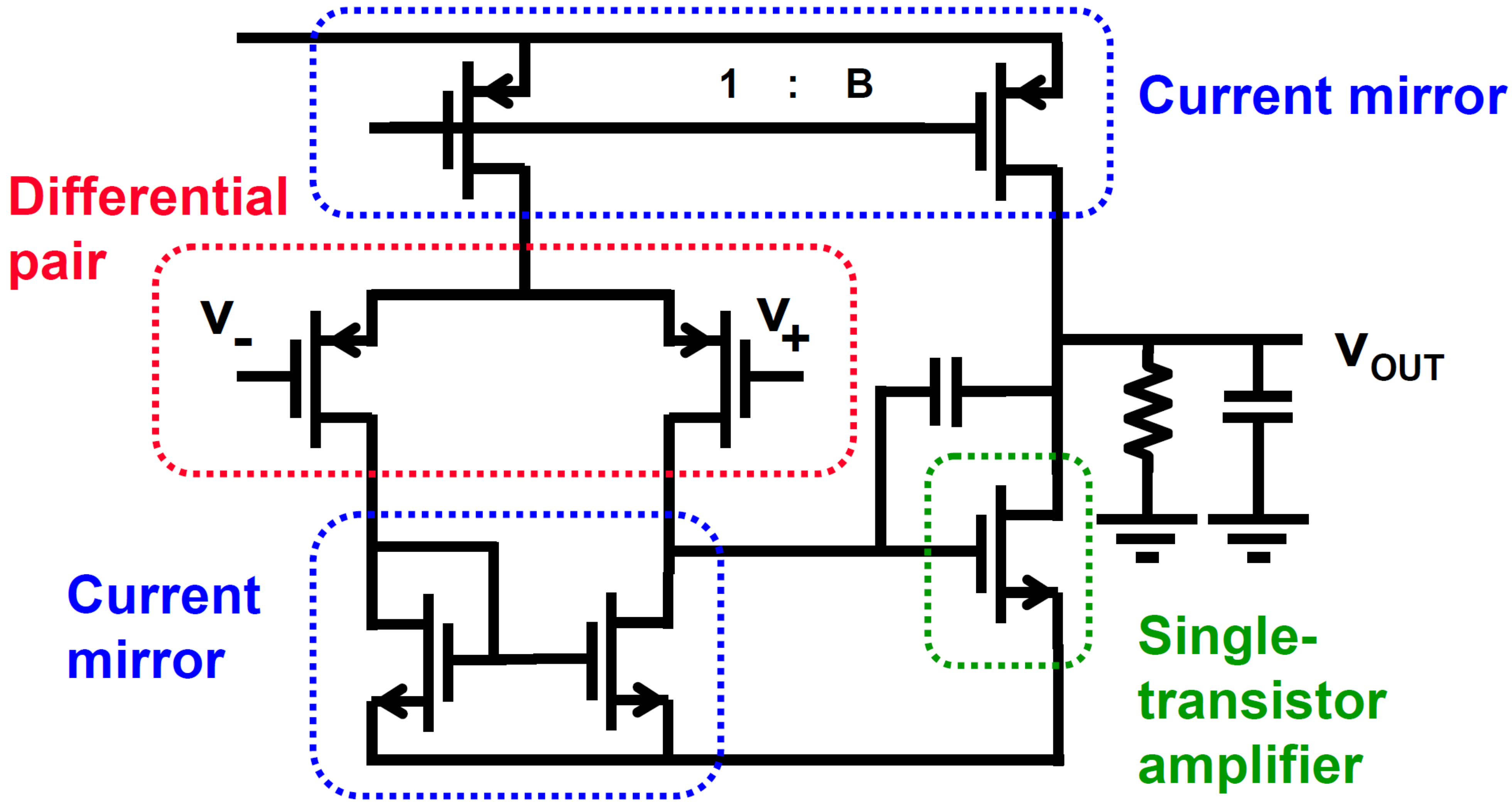
CMOS模拟集成电路设计

第二章：模拟电路的基本构成

胡远奇

运算放大器

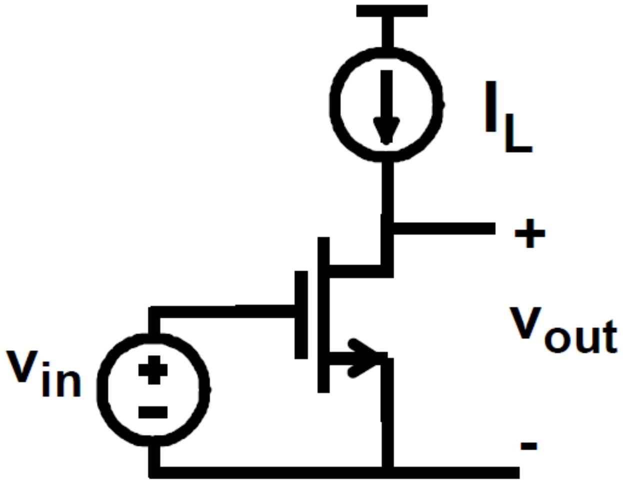


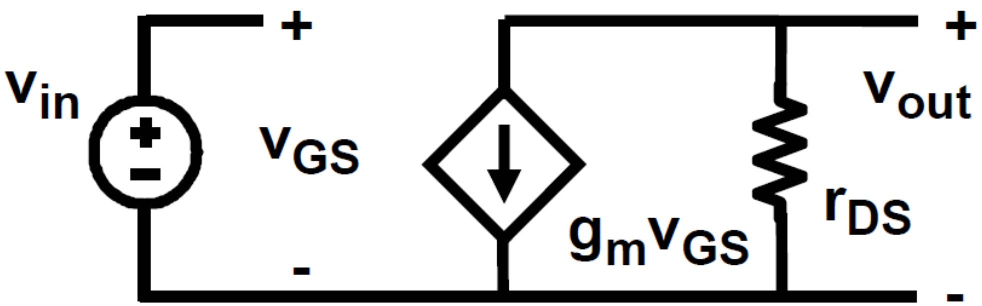
1 : B
Current mirror
Differential pair
V-
V+
VOUT
Current mirror
Single-transistor amplifier

模拟电路的基本结构

1. **单晶体管放大器**
2. 源极跟随器
3. Cascode （共源共栅极）
4. 电流镜
5. 差分对

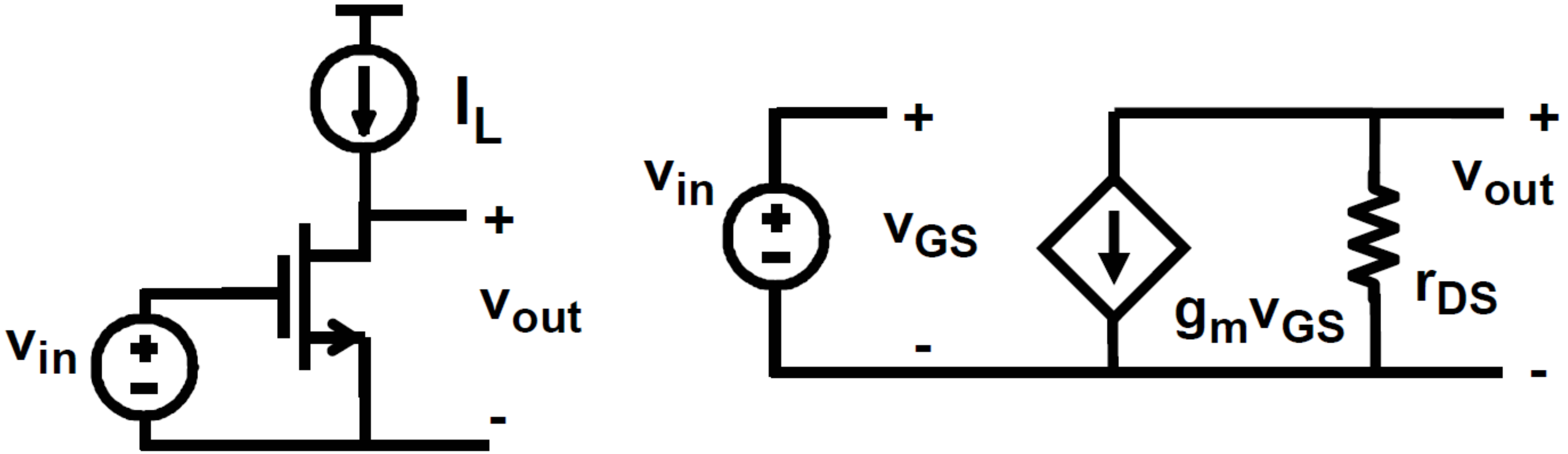
单晶体管放大器





$A_v =$

单晶体管放大器



$$A_v = g_m r_{DS} = \frac{2\ I_{DS}}{V_{GS}-V_T}\ \frac{V_E\ L}{I_{DS}} = \frac{2\ V_E\ L}{V_{GS}-V_T}$$

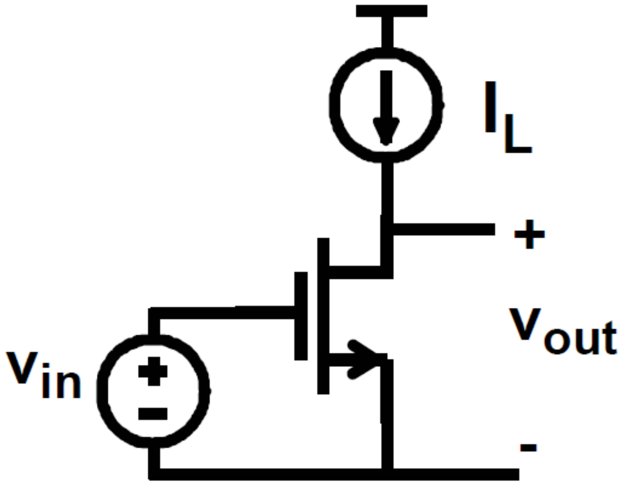
$A_v \approx 100$ if $V_E L \approx 10$ V and $V_{GS}-V_T \approx 0.2$ V

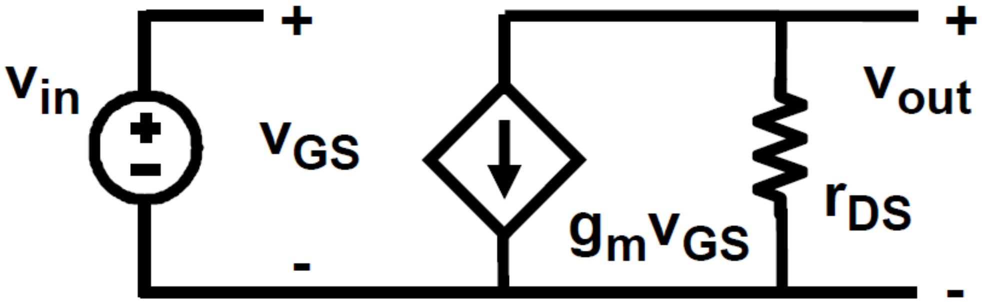
单晶体管放大器

如何获得高增益?

降低V_{GS}-V_T	增加L
0.15-0.2V	4-5x minL
进一步减小会牺牲信噪比SNR和跨导gm	进一步增大会牺牲速度和面积

单晶体管放大器

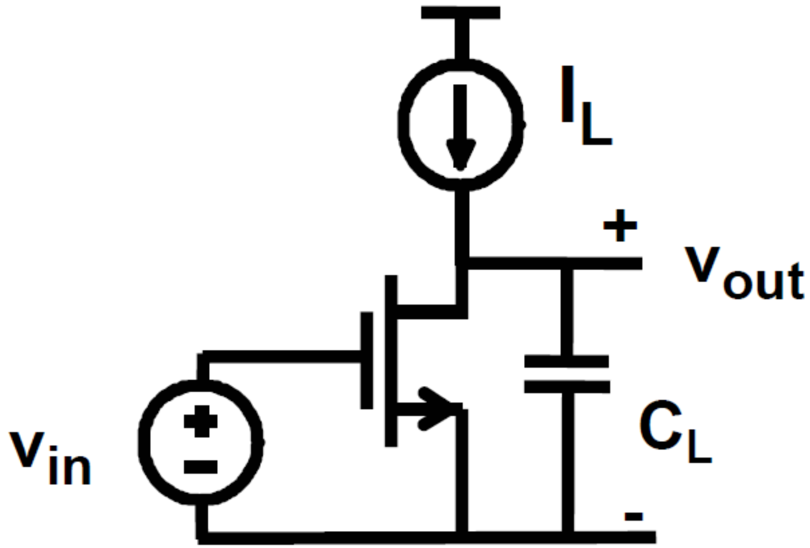




- 问：对于一个55nm工艺的单晶体管放大器，其典型的放大倍数是多少？（V_E=4V/um）

单晶体管放大器的频率特性

- 如果只有大的**负载**电容



$$A_{v0} = g_m r_{DS}$$

$$BW = \frac{1}{2\pi\, r_{DS} C_L}$$

$$\boxed{GBW = \frac{g_m}{2\pi\, C_L}}$$

For all single-stage
Operational amplifiers

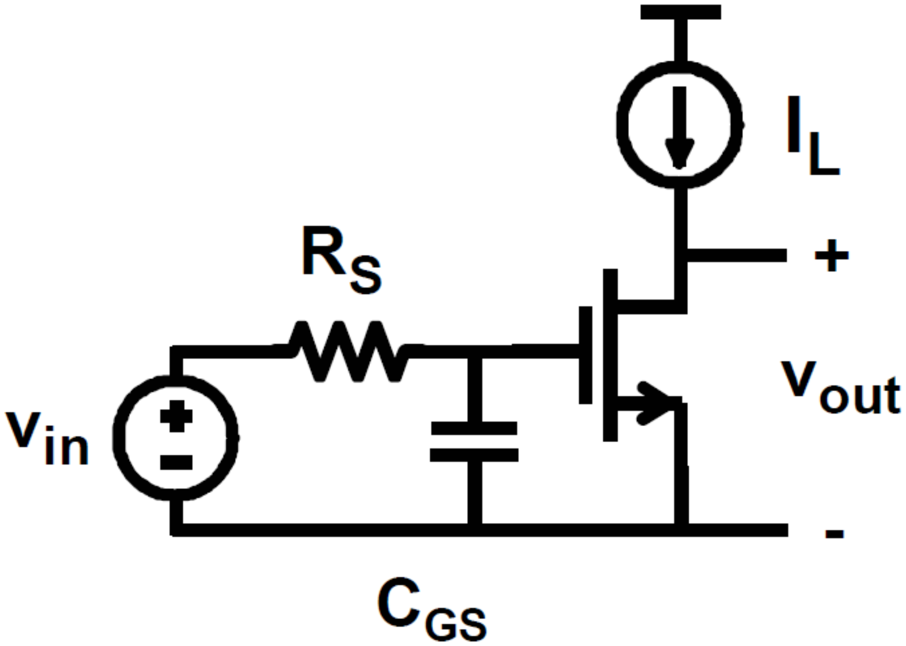
单晶体管放大器的频率特性

- ❑设计指标GBW=100M，负载电容2pF的NMOS单晶体放大器，根据工艺指标计算相应的直流偏置电流和典型晶体管尺寸。

$L_{min} = 0.35\ \mu m$ $KP_n \approx 300\ \mu A/V^2$

单晶体管放大器的频率特性

- 如果只有大的**输入**电容

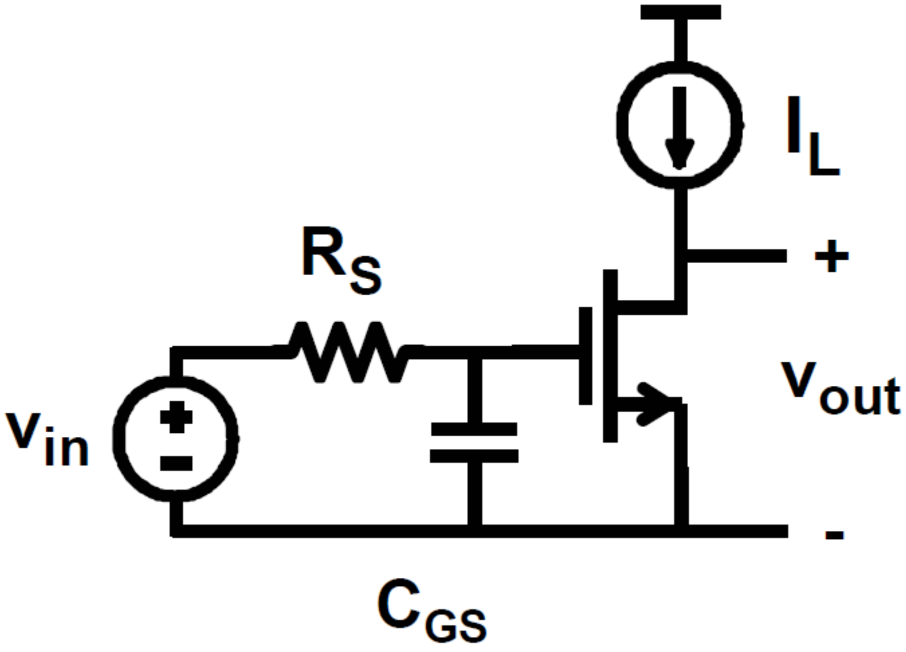


$$A_{v0} = g_m r_{DS}$$

$$BW = \frac{1}{2\pi R_S C_{GS}}$$

单晶体管放大器的频率特性

- 如果只有大的**输入**电容



$$A_{v0} = g_m r_{DS}$$

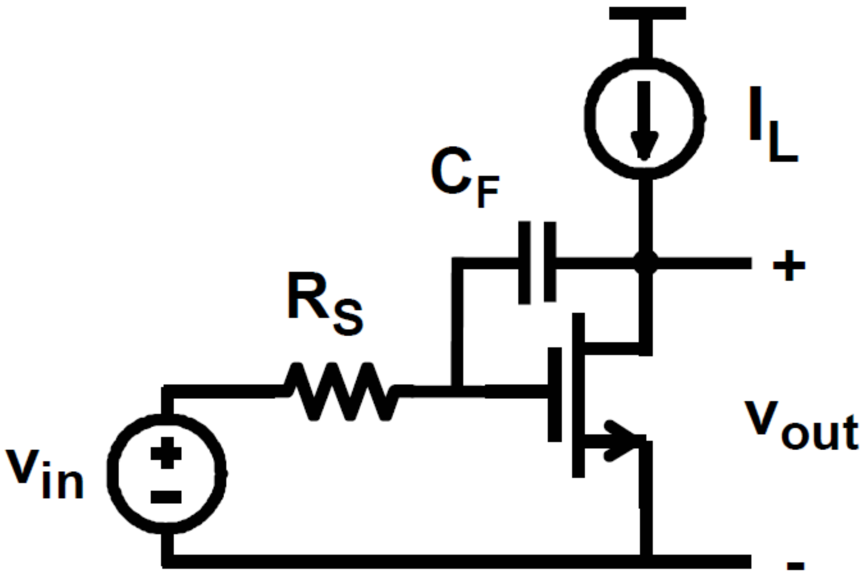
$$BW = \frac{1}{2\pi R_S C_{GS}}$$

GBW和长度L无关！

$$GBW = \frac{g_m}{2\pi C_{GS}} \frac{r_{DS}}{R_S} = f_T \frac{r_{DS}}{R_S} \sim \frac{1}{WC_{ox}} \frac{1}{V_{GS}-V_T}$$

