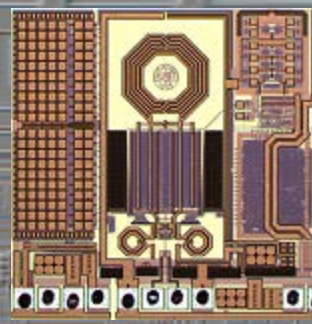




模拟集成电路设计原理

(Principle of Analog Integrated Circuit Design, INF0130025.02)

2014年11月6日

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<http://rfic.fudan.edu.cn/Courses.htm>

复旦大学/微电子学院/射频集成电路设计研究小组

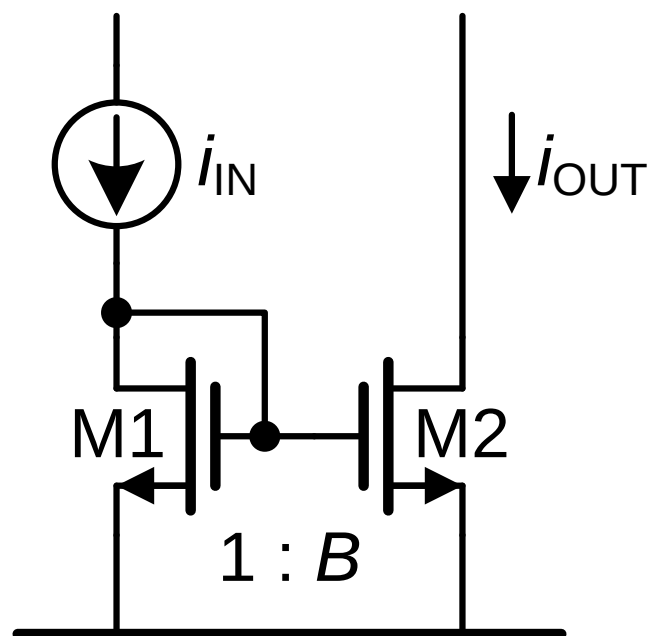
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差分电压放大器

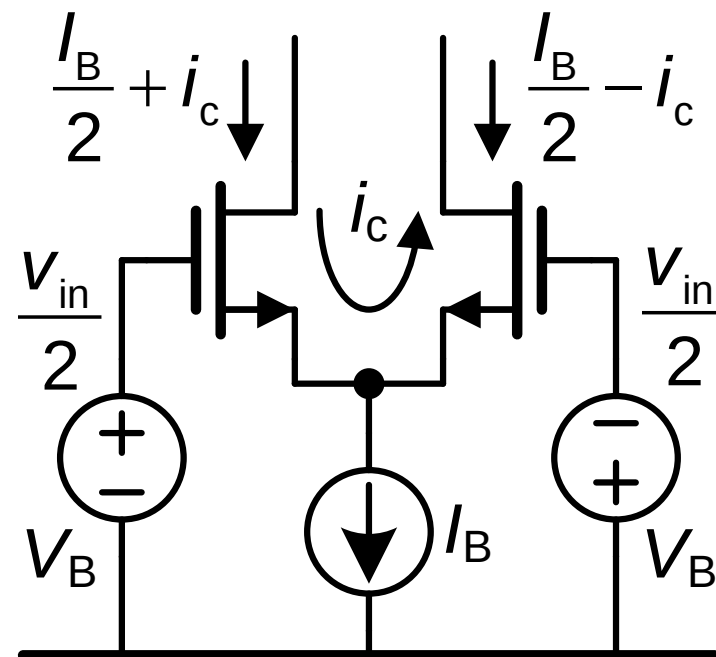
差分电流放大器

双晶体管电路



$$i_{OUT} = B i_{IN}$$

电流镜/放大器



$$i_c = g_m \frac{V_{in}}{2}$$

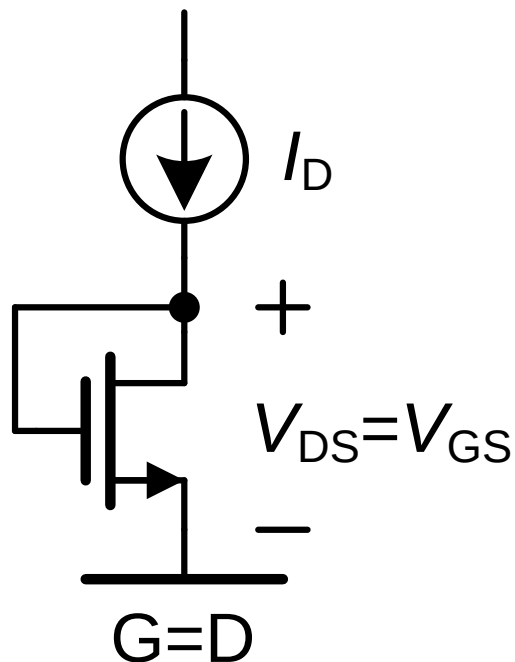
差分电压放大器

目录

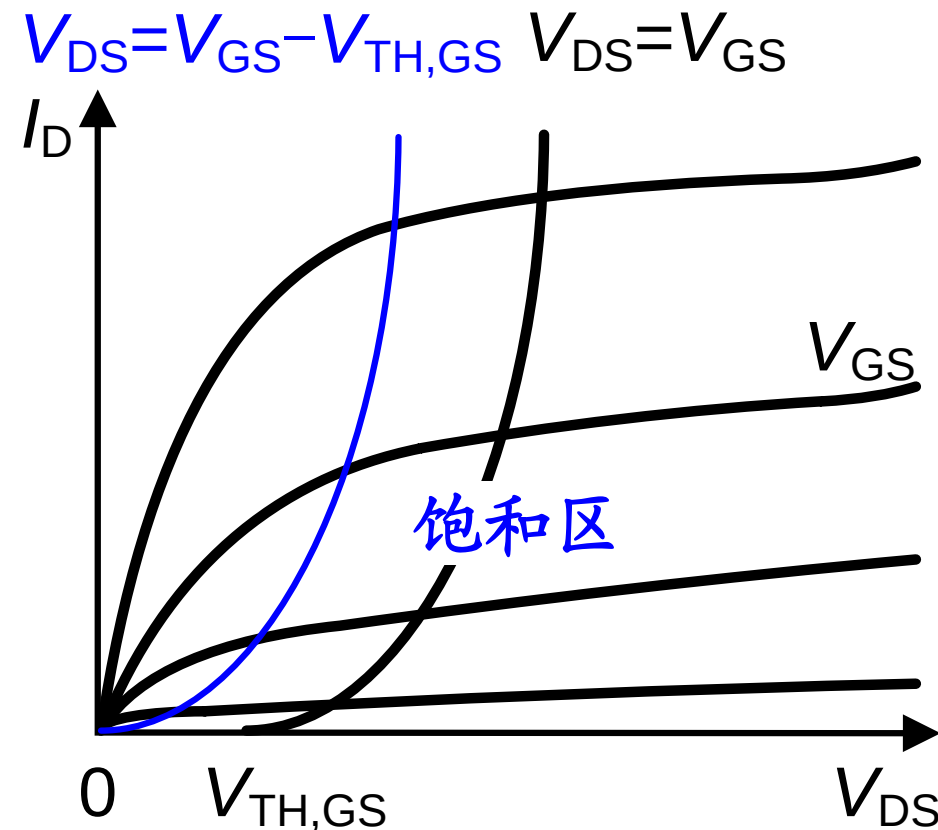
- 电流镜
- 差分对
- 差分电压放大器和差分电流放大器

Ref.: W. Sansen : Analog Design Essentials, Springer 2006

二极管连接的MOST

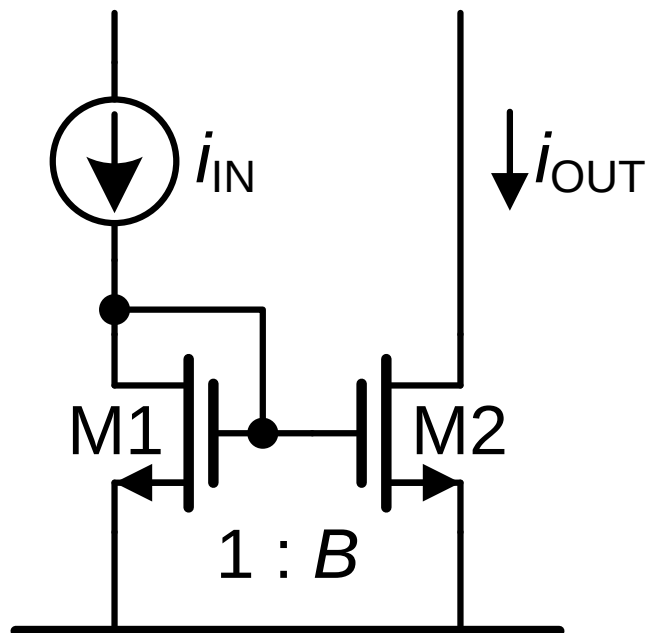


$$I_D = K'_n \frac{W}{L} (V_{GS} - V_{TH,GS})^2$$

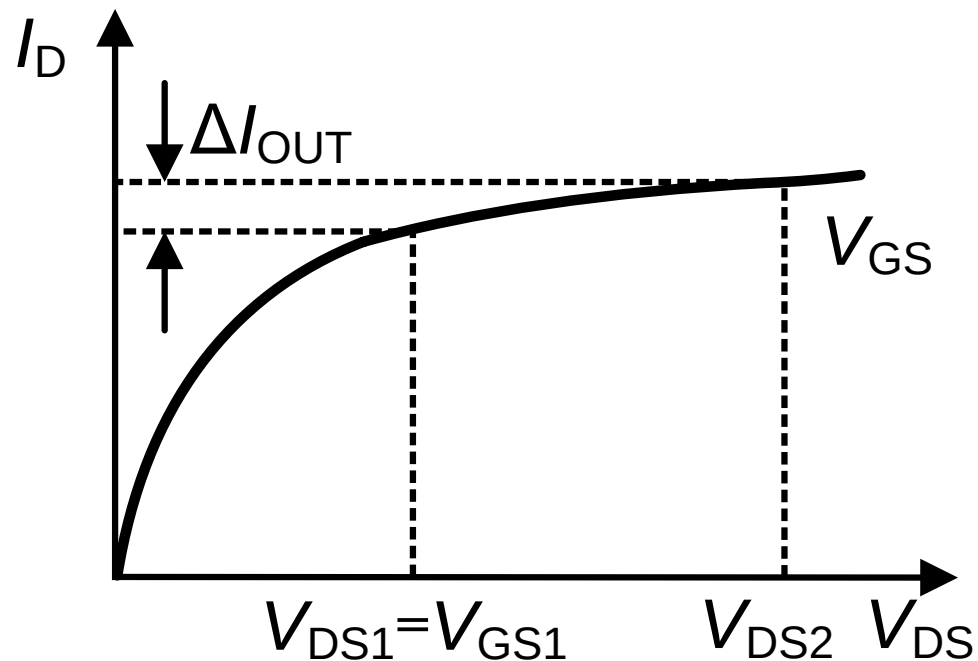


$$g_m = \frac{dI_D}{dV_{GS}}$$

电流镜

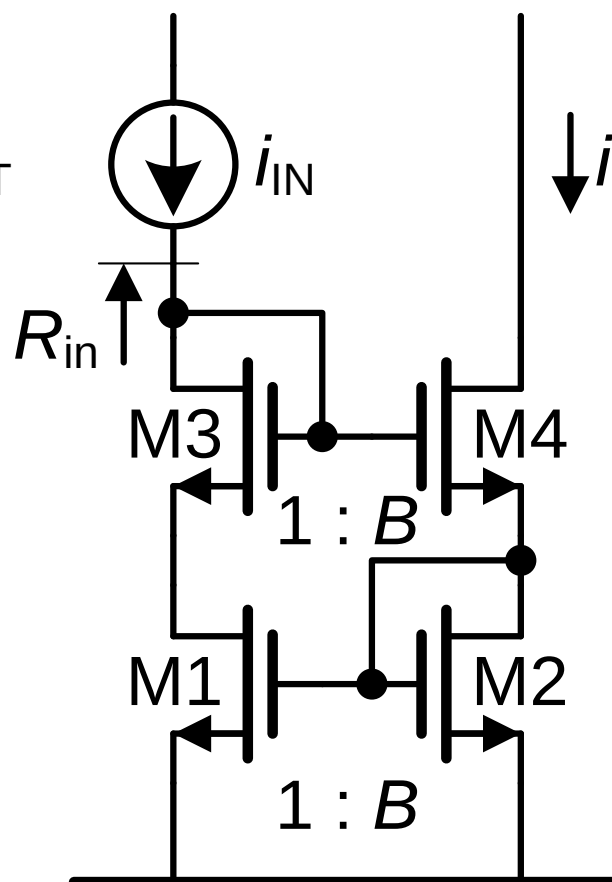
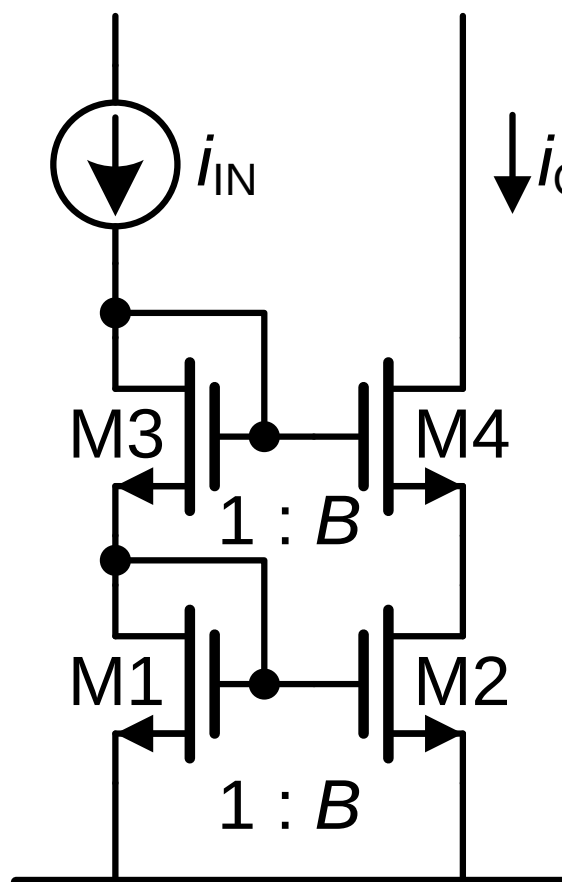


$$i_{OUT} = B i_{IN}$$



$$\frac{\Delta I_{OUT}}{I_{OUT}} = \frac{V_{DS2} - V_{DS1}}{V_E L_2}$$

改进的电流镜



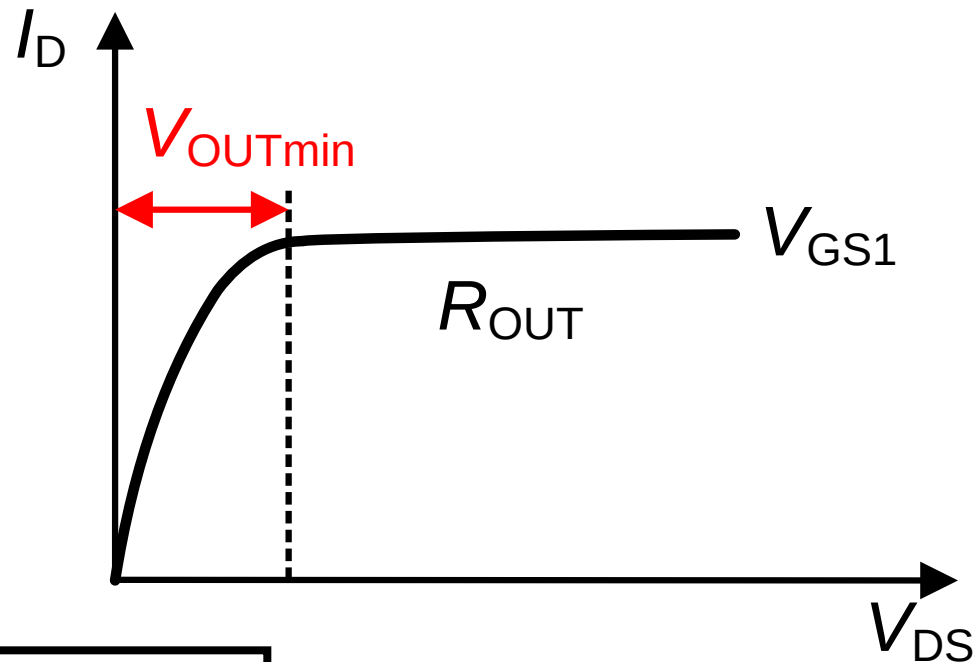
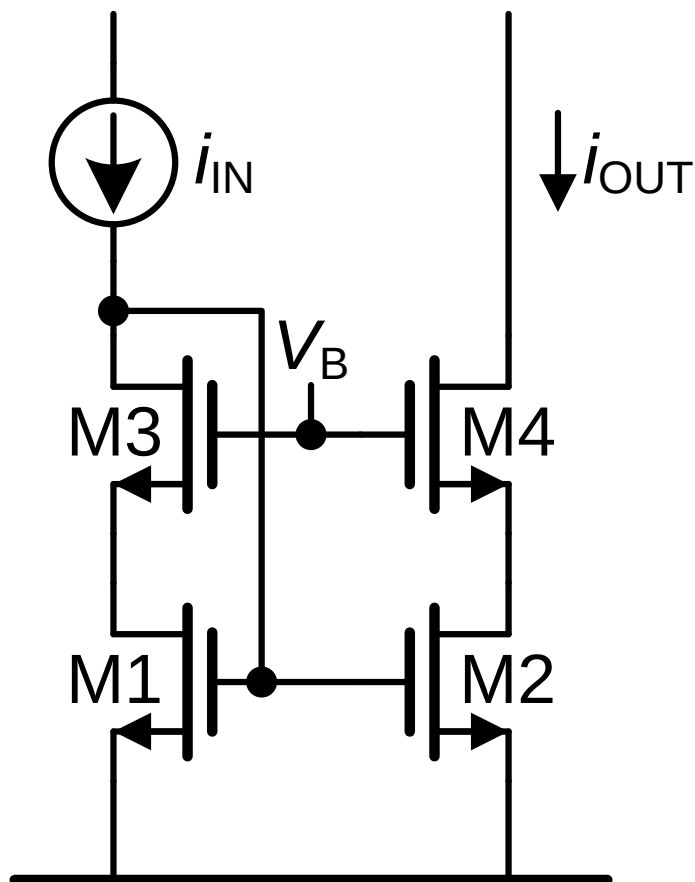
反馈 $T = g_{m1} R_{in}$

$$V_{DS2} = V_{DS1}$$

$$R_{out} = r_{ds2} g_{m4} r_{ds4}$$

$$\begin{aligned} V_{OUTmin} &= V_{GS} + V_{DS} \\ &\approx 0.9 + 0.2 \\ &= 1.1 \text{ V} \\ &\text{太大!!!} \end{aligned}$$

