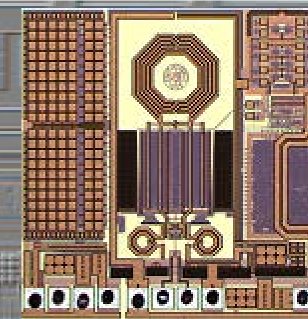

模拟集成电路设计原理

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

2014年10月23日

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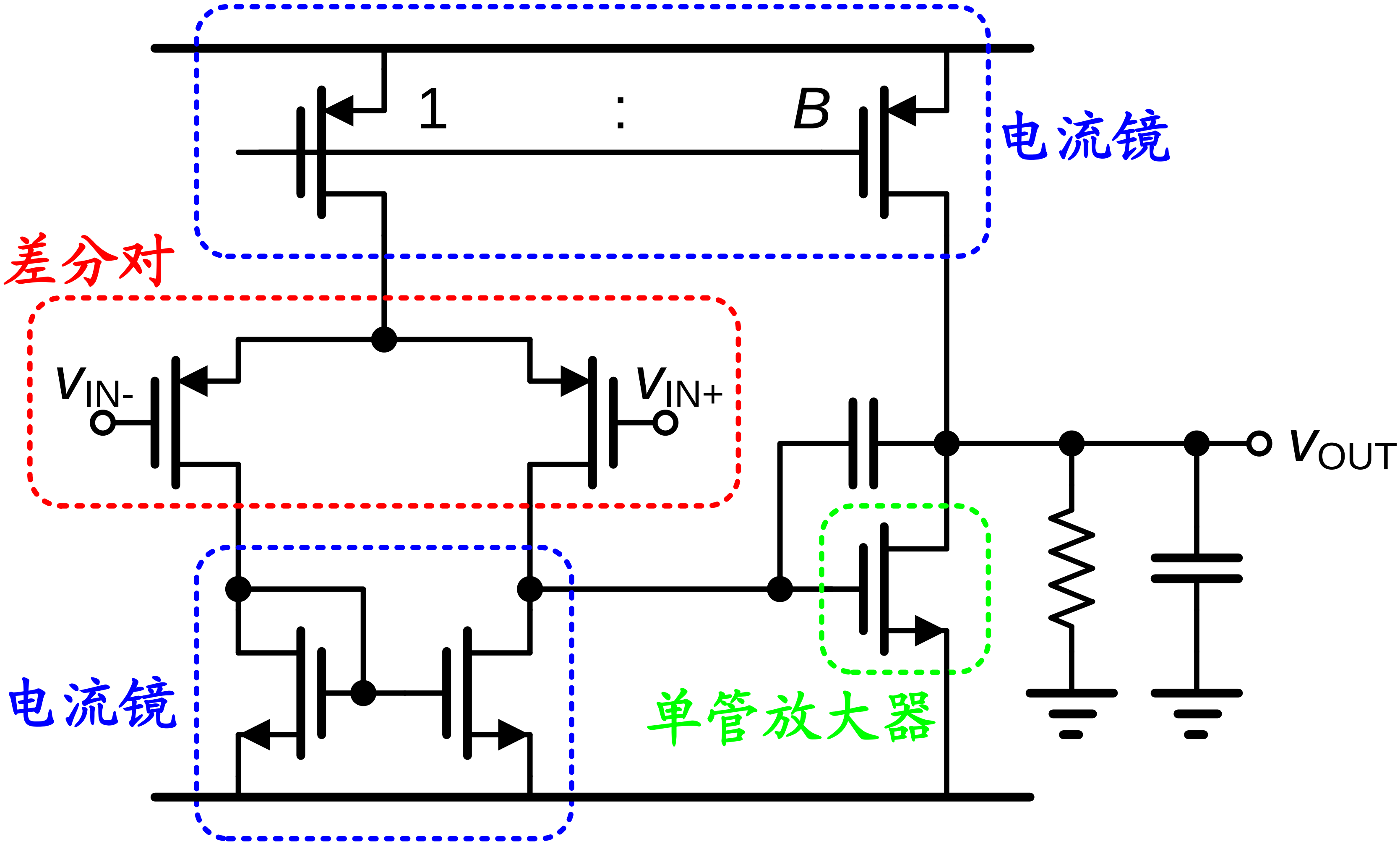
http://rfic.fudan.edu.cn/Courses.htm

复旦大学/微电子学院/射频集成电路设计研究小组

共源放大器，
源极跟随器和共栅放大器

运算放大器(Opamp)

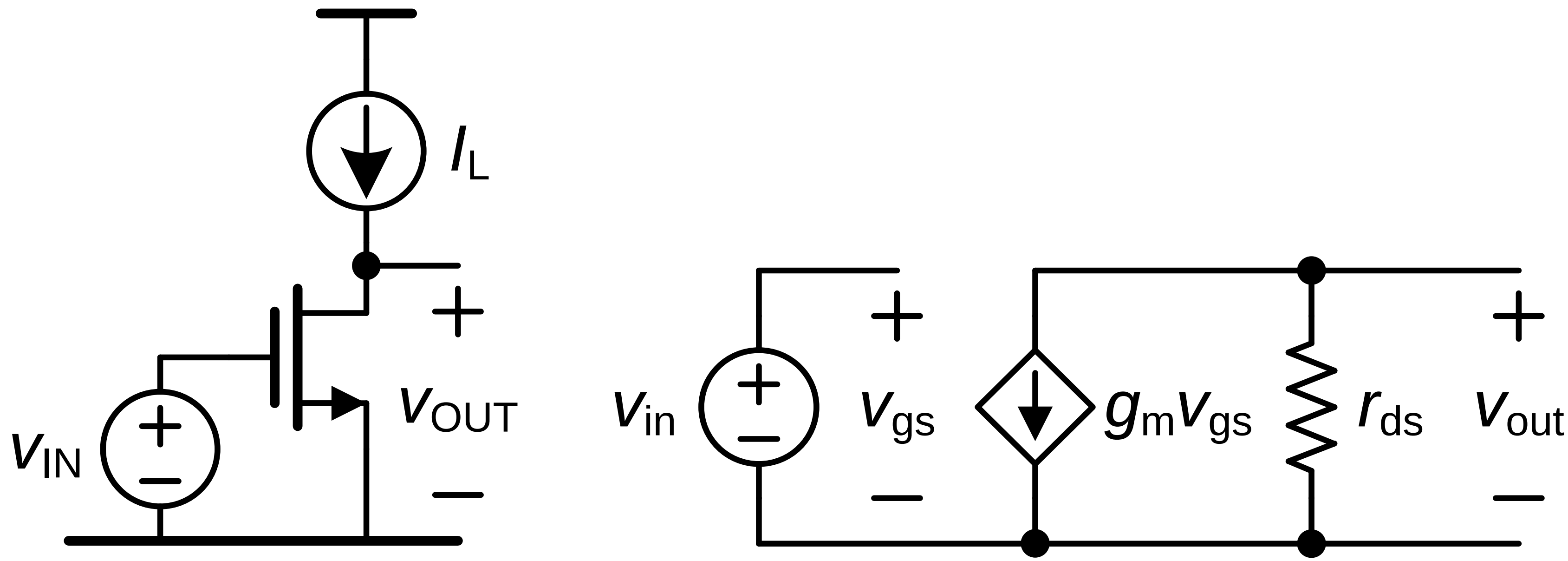


目录

- 共源放大器
- 源极跟随器
- 共栅放大器

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

共源放大器 1



$$A_V = g_m r_{ds} = \frac{2I_D}{V_{GS} - V_{TH,GS}} \frac{V_E L}{I_D} = \frac{2V_E L}{V_{GS} - V_{TH,GS}}$$

如果 $V_{GS} - V_{TH,GS} = 0.2$ V、$V_E L \approx 10$ V，则 $A_V \approx 100$。

共源放大器 2

高增益?

小(V_{GS}-$V_{TH,GS}$)，大L!!!

0.15~0.2 V　4~5L_{min}

MOST或BJT晶体管放大器？

MOST:

$$A_V = \frac{V_E L}{(V_{GS} - V_{TH,GS})/2}$$

如果$V_{GS} - V_{TH,GS} = 0.2\ \text{V}$、$V_E L \approx 10\ \text{V}$，则$A_V \approx 100$。

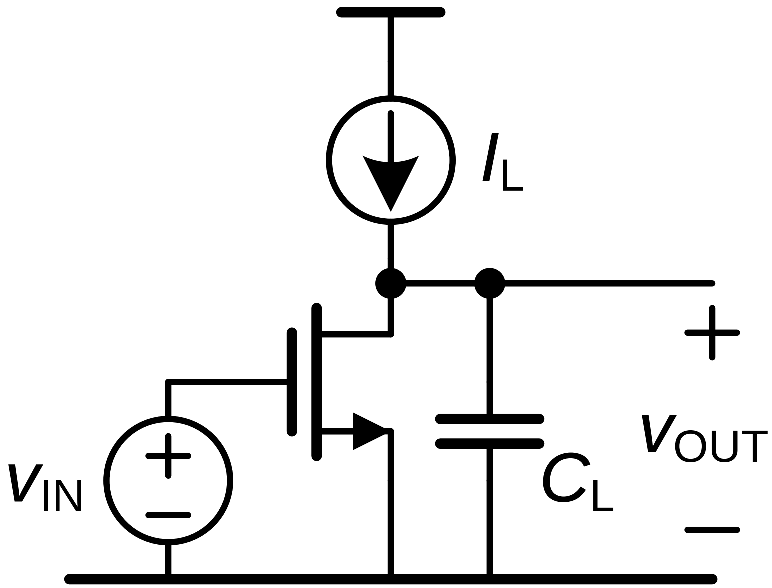
Bipolar:

$$A_V = \frac{V_A}{V_T}$$

如果 $V_E \approx 26\ \text{V}$、$V_T = kT/q \approx 26\ \text{mV}$，则$A_V \approx 1000$ 。

