中国科学技术大学 | 国家示范性微电子学院
University of Science and Technology of China | School of Microelectronics

模拟集成电路设计课程

第5章 电流镜与偏置技术

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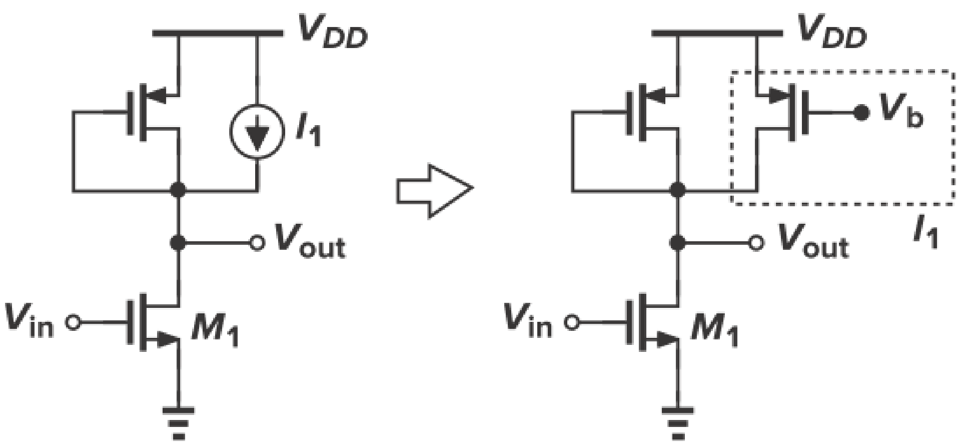
本章内容

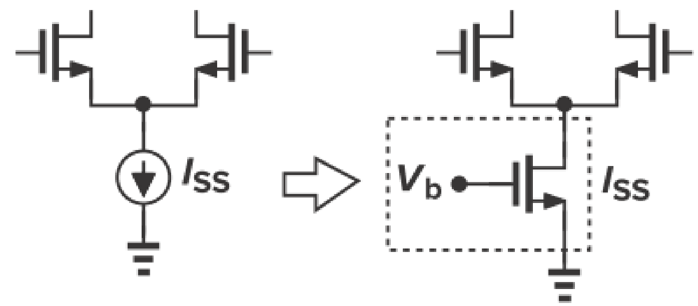
- 5.1 基本电流镜
- 5.2 共源共栅电流镜
- 5.3 有源电流镜放大器
- 5.4 偏置技术 (自学)

5. 1 基本电流镜

- 工作在饱和区的MOS管可以当作电流源
- 电流源的要求：很大的输出电阻，且不消耗过多的电压余度



增大增益



尾电流源

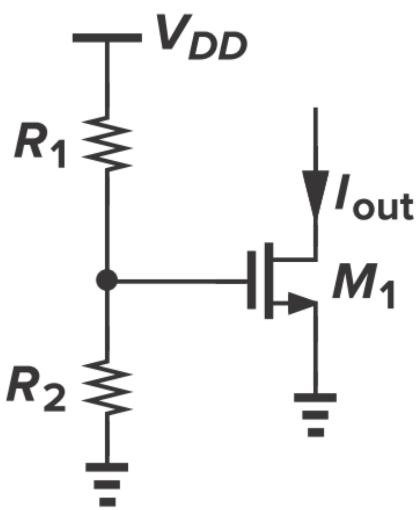
如何确定电流源的偏置？

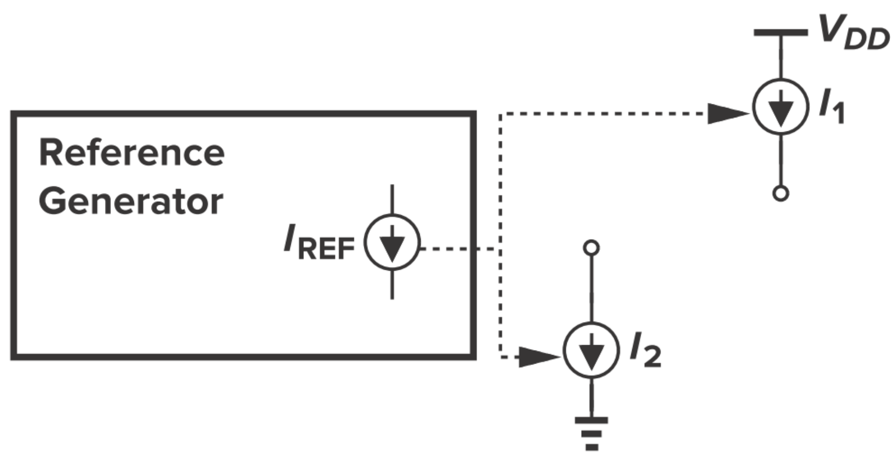
- 电阻分压？

$$I_{out} \approx \frac{1}{2}\mu_n C_{ox}\frac{W}{L}\left(\frac{R_2}{R_1+R_2}V_{DD}-V_{TH}\right)^2$$

严重受PVT变化影响

- 即使给定了一个精确的栅源电压，电流也无法准确确定





- 在模拟电路中，电流源的设计是基于对基准电流的“复制”
- 基准电流I_{REF}由专门的基准产生电路提供

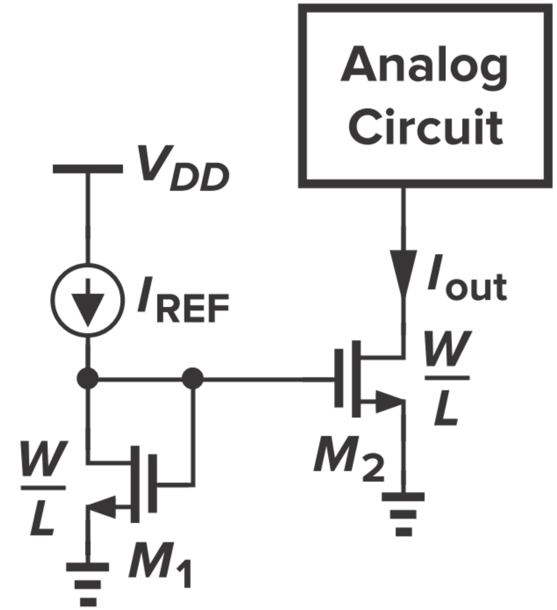
基本电流镜

- 忽略沟道长度调制效应

$$I_{REF} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_1 (V_{GS} - V_{TH})^2$$

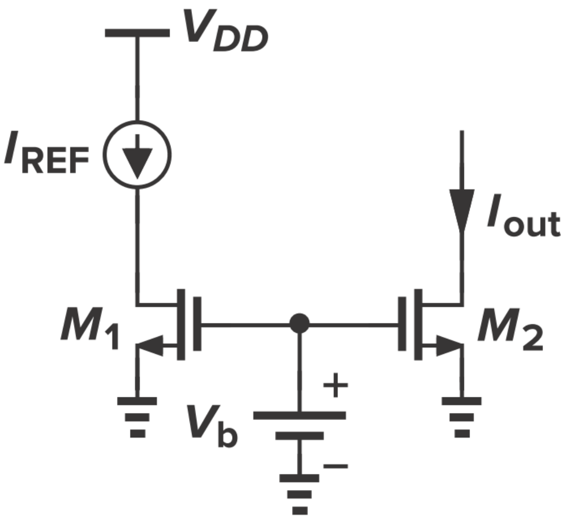
$$I_{out} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_2 (V_{GS} - V_{TH})^2$$

$$\Rightarrow \quad I_{out} = \frac{(W/L)_2}{(W/L)_1} I_{REF}$$

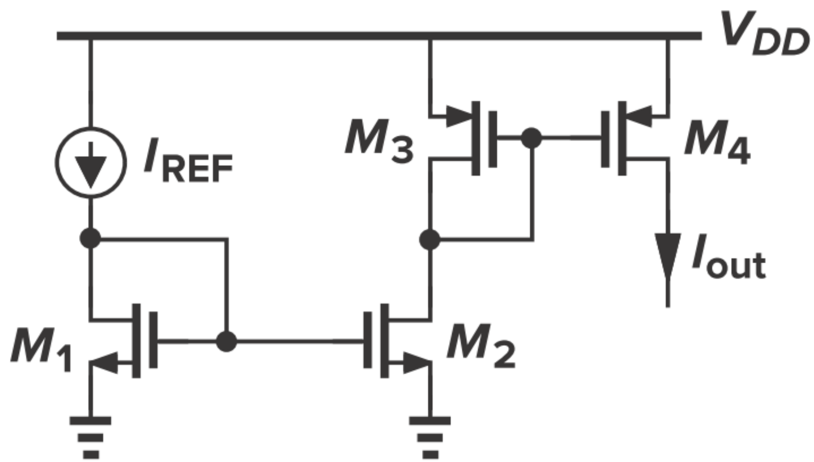


不受工艺和温度的影响，仅与器件尺寸比率相关

- V_{GS}必须由I_{REF}产生，否则不能完成电流复制



例5.1 M_4的漏电流？



$$I_{D2} = I_{REF}[(W/L)_2/(W/L)_1]$$

$$|I_{D3}| = |I_{D2}| \quad \Rightarrow \quad |I_{D4}| = \alpha\beta I_{REF}$$

$$I_{D4} = I_{D3} \times [(W/L)_4/(W/L)_3]$$

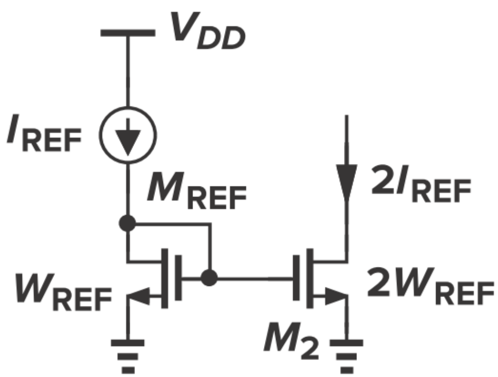
$$\alpha = (W/L)_2/(W/L)_1$$

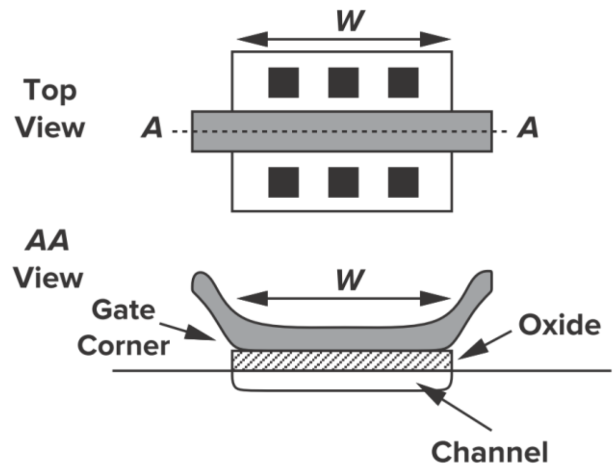
$$\beta = (W/L)_4/(W/L)_3$$

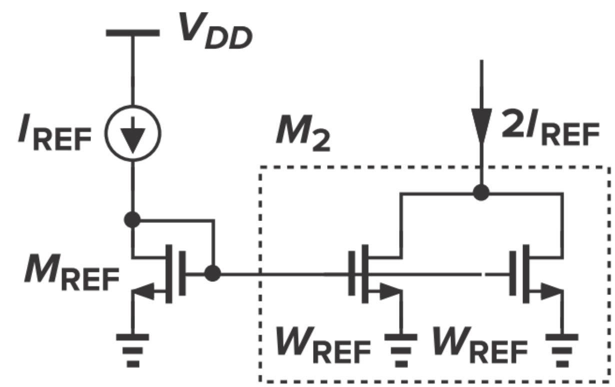
应避免长的电流镜链

可放大或缩小 I_{REF}

如何设计电流镜的尺寸？



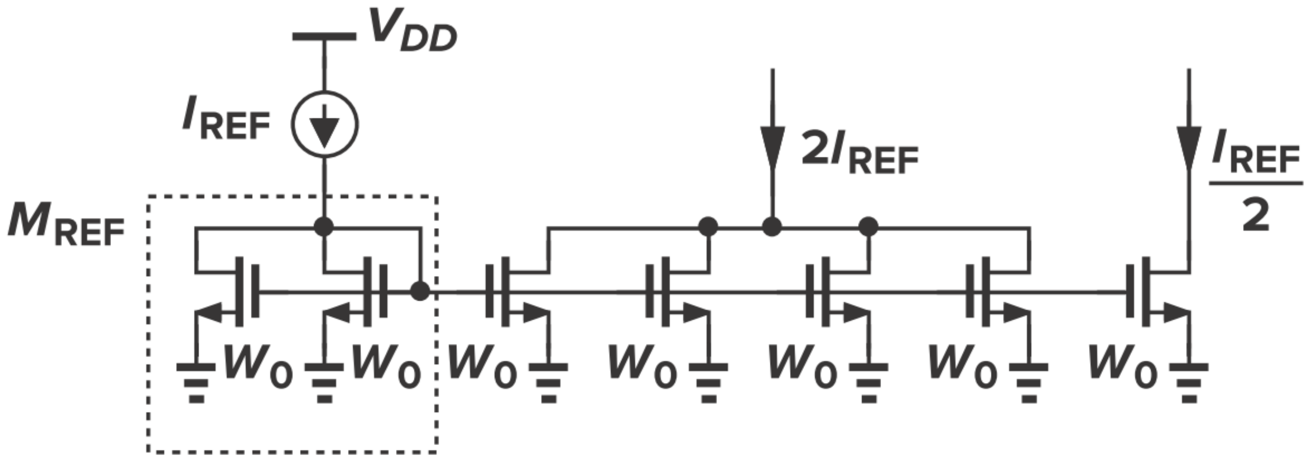




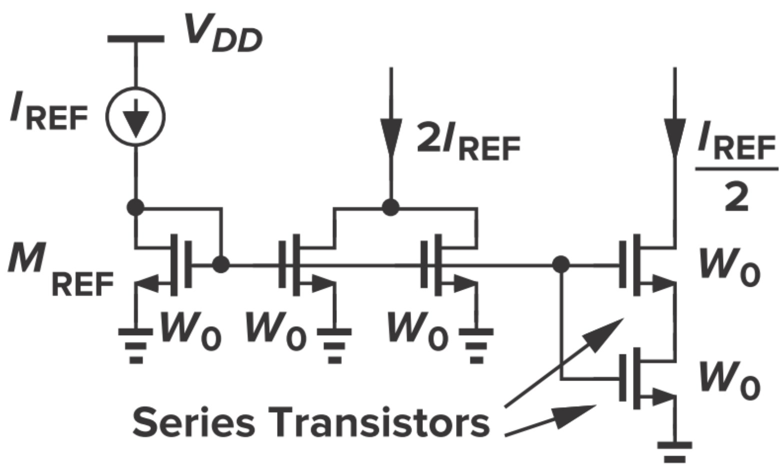
- 电流镜中的所有晶体管都采用相同的栅长
  - 保证相同的L_{eff}
  - 短沟道器件的阈值电压对沟道长度有一定的依赖性
- 电流值之比只能通过调节晶体管的宽度来实现
- 采用“单元”晶体管，重复此器件实现电流复制