低电压电流镜

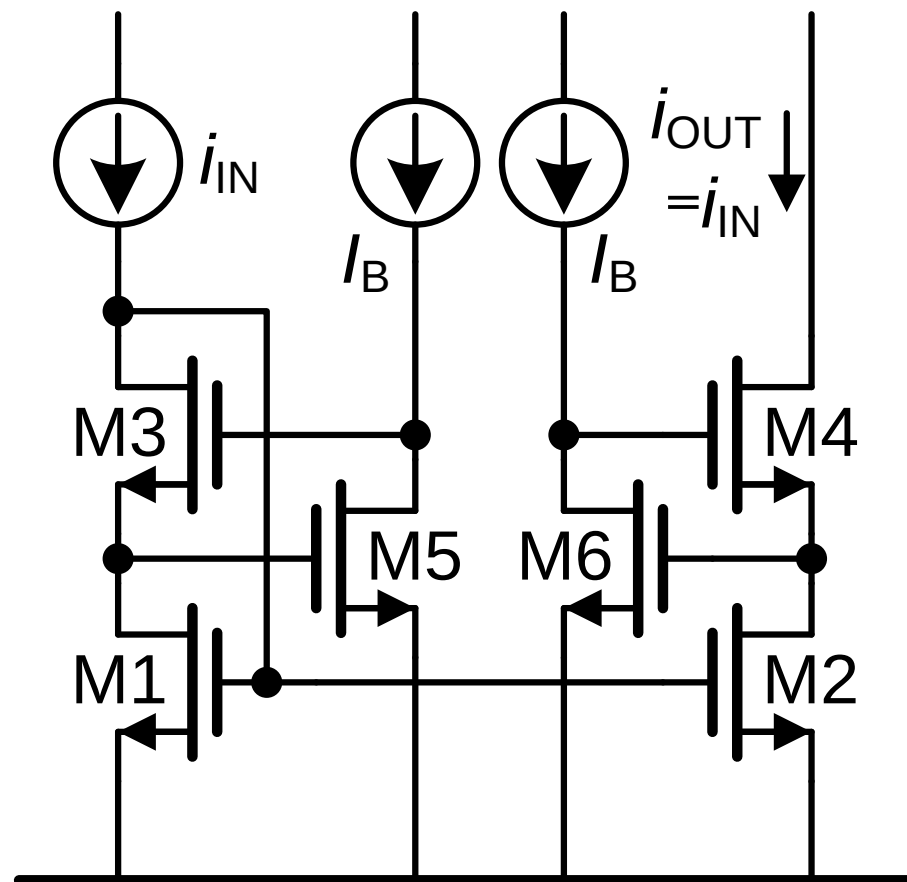
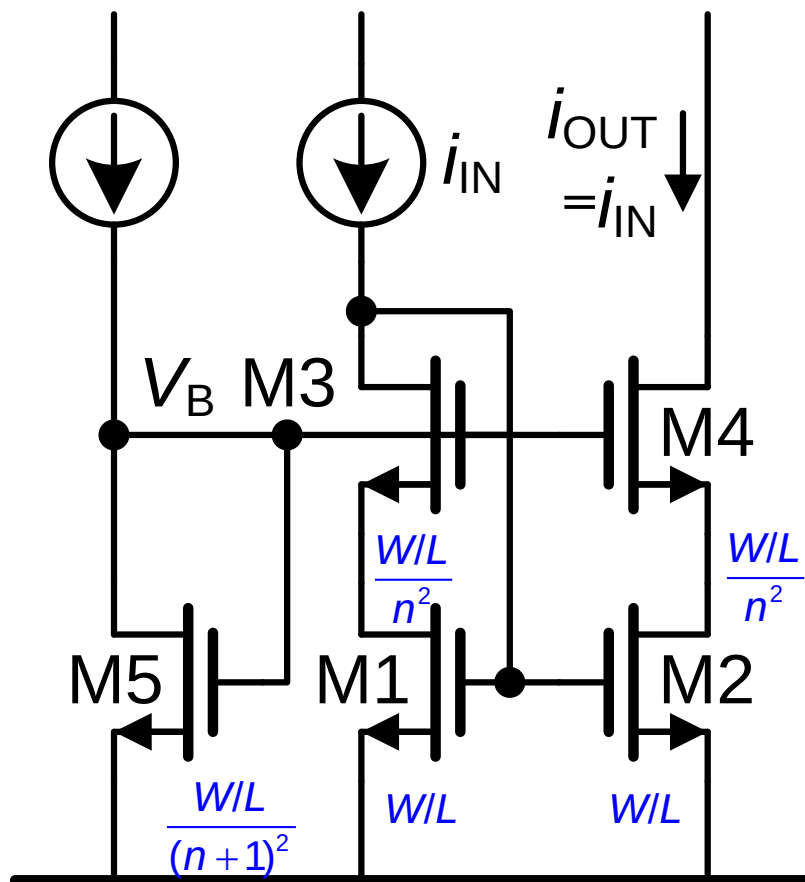


$$\boxed{V_{DS2} = V_{DS1}} \quad R_{out} = r_{ds2} g_{m4} r_{ds4}$$

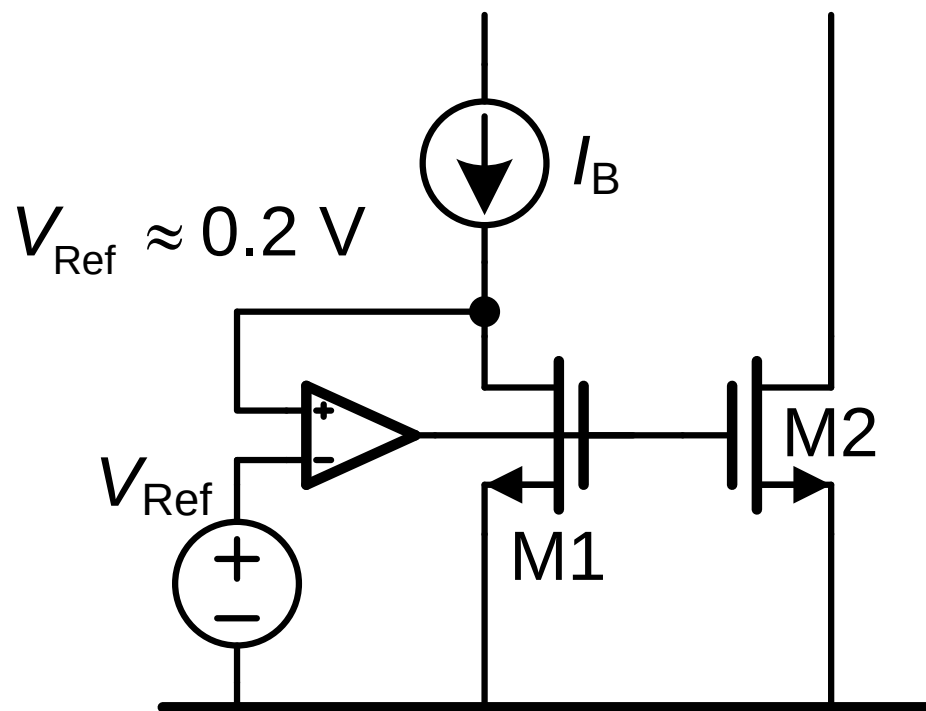
$$V_{OUTmin} = V_{DS2} + V_{DS4}$$

$$\approx 0.2 + 0.2 = 0.4 \text{ V 很小!}$$

低电压电流镜



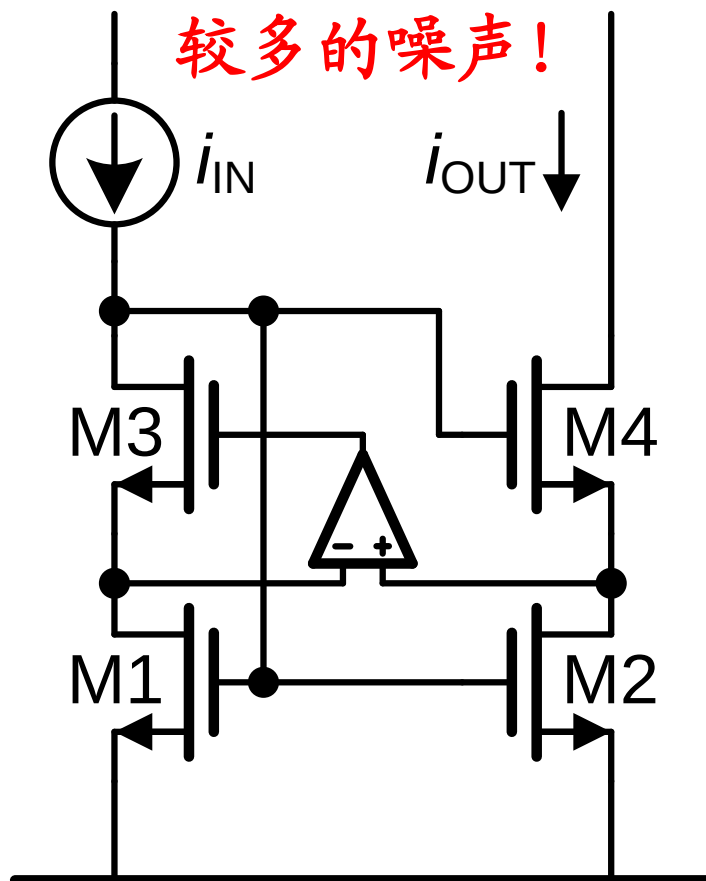
低电压二极管连接的MOST



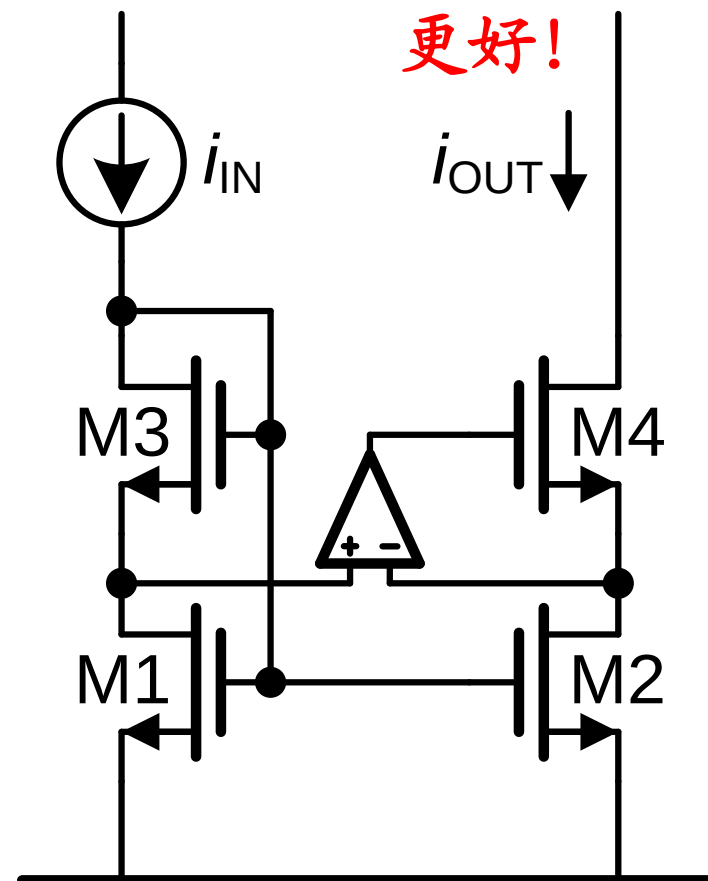
$$V_{DSmin} \approx 0.2 \text{ V}$$

$$R_{out} = r_{ds2}$$

低电压电流镜

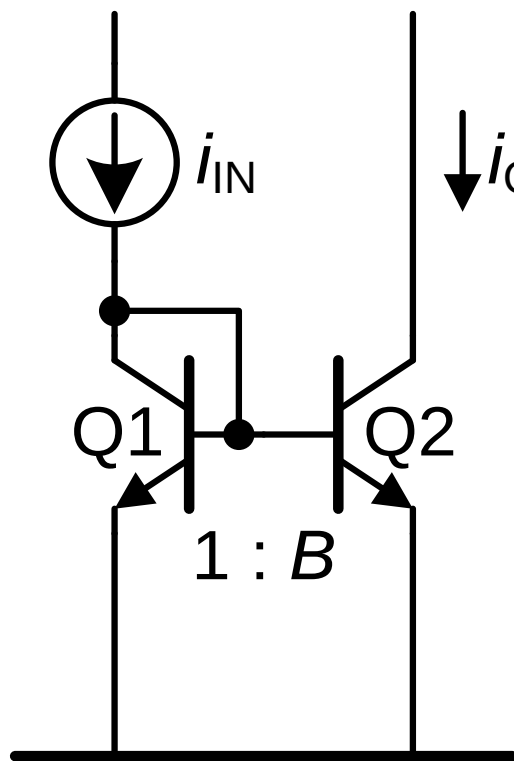


$$V_{OUTmin} \approx 50 \text{ mV}$$

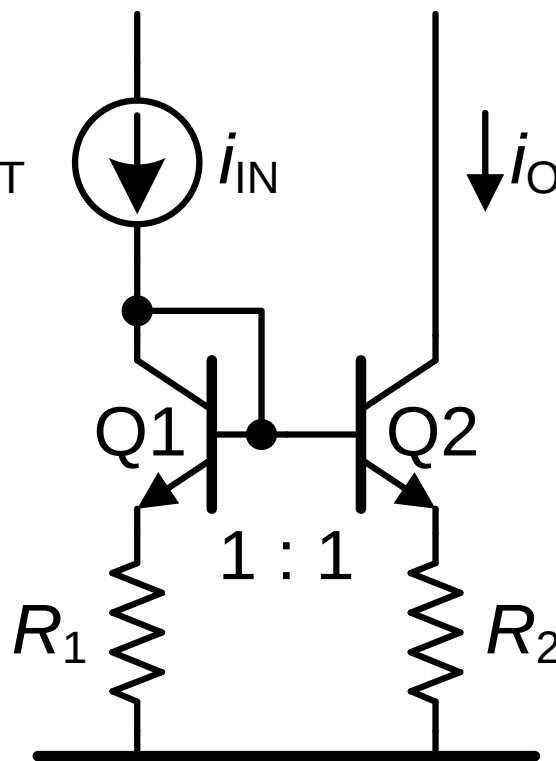


Ref.: Charlon, .., ESSCIRC 2004

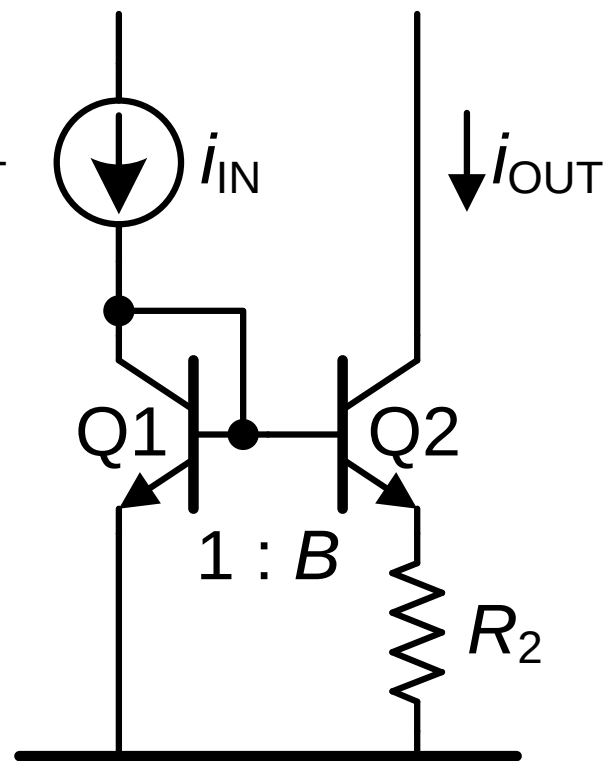
电流镜



$$i_{OUT} = B i_{IN}$$



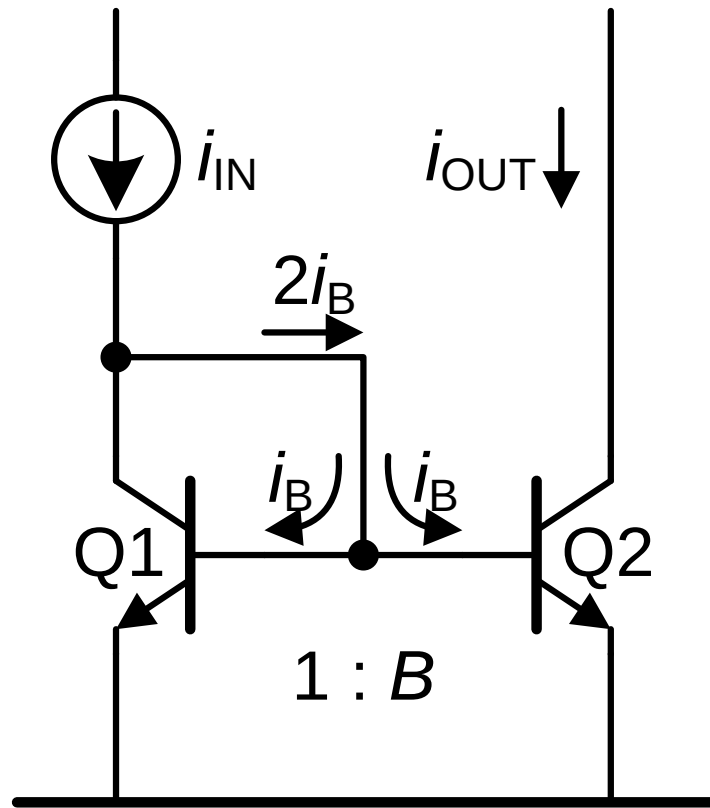
$$\frac{i_{OUT}}{i_{IN}} = \frac{R_1}{R_2}$$



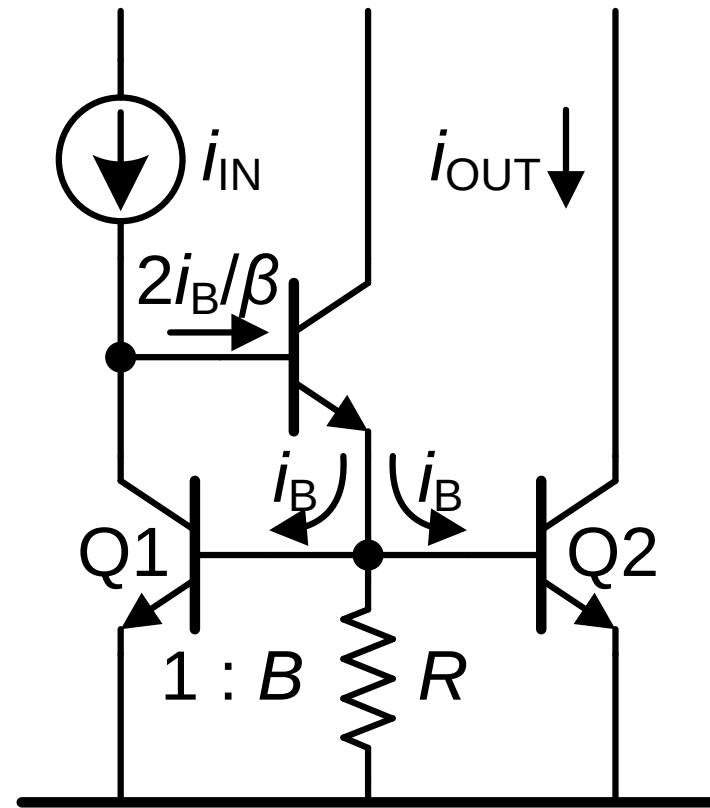
$$i_{OUT} = \frac{kT/q}{R} \ln B \frac{i_{IN}}{i_{OUT}}$$

