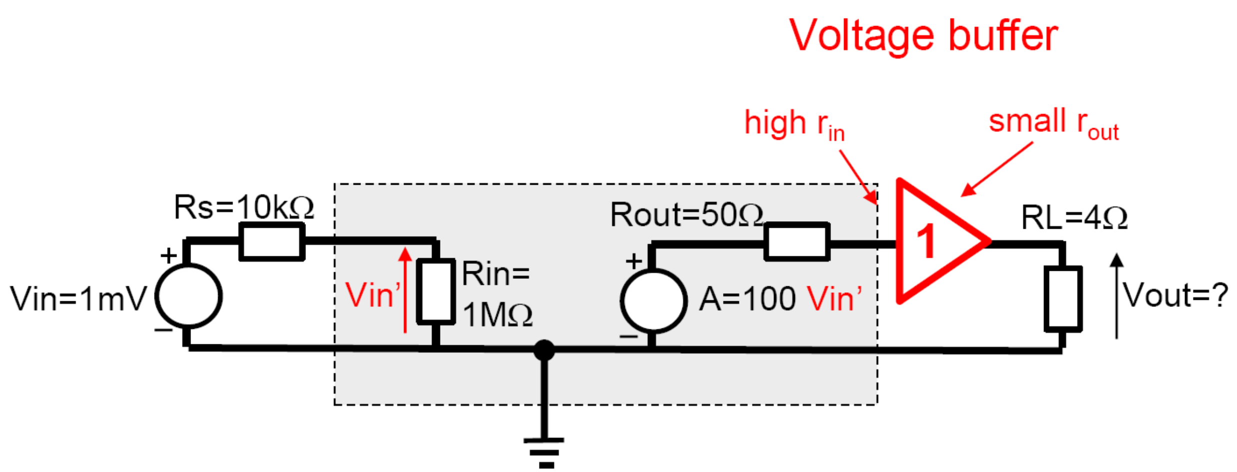
Voltage buffer
(gain = 1V/V, rin –high, rout – small)

Ex.: Vin = 1 mV, A=100 V/V, Rs=10kΩ, Rin=1MΩ, Rout=50Ω, RL=4Ω. Calculate Vout=?

