模拟集成电路设计课程

第3章 单级放大器

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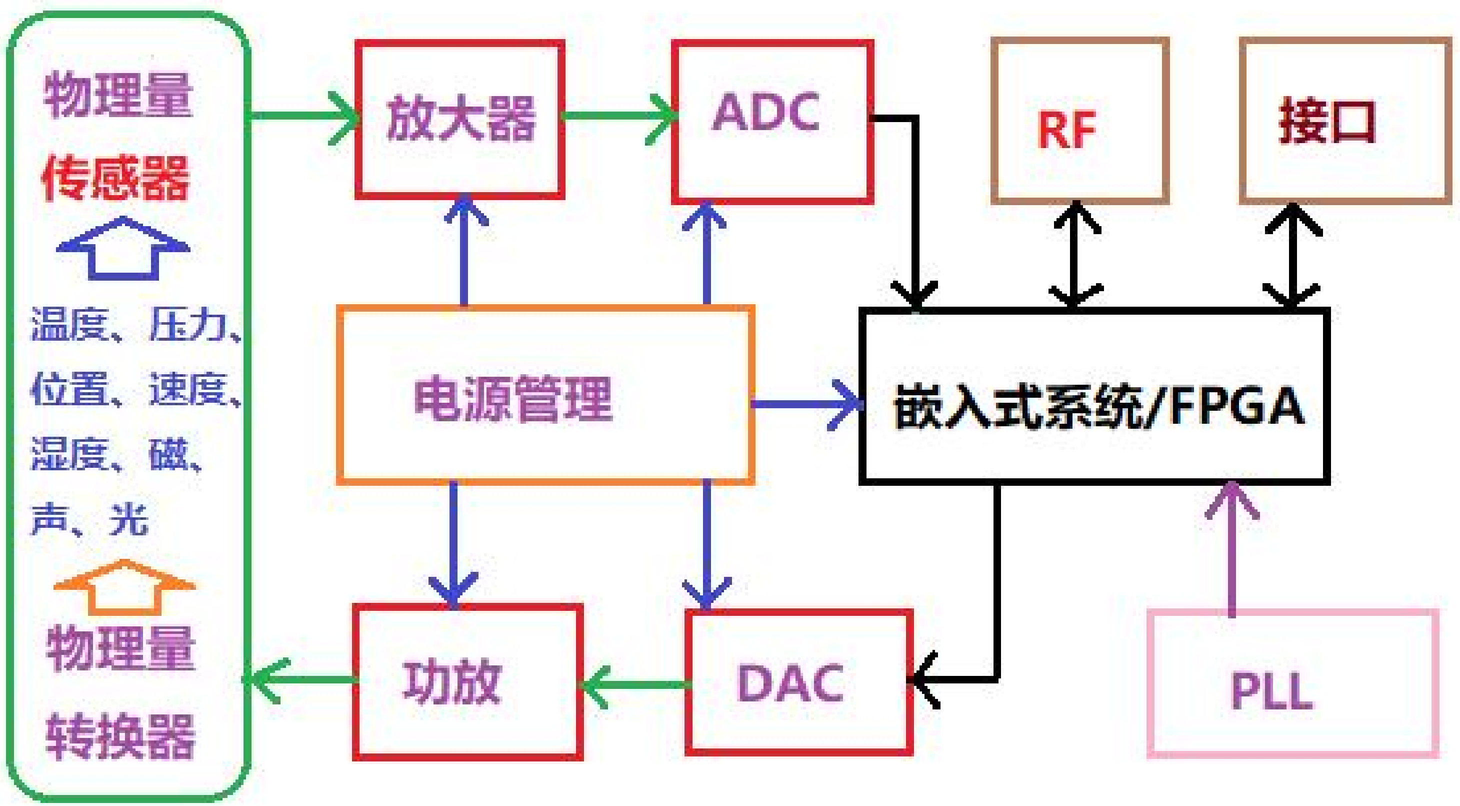
本章内容

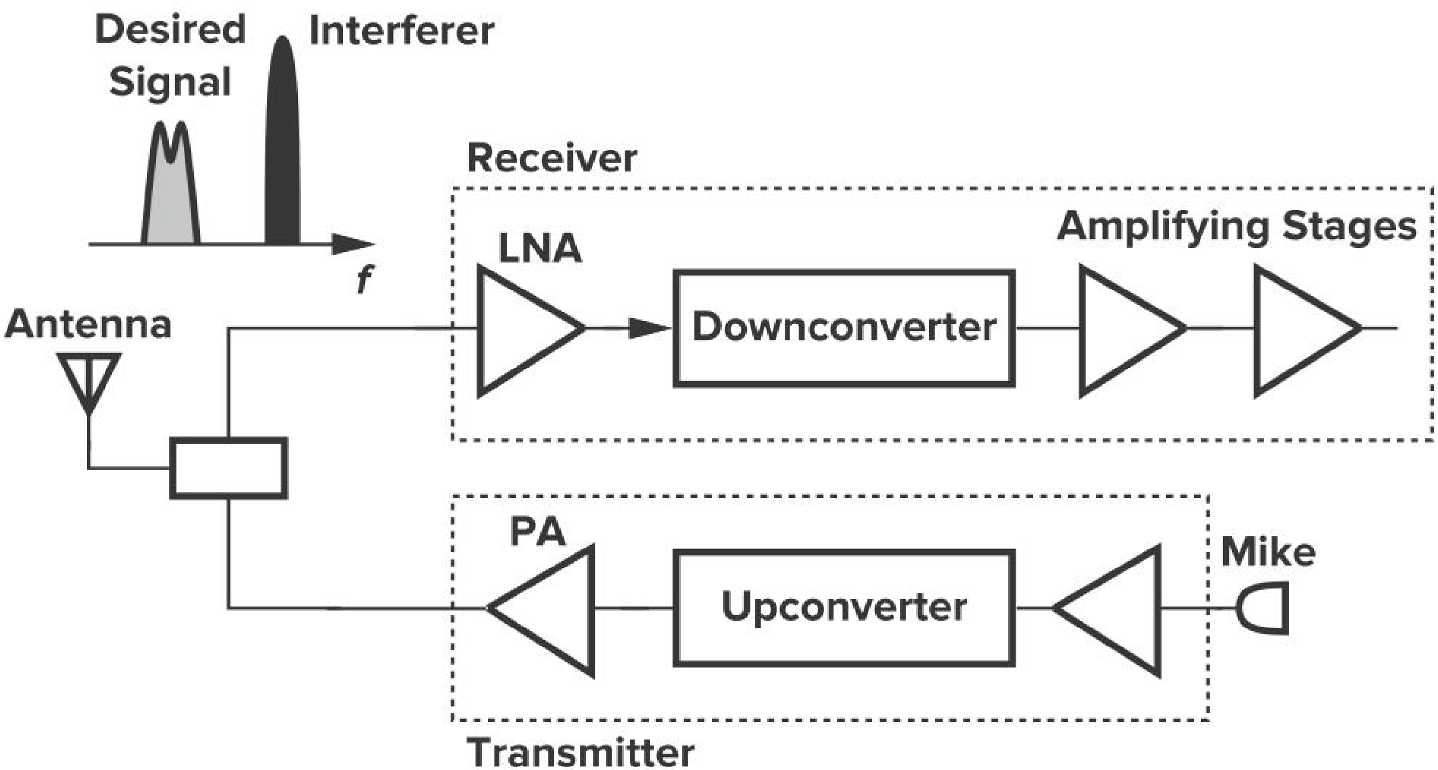
- 3.1 模拟电路设计基本概念
- 3.2 共源级放大器
- 3.3 共漏级放大器
- 3.4 共栅级放大器
- 3.5 共源共栅级放大器

放大器应用举例

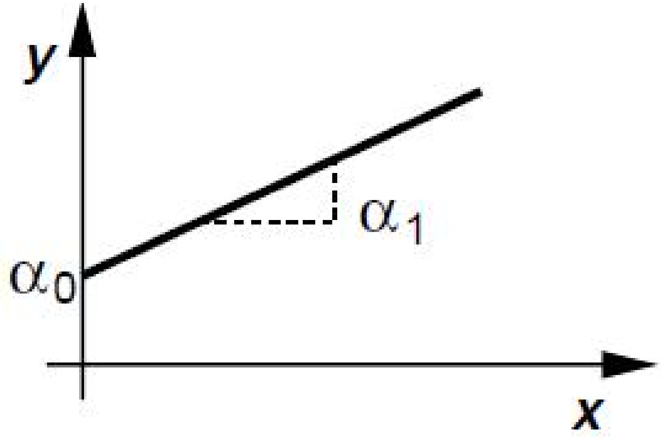
- 信号处理链路中几乎所有电路模块都包含不同性能的放大器：

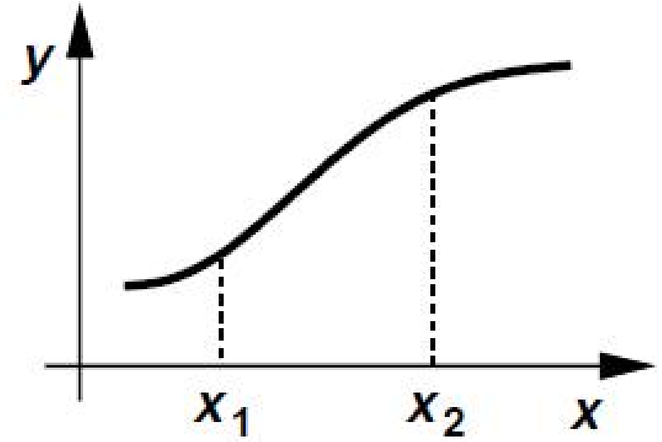


射频前端的放大器


Desired Signal
Interferer
f
Receiver
LNA
Amplifying Stages
Downconverter
Antenna
PA
Mike
Upconverter
Transmitter

理想vs非理想放大器





- 理想放大器

$$y(t) = \alpha_0 + \alpha_1 x(t)$$

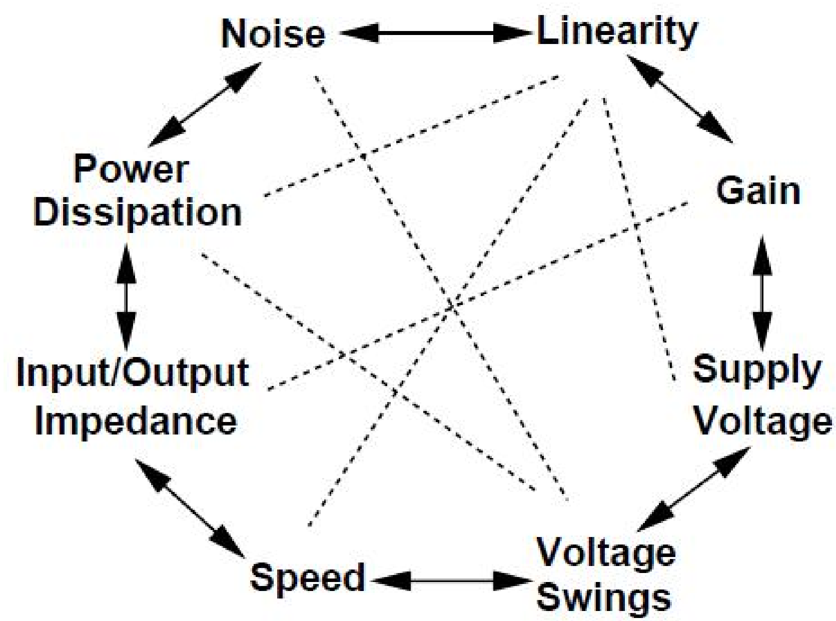
  - 大信号特性是一条直线
  - α_1表示“增益”，α_0表示“直流偏置”

- 非理想放大器

$$y(t) = \alpha_0 + \alpha_1 x(t) + \alpha_2 x^2(t) + \cdots + \alpha_n x^n(t)$$

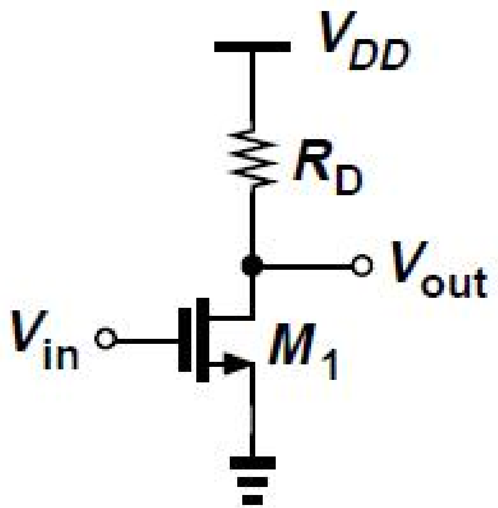
  - 信号幅度变大，偏置点受到很大扰动
  - 增益是变化的，导致信号失真

模拟设计的关键:Trade-off 折中



- 放大器的主要性能参数
  - 增益、速度（带宽）、功耗、电源电压、线性度、噪声、电压摆幅、输入/输出阻抗、面积
  - 参数之间互相牵制，导致设计变成一个多维优化问题
  - 没有最优的设计，只有最适合的设计，模拟设计追求的是高性价比

3. 2 共源级放大器

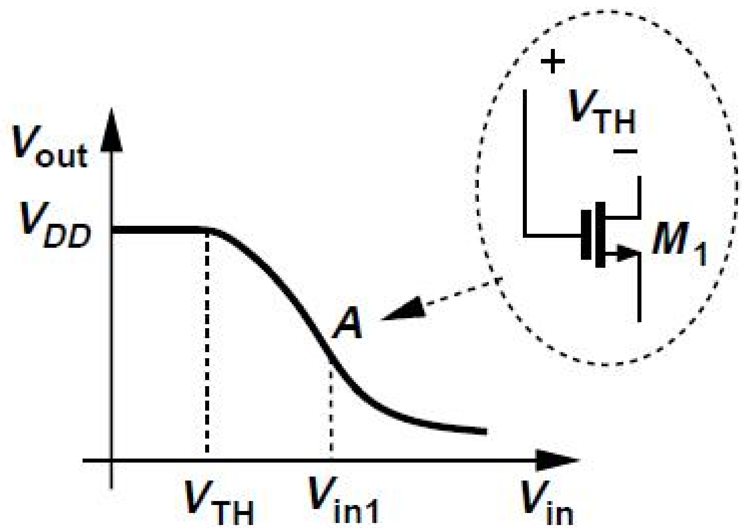


- 在低频时输入阻抗很高
- 当$V_{in} < V_{TH}$时，M_1截止

$$V_{out} = V_{DD}$$

- 当$V_{in} > V_{TH}$时, M_1导通后工作在饱和区

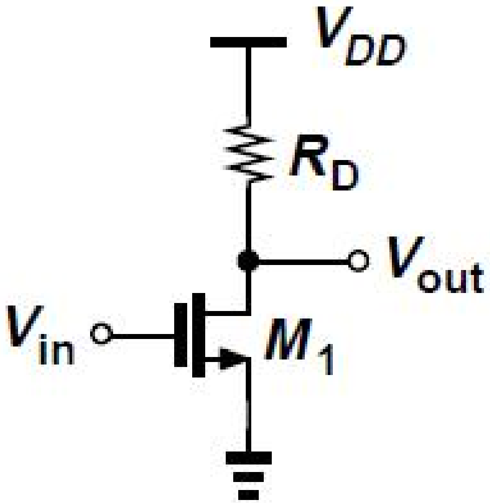
$$V_{out} = V_{DD} - R_D \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{in} - V_{TH})^2$$



- 当$V_{in} > V_{in1}$时, M_1进入线性区, $V_{out} = V_{in1} - V_{TH}$

$$V_{in1} - V_{TH} = V_{DD} - R_D \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{in1} - V_{TH})^2$$

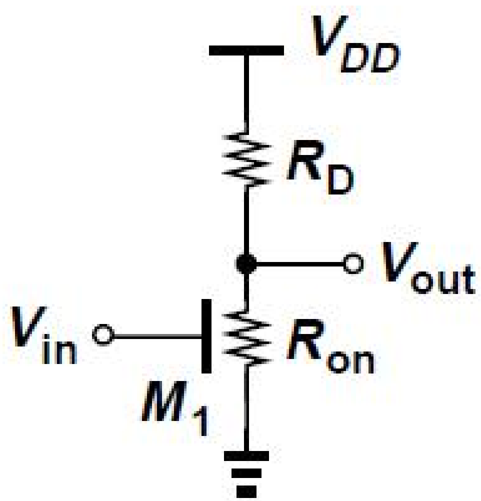
共源级放大器



- 当 V_{in} 足够高使得 $V_{out} << 2(V_{in} - V_{TH})$, M_1进入深线性区

$$V_{out} = V_{DD}\frac{R_{on}}{R_{on}+R_D}$$

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

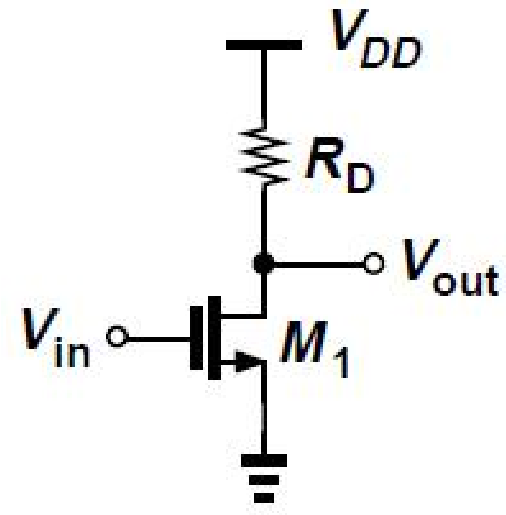


小信号增益

- 饱和区的小信号增益

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

$$A_v=\frac{\partial V_{out}}{\partial V_{in}}=-R_D\mu_nC_{ox}\frac{W}{L}(V_{in}-V_{TH})=-g_mR_D$$

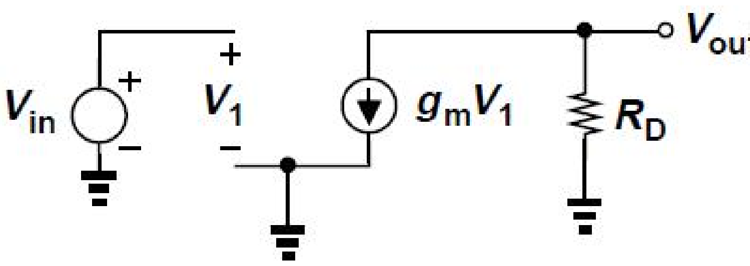


为何增益为负？

- 利用小信号模型可得到同样的结果

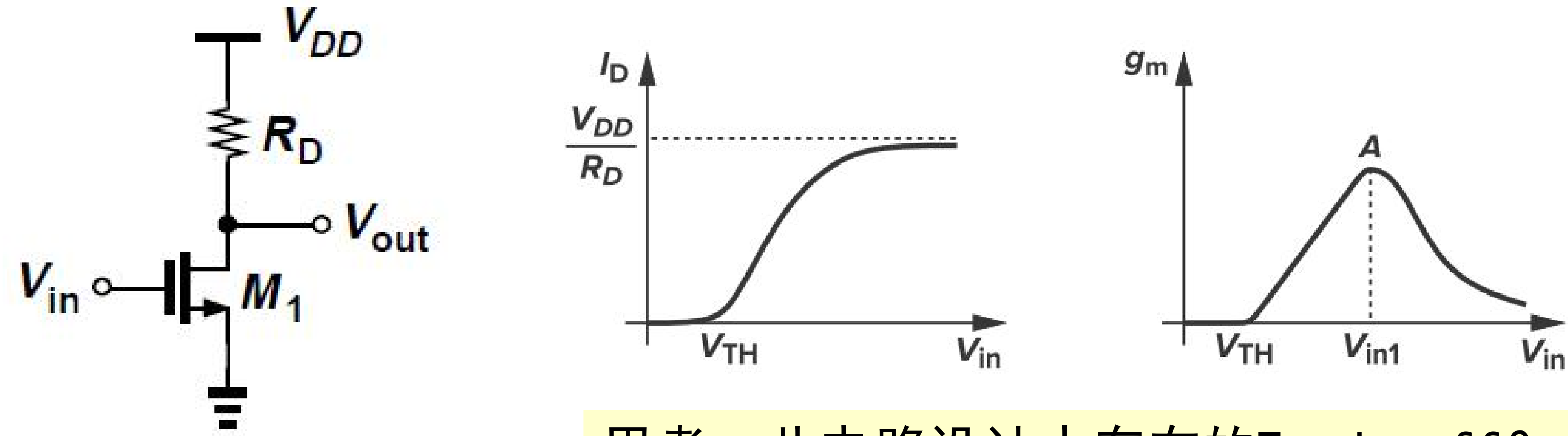
$$V_{out}=-g_mV_1R_D=-g_mV_{in}R_D$$

$$g_m=\mu_nC_{ox}(W/L)(V_{GS}-V_{TH})$$



跨导和增益均随着输入信号变化，导致非线性

例3.1 I_D和g_m随V_{in}的变化



思考：此电路设计中存在的Trade-off？

- 饱和区 $g_m = \mu_n C_{ox}(W/L)(V_{in} - V_{TH})$
- 线性区 $g_m = \mu_n C_{ox}(W/L)V_{DS}$

- 增益、输出摆幅、带宽之间的折中
- 注意静态工作点的设置，避免进入线性区

考虑沟道长度调制效应

- 从I-V特性考虑：

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

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

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

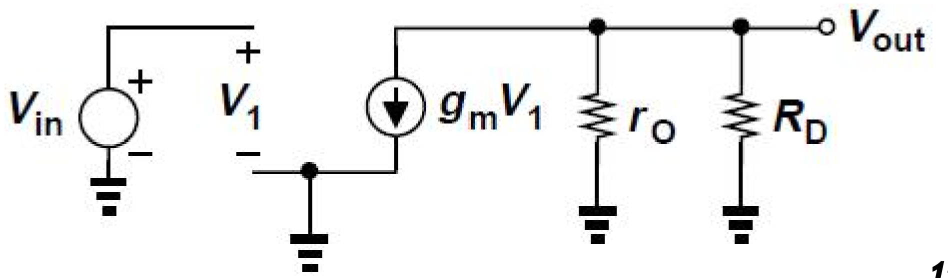
$$\Longrightarrow \quad A_v = -R_D g_m - \frac{R_D}{r_O}A_v \qquad (\, r_O = 1/(\lambda I_D)\,)$$

$$\Longrightarrow \quad A_v = -g_m \frac{r_O R_D}{r_O + R_D} = -g_m (r_O \| R_D)$$