Ref.: Widlar, JSSC Aug 69, 184-191

改进的电流镜

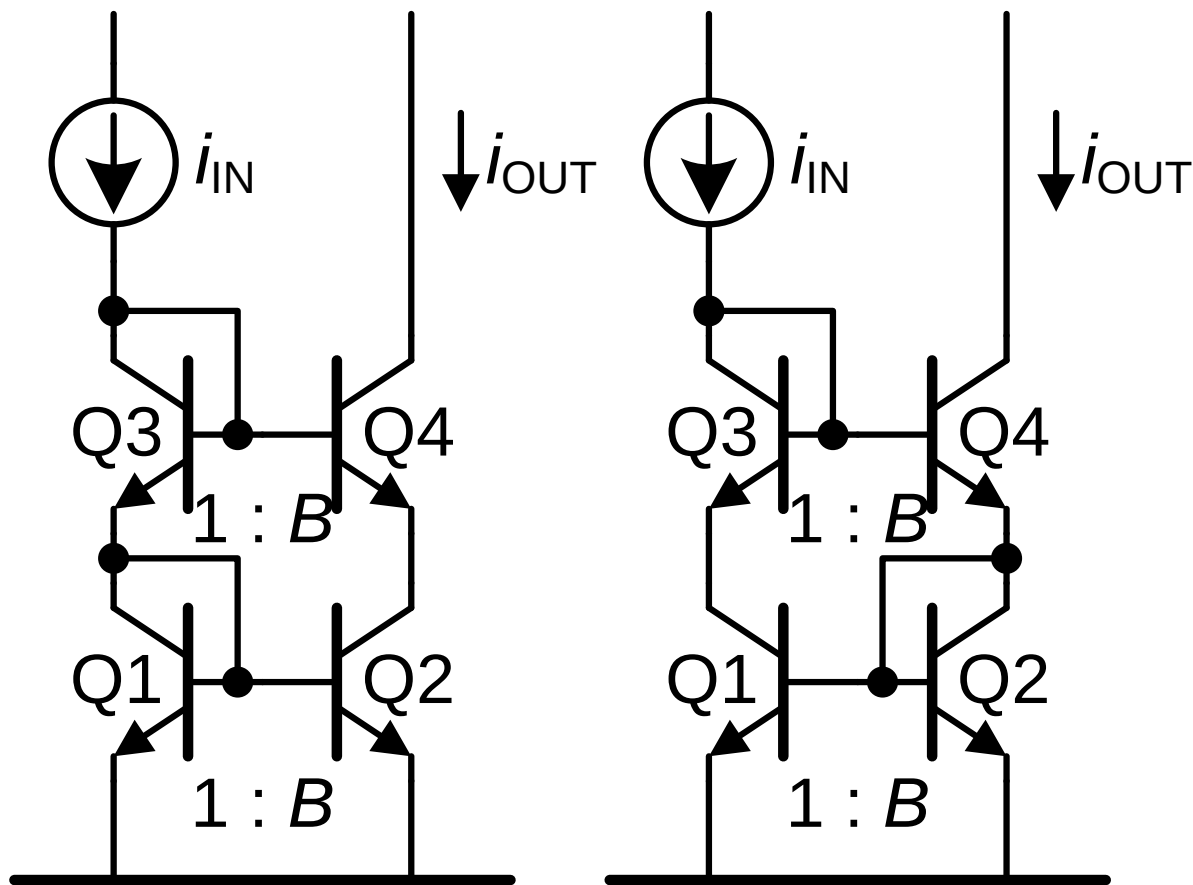


$$\text{误差} \propto \frac{2}{\beta}$$



$$\text{误差} \propto \frac{2}{\beta^2}$$

改进的电流镜



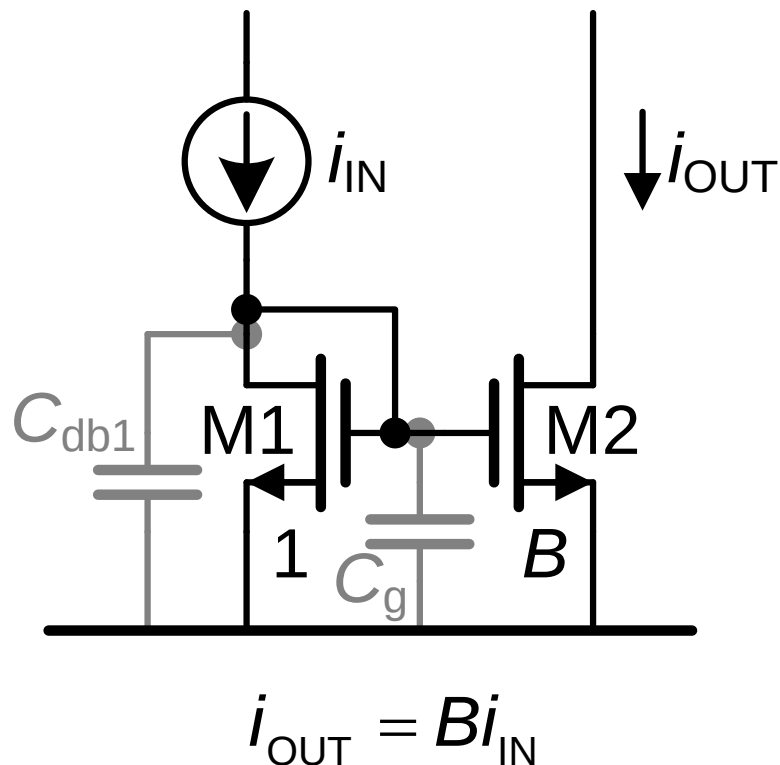
$$V_{CE2} = V_{CE1}$$

$$R_{out} = r_{o2} g_{m4} r_{o4}$$

$$\begin{aligned} V_{OUTmin} &= V_{BE} + V_{CE} \\ &\approx 0.7 + 0.1 \\ &= 0.8 \text{ V} \\ &\text{太大!!!} \end{aligned}$$

Ref.: Wilson, JSSC Dec.68, 341-348

高频时的电流镜



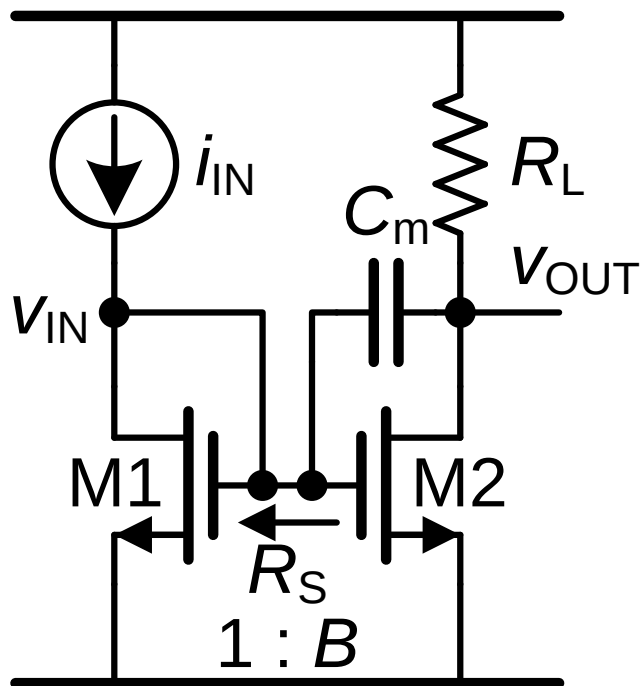
$$R_{\text{out}} = r_{\text{ds}}$$

$$C_g = (1 + B)C_{\text{gs1}}$$

$$BW = \frac{g_{m1}}{2\pi(C_g + C_{\text{db1}})} \approx f_T \frac{1}{2 + B}$$

Ref.: Gilbert, JSSC Dec.68, 353-365

电流密勒效应



$$A_1 = B$$

$$R_{in} = \frac{1}{g_{m1}}$$

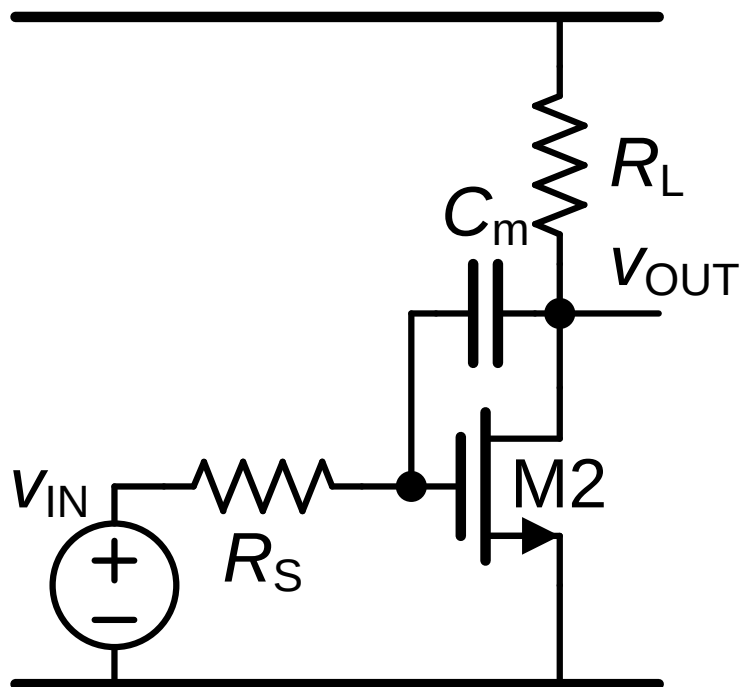
$$R_S = \frac{1}{g_{m1}}$$

$$v_{in} \approx i_{in} R_S$$

$$B = \frac{g_{m2}}{g_{m1}}$$

Ref.: Rincon-Mora, JSSC Jan. 2000, 26-32

电流密勒效应的等效电路



密勒效应：

$$f_{-3\text{dB}} = \frac{1}{2\pi R_S A_{V2} C_m}$$

$$R_S = \frac{1}{g_{m1}}$$

$$A_{V2} = g_{m2} R_L$$

$$f_{-3\text{dB}} = \frac{1}{2\pi (1+B) C_m R_L}$$

$$f_z = -\frac{g_{m2}}{2\pi C_m}$$

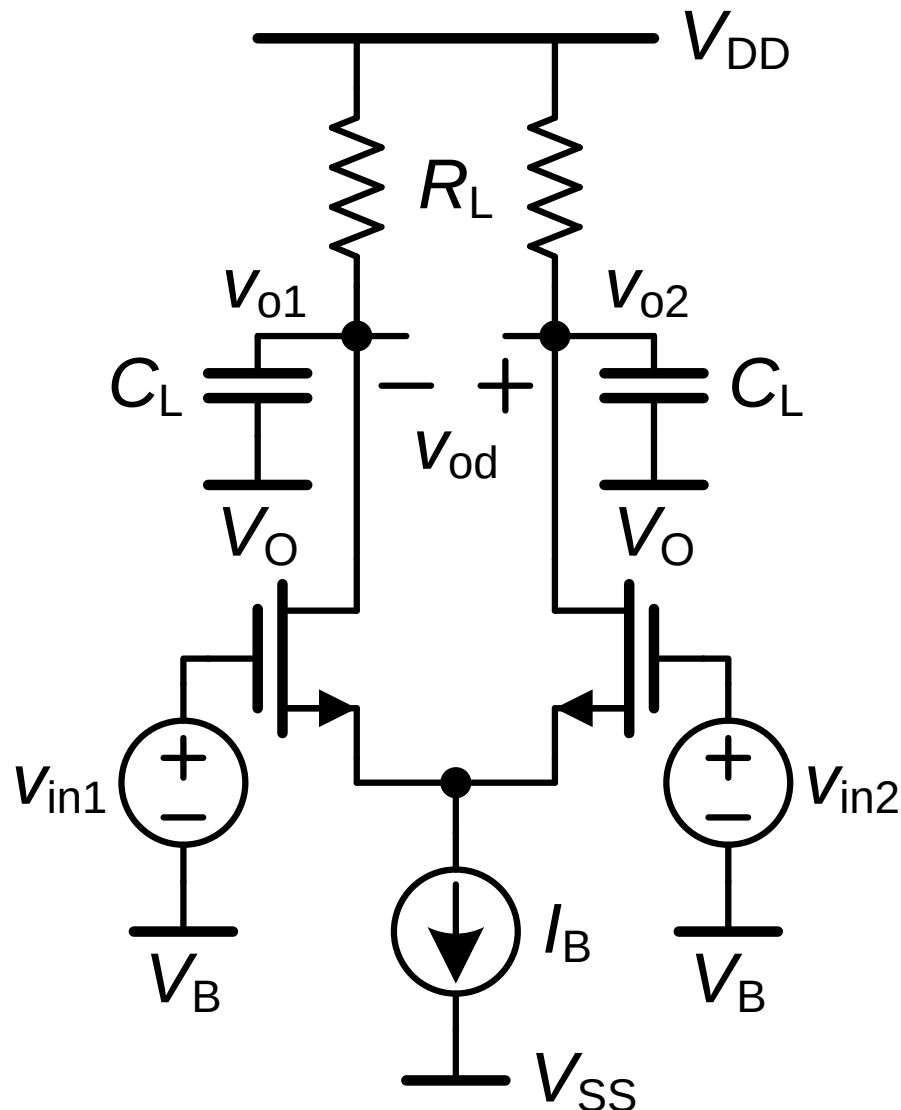
目录

- 电流镜

- 差分对

- 差分电压放大器和差分电流放大器

差分电压放大器



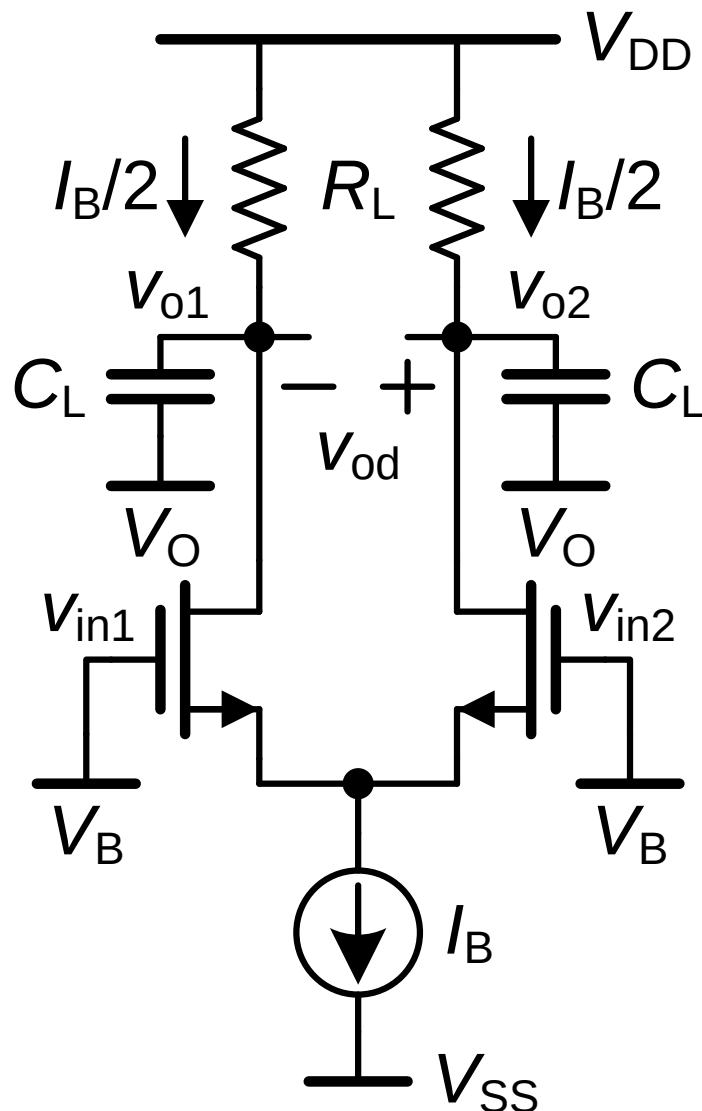
两个相同的晶体管

重新定义 V_{in} 和 V_o :

$$\begin{cases} V_{ind} = V_{in1} - V_{in2} \\ V_{inc} = \frac{V_{in1} + V_{in2}}{2} \end{cases}$$

$$\begin{cases} V_{od} = V_{o1} - V_{o2} \\ V_{oc} = \frac{V_{o1} + V_{o2}}{2} \end{cases}$$

差分电压放大器：直流

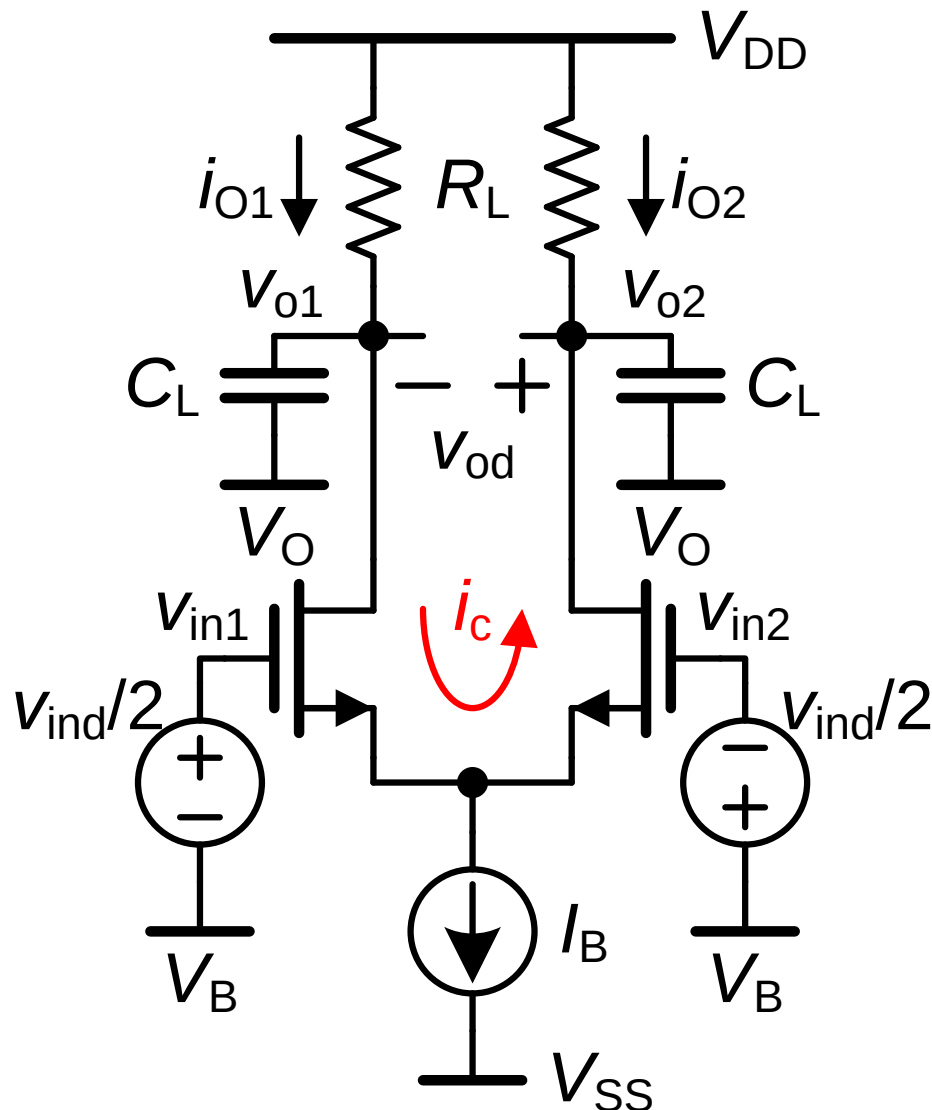


$$V_{in1} = V_{in2} = 0$$

$$V_{O1} = V_{O2} = V_{DD} - R_L I_B / 2$$

$$\begin{aligned} V_{od} &= V_{O1} - V_{O2} \\ &= (V_{O1} - V_O) - (V_{O2} - V_O) \\ &= 0 \end{aligned}$$