单晶体管放大器的频率特性

- 如果只有大的**反馈**电容



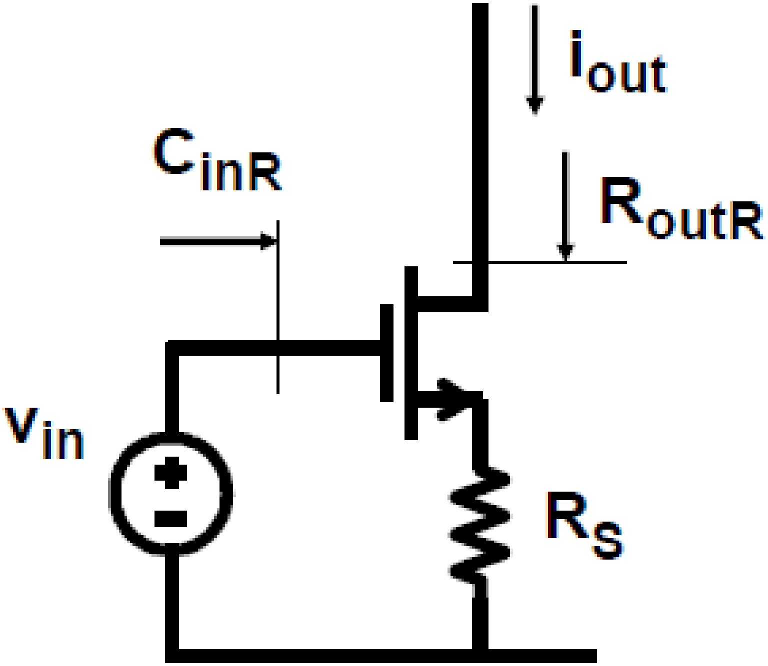
$$A_{v0} = g_m r_{DS}$$

$$BW = \frac{1}{2\pi\, R_S\, A_{v0}\, C_F}$$

$$GBW = \frac{1}{2\pi\, R_S\, C_F}$$

GBW和晶体管的参数无关！

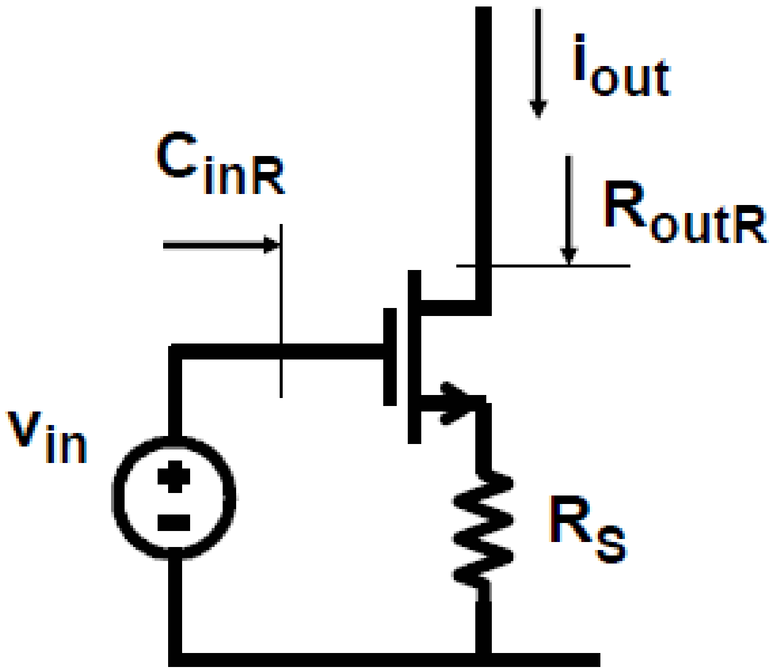
Source Degeneration

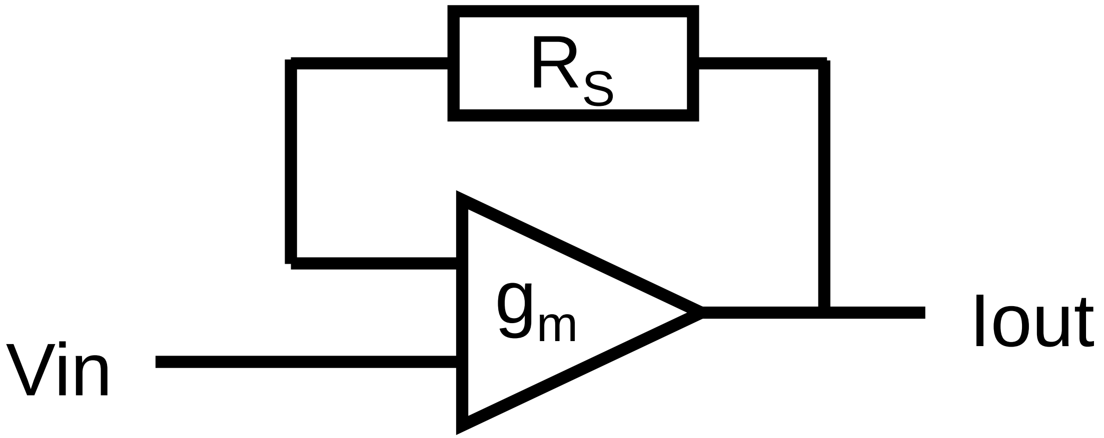


Source Degeneration

是一种**负反馈**形式

Source Degeneration



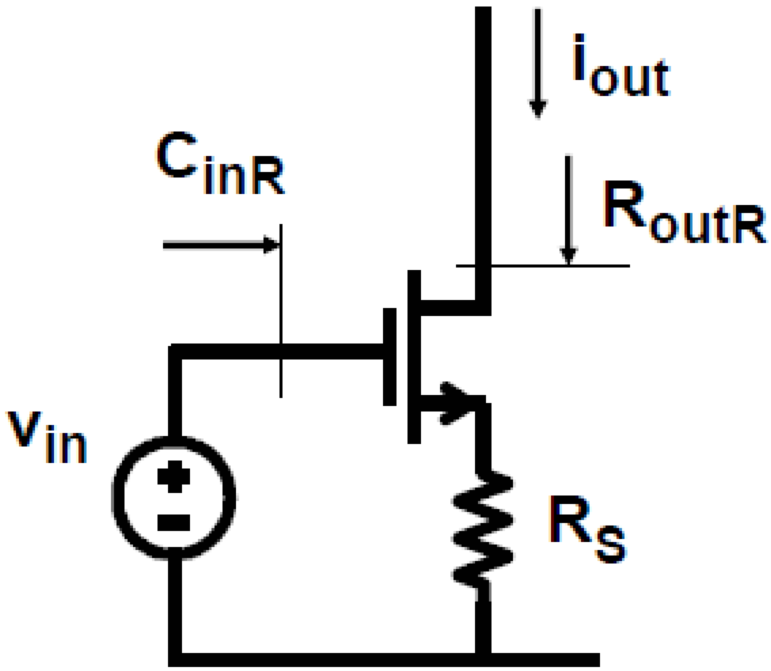


Source Degeneration
是一种**负反馈**形式

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

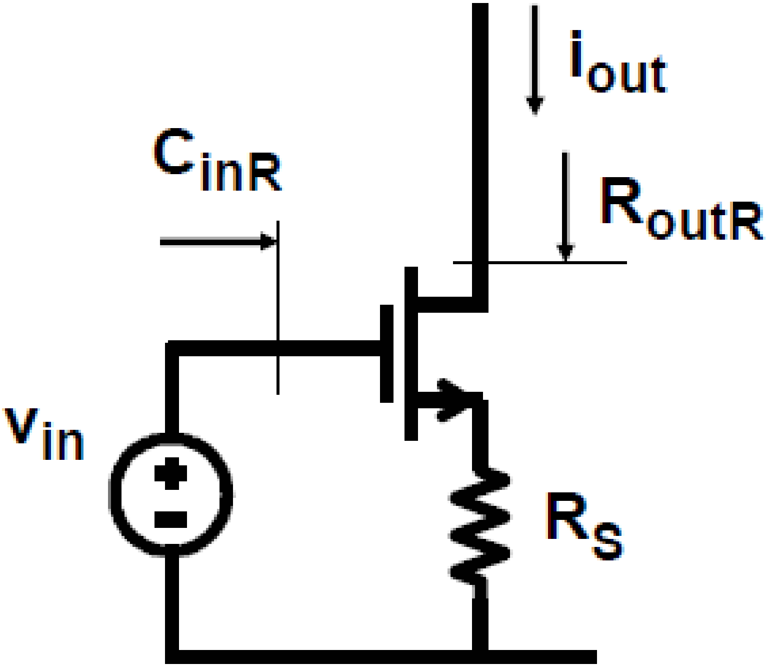
$$C_{inR} = \frac{C_{GS}}{1 + g_m R_S}$$

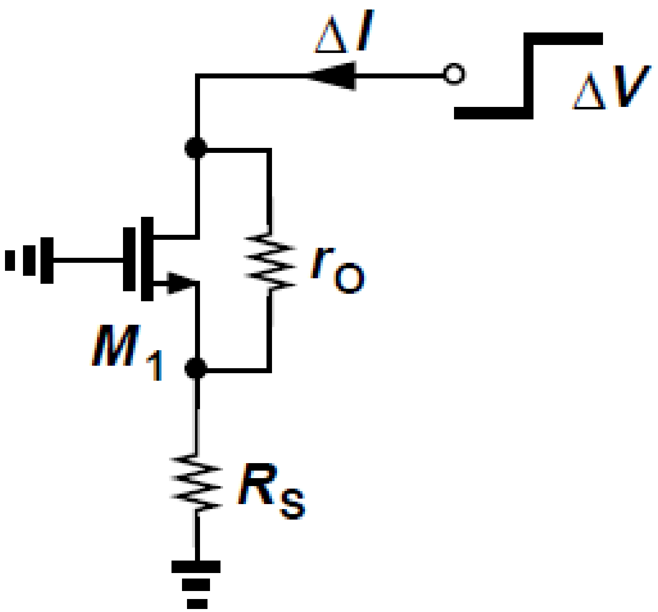
Source Degeneration



- 在输出端施加电压变化ΔV并测量输出电流的最终变化ΔI

Source Degeneration





- $R_{outR} = r_{DS}\,(1+ g_m R_S) \approx (g_m r_{DS})\,R_S$

R_S造成额外的噪声

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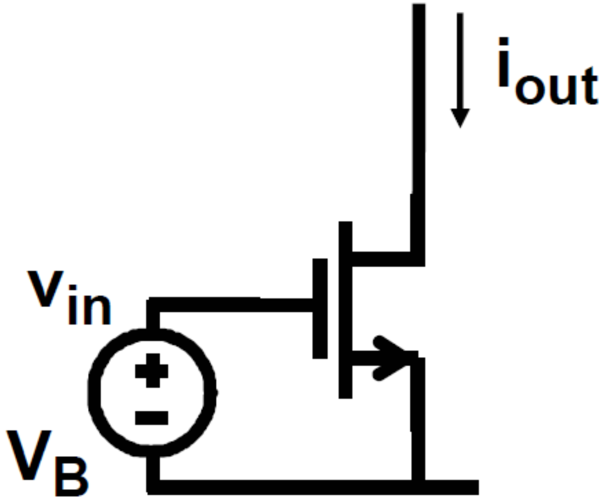
源极跟随器 (Source Follower)

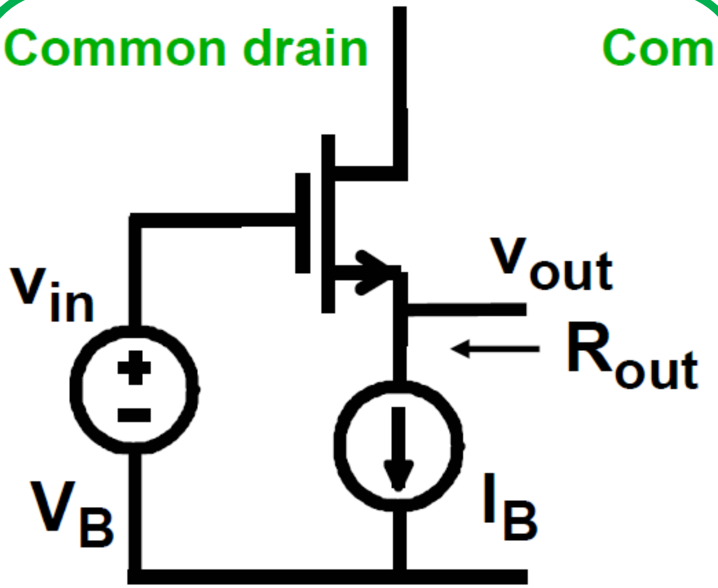
Common source



$$i_{out} = g_m v_{in}$$

Amplifier

Common drain



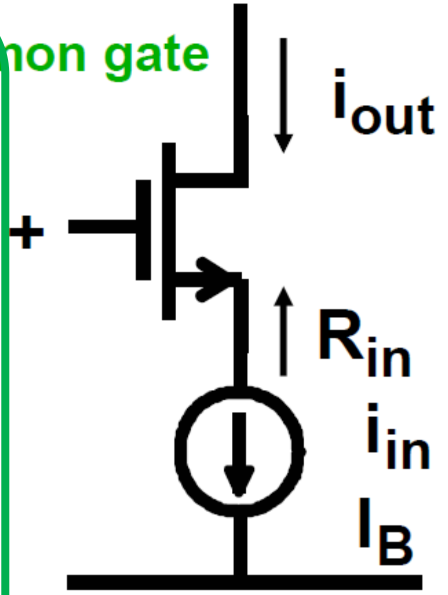
$$v_{out} = v_{in}$$

$$R_{out} \approx 1/g_m$$

Source follower

Voltage buffer

Common gate



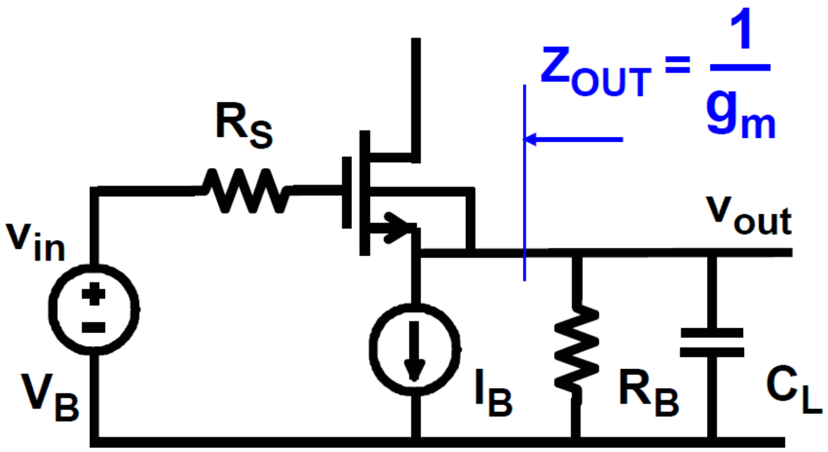
$$i_{out} = i_{in}$$

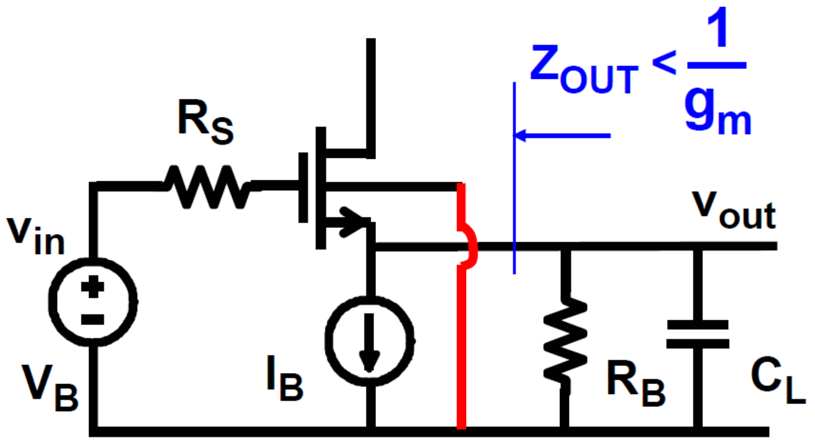
$$R_{in} \approx 1/g_m$$

Cascode

Current buffer

源极跟随器 (Source Follower)





I_B为常数

⬇

V_{GS}为常数

⬇

$\Delta V_{OUT} = \Delta V_{IN}$

⬇

$A_V = 1$

V_{GS}不为常数

⬇

$A_V = \frac{1}{n} < 1$

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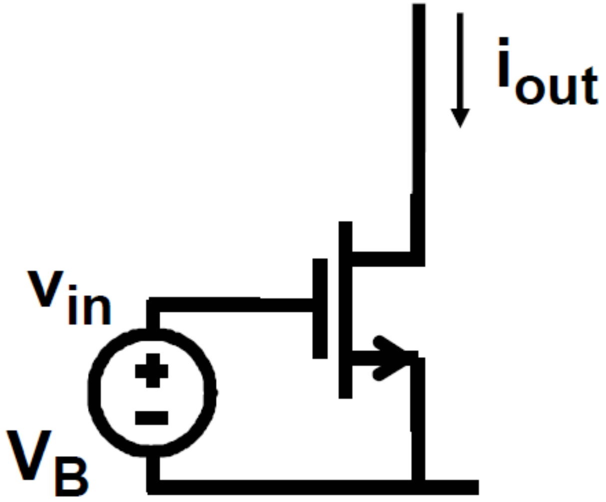
Cascode