沟道长度调制效应使增益减小！

- 从小信号模型：

更加简洁！

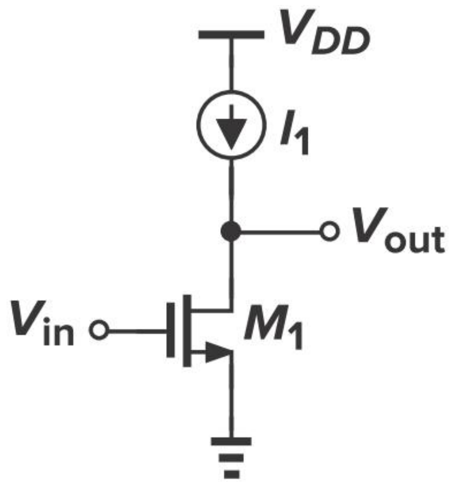


晶体管的本征增益

- R_D被替换为电流源 $(R_D = \infty)$

$$A_v = -g_m r_O$$

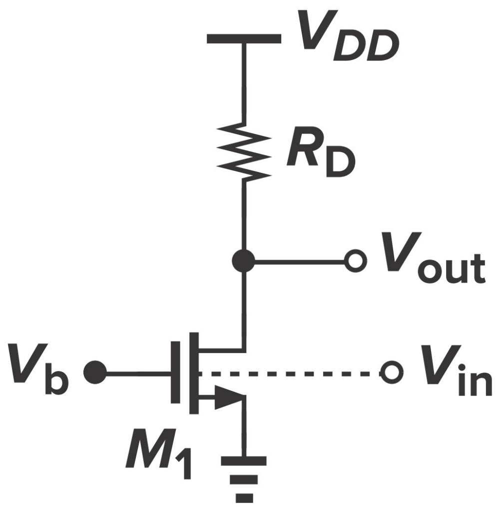
单个器件能够得到的最大电压增益。
亚微米工艺$g_m r_o$约几十~几百，
纳米工艺约几~几十。



- 电流、宽长比均相同，0.18μm/65nm本征增益仿真结果比较

Process	Id	W/L	Vgs	Vth	Gm	Ro	Intrinsic Gain
65nm	5μA	240n/240n（Lmin=60n）	448.2mV	347mV	53.72u	591.1k	30.04dB
180nm	5μA	720n/720n（Lmin=180n）	658.6mV	487.9mV	43.52u	2.51M	40.77dB

例3.4 衬底作为控制端，计算增益



$$\lambda = 0$$

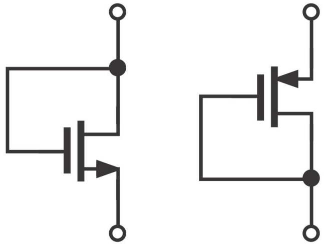
$$A_v = -g_{mb} R_D$$

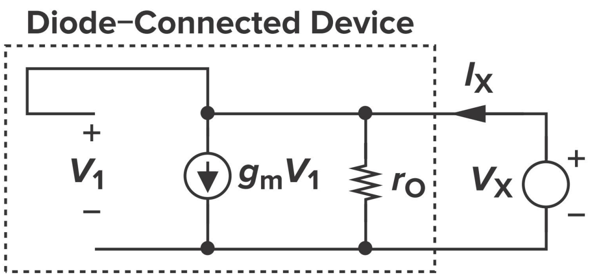
如果考虑沟道长度调制，
增益是多少？

二极管连接的MOSFET

- 二极管连接：MOS管的栅端和漏端短接，可以看成一个小信号电阻

总是工作在饱和区





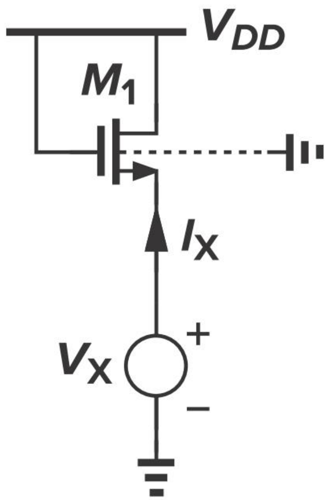
- 从小信号等效电路得到阻抗

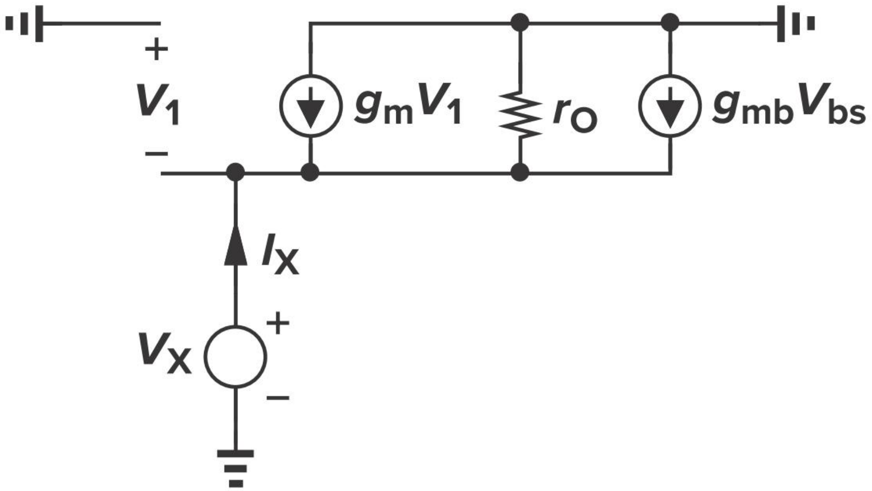
$$V_1 = V_X \qquad I_X = V_X/r_O + g_m V_X$$

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

二极管连接的MOSFET

- 考虑体效应





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

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

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

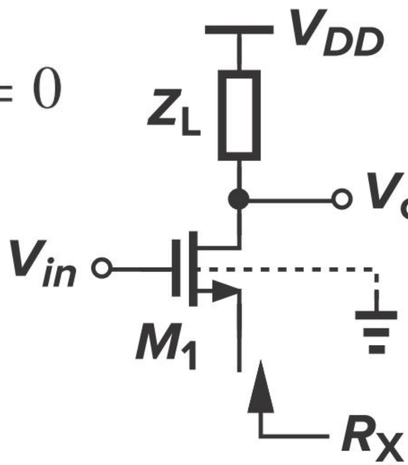
$$= \frac{1}{g_m + g_{mb}} \| r_O$$

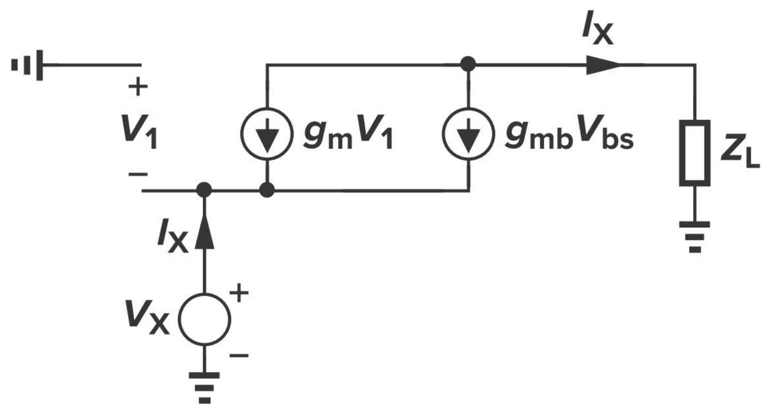
$$\approx \frac{1}{g_m + g_{mb}}$$

阻抗变小，
如何理解？

例3.5 计算从源极看到的阻抗

$\lambda = 0$





$$V_1 = -V_X$$

$$V_{bs} = -V_X$$

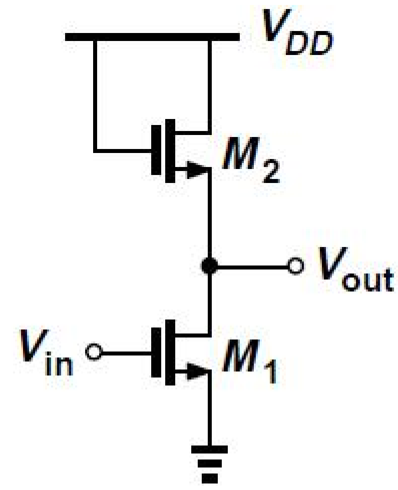
$$(g_m + g_{mb})V_X = I_X$$

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

- 与二极管连接区别在于漏端不是交流地
- $\lambda = 0$，结果一样 如何理解？
- 不考虑体效应，源到看进去的电阻为$1/g_m$

采用二极管连接的负载的共源级

- 直接使用电阻做负载的公式



$$A_v = -g_m R_D$$

$$A_v = -g_{m1} \frac{1}{g_{m2} + g_{mb2}}$$

$$= -\frac{g_{m1}}{g_{m2}} \frac{1}{1+\eta} \qquad (\eta = g_{mb2}/g_{m2})$$

- 展开g_{m1} and g_{m2}

$$A_v = -\frac{\sqrt{2\mu_n C_{ox}(W/L)_1 I_{D1}}}{\sqrt{2\mu_n C_{ox}(W/L)_2 I_{D2}}} \frac{1}{1+\eta} = -\sqrt{\frac{(W/L)_1}{(W/L)_2}} \frac{1}{1+\eta}$$

- 忽略η随输出电压的变化，则增益与偏置电压和电流无关，输入输出成线性关系

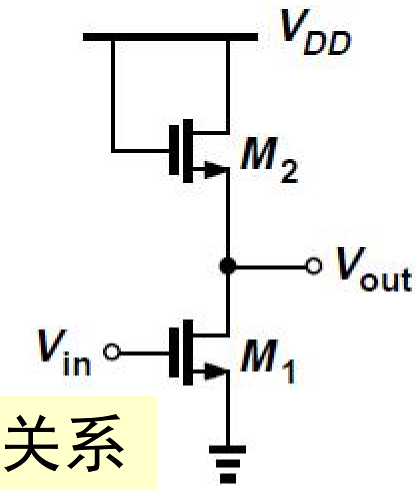
M1需要工作在饱和区

采用二极管连接的负载的共源级

- 大信号分析

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

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



线性关系

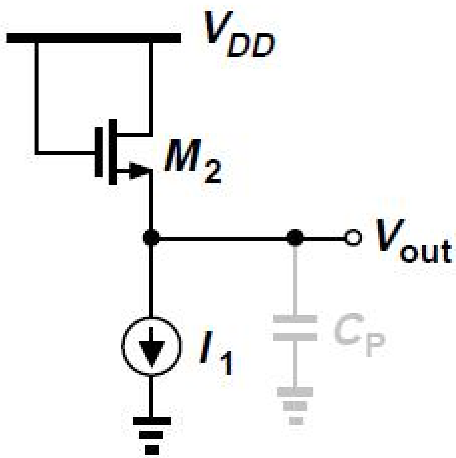
- 对V_{in}求微分

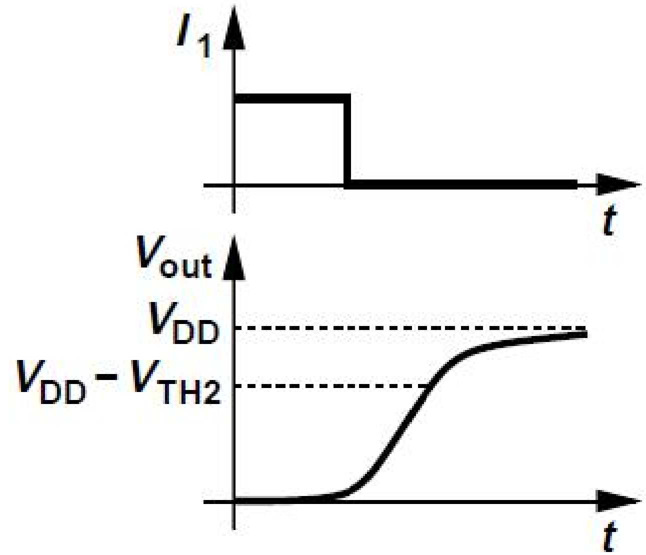
$$\sqrt{\left(\frac{W}{L}\right)_1}=\sqrt{\left(\frac{W}{L}\right)_2}\left(-\frac{\partial V_{out}}{\partial V_{in}}-\frac{\partial V_{TH2}}{\partial V_{in}}\right)$$

由 $\partial V_{TH2}/\partial V_{in}=(\partial V_{TH2}/\partial V_{out})(\partial V_{out}/\partial V_{in})=\eta(\partial V_{out}/\partial V_{in})$

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

采用二极管连接的负载的共源级



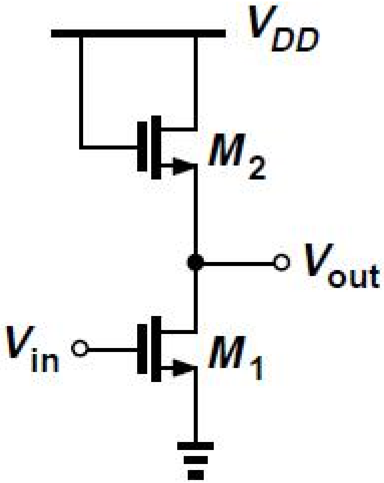


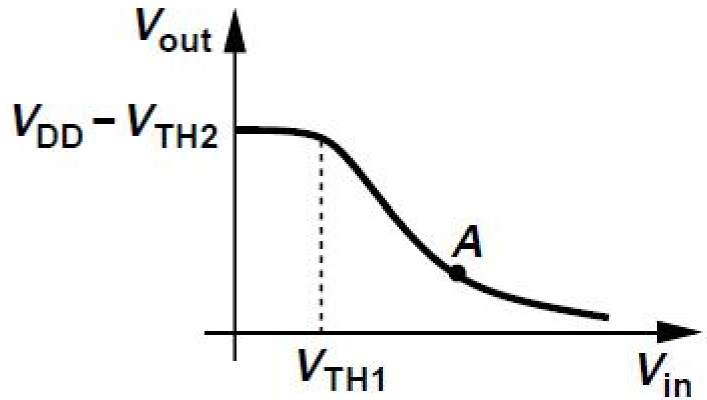
- 假如I_1下降到0，输出电压如何变化？

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

- 亚阈值导电，V_{out}最终为V_{DD}
- 假如电路工作在高频，在I_1较小的情况下下V_{out}在V_{DD}-V_{TH2}附近

直流工作点



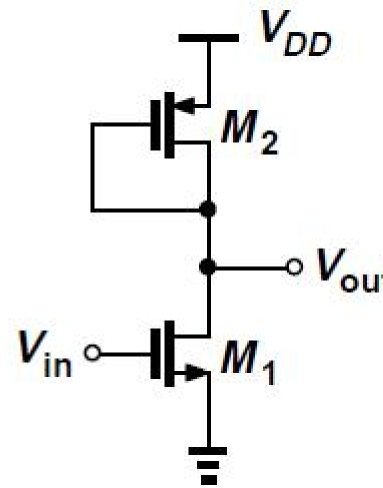


- 当 $V_{in} < V_{TH1}$, $V_{out} = V_{DD} - V_{TH2}$
- 当 $V_{in} > V_{TH1}$, V_{out} 近似沿直线变化
- 当$V_{in} > V_{out} + V_{TH1}$ (越过A点后), M_1 进入线性区，特性曲线呈现非线性

用PMOS作二极管连接

- 优点：无体效应
- 忽略沟道长度调制效应

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



很难
高增益

- 增益是器件宽长比的弱函数
- 提高增益需要“强”的输入器件和“弱”的负载器件

$$\mu_n \left(\frac{W}{L}\right)_1 (V_{GS1} - V_{TH1})^2 = \mu_p \left(\frac{W}{L}\right)_2 (V_{GS2} - V_{TH2})^2$$

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

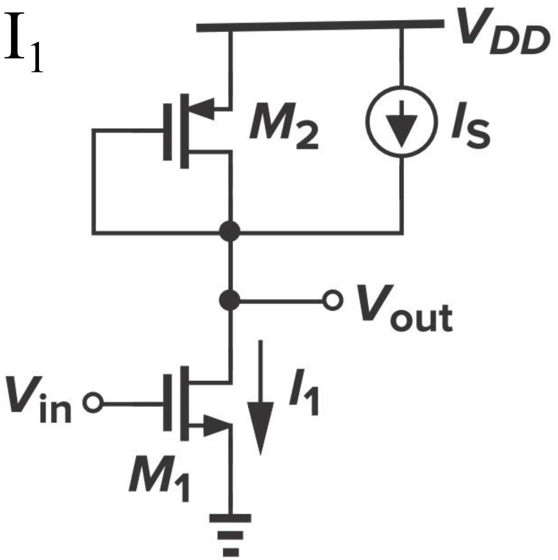
$$|A_v| = \frac{g_{m1}}{g_{m2}} = \frac{\mu_n C_{ox} (W/L)_1 (V_{GS1} - V_{TH1})}{\mu_p C_{ox} (W/L)_2 |V_{GS2} - V_{TH2}|}$$

如何理解？

例 3.6

- M_1偏置在饱和区，漏电流为I_1，$I_S=0.75I_1$

求增益？



$$|I_{D2}| = I_1/4$$

$$A_v = -\frac{g_{m1}}{g_{m2}} = -\sqrt{\frac{4\mu_n(W/L)_1}{\mu_p(W/L)_2}}$$

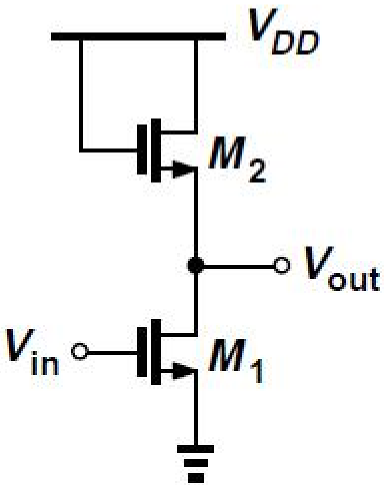
又因为：

$$\mu_n\left(\frac{W}{L}\right)_1(V_{GS1}-V_{TH1})^2 = 4\mu_p\left(\frac{W}{L}\right)_2(V_{GS2}-V_{TH2})^2$$

$$\frac{|V_{GS2}-V_{TH2}|}{V_{GS1}-V_{TH1}} = \frac{A_v}{4}$$

相同增益下过驱动电压减小4倍

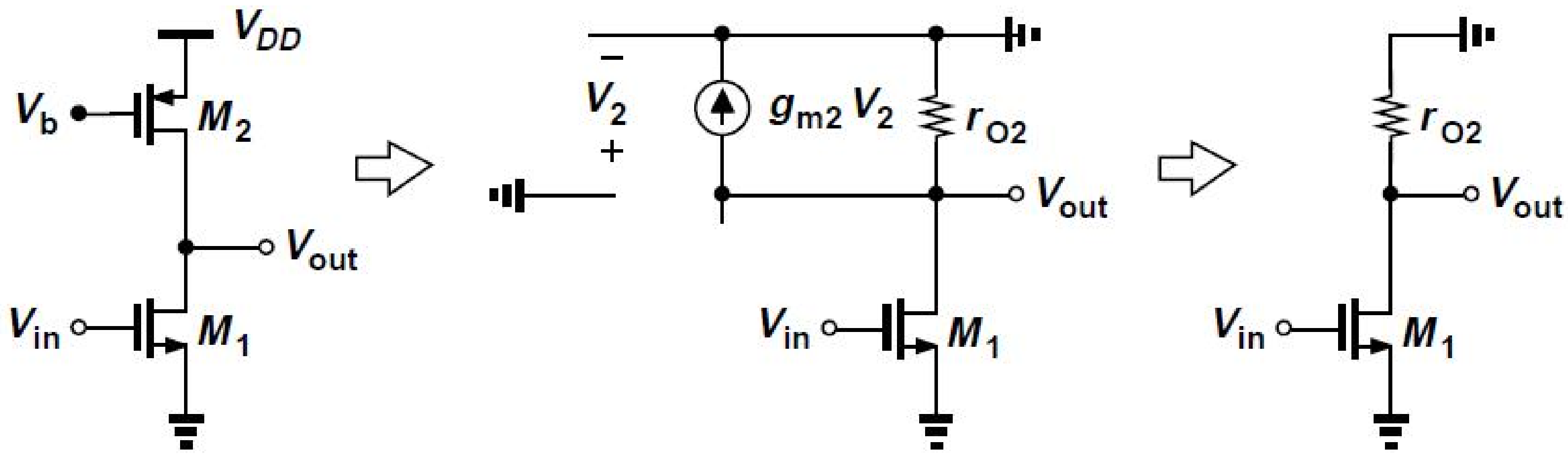
考虑沟道长度调制效应



$$A_v = -g_{m1}\left(\frac{1}{g_{m2}} \| r_{O1} \| r_{O2}\right)$$

采用电流源做负载的共源级

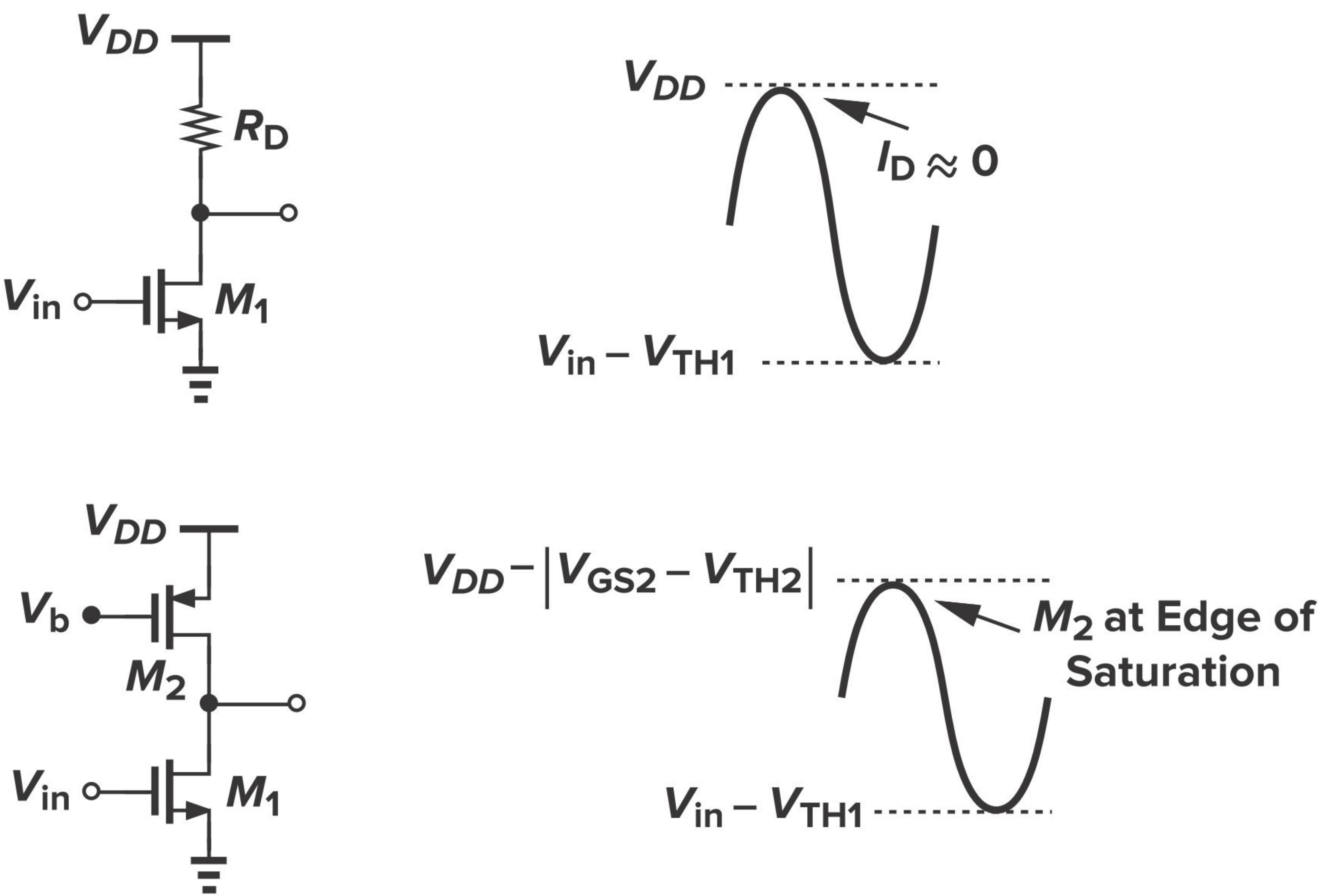
- 前面两种电路均存在增益和输出电压摆幅的折中
- 用电流源做负载,可以实现高阻但不影响输出摆幅