放大10^6倍，MOST需要3级，双极型晶体管只需要2级

增益带宽乘积：输出负载电容C_L



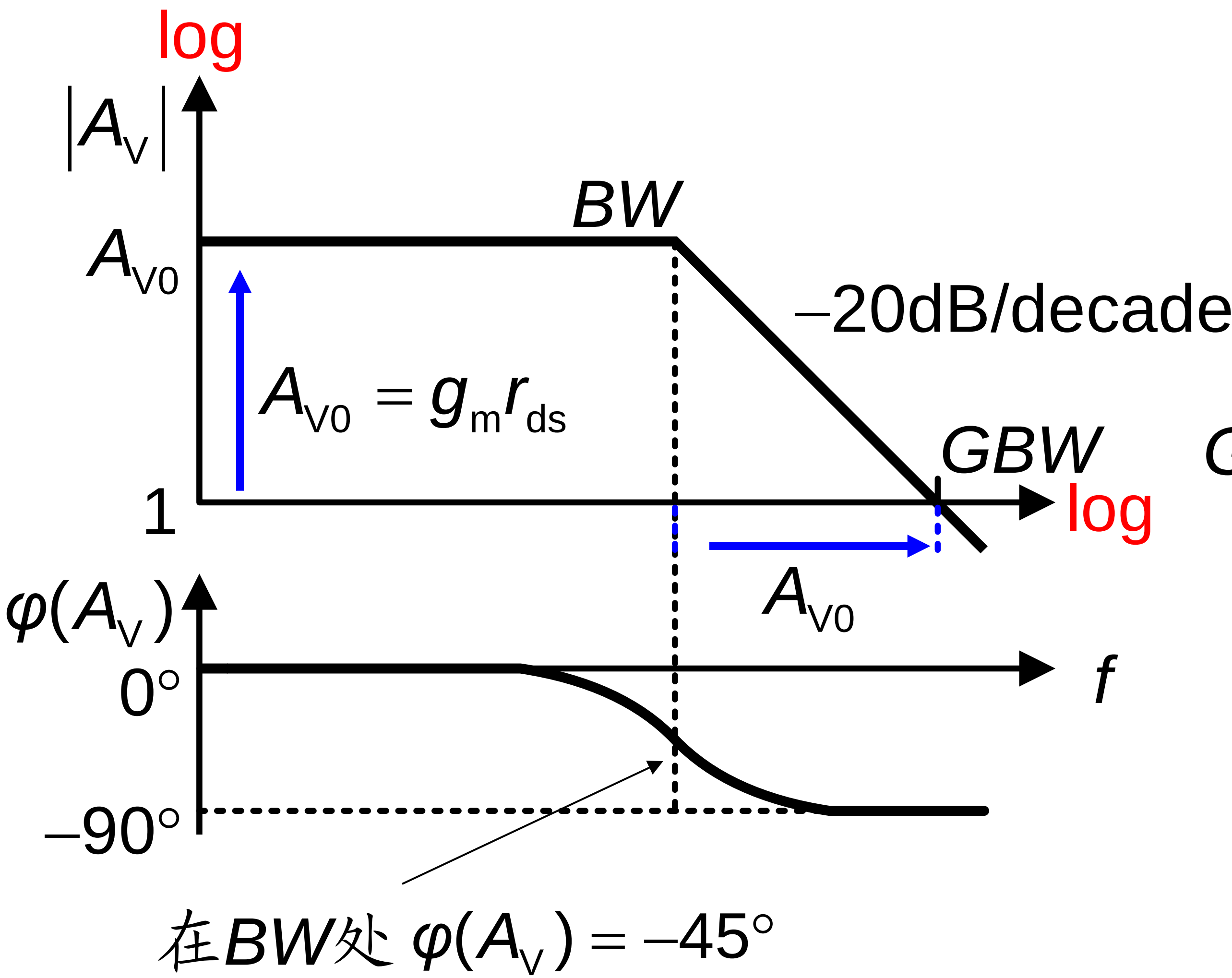
$$A_{V0} = g_m r_{ds}$$

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

适用于所有的单级运算放大器 →

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

增益A_{V0}、BW和GBW



$$A_V = \frac{A_{V0}}{1 + j\frac{f}{BW}}$$

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

练习

已知：GBW=100 MHz，C_L=3 pF

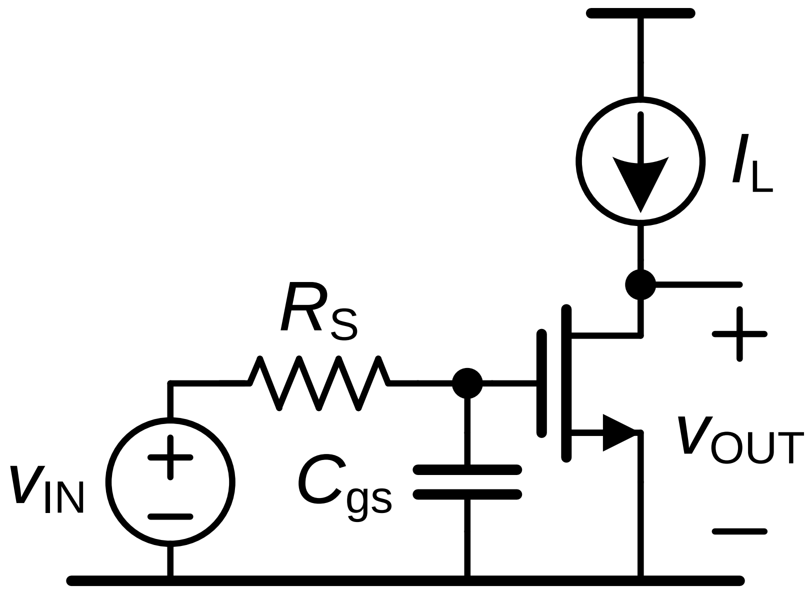
求：I_D、L、W、$\dfrac{GBW \cdot C_L}{I_D}$

$$K_n^{'} \approx 50\ \mu A/V^2$$

$$L_{min} = 0.5\ \mu m$$

$$FOM = \frac{GBW \cdot C_L}{I_D}$$

增益带宽乘积：输入电容C_{gs}



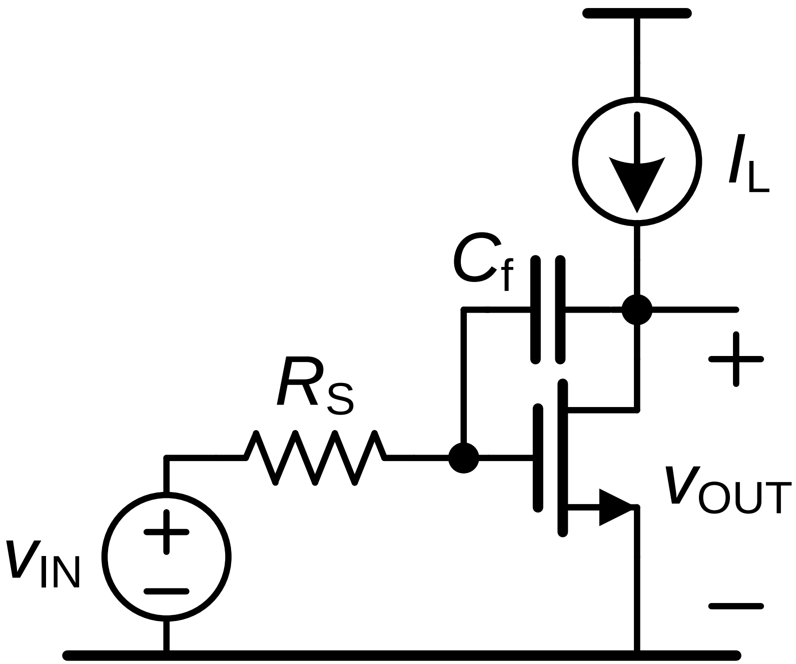
$$A_{V0} = g_m r_{ds}$$

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

$$GBW = \frac{g_m}{2\pi C_{gs}} \frac{r_{ds}}{R_S} = f_T \frac{r_{ds}}{R_S} \sim \frac{1}{WC_{ox}} \frac{1}{V_{GS} - V_{TH,GS}}$$

W？ L？ $V_{GS}-V_{TH,GS}$？

增益带宽乘积：密勒电容C_m

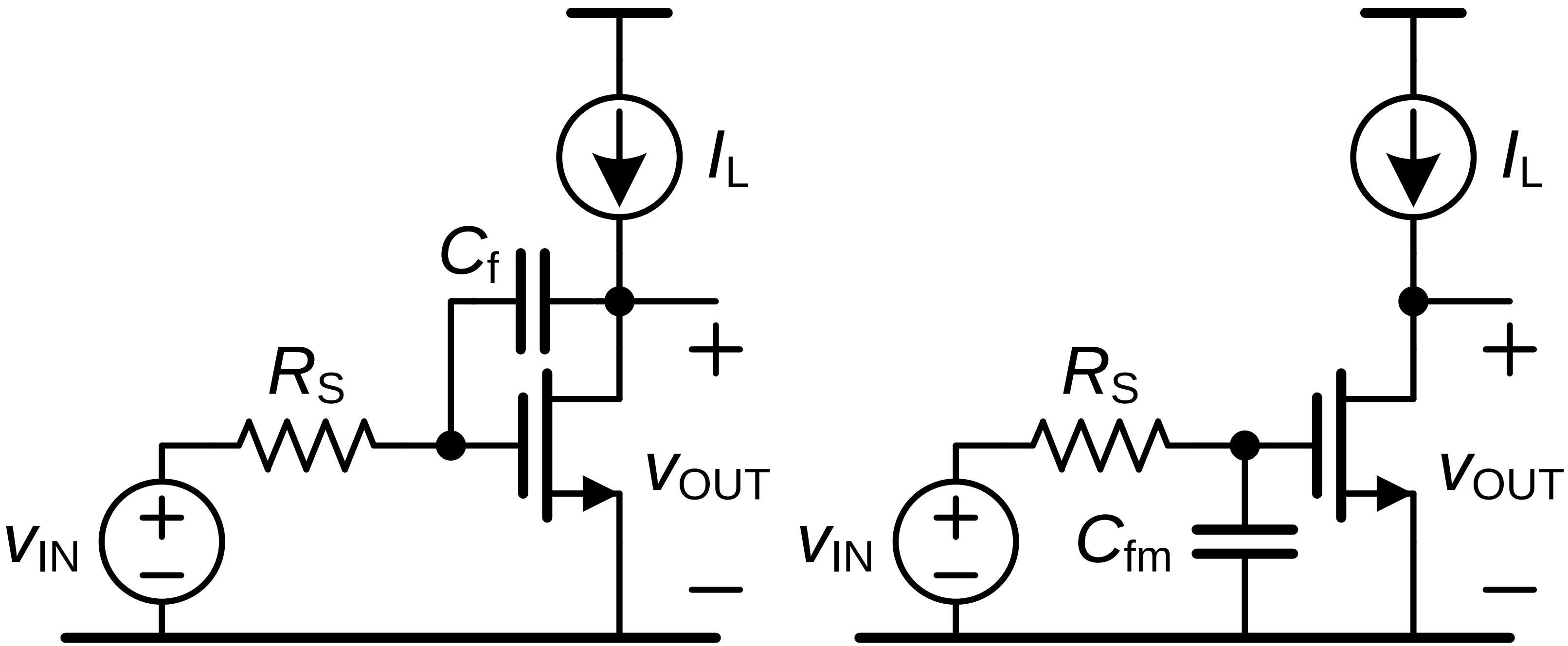


$$A_{V0} = g_m r_{ds}$$

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

$$GBW = \frac{1}{2\pi R_S C_f}$$

密勒效应

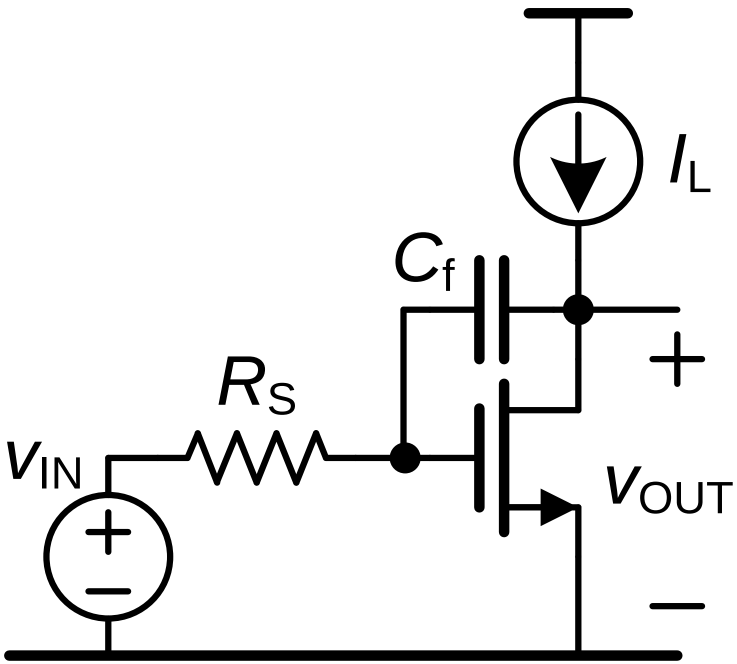


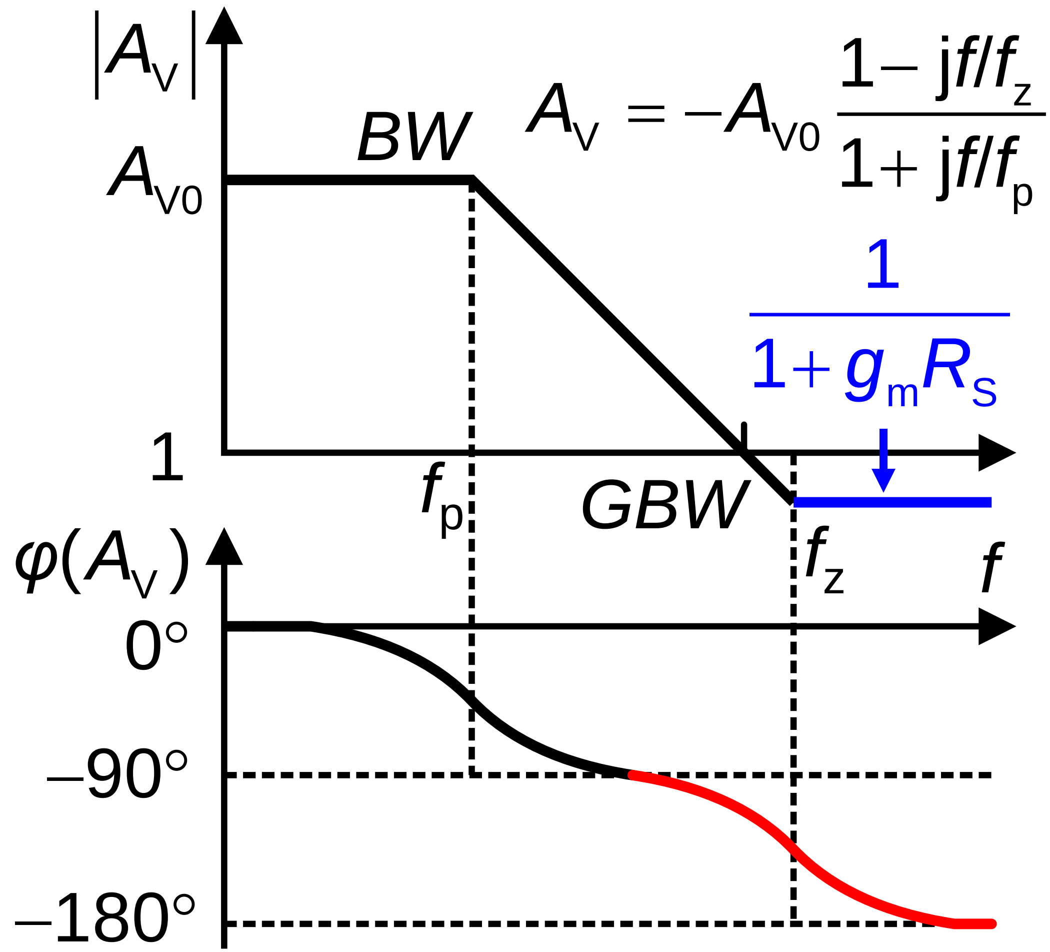
$$A_{V0} = g_m r_{ds}$$

$$C_{fm} = (1 + A_{V0}) C_f$$

Ref.: Miller, Dependence of the input impedance of a three-electrode vacuum tube upon the load in the plate circuit, Scient. Papers Bur. Standards, 1920, 367-385.

密勒电容的反馈效应

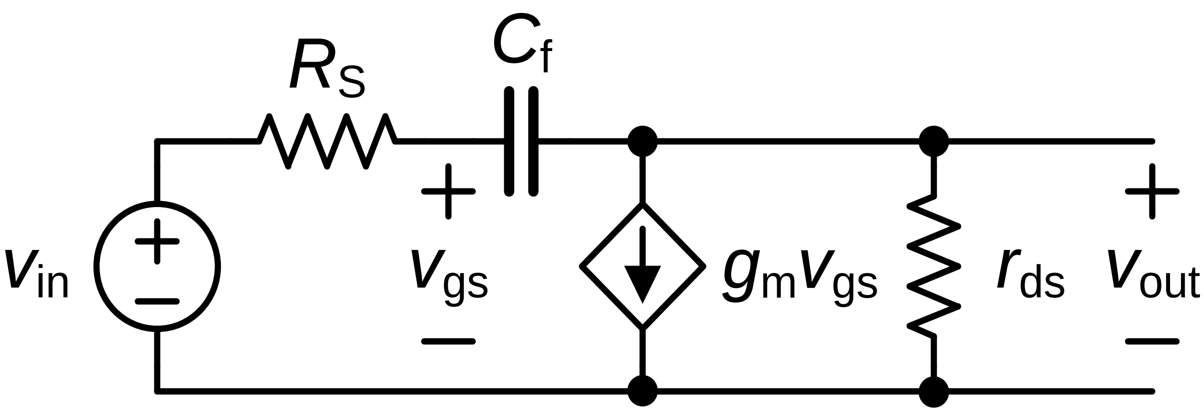




$$A_V = -A_{V0}\frac{1-jf/f_z}{1+jf/f_p}$$

$$f_z = \frac{g_m}{2\pi C_f} \quad f_p = \frac{1}{2\pi R_S A_{V0} C_f}$$

就相位而言，一个正零点相当于一个负极点！！！



$$\frac{v_{out}-v_{in}}{R_S+1/sC_f}+g_m\left(\frac{v_{out}-v_{in}}{R_S+1/sC_f}R_S+v_{in}\right)+\frac{v_{out}}{r_{ds}}=0$$