如何产生$I_{REF}/2$的电流

- 二极管连接器件本身由两个“单元”器件构成

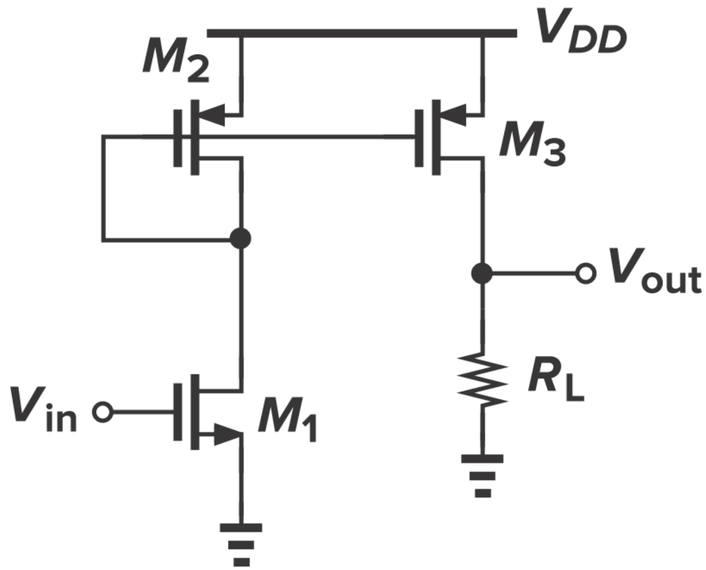


- 如果要生成多个电流，也可通过缩放沟道长度实现



例5. 2 电流镜作为放大器

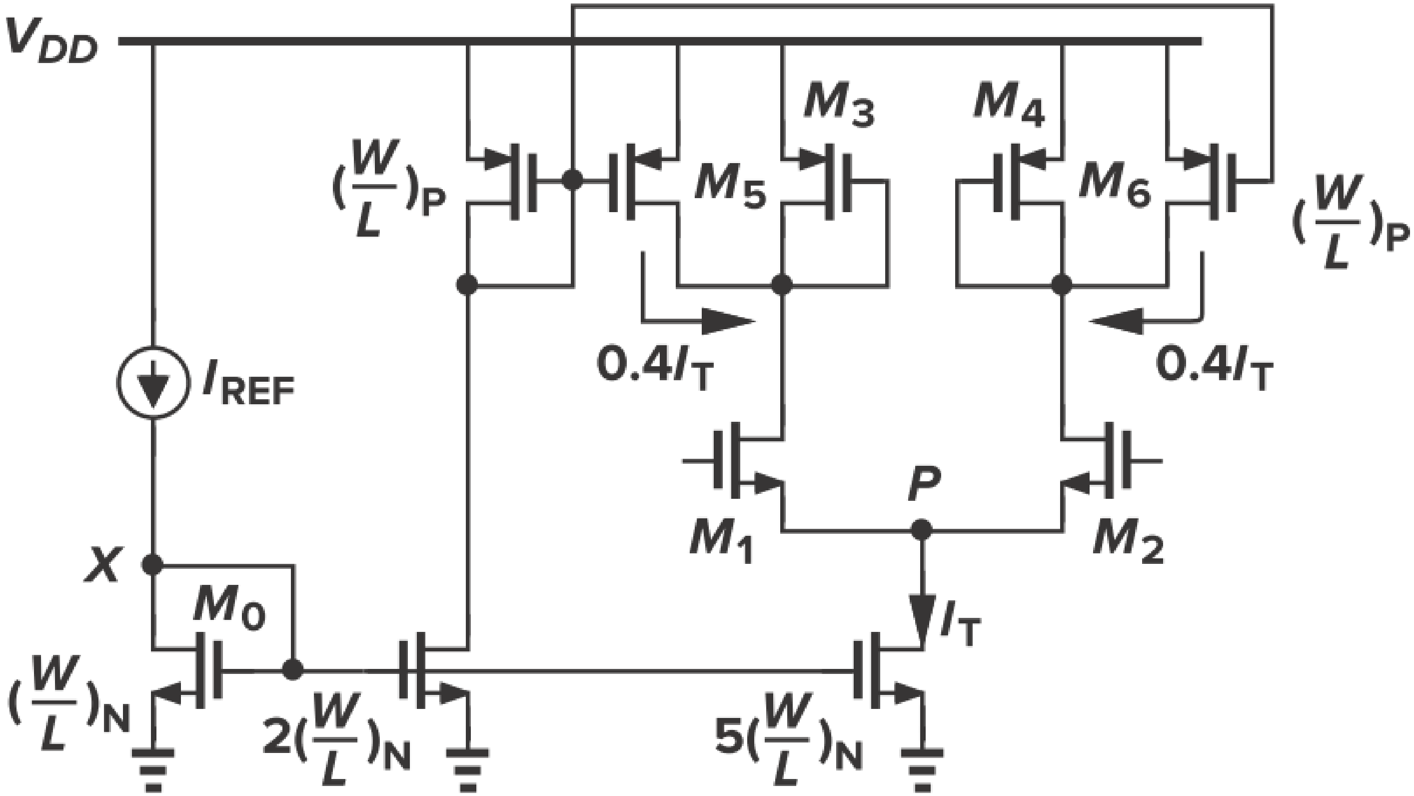
- 计算小信号增益



$$A_v = g_{m1} R_L (W/L)_3 / (W/L)_2.$$

以功耗为代价！

基本电流镜应用实例



V_{DD}
M_3
M_4
$(\frac{W}{L})_P$
M_5
M_6
$(\frac{W}{L})_P$
$0.4I_T$
$0.4I_T$
I_{REF}
P
M_1
M_2
X
M_0
I_T
$(\frac{W}{L})_N$
$2(\frac{W}{L})_N$
$5(\frac{W}{L})_N$

基本电流镜的问题

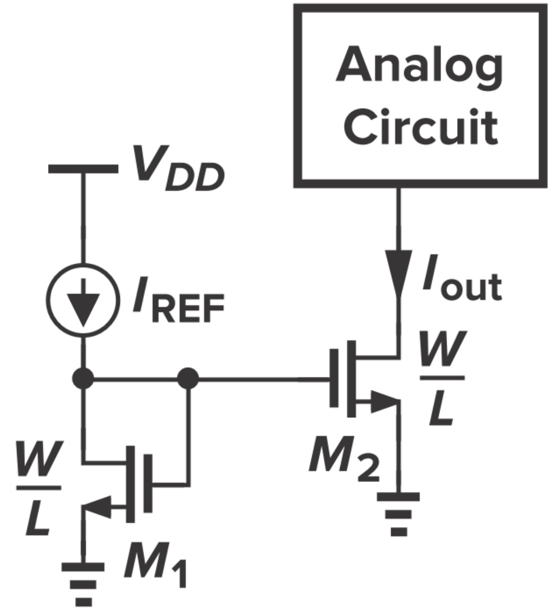
- 考虑沟道长度调制效应

$$I_{D1} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_1 (V_{GS} - V_{TH})^2(1+\lambda V_{DS1})$$

$$I_{D2} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_2 (V_{GS} - V_{TH})^2(1+\lambda V_{DS2})$$

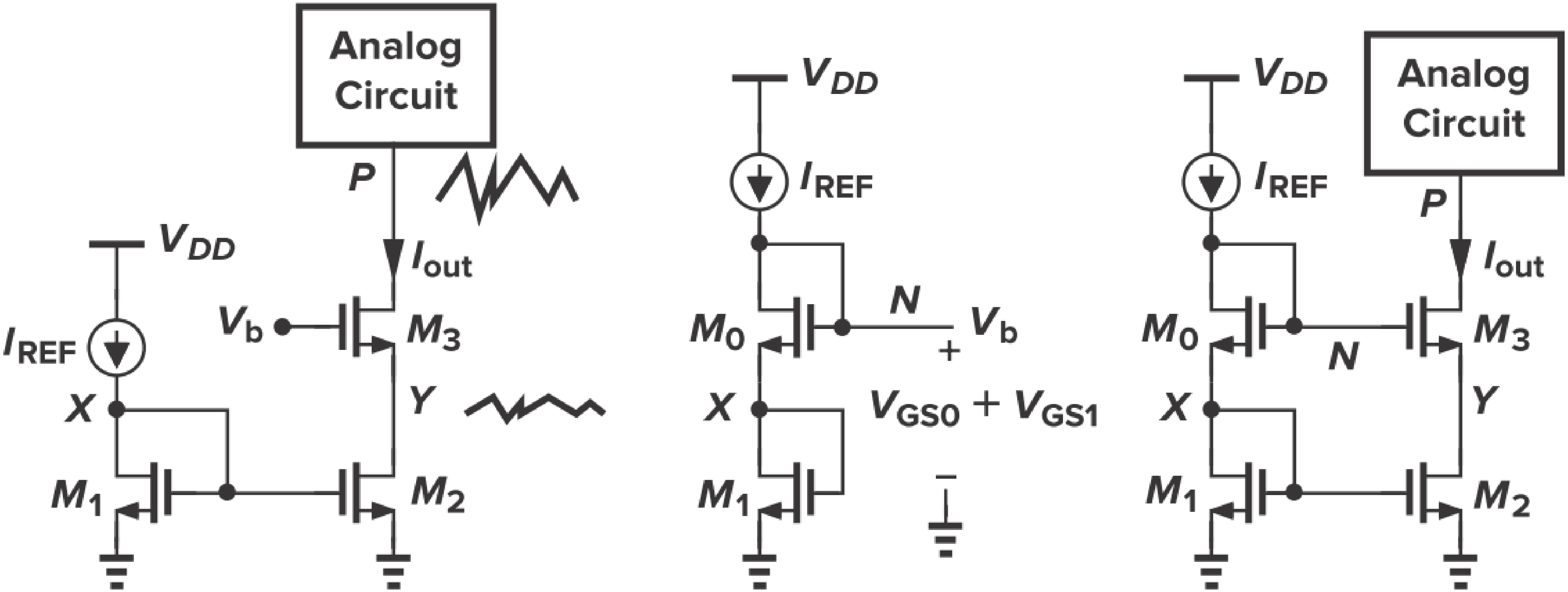
$$\Rightarrow \quad \frac{I_{D2}}{I_{D1}} = \frac{(W/L)_2}{(W/L)_1}\cdot\frac{1+\lambda V_{DS2}}{1+\lambda V_{DS1}}$$

$$V_{DS1} = V_{GS1} = V_{GS2} \neq V_{DS2}$$



- 设计电路使得V_{DS1}和V_{DS2}相等
  - 迫使V_{DS2}等于V_{DS1}
  - 迫使V_{DS1}等于V_{DS2}

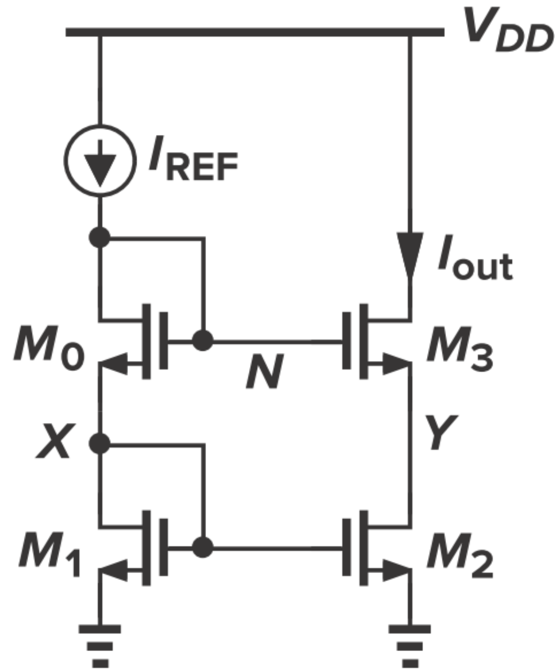
共源共栅电流镜



- 共源共栅器件可以起屏蔽作用，减小V_Y电压的变化
- $V_b - V_{GS3} = V_{DS2} = V_{GS1} \Rightarrow V_b = V_{GS3} + V_{GS1}$
- 通过设计M_0和M_3的宽长比使得$V_{GS0} = V_{GS3}$