- 增益: $A_v = -g_{m1}(r_{O1} \| r_{O2})$
- 输出摆幅: $V_{in}-V_{TH1}<V_{out}<V_{DD}-|V_{GS2}-V_{TH2}|$
- 输出电压不易确定
- 本征增益 $g_{m1}r_{O1} = \sqrt{2\left(\frac{W}{L}\right)_1 \mu_n C_{ox} I_D}\frac{1}{\lambda I_D}$

如何增大摆幅和增益?

电阻和电流源负载最大摆幅的比较



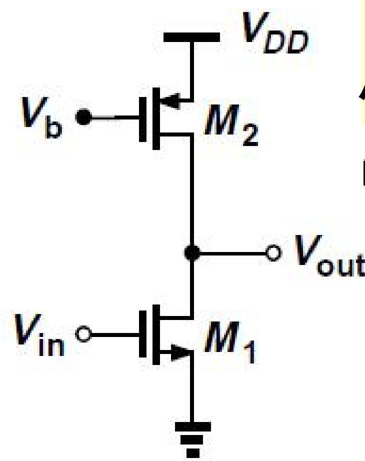
有源负载的共源级

- 能否让M_2也起到放大作用？
- Inverter-based amplifier
- 增益：

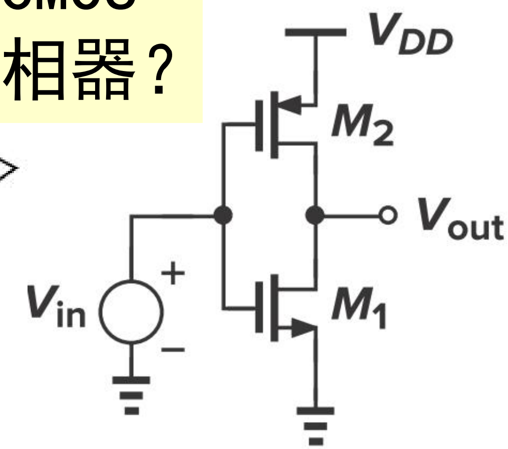
$$A_v = -(g_{m1} + g_{m2})(r_{O1}||r_{O2})$$

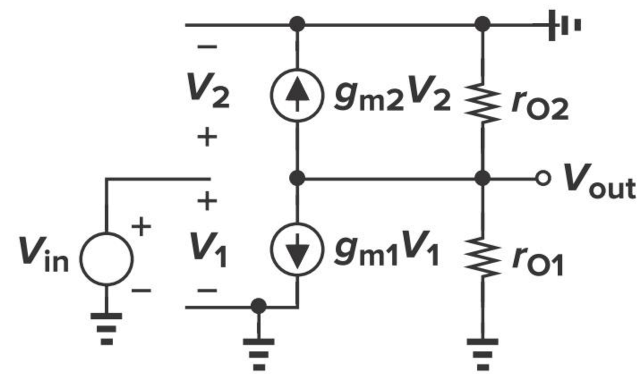
更高的跨导

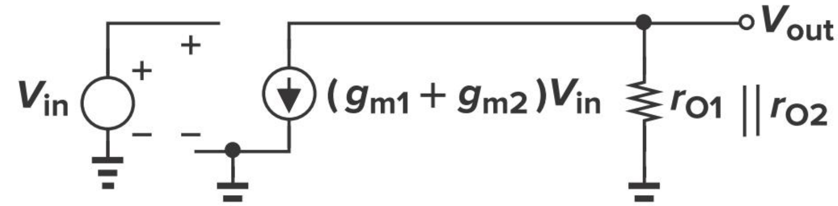
- 缺点：
  - 偏置电流非常易受PVT的影响
  - 对电源噪声敏感
  - 输入信号范围很窄



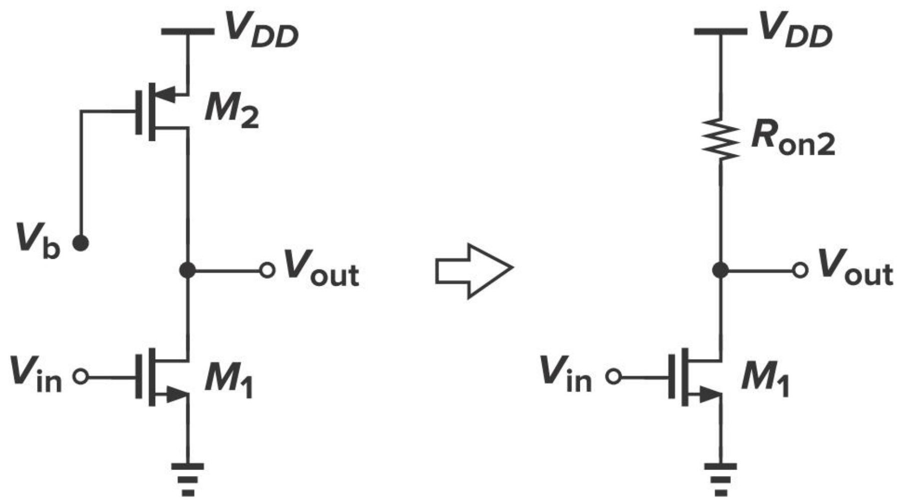
CMOS 反相器？







线性区MOS做负载



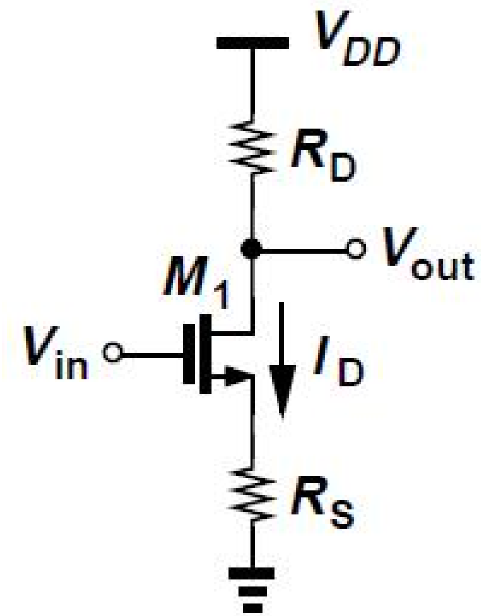
- 深线性区的MOS管可以看作是一个电阻

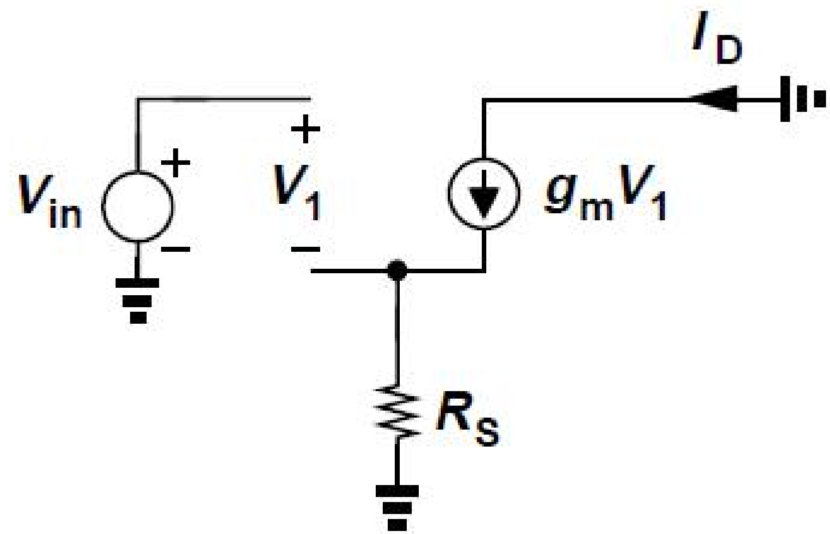
$$R_{on2} = \frac{1}{\mu_p C_{ox}(W/L)_2(V_{DD} - V_b - |V_{THP}|)}$$

- PVT影响显著；V_b很难精确产生
- 优点：消耗的电压余度小于二极管连接的负载

带源极负反馈的共源级

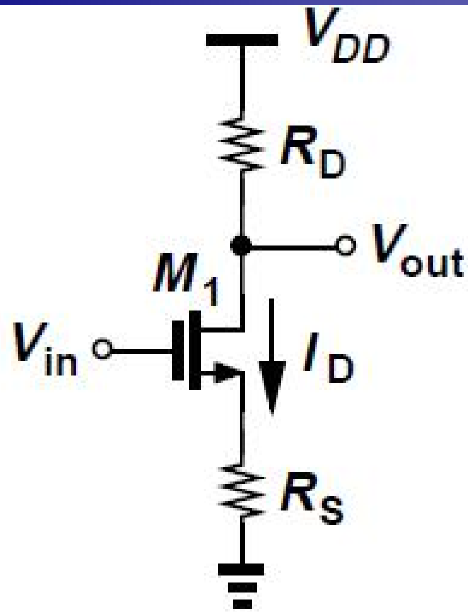
- 如何从g_m入手改善非线性？

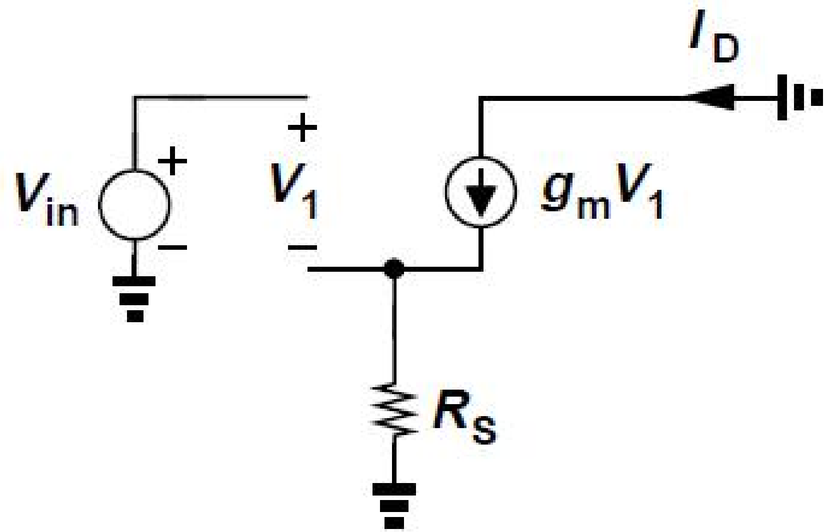




- V_{in}增加 ⇨ I_D增加 ⇨ R_S压降增加
- 输入电压的一部分降落在电阻R_S上，而不是完全变成栅源的过驱动电压

带源极负反馈的共源级





- 定义电路的等效跨导 $G_m = \partial I_D / \partial V_{in} = \dfrac{\partial I_D}{\partial V_{GS}} \dfrac{\partial V_{GS}}{\partial V_{in}}$

$$V_{GS} = V_{in} - I_D R_S$$

$$\Rightarrow \partial V_{GS} / \partial V_{in} = 1 - R_S \partial I_D / \partial V_{in}$$

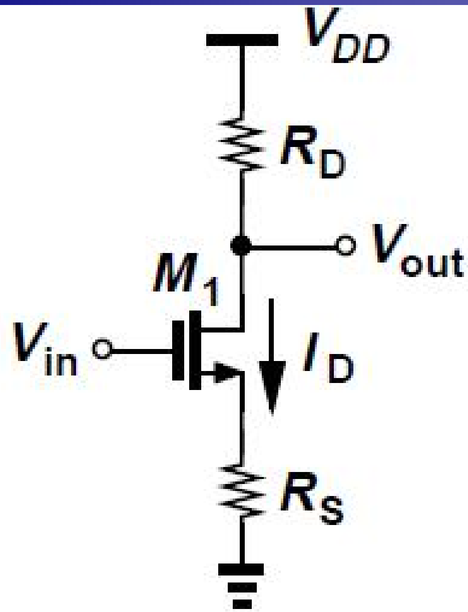
$$\Rightarrow G_m = g_m \left(1 - R_S \frac{\partial I_D}{\partial V_{in}} \right)$$

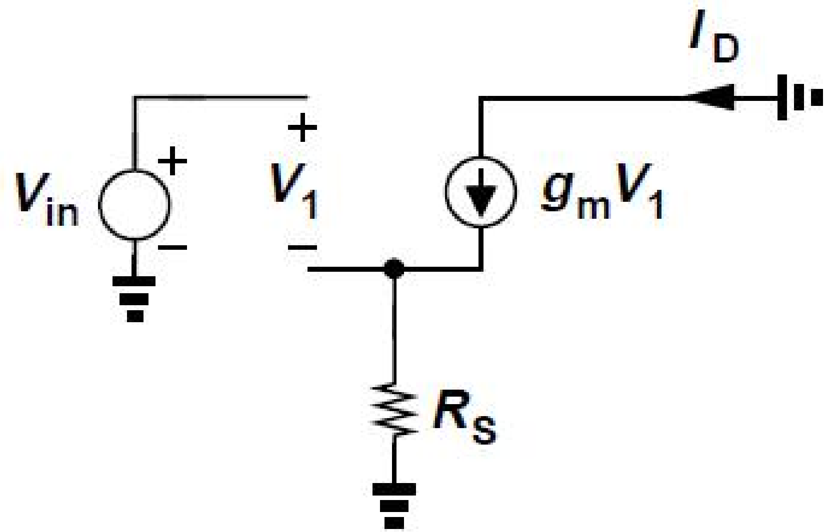
$$\Rightarrow G_m = \frac{g_m}{1 + g_m R_S}$$

$$A_v = -G_m R_D$$

$$\Rightarrow \quad = \frac{-g_m R_D}{1 + g_m R_S}$$

带源极负反馈的共源级





- 小信号模型

$$V_{in} = V_1 + I_D R_S$$
$$I_D = g_m V_1$$
$$\Rightarrow \quad I_D = \frac{g_m}{1 + g_m R_S} V_{in}$$

- 假如 $R_S \gg 1/g_m$

V_{in}的变化基本都加在R_S上

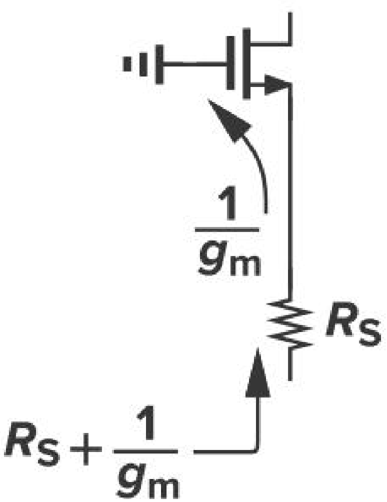
$$G_m = \frac{g_m}{1 + g_m R_S} \approx 1/R_S$$

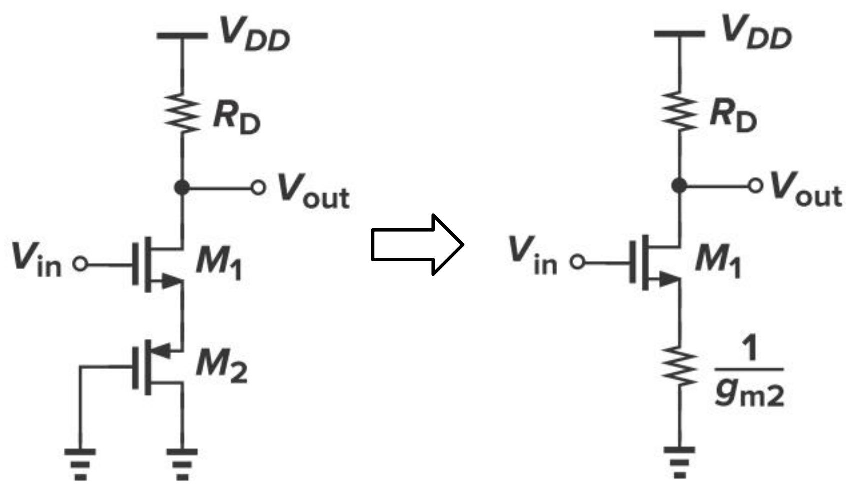
以牺牲增益为代价

增益的简便算法

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

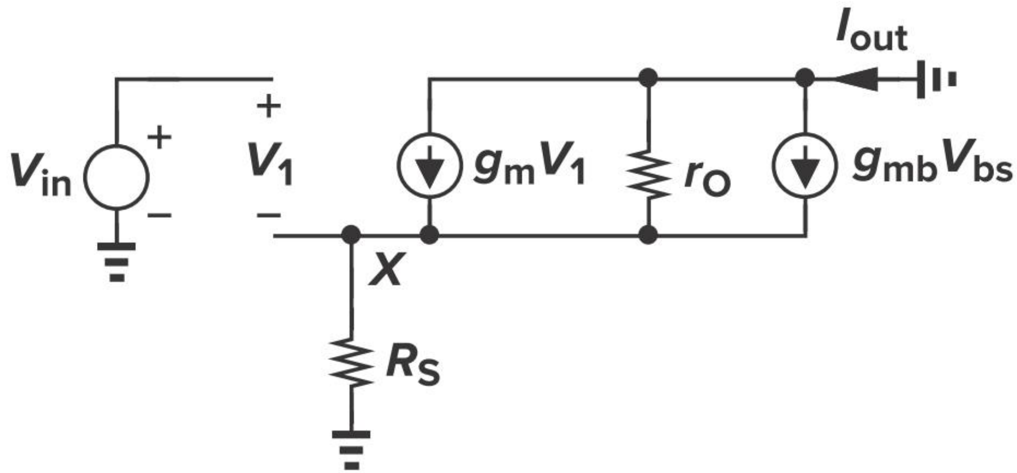
$$\frac{\text{漏极通路上看到的电阻}}{\text{源极通路上看到的电阻}}$$





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

考虑体效应和沟道长度调制效应

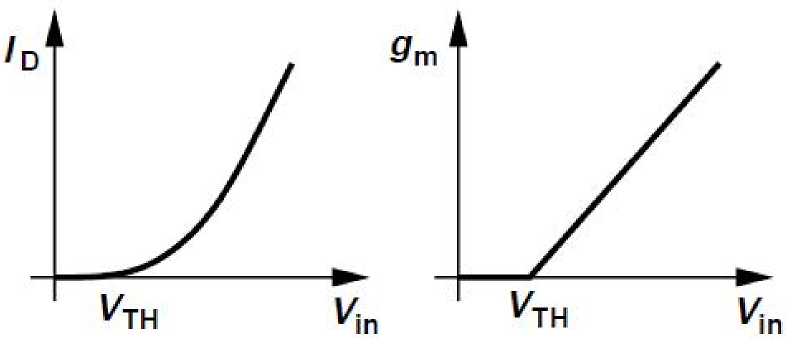


$$I_{out} = g_m V_1 - g_{mb} V_X - \frac{I_{out} R_S}{r_O}$$

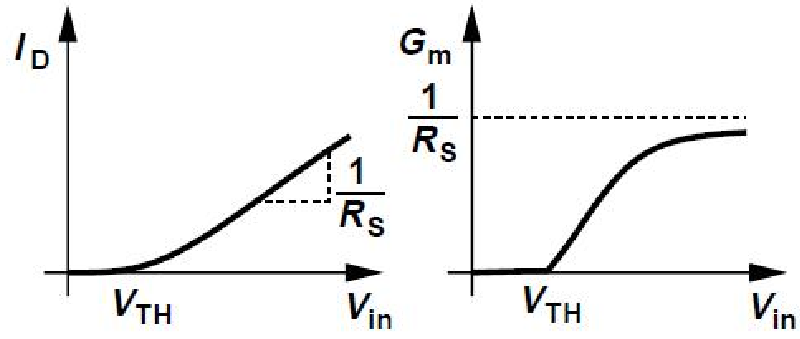
$$= g_m(V_{in} - I_{out} R_S) + g_{mb}(-I_{out} R_S) - \frac{I_{out} R_S}{r_O}$$