整理得 $$\frac{g_m/sC_f-1}{R_S+1/sC_f}v_{in}=-\frac{(g_mR_S+1)v_{out}}{R_S+1/sC_f}-\frac{v_{out}}{r_{ds}}$$

$$A_V=\frac{v_{out}}{v_{in}}=-g_m r_{ds}\frac{1-\frac{C_f}{g_m}s}{1+[r_{ds}+(1+g_m r_{ds})R_S]sC_f}$$

$$=-A_{V0}\frac{1-\frac{C_f}{g_m}s}{1+[r_{ds}+(1+A_{V0})R_S]sC_f}$$

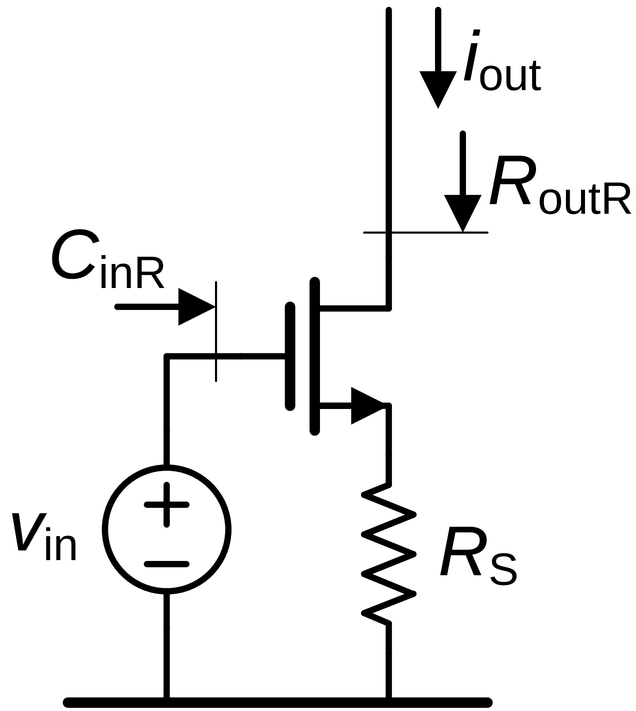
$$f_z=\frac{g_m}{2\pi C_f}$$

C_f的并联等效电阻 $r_{ds}+(1+g_m r_{ds})R_S$

$$f_p=-\frac{1}{2\pi R_S A_{V0} C_f}$$

密勒效应

源极接电阻的退化共源放大器

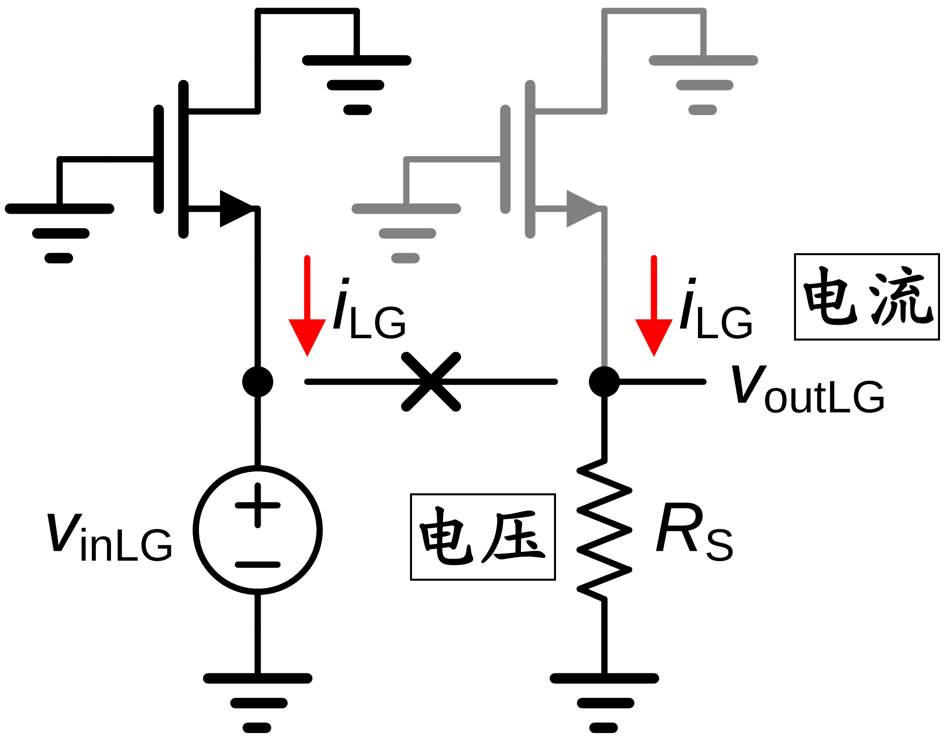


$$g_{mR} = \frac{g_m}{1+g_m R_S} \approx \frac{1}{R_S}$$

$$R_{outR} = r_{ds} + (1+g_m r_{ds})R_S \approx (g_m r_{ds})R_S$$

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

但是，R_S引入额外的噪声！



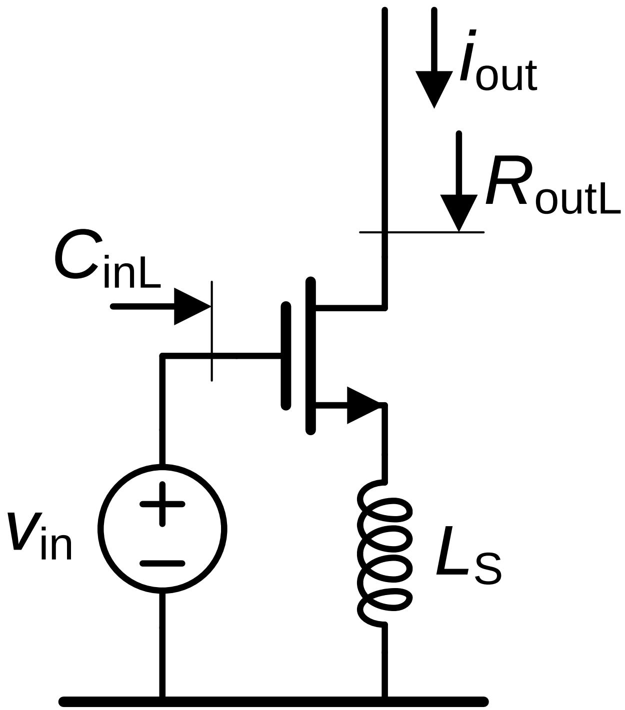
$$i_{LG} = -g_m v_{inLG}$$

$$v_{outLG} = i_{LG} R_S$$

$$A_{LG} = \frac{v_{outLG}}{v_{inLG}} = -g_m R_S$$

串联-串联反馈(电压-电流反馈)

源极接电感的退化共源放大器



$$g_{\mathrm{mL}} = \frac{g_{\mathrm{m}}}{1 + g_{\mathrm{m}} L_{\mathrm{S}} s}$$

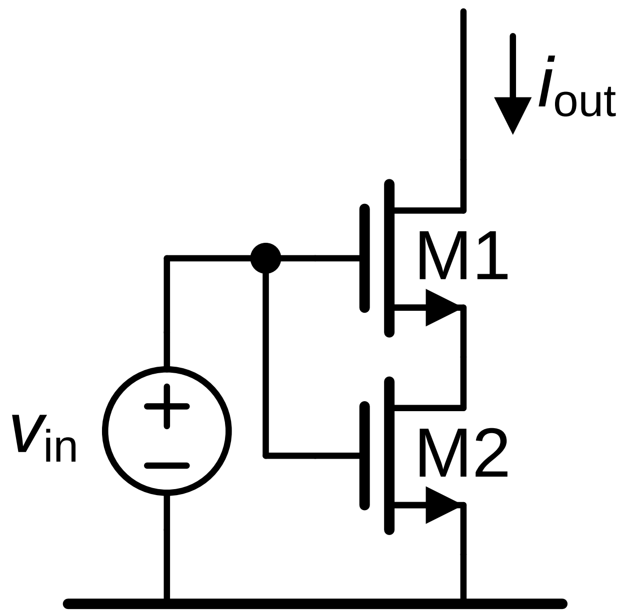
$$R_{\mathrm{outL}} = (1 + g_{\mathrm{m}} L_{\mathrm{S}} s) r_{\mathrm{ds}} + L_{\mathrm{S}} s$$

$$Z_{\mathrm{inL}} = g_{\mathrm{m}} \frac{L_{\mathrm{S}}}{C_{\mathrm{gs}}} + \frac{1 + L_{\mathrm{S}} C_{\mathrm{gs}} s^2}{C_{\mathrm{gs}} s}$$

$$Z_{\mathrm{inL}} = L_{\mathrm{S}} \omega_{\mathrm{T}} + L_{\mathrm{S}} s + \frac{1}{C_{\mathrm{gs}} s}$$

没有额外的噪声！

源极接线性MOST的退化共源放大器



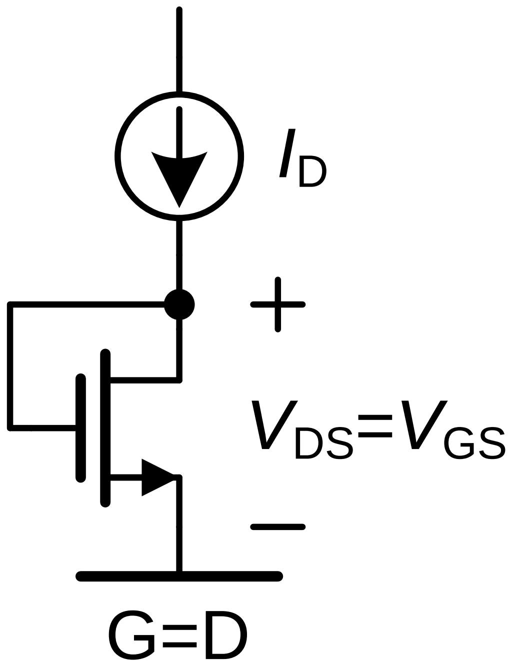
$$V_{DS2} = V_{GS2} - V_{GS1} \approx 0.2\ \text{V}$$

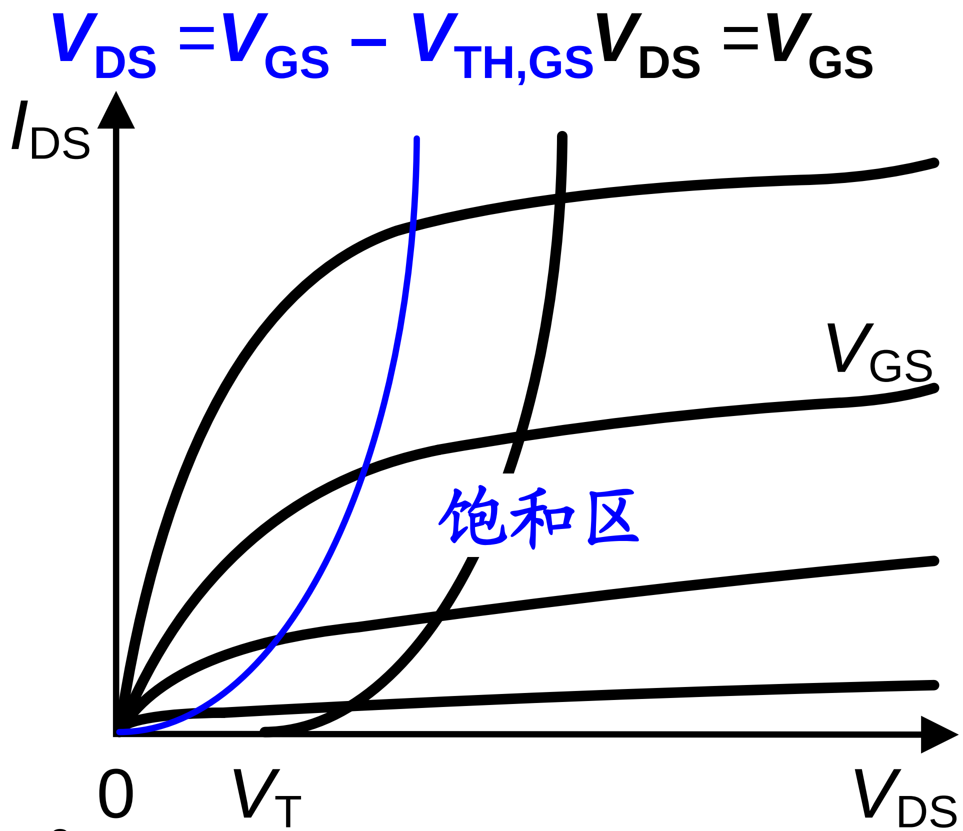
$$r_{ds2} = \frac{1}{KP \cdot W_2 / L_2 \cdot (V_{GS2} - V_{TH,GS2})}$$