例 5. 3

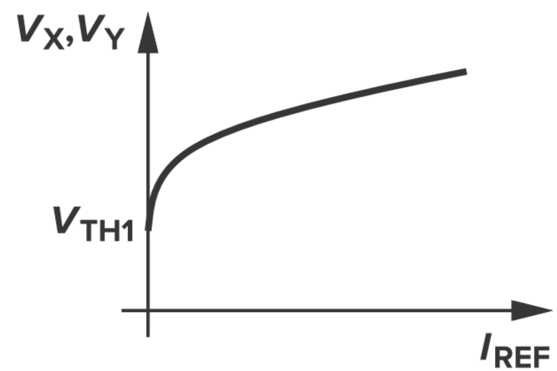
- 画出V_X和V_Y与I_{REF}的函数关系草图，电流源两端需要的电压为0.5V，求出最大I_{REF}



$$V_Y = V_X \approx \sqrt{2I_{REF}/[\mu_n C_{ox}(W/L)_1]} + V_{TH1}$$

$$V_N = V_{GS0} + V_{GS1}$$

$$= \sqrt{\frac{2I_{REF}}{\mu_n C_{ox}}}\left[\sqrt{\left(\frac{L}{W}\right)_0} + \sqrt{\left(\frac{L}{W}\right)_1}\right] + V_{TH0} + V_{TH1}$$



$$I_{REF,max} = \frac{\mu_n C_{ox}}{2}\frac{(V_{DD} - 0.5\ \mathrm{V} - V_{TH0} - V_{TH1})^2}{(\sqrt{(L/W)_0} + \sqrt{(L/W)_1})^2}$$

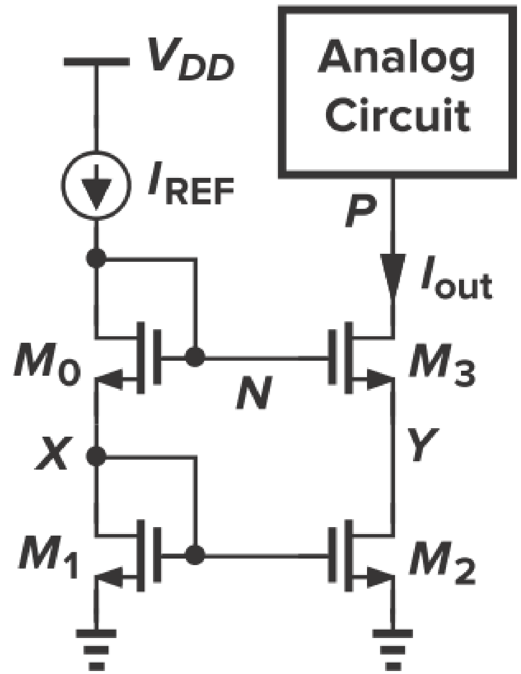
电压余度分析

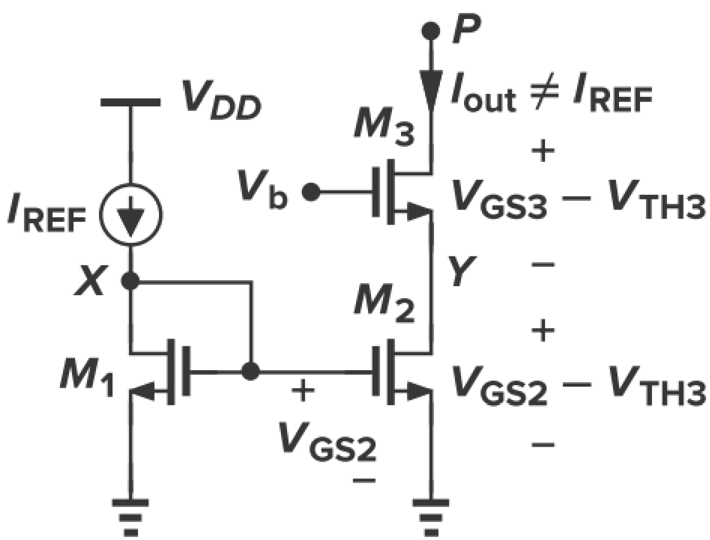
- P点允许的最小电压为

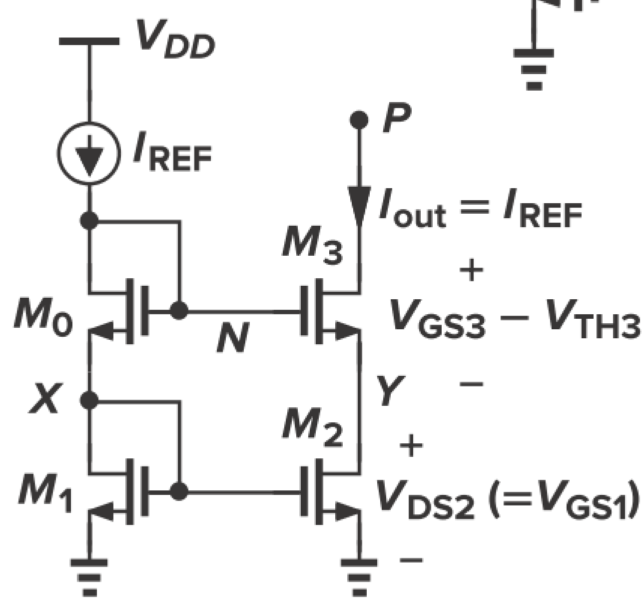
$$V_N - V_{TH} = V_{GS0} + V_{GS1} - V_{TH}$$