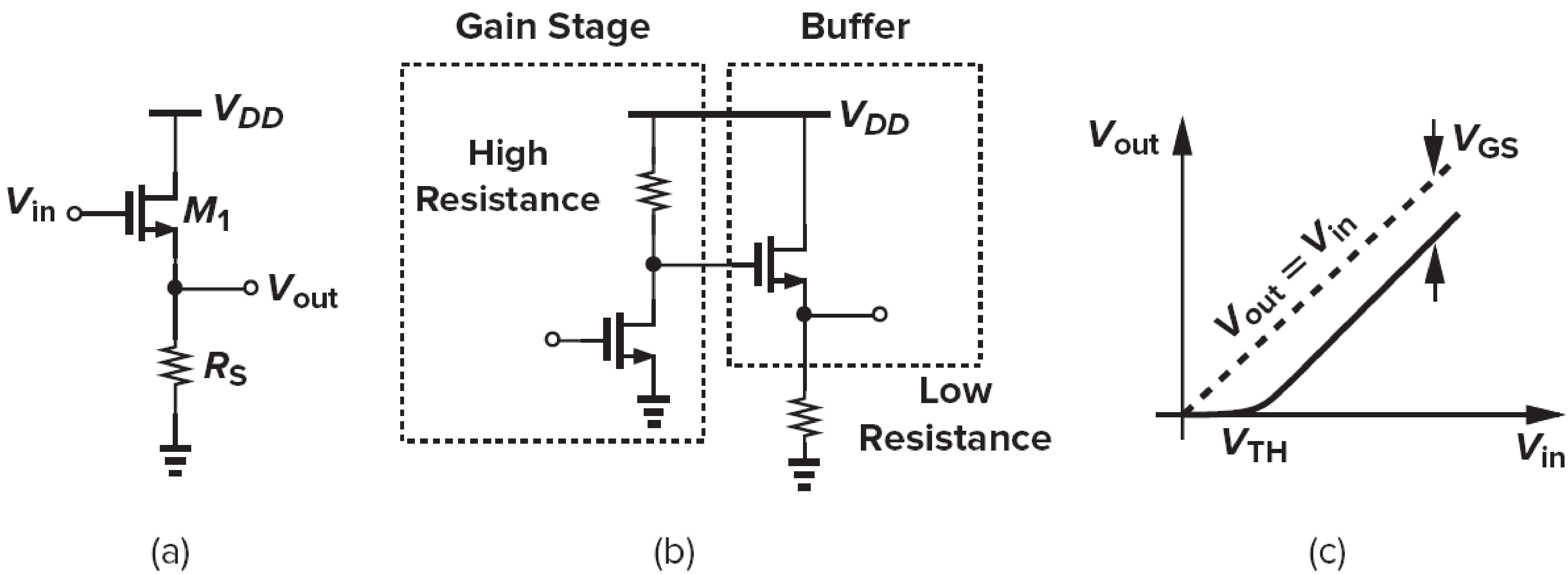


Vout = 1 mV × (voltage divider at input) × 100V/V × (voltage divider at output)
Vout = 1 mV × (1M/(10k+1M)) × 100V/V × (4/(4+50)) = 7.4m
Comment: It will be better if Rout is small (for voltage amplifier Rout should be small)

Solution:

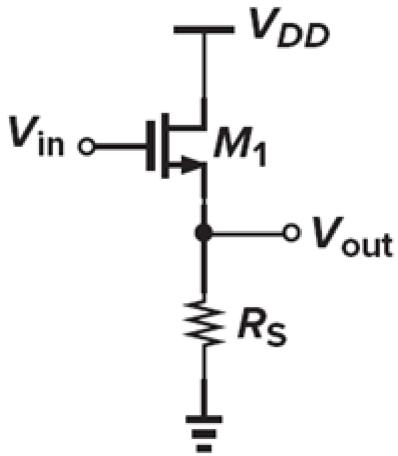


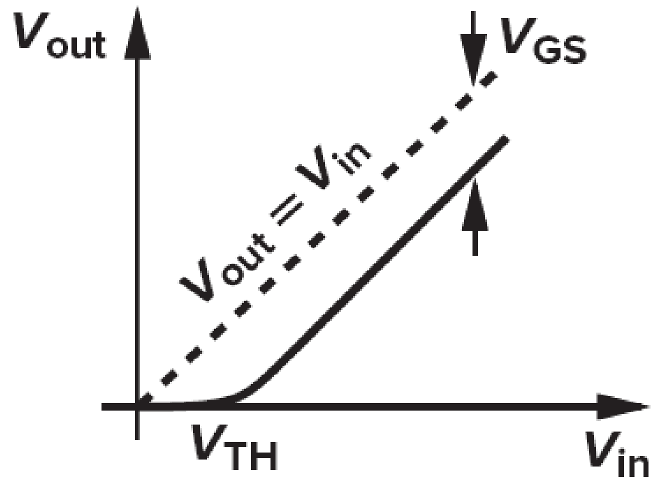
Common drain = source follower (voltage buffer)



(a) Source follower, (b) example of its role as a buffer, and (c) its input-output characteristic.

Source follower
(DC-DC characteristic = large-signal behavior)





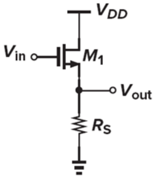
Beginning with the large-signal behavior of the source follower, we note that for *Vin* < V_{TH}, *M*1 is off and *Vout* = 0. As *Vin* exceeds V_{TH}, *M*1 turns on in saturation and I_{D1} flows through R_S . As *Vin* increases further, *Vout* follows the input with a difference (level shift) equal to V_{GS}. We can express the input-output characteristic as *Vout* =$I_D R_S$

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

where channel-length modulation is neglected. Let us calculate the small-signal gain of the circuit by differentiating both sides of above eq. with respect to *Vin* (see next slide) and we obtain:

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

Source follower
(HOMEWORK: gain calculation from DC-DC characteristic)



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

Let us calculate the small-signal gain of the circuit by differentiating both sides of above eq. with respect to *Vin:*