差分电压放大器：交流增益



差分输入电压：

$$V_{\text{ind}} = V_{\text{in1}} - V_{\text{in2}}$$

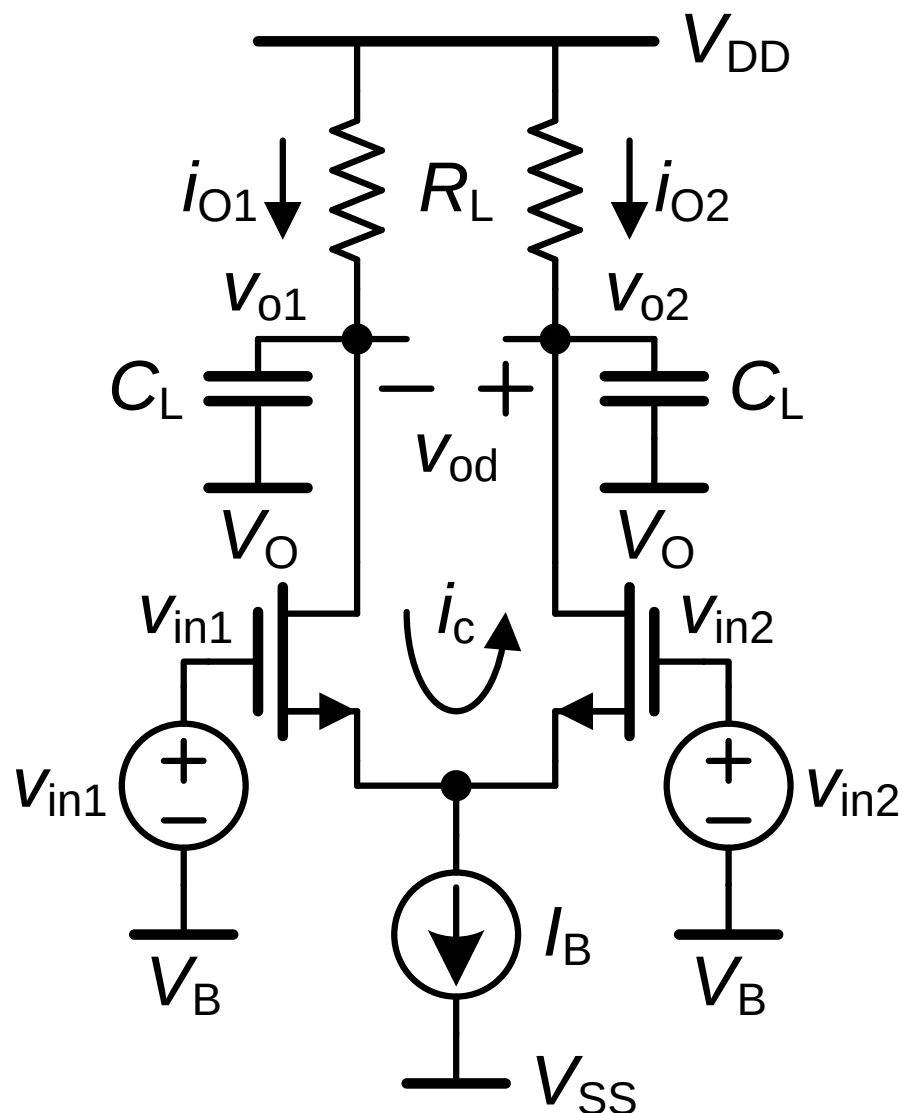
环路电流：

$$i_c = g_m \frac{V_{\text{ind}}}{2}$$

$$V_{\text{od}} = 2R_L i_c$$

$$A_v = \frac{V_{\text{od}}}{V_{\text{ind}}} = g_m R_L$$

差分电压放大器



$$A_v = g_m R_L$$

与单个晶体管相同 !!

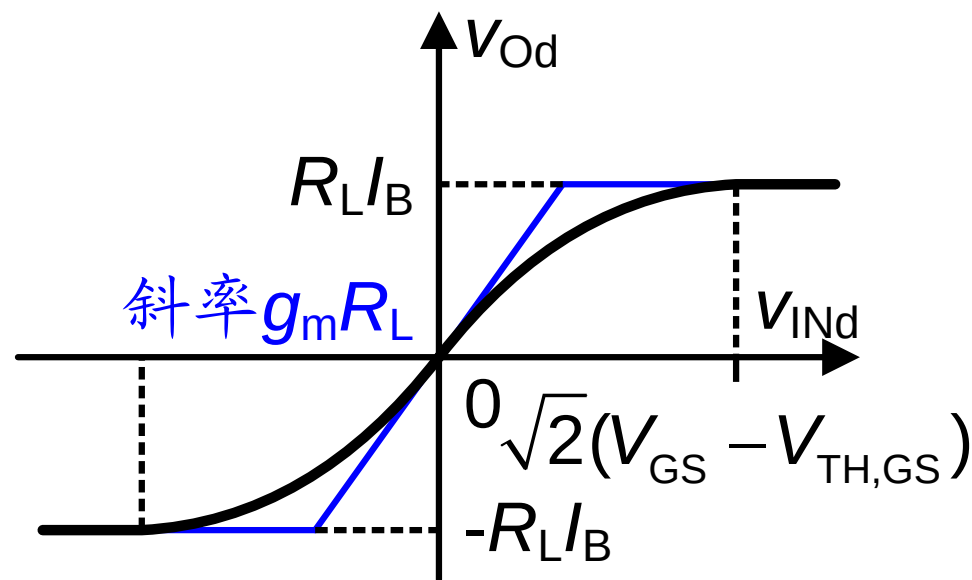
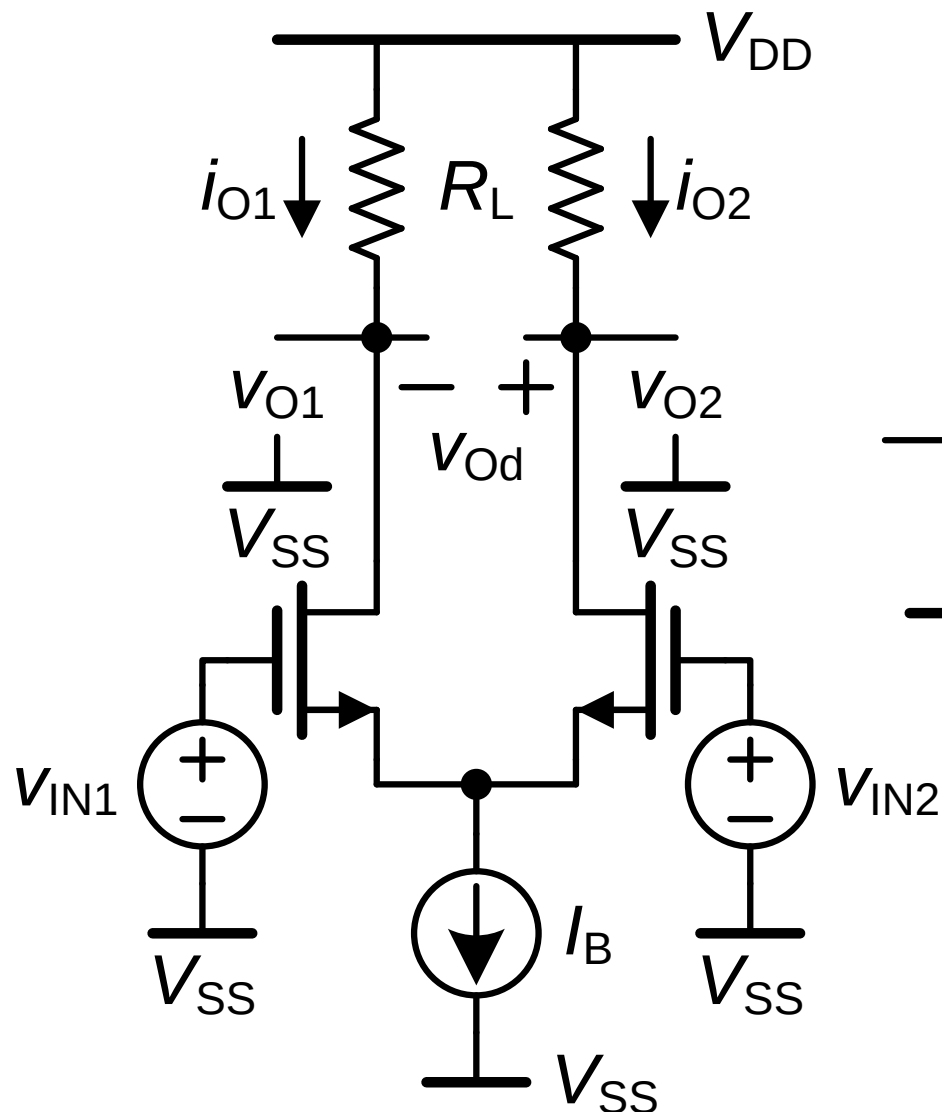
优点:

V_{DD} 的噪声: $PSRR_{DD}$

V_{SS} 的噪声: $PSRR_{SS}$

地噪声: $CMRR$

CMOS差分电压放大器：直流范围



$V_{GS} - V_{TH,GS}$ 决定斜率、范围...增益!

CMOS差分电压放大器：大信号输入

$$\frac{i_{\text{Od}}}{I_{\text{B}}} = \frac{V_{\text{INd}}}{V_{\text{GS}} - V_{\text{TH,GS}}} \sqrt{1 - \frac{1}{4} \left(\frac{V_{\text{INd}}}{V_{\text{GS}} - V_{\text{TH,GS}}} \right)^2}$$

V_{INd} 为差分输入电压

i_{Od} 为差分输出电流

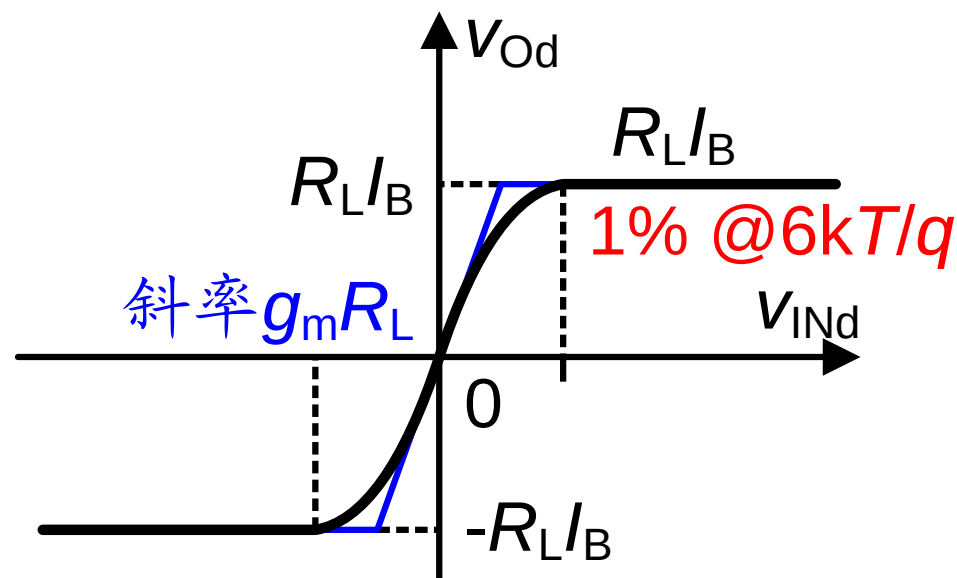
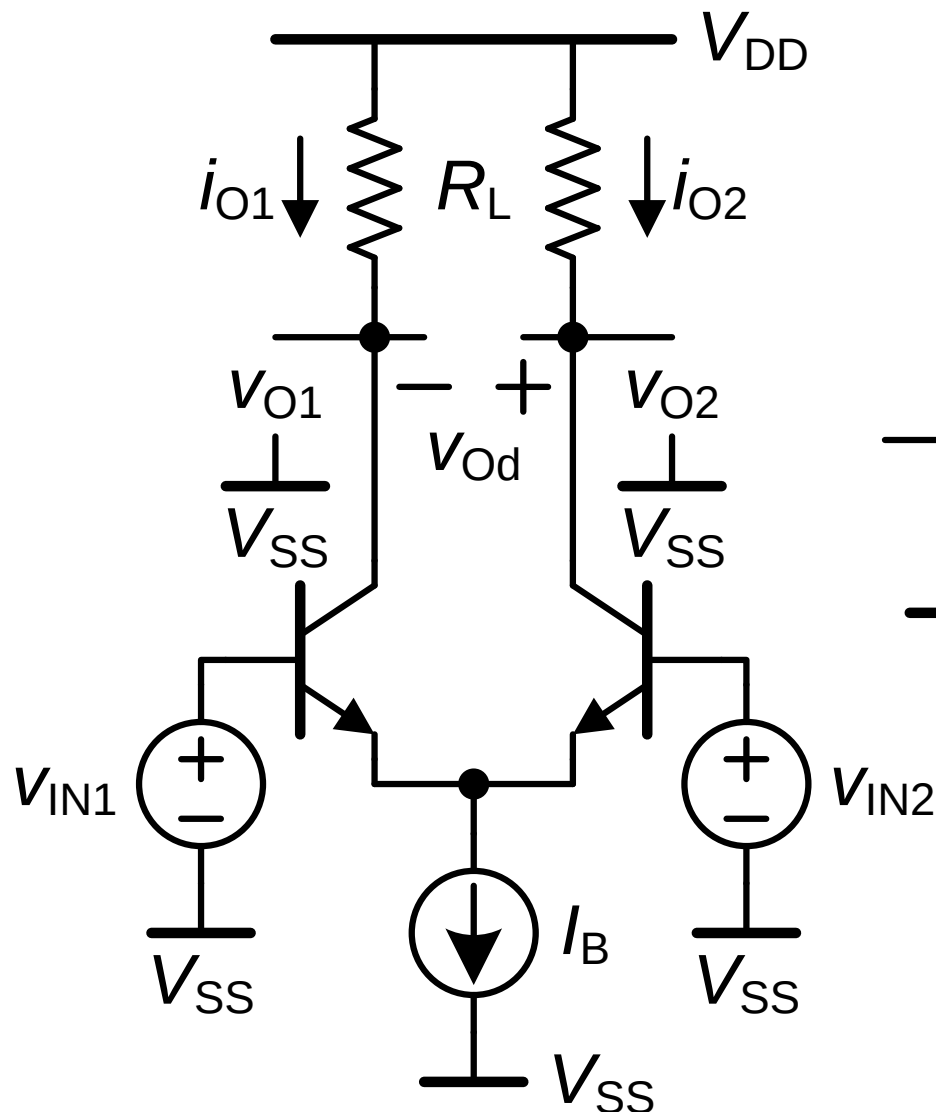
i_{od} 为差分小信号输出电流 ($g_{\text{m}} v_{\text{ind}}$)

或两倍的环路电流 ($g_{\text{m}} v_{\text{ind}}/2$)

I_{B} 为差分对的总的直流电流

注意 $g_{\text{m}} = \frac{I_{\text{B}}}{V_{\text{GS}} - V_{\text{TH,GS}}} = 2K' \frac{W}{L} (V_{\text{GS}} - V_{\text{TH,GS}})$

双极型差分电压放大器：直流范围



kT/q 决定斜率、
增益、范围

内部 R_E 增加范围！

双极型差分电压放大器：大信号输入

$$\frac{i_{\text{Od}}}{I_{\text{B}}} = \tanh \frac{V_{\text{INd}}}{2kT/q} \quad \tanh x = \frac{e^x - e^{-x}}{e^x + e^{-x}} = \frac{2e^x - 1}{2e^x + 1}$$

V_{INd} 为差分输入电压

i_{Od} 为差分输出电流

i_{od} 为差分小信号输出电流($g_{\text{m}}v_{\text{ind}}$)

或两倍的环路电流($g_{\text{m}}v_{\text{ind}}/2$)

