

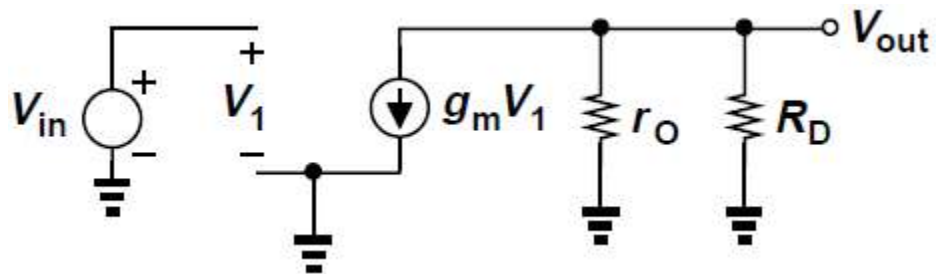
# Common-Source stage with resistive load

- For large values of  $R_D$ , channel-length modulation of  $M_1$  becomes significant,  $V_{out}$  equation becomes

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

- Voltage gain is  $A_v = -g_m \frac{r_O R_D}{r_O + R_D}$

- Above result is also obtained from small-signal equivalent circuit



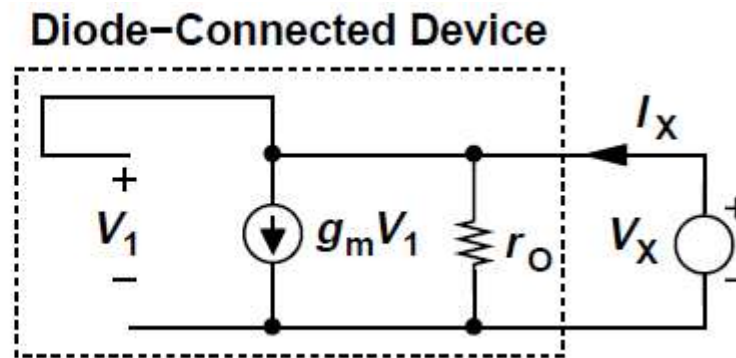
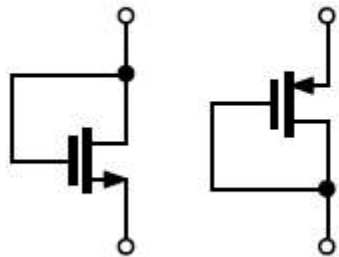
$$V_1 = V_{in}$$

$$g_m V_1 (r_O \parallel R_D) = -V_{out}$$

$$V_{out}/V_{in} = -g_m (r_O \parallel R_D)$$

# Diode-Connected MOSFET

- A MOSFET can operate as a small-signal resistor if its gate and drain are shorted, called a “diode-connected” device
- Transistor always operates in saturation