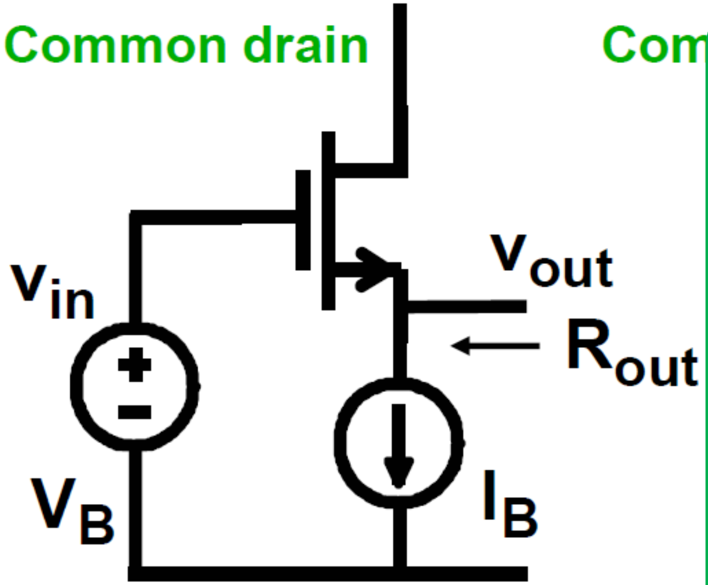
Common source



$i_{out} = g_m v_{in}$

Amplifier

Common drain



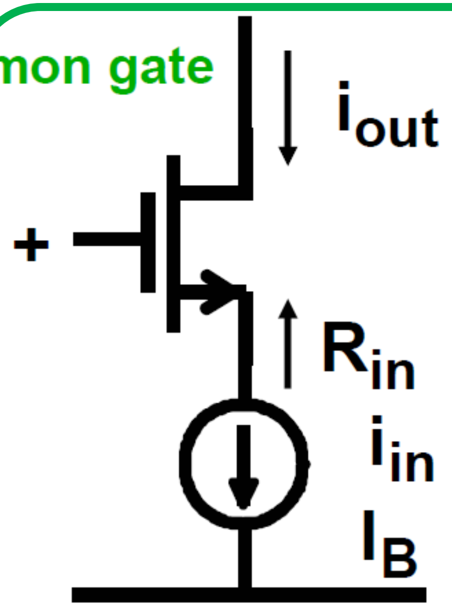
$v_{out} = v_{in}$

$R_{out} \approx 1/g_m$

Source follower

Voltage buffer

Common gate



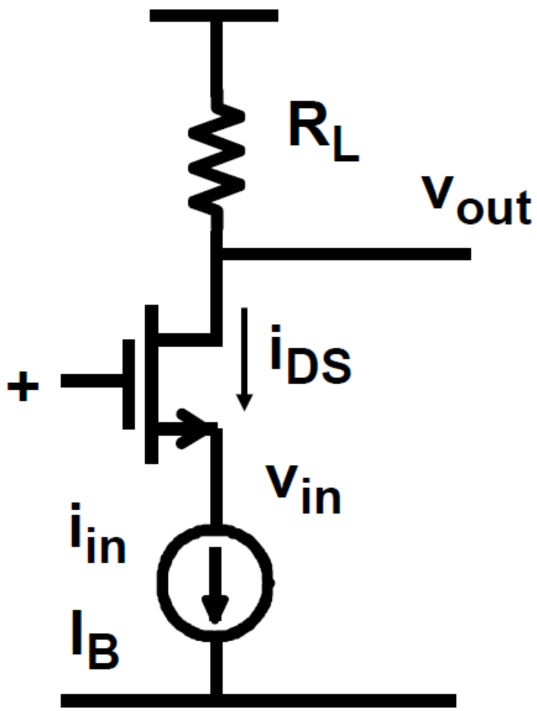
$i_{out} = i_{in}$

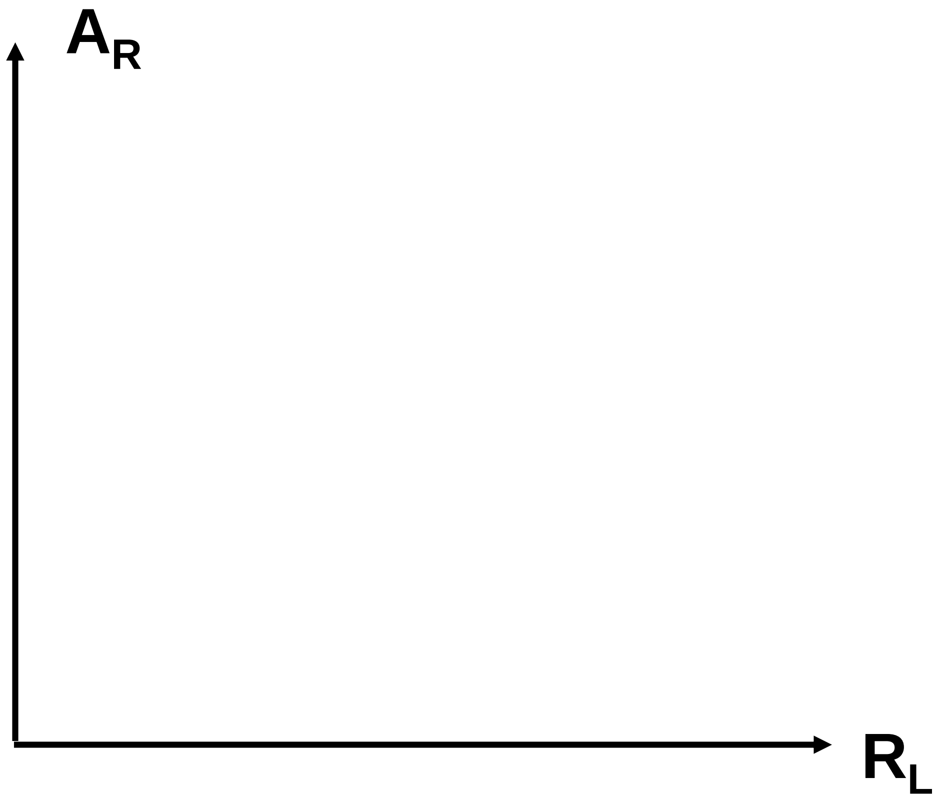
$R_{in} \approx 1/g_m$

Cascode

Current buffer

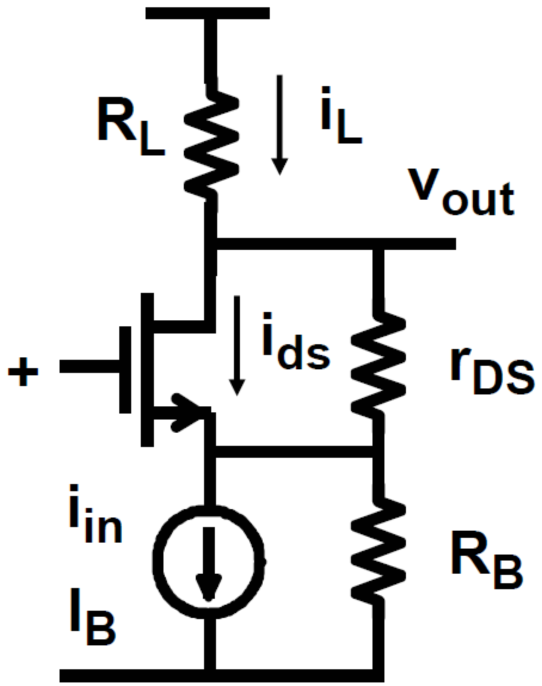
Cascode

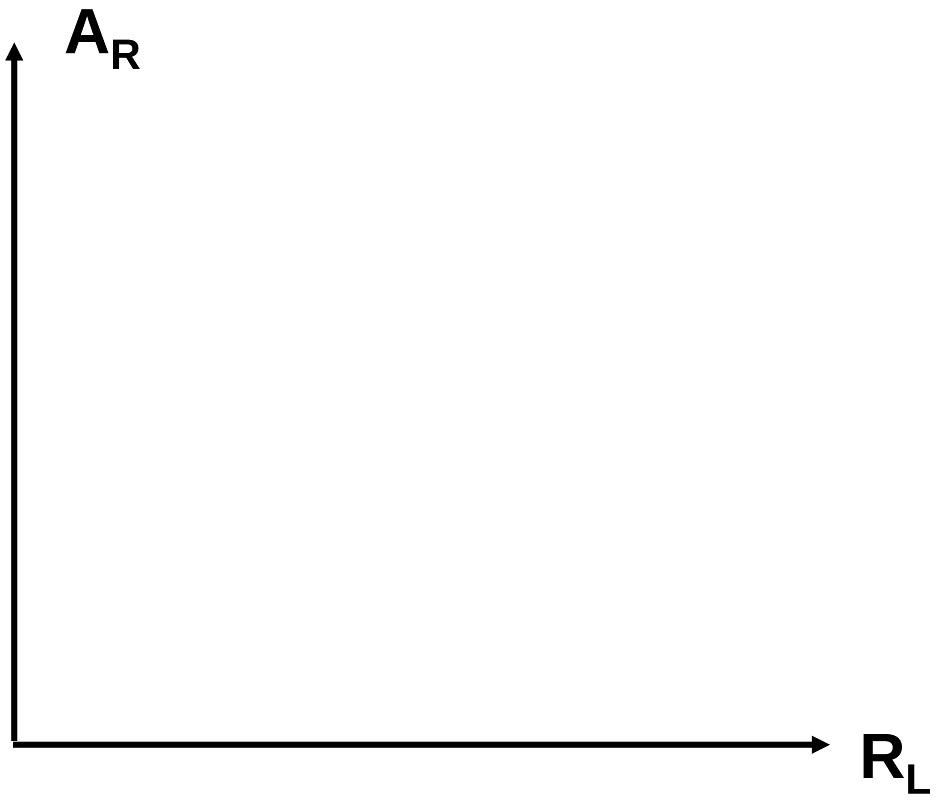




- 定义跨阻增益 $A_R=v_{out}/i_{in}$

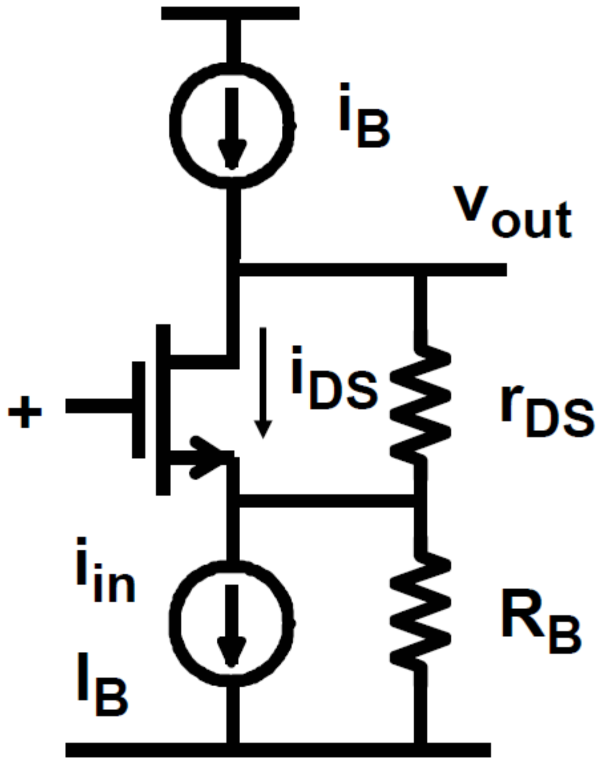
Cascode

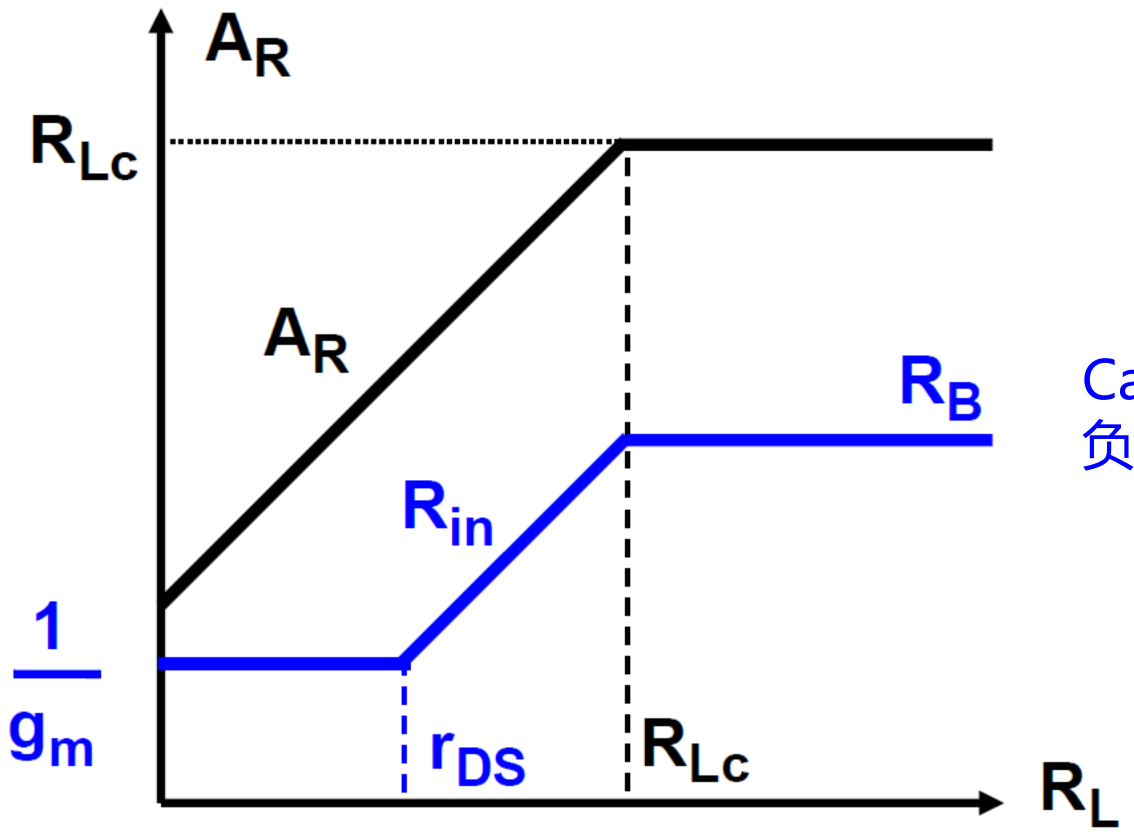




- 分析输入电阻R_{in}

Cascode



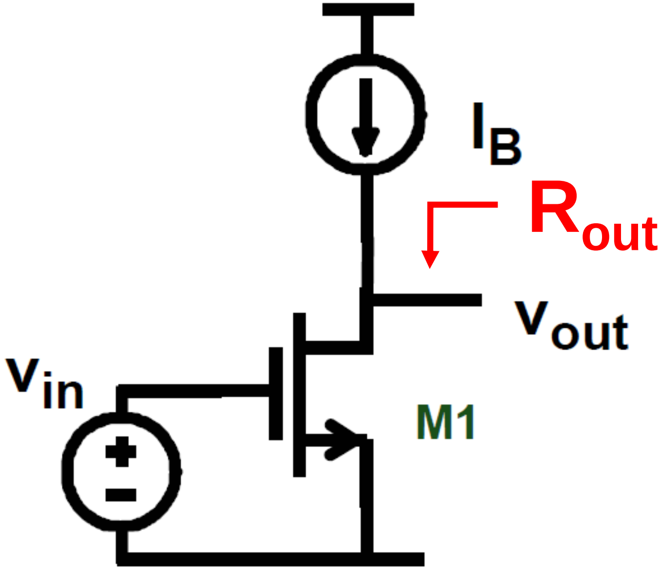


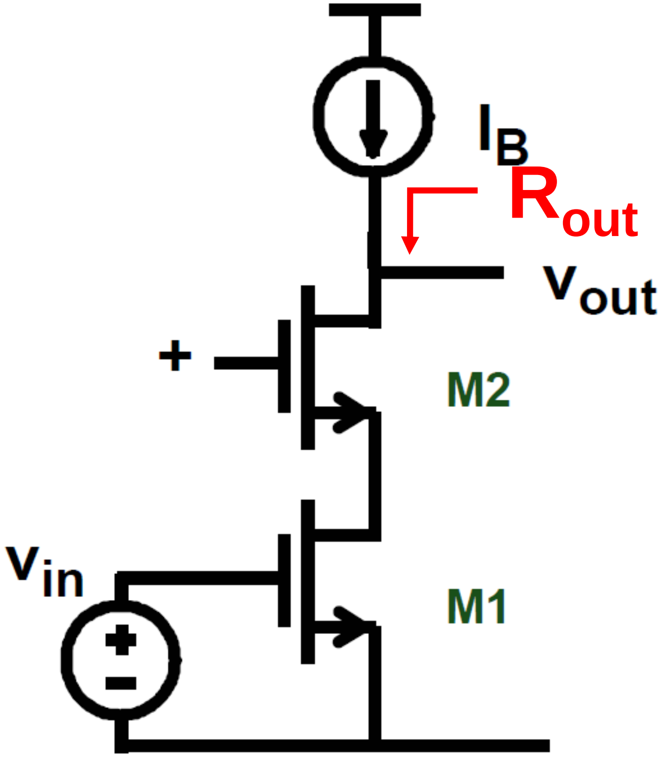
Cascode可以将负载电阻缩小A倍

$$A_R = \frac{v_{out}}{i_{in}} \qquad R_{in} = \frac{v_{in}}{i_{in}}$$

$$R_{in} = \frac{r_{DS} + R_L}{g_m r_{DS}} || R_B$$