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

大信号特性



R_S=0



R_S≠0

- I_D和g_m随V_{in}变化

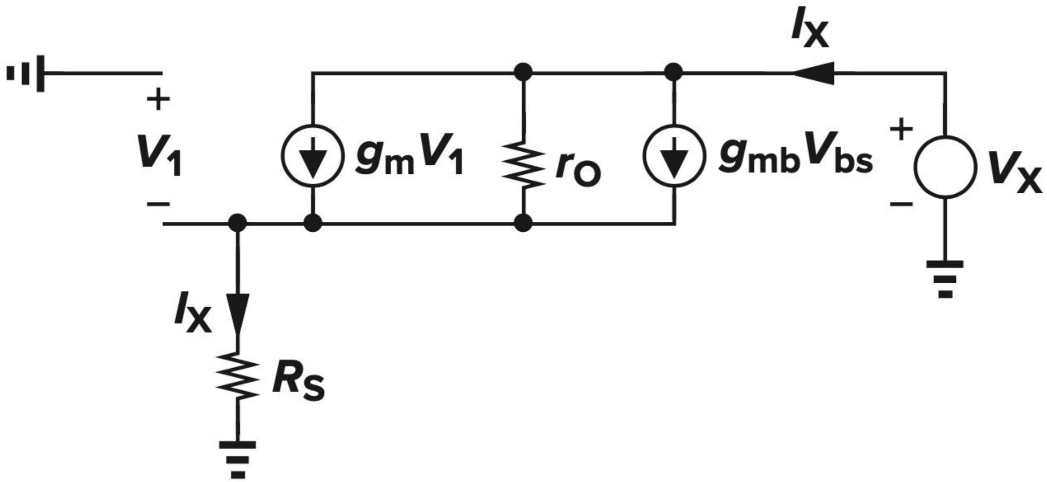
- 小电流时，$1/g_m \gg R_S$

$$G_m \approx g_m$$

- 随着输入增加，$1+g_mR_S$ 变得更显著，

$$G_m \approx 1/R_S$$

输出阻抗



暂时
不考虑R_D

- 考虑沟道长度调制效应和体效应

$$V_1 = -I_X R_S$$

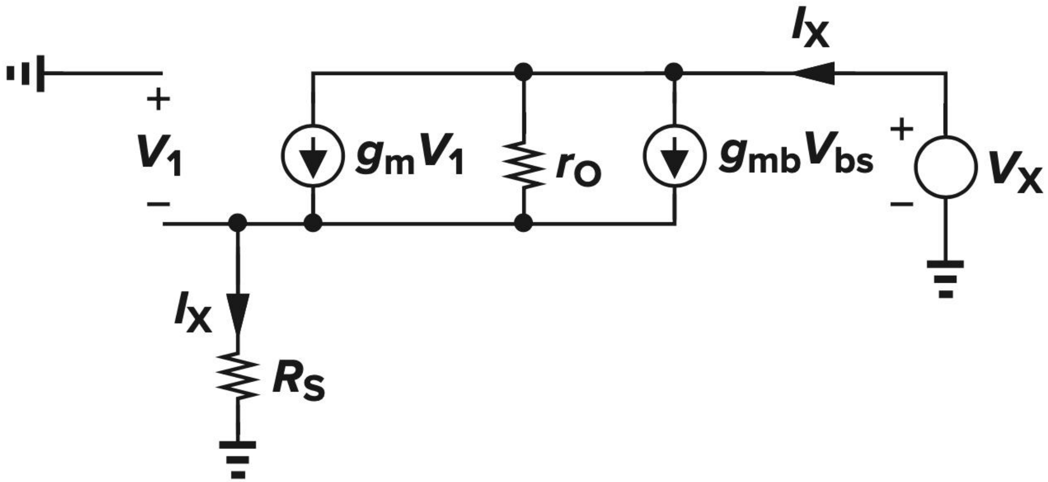
$$\Rightarrow \quad I_X - (g_m + g_{mb})V_1 = I_X + (g_m + g_{mb})R_S I_X$$

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

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

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

输出阻抗



暂时
不考虑R_D

- 考虑沟道长度调制效应和体效应

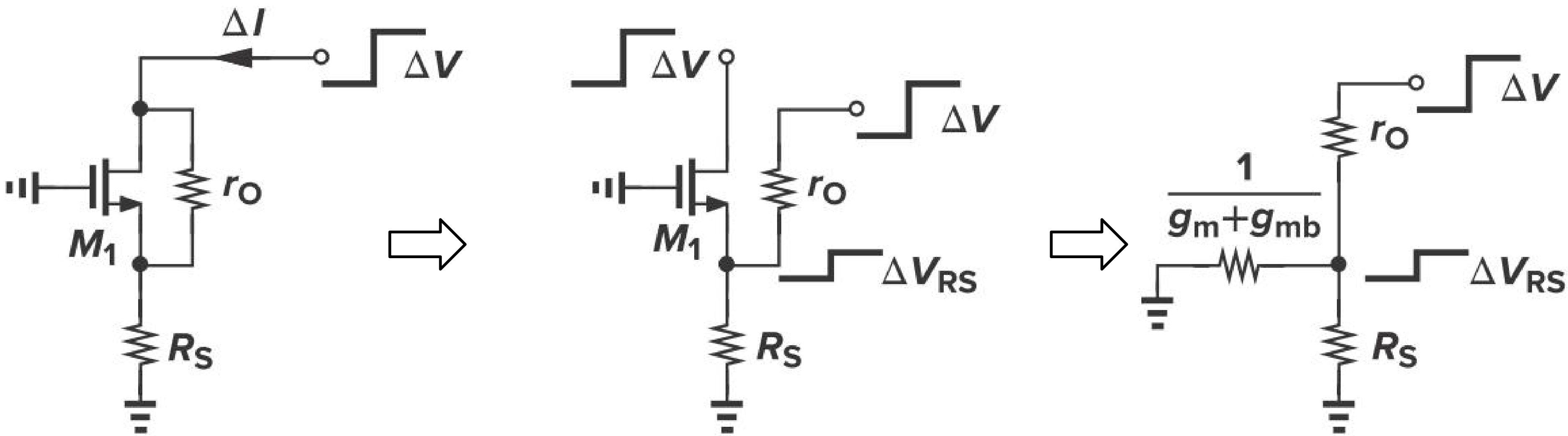
$$R_{out} = [1 + (g_m + g_{mb})r_O]R_S + r_O$$

- 假如 $(g_m + g_{mb})r_O \gg 1$

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

如何直观
理解？

直观理解输出阻抗

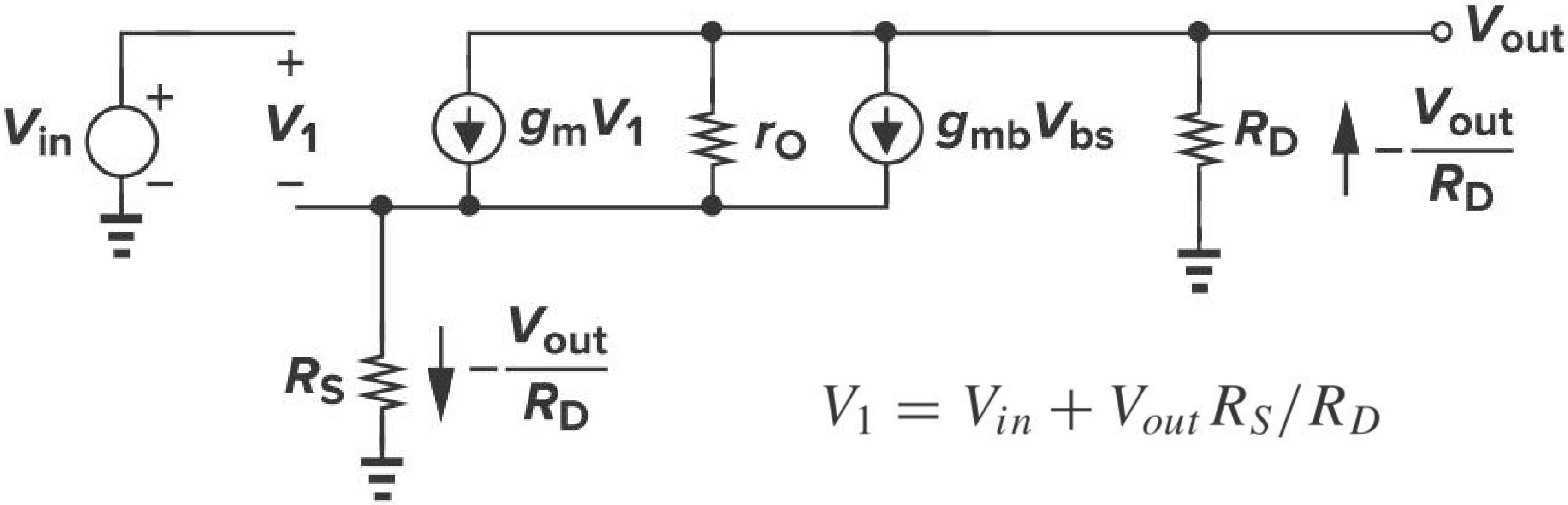


$$\Delta V_{RS} = \Delta V \frac{\frac{1}{g_m + g_{mb}} \| R_S}{\frac{1}{g_m + g_{mb}} \| R_S + r_O}$$

$$\Rightarrow \quad \Delta I = \frac{\Delta V_{RS}}{R_S} = \Delta V \frac{1}{[1 + (g_m + g_{mb})] R_S r_O + R_S}$$

$$\Rightarrow \quad \frac{\Delta V}{\Delta I} = [1 + (g_m + g_{mb}) R_S] r_O + R_S$$

小信号增益



$$V_1 = V_{in} + V_{out} R_S / R_D$$

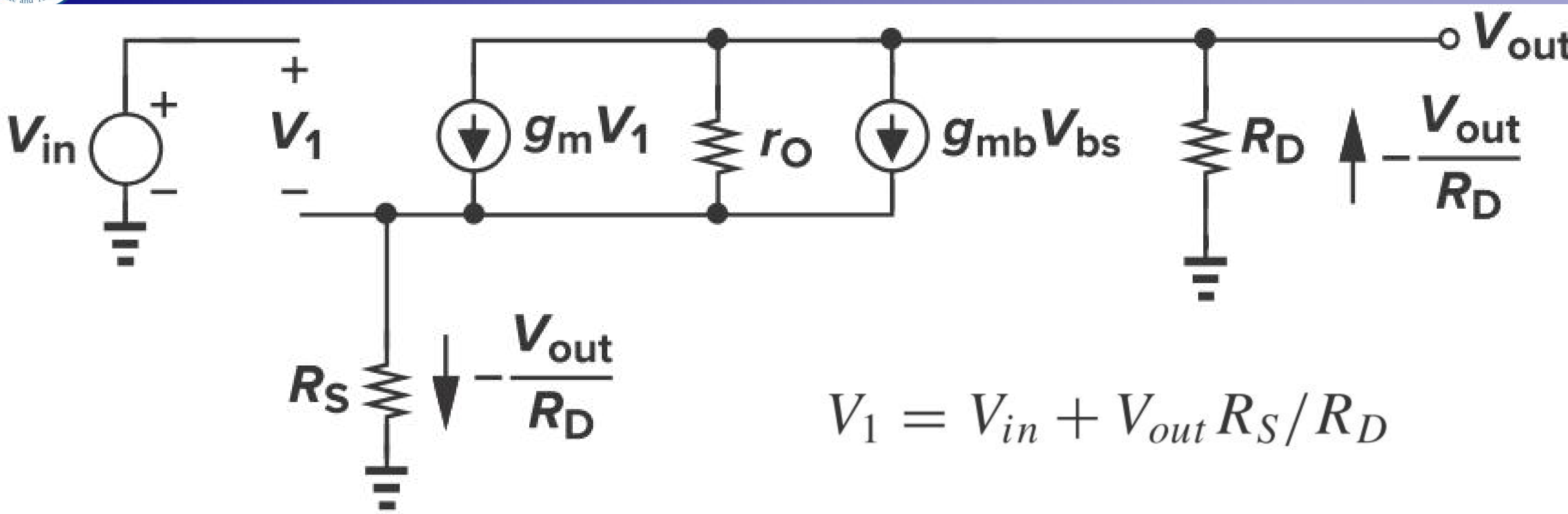
$$I_{ro} = -\frac{V_{out}}{R_D} - (g_m V_1 + g_{mb} V_{bs})$$

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

$$V_{out} = I_{ro} r_O - \frac{V_{out}}{R_D} R_S$$

$$= -\frac{V_{out}}{R_D} r_O - \left[g_m \left(V_{in} + V_{out} \frac{R_S}{R_D} \right) + g_{mb} V_{out} \frac{R_S}{R_D} \right] r_O - V_{out} \frac{R_S}{R_D}$$

小信号增益



$$V_1 = V_{in} + V_{out} R_S / R_D$$

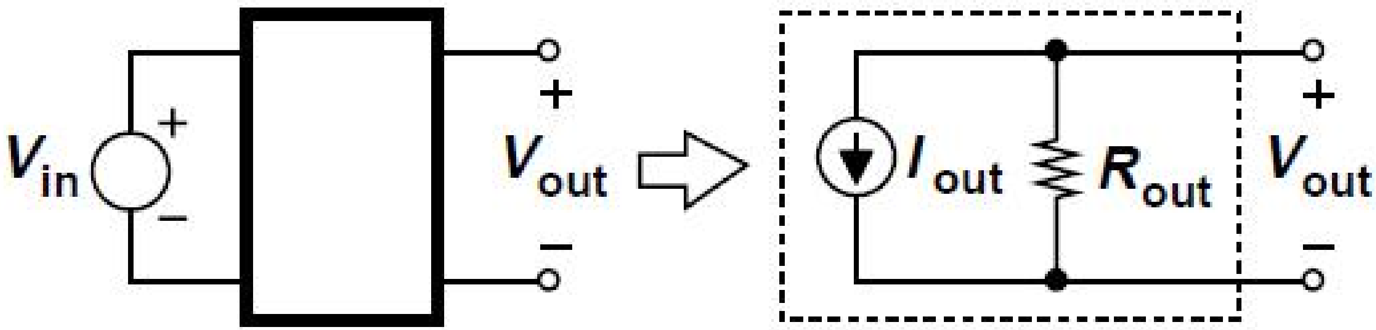
$$\frac{V_{out}}{V_{in}} = \frac{-g_m r_O R_D}{R_D + R_S + r_O + (g_m + g_{mb}) R_S r_O}$$

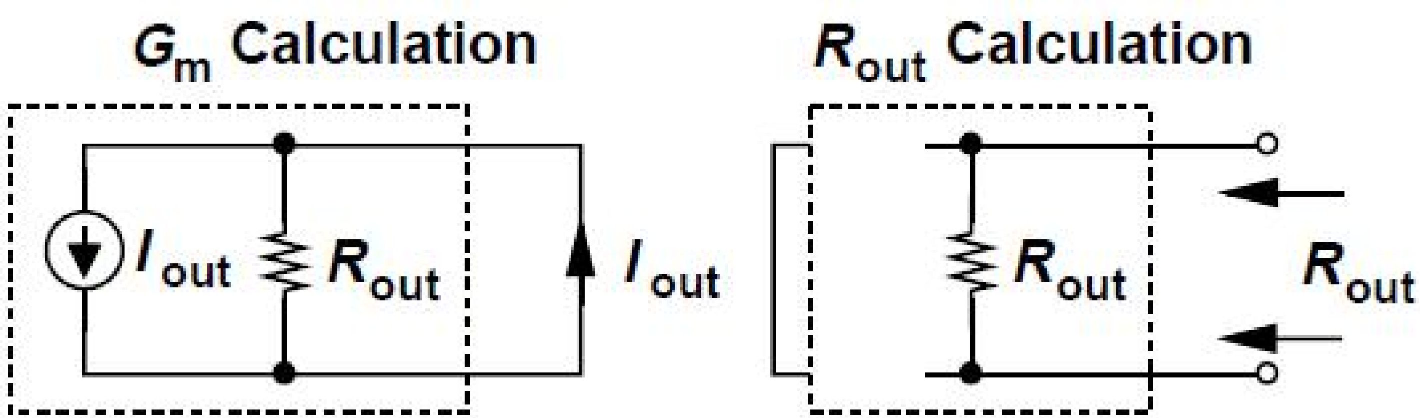
$$A_v = \frac{-g_m r_O R_D [R_S + r_O + (g_m + g_{mb}) R_S r_O]}{R_D + R_S + r_O + (g_m + g_{mb}) R_S r_O} \cdot \frac{1}{R_S + r_O + (g_m + g_{mb}) R_S r_O}$$

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

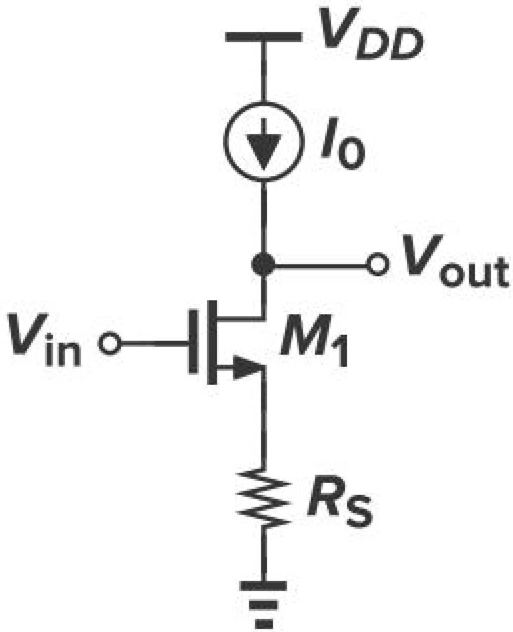
等效定理

- 在一个线性电路，输出增益等于$-G_m R_{out}$
  - G_m 表示输出短接到地的跨导 I_{out}/V_{in}
  - R_{out} 表示输入电压为0时的输出阻抗





例3.11 计算增益



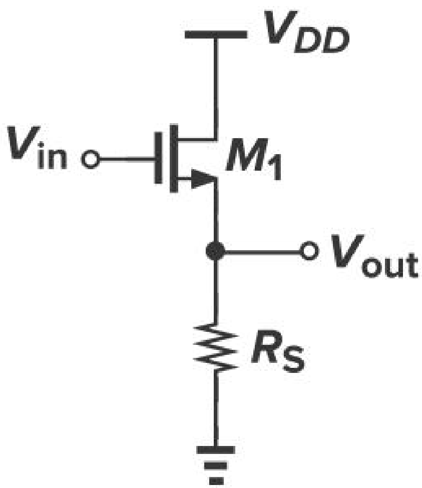
Rs电流不变，
小信号压降为0

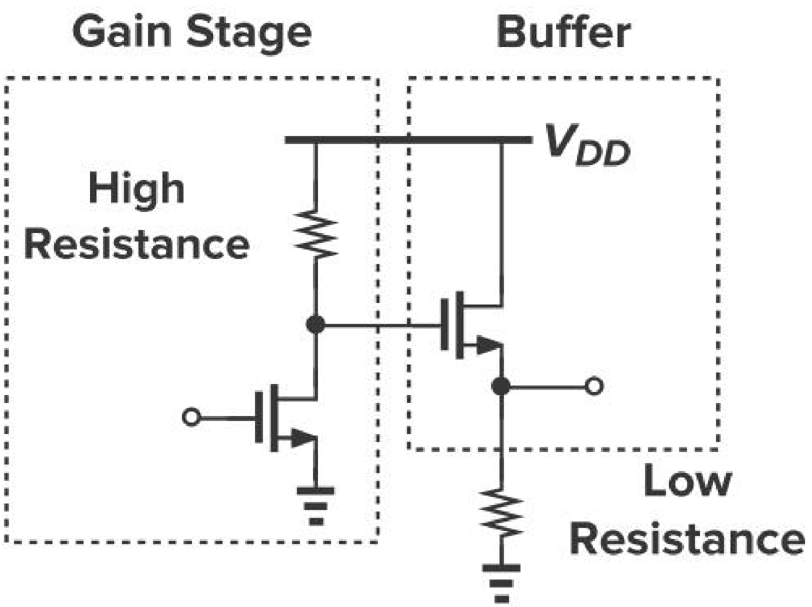
小信号电流
去哪了？

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

3.3 源跟随器

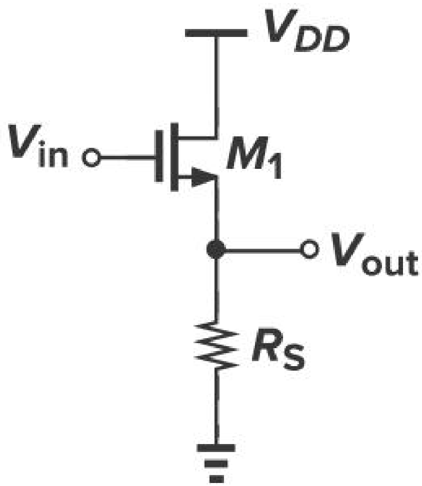
- 如何在不降低增益的情况下，驱动低阻抗负载？

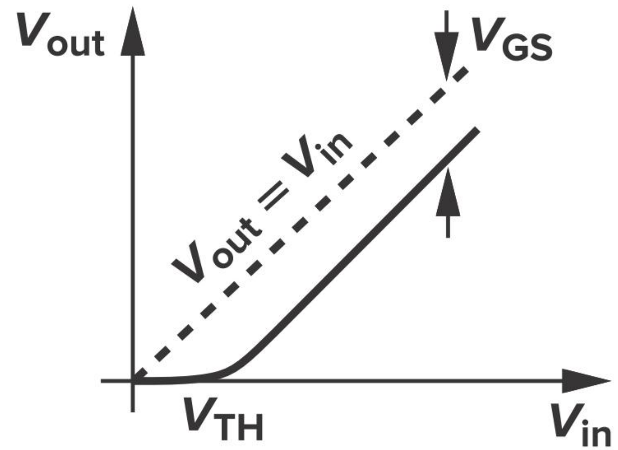




- 起到电压缓冲器(Voltage buffer)的作用
- 高输入阻抗，低输出阻抗，输出跟随输入

大信号特性

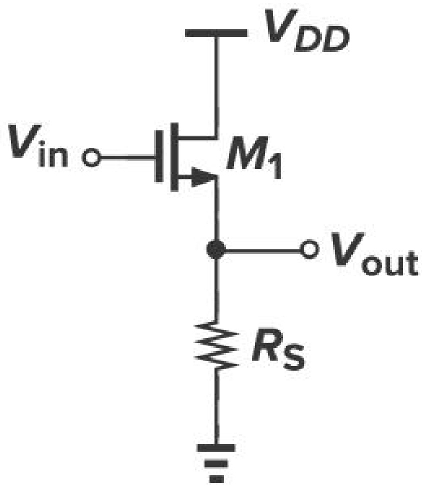


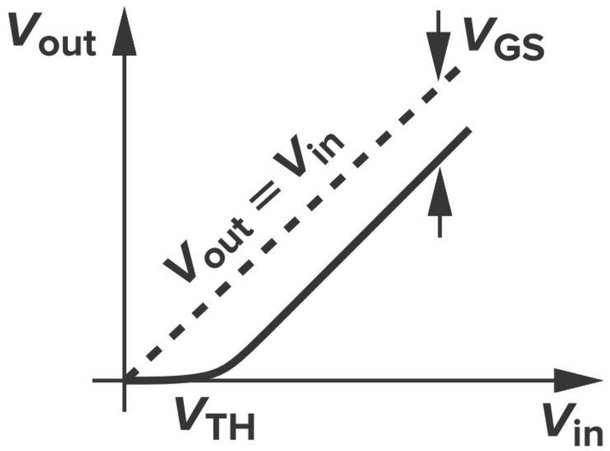


- 当$V_{in} < V_{TH}$, M_1 截止，$V_{out} = 0$
- 当V_{in}超过V_{TH}, M_1 开始进入饱和区，V_{out} 跟随输入电压变化，压差保持为V_{GS}
- 输入-输出特性可以表示为 （不考虑沟道长度调制效应）