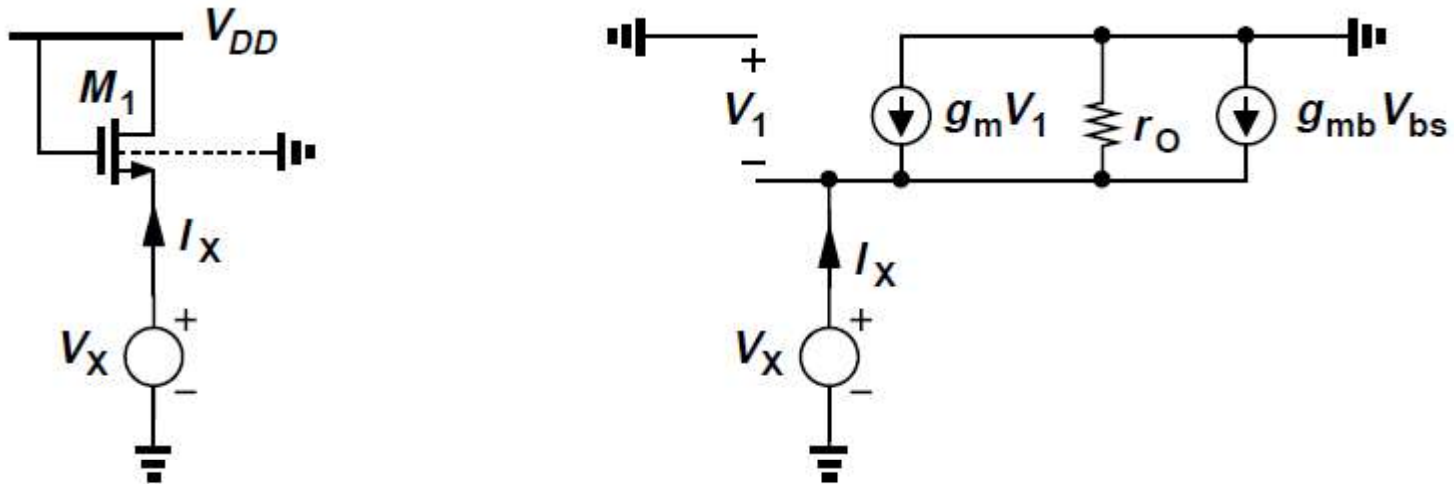


- Impedance of the device can be found from small-signal equivalent model

$$V_1 = V_X \quad I_X = V_X/r_O + g_m V_X$$

$$V_X/I_X = (1/g_m) \parallel r_O \approx 1/g_m$$

# Diode-Connected MOSFET



- Including body-effect, impedance “looking into” the source terminal of diode-connected device is found as

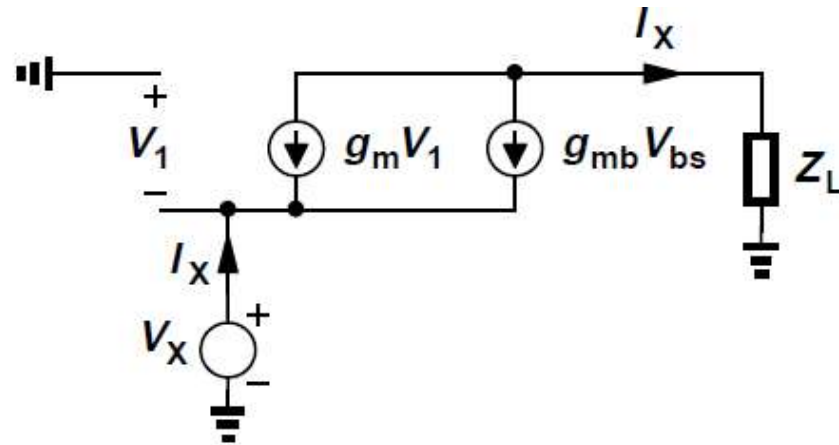
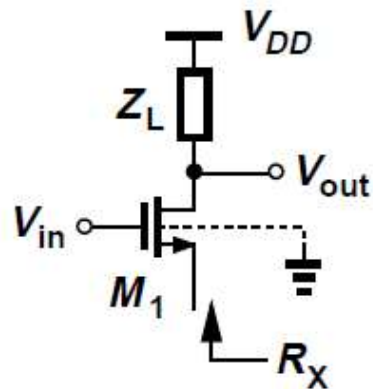
$$V_1 = -V_X \quad V_{bs} = -V_X$$

$$(g_m + g_{mb})V_X + \frac{V_X}{r_O} = I_X$$

$$\begin{aligned} \frac{V_X}{I_X} &= \frac{1}{g_m + g_{mb} + r_O^{-1}} \\ &= \frac{1}{g_m + g_{mb}} \parallel r_O \\ &\approx \frac{1}{g_m + g_{mb}} \end{aligned}$$

# Diode-Connected MOSFET: Example

- Find  $R_x$  if  $\lambda = 0$



$$V_1 = V_X$$

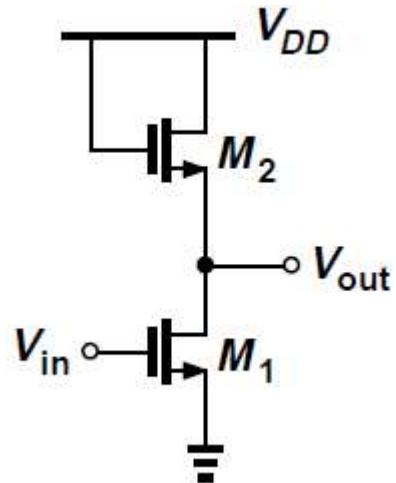
$$V_{bs} = -V_X$$

- Set independent sources to zero, apply  $V_X$  and find result  $(g_m + g_{mb})V_X = I_X$  but only when  $\lambda = 0$