$$R_{outM} = r_{ds1}(1 + g_{m1} r_{ds2}) + r_{ds2}$$

$$C_{inM} = \frac{C_{gs1}}{1 + g_{m1} r_{ds2}} + C_{gs2}$$

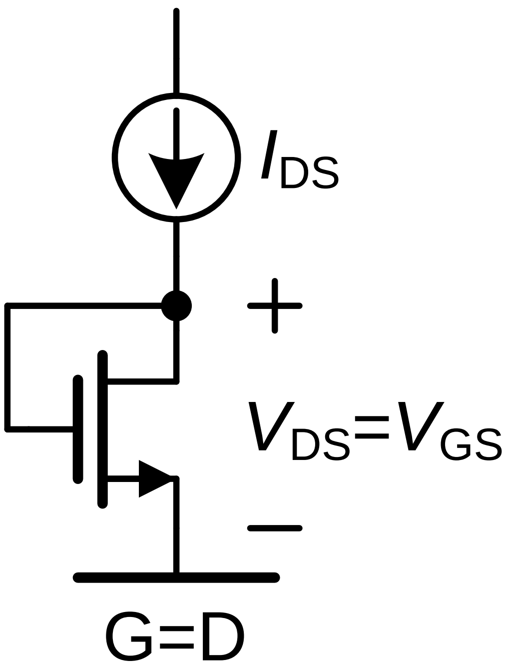
二极管连接MOST：并联反馈

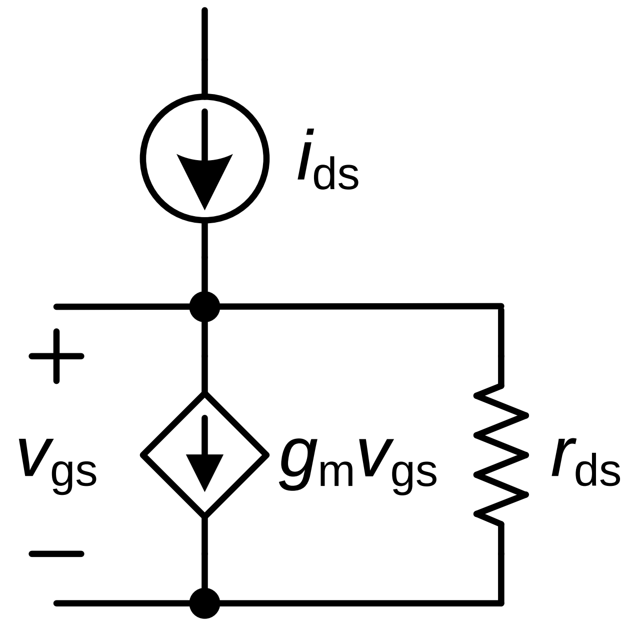




$$I_D = K_n' \frac{W}{L}(V_{DS} - V_{TH,GS})^2$$

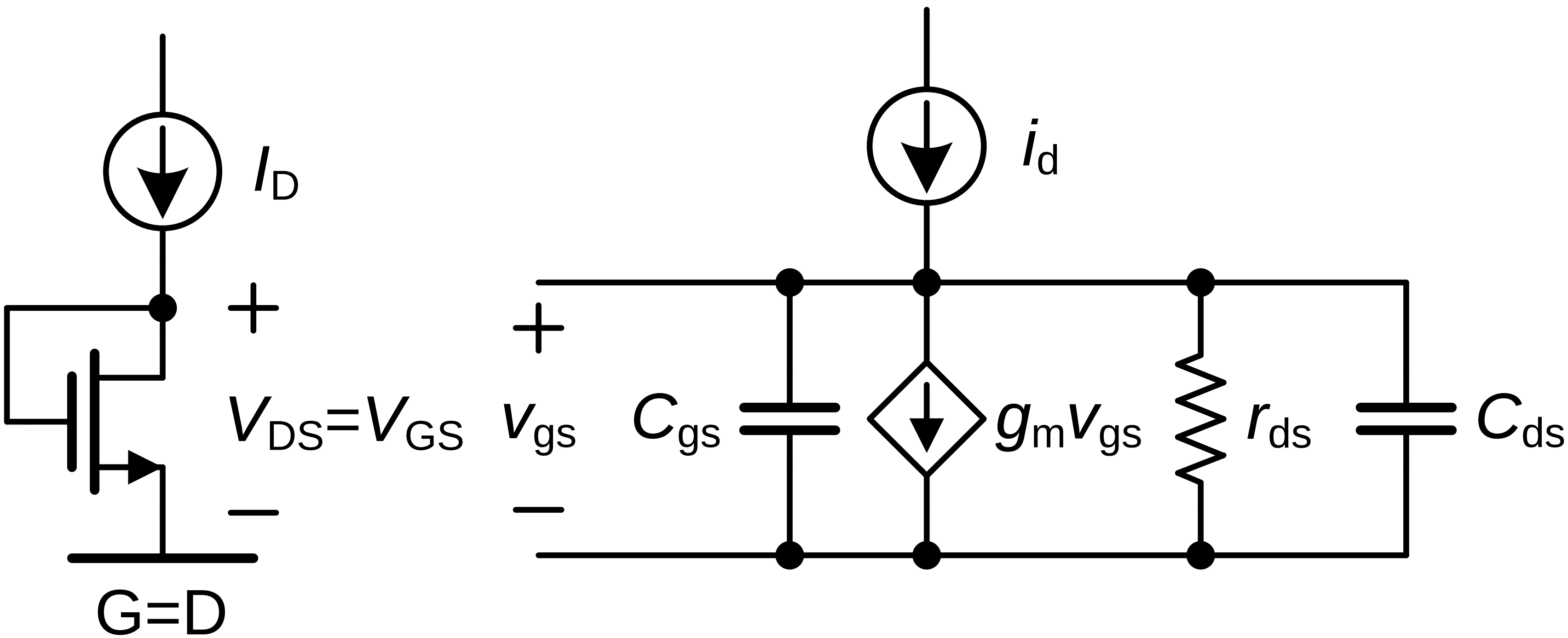
二极管连接MOST：小信号模型





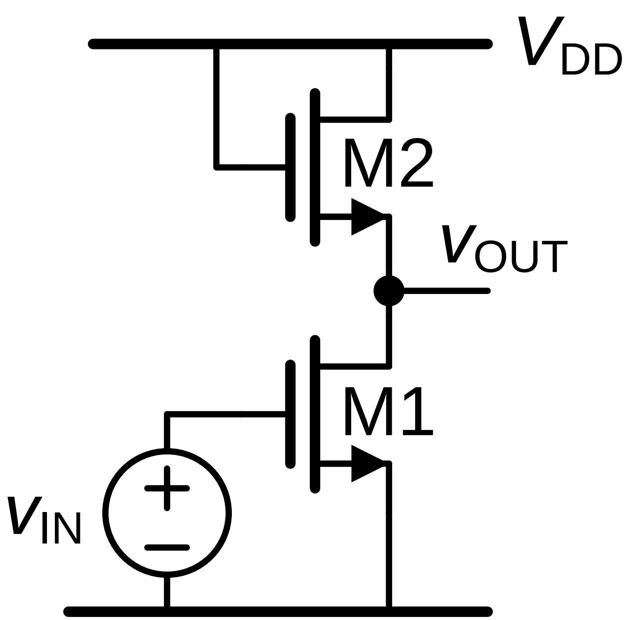
$$r_{out} = (1/g_m) \| r_{ds} \approx 1/g_m$$

二极管连接MOST：高频特性



$$BW = \frac{g_m}{2\pi(C_{gs} + C_{ds})} \overset{C_{gs} \approx C_{ds}}{\approx} \frac{f_T}{2}$$

宽带放大器

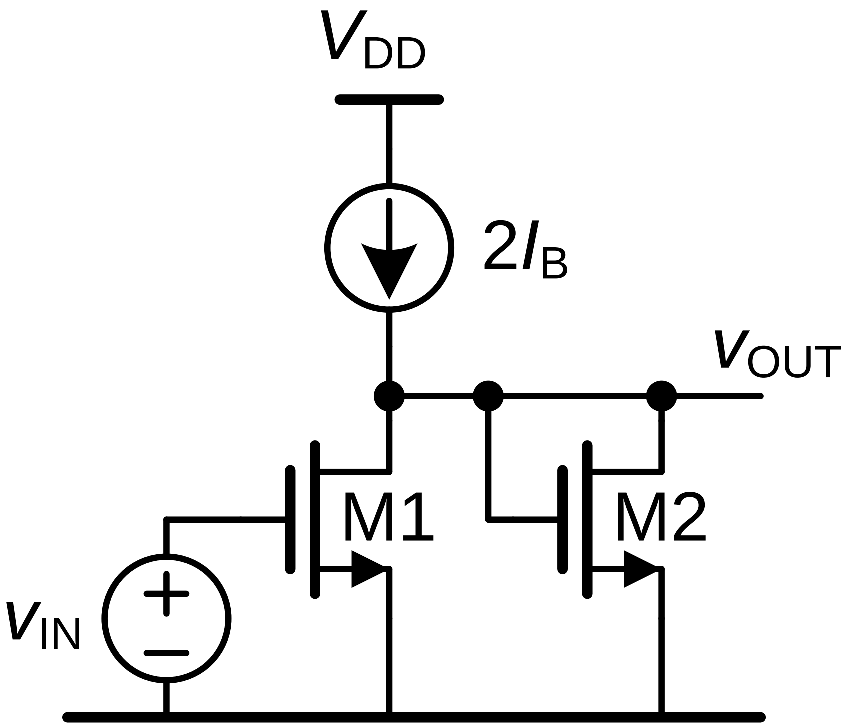


$$V_{OUT} = V_{DD} - V_{GS2}(V_{OUT})$$

$$A_{V0} = \frac{g_{m1}}{g_{m2}} = \sqrt{\frac{(W/L)_1}{(W/L)_2}} = \frac{V_{GS2} - V_{TH,GS2}}{V_{GS1} - V_{TH,GS1}}$$

$$R_{out} = 1/g_{m2}$$

线性宽带放大器



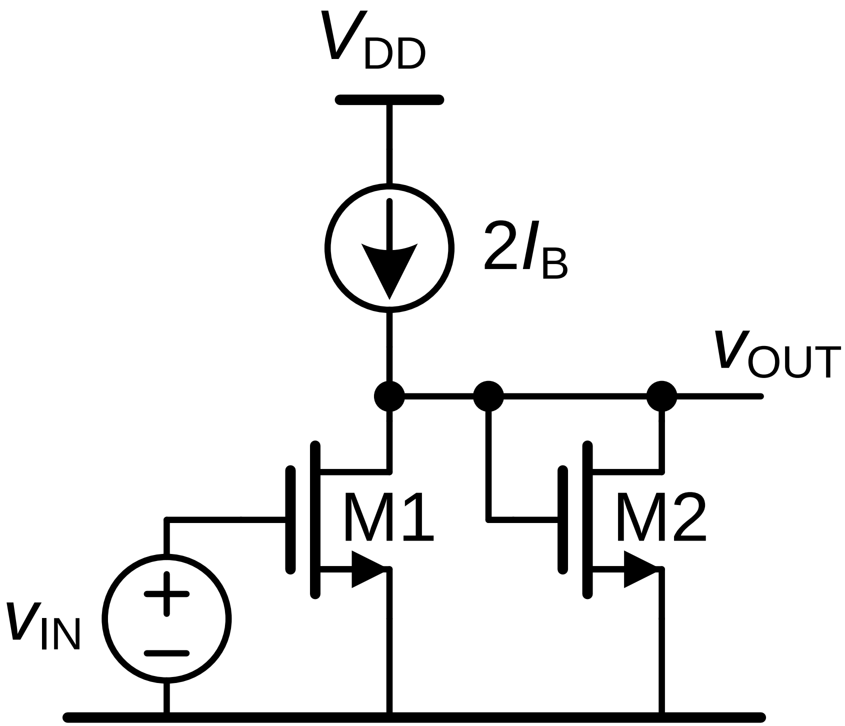
- 只有NMOS管+电流镜
- 输入/输出直流电平相同
- 无衬偏效应
- 高电源抑制比(PSRR)
- 双倍功耗!

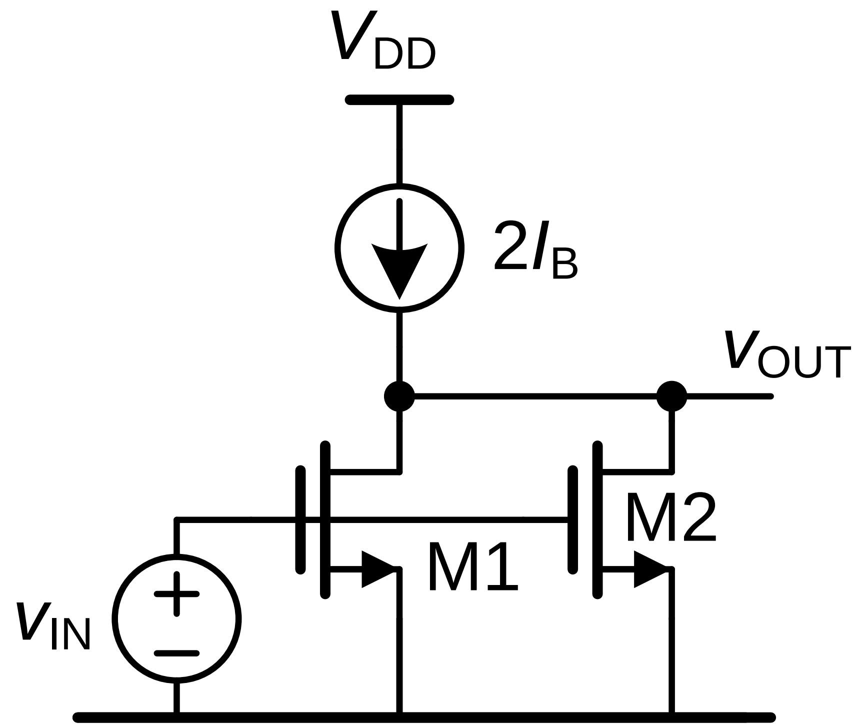
$$V_{OUT} = V_{GS2}$$

$$R_{out} = 1/g_{m2}$$

$$A_{V0} = \frac{g_{m1}}{g_{m2}} = \sqrt{\frac{(W/L)_1}{(W/L)_2}} = \frac{V_{GS2} - V_{TH,GS2}}{V_{GS1} - V_{TH,GS1}}$$

宽带放大器





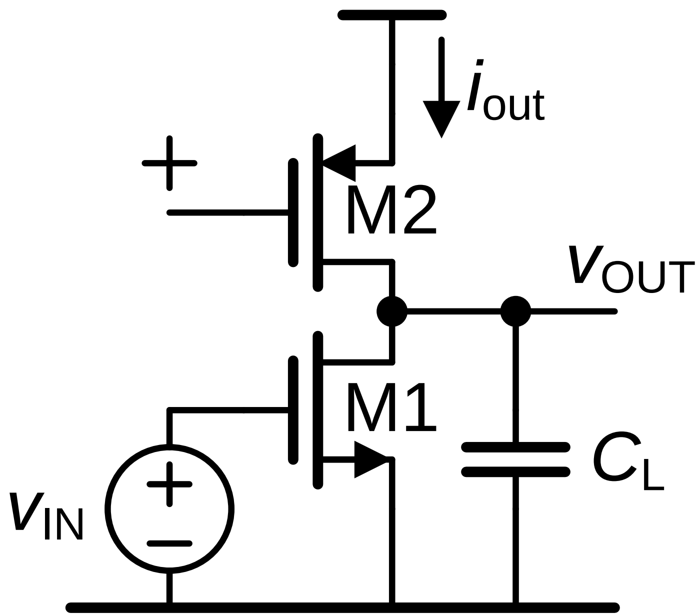
$$A_{V0}=\frac{g_{m1}}{g_{m2}}=\sqrt{\frac{(W/L)_1}{(W/L)_2}}=\frac{V_{GS2}-V_{TH,GS2}}{V_{GS1}-V_{TH,GS1}}$$