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

小信号特性





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

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

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

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

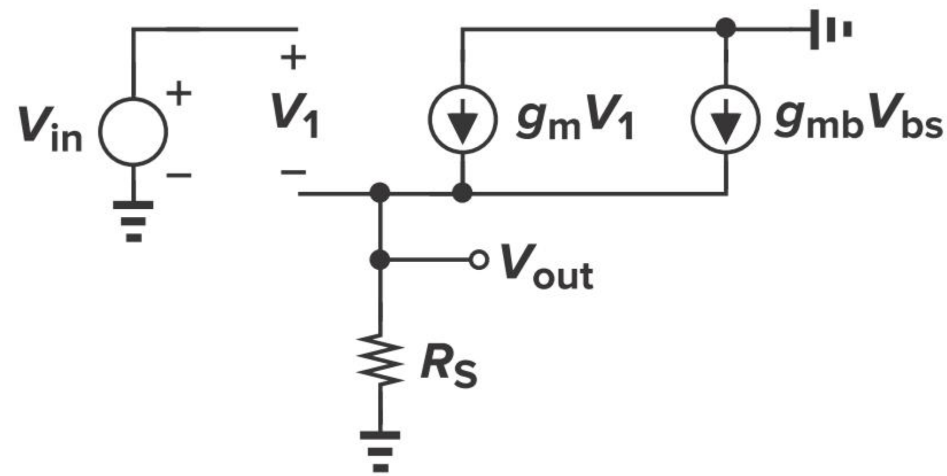
小信号特性

- 小信号模型

$$V_{in} - V_1 = V_{out}$$

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

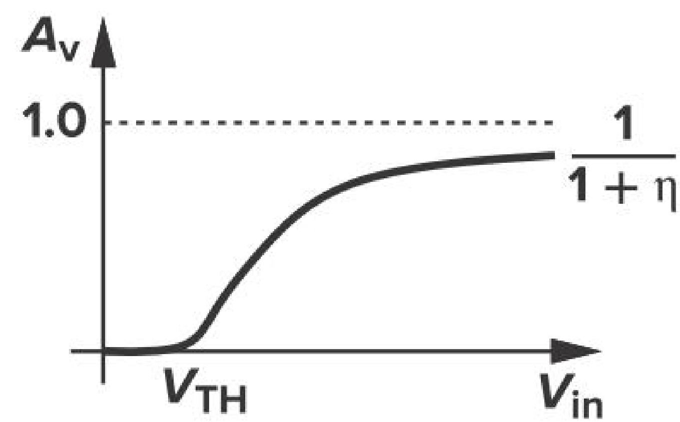
$$g_m V_1 - g_{mb} V_{out} = V_{out}/R_S$$



$$\Rightarrow \quad V_{out}/V_{in} = g_m R_S/[1+(g_m+g_{mb})R_S]$$

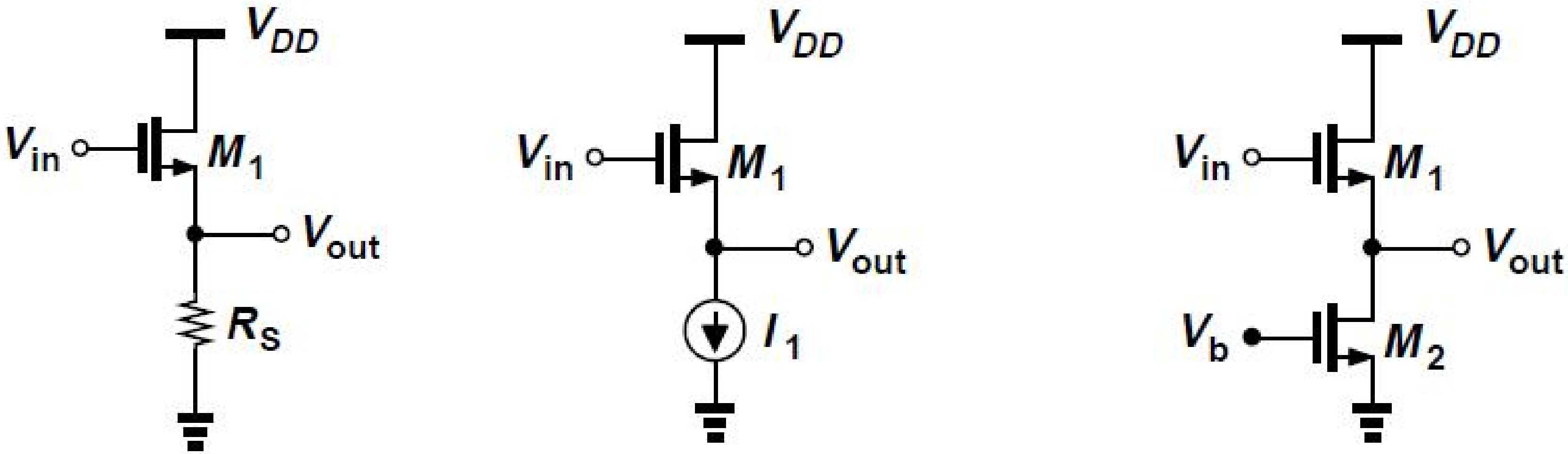
- 增益随着V_{in}增大而增大，但是总小于1，最终趋近于

$$g_m/(g_m+g_{mb}) = 1/(1+\eta)$$



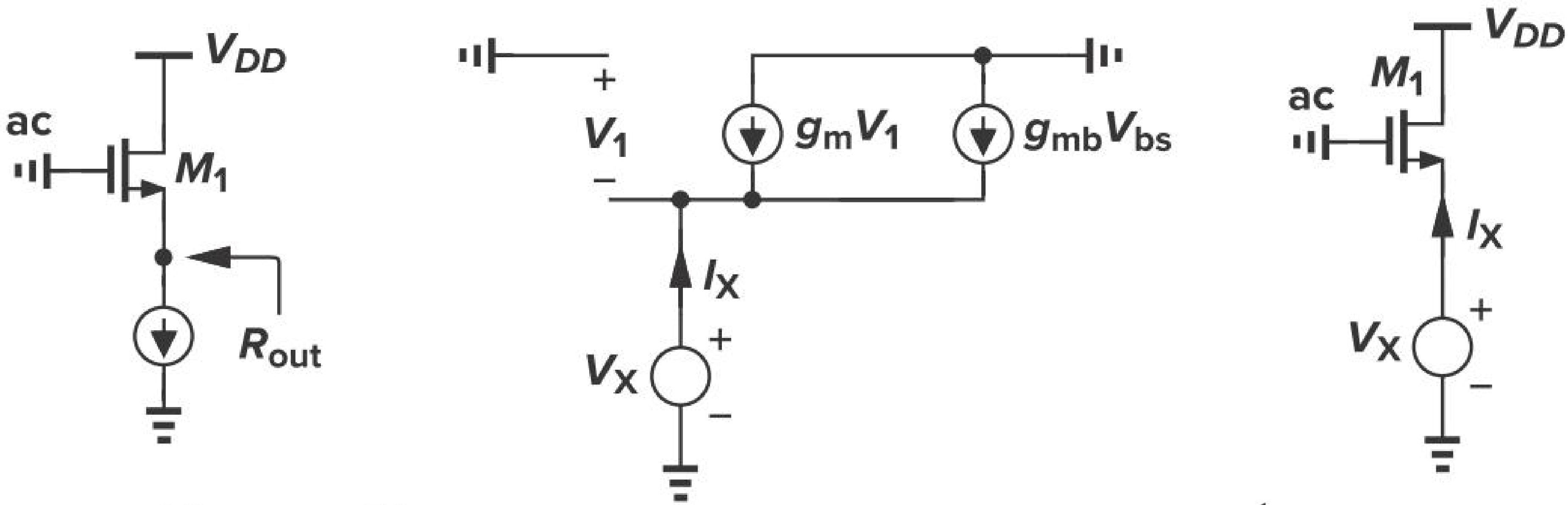
即使Rs无穷大，增益也小于1

采用电流源的源跟随器



- M_1的漏电流严重依赖于输入电平
- 即使V_{TH}保持恒定，V_{out}也无法“忠实”的跟随V_{in}
- 采用电流源代替电阻
- 如果I_1是理想电流源，不考虑二级效应，增益为1

源跟随器的输出电阻



$$V_X = -V_{bs}$$

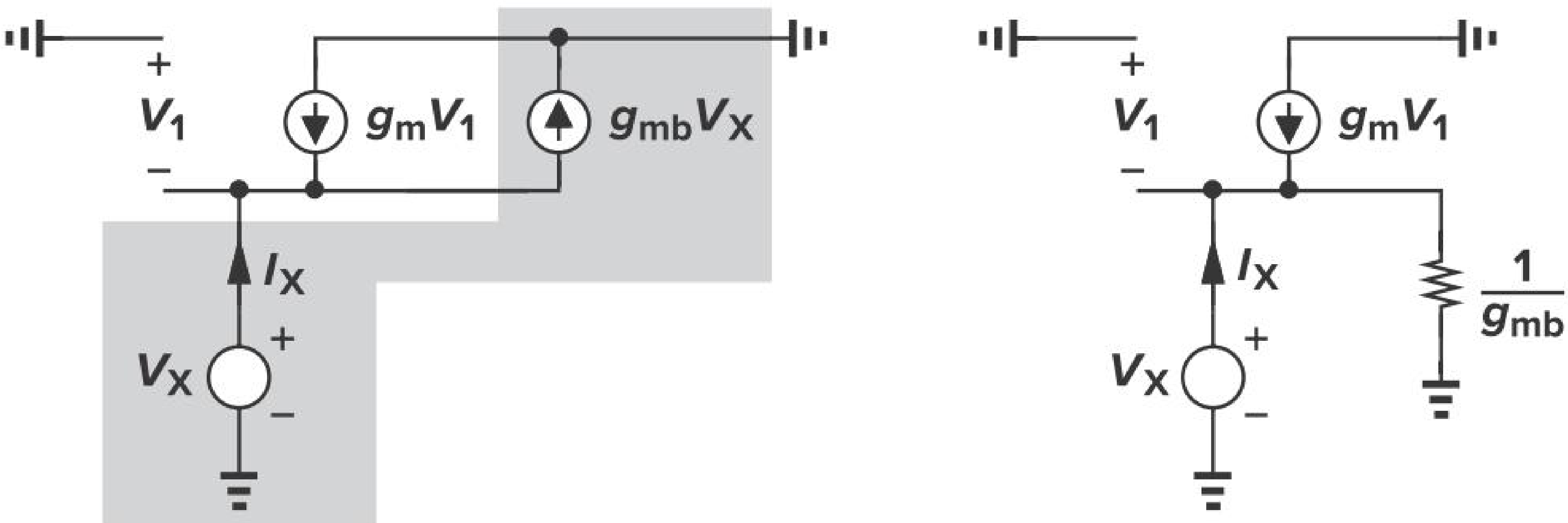
$$I_X - g_m V_X - g_{mb} V_X = 0$$

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

- 体效应减小了输出电阻

体效应改变了阈值电压

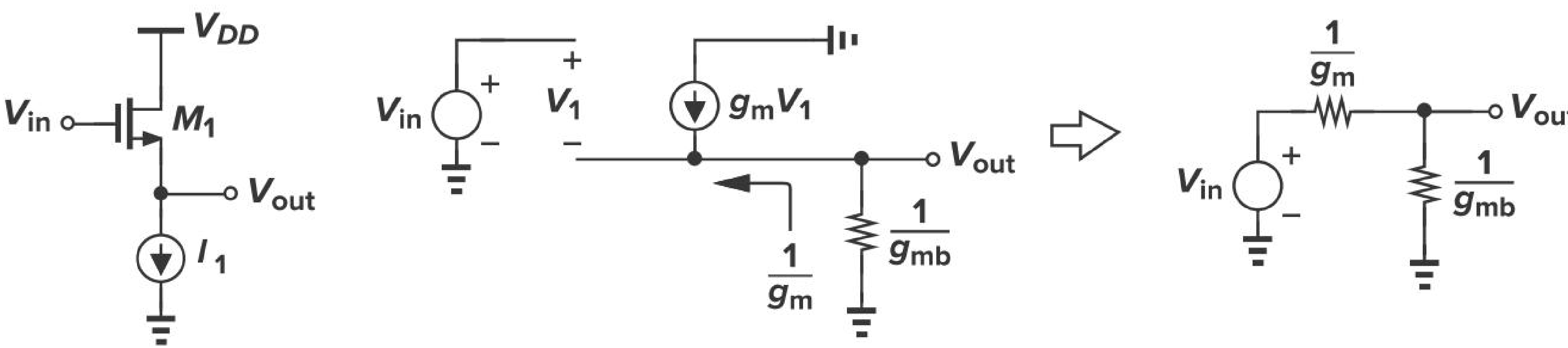
源跟随器的输出电阻



- 体效应表现为一个电阻的特性，阻值为$1/g_{mb}$

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

戴维南等效电路

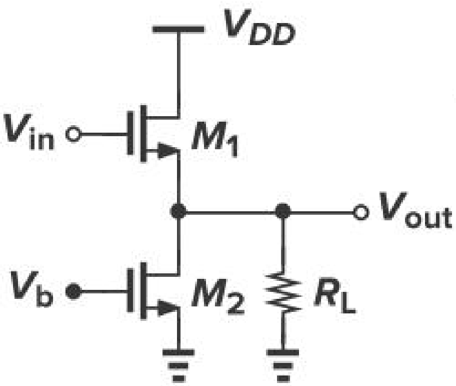


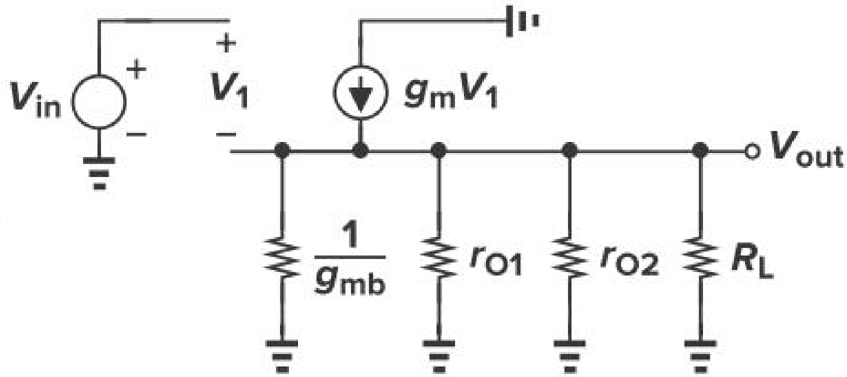
- R_{out}： 令V_{in}=0 ⇨ $1/g_m$
- I_{out}： V_{out}接地 ⇨ g_mV_{in}

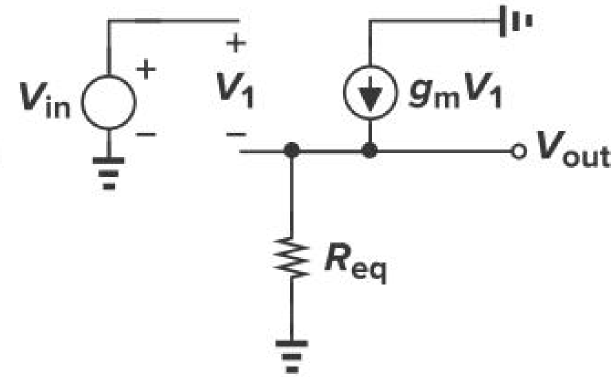
⇨ 开路电压V_{in}

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

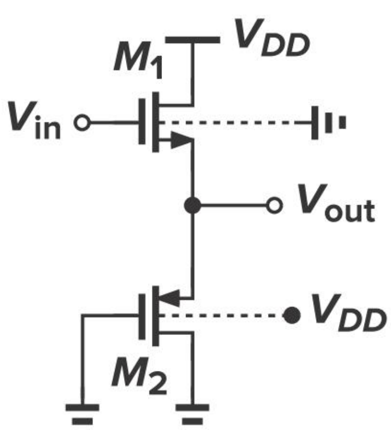
考虑沟道长度调制效应和负载







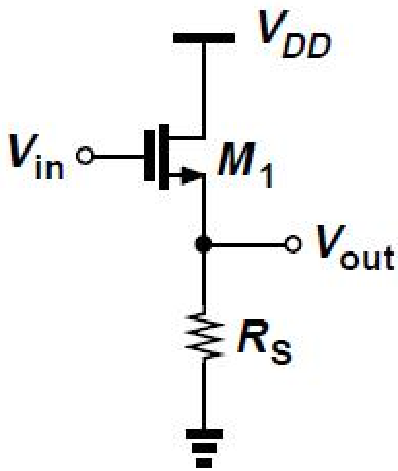
$$A_v = \frac{R_{eq}}{R_{eq} + \dfrac{1}{g_m}} \qquad R_{eq} = (1/g_{mb})||r_{O1}||r_{O2}||R_L$$

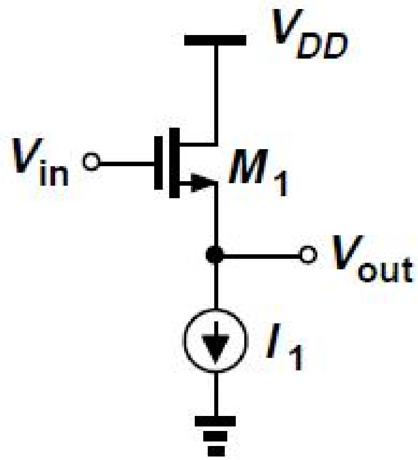


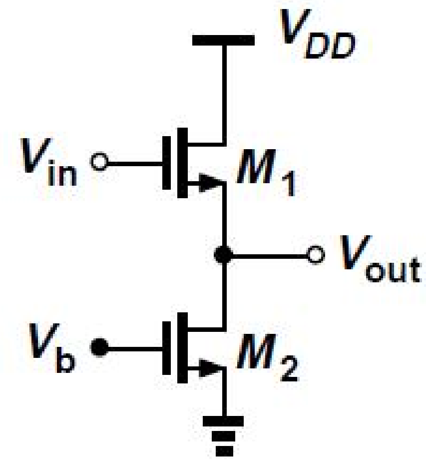
增益？

$$A_v = \frac{\dfrac{1}{g_{m2}+g_{mb2}}\|r_{O2}\|r_{O1}\|\dfrac{1}{g_{mb1}}}{\dfrac{1}{g_{m2}+g_{mb2}}\|r_{O2}\|r_{O1}\|\dfrac{1}{g_{mb1}}+\dfrac{1}{g_{m1}}}$$

源跟随器存在的问题

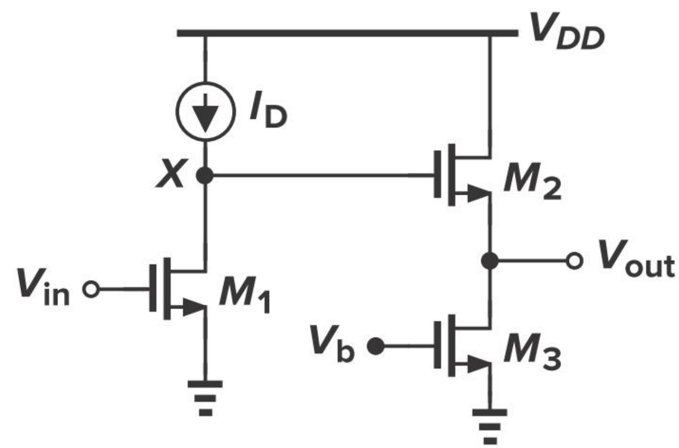






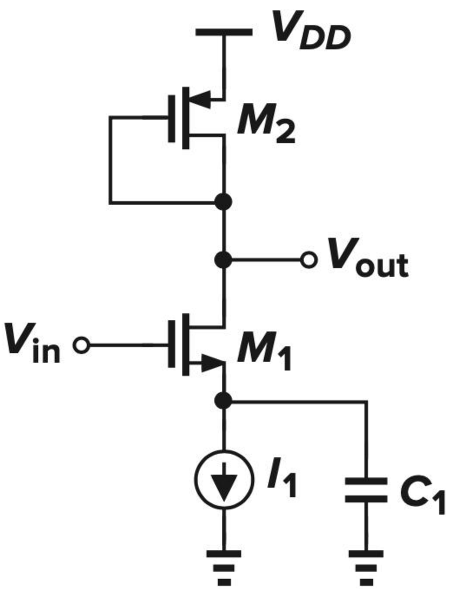
- 三个问题：非线性、电压余度减小和驱动能力不强
- 体效应影响阈值电压
- 晶体管的r_o随V_{DS}改变