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

- Result is same compared to when drain of  $M_1$  is at ac ground, but only when  $\lambda = 0$
- Loosely said that looking into source of MOSFET, we see  $1/g_m$  when  $\lambda = \gamma = 0$

# CS Stage with Diode-Connected Load



- Neglecting channel-length modulation, using impedance result for diode-connected device,

$$\begin{aligned}
 A_v &= -g_{m1} \frac{1}{g_{m2} + g_{mb2}} \\
 &= -\frac{g_{m1}}{g_{m2}} \frac{1}{1 + \eta},
 \end{aligned}$$

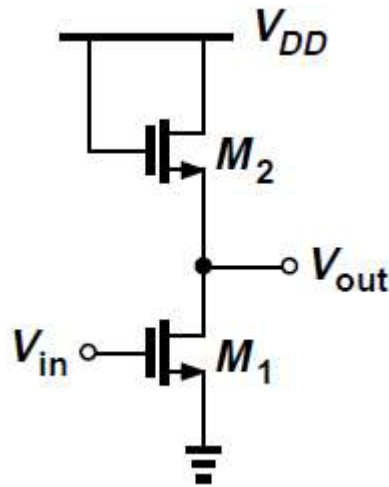
where,  $\eta = g_{mb2}/g_{m2}$ .

- Expressing  $g_{m1}$  and  $g_{m2}$  in terms of device dimensions,

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

- This shows that gain is a weak function of bias currents and voltages, i.e., relatively linear input-output characteristic

# CS Stage with Diode-Connected Load



- From large-signal analysis,

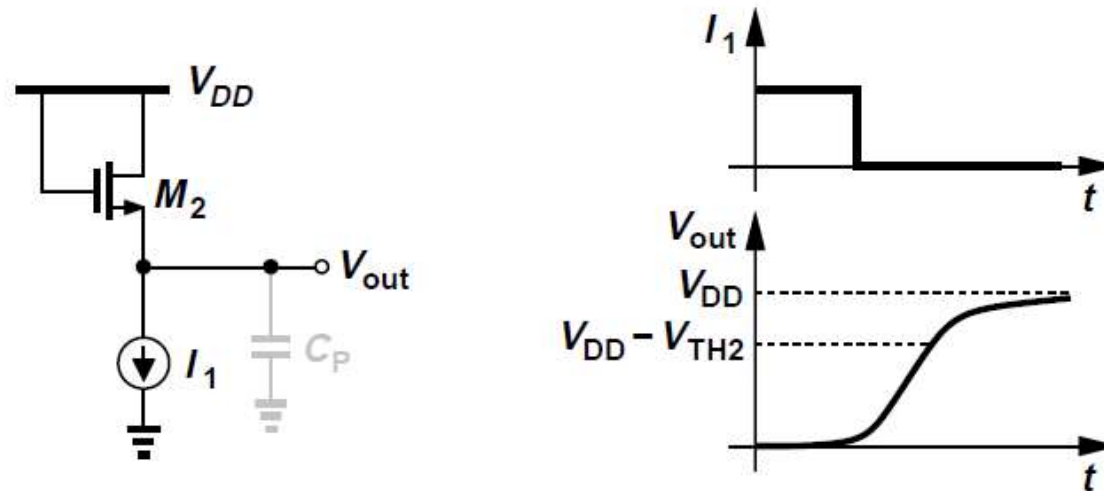
$$\frac{1}{2}\mu_n C_{ox} \left(\frac{W}{L}\right)_1 (V_{in} - V_{TH1})^2 = \frac{1}{2}\mu_n C_{ox} \left(\frac{W}{L}\right)_2 (V_{DD} - V_{out} - V_{TH2})^2$$