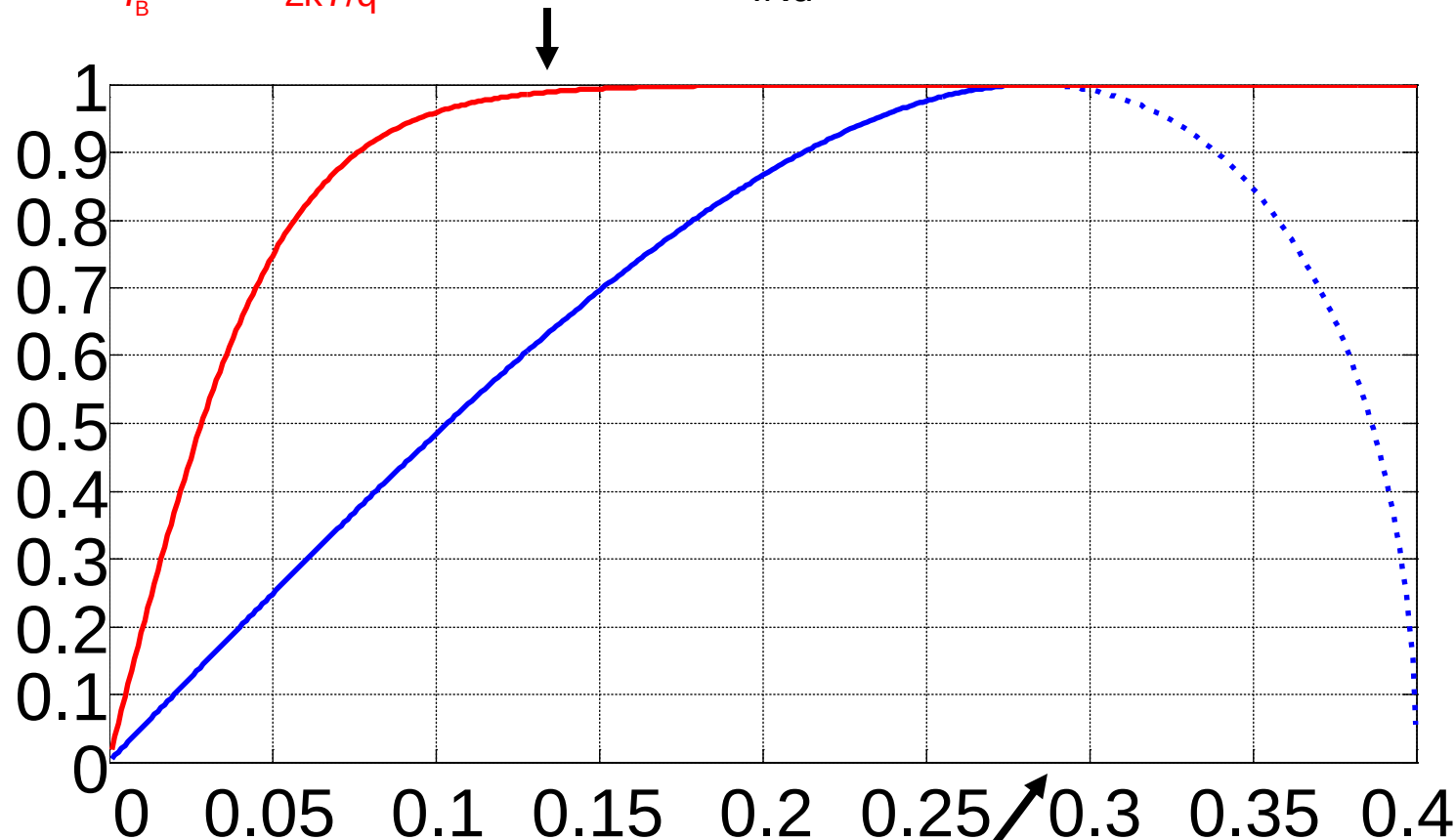
I_{B} 为差分对的总的直流电流

注意： $g_{\text{m}} = \frac{I_{\text{B}}}{2kT/q}$

差分电压放大器：转移曲线

$$\frac{i_{Od}}{I_B} = \tanh \frac{V_{INd}}{2kT/q}$$

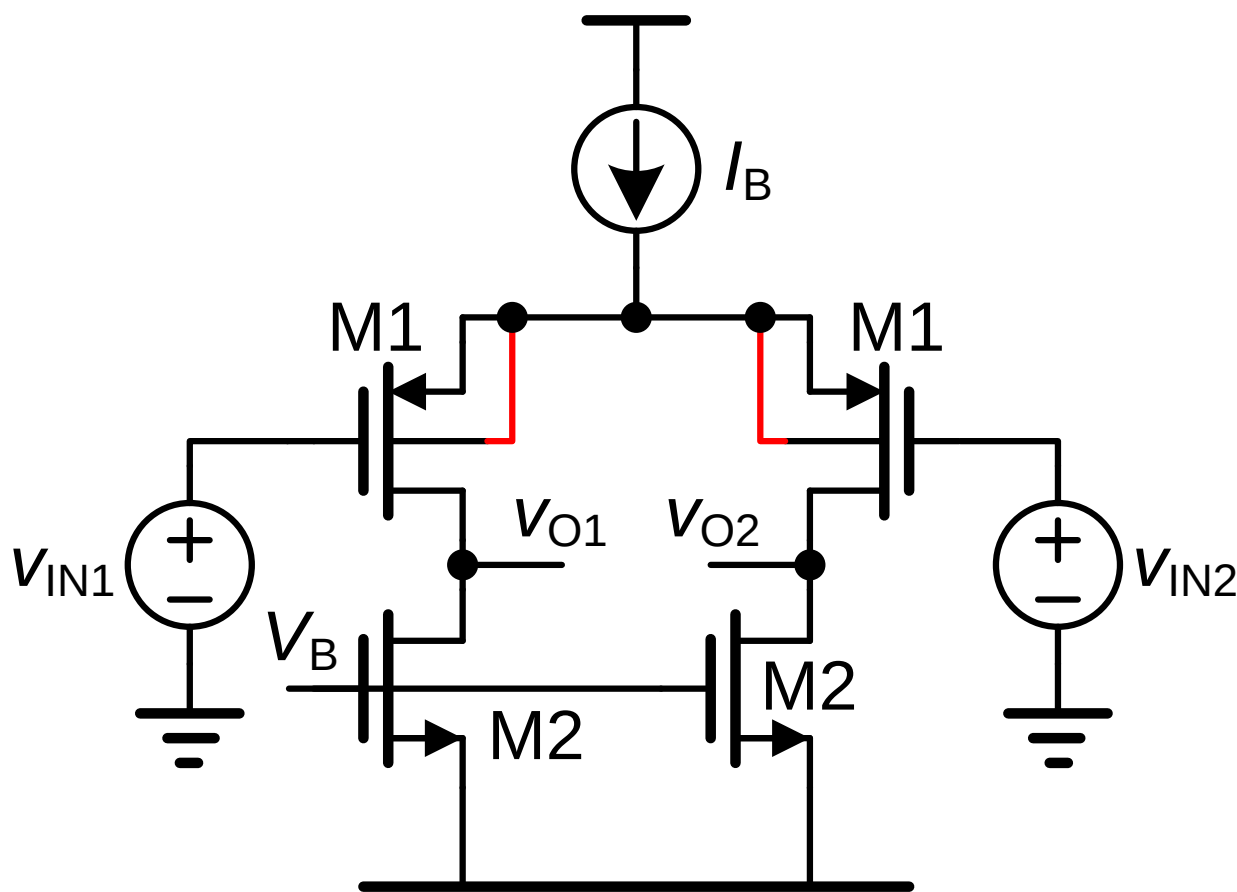
$$-1\% \quad V_{INd} \approx 2.67 \times 2kT/q = 0.14 \text{ V}$$



$$\frac{i_{Od}}{I_B} = \frac{V_{INd}}{V_{GS} - V_{TH,GS}} \sqrt{1 - \frac{1}{4} \left(\frac{V_{INd}}{V_{GS} - V_{TH,GS}} \right)^2}$$

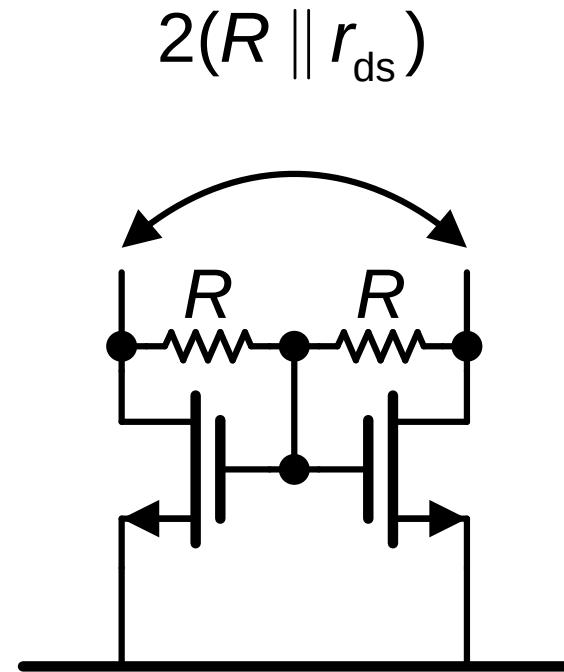
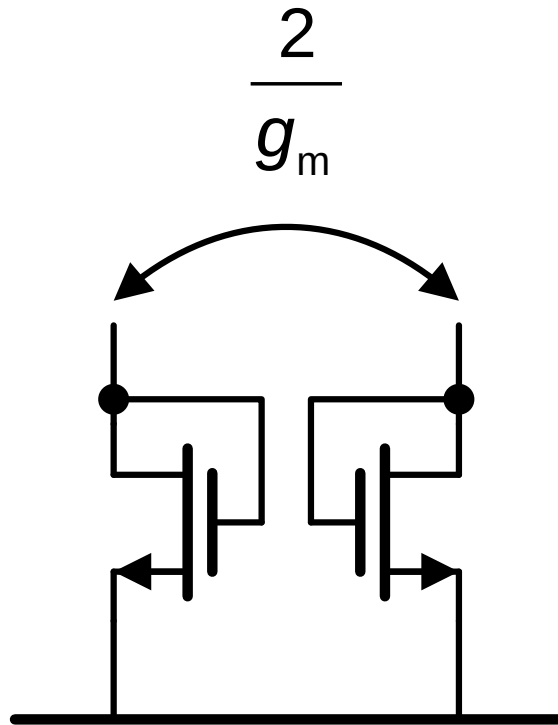
$$V_{INd} = \sqrt{2} (V_{GS} - V_{TH,GS}) = \sqrt{2} \times 0.2 \text{ V}$$

增益为 $g_m r_{ds}$ 的差分电压放大器

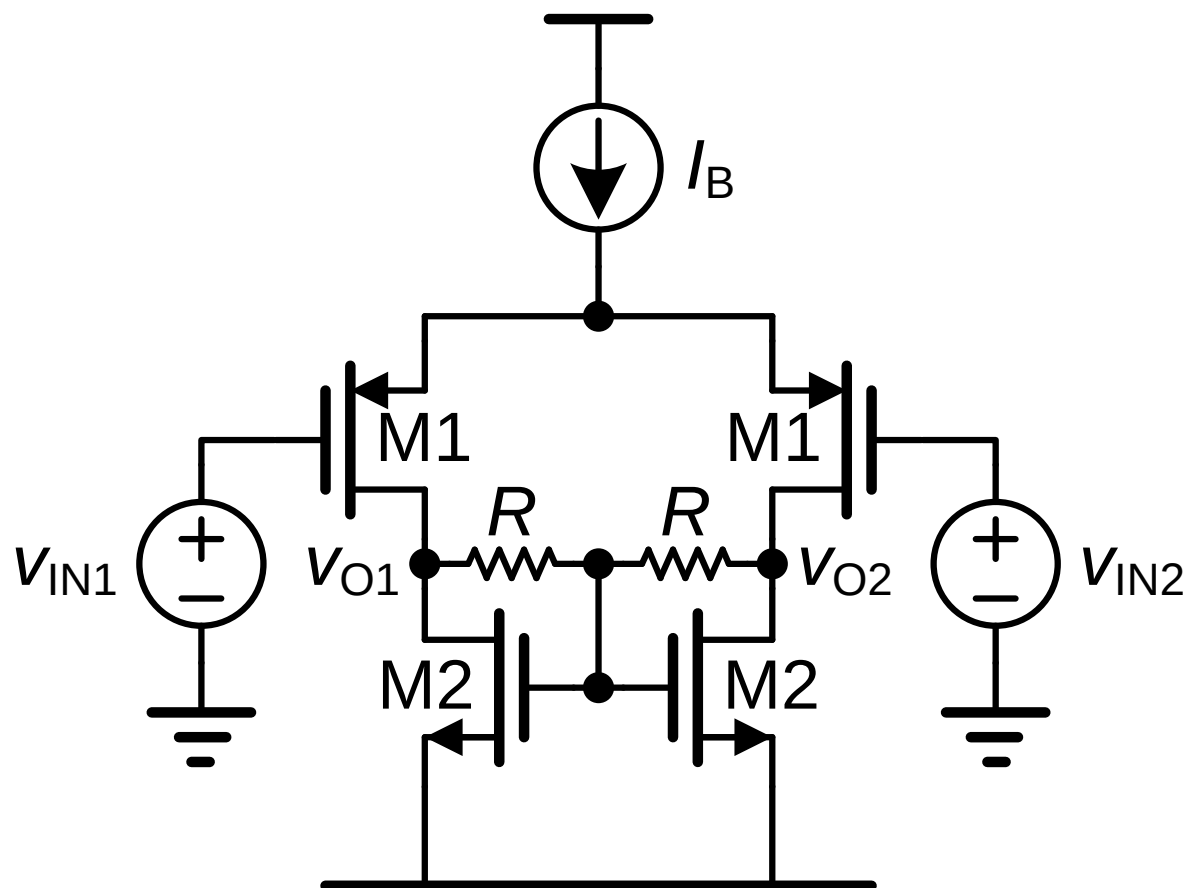


$$A_V = g_{m1}(r_{ds1} \parallel r_{ds2})$$

接电阻的二极管连接MOST



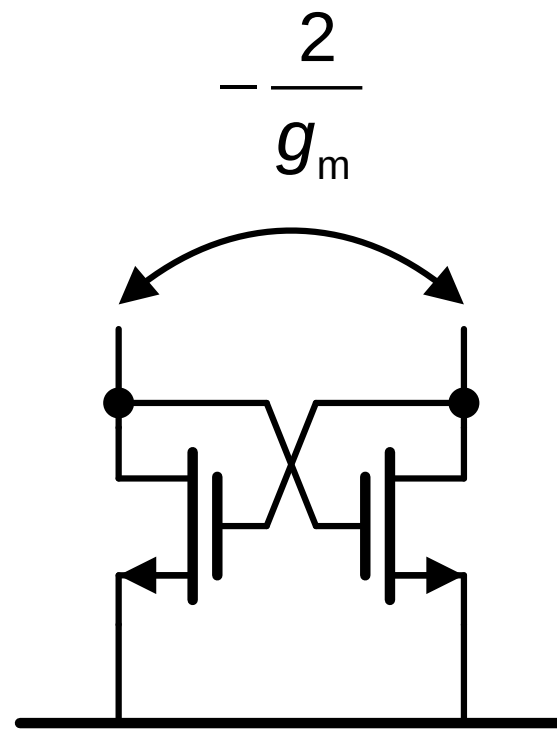
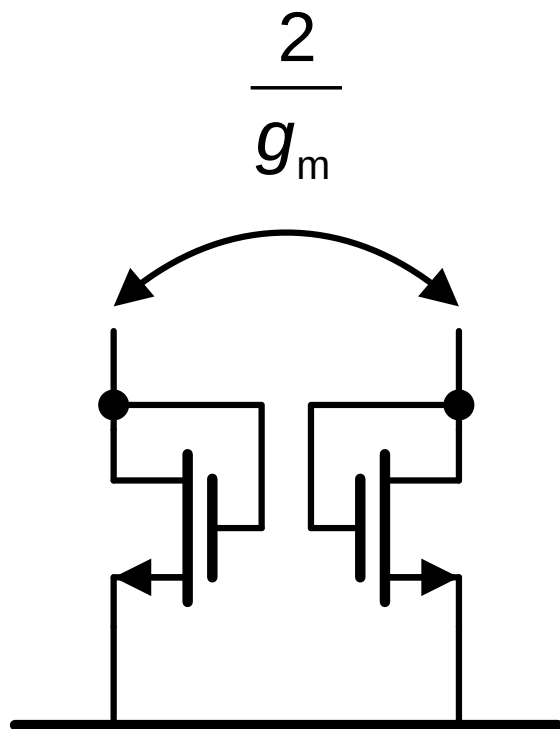
高增益差分电压放大器



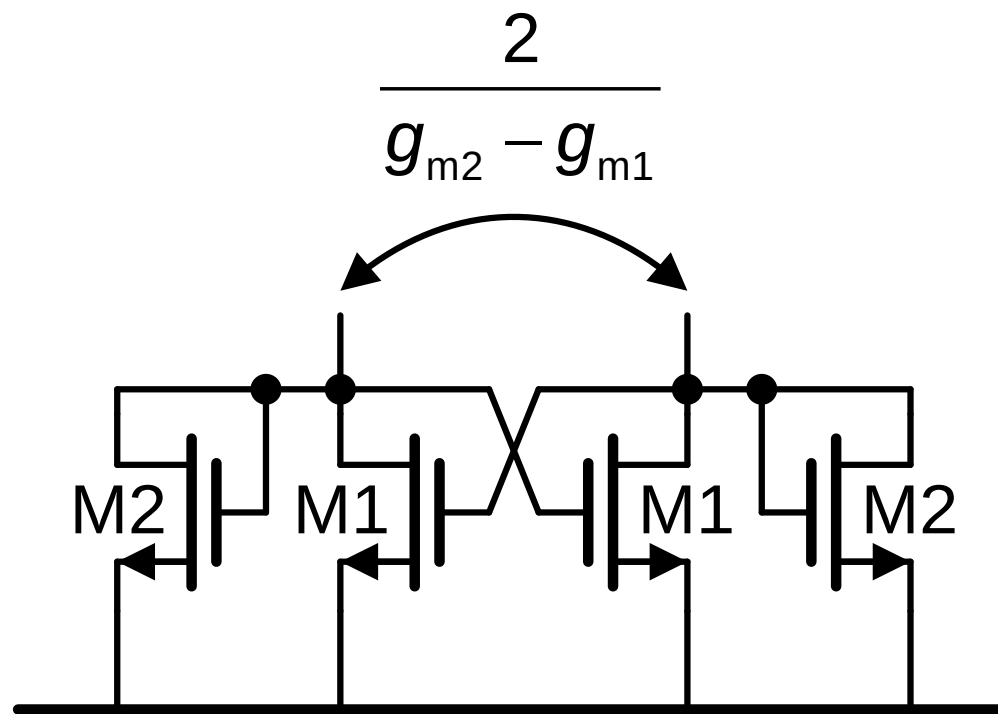
$$A_V = g_{m1}(R \parallel r_{ds})$$

$$r_{ds} = r_{ds1} \parallel r_{ds2}$$

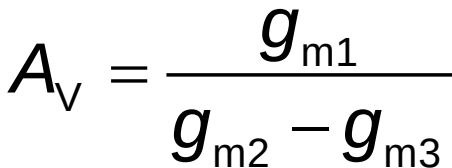
差分二极管连接MOST 1



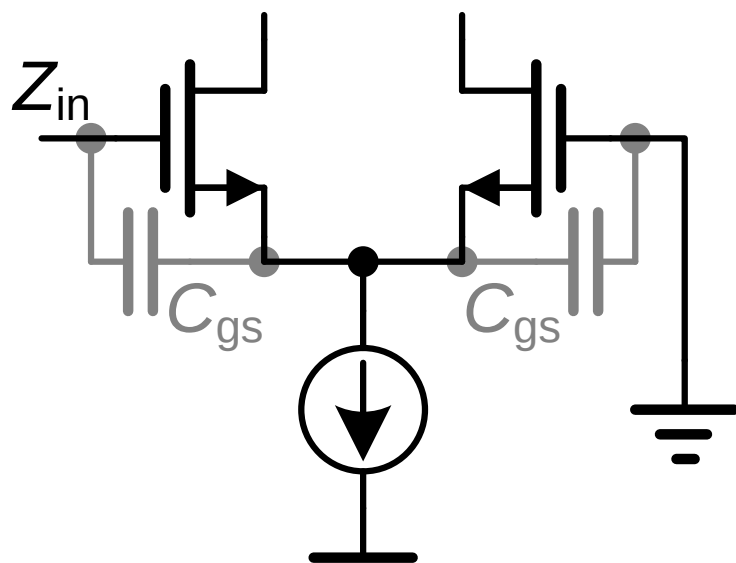
差分二极管连接MOST 2



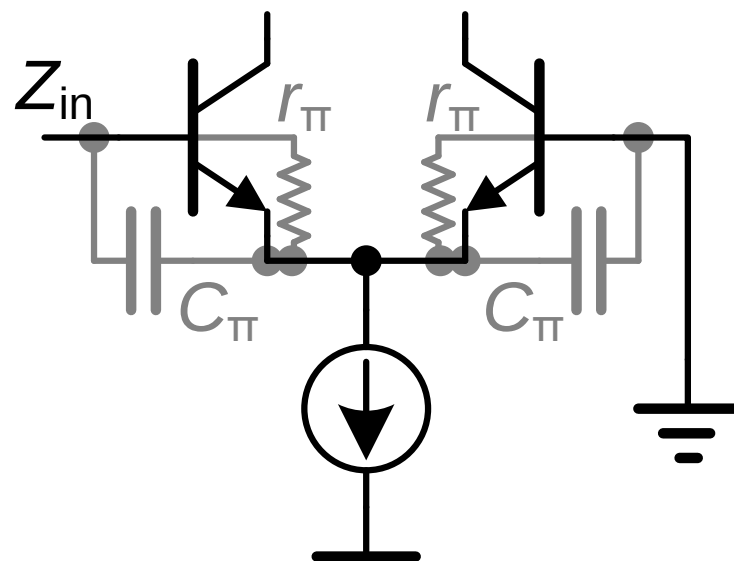
值接近 ∞ !