$$= (V_{GS0} - V_{TH}) + (V_{GS1} - V_{TH}) + V_{TH}$$

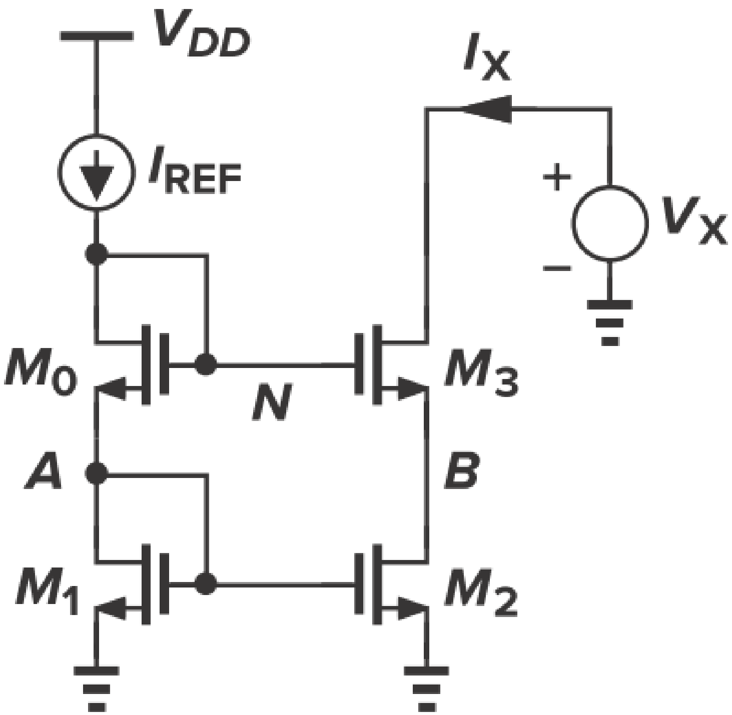
浪费了一个阈值电压的余度

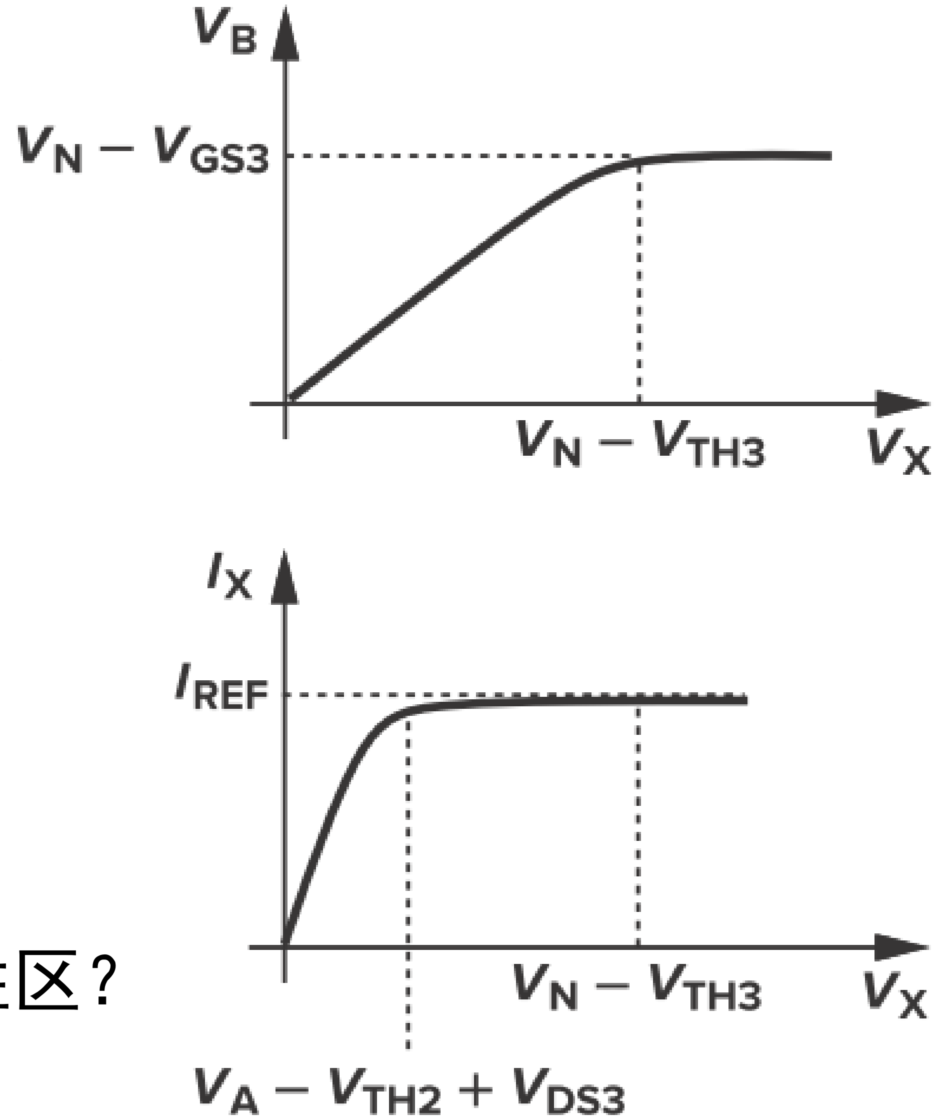






例5. 4 大信号分析

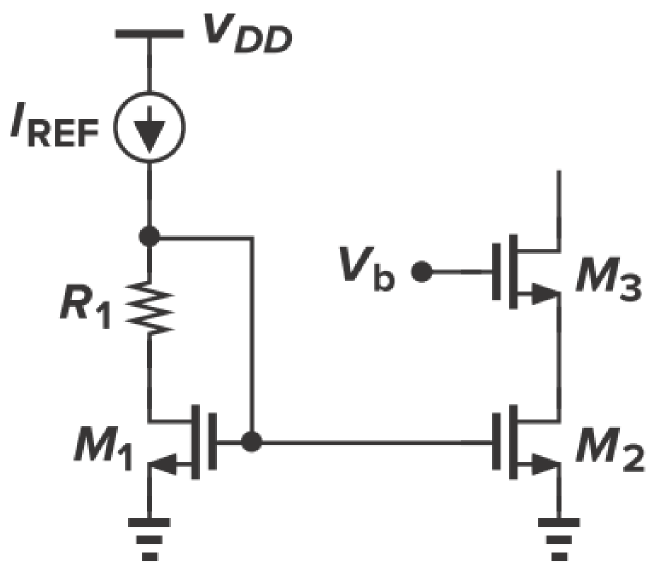


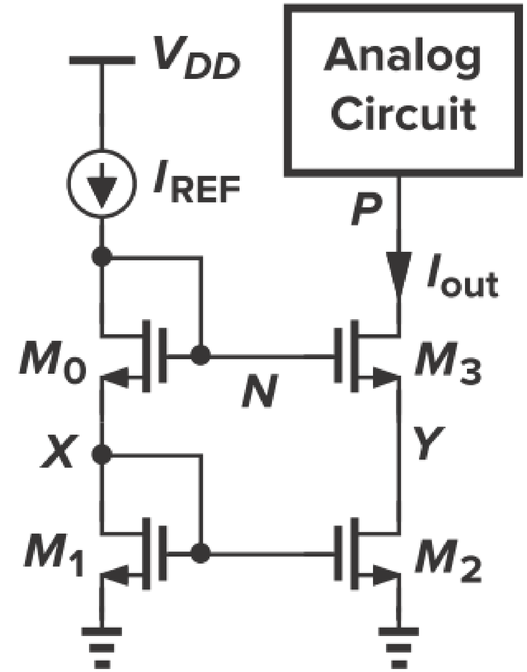


- M_2和M_3谁先进入线性区？

如何减小电压余度的损失？

- 希望V_{DS2}只消耗一个过驱动电压
- 如何使V_{DS1}只消耗一个过驱动电压？



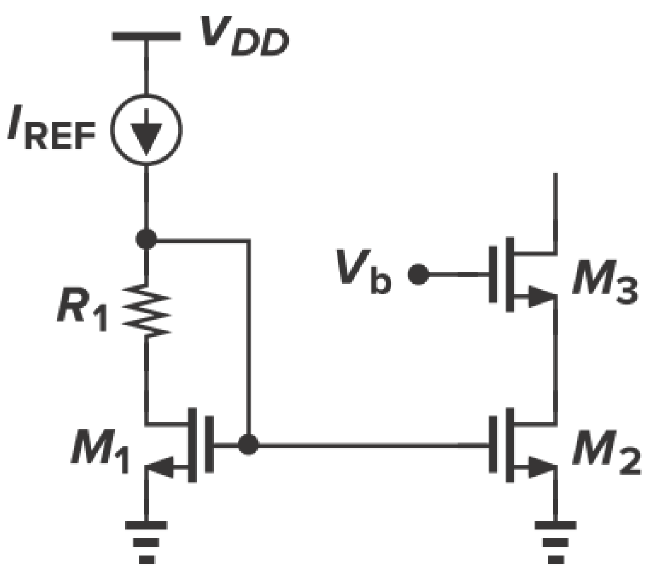


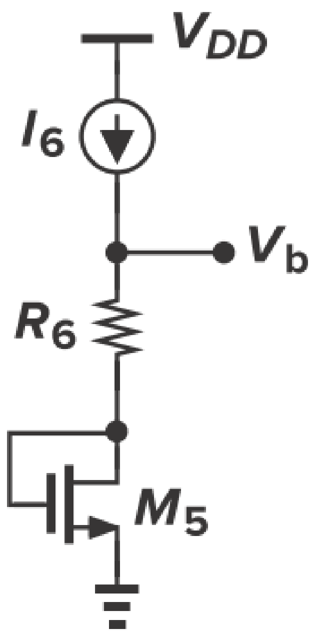
很难保证 $R_1 I_{REF} \approx V_{TH1} \Rightarrow V_{DS1} = V_{GS1} - R_1 I_{REF} \approx V_{GS1} - V_{TH1}$

如何产生 $V_b = V_{GS3} + (V_{GS1} - V_{TH1}) \Rightarrow V_{DS1} = V_{DS2}$

如何产生V_b

$$V_b = V_{GS3} + (V_{GS1} - V_{TH1})$$





$$V_b = V_{GS5} + R_6 I_6$$

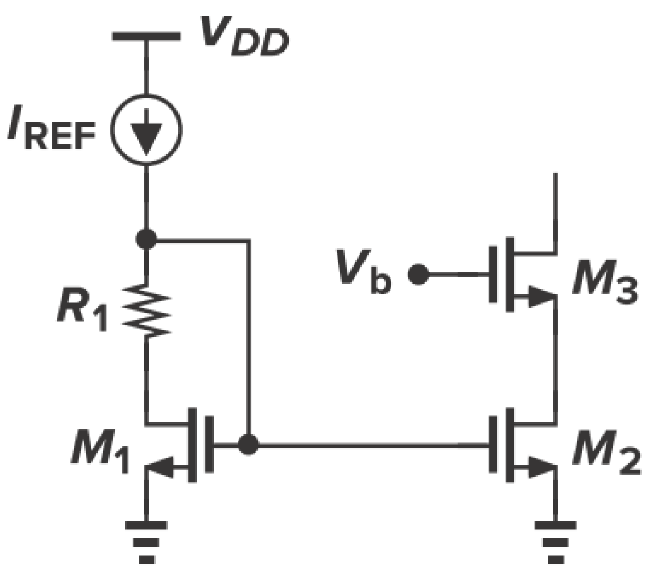
$$V_{GS5} = V_{GS3}$$

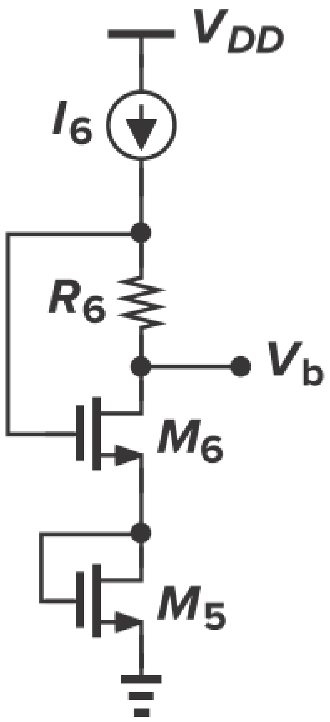
$$R_6 I_6 = V_{GS1} - V_{TH1} = V_{GS1} - R_1 I_{REF}$$

很难实现！

如何产生V_b

$$V_b = V_{GS3} + (V_{GS1} - V_{TH1})$$

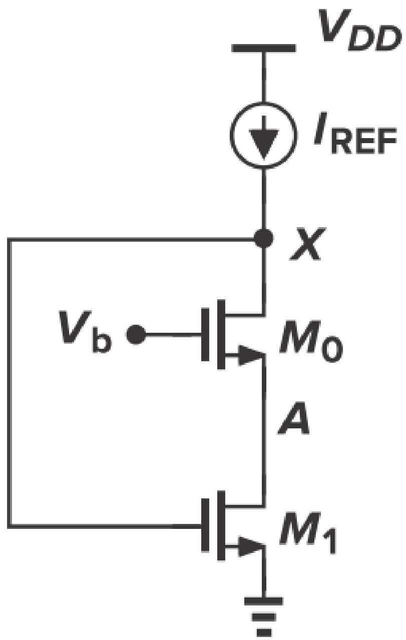




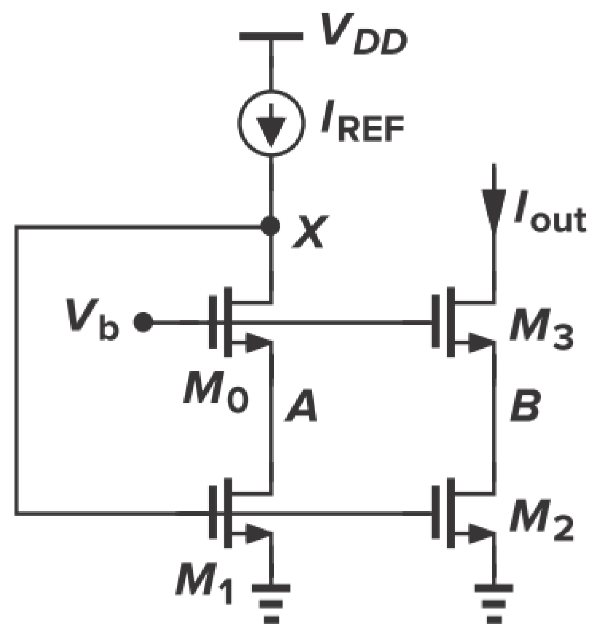
$$V_{GS5} = V_{GS3}$$

$$V_{GS6} - R_6 I_6 = V_{GS1} - V_{TH1} = V_{GS1} - R_1 I_{REF}$$

低压共源共栅电流镜



$$V_{DS1} = V_b - V_{GS0}$$

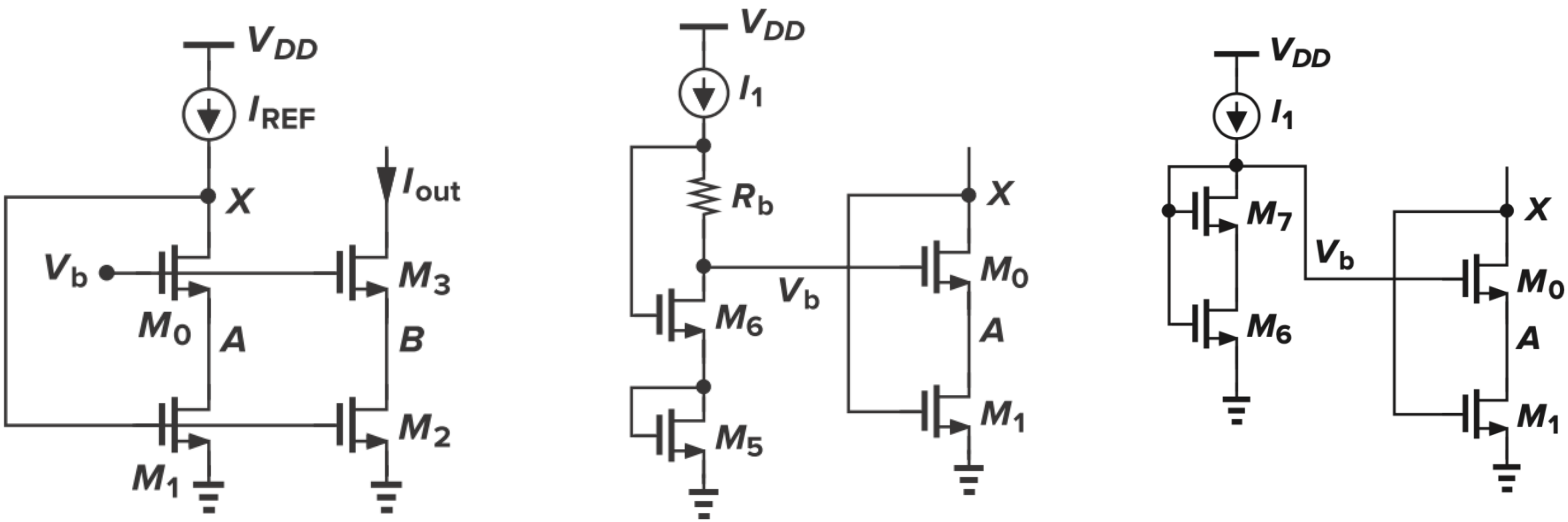


$$V_{GS0} = V_{GS3}$$

低压共源共栅结构

- 如何选择V_b?
- 如何产生V_b?

低压共源共栅电流镜



- 如何选择V_b?

M_0工作在饱和区 $\Rightarrow V_b - V_{TH0} \leq V_X \ (= V_{GS1})$

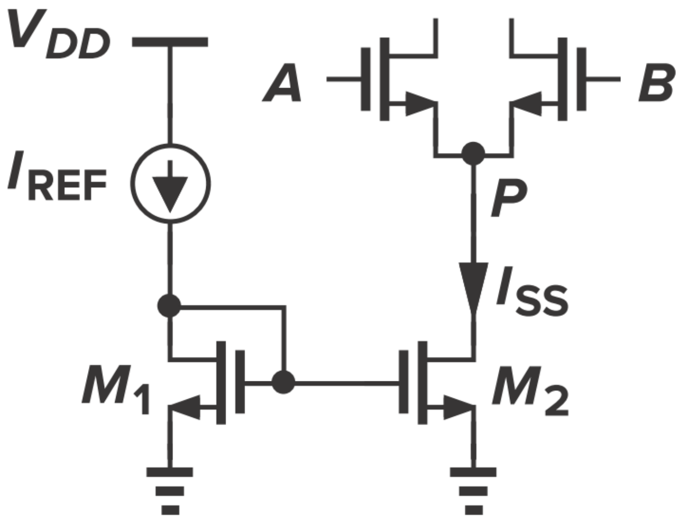
M_1工作在饱和区 $\Rightarrow V_{GS1} - V_{TH1} \leq V_A \ (= V_b - V_{GS0})$

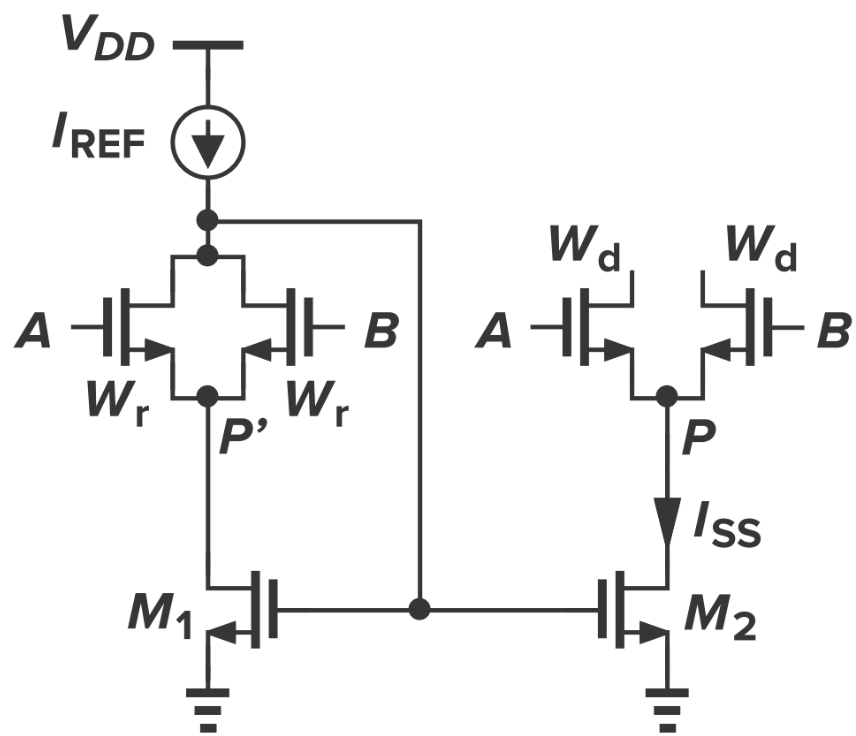
$$\Rightarrow V_{GS0} + (V_{GS1} - V_{TH1}) \leq V_b \leq V_{GS1} + V_{TH0}$$

- 如何产生V_b?