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

- If  $V_{TH2}$  does not vary much with  $V_{out}$ , input-output characteristic is relatively linear.
- Squaring function of  $M_1$  (from its input voltage to its drain current) and square root function of  $M_2$  (from its drain current to its overdrive) act as inverse functions

$$f^{-1}(f(x)) = x$$

# CS Stage with Diode-Connected Load

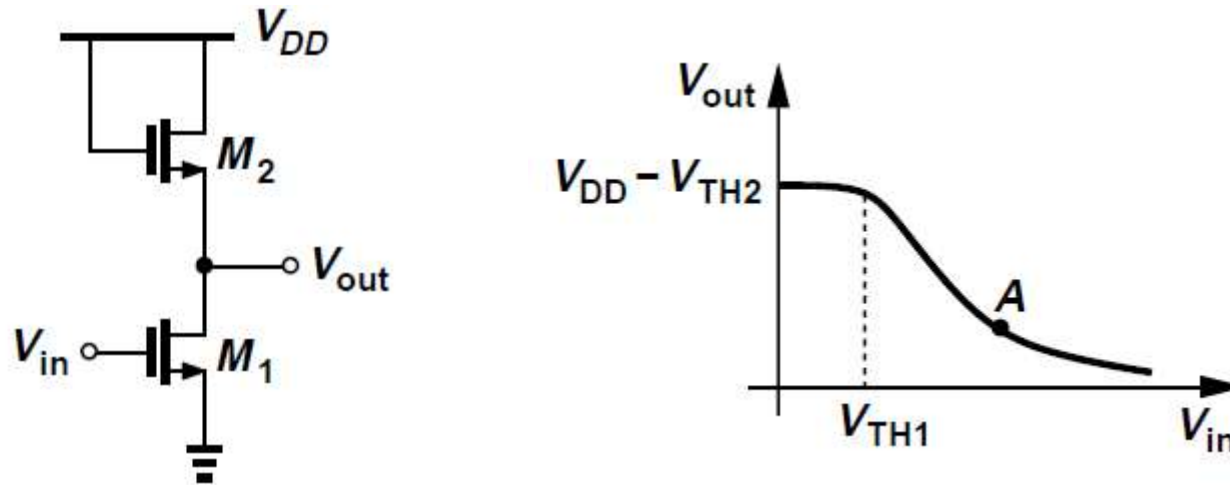


- As  $I_1$  falls, so does overdrive of  $M_2$  so that

$$V_{GS2} \approx V_{TH2} \quad V_{out} \approx V_{DD} - V_{TH2}$$

- Subthreshold conduction of  $M_2$  eventually brings  $V_{out}$  to  $V_{DD}$ , but at very low current levels, finite capacitance at output node  $C_P$  slows down the change in  $V_{out}$  from  $V_{DD} - V_{TH2}$  to  $V_{DD}$ .
- In high-frequency circuits,  $V_{out}$  remains around  $V_{DD} - V_{TH2}$  when  $I_1$  falls to small values.

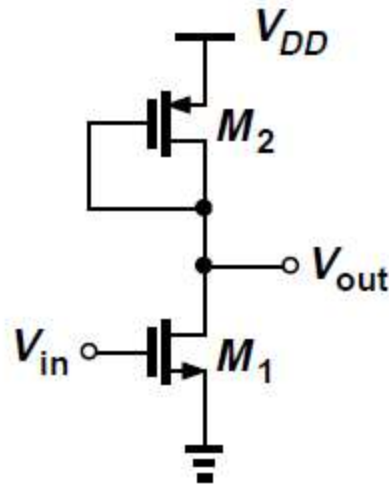
# CS Stage with Diode-Connected Load



- For  $V_{in} < V_{TH1}$ ,  $V_{out} = V_{DD} - V_{TH2}$
- When  $V_{in} > V_{TH1}$ , previous large-signal analysis predicts that  $V_{out}$  approximately follows a single line
- As  $V_{in}$  exceeds  $V_{out} + V_{TH1}$  (to the right of point A),  $M_1$  enters the triode region and the characteristic becomes nonlinear.



# CS Stage with Diode-Connected PMOS device



- Diode-connected load can be implemented as a PMOS device, free of body-effect
- Small-signal voltage gain neglecting channel-length modulation