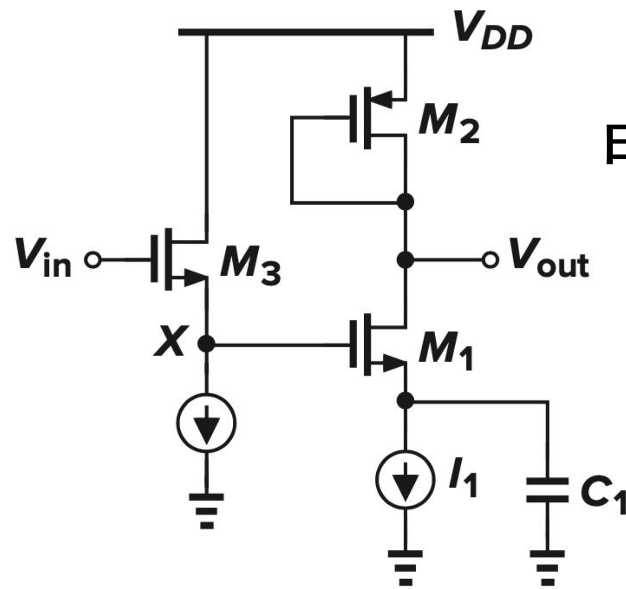
$$V_{GS1} - V_{TH1} \Rightarrow V_{GS2} + (V_{GS3} - V_{TH3})$$



有时可起到电平移位的作用

例3. 15 源跟随器的电平移位作用





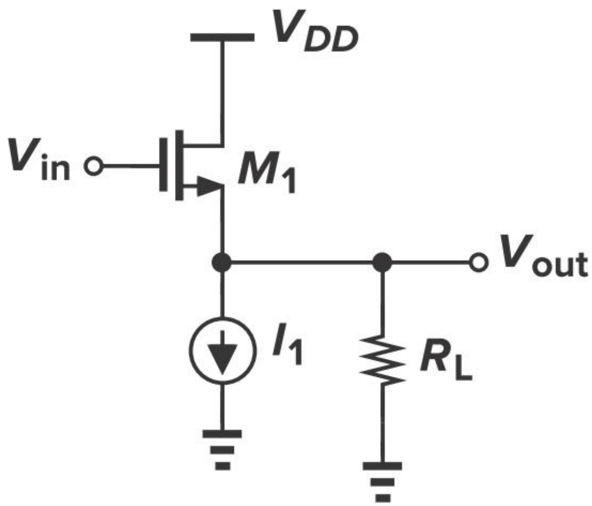
电容交流短路

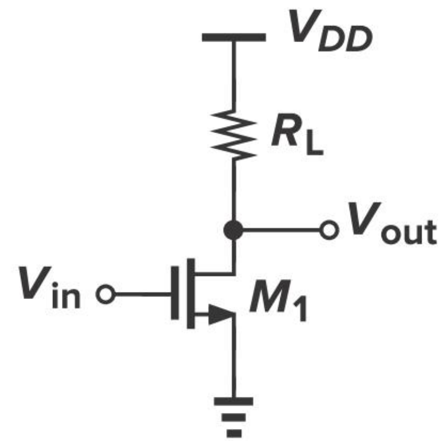
$$A_v = -g_{m1}[r_{O1} \| r_{O2} \| (1/g_{m2})]$$

- 保证M1工作在饱和区，V_{in}的最大直流电平？

$$V_{DD} - |V_{GS2}| + V_{TH1} \qquad V_{GS3} + V_{DD} - |V_{GS2}| + V_{TH1}$$

共源级和源跟随器的比较





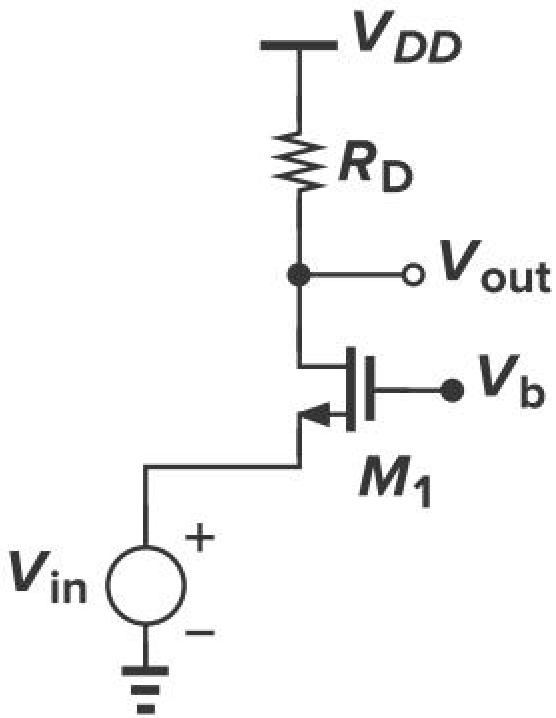
$$\frac{V_{out}}{V_{in}}|_{SF} \approx \frac{R_L}{R_L + 1/g_{m1}}$$
$$\approx \frac{g_{m1}R_L}{1 + g_{m1}R_L}$$

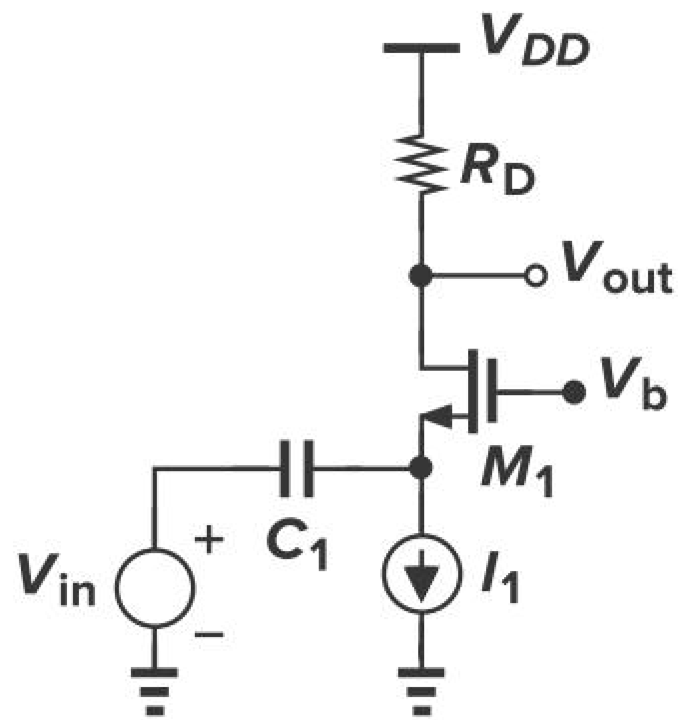
$$\frac{V_{out}}{V_{in}}|_{CS} \approx -g_{m1}R_L$$

- 源跟随器驱动能力较弱

3.4 共栅放大器

- 源端输入，漏端输出

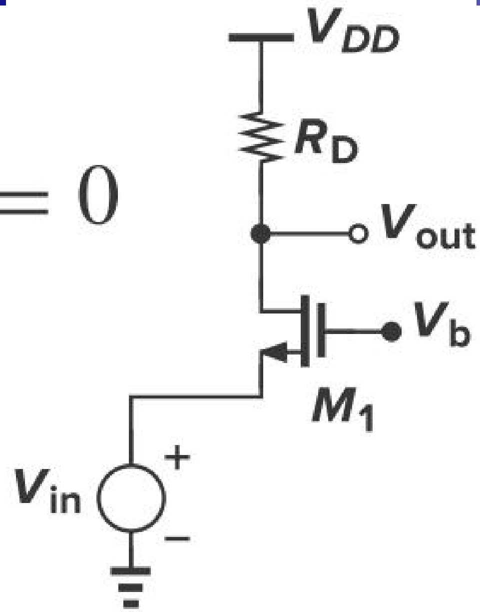


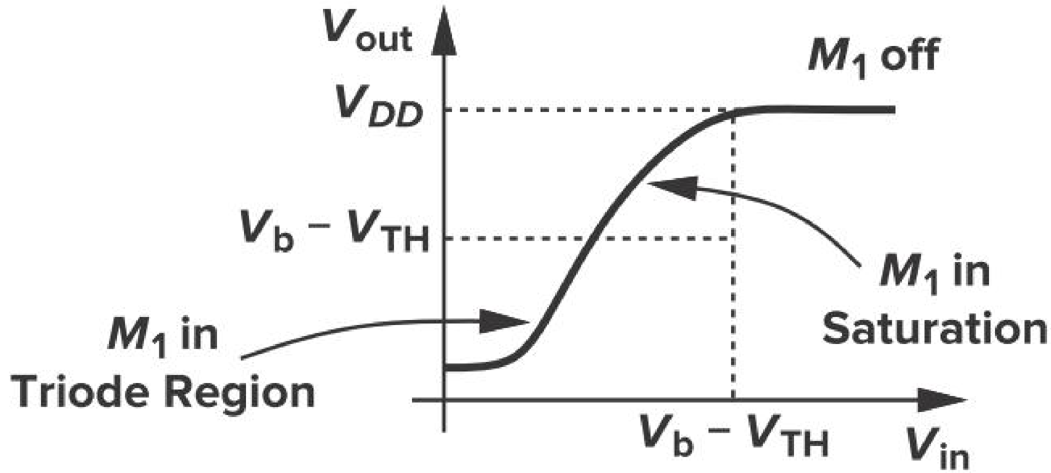


- M_1的偏置电流流过输入信号源；需要确认工作点
- 电流源偏置，信号通过电容耦合到电路，工作点由I_1确定

大信号特性

$\lambda = 0$





- 当$V_{in} \geq V_b$-V_{TH}，M_1截止，V_{out}= V_{DD}
- V_{in}减小，M_1处于饱和区

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

- 当V_{in} 继续减小，V_{out}也减小，M_1进入线性区

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

小信号增益

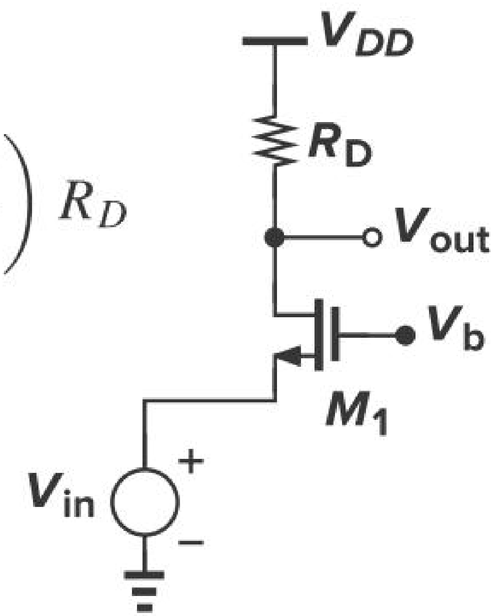
$$V_{out} = V_{DD} - \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_b - V_{in} - V_{TH})^2 R_D$$

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

由于 $\partial V_{TH}/\partial V_{in} = \partial V_{TH}/\partial V_{SB} = \eta$

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

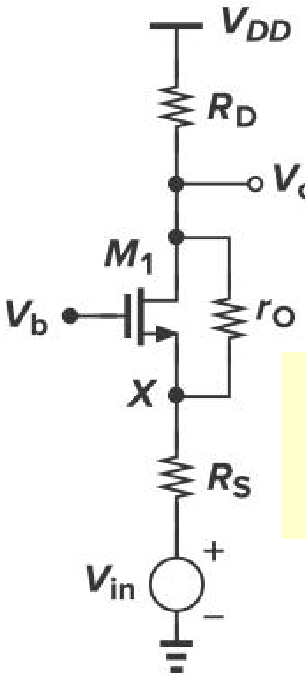
$$= g_m(1+\eta)R_D$$

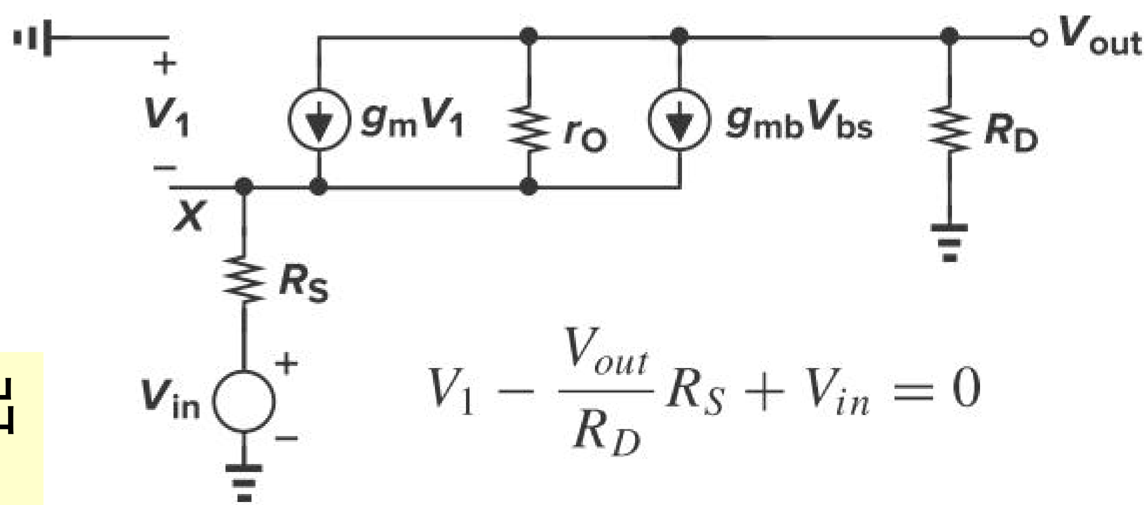


体效应增加了共栅级的等效跨导，但是与输入相关

与对带源级负反馈的共源级的跨导影响有何不同？

用小信号模型推导增益





前级输出阻抗

$$V_1 - \frac{V_{out}}{R_D} R_S + V_{in} = 0$$

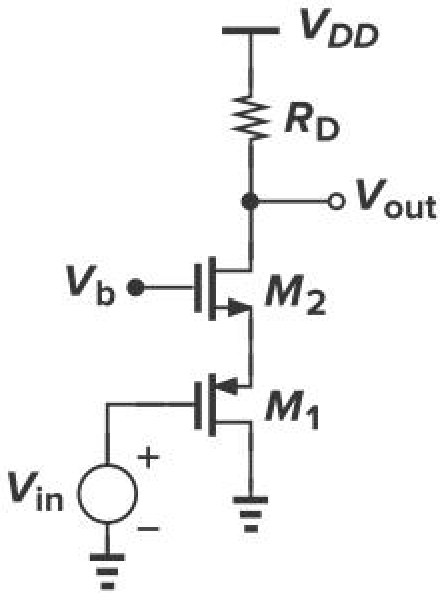
$$r_O\left(\frac{-V_{out}}{R_D} - g_m V_1 - g_{mb} V_1\right) - \frac{V_{out}}{R_D} R_S + V_{in} = V_{out}$$

$$\Rightarrow \quad r_O\left[\frac{-V_{out}}{R_D} - (g_m + g_{mb})\left(V_{out}\frac{R_S}{R_D} - V_{in}\right)\right] - \frac{V_{out} R_S}{R_D} + V_{in} = V_{out}$$

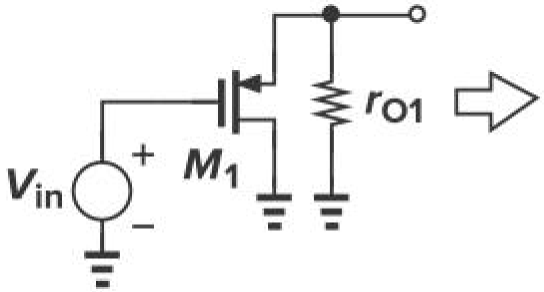
$$\Rightarrow \quad \frac{V_{out}}{V_{in}} = \frac{(g_m + g_{mb}) r_O + 1}{r_O + (g_m + g_{mb}) r_O R_S + R_S + R_D} R_D$$

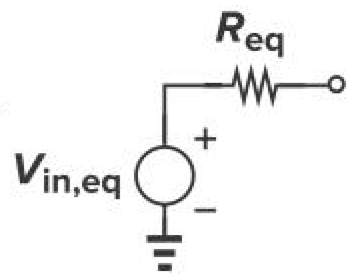
共源级：$$\frac{V_{out}}{V_{in}} = \frac{-g_m r_O R_D}{R_D + R_S + r_O + (g_m + g_{mb}) R_S r_O}$$

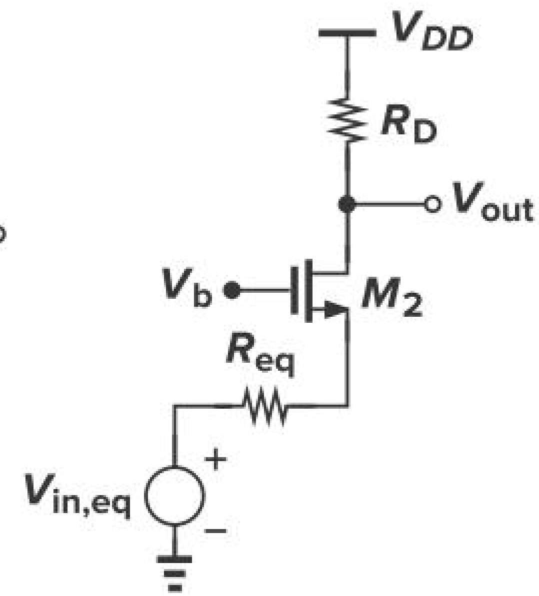
例3. 18 求电压增益



$\lambda \neq 0$ and $\gamma \neq 0$



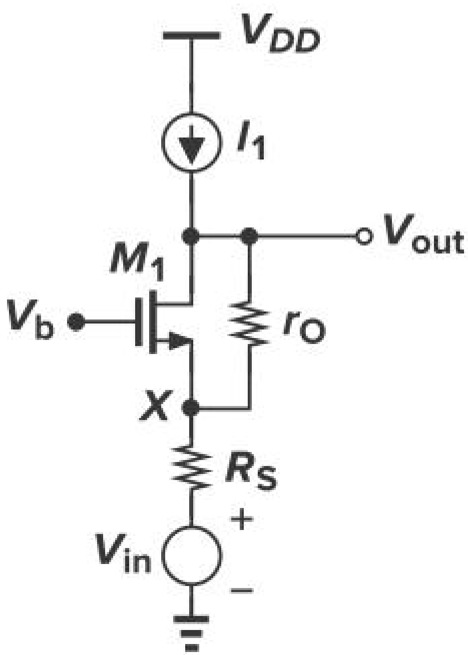




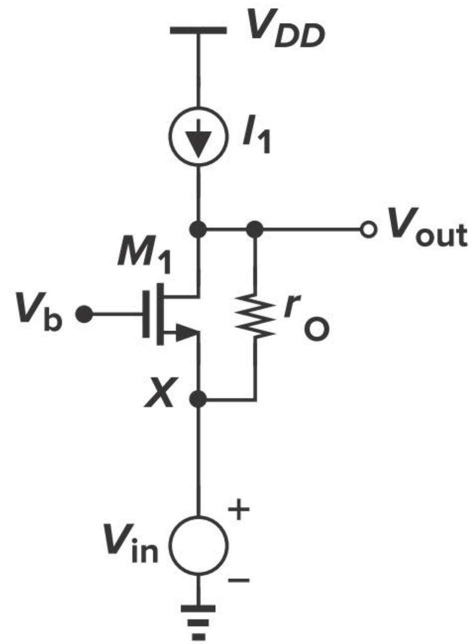
$$V_{in,eq} = \frac{r_{O1} \left\| \frac{1}{g_{mb1}} \right.}{r_{O1} \left\| \left(\frac{1}{g_{mb1}} + \frac{1}{g_{m1}} \right) \right.} V_{in} \qquad R_{eq} = r_{O1} \left\| \frac{1}{g_{mb1}} \right\| \frac{1}{g_{m1}}$$

$$\frac{V_{out}}{V_{in}} = \frac{(g_{m2} + g_{mb2})r_{O2} + 1}{r_{O2} + [1 + (g_{m2} + g_{mb2})r_{O2}] \left(r_{O1} \left\| \frac{1}{g_{mb1}} \right\| \frac{1}{g_{m1}} \right) + R_D} R_D \frac{r_{O1} \left\| \frac{1}{g_{mb1}} \right.}{r_{O1} \left\| \left(\frac{1}{g_{mb1}} + \frac{1}{g_{m1}} \right) \right.}$$