Cascode vs 单晶体管





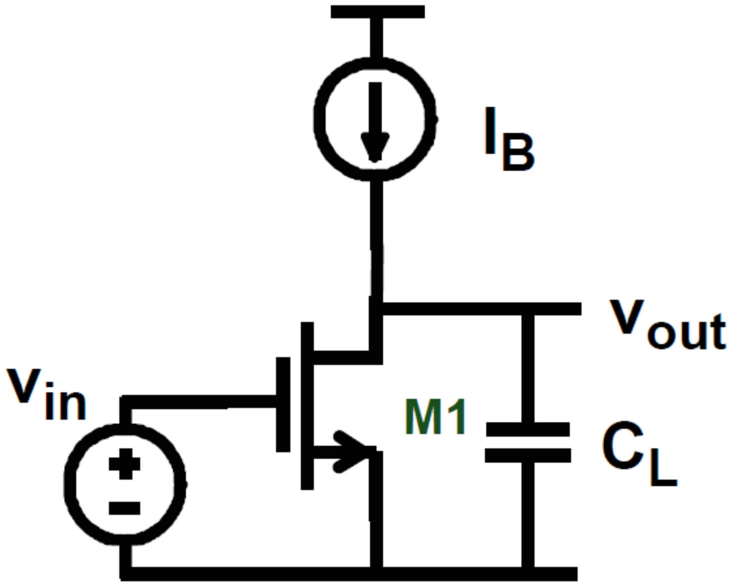
$$A_v = (g_m r_{DS})_1$$

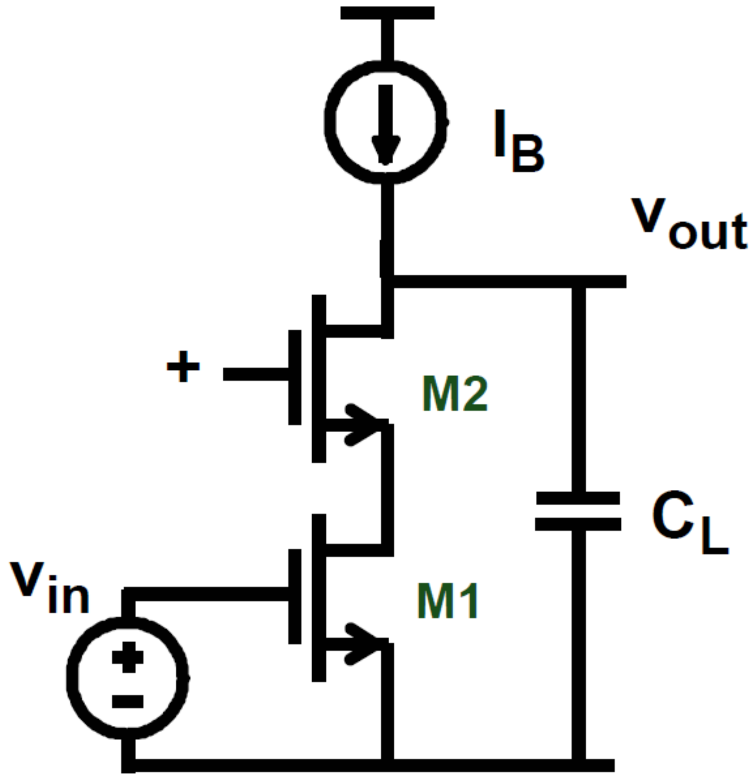
$$R_{out} = r_{DS1}$$

$$A_v = (g_m r_{DS})_1 (g_m r_{DS})_2$$

$$R_{out} = r_{DS1}\,(g_m r_{DS})_2$$

Cascode vs 单晶体管

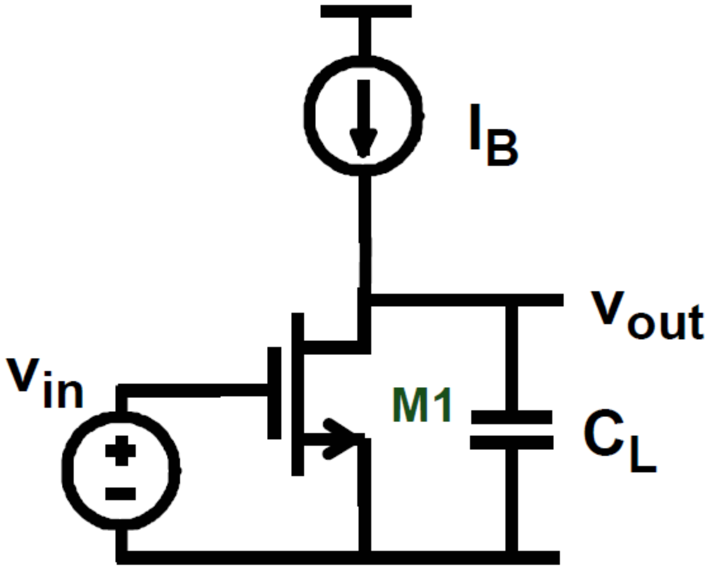


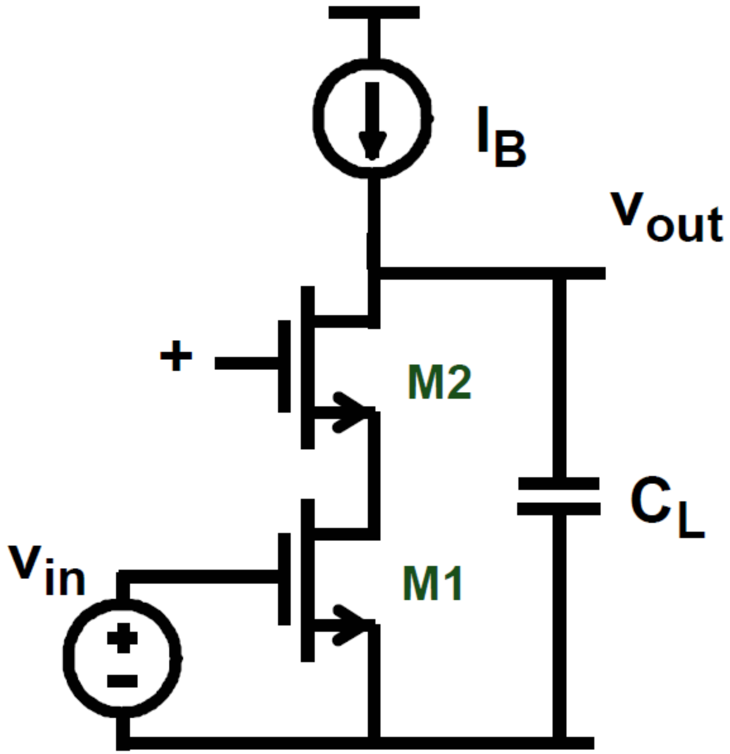


BW =

GBW =

Cascode vs 单晶体管



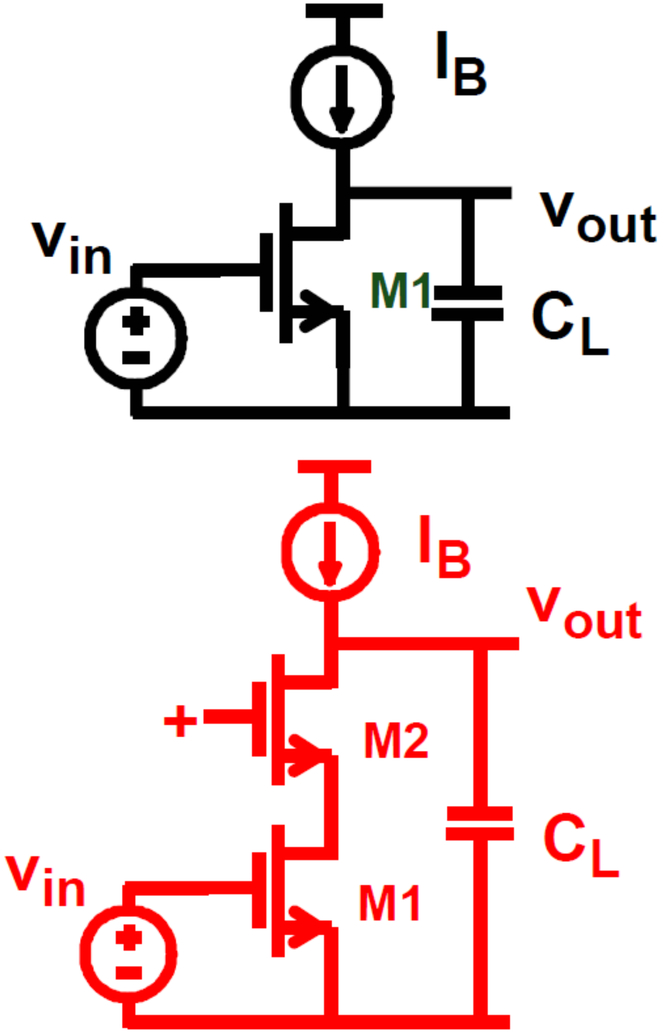


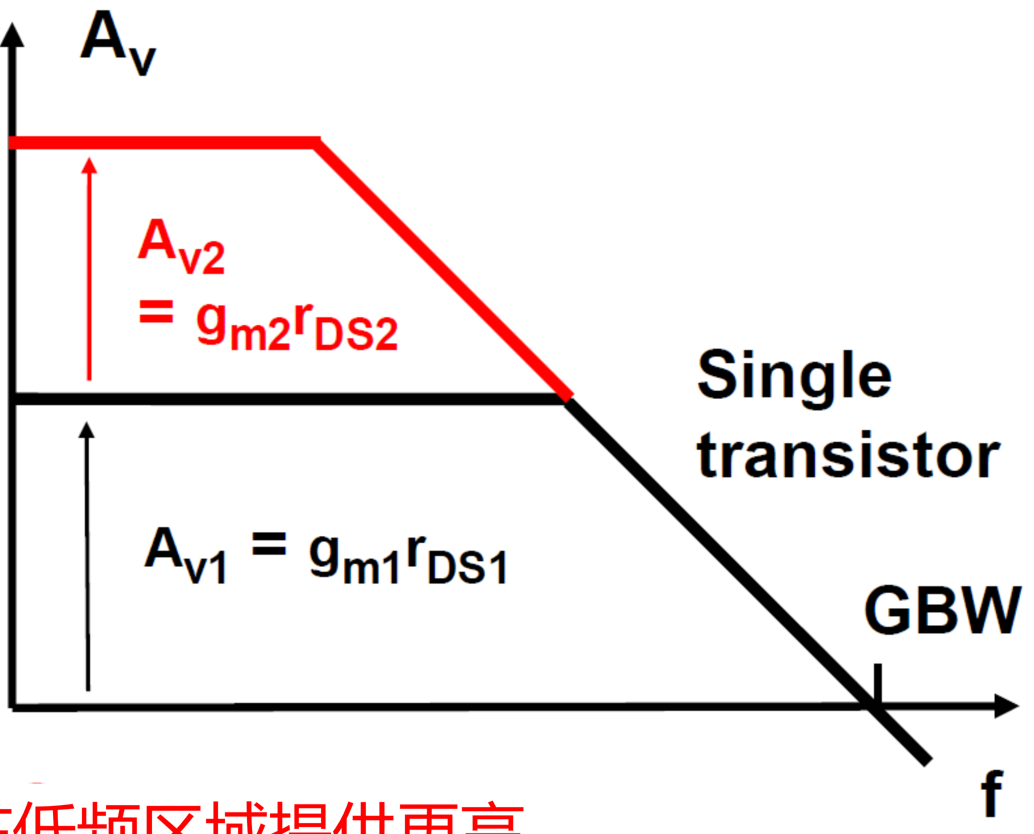
$$BW = \frac{1}{2\pi R_{out} C_L} \qquad GBW = \frac{g_{m1}}{2\pi C_L}$$

for both !

- 增益带宽积不变!

Cascode vs 单晶体管

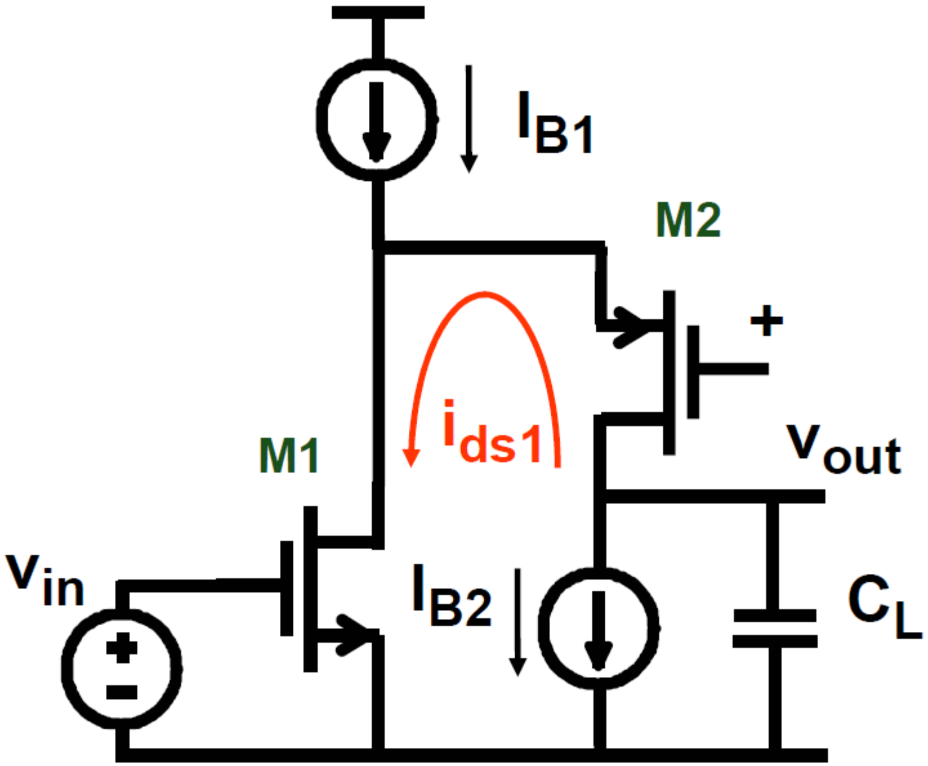




在低频区域提供更高的增益，没有额外的电流消耗

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

折叠式Cascode



$$I_{DS1} = I_{B1} - I_{B2} \approx I_{B1} / 2$$

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

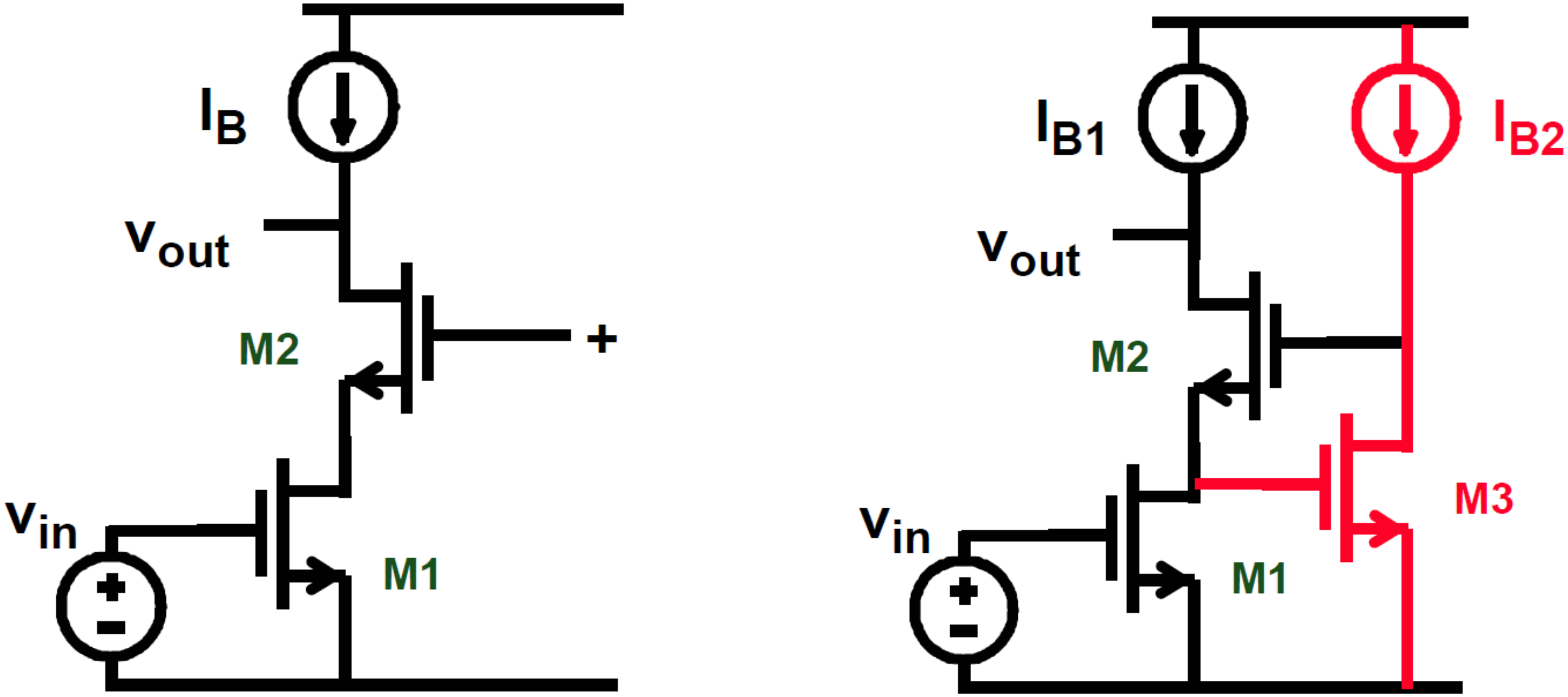
$$R_{out} = r_{DS1}\, g_{m2}\, r_{DS2}$$