例 5. 6 基本电流镜的改进

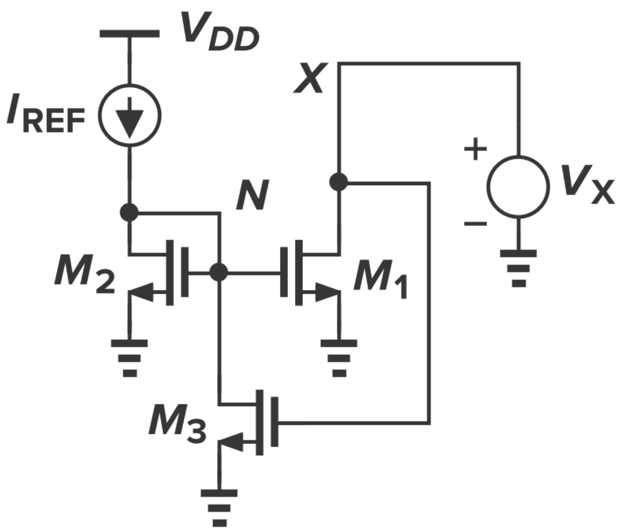
- 无法使用共源共栅电流镜

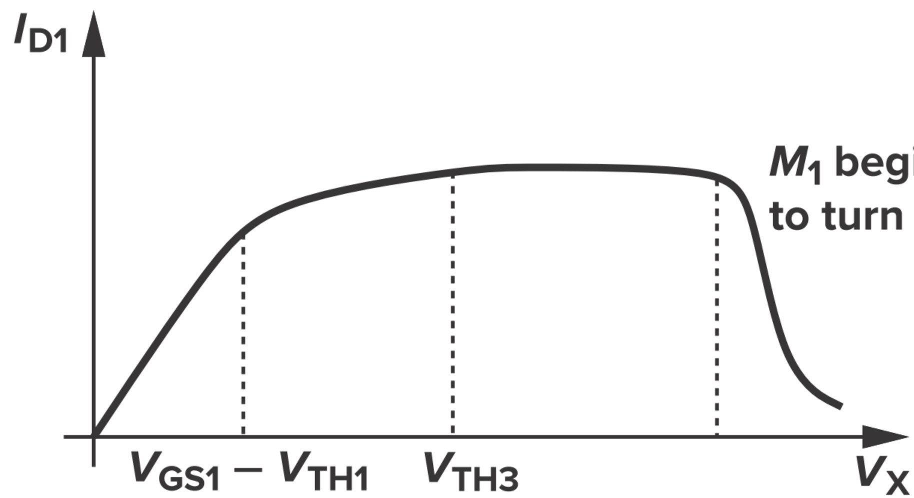




- 设法使V_{DS1}等于V_{DS2}
- A点和B点共模输入电平不可过大，否则复制的差动对进入线性区，引入误差

例 5. 7 另一种高输出阻抗的电流镜



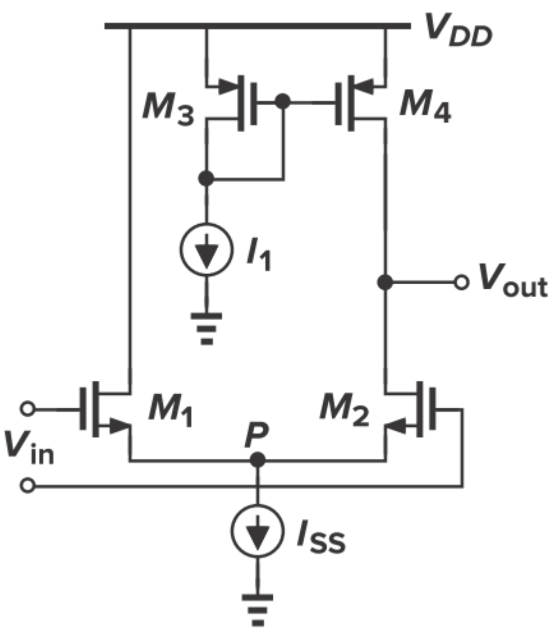


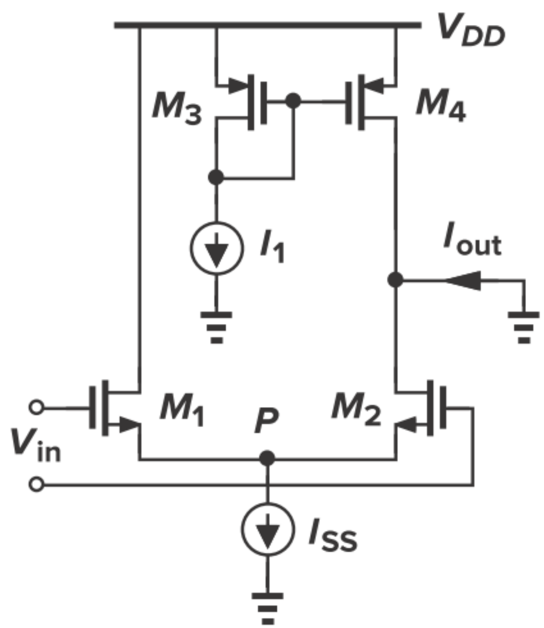
有电压余度限制，
$V_X > V_{TH3}$

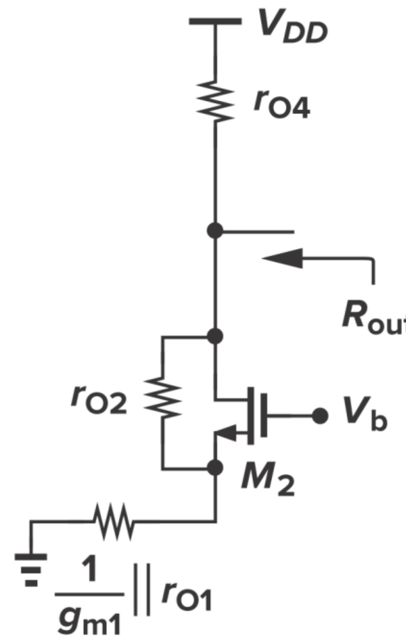
- 小信号特性？

- 大信号特性？

- 电流镜作为单端输出差动放大器的电流源负载







$$|A_v| = G_m R_{out}$$

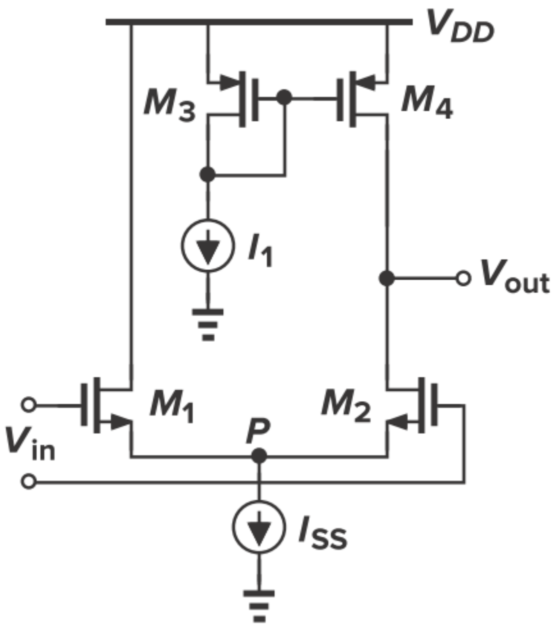
$$G_m = I_{out}/V_{in} = (g_{m2}V_{in}/2)/V_{in} = g_{m2}/2$$

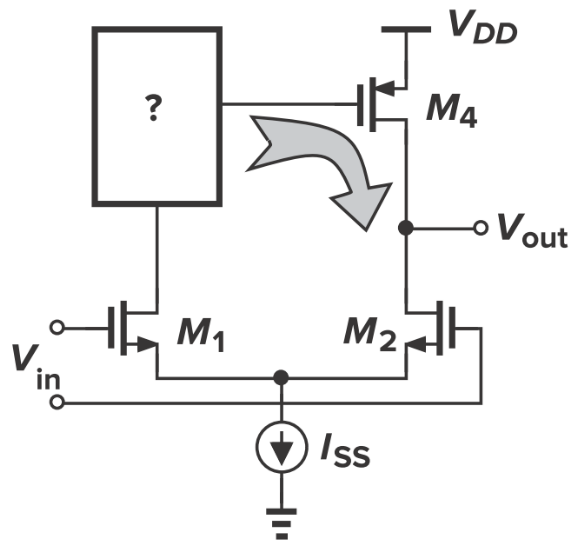
$$R_{deg} = (1/g_{m1})||r_{O1}$$

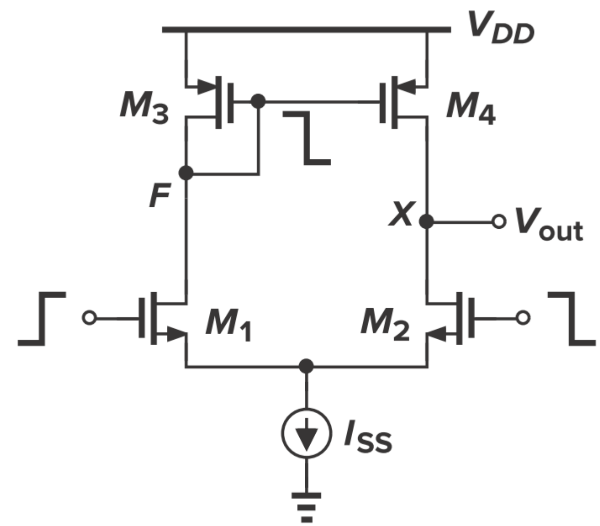
$$R_{out} = [(1 + g_{m2}r_{O2})R_{deg} + r_{O2}] \| r_{O4} = (2r_{O2})\|r_{O4}$$

$$\Rightarrow \quad |A_v| = \frac{g_{m2}}{2}[(2r_{O2})\|r_{O4}]$$

有源负载差动对



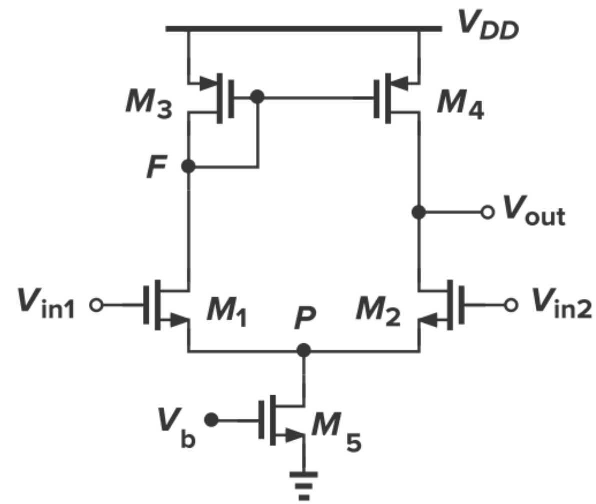


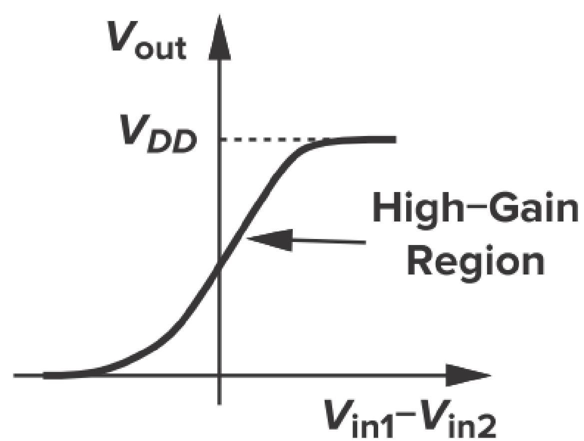


- M_1的小信号漏电流被浪费了
- 如何把这部分电流利用起来？
- 五管OTA：M_3和M_4相同且构成有源电流镜
- M_3如何提高增益的？

大信号分析

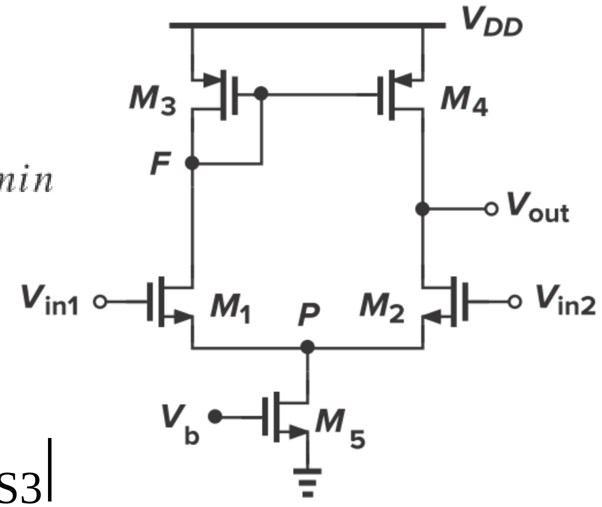
- 当V_{in1}比V_{in2}小很多，M_1，M_3和M_4均关断。没有电流能从V_{DD}流出，M_2和M_5都工作在深线性区，$V_{out} = 0$。
- 当V_{in1}接近V_{in2}，M_1导通，使I_{D5}的一部分流过M_3，使M_4导通。V_{out}开始依赖于I_{D4}和I_{D2}之间的差值。
- 当V_{in1}和V_{in2}非常接近时，M_2和M_4都工作在饱和区，小信号增益很高。
- 当V_{in1}大于V_{in2}时，I_{D4}增大而I_{D2}减小，V_{out}增大，最终使M_4进入线性区。
- 当V_{in1}比V_{in2}大很多，M_2关断，M_4的电流为0且工作的深线性区，$V_{out} = V_{DD}$