输入阻抗

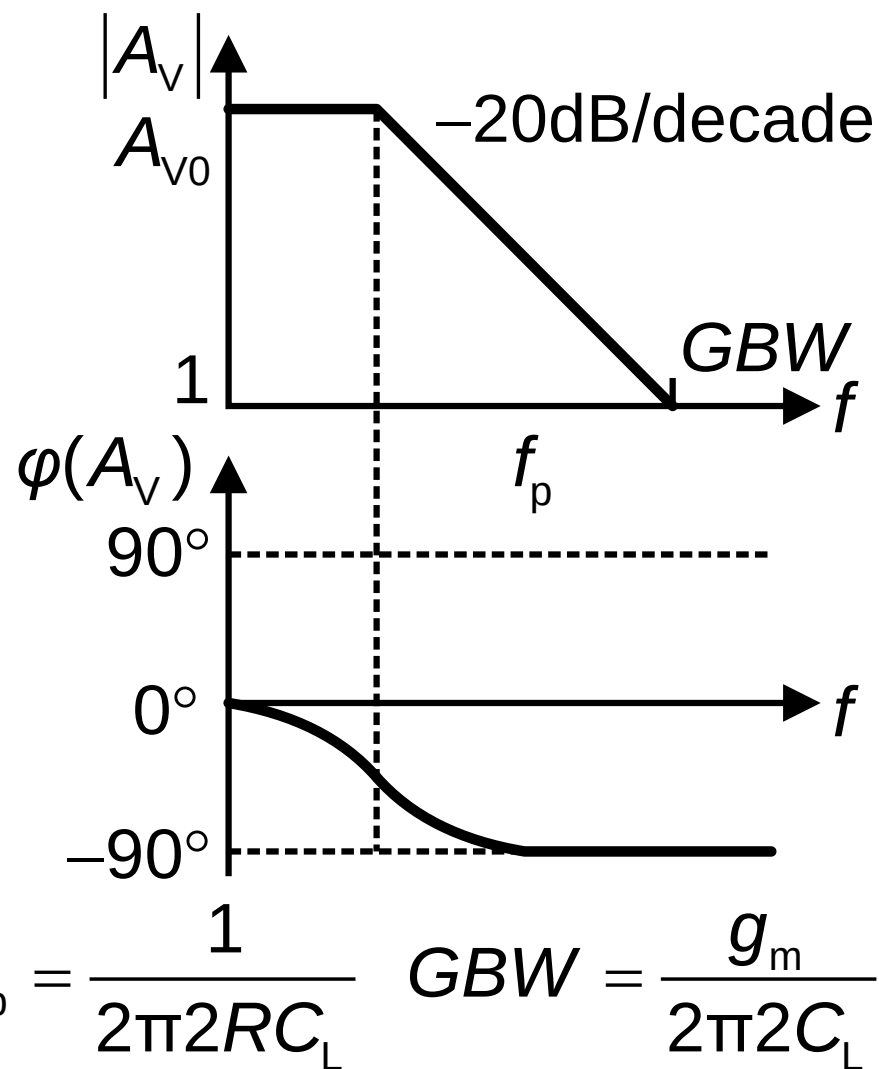
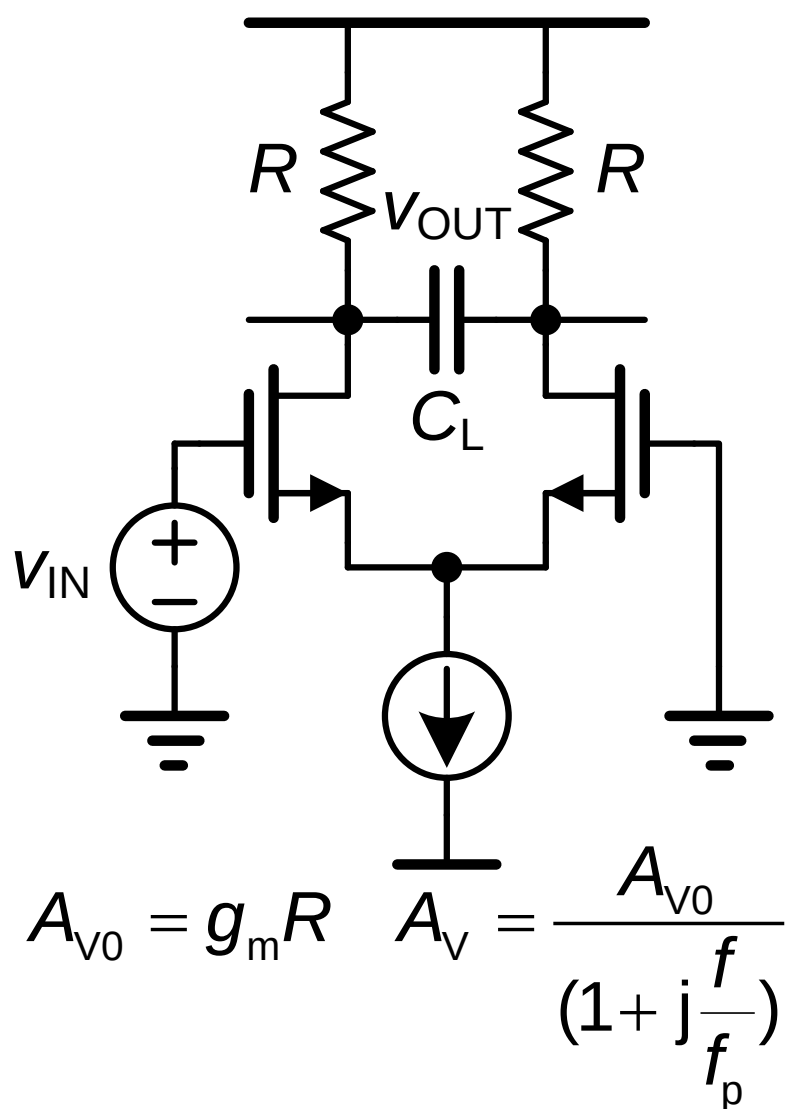


$$C_{in} = \frac{C_{gs}}{2}$$

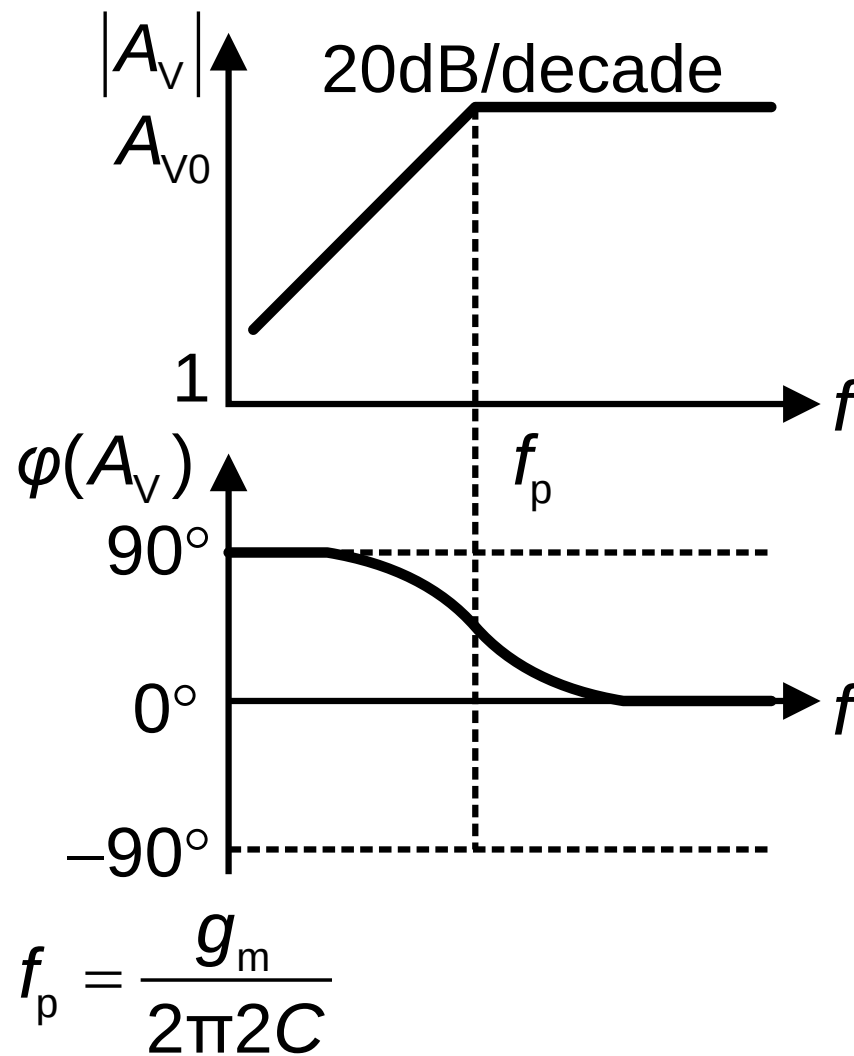
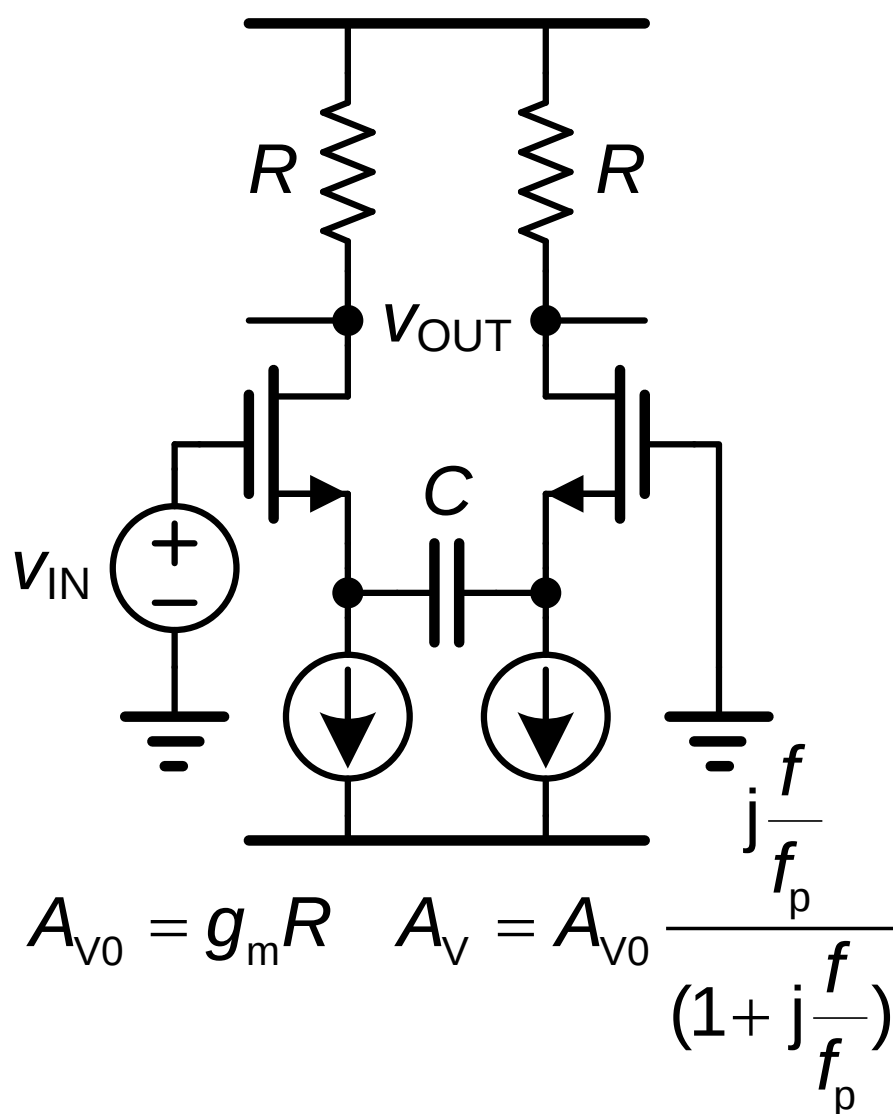