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

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

- 主要参数指标与套筒式一致，功耗是其两倍！

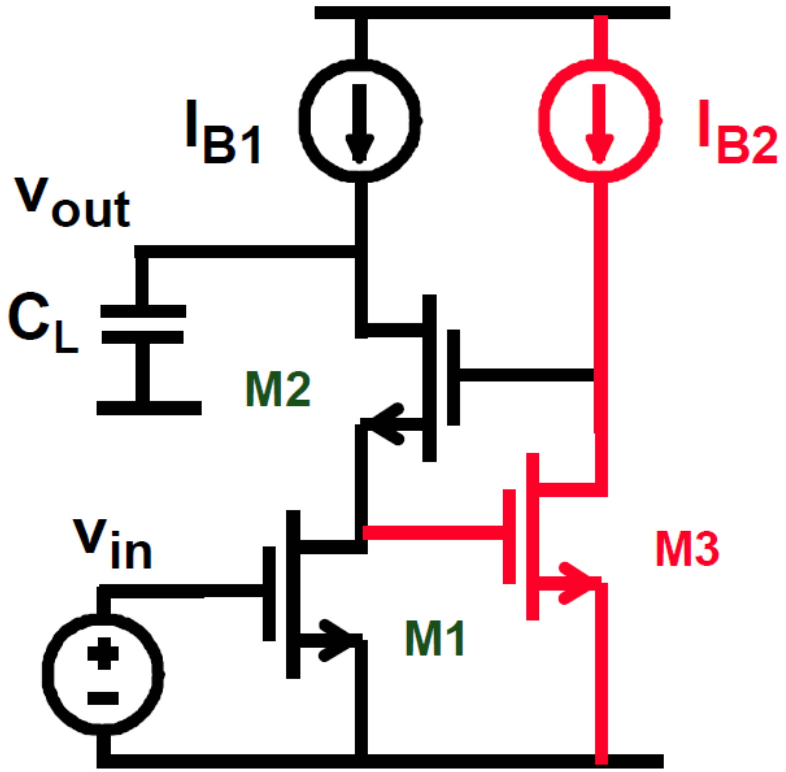
调节式 (Regulated) Cascode

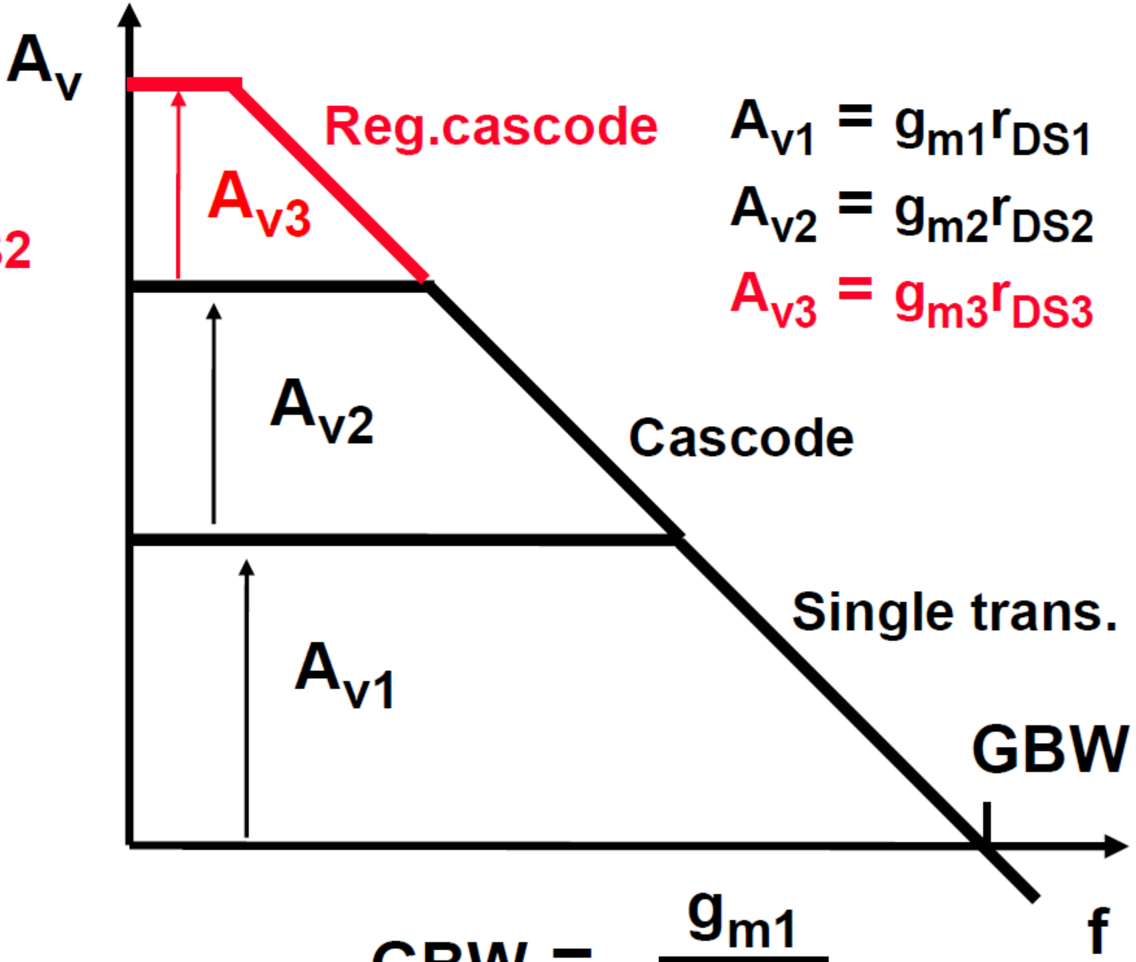


$A_v = (g_m r_{DS})_1 (g_m r_{DS})_2$

$A_v = (g_m r_{DS})_1 (g_m r_{DS})_2 (g_m r_{DS})_3$

调节式 (Regulated) Cascode





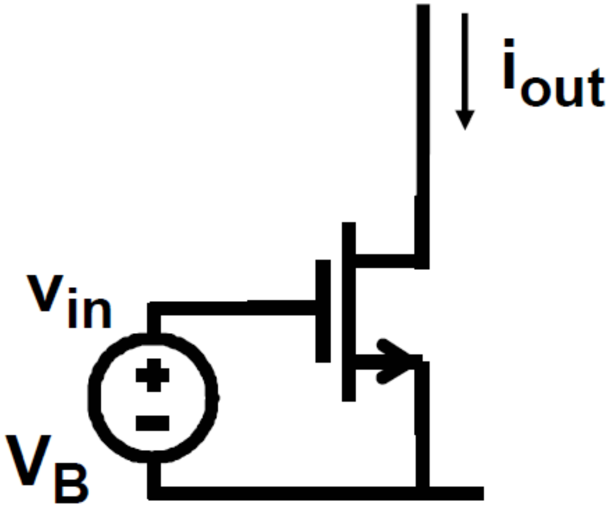
$A_{v1} = g_{m1}r_{DS1}$

$A_{v2} = g_{m2}r_{DS2}$

$A_{v3} = g_{m3}r_{DS3}$

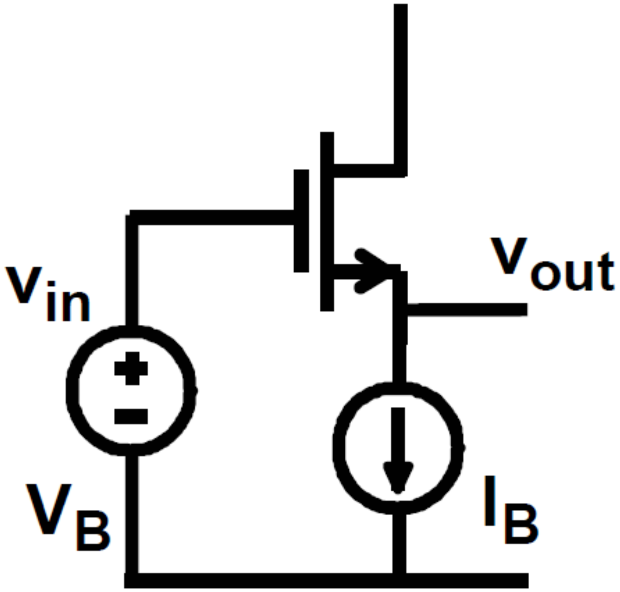
$$GBW = \frac{g_{m1}}{2\pi C_L}$$

单晶体管结构对比



$i_{out} = g_m v_{in}$

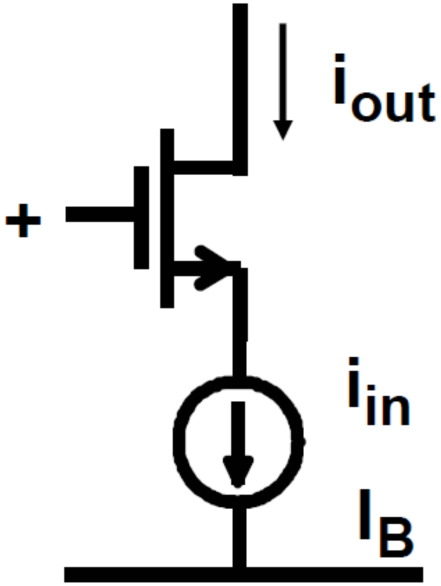
Amplifier



$v_{out} = v_{in}$

$Z_{out} \approx 1/g_m$

Source follower



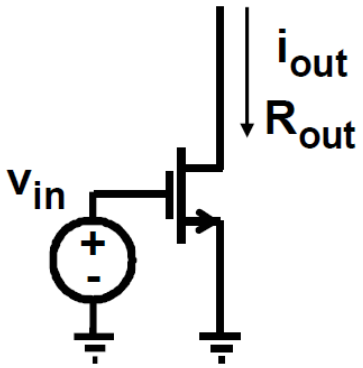
$i_{out} = i_{in}$

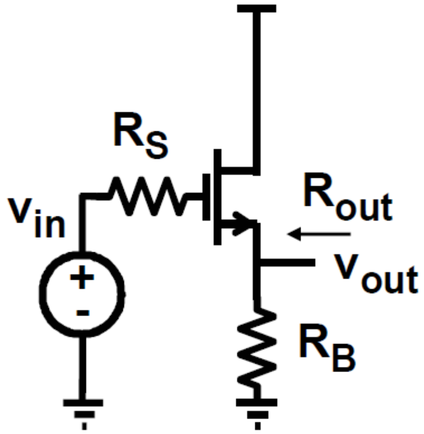
$Z_{in} \approx 1/g_m$

Cascode

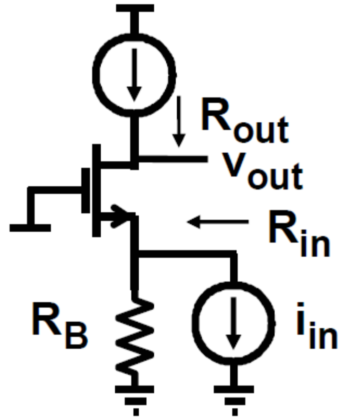
低频特性对比

- 放大器
- 源极跟随器
- Cascode





$R_B > 1/g_m$



$R_B > 1/g_m$

A_G	g_m	A_V	1	A_R	$g_m r_o R_B$
R_{in}	∞		∞		R_B
R_{out}	r_o		$1/g_m$		$g_m r_o R_B$

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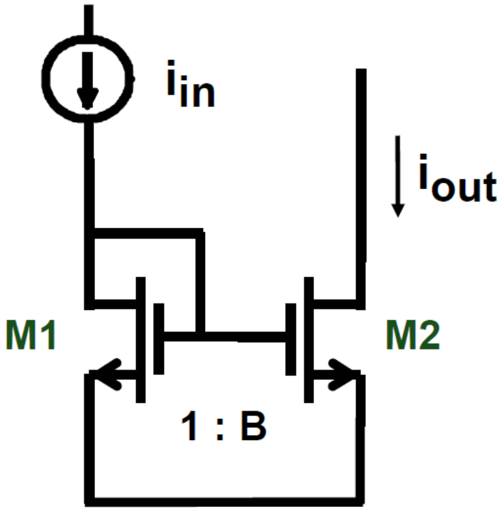
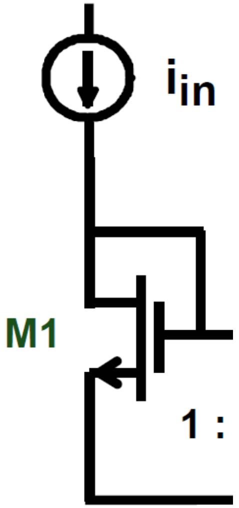
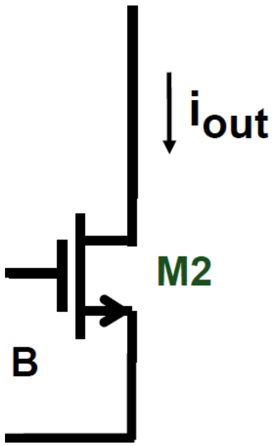
电流镜 (Current Mirror)



$i_{out} = B\, i_{in}$

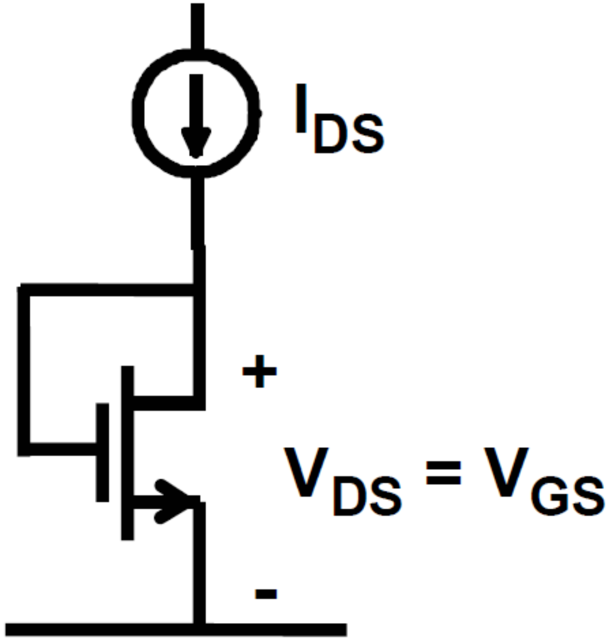
- 理想电流镜





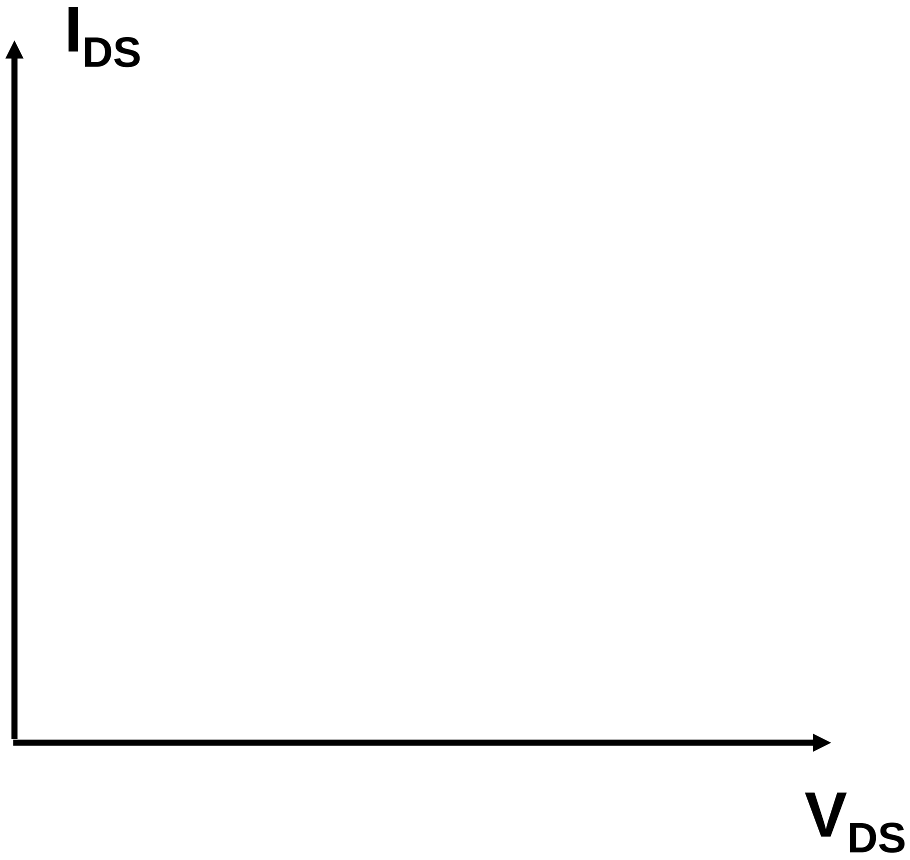
- 二极管连接晶体管
- 单晶体管放大器

二极管连接晶体管（Diode-connected）

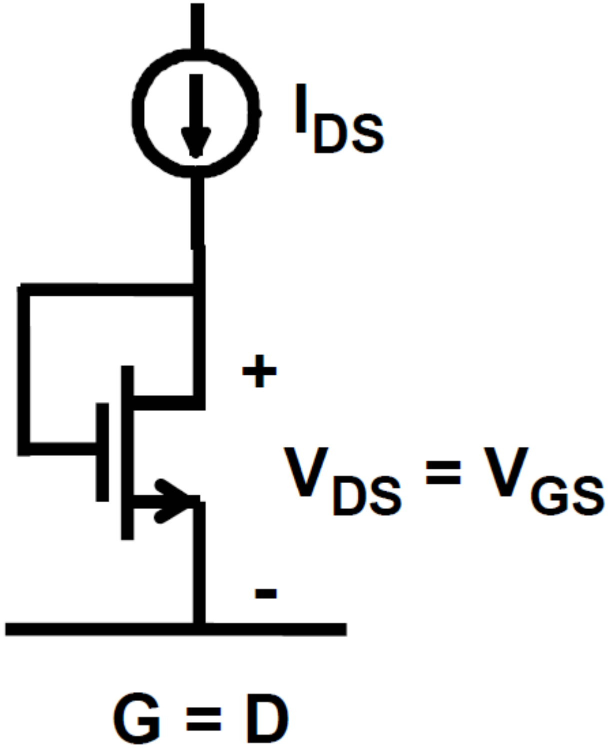


G = D

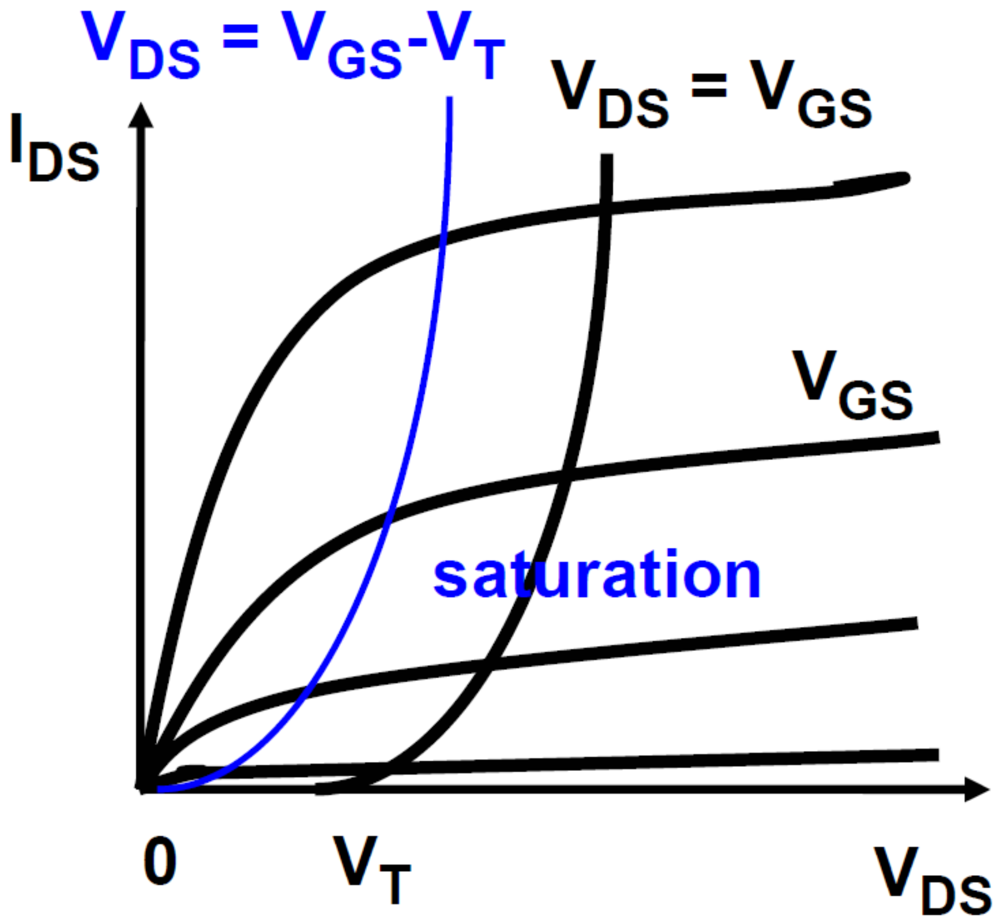
$$I_{DS} = K'_n \frac{W}{L} (V_{DS}-V_T)^2$$



二极管连接晶体管（Diode-connected）

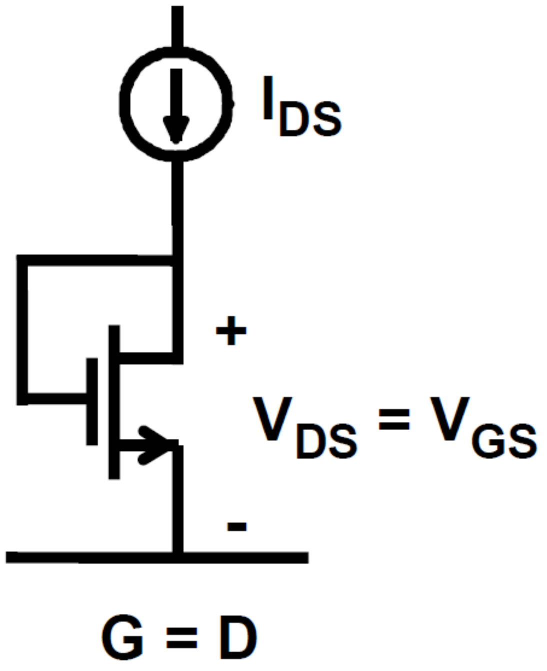


$$I_{DS} = K'_n \frac{W}{L} (V_{DS}-V_T)^2$$

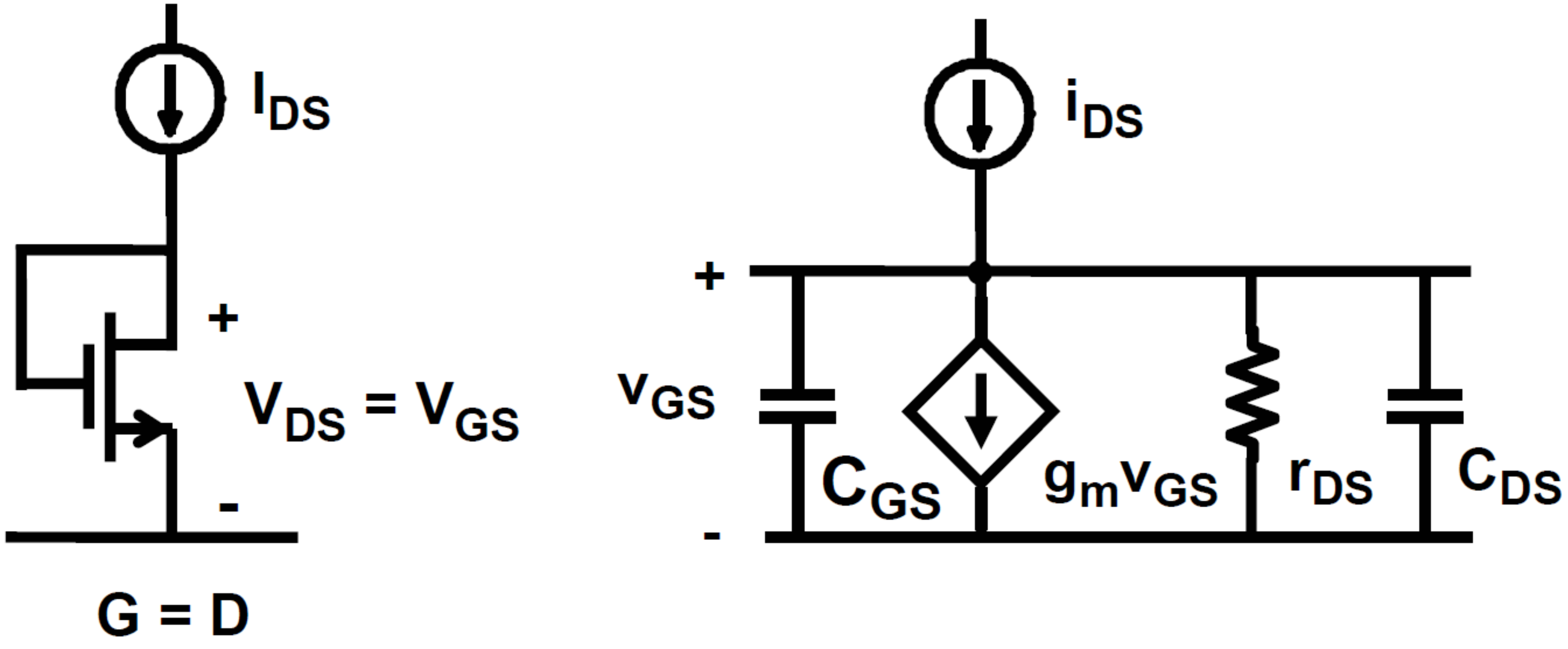


二极管连接的小信号模型

- 求二极管连接方式的输入电阻和带宽?