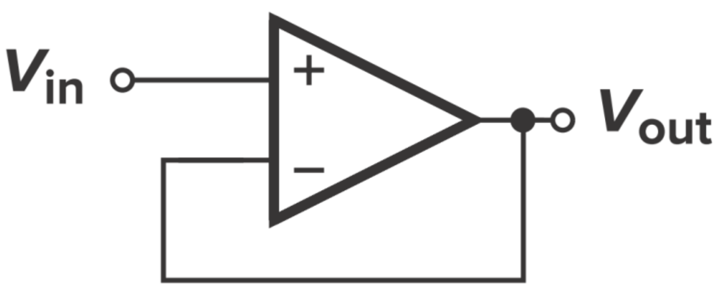


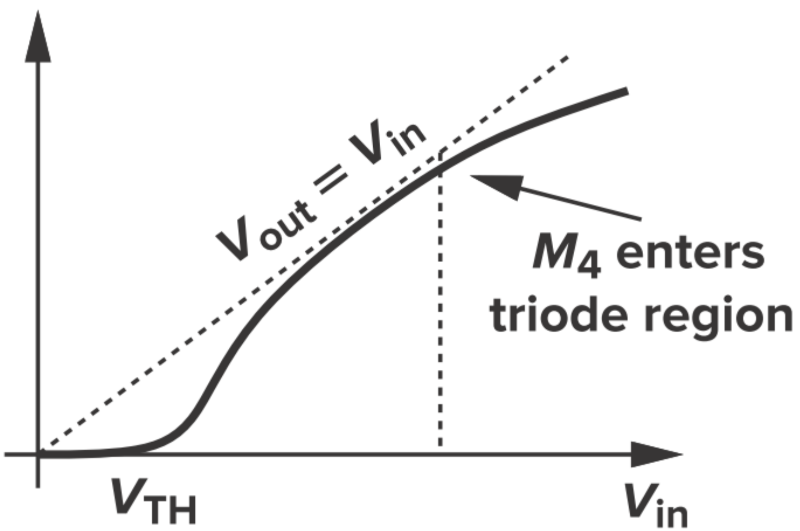


输入/输出共模电平

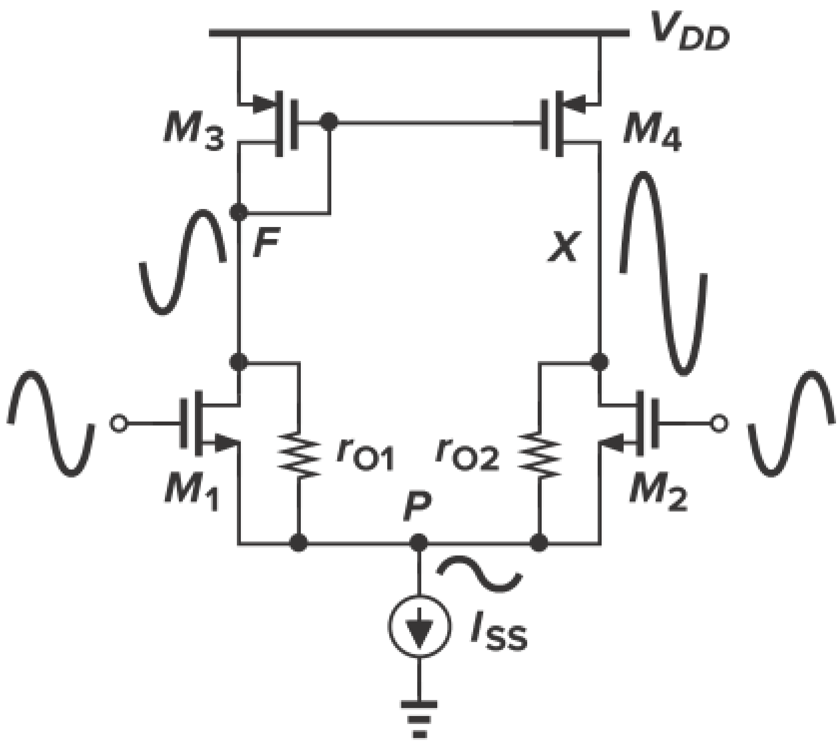
- 为了得到最大摆幅，输入共模电平应该尽可能低，最低值为$V_{GS1,2}+V_{DS5,min}$
- 输入共模电平对输出摆幅的限制是此电路的一个严重缺点
- 如果电路完全对称，$V_{out}=V_F=V_{DD}-|V_{GS3}|$
- 由于电路存在不对称，会导致V_{out}产生一个大的偏差，容易使M_2或M_4进入线性区。该电路很少开环使用。







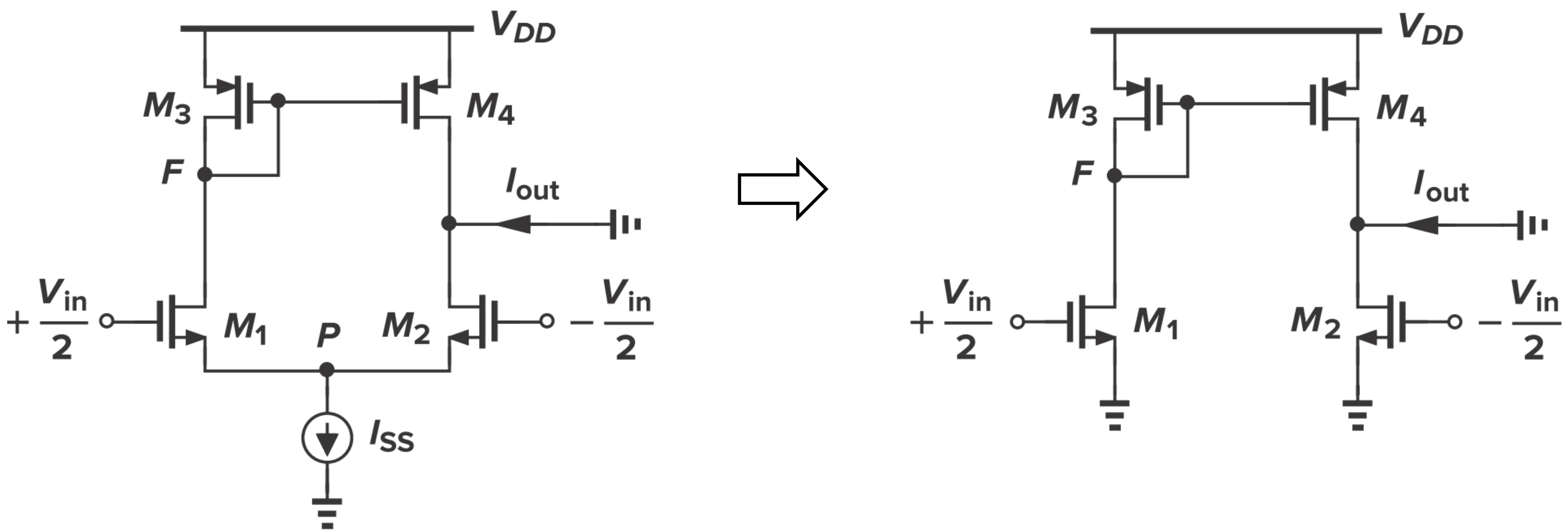
小信号分析



- 能否使用半边电路方法分析?
- Y点的电压变化幅度比F点大，左边是二极管连接负载，右边类似电流源负载

近似分析

- 计算G_m



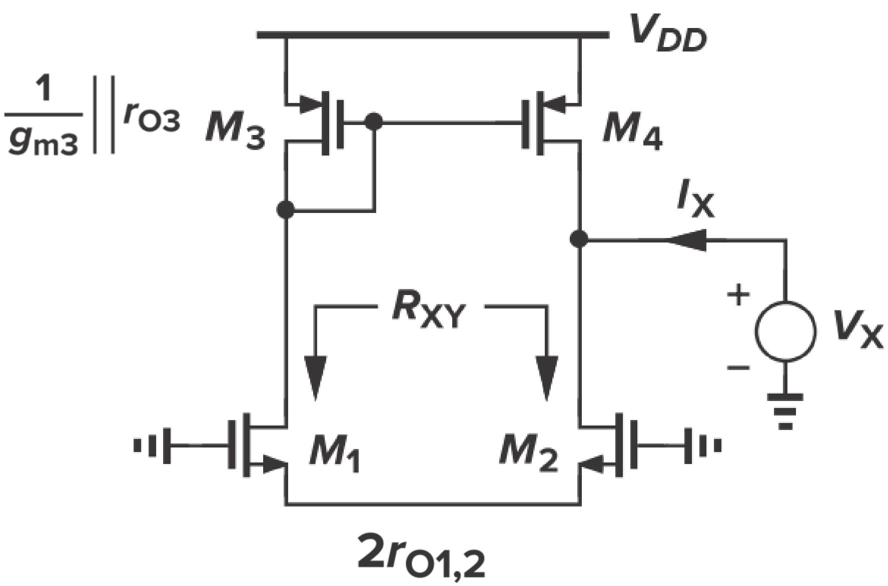
- 节点F的摆幅很小，F点对P点的影响可以忽略不计，P点可近似看成虚地点

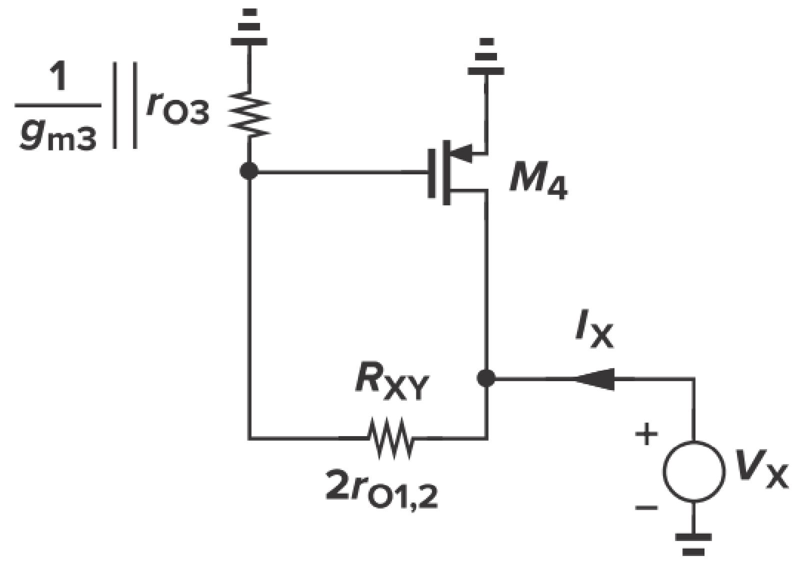
$$I_{D1} = |I_{D3}| = |I_{D4}| = g_{m1,2}V_{in}/2$$

$$I_{D2} = -g_{m1,2}V_{in}/2 \Rightarrow I_{out} = -g_{m1,2}V_{in} \Rightarrow |G_m| = g_{m1,2}$$

近似分析

- 计算R_{out}



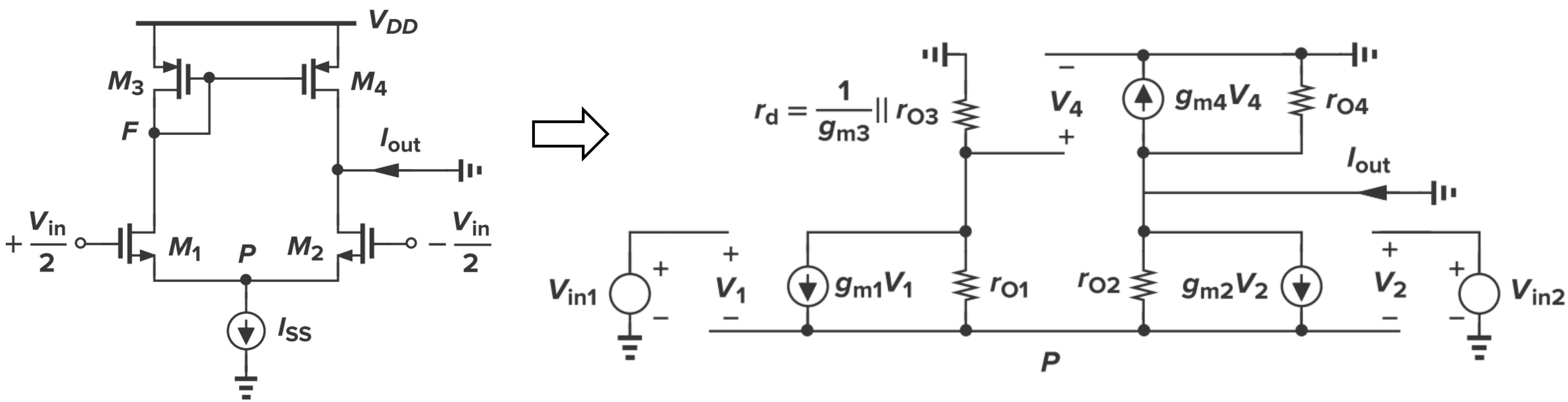


$$I_X = \frac{V_X}{2r_{O1,2} + \frac{1}{g_{m3}}||r_{O3}}\left[1 + \left(\frac{1}{g_{m3}}||r_{O3}\right) g_{m4}\right] + \frac{V_X}{r_{O4}}$$

$$\Rightarrow \quad R_{out} \approx r_{O2}\|r_{O4} \quad \Rightarrow \quad |A_v| = G_m R_{out} = g_{m1,2}(r_{O2}\|r_{O4})$$