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

Since $\partial V_{TH}/\partial V_{in} = (\partial V_{TH}/\partial V_{SB})(\partial V_{SB}/\partial V_{in}) = \eta \partial V_{out}/\partial V_{in}$,

$$\frac{\partial V_{out}}{\partial V_{in}} = \frac{\mu_n C_{ox}\frac{W}{L}(V_{in} - V_{TH} - V_{out})R_S}{1 + \mu_n C_{ox}\frac{W}{L}(V_{in} - V_{TH} - V_{out})R_S(1+\eta)}$$

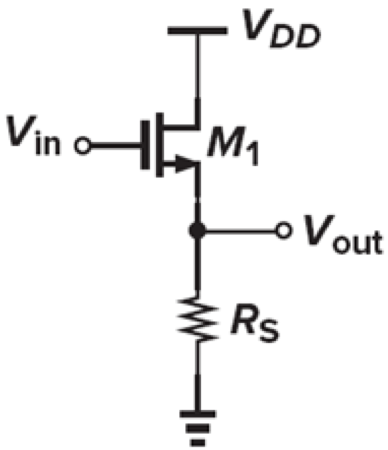
Also, note that

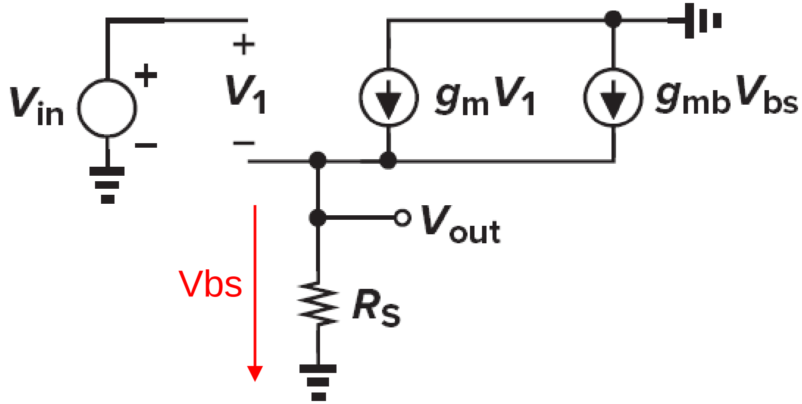
$$g_m = \mu_n C_{ox}\frac{W}{L}(V_{in} - V_{TH} - V_{out})$$

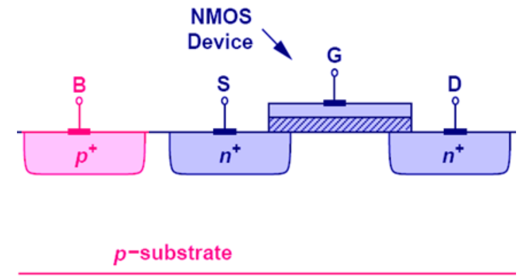
Consequently,

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

Source follower biased with current source







NMOS – substrate (bulk) connect to GND

Two simple equation:

$V_{in} = V_1 + V_{out} \Rightarrow V_1 = V_{in} - V_{out}$

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

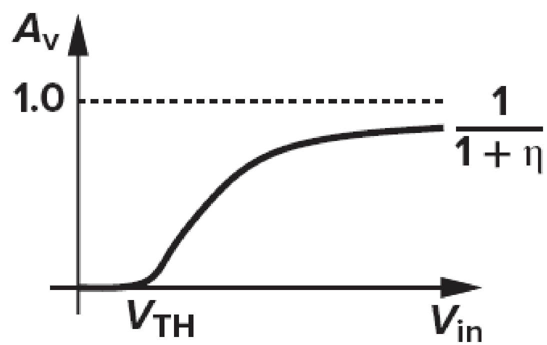
Nothing that: $V_{out} = -V_{bs}$

We have:

$V_{out} = R_S (g_m (V_{in} - V_{out}) - g_{mb} V_{out})$

$V_{out}/V_{in} = g_m R_S / (1 + (g_m + g_{mb}) R_S)$

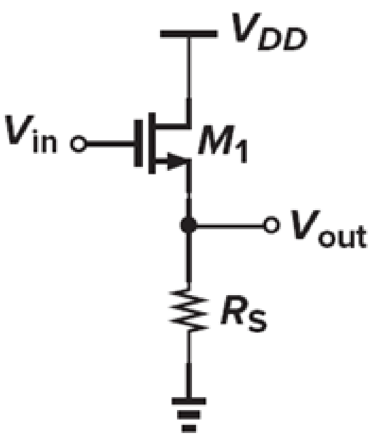
$$A_v \approx \frac{g_m}{g_m + g_{mb}}$$



≈ 0.8

$\eta = g_{mb}/g_m \approx 0.25$

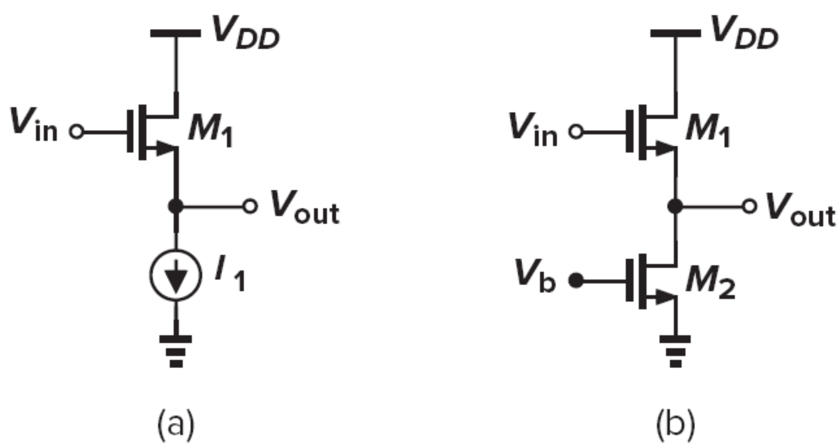
Source follower
(more easilly: gain calculation from small-signal model)



In the source follower of Fig. (left), the drain current of M1 heavily depends on the input dc level:

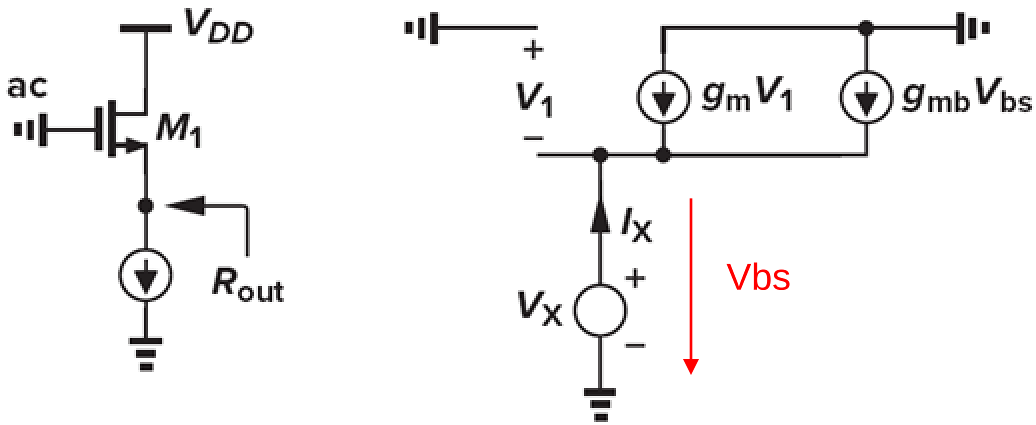
Vin ↑ I_D ↑ then V_{GS} ↑

means that Vout = Vin − V_{GS} does not follow Vin faithfully, thereby incurring nonlinearity. To alleviate this issue, the resistor can be replaced by a constant current source as shown in Fig. (bottom). The current source itself is implemented as an NMOS transistor operating in the saturation region.



Source follower using (a) an ideal current source, and (b) an NMOS transistor as a current source.