例3.19 求电流源为负载的增益



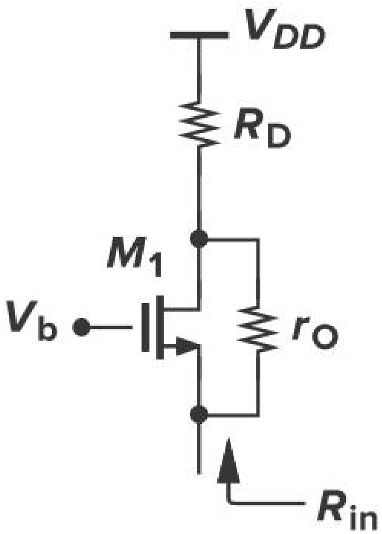
⇨

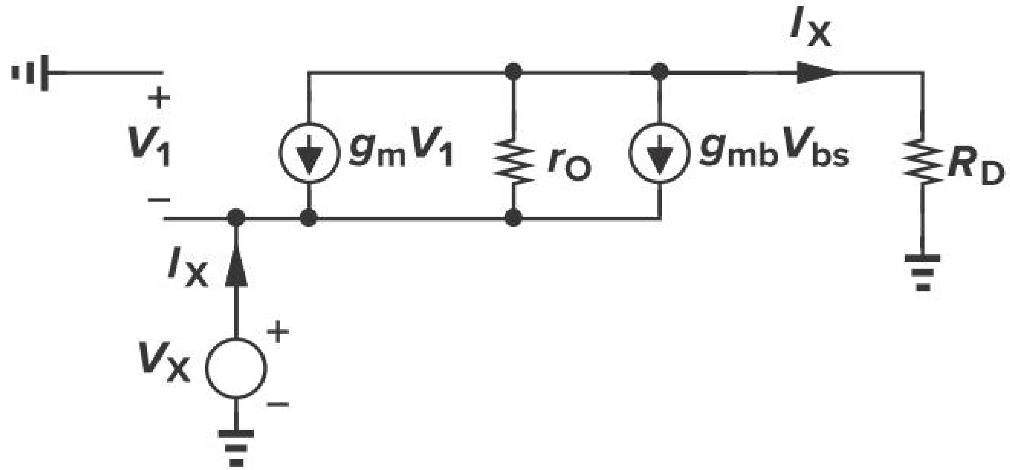


$$A_v = \frac{(g_m + g_{mb})r_O + 1}{r_O + (g_m + g_{mb})r_O R_S + R_S + R_D} R_D$$

$R_D = \infty$ ⇨ $A_v = (g_m + g_{mb})r_O + 1$

共栅级的输入阻抗





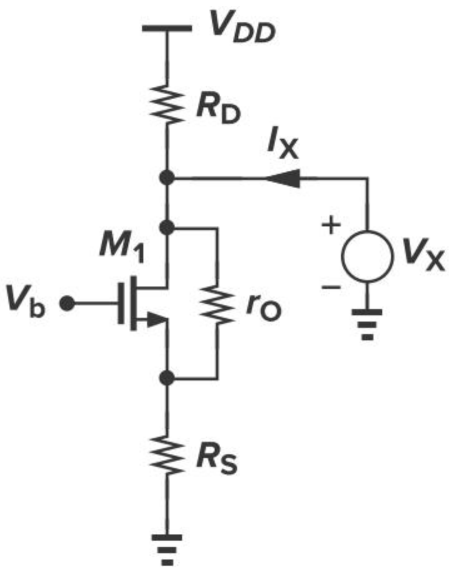
$$R_DI_X + r_O[I_X - (g_m + g_{mb})V_X] = V_X$$

$$\frac{V_X}{I_X} = \frac{R_D + r_O}{1 + (g_m + g_{mb})r_O} \approx \frac{R_D}{(g_m + g_{mb})r_O} + \frac{1}{g_m + g_{mb}}$$

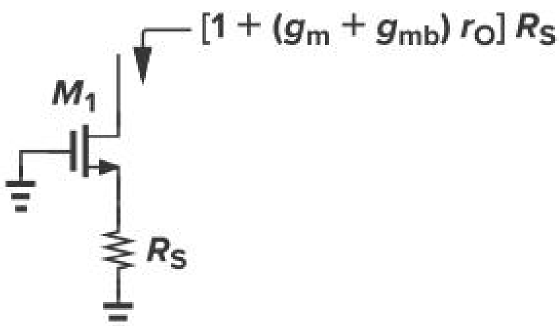
- $R_D=0$, $$\frac{V_X}{I_X} = \frac{r_O}{1 + (g_m + g_{mb})r_O} = \frac{1}{\frac{1}{r_O} + g_m + g_{mb}}$$
- $R_D=\infty$ (理想电流源），$I_X = 0$

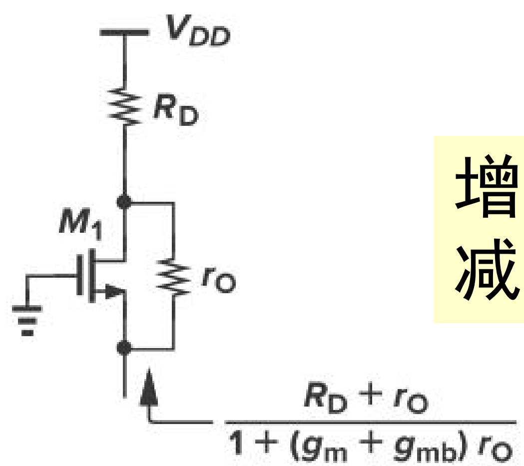
只有R_D较小时，共栅级输入阻抗才比较低

共栅级的输出阻抗



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





增大源端电阻，
减小漏端电阻

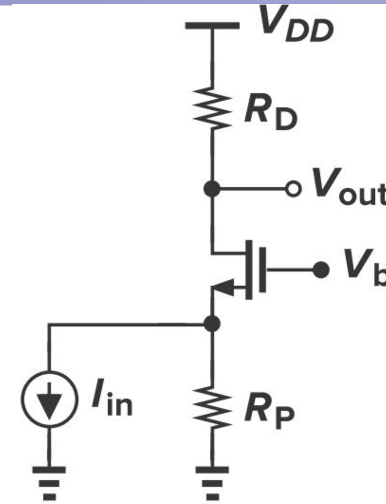
例3. 20 计算V_{out}/I_{in}和R_{out}

- 共栅级电路的输入信号可以是电流
- V_{out}/I_{in}

$$\frac{V_{out}}{I_{in}} = \frac{(g_m + g_{mb})r_O + 1}{r_O + (g_m + g_{mb})r_O R_P + R_P + R_D} R_D R_P$$

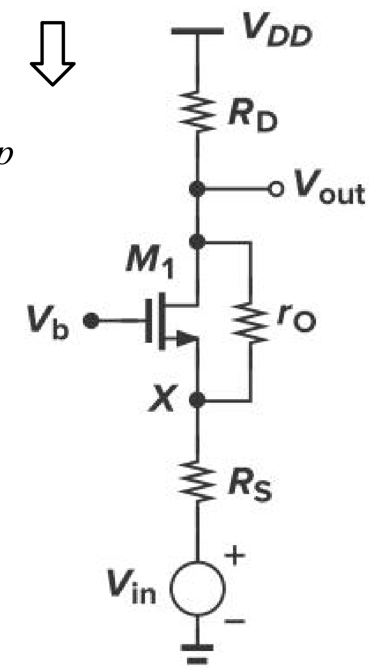
- R_{out}

$$R_{out} = \{[1 + (g_m + g_{mb})r_O]R_P + r_O\} \| R_D$$

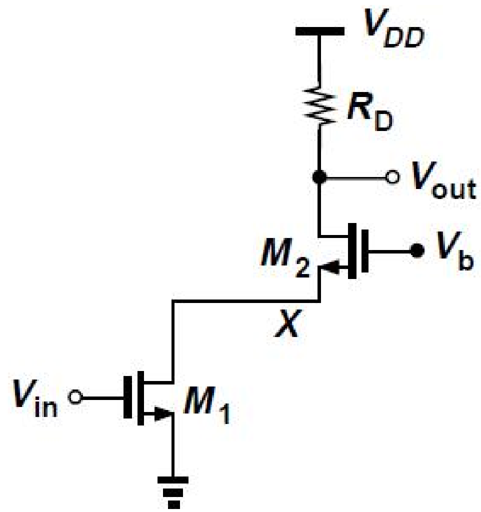


$R_p = R_s$

$V_{in} = I_{in} R_p$



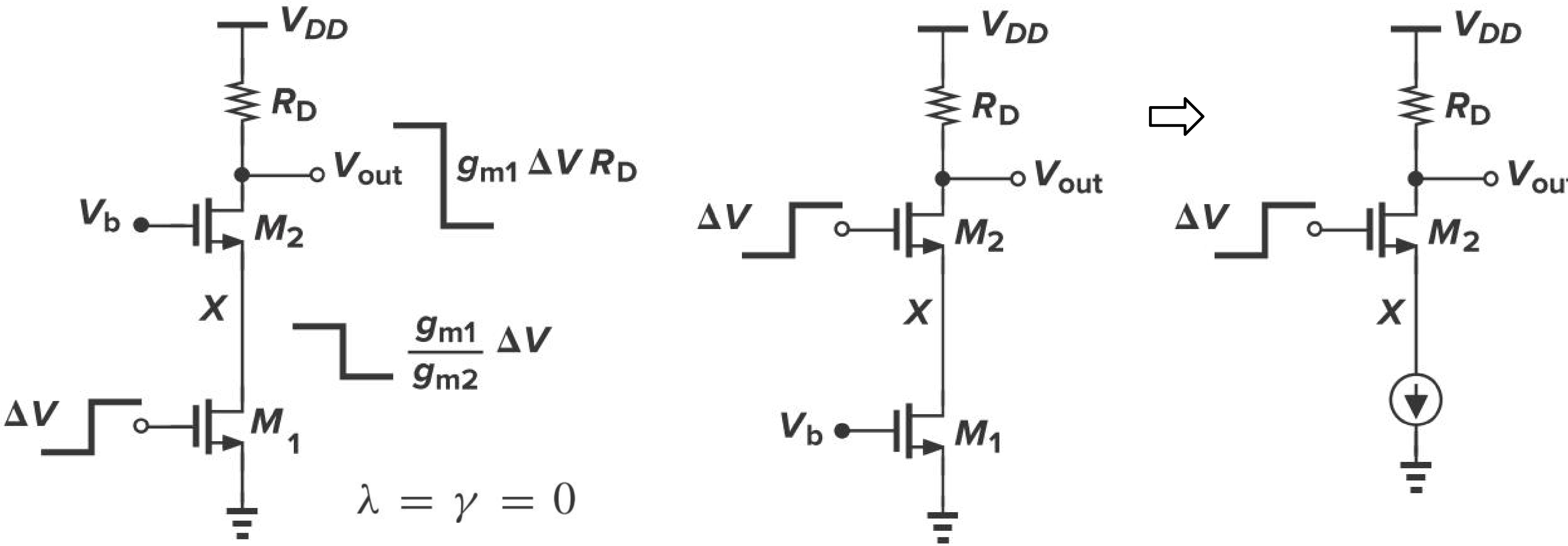
3.5 共源共栅级



M$_2$的作用？

- Cascode结构：共源级和共栅级的级联
- M$_1$产生于输入电压V$_{in}$成正比的小信号漏电流，该电流通过M$_2$流经R$_D$
- M$_1$输入器件，M$_2$共源共栅(cascode)器件
- 流经M$_1$和M$_2$的偏置电流和信号电流均相等
- 套筒式共源共栅(Telescopic cascode): M$_1$和M$_2$为同一类型MOSFET

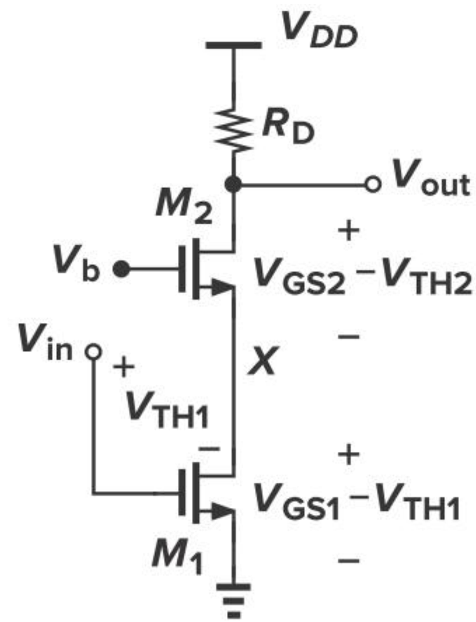
共源共栅级：定性分析



- 假设V_{in}增加ΔV, I_{D1}增加$g_{m1}\Delta V$，V_X下降$g_{m1}\Delta V\cdot(1/g_{m2})$，$V_{out}$下降$g_{m1}\Delta VR_D$
- 假如V_{in}固定，M_2栅极增加ΔV，V_x和V_{out}如何变化？
- V_b到V_{out}增益为0

共源共栅结构的偏置条件

- M_1工作在饱和区 ⇨ $V_X \geq V_{in} - V_{TH1}$
- M_2工作在饱和区 ⇨ $V_{out} \geq V_b - V_{TH2}$



$$V_X = V_b - V_{GS2}$$

⇨ $$V_b > V_{in} + V_{GS2} - V_{TH1}$$

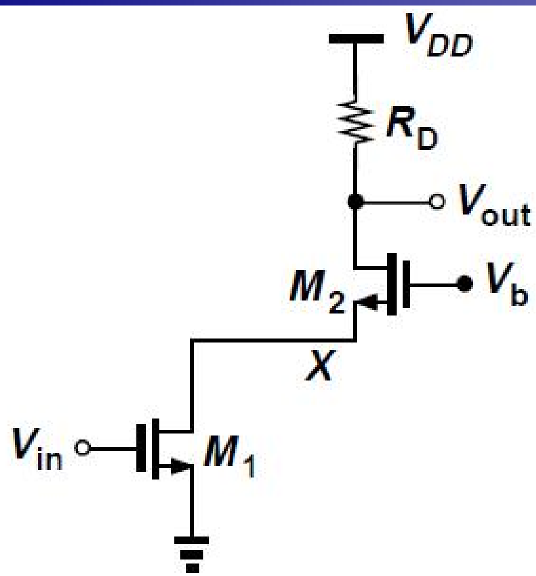
⇨ $$V_{out} \geq V_{in} - V_{TH1} + V_{GS2} - V_{TH2}$$

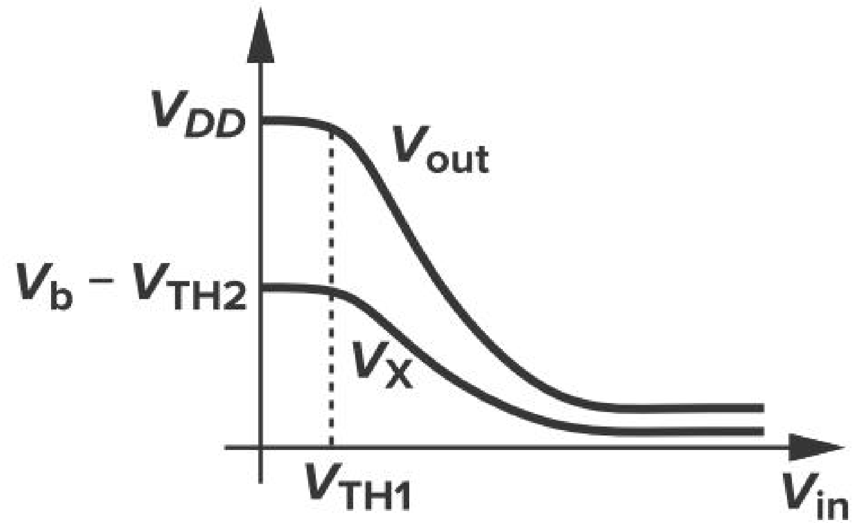
$$= (V_{GS1} - V_{TH1}) + (V_{GS2} - V_{TH2})$$

- M_2减小了输出电压的摆幅

两个过驱动电压

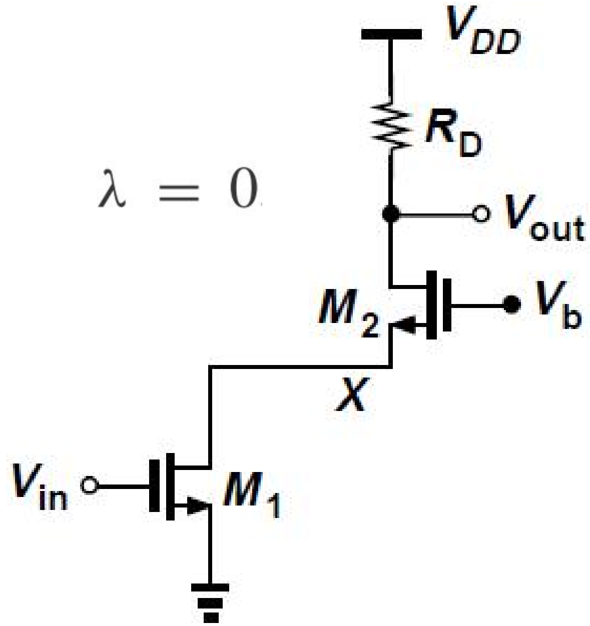
大信号特性

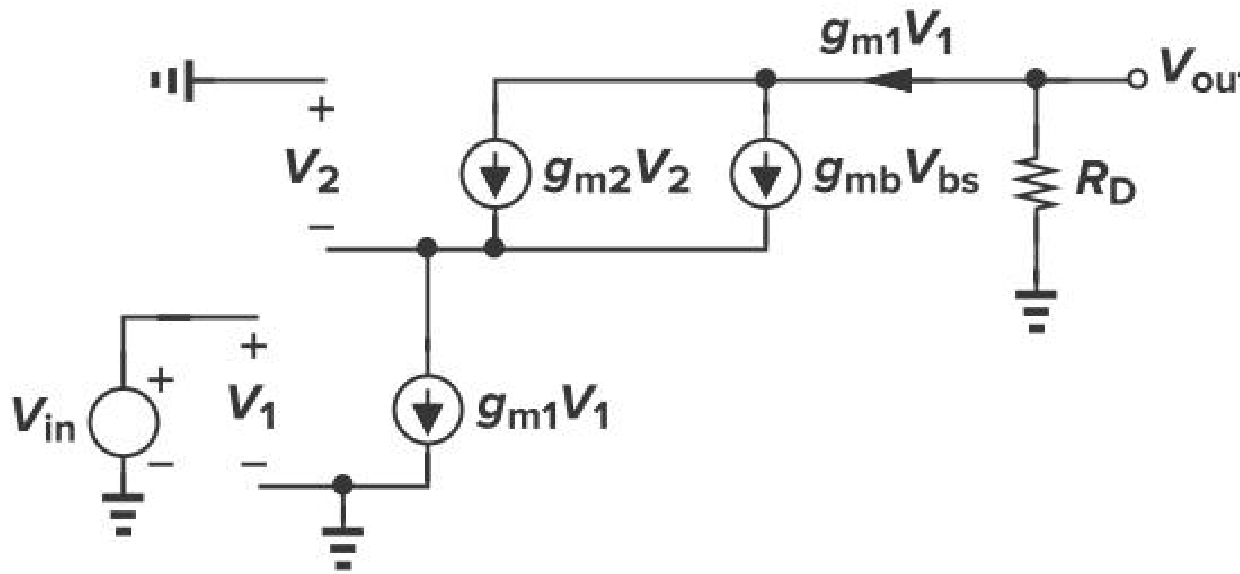




- 当$V_{in} \le V_{TH1}$, M_1和M_2 截止, $V_{out}=V_{DD}$, $V_X \approx V_b - V_{TH2}$
- 当$V_{in} > V_{TH1}$, M_1抽取电流, V_{out}下降
- 随着I_{D2}增大, V_{GS2}也必须增大，导致V_X下降
- 当V_{in}变得足够大，会出现2种结果:
  - V_X 降到比V_{in}低一个V_{TH1}, M_1进入线性区
  - V_{out}降到比V_b低一个V_{TH2}, M_2进入线性区
  - 具体哪种情况取决于器件尺寸、R_D 和 V_b

小信号特性





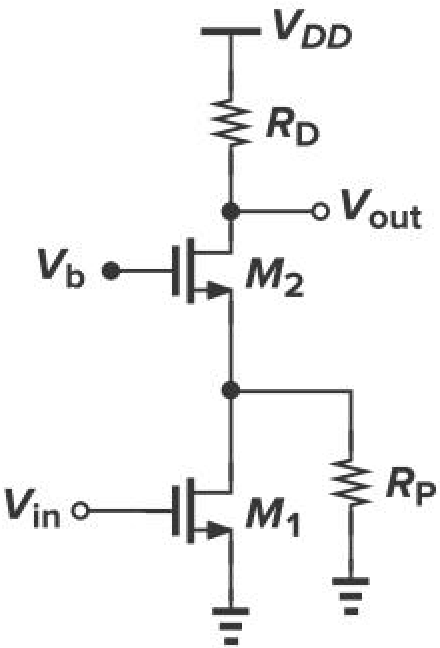
- M_1的漏电流必定流过M_2，所以电压增益与共源级的结果相同
- 与M_2的跨导和体效应无关

例3.21 计算电压增益

- M₁的小信号漏电流$g_{m1}V_{in}$，被R_p （例如r_{o1}或节点寄生电容）和向M$_2$源极看进去的阻抗$1/(g_{m2}+g_{mb2})$分流

⇨ $$I_{D2} = g_{m1}V_{in}\frac{(g_{m2}+g_{mb2})R_P}{1+(g_{m2}+g_{mb2})R_P}$$

⇨ $$A_v = -\frac{g_{m1}(g_{m2}+g_{mb2})R_P R_D}{1+(g_{m2}+g_{mb2})R_P}$$



$\lambda = 0$

计算电路的精确的电压增益

- M_1的小信号电路中的一部分被r_{o1}分流到地，等效G_m略小于g_{m1}
- 从M_2源端看进去的阻抗为

$$[1/(g_{m2}+g_{mb2})]||r_{O2}$$

- 流进M_2的电流为

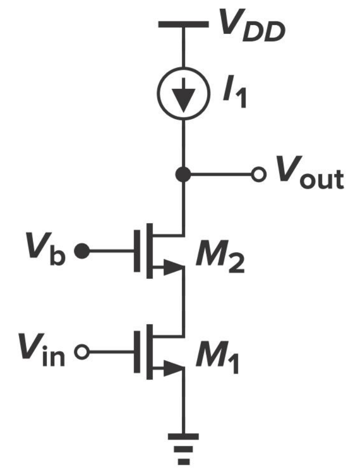
$$I_{out}=g_{m1}V_{in}\frac{r_{O1}}{r_{O1}+\frac{1}{g_{m2}+g_{mb2}}\left\|r_{O2}\right.}$$