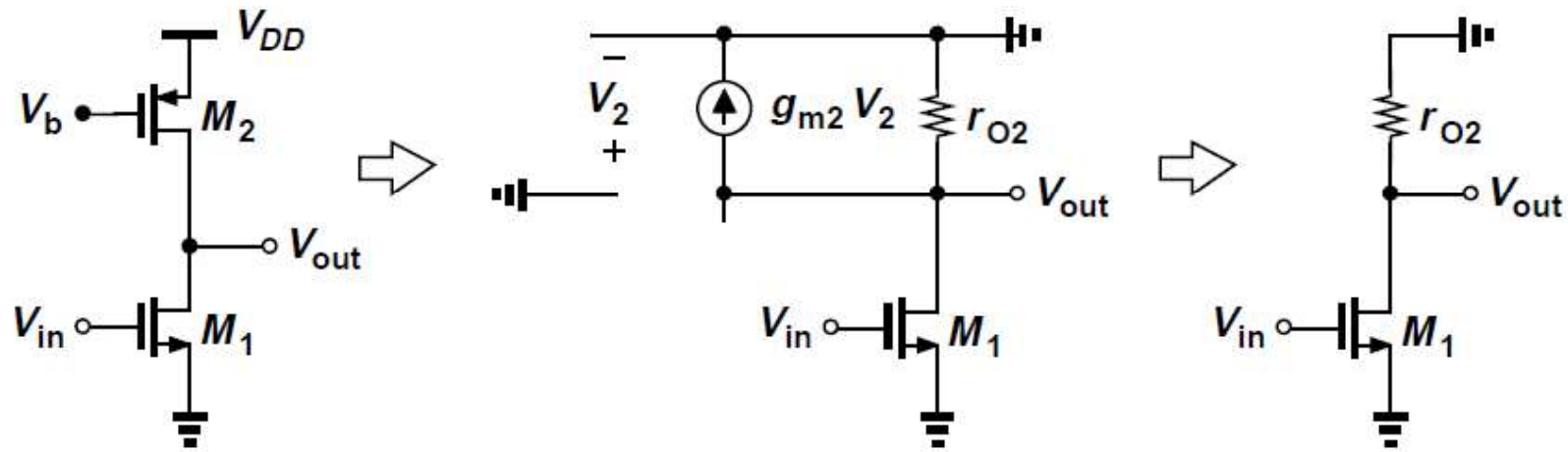
$$A_v = -\sqrt{\frac{\mu_n(W/L)_1}{\mu_p(W/L)_2}}$$

- Gain is a relatively weak function of device dimensions
- Since  $\mu_n \approx 2\mu_p$ , high gain requires “strong” input device (narrow) and “weak” load device (wide)
- This limits voltage swings since for  $\lambda = 0$ , we get

$$\frac{|V_{GS2} - V_{TH2}|}{V_{GS1} - V_{TH1}} = A_v$$

- For diode-connected loads, swing is constrained by both required overdrive voltage and threshold voltage, i.e., for small overdrive, output cannot exceed  $V_{DD} - |V_{TH}|$ .

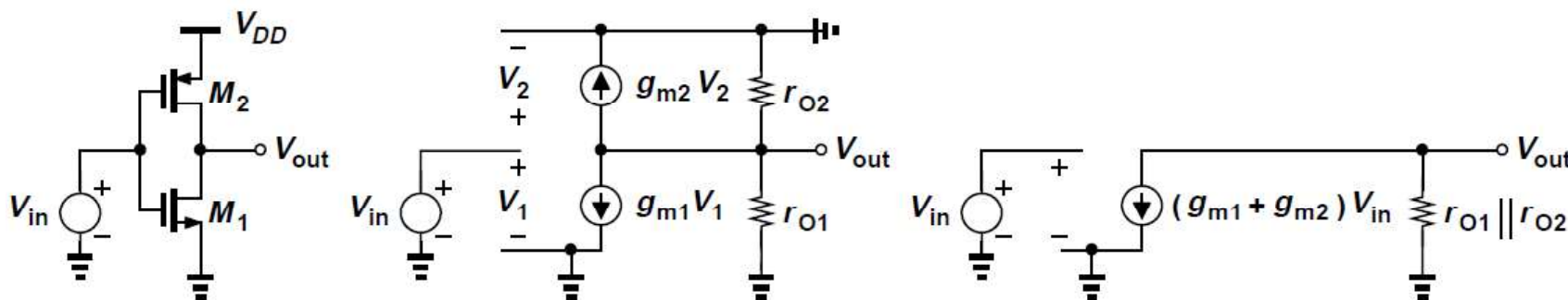
# CS Stage with Current-Source Load



- Current-source load allows a high load resistance without limiting output swing
- Voltage gain is  $A_v = -g_{m1}(r_{O1} \parallel r_{O2})$
- Overdrive of  $M_2$  can be reduced by increasing its width,  $r_{o2}$  can be increased by increasing its length
- Output bias voltage is not well-defined
- Intrinsic gain of  $M_n$  increases with  $L$  and decreases with  $I_D$

$$g_{m1}r_{O1} = \sqrt{2 \left( \frac{W}{L} \right)_1 \mu_n C_{ox} I_D} \frac{1}{\lambda I_D}$$