$$A_{V0}=g_m R_{out}$$

$$R_{out}=1/g_{m2}$$

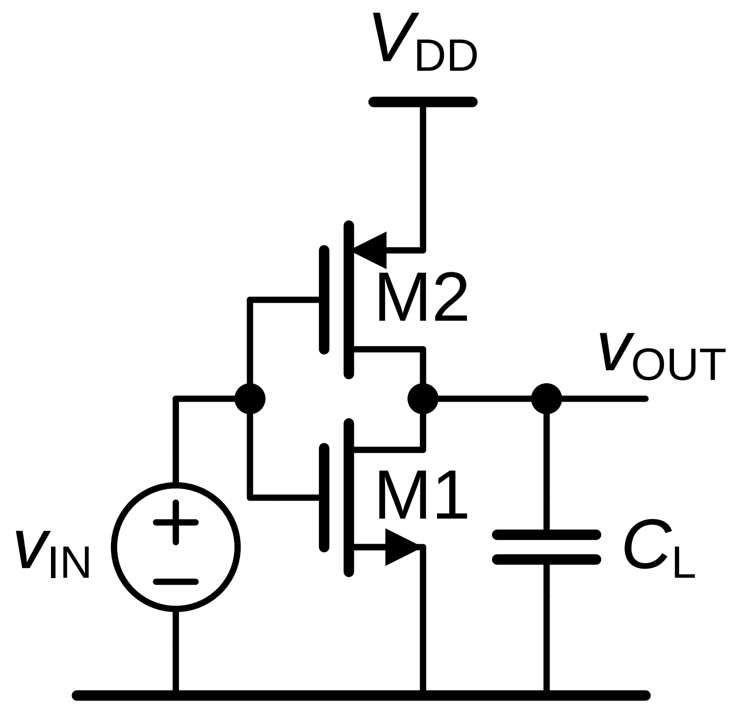
$$R_{out}=r_{ds1}\,||\,r_{ds2}$$

A类和AB类放大器



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

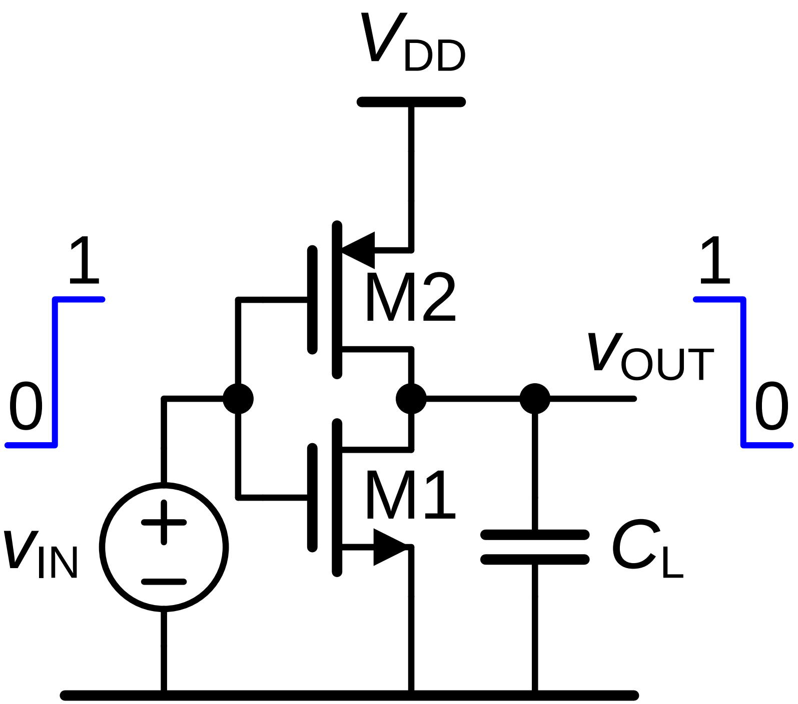
A类



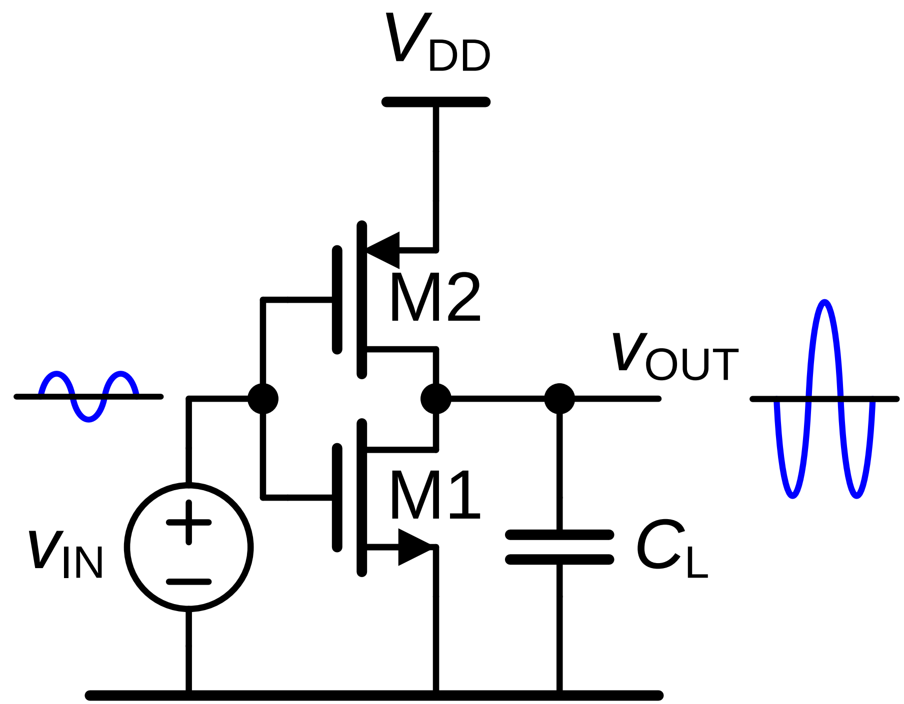
$$v_{out} = A_V v_{in}$$

AB类

CMOS反相放大器

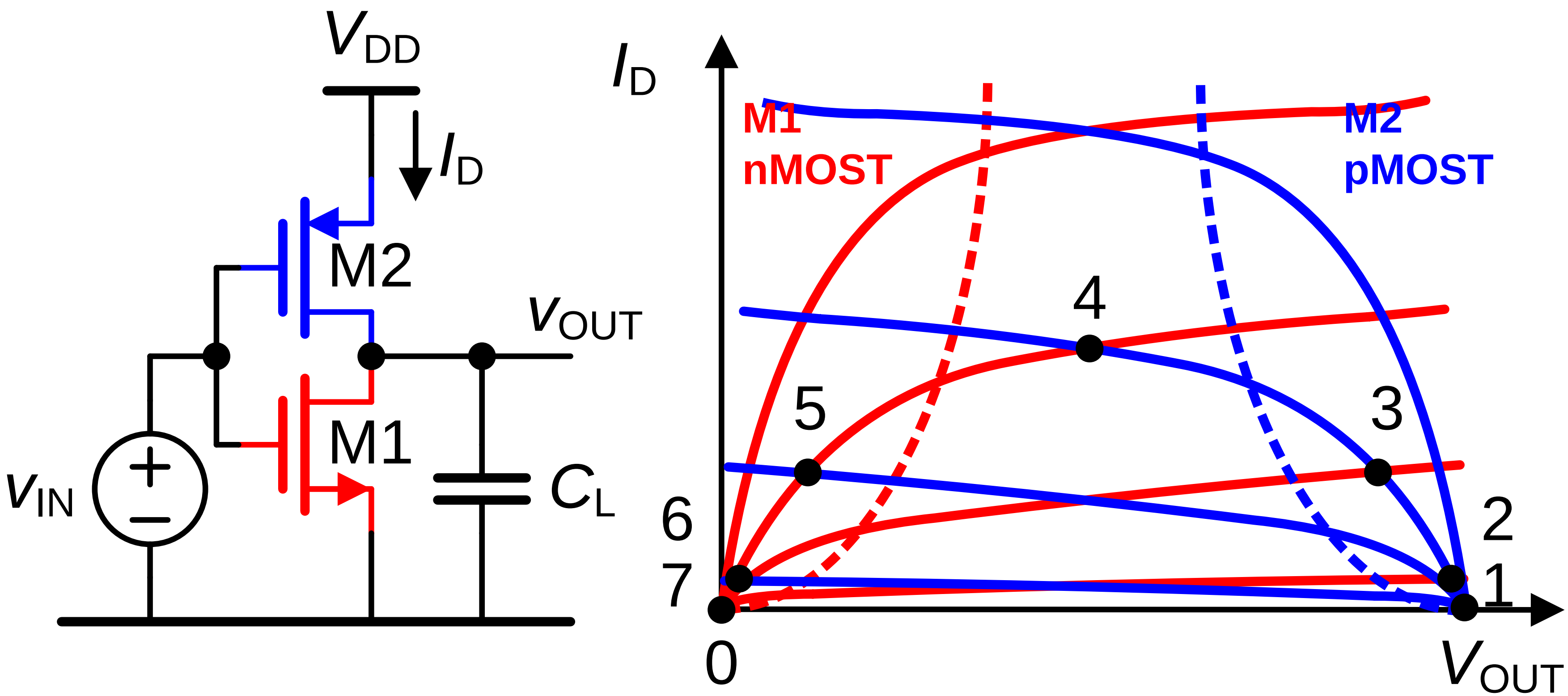


数字反相器



模拟放大器

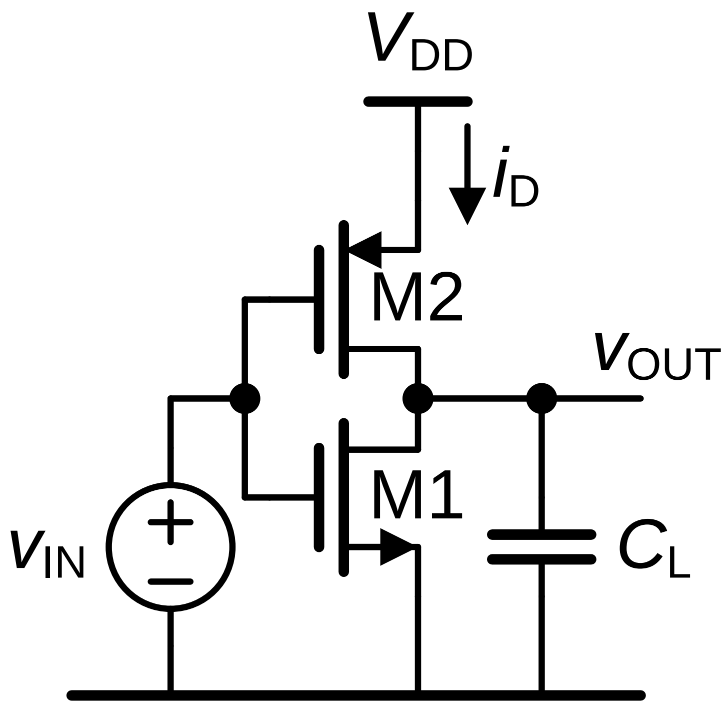
nMOST和pMOST的工作点



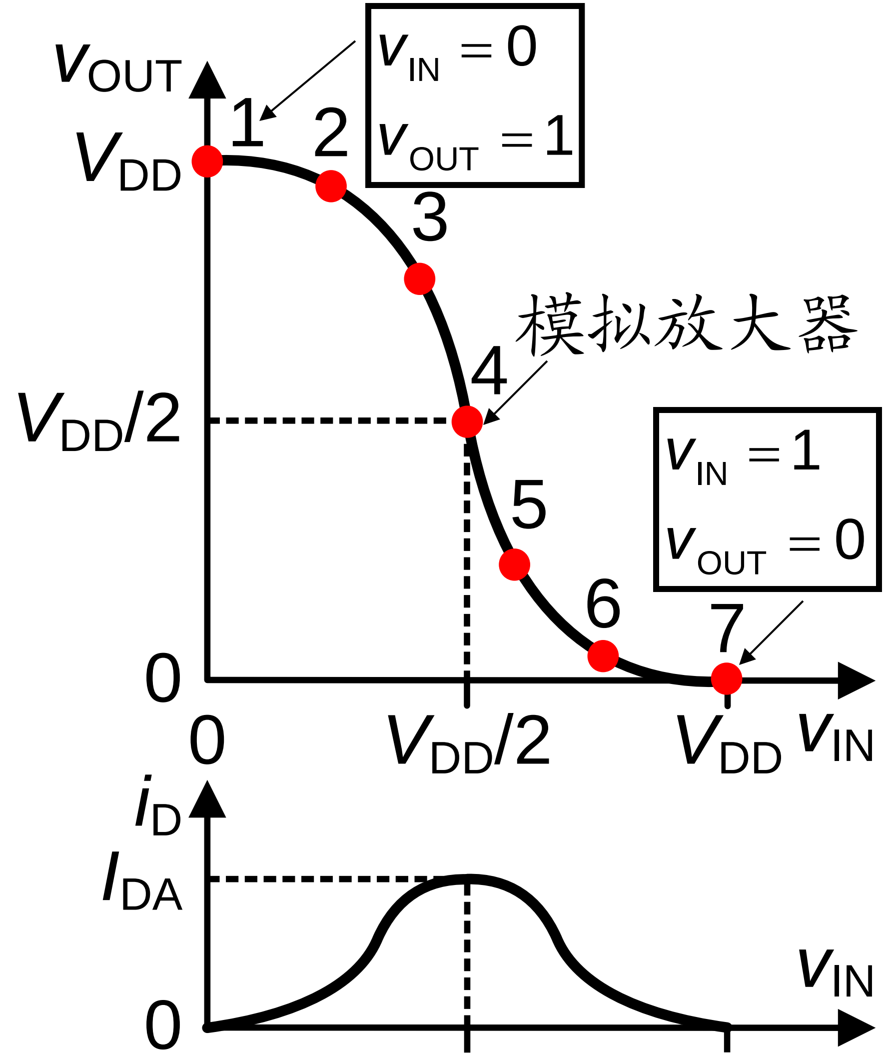
$$V_{DD} = V_{DSn} + V_{DSp}$$
$$= V_{GSn} + V_{GSp}$$

$$V_{DSn} = V_{OUT} \qquad V_{DSp} = V_{DD} - V_{OUT}$$
$$V_{GSn} = V_{IN} \qquad V_{GSp} = V_{DD} - V_{IN}$$

传输特性

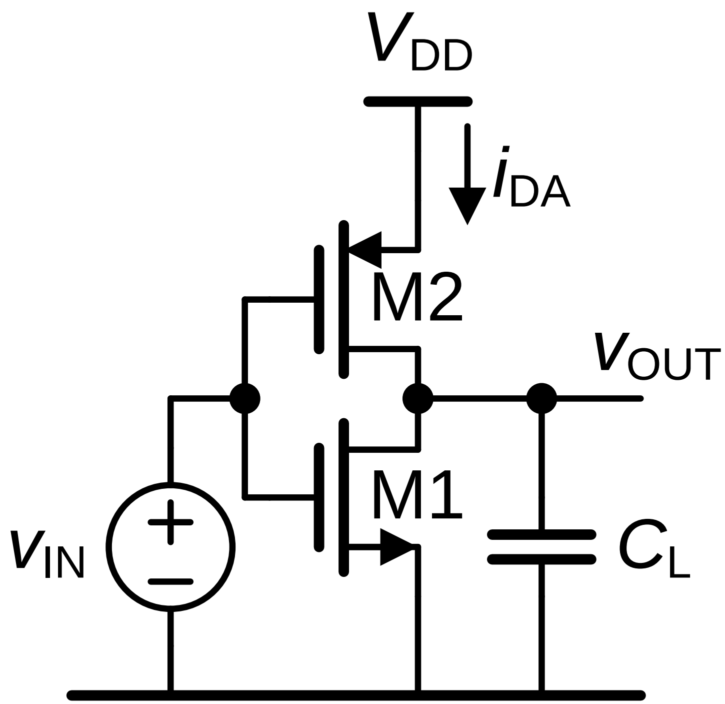


VDD
iD
M2
vOUT
vIN
M1
CL



vOUT
VDD
vIN = 0
vOUT = 1
1
2
3
模拟放大器
4
VDD/2
5
vIN = 1
vOUT = 0
6
7
0
0
VDD/2
VDD
vIN
iD
IDA
vIN
0