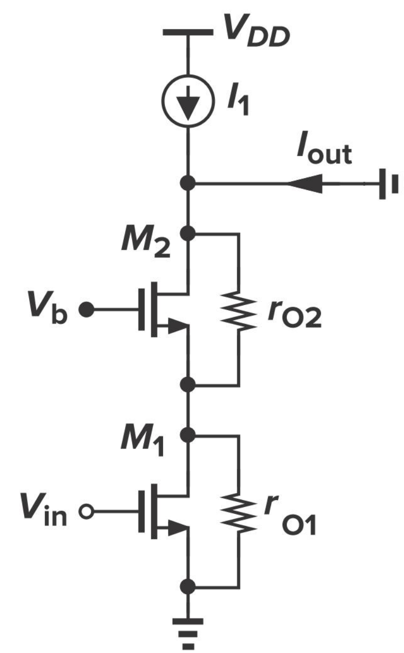
- 等效G_m

$$G_m=\frac{g_{m1}r_{O1}[r_{O2}(g_{m2}+g_{mb2})+1]}{r_{O1}r_{O2}(g_{m2}+g_{mb2})+r_{O1}+r_{O2}}$$

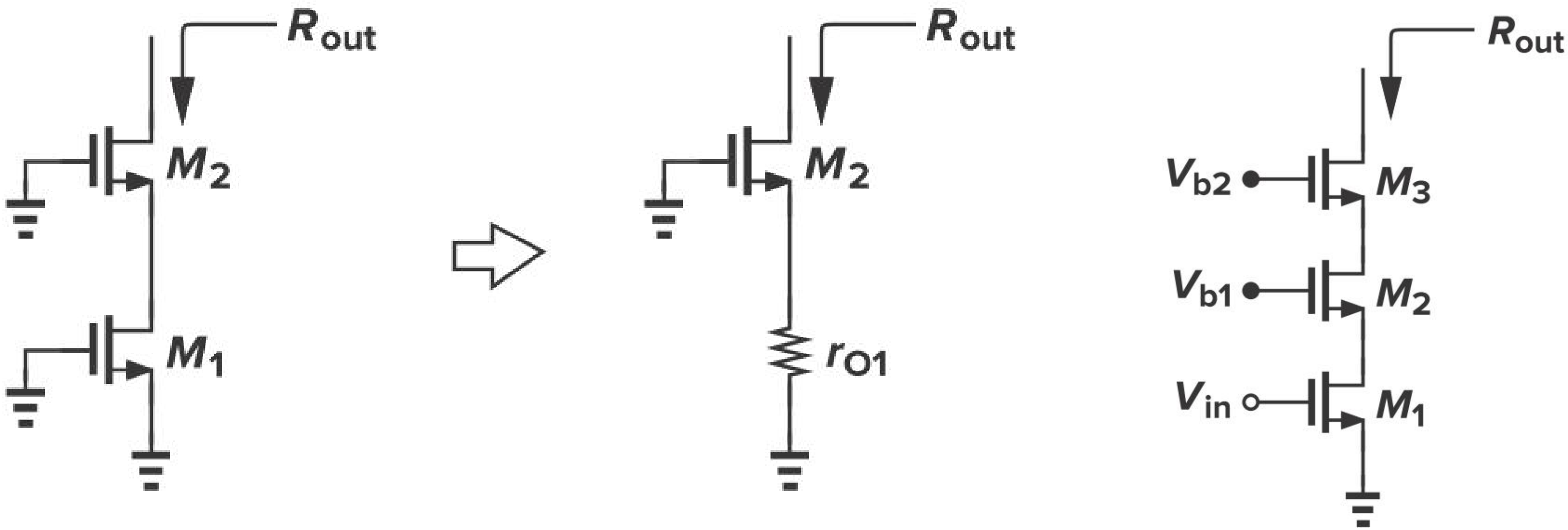
- 增益

$$|A_v|=G_mR_{out}=g_{m1}r_{O1}[(g_{m2}+g_{mb2})r_{O2}+1]$$





共源共栅级的输出阻抗



$$R_{out} = [1 + (g_{m2} + g_{mb2})r_{O2}]r_{O1} + r_{O2}$$

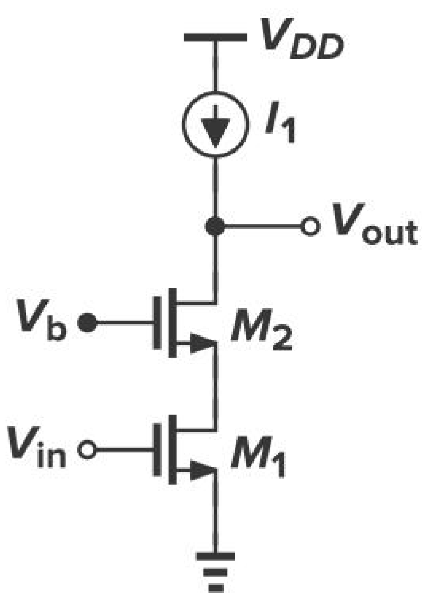
- 假设 $g_m r_O \gg 1$,

$$R_{out} \approx (g_{m2} + g_{mb2})r_{O2}r_{O1}$$

- M_2将M_1的输出阻抗提高了 $(g_{m2} + g_{mb2})r_{O2}$ 倍
- 可扩展到三个甚至更多器件层叠来获得更高的输出阻抗

共源共栅级对增益的提高

- 可以通过增大G_m或者/和 R_{out}增大电压增益
- G_m通常由晶体管的跨导决定，需要与偏置电流、器件电容之间进行折中
- 通过cascode结构将R_{out}最大化，但是减小输出摆幅



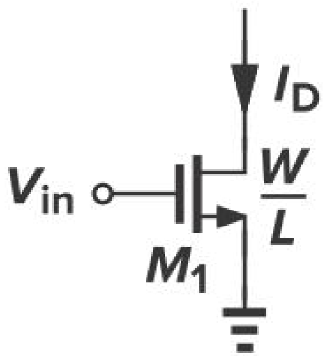
$$G_m \approx g_{m1}$$

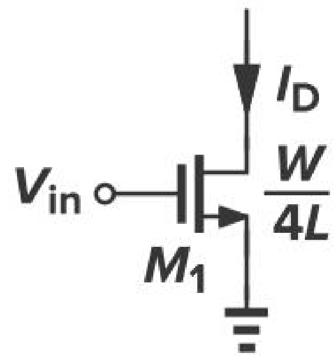
$$R_{out} \approx (g_{m2} + g_{mb2}) r_{O2} r_{O1}$$

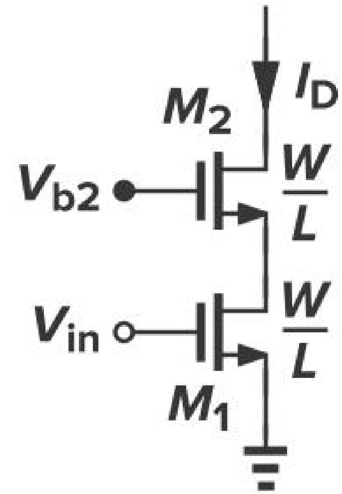
$$\Rightarrow A_v = (g_{m2} + g_{mb2}) r_{O2} g_{m1} r_{O1}$$

将增益提高了本征增益倍

比较两种提高阻抗的方法







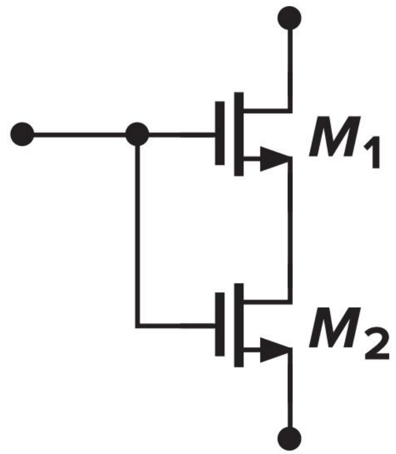
$$g_m r_O = \sqrt{2\mu_n C_{ox}\frac{W}{L}I_D}\frac{1}{\lambda I_D}$$

增益增大2倍，
跨导降为一半

增益增大
$g_m r_o$倍

- 增加晶体管的沟道长度和采用共源共栅结构
- 两者消耗的电压余度相同

Poor Man's Cascode



$$V_{GS1} > V_{TH1}$$

$$V_{DS2} = V_{GS2} - V_{GS1} < V_{GS2} - V_{TH2}.$$

- “最简单”的共源共栅电流源，省掉了共源共栅器件的偏置电压
- M_1和M_2工作在哪个区？
- 如果M_1和M_2的尺寸相等，此结构等同于沟道长度2倍的一个晶体管
- 现代CMOS工艺中，晶体管可以有不同的阈值电压，如何选择可以使其变成真正的cascode？

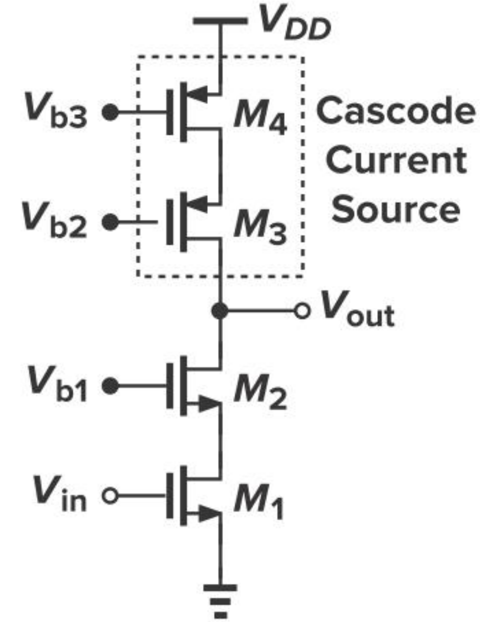
采用共源共栅结构作为电流源

- 共源共栅结构可以用来产生一个近似理想的电流源，具有高输出阻抗

$$[1+(g_{m3}+g_{mb3})r_{O3}]r_{O4}+r_{O3}$$

- 代价：牺牲了电压余度

- 总的输出阻抗为:



$$R_{out}=\{[1+(g_{m2}+g_{mb2})r_{O2}]r_{O1}+r_{O2}\}\|\{[1+(g_{m3}+g_{mb3})r_{O3}]r_{O4}+r_{O3}\}$$

- 假设 $G_m \approx g_{m1}$，电压增益约为

$$|A_v| \approx g_{m1}[(g_{m2}r_{O2}r_{O1})\|(g_{m3}r_{O3}r_{O4})]$$

直流输出电平需另外确定

上下两端输出阻抗要平衡

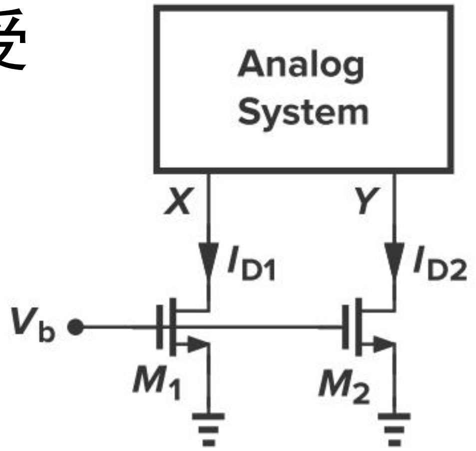
屏蔽特性

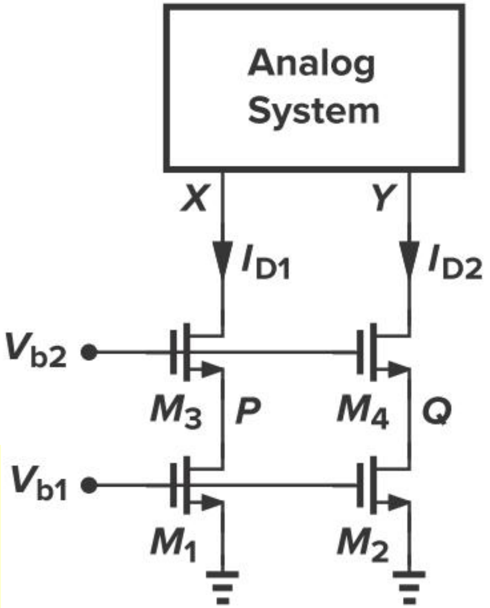
- 共源共栅管“屏蔽”输入器件，使它受输出电压变化的影响很小

$$I_{D1}-I_{D2}=\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_b-V_{TH})^2(\lambda V_{DS1}-\lambda V_{DS2})$$
$$=\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_b-V_{TH})^2(\lambda\Delta V)$$

$$\Delta V_{PQ}=\Delta V\frac{r_{O1}}{[1+(g_{m3}+g_{mb3})r_{O3}]r_{O1}+r_{O3}}$$
$$\approx\frac{\Delta V}{(g_{m3}+g_{mb3})r_{O3}}$$

$$I_{D1}-I_{D2}=\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_b-V_{TH})^2\frac{\lambda\Delta V}{(g_{m3}+g_{mb3})r_{O3}}$$

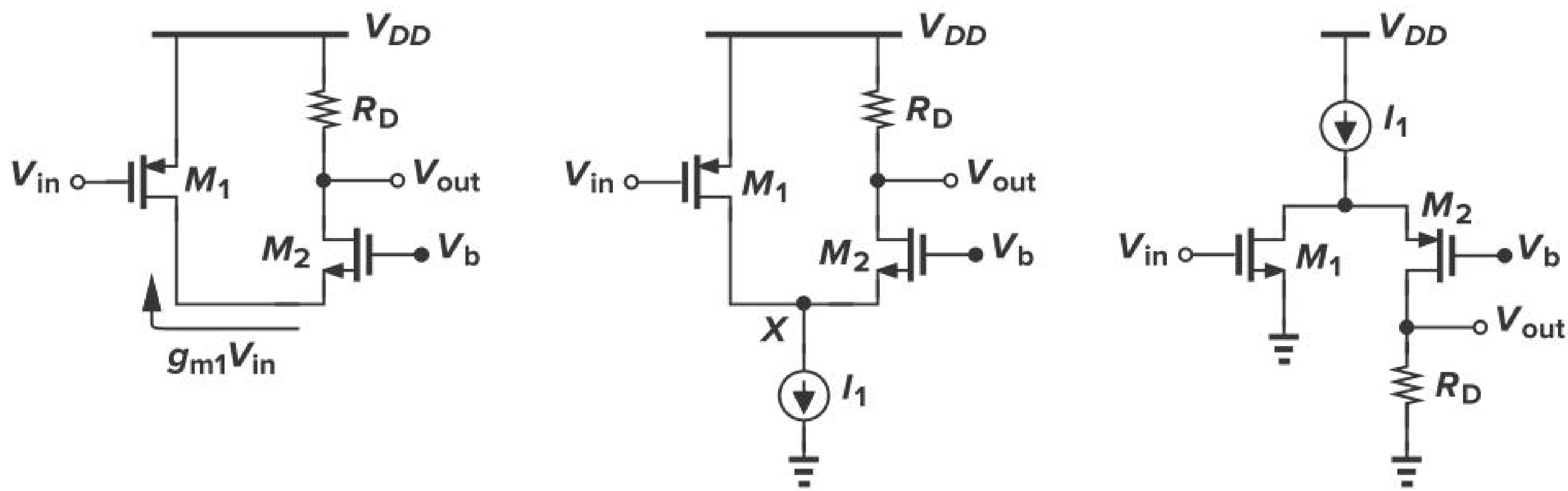




Cascode结构可以显著减小电流镜的电流失配，但是要保证工作在饱和区

折叠式共源共栅

- 输入管和Cascode管也可以不是同一种MOSFET



- 偏置电流比套筒式大
- 在第九章详细比较两种结构的优缺点

折叠式结构的大信号分析

- 当$V_{in}>V_{DD}-|V_{TH1}|$, M_1截止，电流I_1全部经过M_2，$V_{out}=V_{DD}-I_1R_D$
- 当$V_{in}<V_{DD}-|V_{TH1}|$, M_1 进入饱和区

$$I_{D2}=I_1-\frac{1}{2}\mu_pC_{ox}\left(\frac{W}{L}\right)_1(V_{DD}-V_{in}-|V_{TH1}|)^2$$

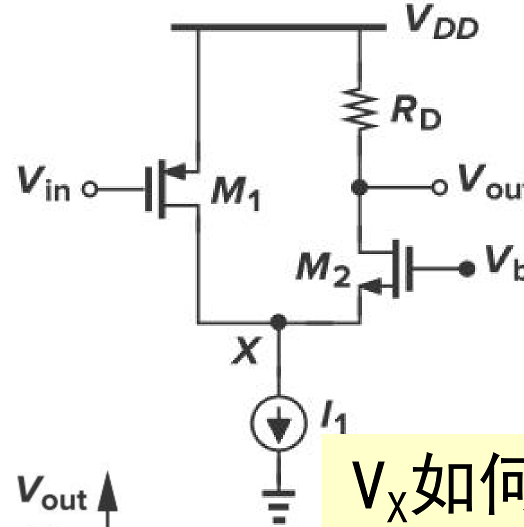
- 当V_{in}继续下降，I_{D2}进一步减小，如果$I_{D1}=I_1$，则I_{D2}下降到0

$$\frac{1}{2}\mu_pC_{ox}\left(\frac{W}{L}\right)_1(V_{DD}-V_{in1}-|V_{TH1}|)^2=I_1$$

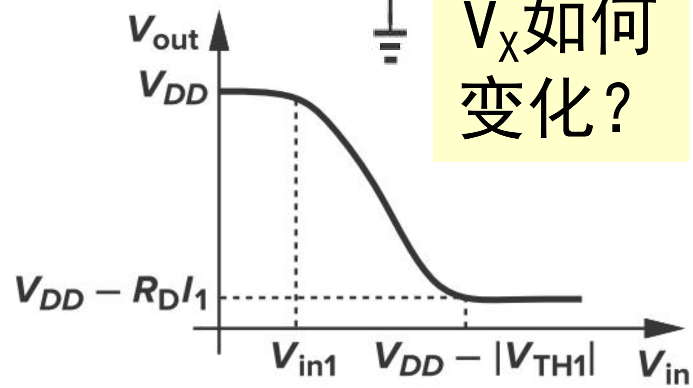
$$\Rightarrow \quad V_{in1}=V_{DD}-\sqrt{\frac{2I_1}{\mu_pC_{ox}(W/L)_1}}-|V_{TH1}|$$

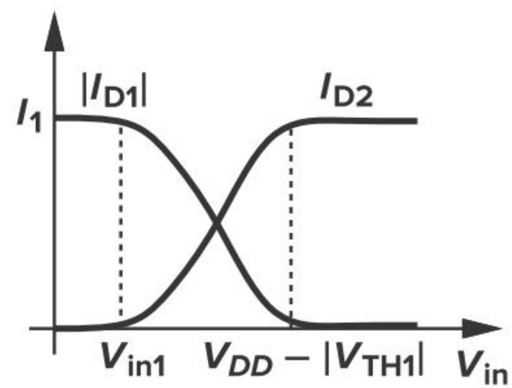
- 当$V_{in}<V_{in1}$，M_1进入线性区

最小输入电压

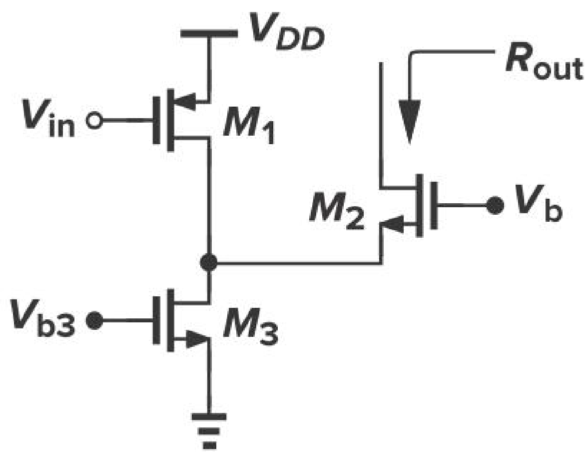


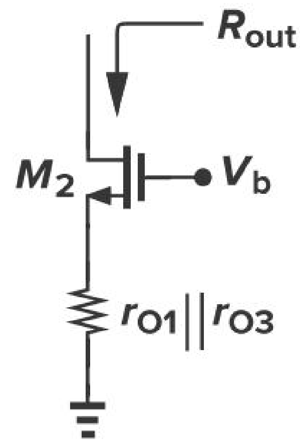
V_X如何变化？

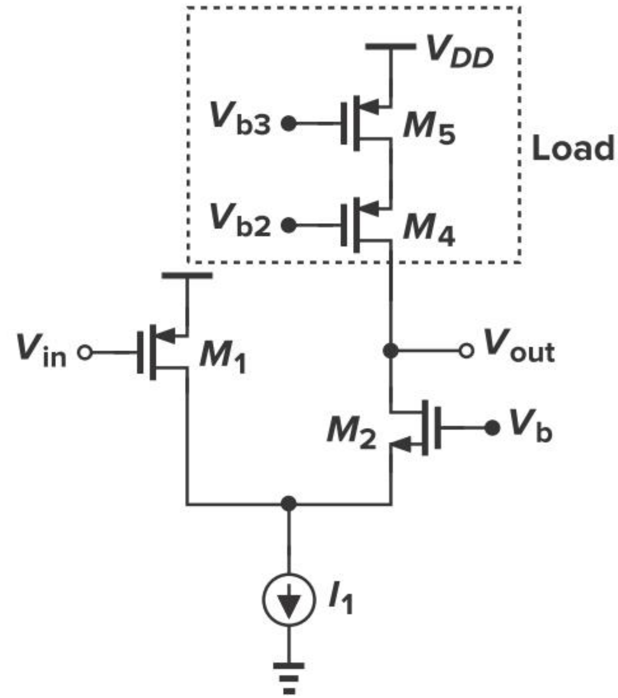




折叠式结构的输出阻抗







$$R_{out} = [1 + (g_{m2} + g_{mb2})r_{O2}](r_{O1} \| r_{O3}) + r_{O2}$$

折叠式的输出阻抗一般比套筒式要小

本章知识要点

- 四种类型的单级放大器
  - 大信号特性
  - 小信号特性
    - 小信号模型
    - 电压增益
    - 输入和输出阻抗
- 共源级放大器的各种负载情况及其优缺点
- 模拟集成电路设计的关键原则

Thank you

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