$$R_{in} = 2r_{\pi} \quad C_{in} = \frac{C_{\pi}}{2}$$

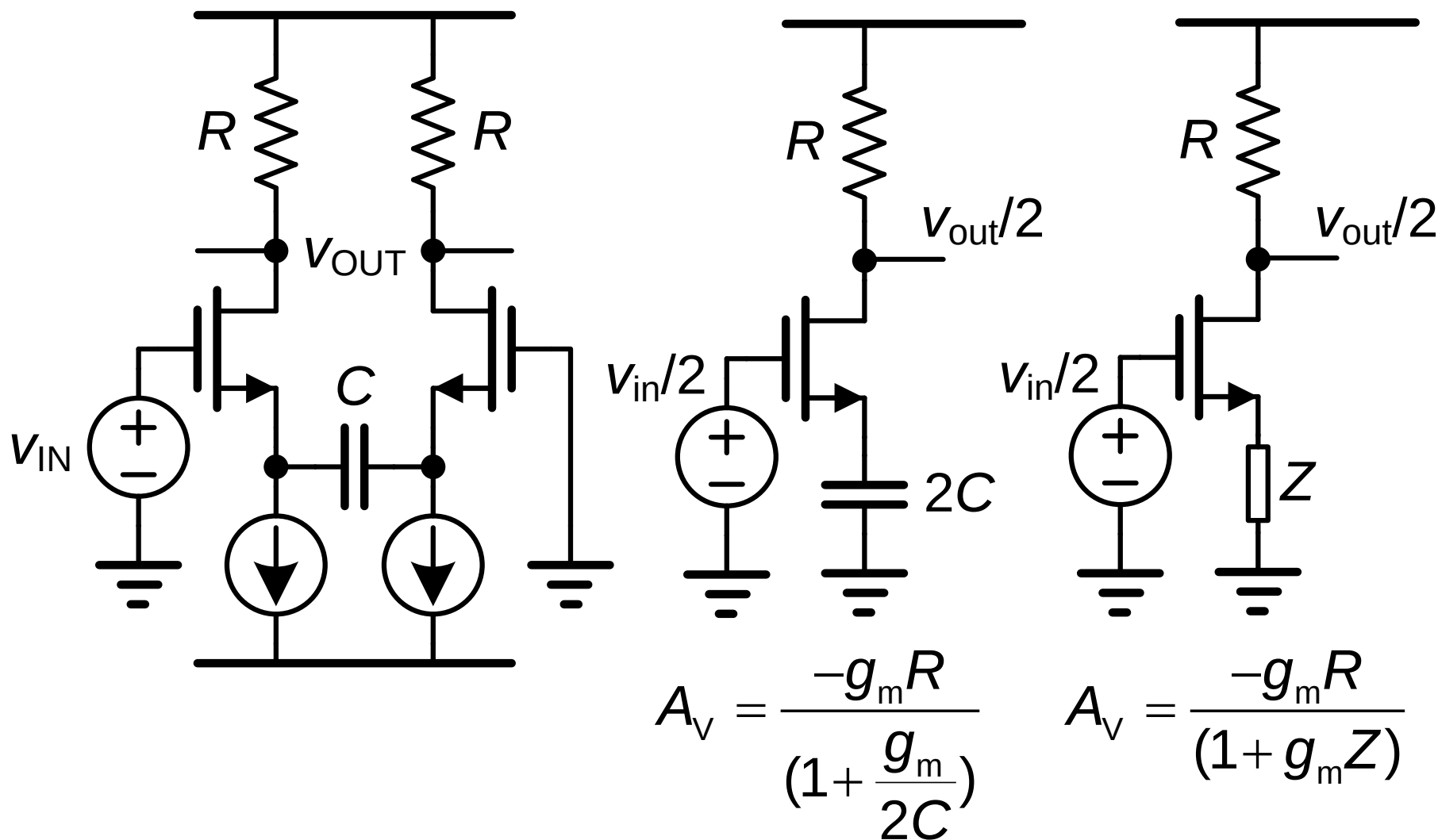
低通差分电压放大器



高通差分电压放大器



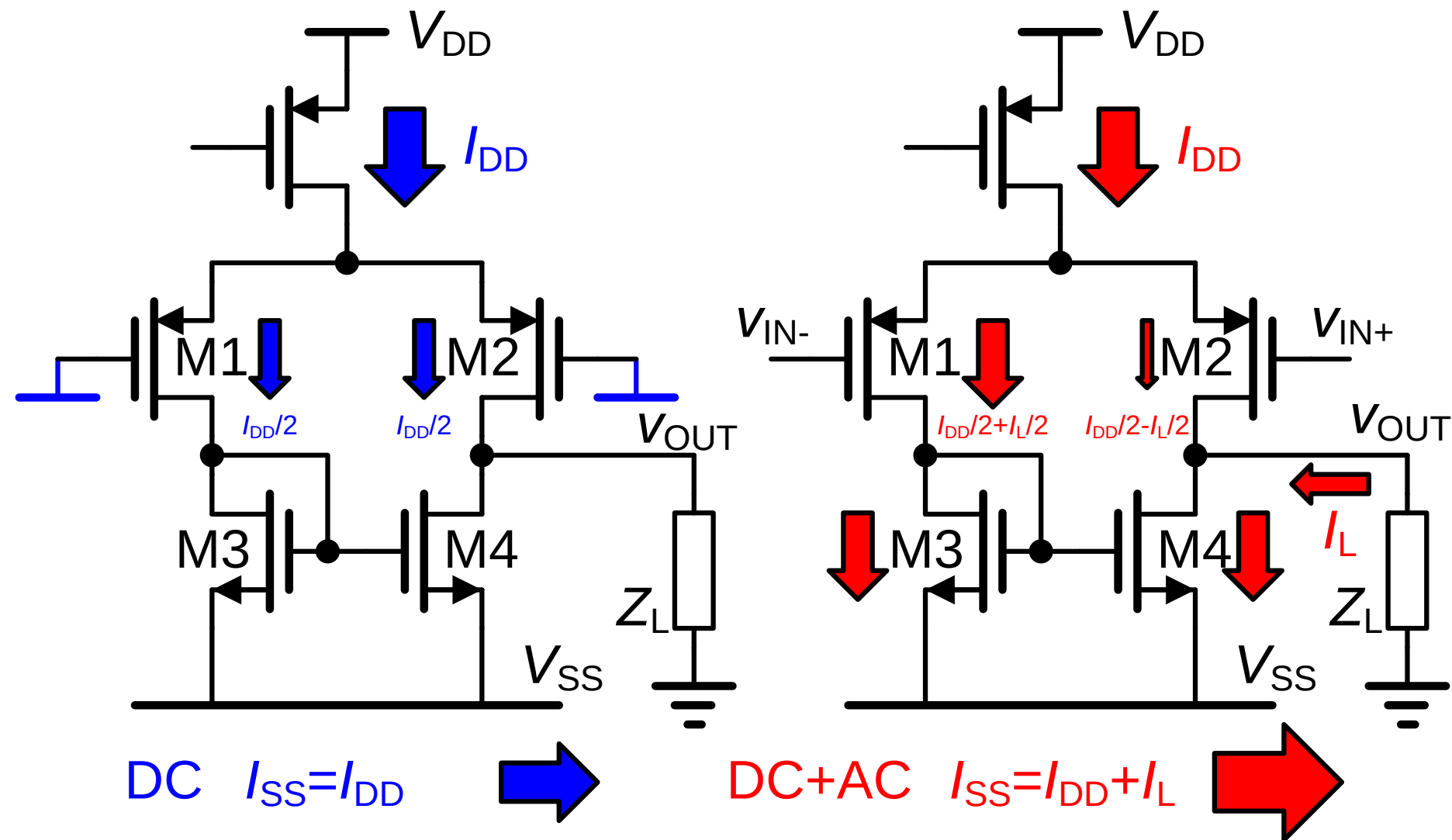
高通差分放大器的计算



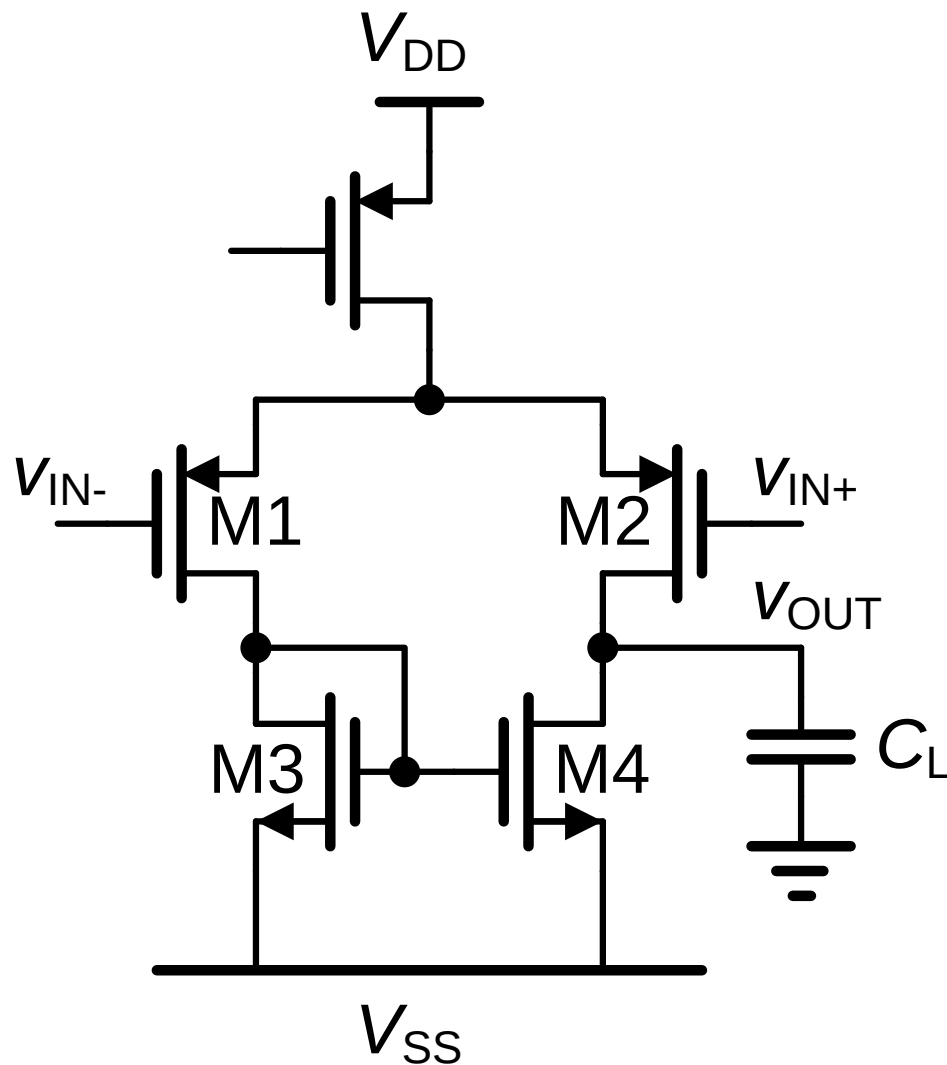
目录

- 电流镜
- 差分对
- 差分电压放大器和差分电流放大器

运算跨导放大器(OTA)