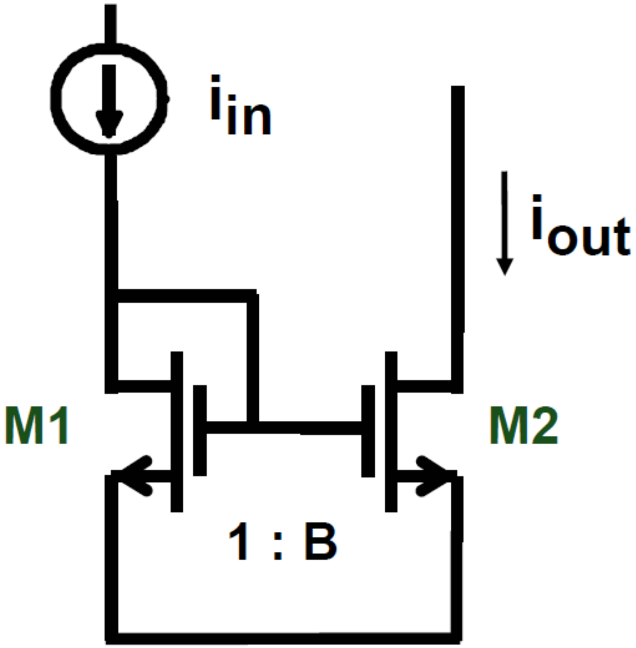
二极管连接的小信号模型

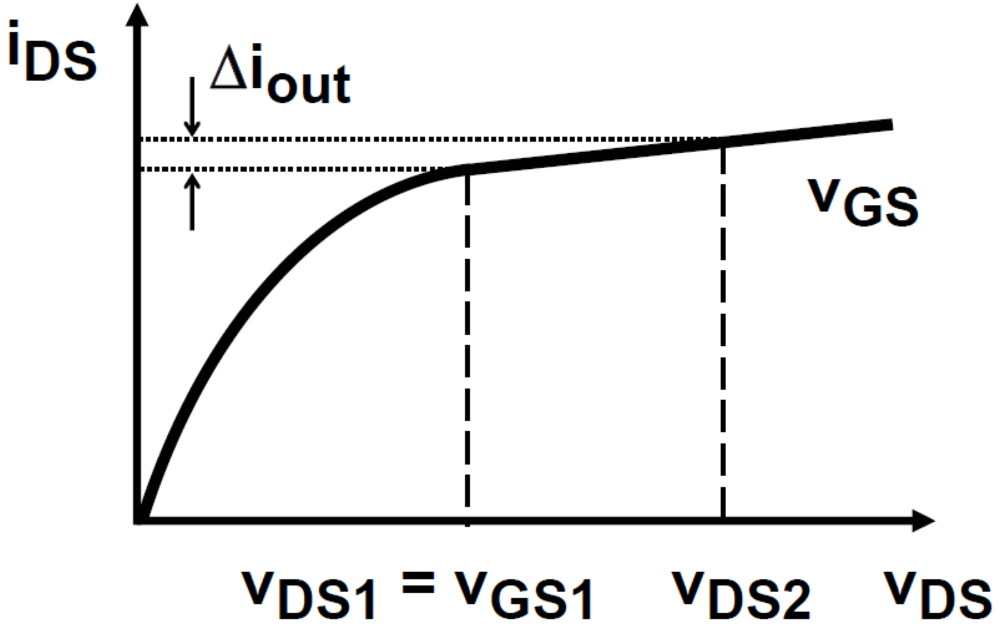


输入电阻 $r_{ds} = 1/g_m \ // \ r_{DS} \approx \boxed{1/g_m}$

带宽 $BW = \dfrac{g_m}{2\pi\,(C_{GS}+C_{DS})} \approx \dfrac{f_T}{2}$

电流镜的输出特性



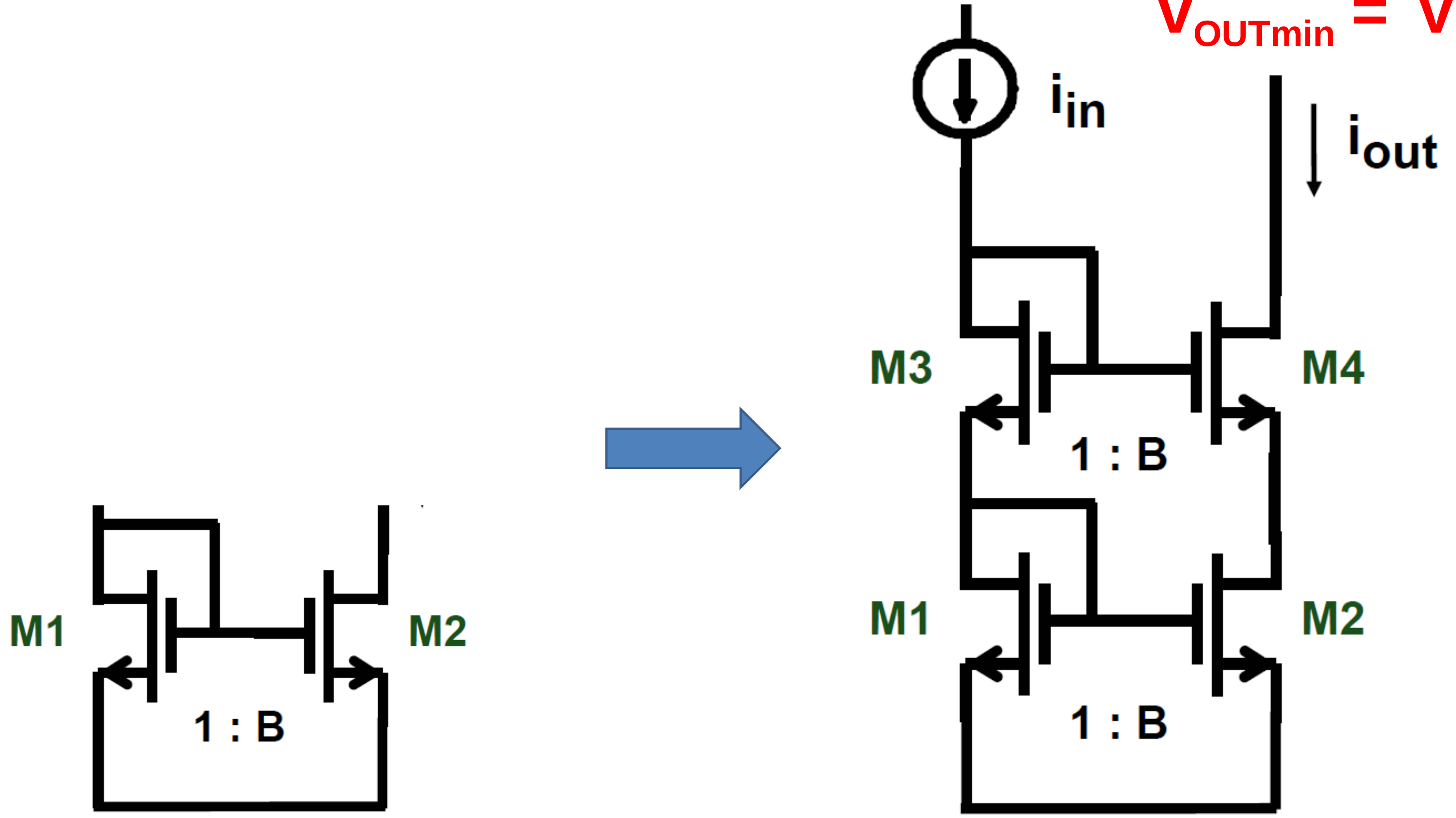


- 电流镜的输出阻抗即是单晶体管放大器的输出阻抗
- 电流镜的输出精度可以描述为

$$\frac{\Delta i_{out}}{i_{out}} =$$

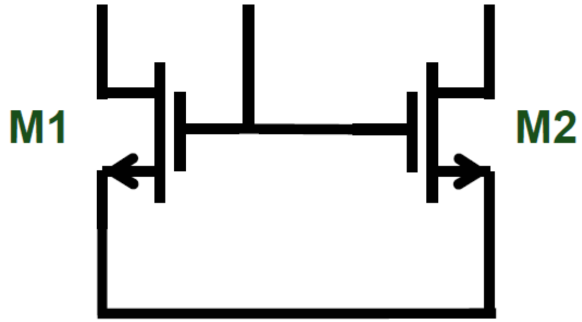
改进型的电流镜

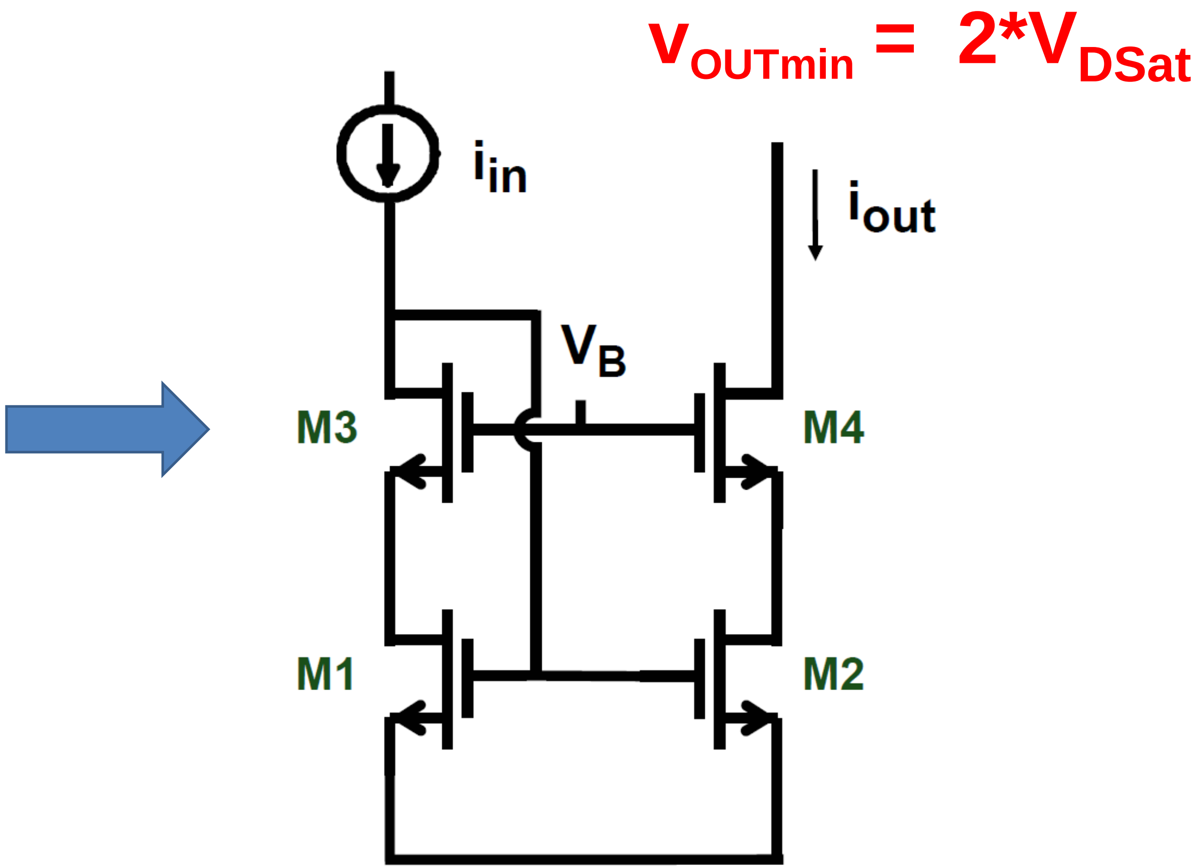
$v_{OUTmin} = V_{GS}+V_{DSat}$



$R_{out} = r_{DS2}\, g_{m4} r_{DS4}$

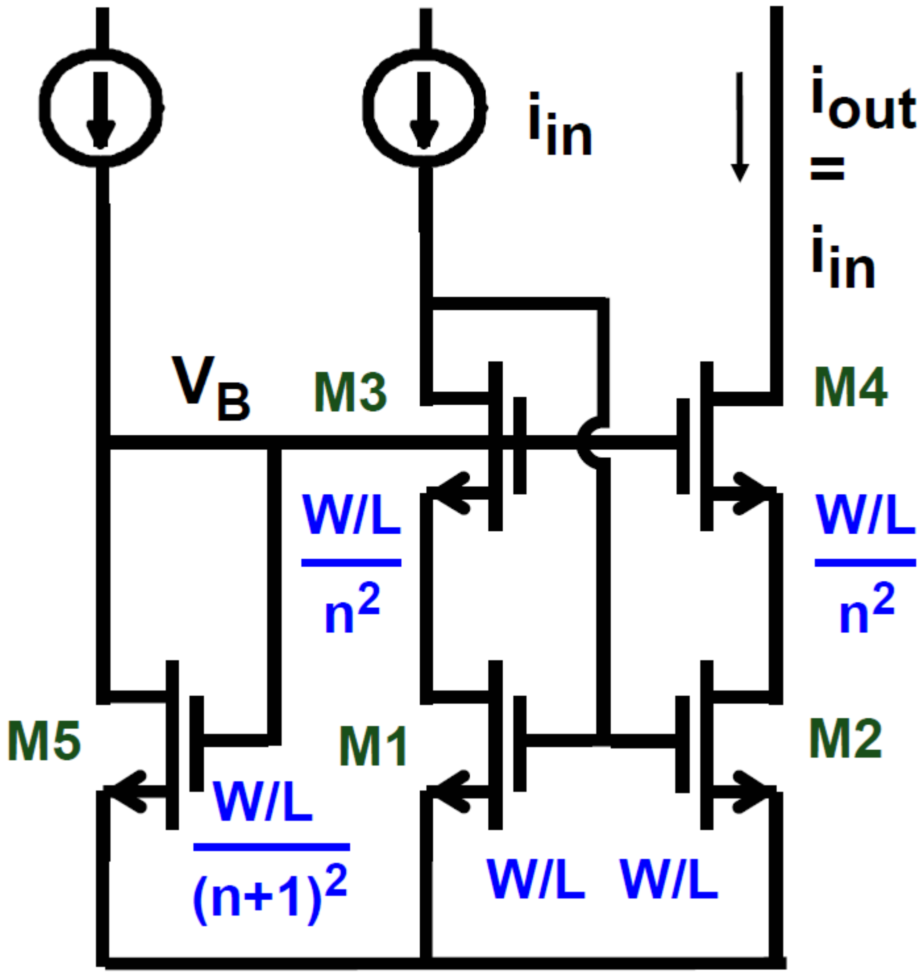
改进型的电流镜



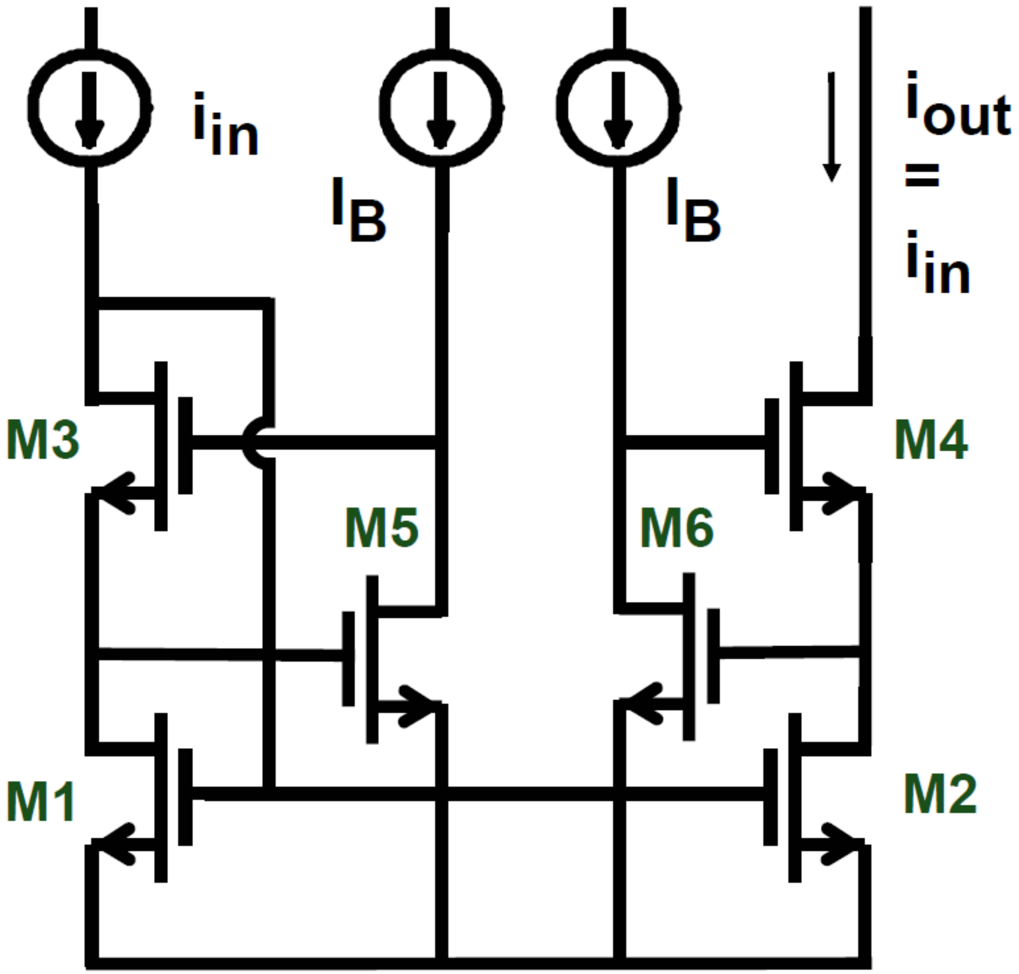


$R_{out} = r_{DS2}\, g_{m4} r_{DS4}$

电流镜案例

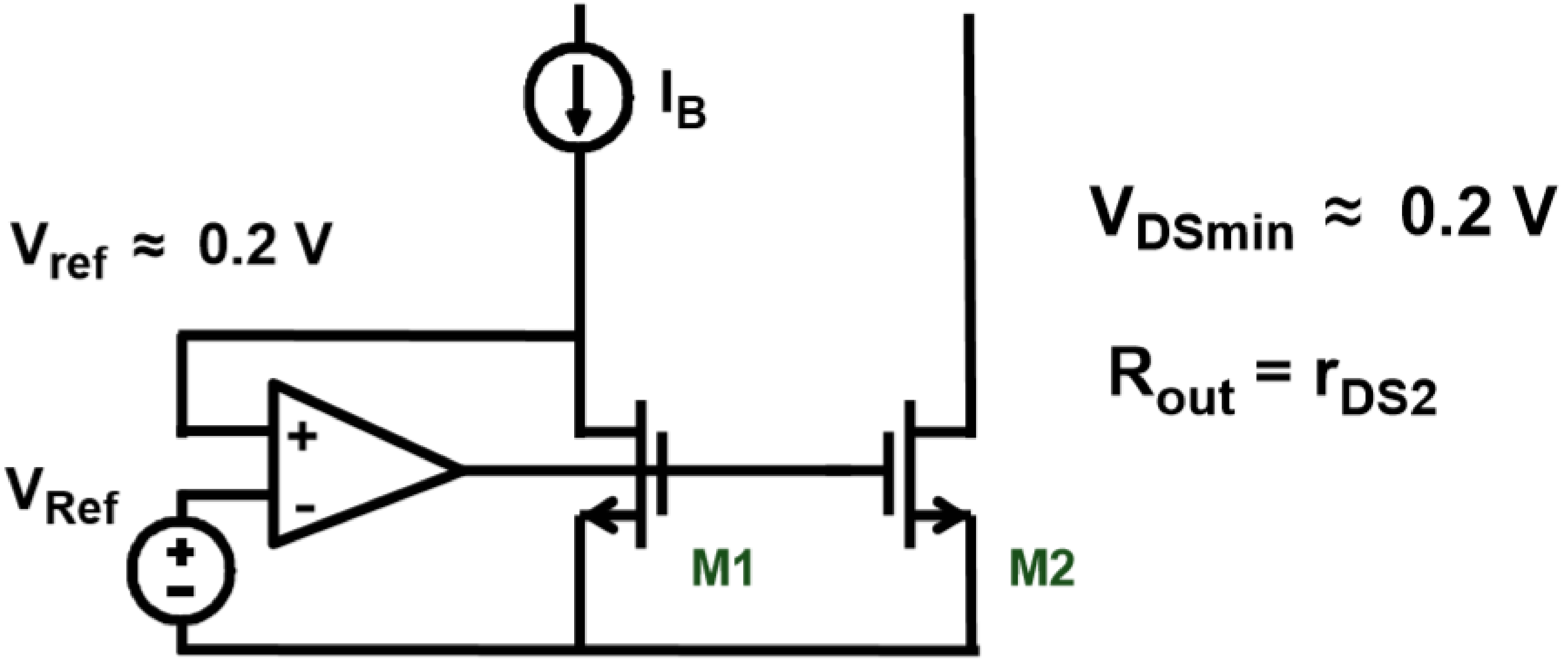


iin
iout
=
iin
VB
M3
M4
W/L
n2
W/L
n2
M5
M1
M2
W/L
(n+1)2
W/L
W/L



iin
IB
IB
iout
=
iin
M3
M4
M5
M6
M1
M2

低电压电流镜

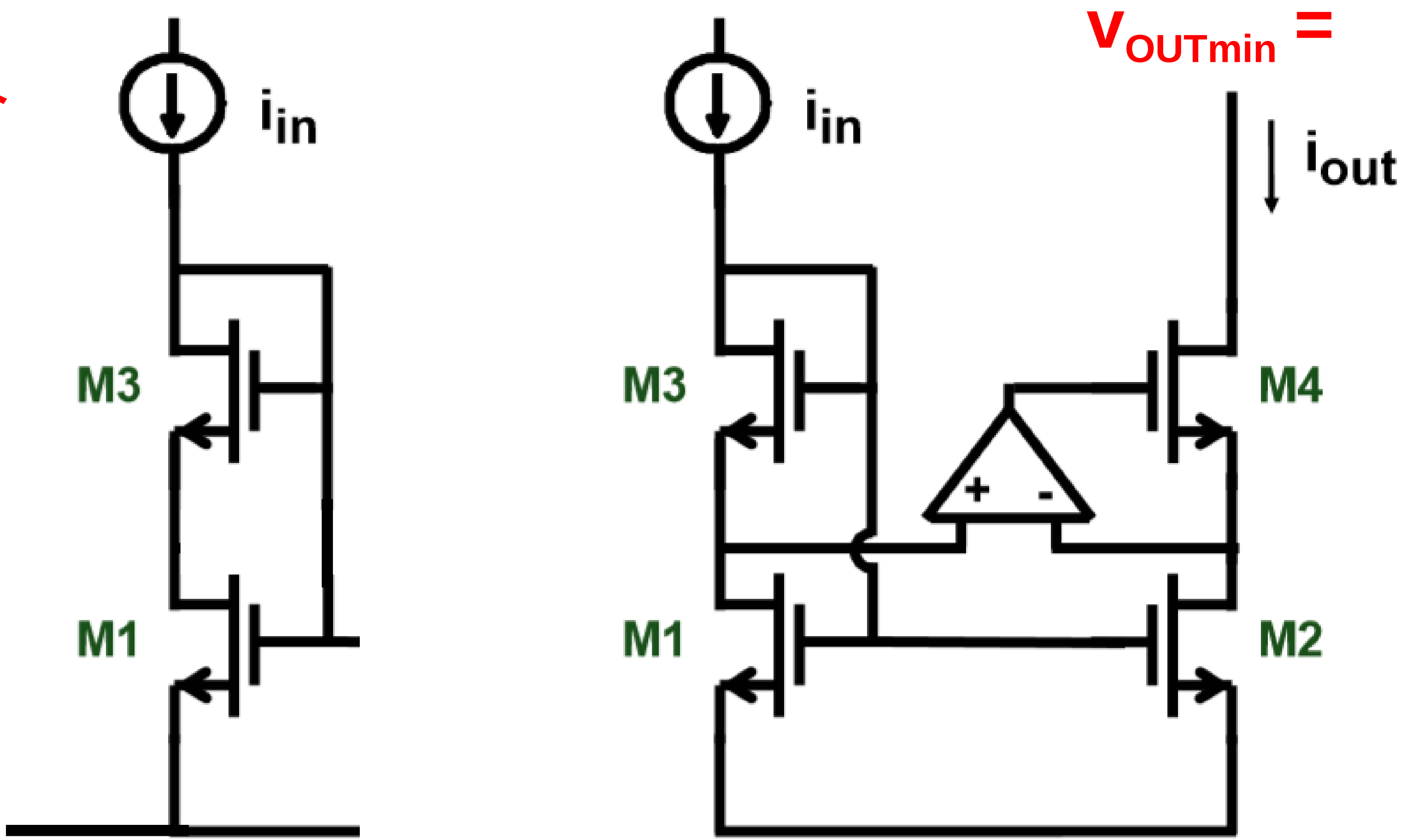


- 该电路**不能**改善输出电阻
- 该电路**可以**改善系统性失配问题

超低电压电流镜

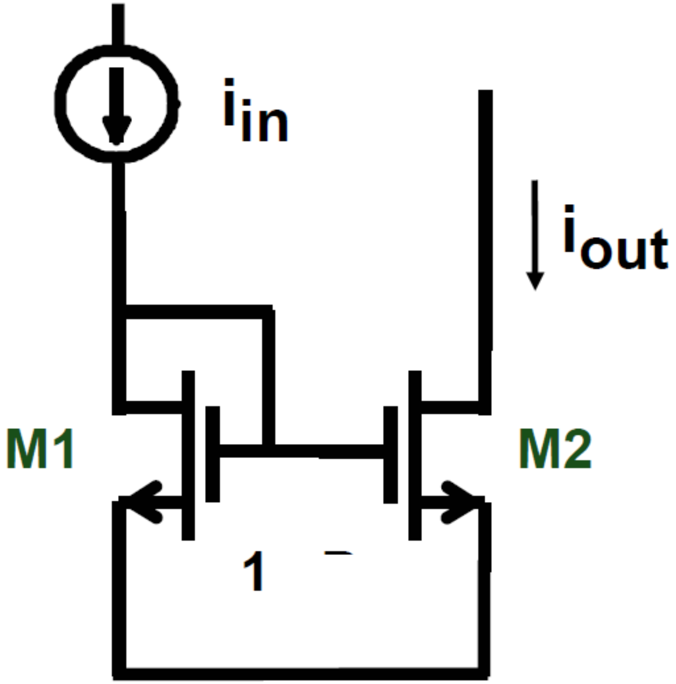
- 此结构是否是合适的Cascode?

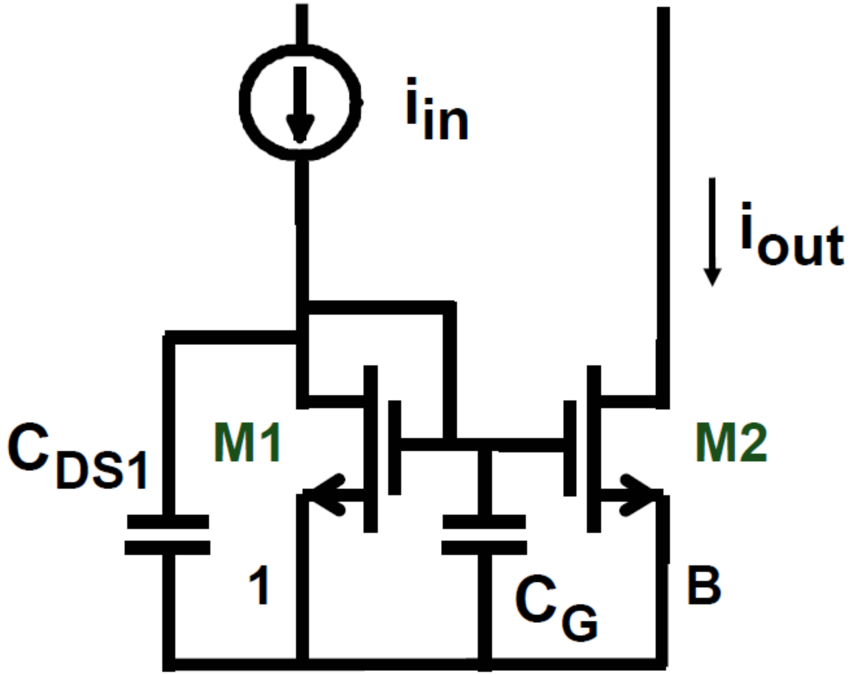
- **不是!**



- 电流镜晶体管工作在线性区，通过运放锁定Vds，使得两个晶体管工作电压完全一致!

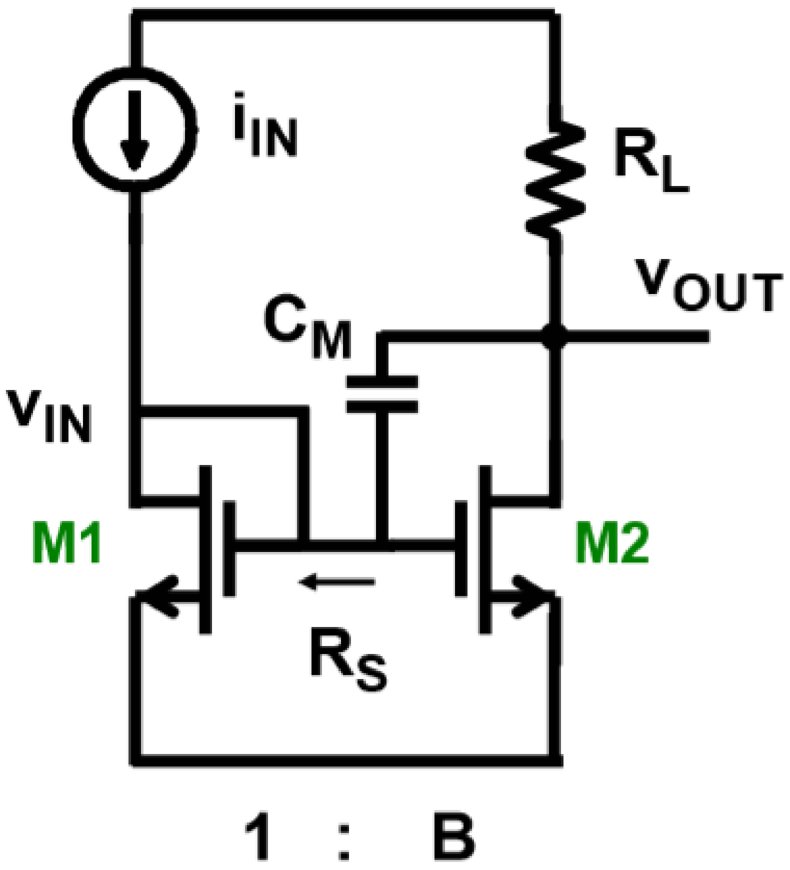