模拟放大器：直流工作点



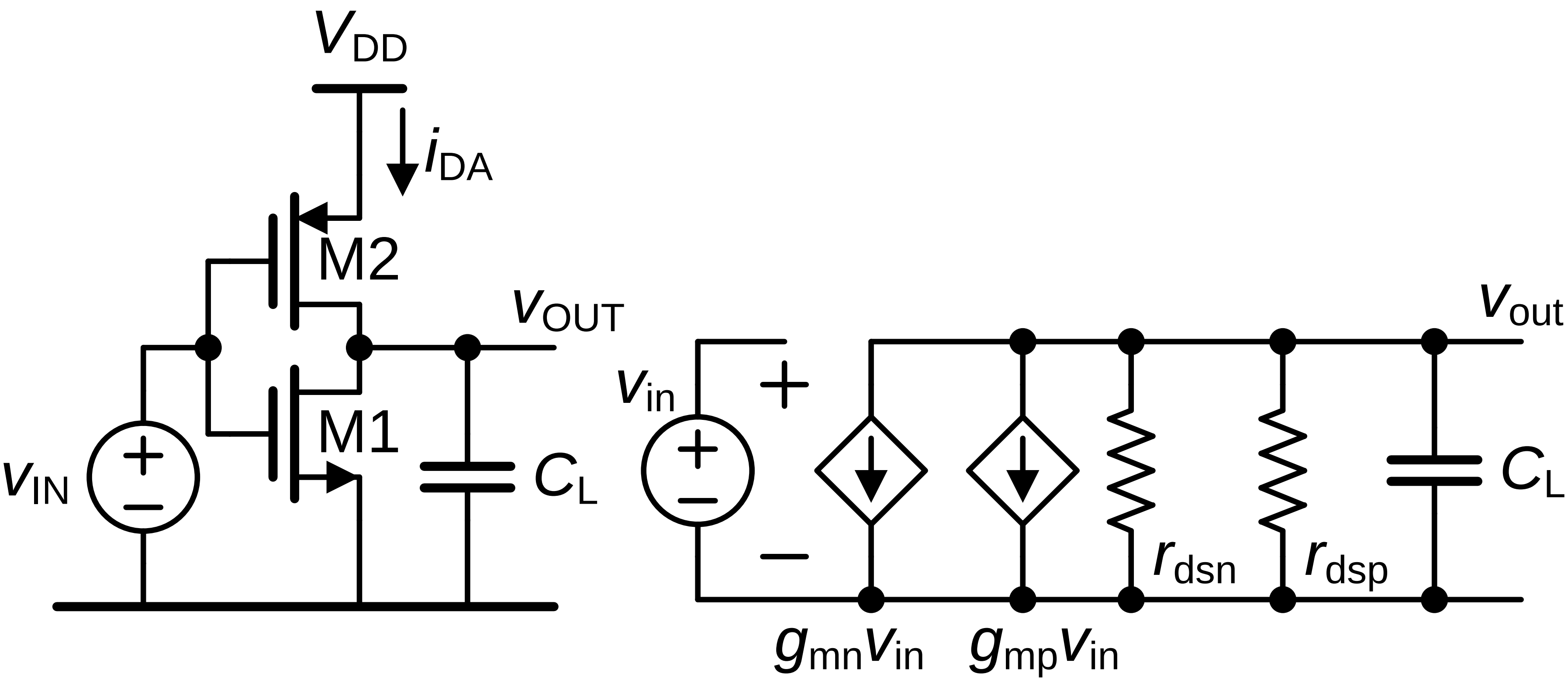
$$V_{IN} = \frac{V_{DD}}{2} \Rightarrow V_{OUT} = \frac{V_{DD}}{2}$$

$$\left.\begin{aligned} I_{Dn} &= K_n' \frac{W_n}{L_n}(V_{IN} - V_{THn})^2 \\ I_{Dp} &= K_p' \frac{W_p}{L_p}(V_{DD} - V_{IN} - V_{THp})^2 \end{aligned}\right\}$$

$$\Rightarrow K_n' \frac{W_n}{L_n} = K_p' \frac{W_p}{L_p}$$

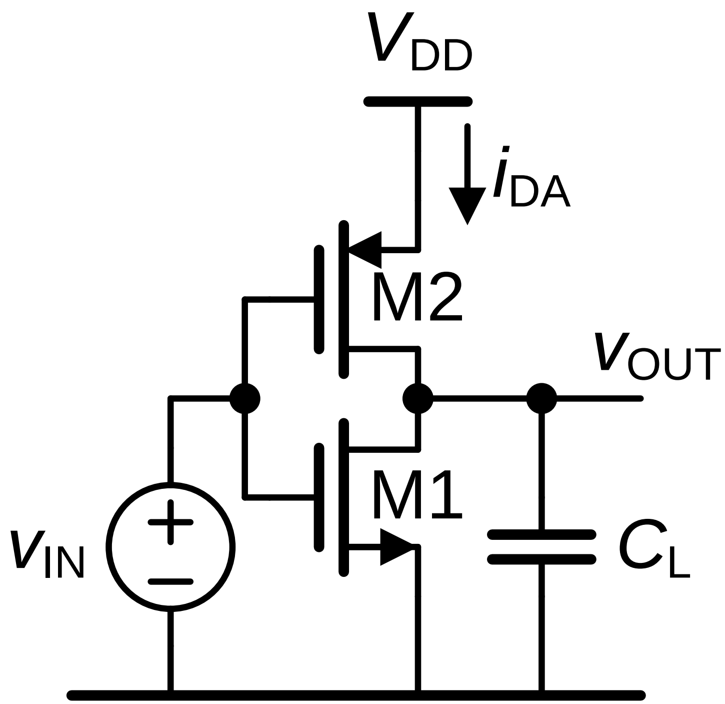
$$I_D = K_n' \frac{W_n}{L_n}\left(\frac{V_{DD}}{2} - V_{THn}\right)^2$$

模拟放大器：交流小信号模型



两个MOST的$V_{GS}-V_{TH,GS}$和I_D相等，则:$g_{mn}=g_{mp}=g_m$

模拟放大器：增益A_V



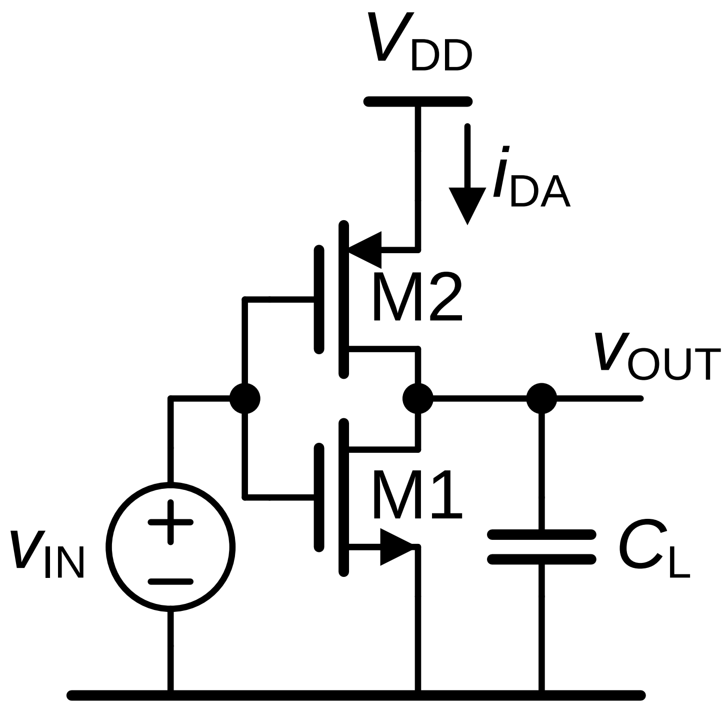
如果 $V_{En}L_n = V_{Ep}L_p = V_E$

$$g_{dsn} = g_{dsp} = g_{ds}$$

$$(g_{ds} = 1/r_{ds})$$

$$A_{V0} = -\frac{2g_m}{2g_{ds}} = -\frac{2V_E}{\frac{V_{DD}}{2} - V_{TH}}$$

模拟放大器：BW & GBW



$$A_{V0} = g_m r_{ds}$$

$$r_{ds} = r_{dsn} \| r_{dsp}$$

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

$$g_m = g_{mn} + g_{mp}$$

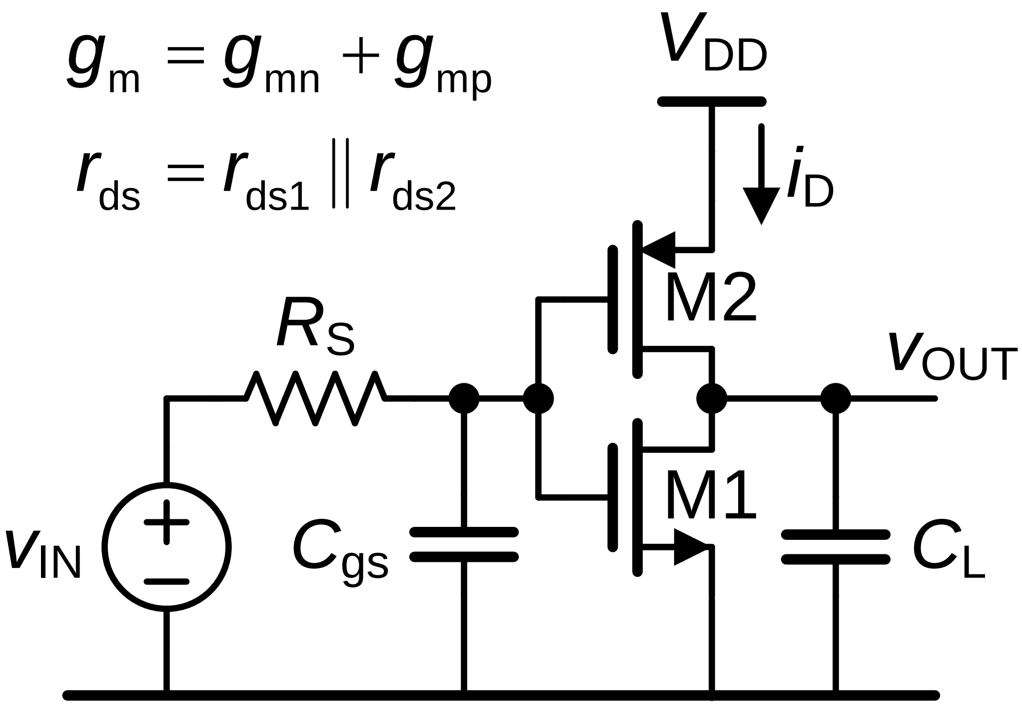
$$r_{ds} = r_{ds1} \| r_{ds2}$$

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

模拟放大器：C_{gs}产生的极点

$$g_m = g_{mn} + g_{mp}$$

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



$$A_{V0} = g_m r_{ds}$$

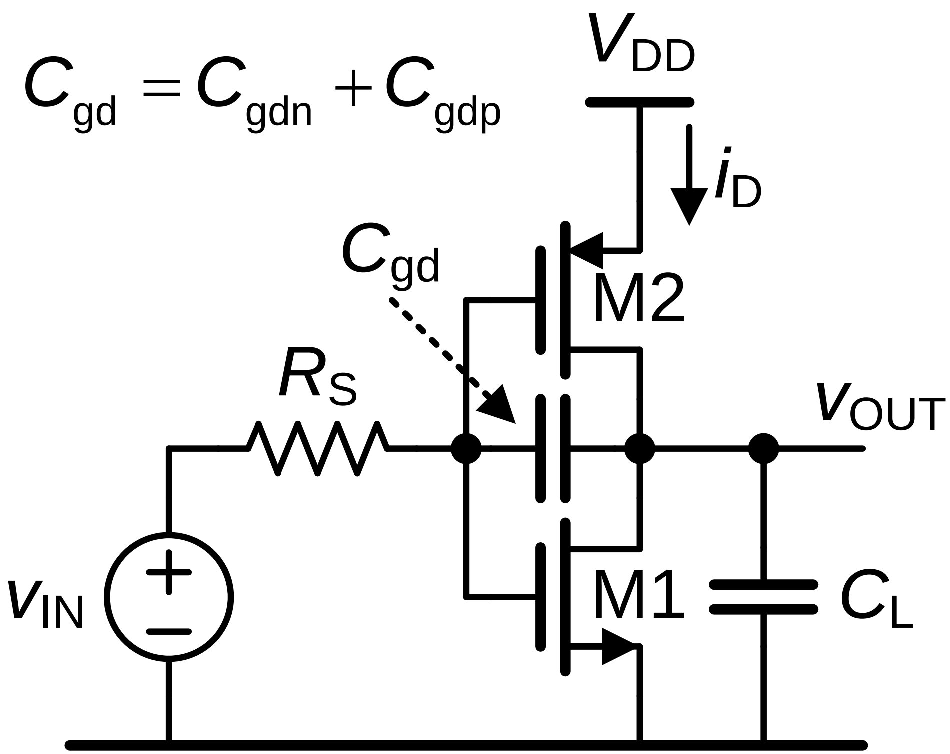
$$BW = \frac{1}{2\pi R_S C_{gs}}$$

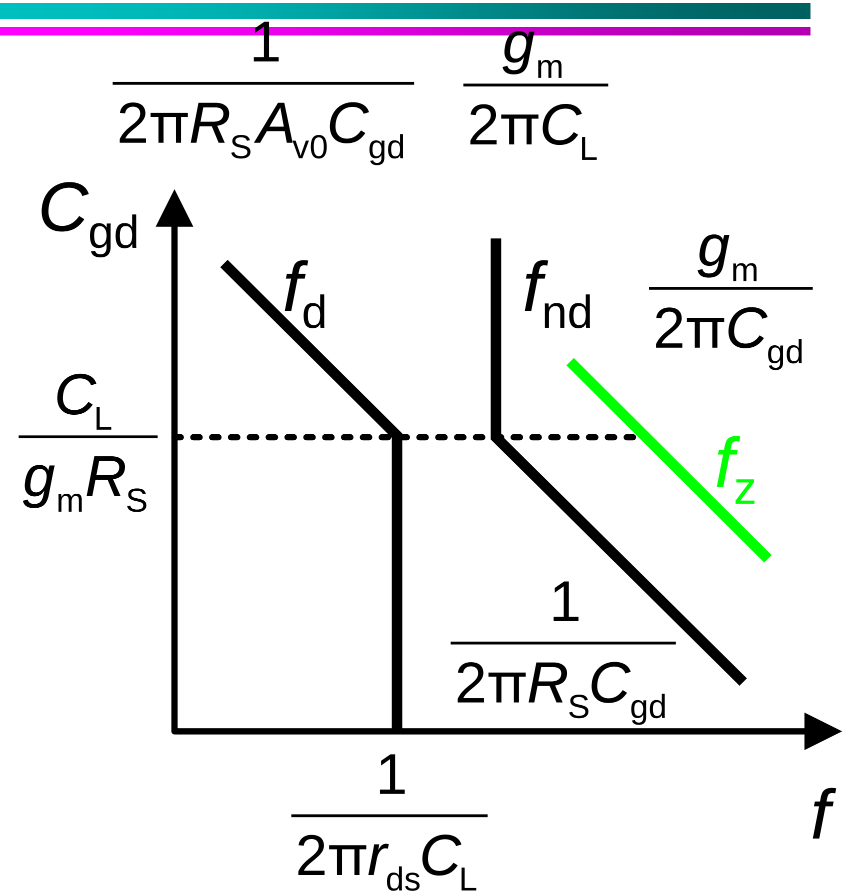
$$C_{gs} = C_{gsn} + C_{gsp}$$

如果 $R_S C_{gs} > r_{ds} C_L$ ： $GBW = \frac{f_T}{2} \frac{r_{ds}}{R_S}$

模拟放大器：C_{gd}产生的极点

$$C_{gd} = C_{gdn} + C_{gdp}$$





$$A_V = \frac{v_{out}}{v_{in}} = -\frac{g_m r_{ds}(1 - sC_{gd}/g_m)}{1 + s[r_{ds}C_L + (r_{ds} + (1+g_m r_{ds})R_S)C_{gd}] + s^2 R_S r_{ds} C_{gd} C_L}$$