# CS Stage with Active Load



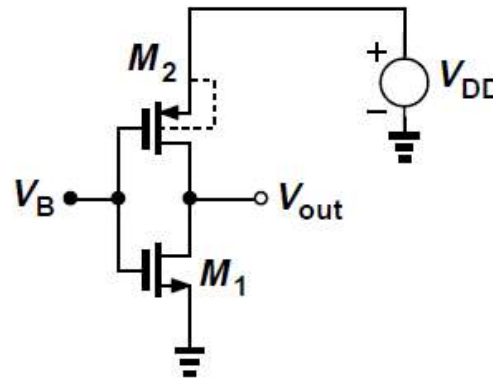
- Input signal is also applied to gate of load device, making it an “active” load
- $M_1$  and  $M_2$  operate in parallel and enhance the voltage gain
- From small-signal equivalent circuit.

$$-(g_{m1} + g_{m2})V_{in}(r_{O1} || r_{O2}) = V_{out}$$

$$A_v = -(g_{m1} + g_{m2})(r_{O1} || r_{O2})$$

- Same output resistance as CS stage with current-source load, but higher transconductance
- Bias current of  $M_1$  and  $M_2$  is a strong function of PVT

# CS Stage with Active Load: Supply sensitivity

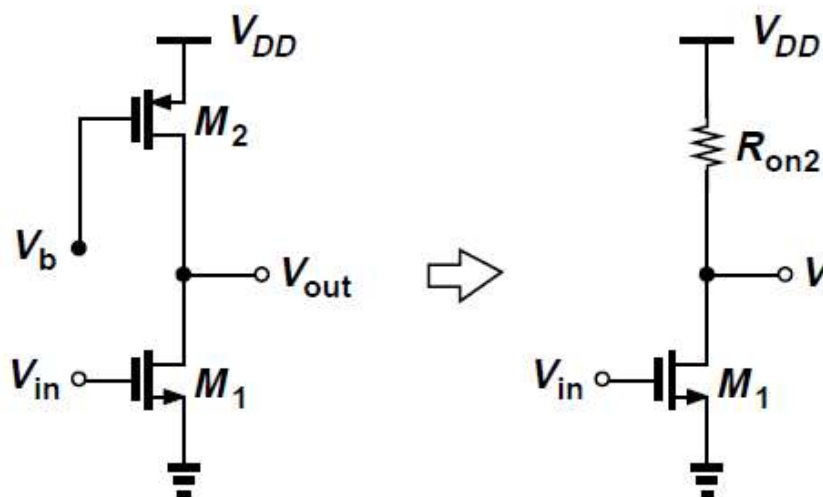


$$V_{GS1} + |V_{GS2}| = V_{DD}$$

- Variations in  $V_{DD}$  or the threshold voltages directly translate to changes in the drain currents
- Supply voltage variations “supply noise” are amplified too
- Voltage gain from  $V_{DD}$  to  $V_{out}$  can be found to be

$$\begin{aligned} \frac{V_{out}}{V_{DD}} &= \frac{g_{m2}r_{O2} + 1}{r_{O2} + r_{O1}} r_{O1} \\ &= \left( g_{m2} + \frac{1}{r_{O2}} \right) (r_{O1} || r_{O2}) \end{aligned}$$

# CS Stage with Triode Load



- A MOS device biased in the deep triode region acts as a resistive load in a CS stage
- $V_b$  is sufficiently low to ensure  $M_2$  is in deep triode region for all output voltage swings

- Voltage gain is  $A_v = -g_{m1}R_{on2}$ , where  $R_{on2}$  is the MOS ON resistance given by

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

- $R_{on2}$  depends on  $\mu_p C_{ox}$ ,  $V_b$  and  $V_{THP}$  which vary with PVT
- Generating a precise value of  $V_b$  is complex, which makes circuit hard to use
- Triode loads consume lesser voltage headroom than diode-connected devices since  $V_{out,max} = V_{DD}$  for the former