电流镜的高频特性





$$BW = \frac{g_m}{2\pi\,(C_G + C_{DS1})} \approx f_T \frac{1}{(2 + B)}$$

电流镜中的密勒效应



Miller effect :

$$f_{-3dB} = \frac{1}{2\pi R_S A_{v2} C_M}$$

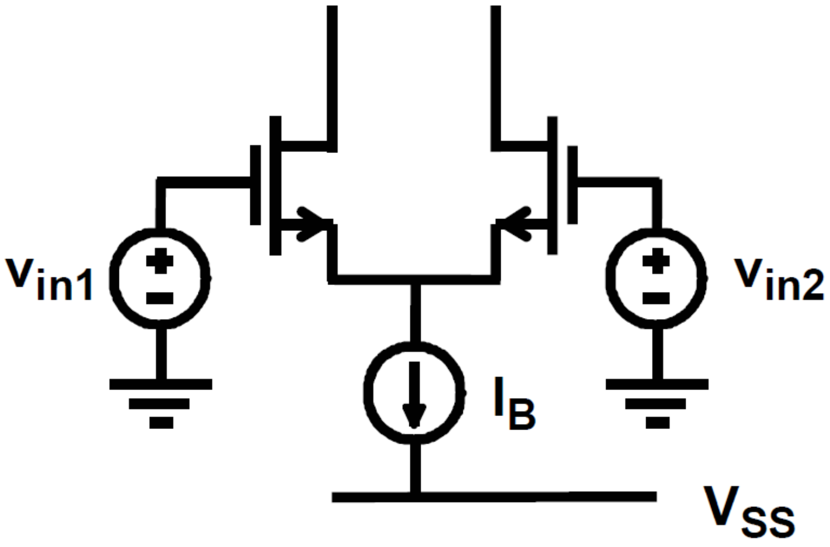
$$R_S = 1/g_{m1} \qquad A_{v2} = g_{m2} R_L$$

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

模拟电路的基本结构

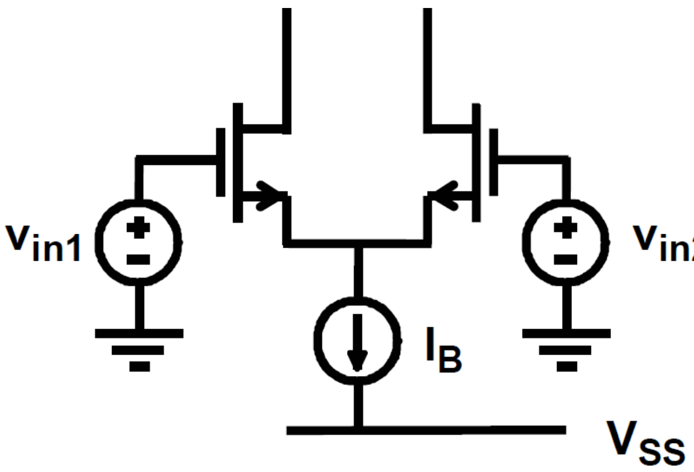
1. 单晶体管放大器
2. 源极跟随器
3. Cascode （共源共栅极）
4. 电流镜
5. **差分对**

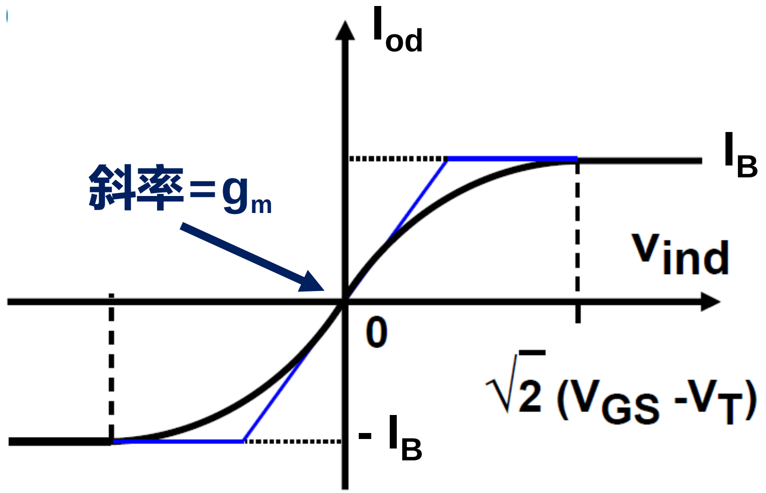
差分对 (Differential Pair)



- 差分对的本质依旧是**电压**输入**电流**输出
- 差分对中的信号均以**差分**形式体现
- 差分对的能效是单晶体放大器的**一半**

差分对 (Differential Pair)





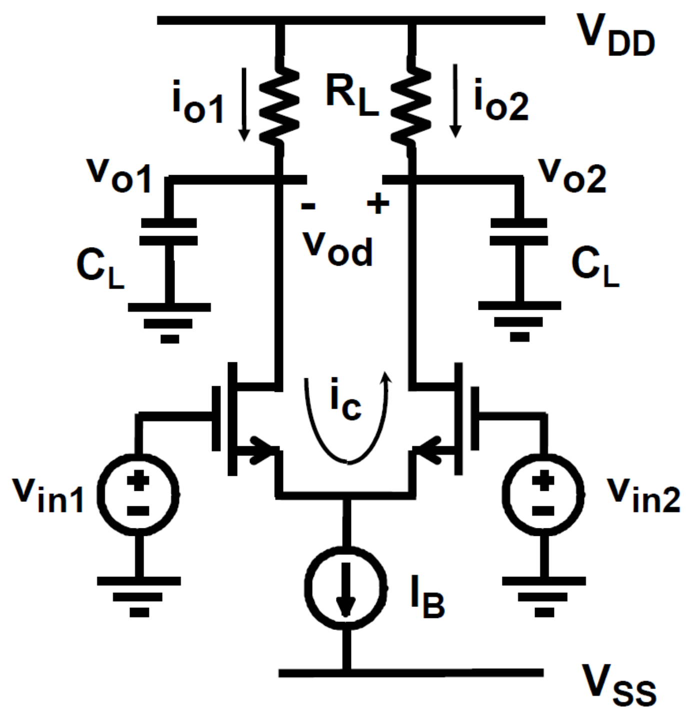
$$\frac{i_{Od}}{I_B} = \frac{v_{Id}}{(V_{GS}-V_T)}\sqrt{1-\frac{1}{4}\left(\frac{v_{Id}}{V_{GS}-V_T}\right)^2}$$

- V_{Id} 为差分输入电压
- I_{Od} 为差分输出电流
- I_B 为差分对总偏置电流

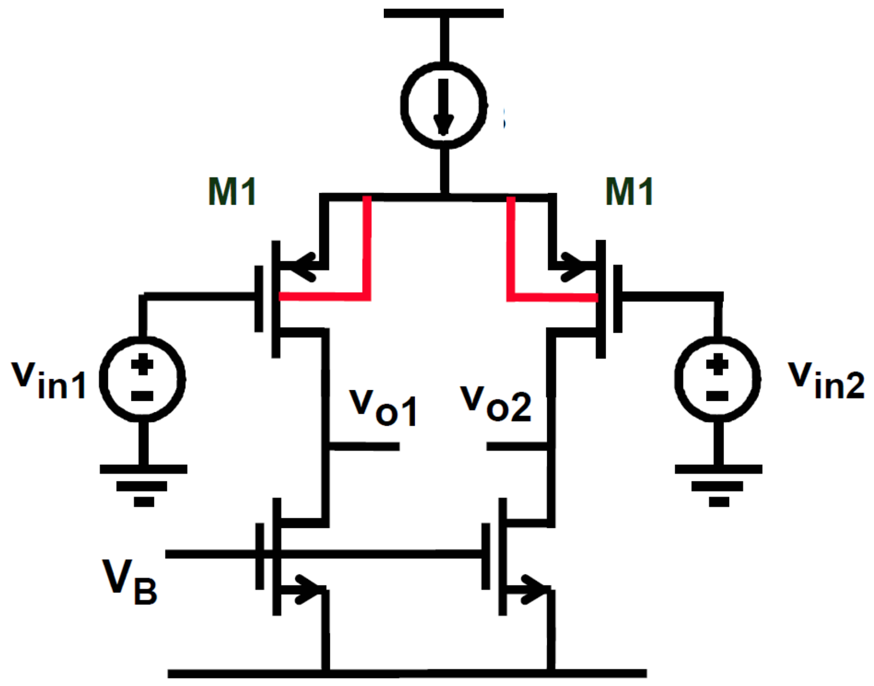
- V_{GS}-V_T决定gm和直流范围

差分放大器

- 差分放大器 = 差分对+负载



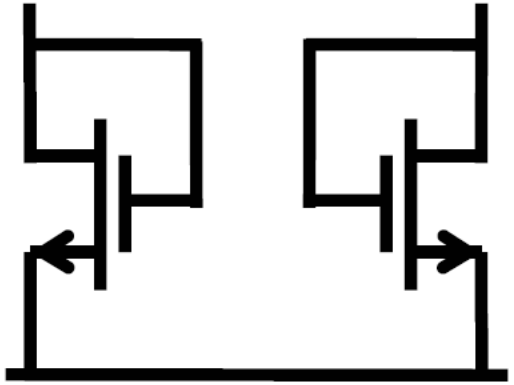
$$A_v = g_m R_L$$

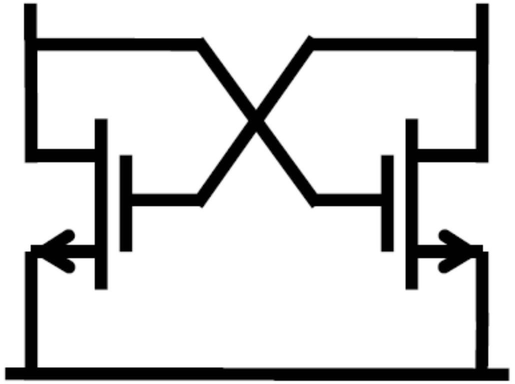


$$A_v = g_{m1}(r_{DS1}//r_{DS2})$$

特殊形态的负载-交叉耦合对

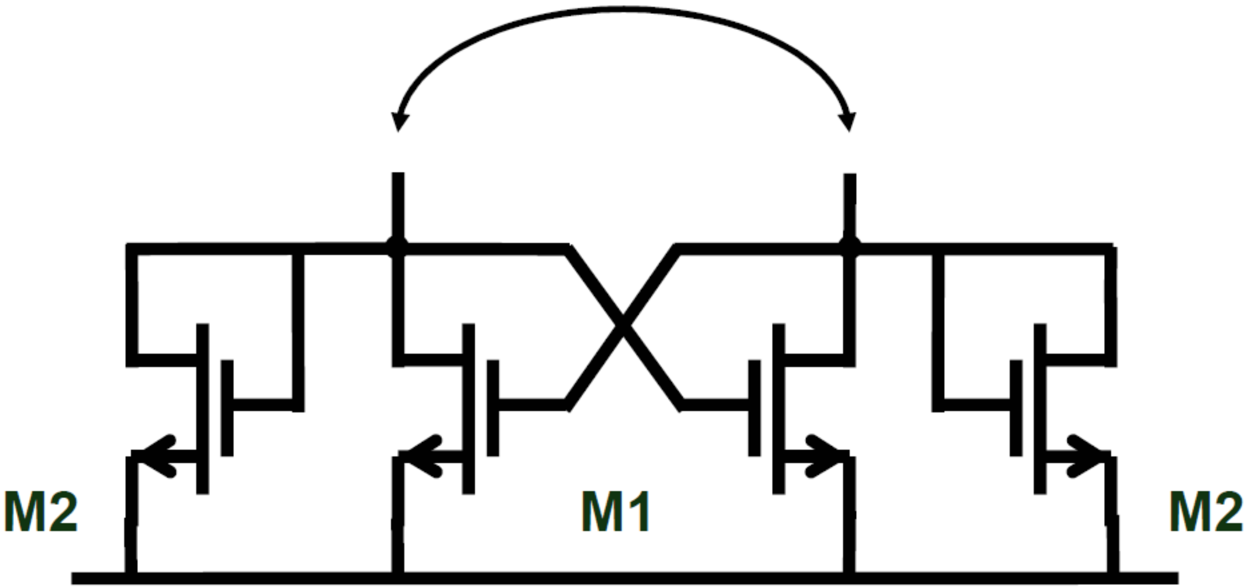
- 交叉耦合对 (Cross Coupled Pair)