$$A = A_0 \frac{1 - cs}{1 + as + bs^2}$$

零点 $z = \frac{1}{c}$

极点 $s_1 = -\frac{1}{a}$ $s_2 = -\frac{a}{b}$

如果 $s_2 \gg s_1$ ：

s很小

$\Downarrow$

$$1 + as + \cancel{bs^2} = 0$$

$\Downarrow$

$$s_1 = -\frac{1}{a}$$

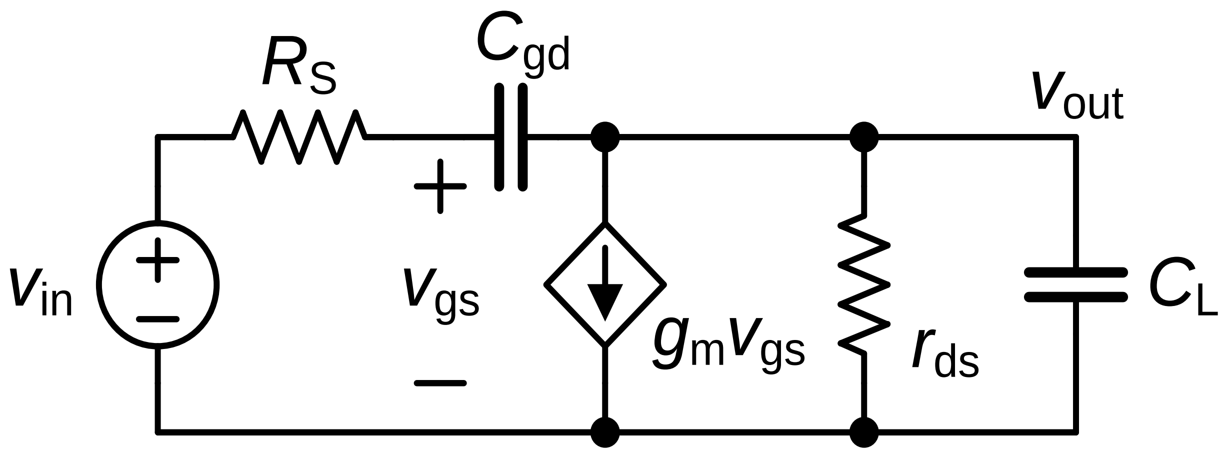
s很大

$\Downarrow$

$$\cancel{1} + as + bs^2 = 0$$

$\Downarrow$

$$s_2 = -\frac{a}{b}$$



$$g_m = g_{mn} + g_{mp}$$

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

$$C_{gd} = C_{gdn} + C_{gdp}$$

$$\frac{v_{out} - v_{in}}{R_S + 1/sC_{gd}} + g_m\left(\frac{v_{out} - v_{in}}{R_S + 1/sC_{gd}} R_S + v_{in}\right) + \frac{v_{out}}{r_{ds}} = -\frac{v_{out}}{1/sC_L}$$

整理得 $$\frac{g_m/sC_{gd} - 1}{R_S + 1/sC_{gd}} v_{in} = -\frac{(g_m R_S + 1)v_{out}}{R_S + 1/sC_{gd}} - \frac{v_{out}}{r_{ds}} - \frac{v_{out}}{1/sC_L}$$

$$A_V = \frac{v_{out}}{v_{in}} = -\frac{g_m r_{ds}(1 - sC_{gd}/g_m)}{1 + s[r_{ds}C_L + (r_{ds} + (1+g_m r_{ds})R_S)C_{gd}] + s^2 R_S r_{ds} C_{gd} C_L}$$

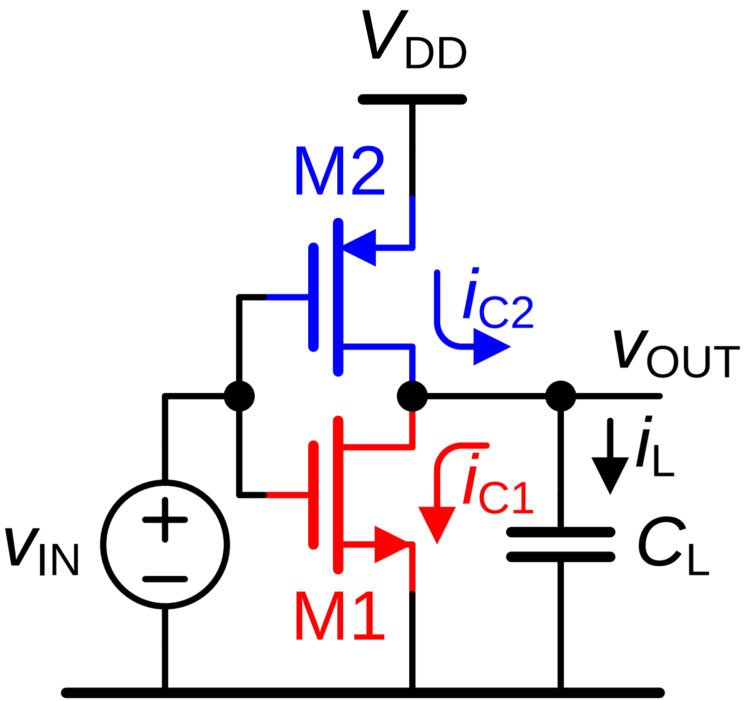
$$f_z = \frac{g_m}{2\pi C_{gd}}, \qquad f_d, \qquad f_{nd} \qquad\qquad A_{V0} = g_m r_{ds}$$

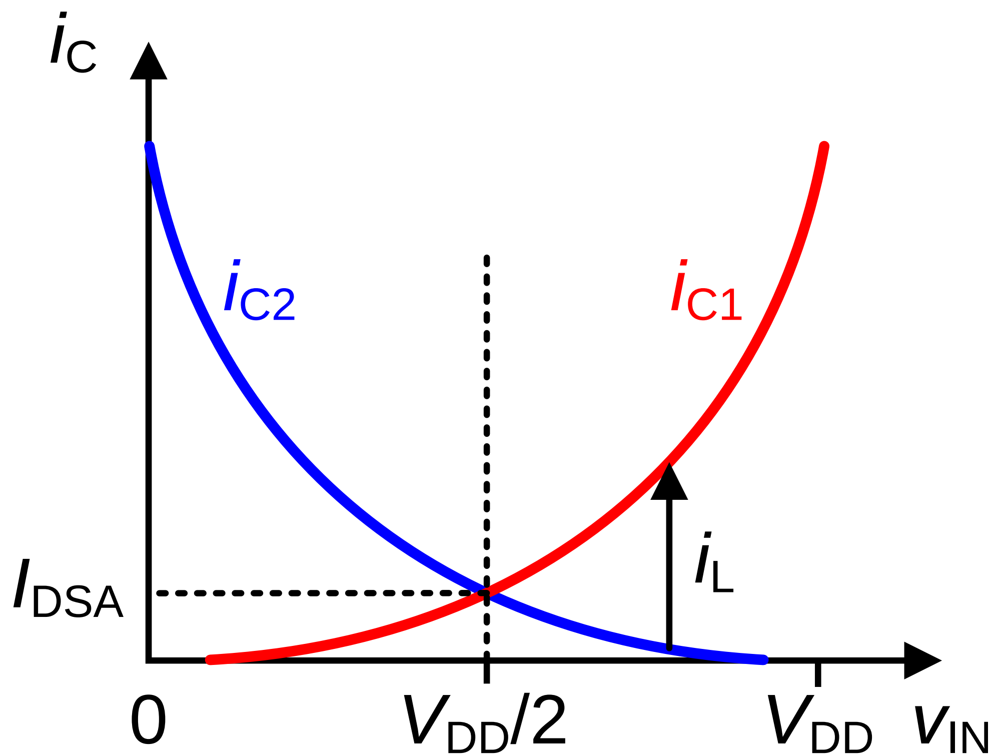
$$C_{gd} \ll C_{gdt} \qquad f_d = -\frac{1}{2\pi r_{ds} C_L} \qquad f_{nd} = -\frac{1}{2\pi R_S C_{gd}}$$

$$C_{gd} \gg C_{gdt} \qquad f_d = -\frac{1}{2\pi R_S A_{v0} C_{gd}} \qquad f_{nd} = -\frac{g_m}{2\pi C_L}$$

$$-\frac{1}{2\pi r_{ds} C_L} = -\frac{1}{2\pi R_S A_{v0} C_{gdt}} \Rightarrow C_{gdt} = \frac{C_L}{g_m R_S}$$

AB类放大器





$$i_L = i_{C2} - i_{C1}$$

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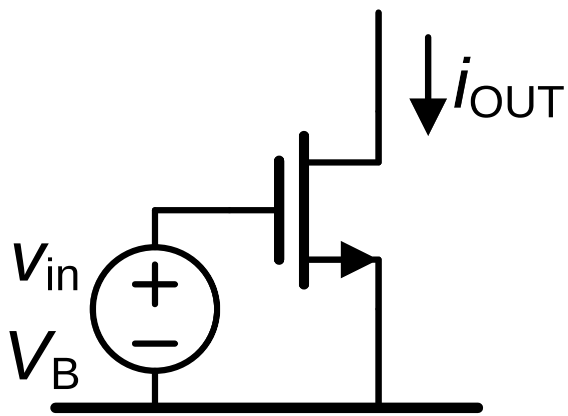
单晶体管级

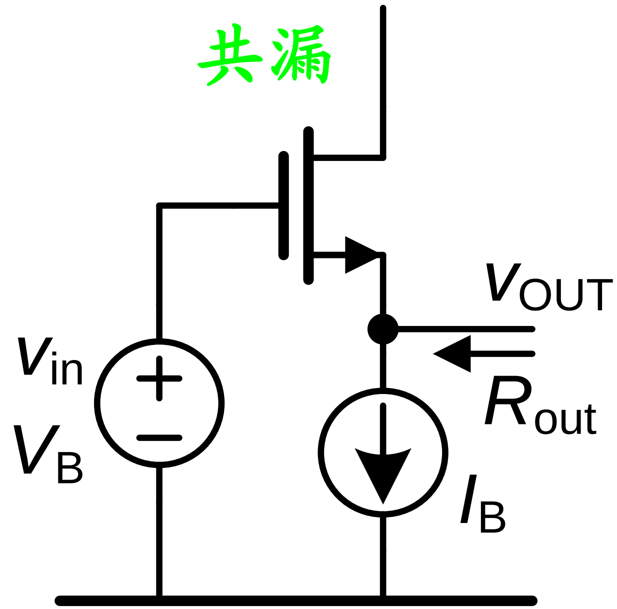
共源



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

共源放大器

共漏



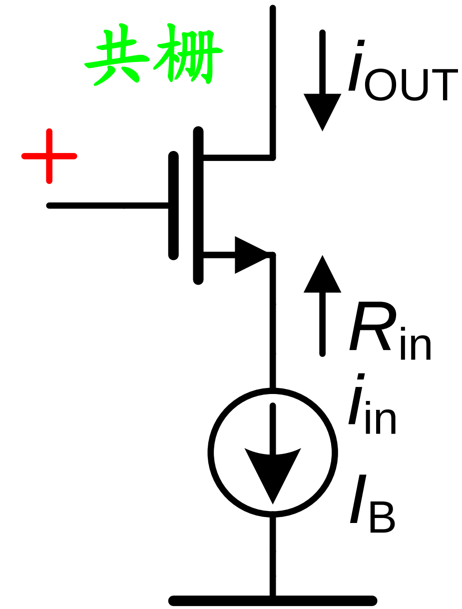
$$v_{out} = v_{in}$$

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

源极跟随器

电压缓冲器

共栅



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

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

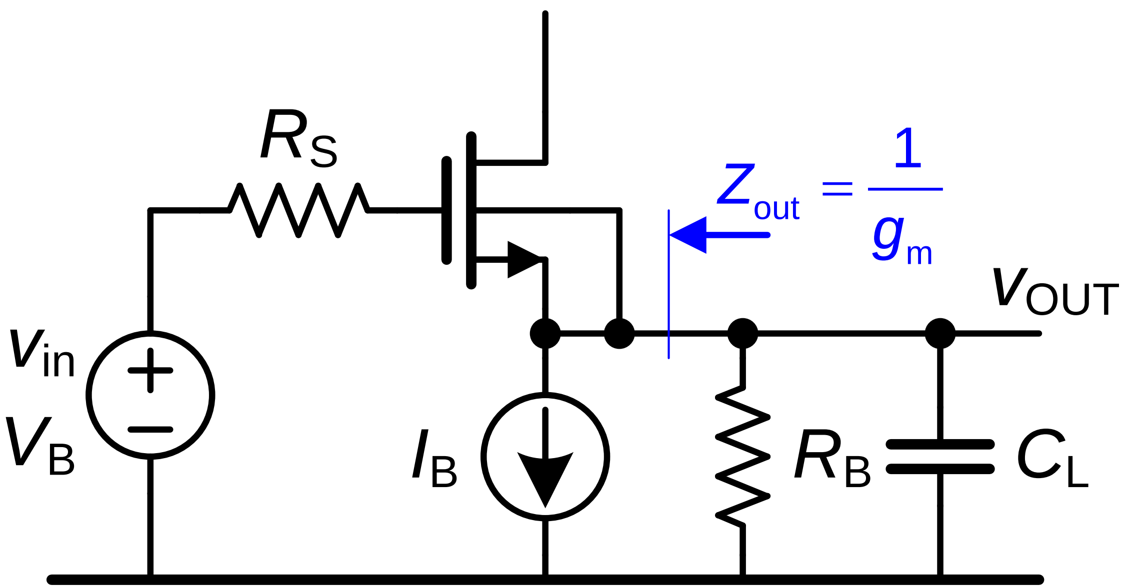
共栅放大器

电流缓冲器

源极跟随器： V_{BS}=0 V (p阱)

$$\boxed{V_{BS}=0\ \text{V}}\quad V_T=V_{T0}+\gamma\left(\sqrt{|2\Phi_F|-0}-\sqrt{|2\Phi_F|}\right)\Rightarrow V_T=V_{T0}$$

$$V_{GS}=V_{T0}+\sqrt{\frac{I_B}{K'W/L}}$$

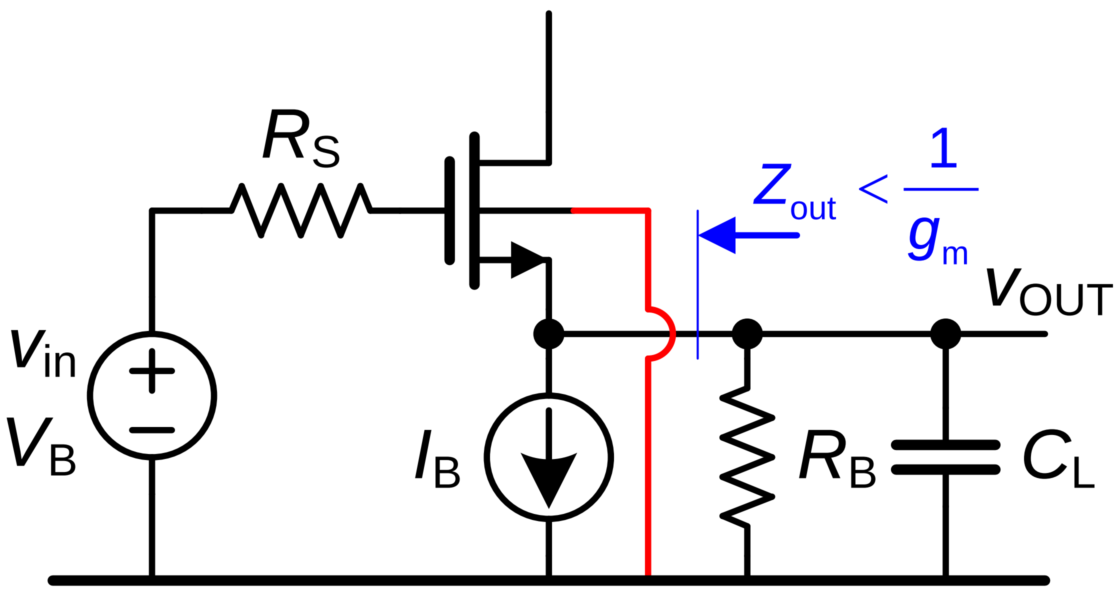


如果 $I_B=\text{ct}$，则 $V_{GS}=\text{ct}$

$$V_{OUT}=V_{IN}-V_{GS}\Rightarrow \Delta V_{OUT}=\Delta V_{IN}\Rightarrow \boxed{A_V=1}$$