精确分析

- 计算G_m



$$\left(-\frac{V_4}{r_d} - g_{m1}V_1\right) r_{O1} + V_{in1} - V_1 = V_4$$

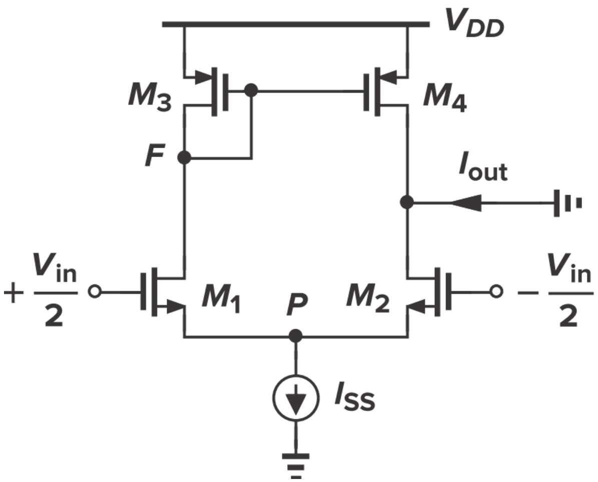
$$g_{m2}V_2 - \frac{V_{in2} - V_2}{r_{O2}} = \frac{V_4}{r_d} \quad \Rightarrow \quad I_{out} = -g_{m1}r_{O1}\frac{g_{m4}r_d + 1}{r_d + 2r_{O1}}(V_{in1} - V_{in2})$$

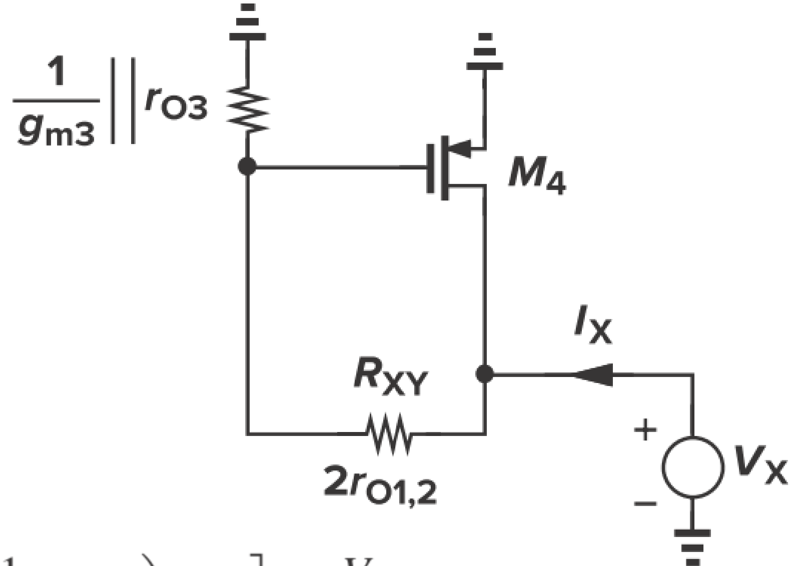
$$V_1 - V_2 = V_{in1} - V_{in2}$$

$$I_{out} = g_{m4}V_4 + V_4/r_d \quad \Rightarrow \quad G_m = -g_{m1}r_{O1}\frac{g_{m4}r_d + 1}{r_d + 2r_{O1}}$$

精确分析

- 计算R_{out}





$$I_X = \frac{V_X}{2r_{O1,2} + \frac{1}{g_{m3}}||r_{O3}}\left[1 + \left(\frac{1}{g_{m3}}||r_{O3}\right)g_{m4}\right] + \frac{V_X}{r_{O4}}$$

$$\Rightarrow \frac{I_X}{V_X} = \frac{1 + g_{m4}r_d}{2r_{O1} + r_d} + \frac{1}{r_{O4}} = \frac{(1 + g_{m4}r_d)r_{O4} + 2r_{O1} + r_d}{(2r_{O1} + r_d)r_{O4}}$$

$$\Rightarrow G_m R_{out} = -g_{m1}r_{O1}\frac{(g_{m4}r_d + 1)r_{O4}}{(g_{m4}r_d + 1)r_{O4} + 2r_{O1} + r_d}$$

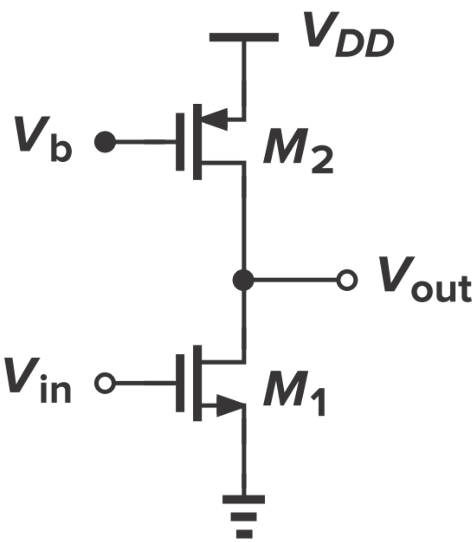
精确分析

- 计算$G_m R_{out}$

$$G_m R_{out} = -g_{m1} r_{O1} \frac{(g_{m4} r_d + 1) r_{O4}}{(g_{m4} r_d + 1) r_{O4} + 2 r_{O1} + r_d}$$

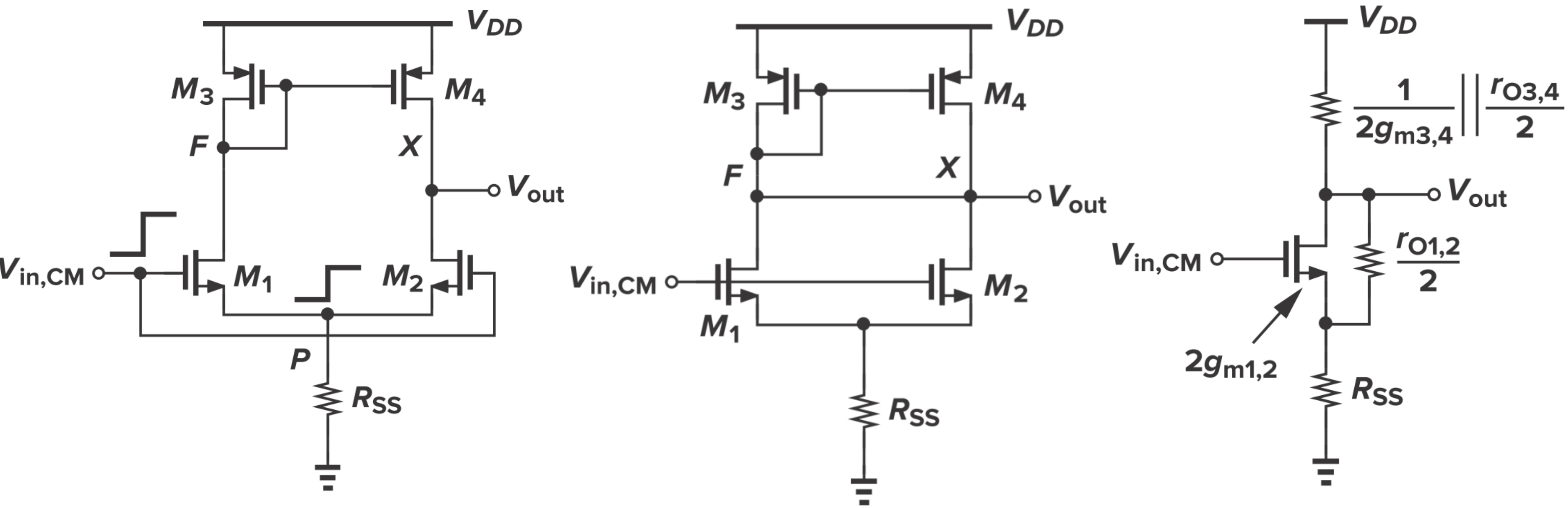
$$\Rightarrow \quad G_m R_{out} = -g_{m1} r_{O1} r_{O4} \frac{2 g_{m3} r_{O3} + 1}{(2 g_{m3} r_{O3} + 1) r_{O4} + 2 r_{O1} (1 + g_{m3} r_{O3}) + r_{O3}}$$

$$= -\frac{g_{m1} r_{O1} r_{O4}}{r_{O1} + r_{O3}} \cdot \frac{2 g_{m3} r_{O3} + 1}{2(g_{m3} r_{O3} + 1)}$$



$$\Rightarrow \quad |A_v| = \boxed{g_{m1}(r_{O1} \| r_{O4})} \frac{2 g_{m4} r_{O4} + 1}{2(g_{m4} r_{O4} + 1)}$$

共模特性



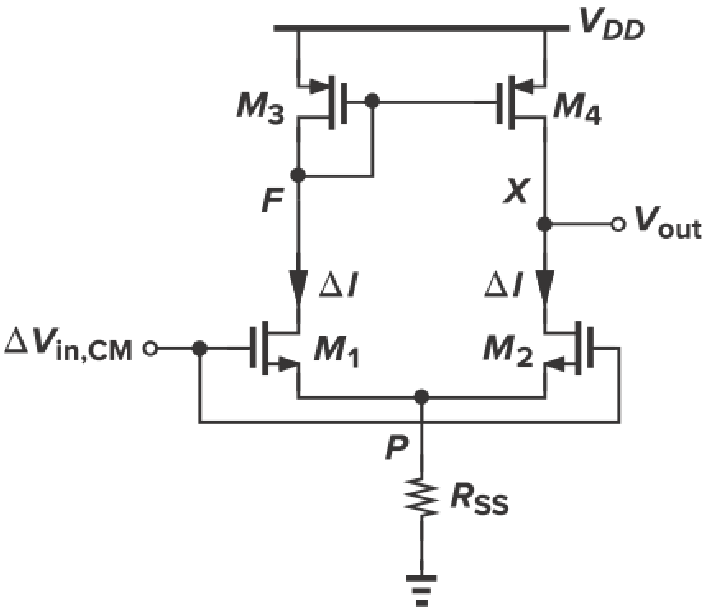
- 共模增益：输入共模电平的变化产生的单端输出的变化

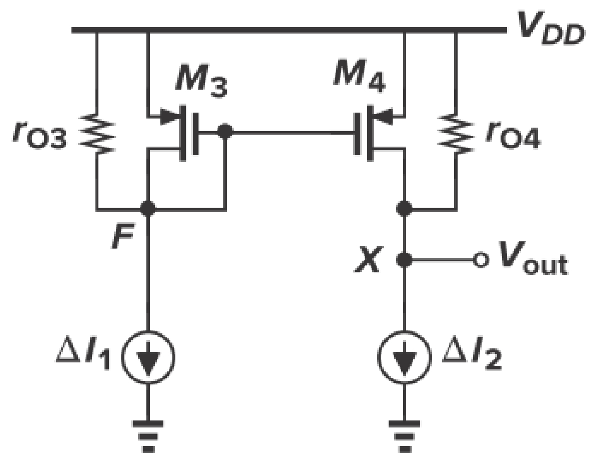
$$A_{CM} = \frac{\Delta V_{out}}{\Delta V_{in,CM}}$$

- 不考虑M_1和M_2的沟道长度调制效应

$$A_{CM} \approx \frac{-\frac{1}{2g_{m3,4}} \left\| \frac{r_{O3,4}}{2} \right.}{\frac{1}{2g_{m1,2}} + R_{SS}} = \frac{-1}{1+2g_{m1,2}R_{SS}} \frac{g_{m1,2}}{g_{m3,4}}$$