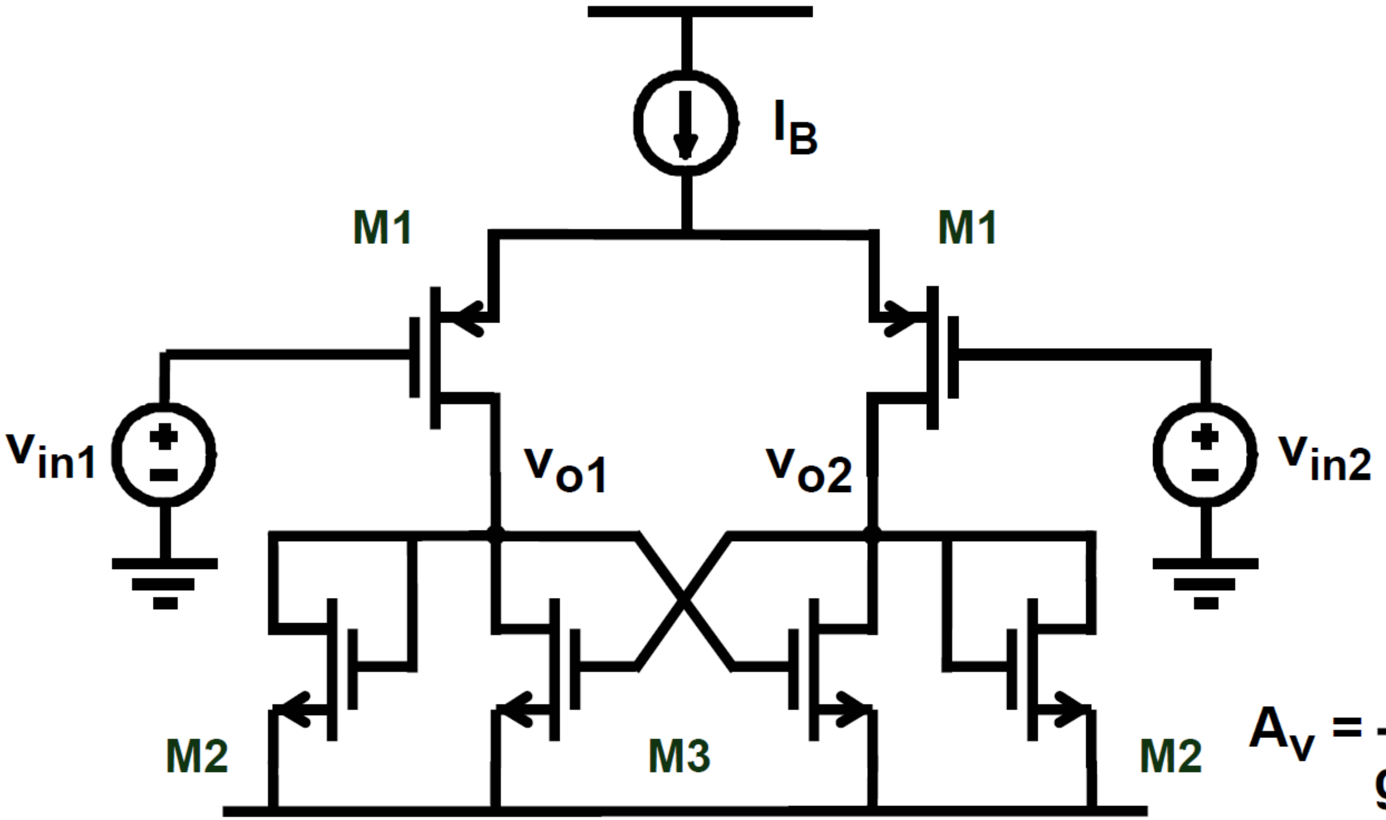
特殊形态的负载-交叉耦合对

差分输入电导：g_{m2} - g_{m1}



实际使用中受到**匹配(matching)**的限制

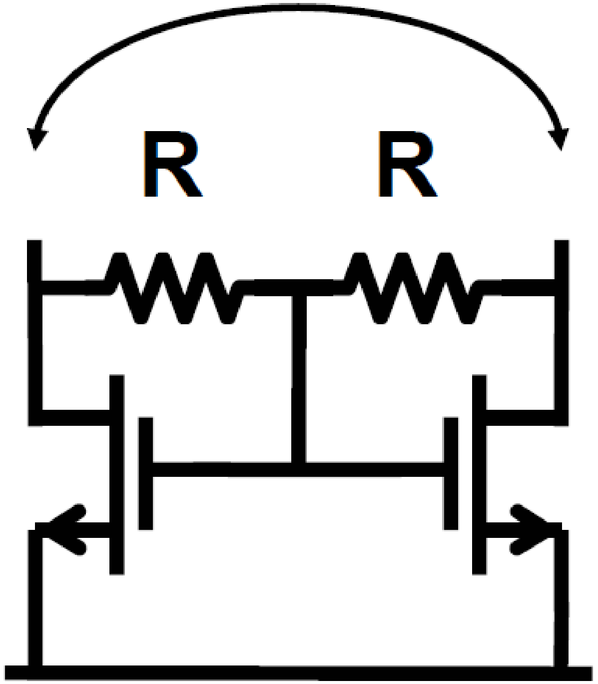
特殊形态的负载-交叉耦合对



$$A_v = \frac{g_{m1}}{g_{m2} - g_{m3}}$$

实际使用中受到**匹配(matching)**的限制

特殊形态的负载-共模反馈

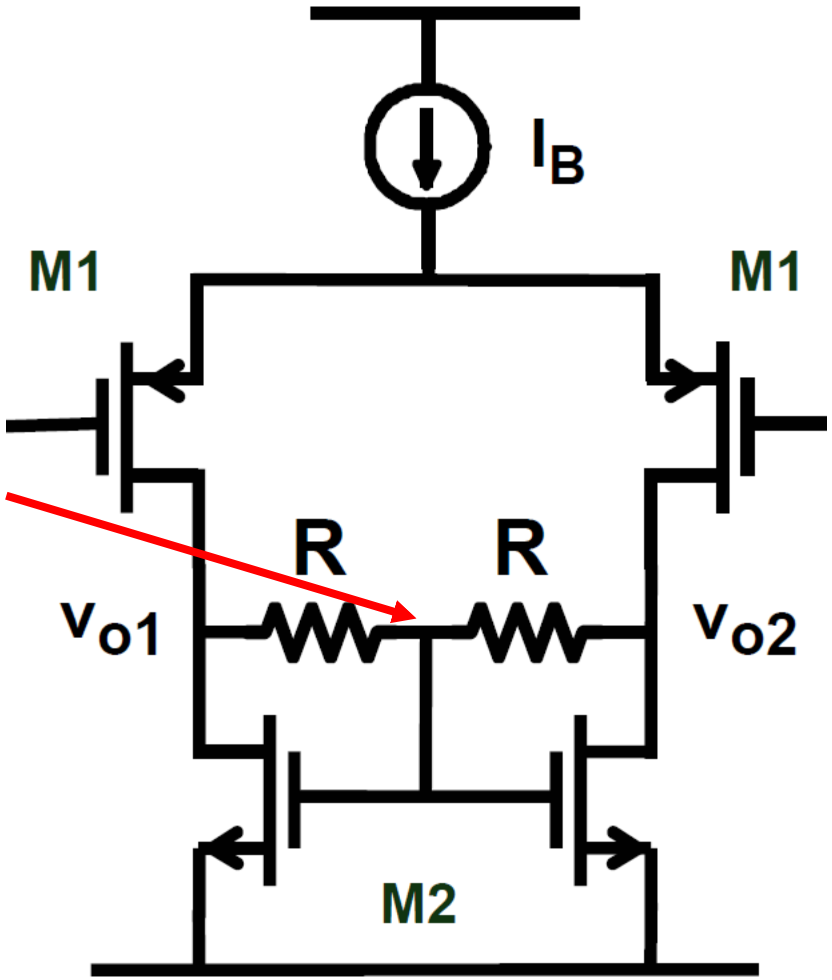


特殊形态的负载

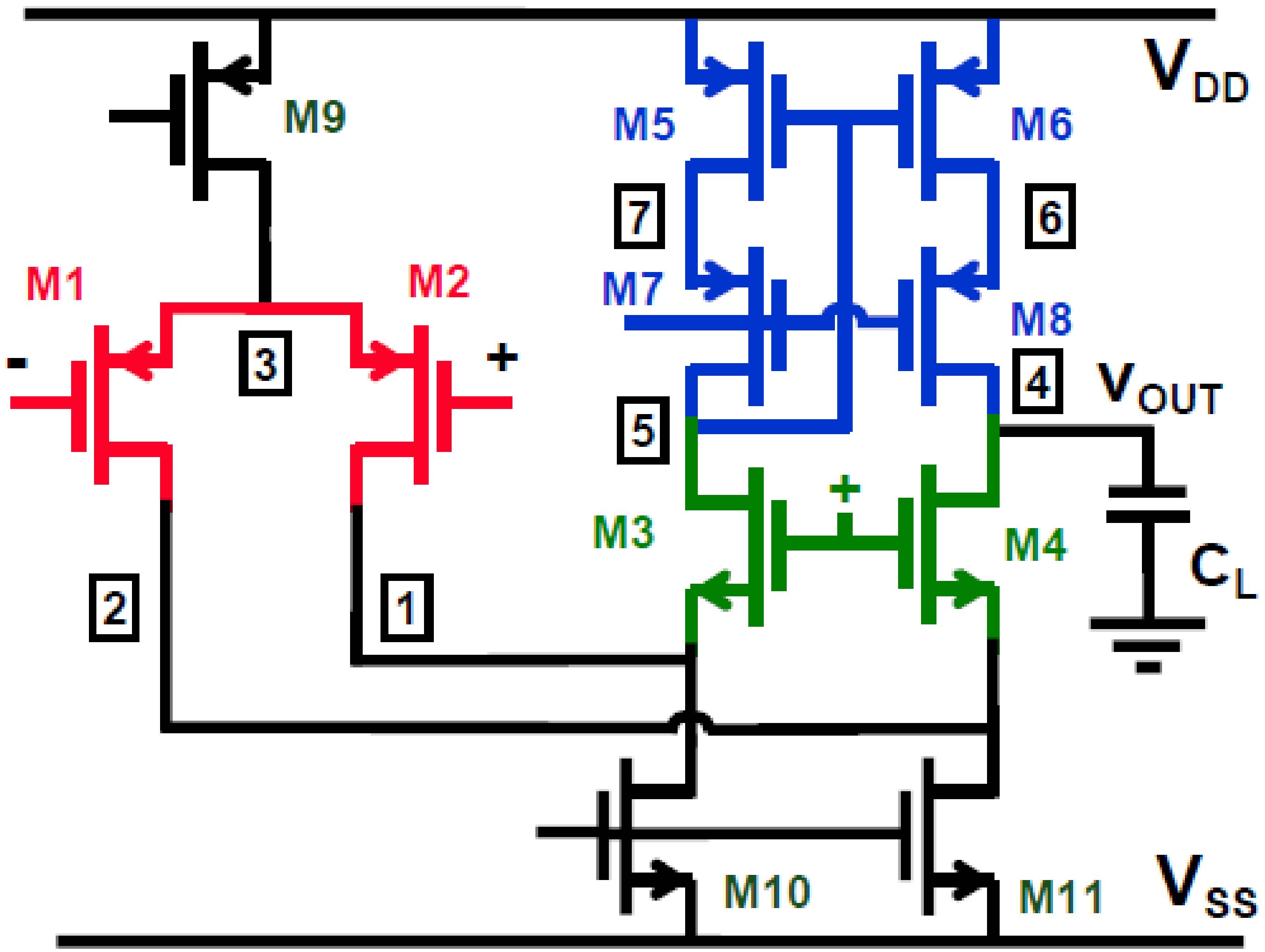
- 本质上是一种**共模反馈**形式

$$A_v = g_{m1}\ (R\ //\ r_o\ )$$

$$r_o = r_{o1}//r_{o2}$$



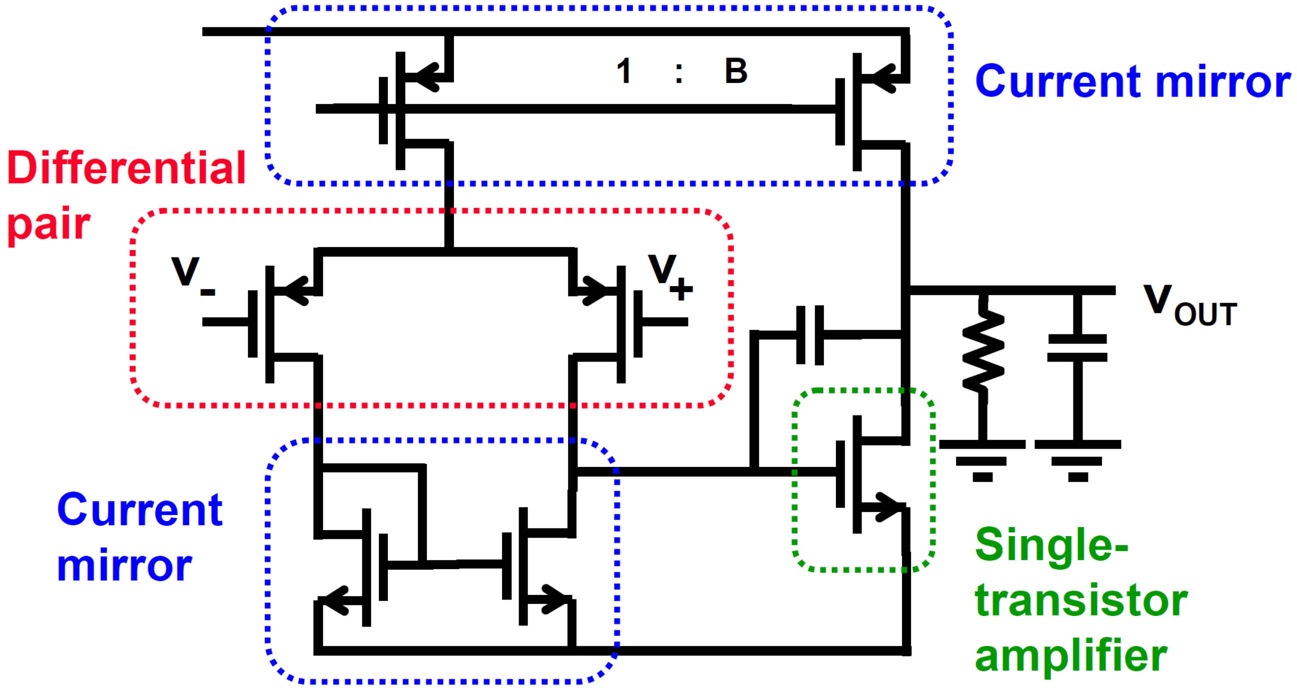
Cascode



- 求该折叠套筒型运放的第一和第二高阻点的阻值，用公式表示。

总结

- 模拟电路的基本构成单元：
  1. 单晶体管
     - 放大器
     - 源极跟随器
     - Cascode
  2. 多晶体管
     - 差分对
     - 电流镜

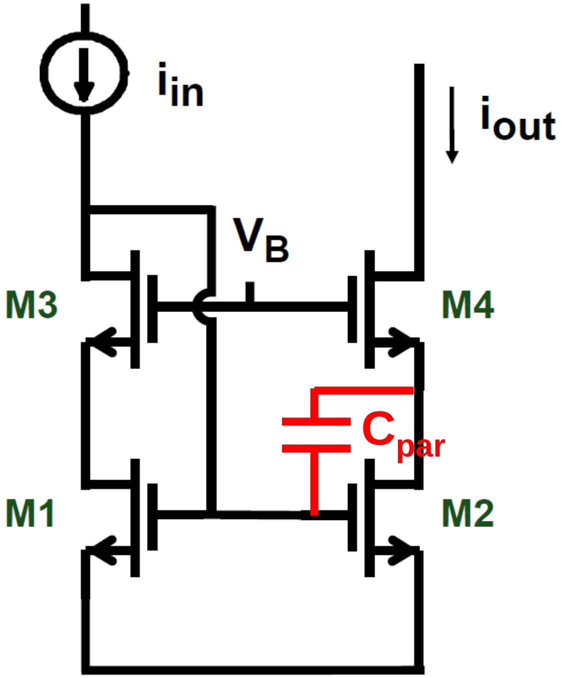


作业1

- 利用仿真结果，找到我们所使用工艺的$u_{0p,n}$, C_{ox}, V_{THn}, V_{THp}

作业2

- 通过公式描述V_B的取值范围（提示：晶体管M1-M4均需要工作在饱和区）
- 在Cascode电流镜中，假设有寄生电容C_{par}，利用公式估算并用仿真验证该电流镜的频率特性。（可以自由设置偏置、晶体管的尺寸以及寄生电容）



作业3

- 假设差分对偏置电流为200uA，W/L=20um/1um，根据理论分析和仿真验证。
  1. 计算g_m>99%*$g_{m,max}$的区间。
  2. 计算差分输出电流为198uA时的差分输入电压。
  3. 如果需要把问题2中求得的电压扩大一倍，差分对的W需要如何修改?