Source follower – R_{out}

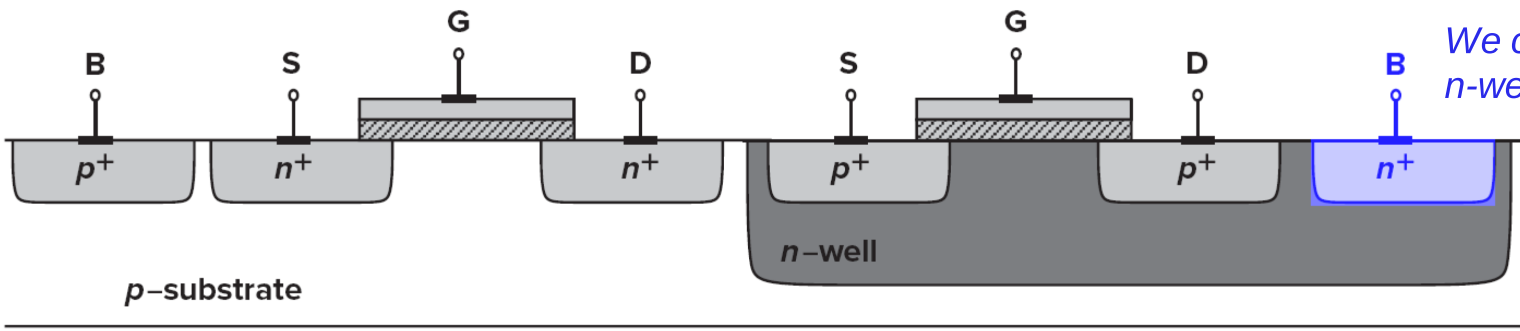


Calculation of the output impedance of a source follower.

Nothing that: $V_X = -V_{bs} = -V_1$

$$I_X - g_m V_X - g_{mb} V_X = 0 \longrightarrow R_{out} = \frac{1}{g_m + g_{mb}}$$

Source follower with no body effects

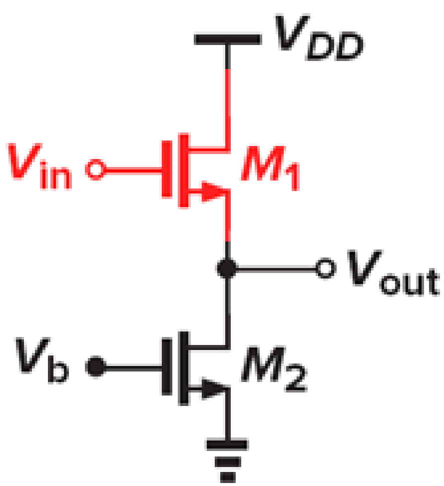


We can design separate n-well with V_{SB}=0

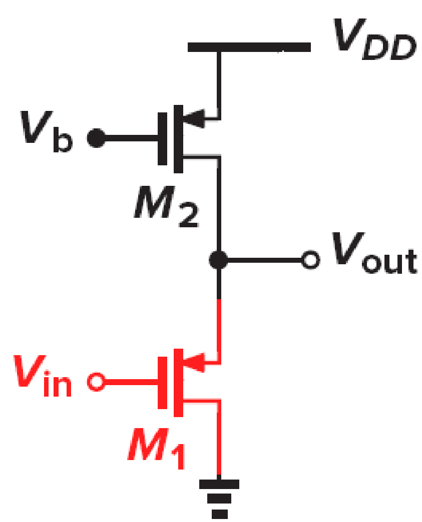
NMOS source follower

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

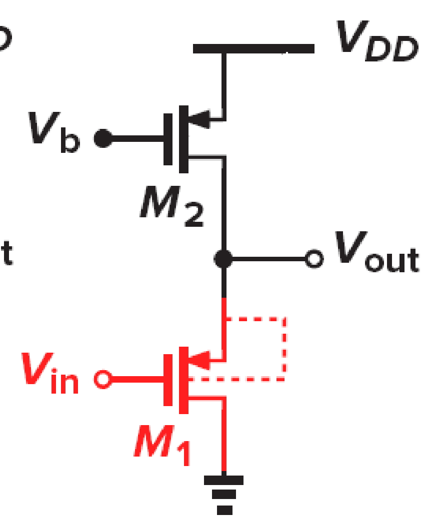
PMOS source follower



g_{m1}, g_{mb1}



g_{m1}, g_{mb1}



g_{m1}

$A_v \approx 1$