共模特性



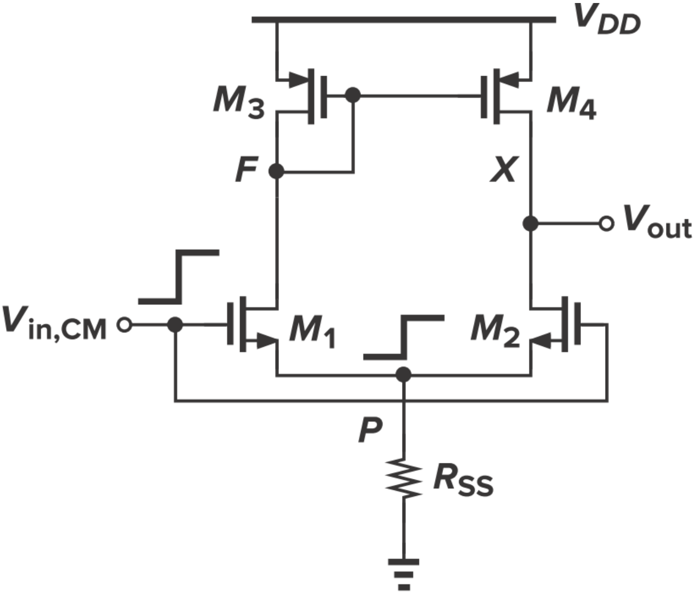


- 为什么共模增益不是0？

$$\Delta V_F = \Delta I_1 \left(\frac{1}{g_{m3}} \middle\| r_{O3} \right) \Rightarrow |\Delta I_{D4}| = g_{m4} \Delta V_F \quad = g_{m4} \Delta I_1 \frac{r_{O3}}{1 + g_{m3} r_{O3}}$$

$$\Rightarrow \Delta V_{out} = \left(\Delta I_1 g_{m4} \frac{r_{O3}}{1 + g_{m3} r_{O3}} - \Delta I_2\right) r_{O4} = -\Delta I \frac{1}{g_{m3} r_{O3} + 1} r_{O4}$$

共模特性



$$A_{CM} \approx \frac{-\dfrac{1}{2g_{m3,4}} \Big\| \dfrac{r_{O3,4}}{2}}{\dfrac{1}{2g_{m1,2}} + R_{SS}} = \frac{-1}{1+2g_{m1,2}R_{SS}} \frac{g_{m1,2}}{g_{m3,4}}$$

$$A_{DM} = g_{m1}(r_{O1}||r_{O4})$$

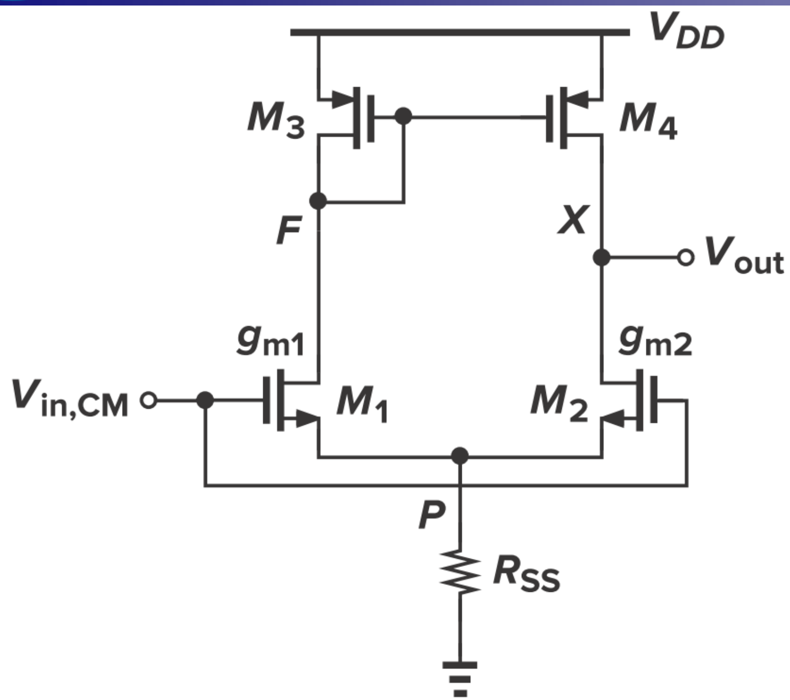
$$\Rightarrow \quad \text{CMRR} = \left|\frac{A_{DM}}{A_{CM}}\right| = g_{m1,2}(r_{O1,2}\|r_{O3,4}) \frac{g_{m3,4}(1+2g_{m1,2}R_{SS})}{g_{m1,2}}$$

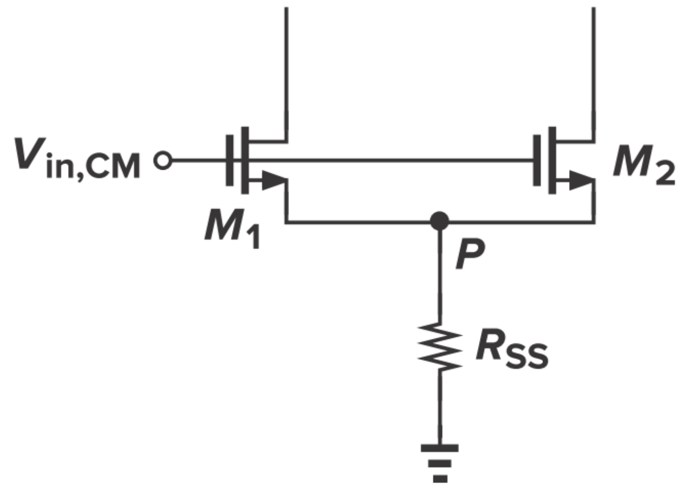
$$= (1+2g_{m1,2}R_{SS})g_{m3,4}(r_{O1,2}\|r_{O3,4})$$

CMRR的数量级是 $(g_m r_o)^2$

- 即使完全匹配，输出信号也会因为输入信号共模变化而变差，特别是在高频时。

失配的影响





$$\Delta V_P = \Delta V_{in,CM} \frac{R_{SS}}{R_{SS} + \dfrac{1}{g_{m1} + g_{m2}}} \Rightarrow$$

$$\Delta I_{D1} = g_{m1}(\Delta V_{in,CM} - \Delta V_P)$$

$$= \frac{\Delta V_{in,CM}}{R_{SS} + \dfrac{1}{g_{m1} + g_{m2}}} \frac{g_{m1}}{g_{m1} + g_{m2}}$$

$$\Delta I_{D2} = g_{m2}(\Delta V_{in,CM} - \Delta V_P)$$

$$= \frac{\Delta V_{in,CM}}{R_{SS} + \dfrac{1}{g_{m1} + g_{m2}}} \frac{g_{m2}}{g_{m1} + g_{m2}}$$

失配的影响

$$|\Delta I_{D4}| = g_{m4}[(1/g_{m3})\|r_{O3}]\Delta I_{D1}$$

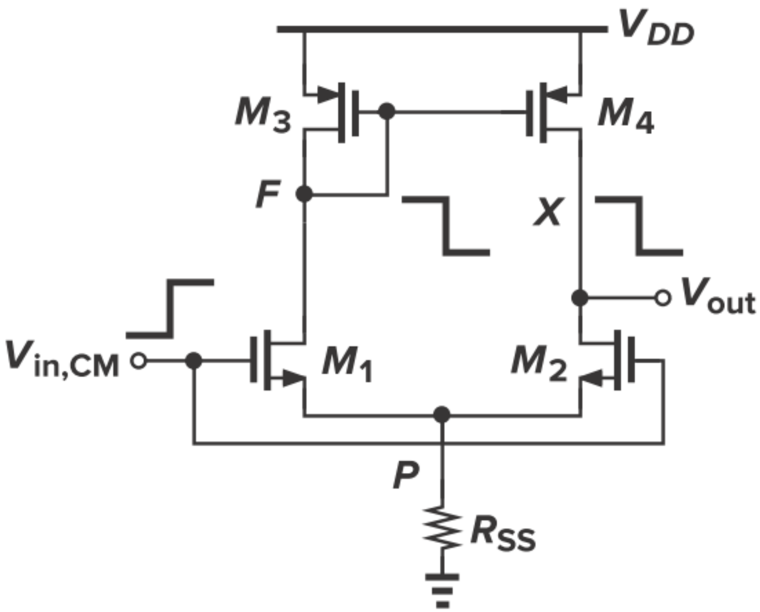
$$\Rightarrow \Delta V_{out} = \left[\frac{g_{m1}\Delta V_{in,CM}}{1+(g_{m1}+g_{m2})R_{SS}}\frac{r_{O3}}{r_{O3}+\dfrac{1}{g_{m3}}} - \frac{g_{m2}\Delta V_{in,CM}}{1+(g_{m1}+g_{m2})R_{SS}}\right]r_{O4}$$

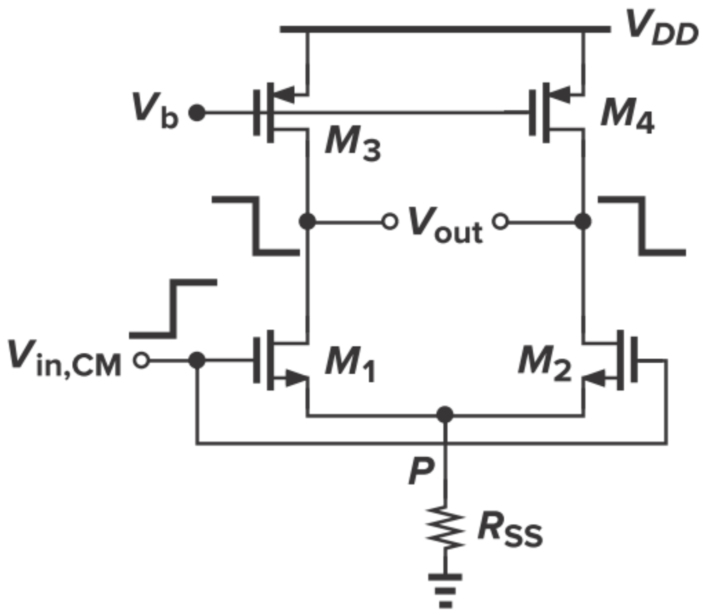
$$= \frac{\Delta V_{in,CM}}{1+(g_{m1}+g_{m2})R_{SS}}\frac{(g_{m1}-g_{m2})r_{O3}-g_{m2}/g_{m3}}{r_{O3}+\dfrac{1}{g_{m3}}}r_{O4}$$

$r_{O3} \gg 1/g_{m3}$

$$\Rightarrow \frac{\Delta V_{out}}{\Delta V_{in,CM}} \approx \frac{(g_{m1}-g_{m2})r_{O3}-g_{m2}/g_{m3}}{1+(g_{m1}+g_{m2})R_{SS}}$$

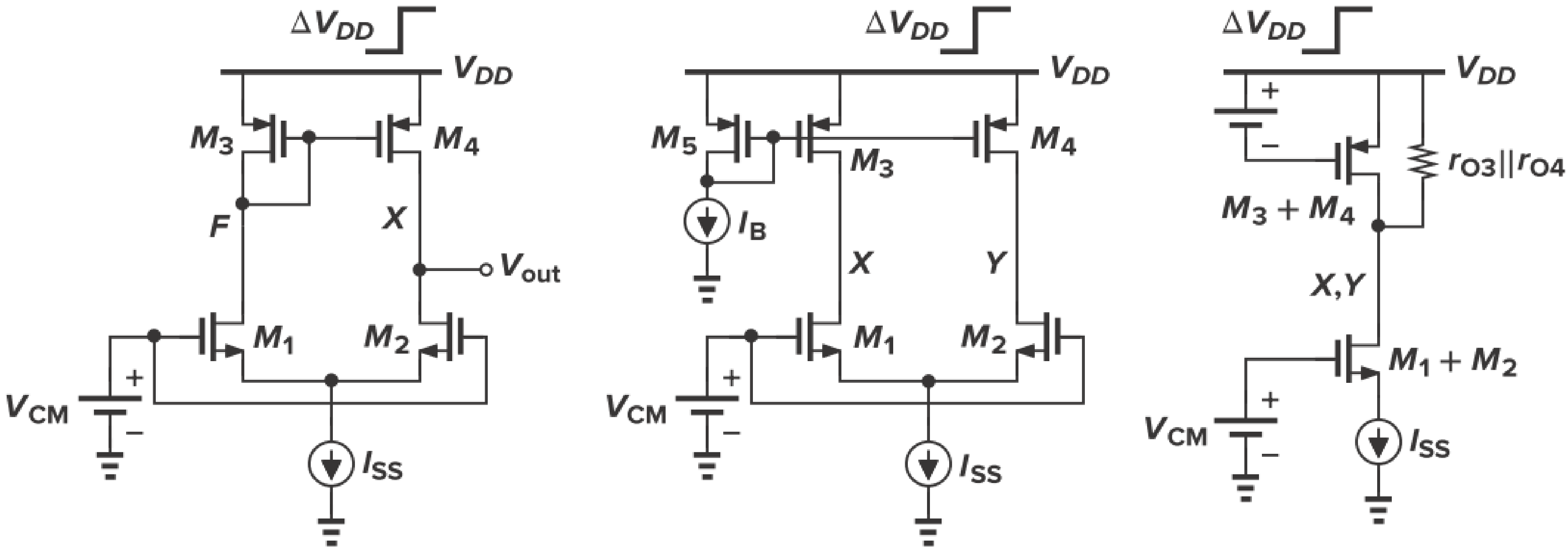
五管OTA与全差分结构的对比





- 五管OTA的两个缺点：
  - 即使电路完全匹配，电路的CMRR仍然有限

五管OTA与全差分结构的对比



- 五管OTA的两个缺点：
  - 即使电路完全匹配，电路的CMRR仍然有限
  - 电源抑制性能较差

本章总结

- 基本电流镜
  - 电流仅于晶体管宽长比的比率有关
  - 采用“单元”晶体管实现比例的缩放
  - 精度受到沟道长度调制效应影响
- 共源共栅电流镜
  - 电压余度问题
  - 低压共源共栅结构
- 有源电流镜（五管OTA）
  - 大信号分析
  - 小信号分析
  - 共模特性

Thank you

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