单级OTA



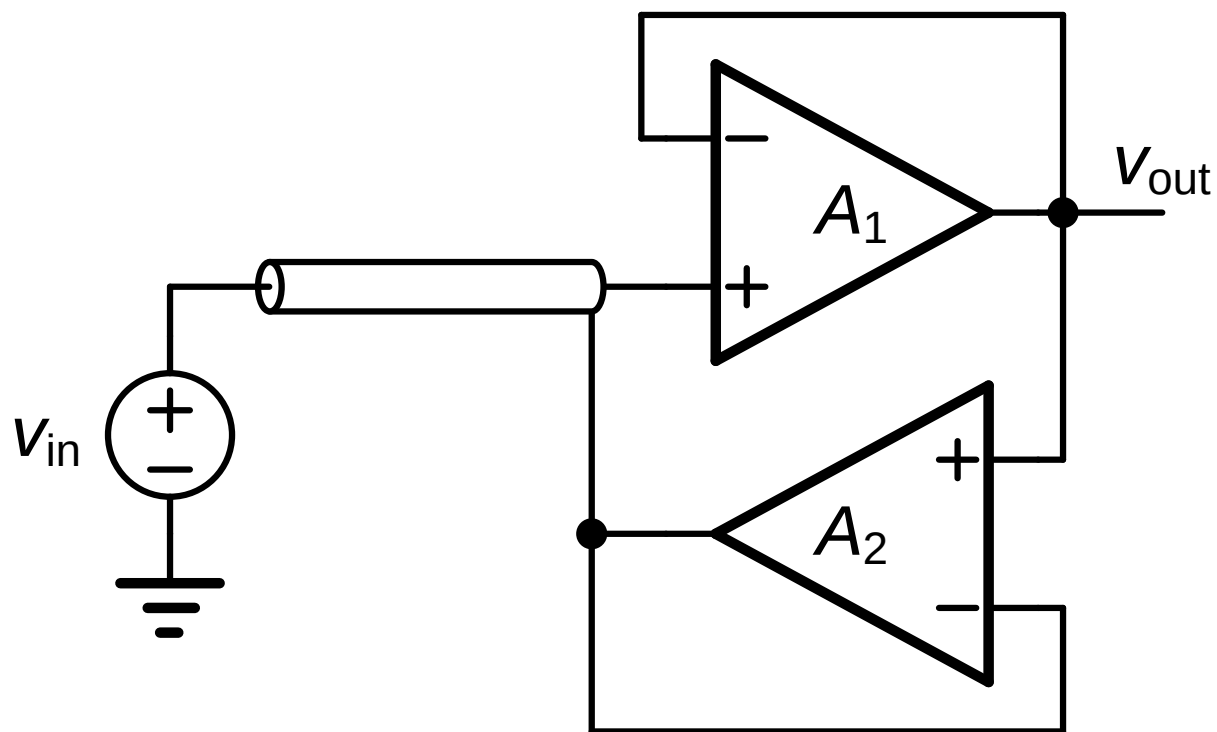
$$A_V = g_{m1} R_{out}$$

$$R_{out} = r_{ds2} \parallel r_{ds4}$$

$$BW = \frac{1}{2\pi R_{out} C_L}$$

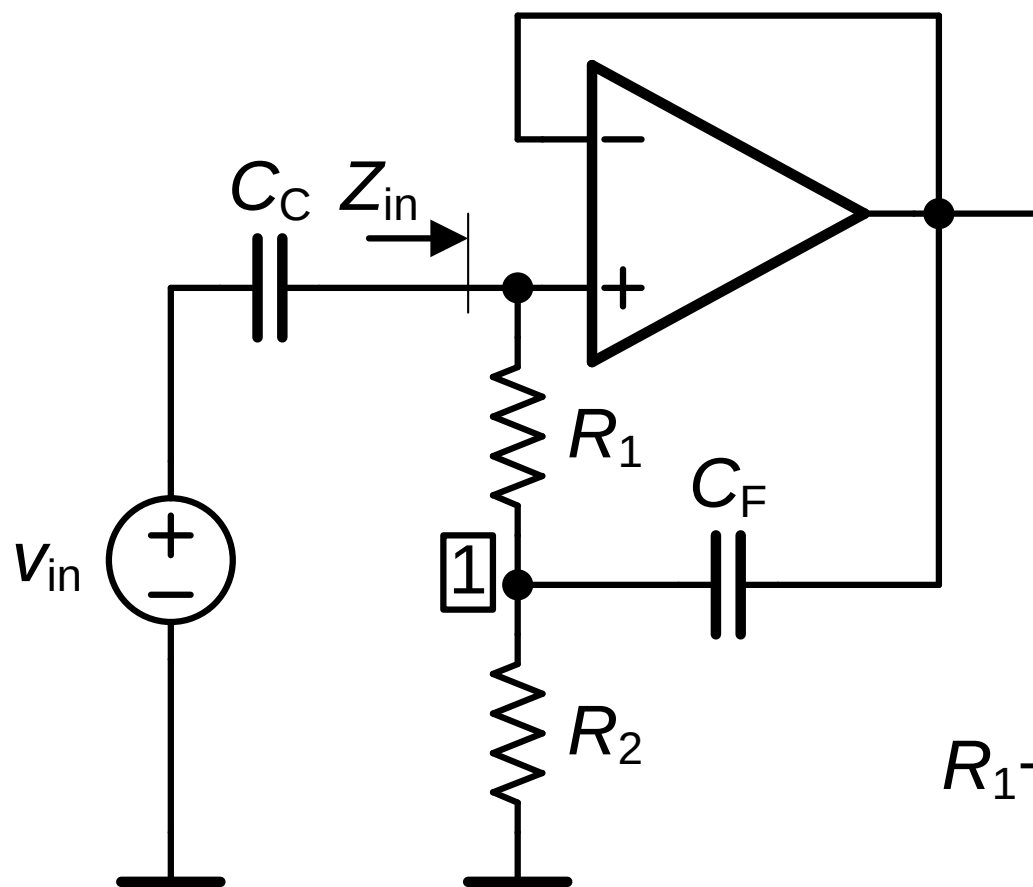
$$GBW = \frac{g_{m1}}{2\pi C_L}$$

电容自举电路



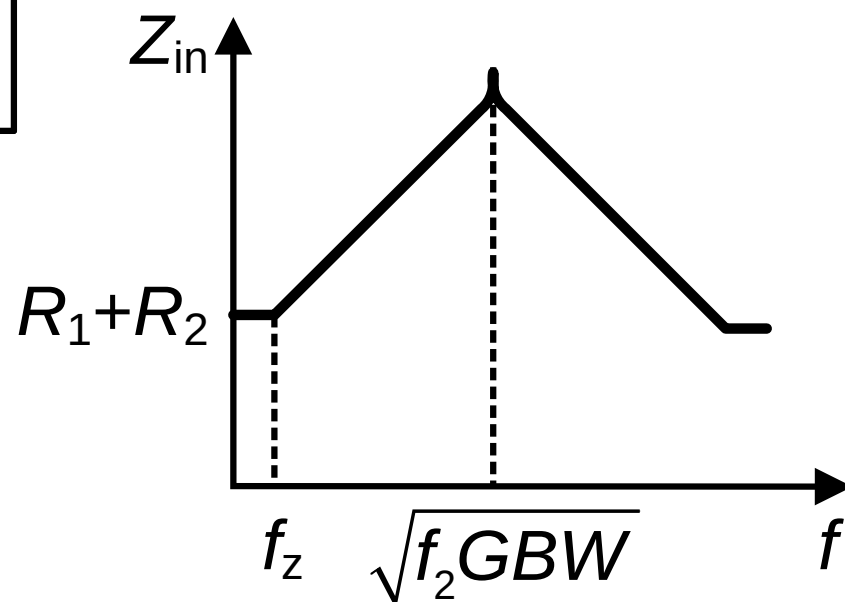
$$C_{\text{coax}} \approx 0 !!!$$

电阻自举电路 1

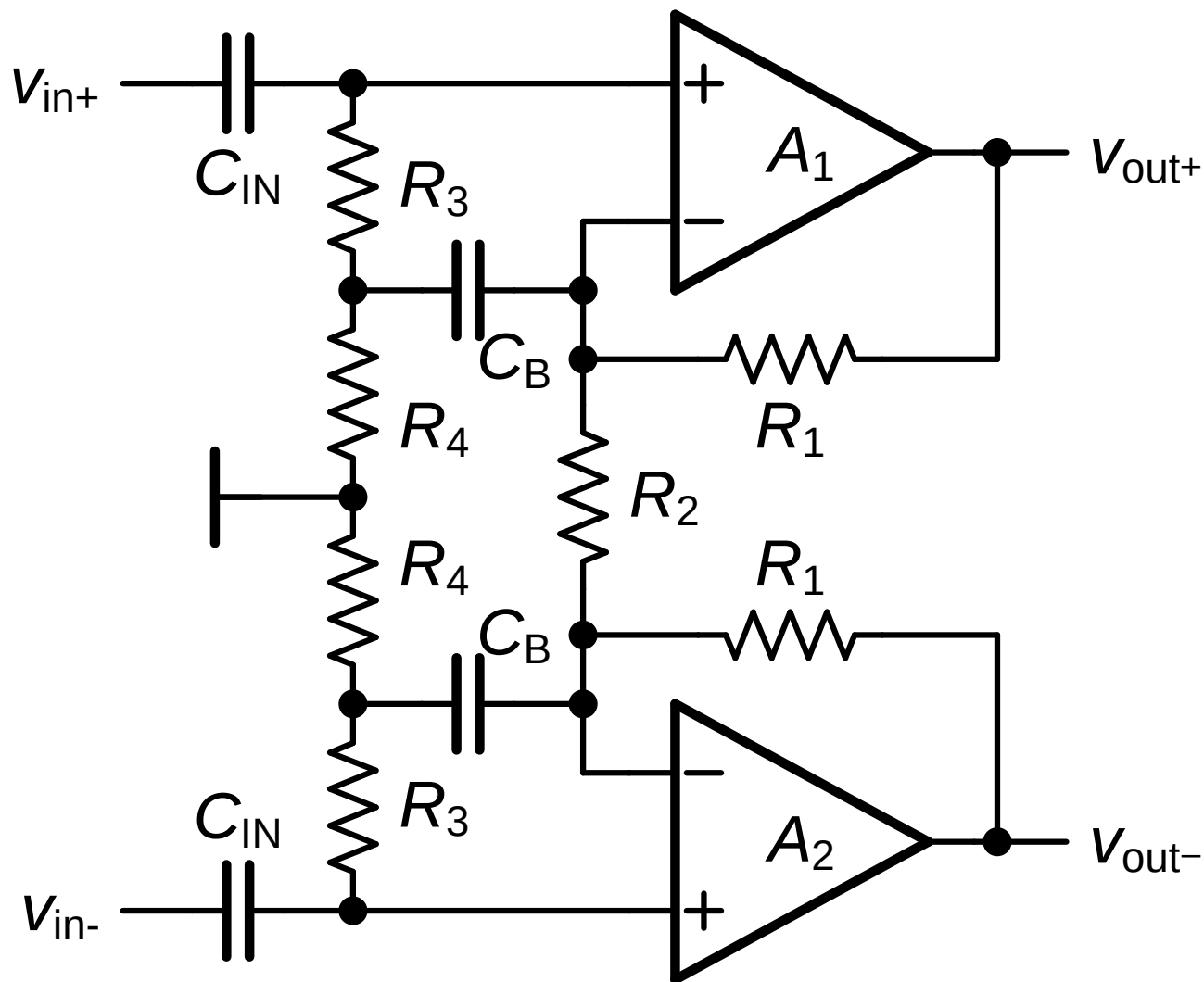


$$f_z = \frac{1}{2\pi(R_1 // R_2)C_F}$$

$$f_2 = \frac{1}{2\pi R_2 C_F}$$

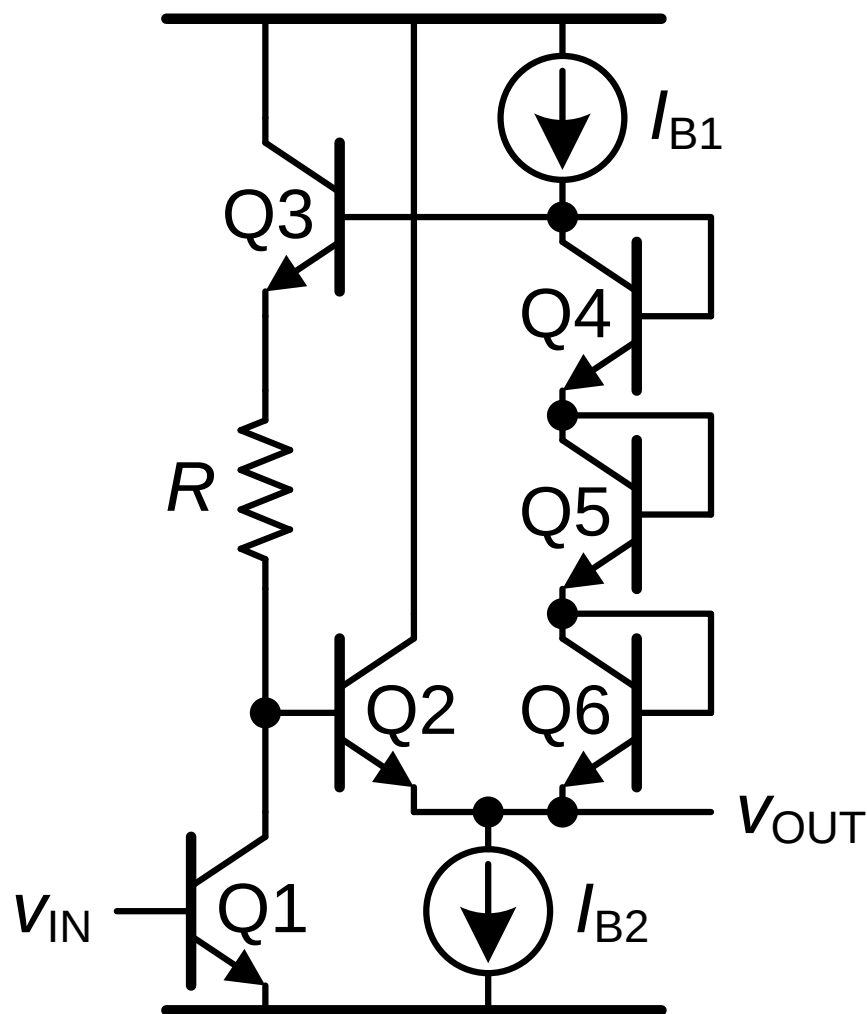


电阻自举电路 2



$$Z_{in} \approx \infty !!!$$

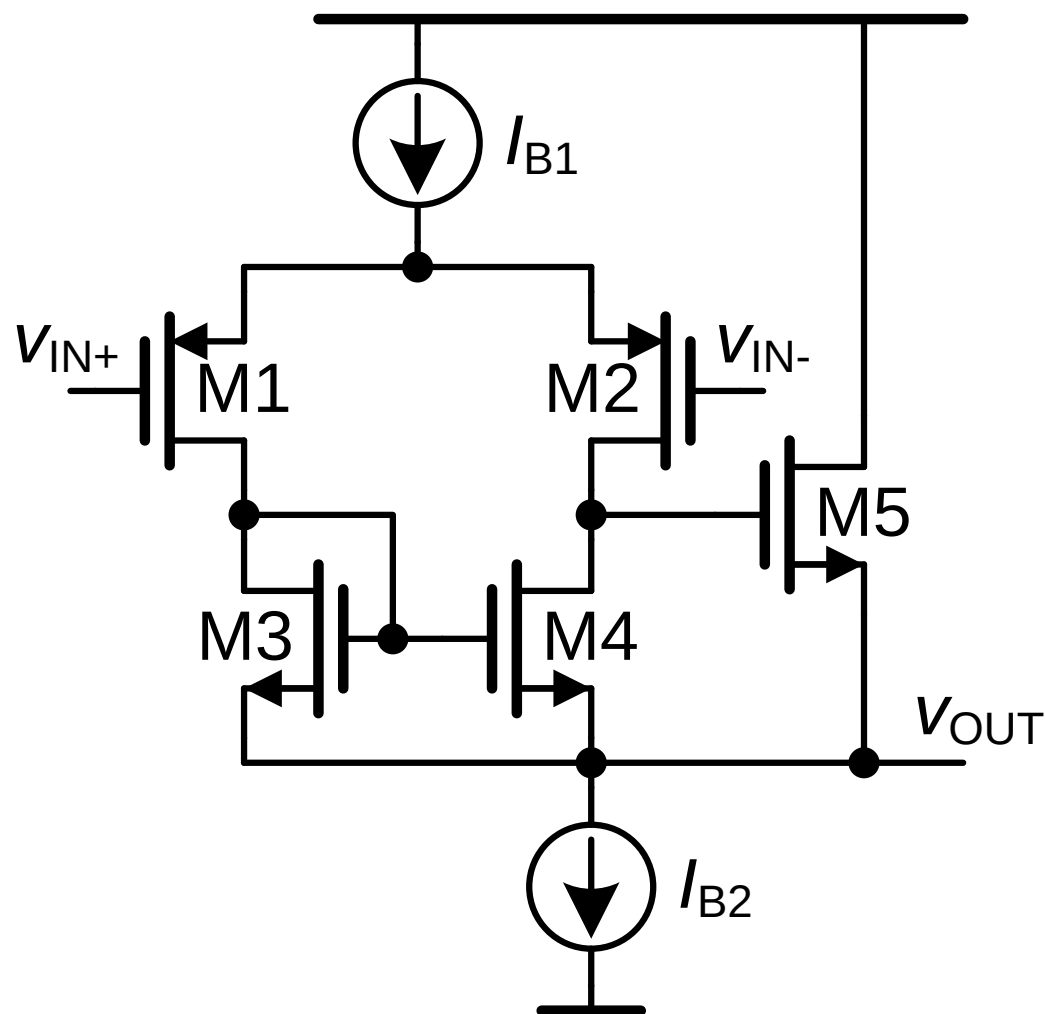
电阻自举电路 3



R 被自举掉了：
增益非常高！

Ref.: Nordholt JSSC June 85, 688-696

电阻自举电路 4

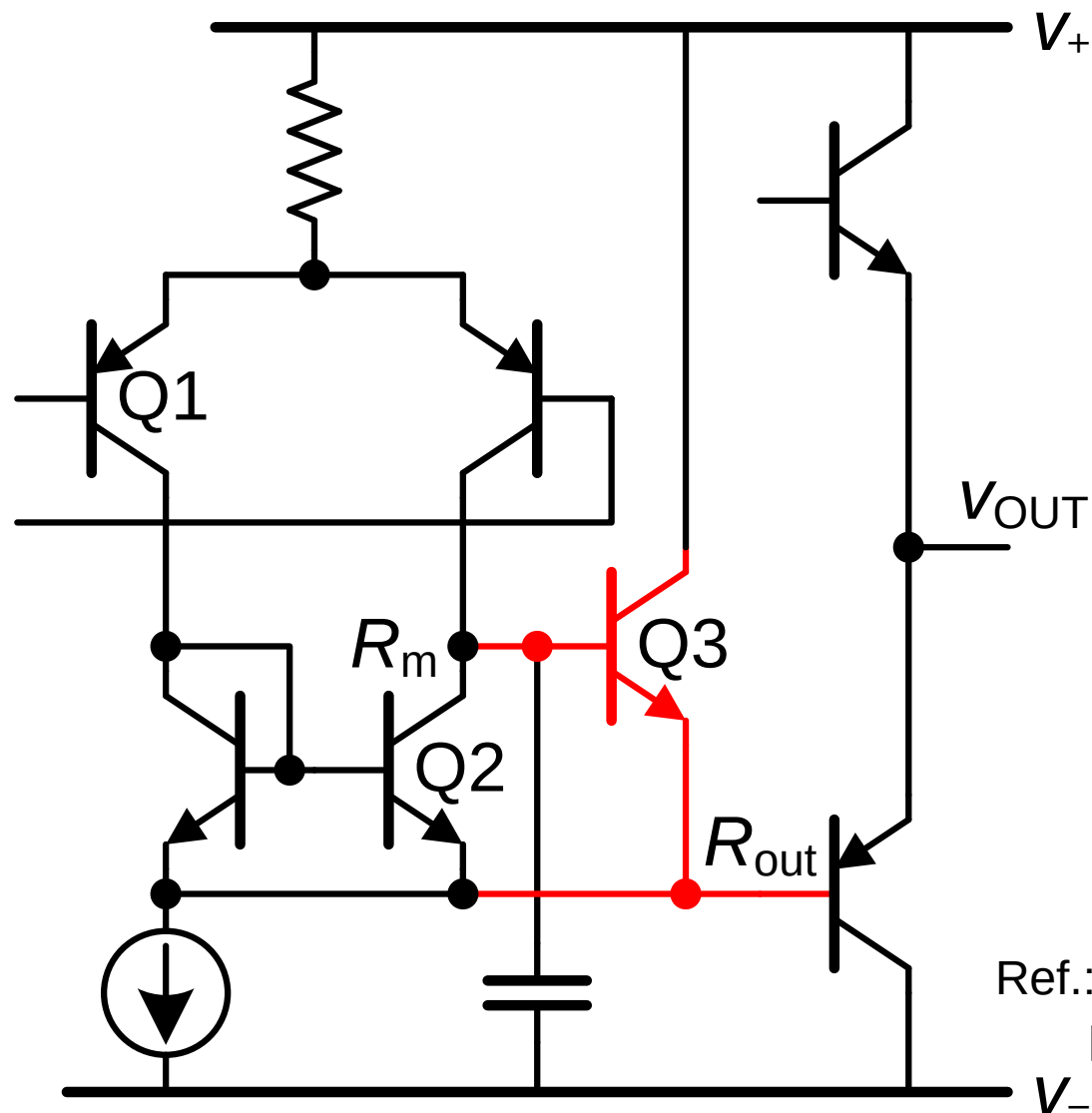


r_{ds4} 被自举掉了!

$$A_v \approx g_{m1} r_{ds2}$$

GBW 相同!

电阻自举电路 5



$$R_m \rightarrow x\beta_3$$

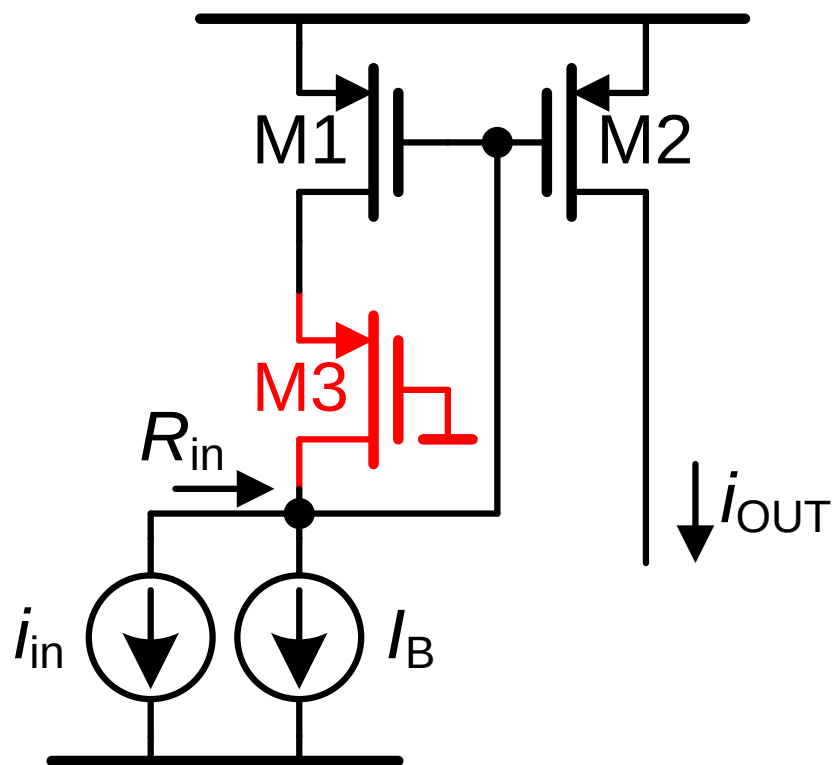
$$R_{out} \rightarrow x \frac{1}{\beta_3}$$

$$A_v \approx g_{m1} r_{o2} x \beta_3$$

*GBW*相同!

Ref.: De Man JSSC June 77,
pp. 217-222 LT1008, LT1012

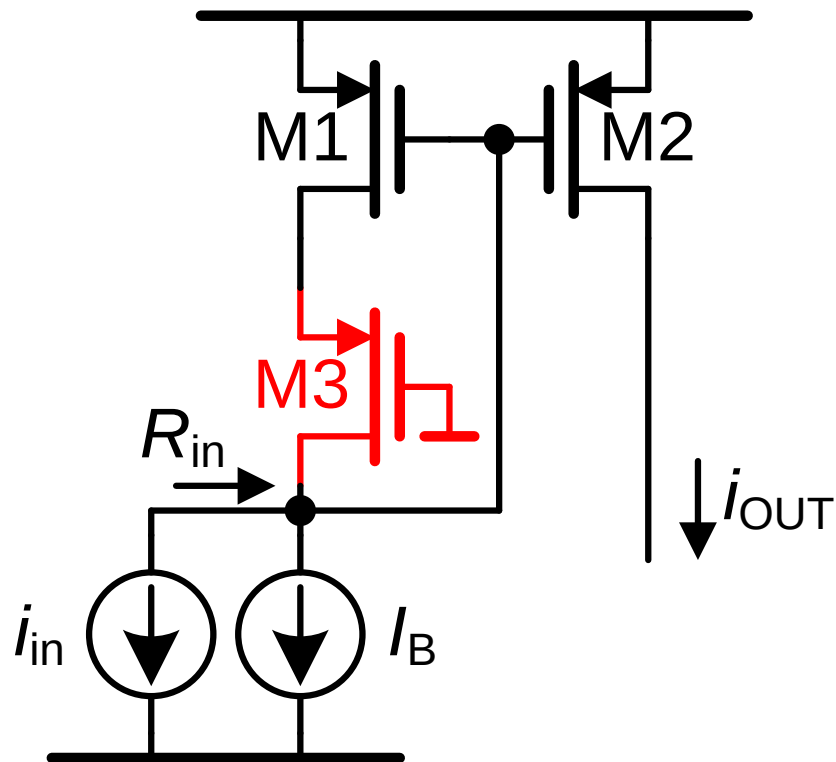
差分电流放大器



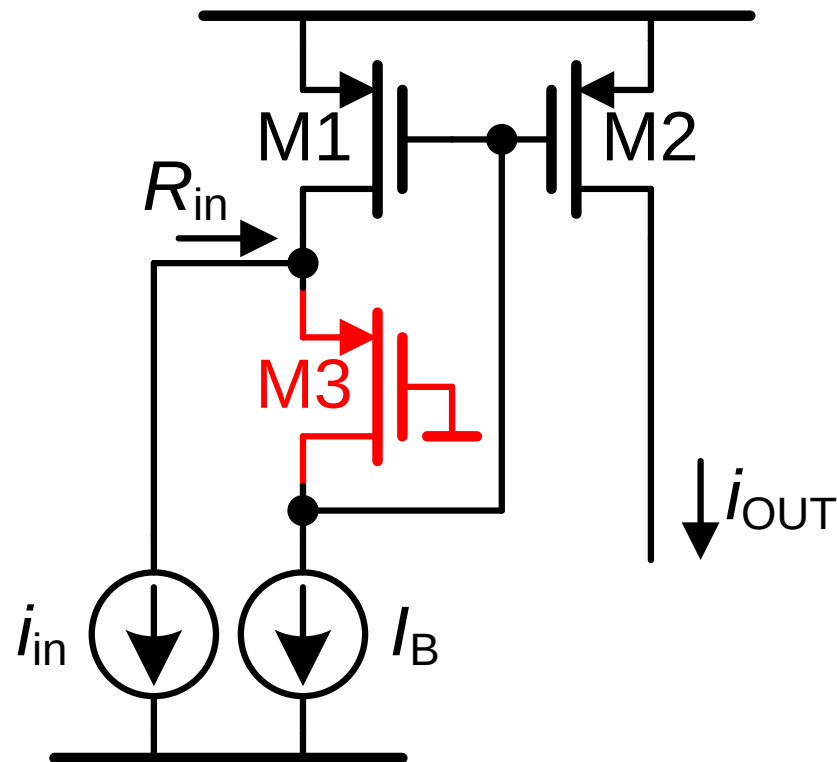
相同！M3未影响其他参数。

$$i_{OUT} = I_B + i_{in} \quad R_{in} = \frac{1}{g_{m1}}$$

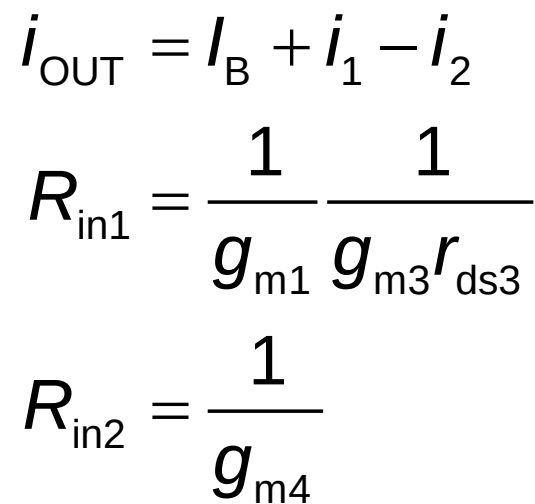
差分电流放大器



$$i_{OUT} = I_B + i_{in} \quad R_{in} = \frac{1}{g_{m1}}$$

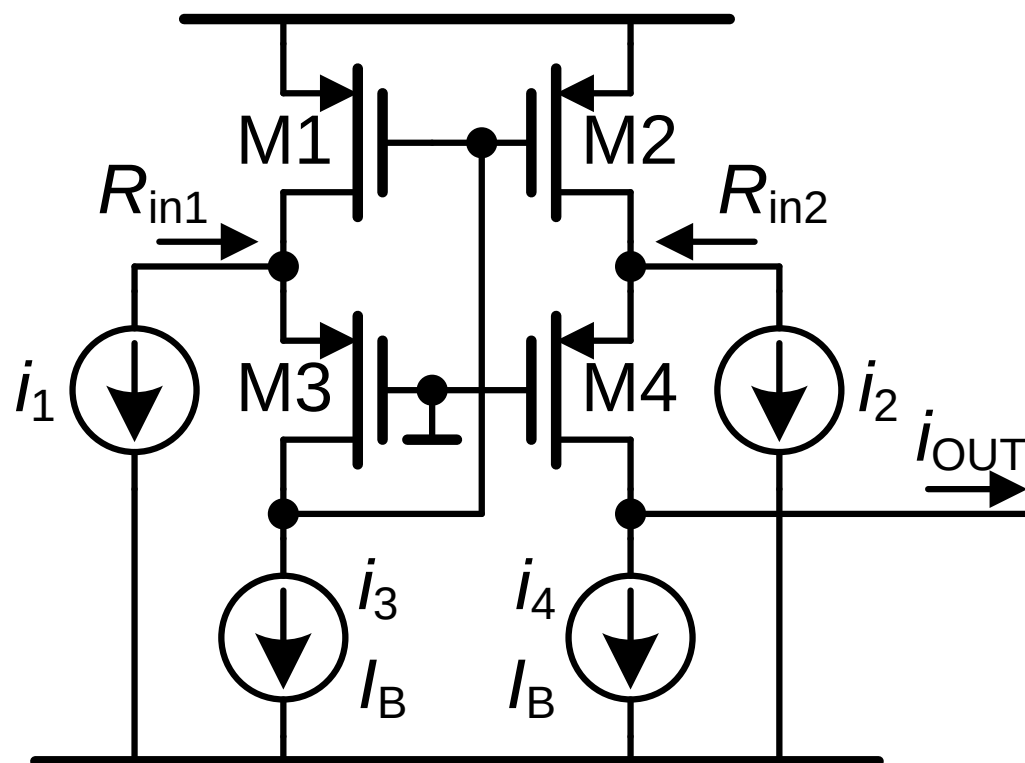


$$R_{in} = \frac{1}{g_{m1}} \frac{1}{g_{m3} r_{ds3}}$$



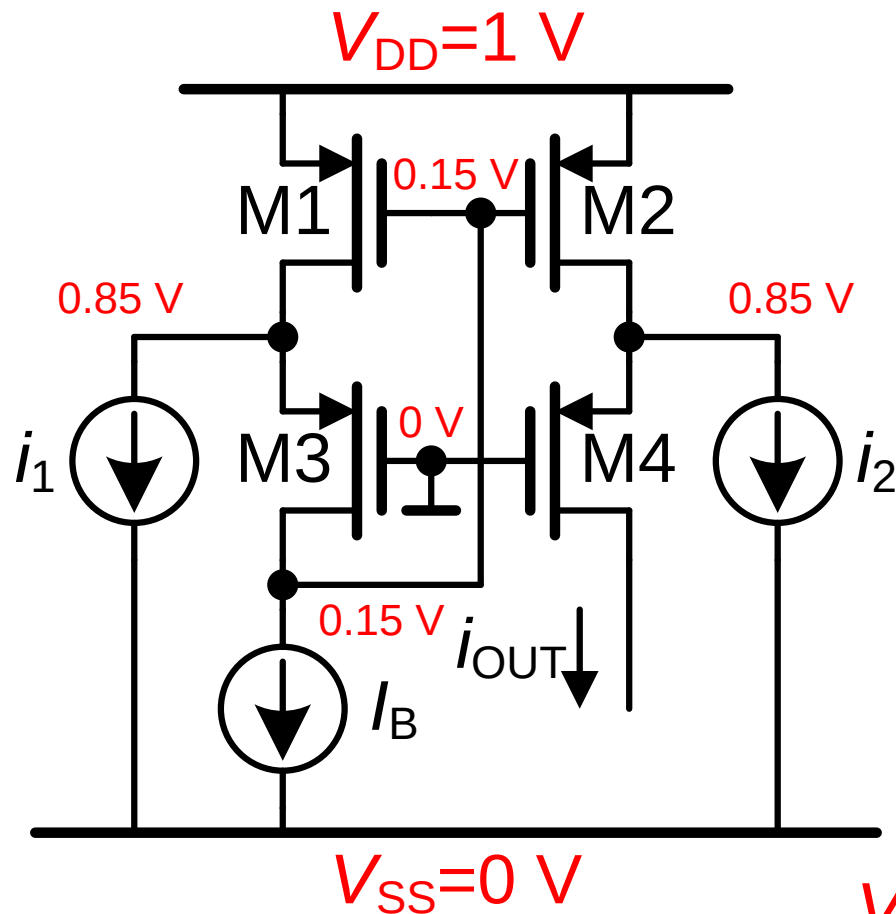
-0349-

4输入电流放大器



$$i_{OUT} = i_1 - i_2 + i_3 - i_4$$

低电压放大器



$$i_{OUT} = I_B + i_1 - i_2$$

$$V_{GS} = 0.85 \text{ V}$$

$$V_{DSsat} = 0.15 \text{ V}$$

$$V_{outmax} = 0.7 \text{ V}$$

$$V_{TH} = 0.7 \text{ V} \Rightarrow V_{DDmin} \approx 1.0 \text{ V}$$

$$V_{TH} = 0.3 \text{ V} \Rightarrow V_{DDmin} \approx 0.6 \text{ V}$$