源极跟随器： $V_{BS}\neq 0$ V (n阱)

$$\boxed{V_{BS}=-V_{OUT}} \qquad V_T=V_{T0}+\gamma\left(\sqrt{|2\Phi_F|+V_{OUT}}-\sqrt{|2\Phi_F|}\right)$$

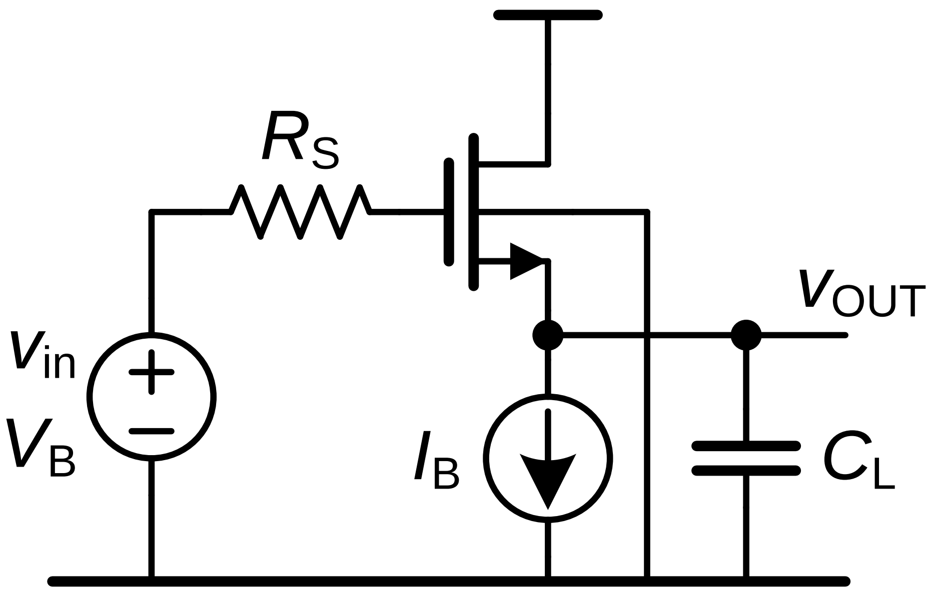


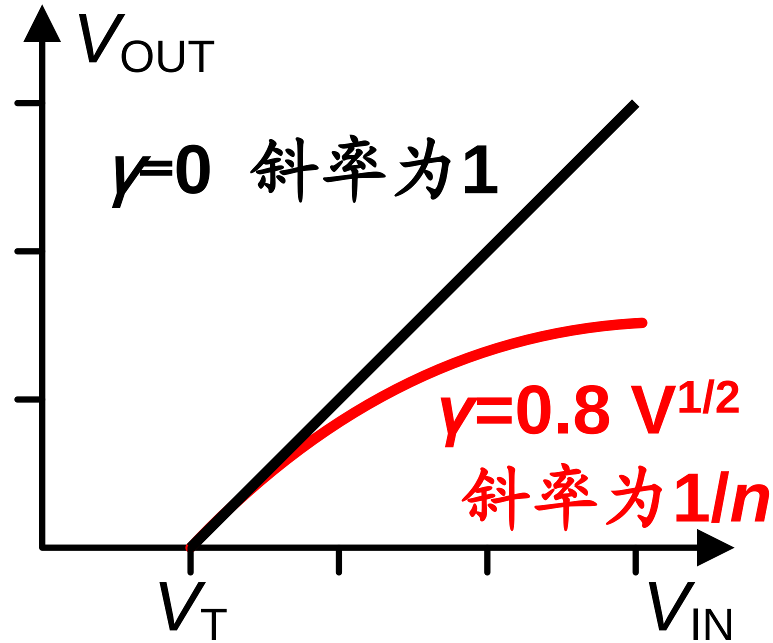
$$V_{GS}=V_T+\sqrt{\frac{I_B}{K'W/L}}$$

如果 $I_B=ct$, $V_{GS}\neq ct$

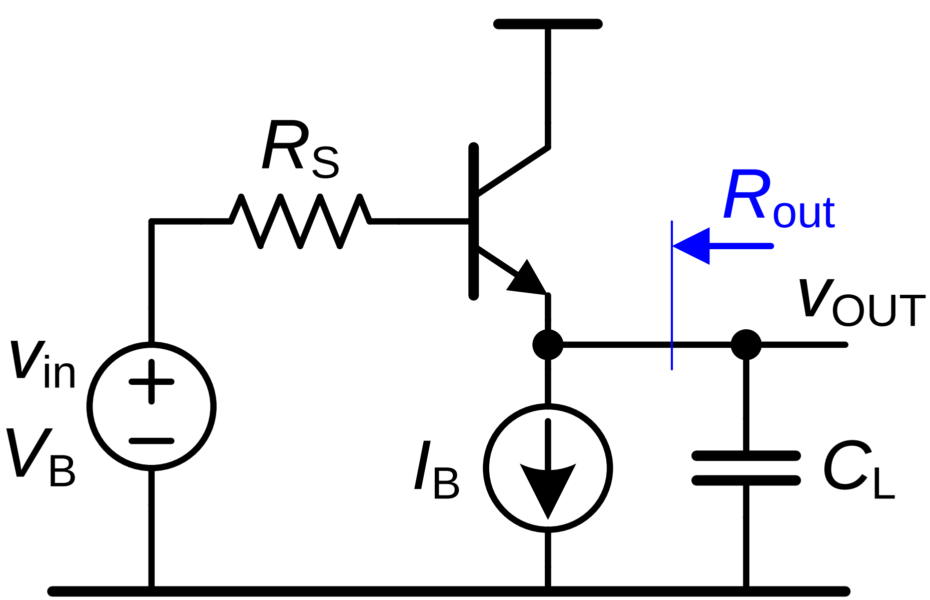
$V_{OUT}=V_{IN}-V_{GS}$ $\Rightarrow$ $\Delta V_{OUT}\neq\Delta V_{IN}$ $\Rightarrow$ $\boxed{A_V=\frac{1}{n}}$

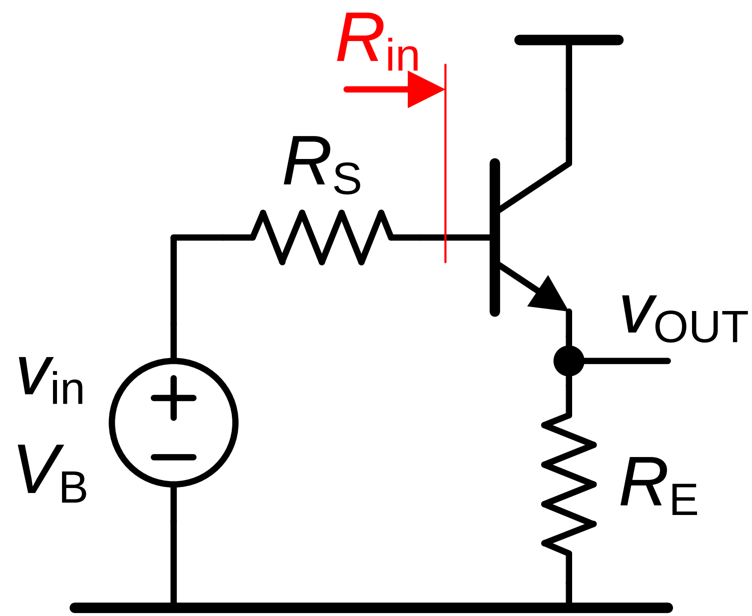
源极跟随器：非线性





射极跟随器



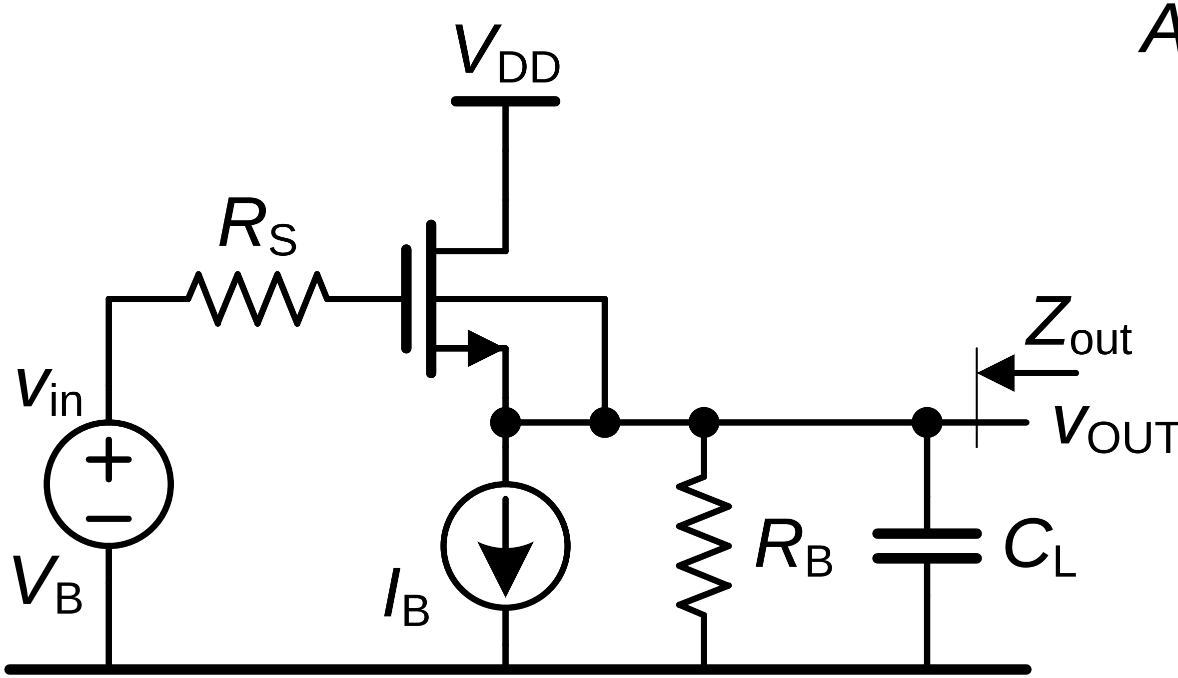


$$A_V = 1 \qquad R_{out} = \frac{1}{g_m} + \frac{R_S + r_B}{\beta+1}$$

$$R_{in} = r_B + r_\pi + (\beta+1)R_E$$

隔离度受限！

接负载电容C_L的源极跟随器



$$A_V = \frac{1 + sC_{gs}/g_m}{1 + as + bs^2}$$

$$a = R_S C_{gd} + \frac{C'_{ds}}{g_m} + \frac{C_{gs}}{g_m}\left(1 + \frac{R_S}{r'_{ds}}\right)$$

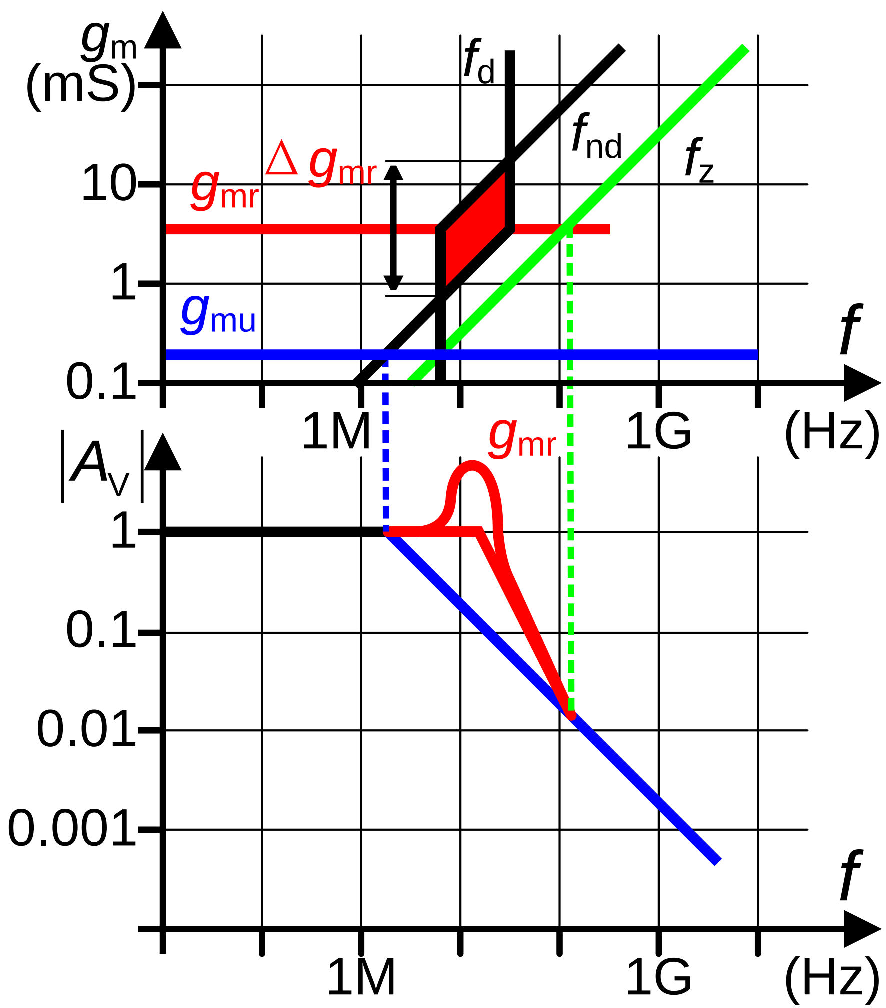
$$b = \frac{R_S C'C'}{g_m}$$

$$r'_{ds} = r_{ds} // R_B$$

$$C'_{sb} = C_L + C_{sb}$$

$$C'C' = C'_{sb} C_{gd} + C'_{sb} C_{gs} + C_{gd} C_{gs}$$

源极跟随器：频响特性随g_m的变化



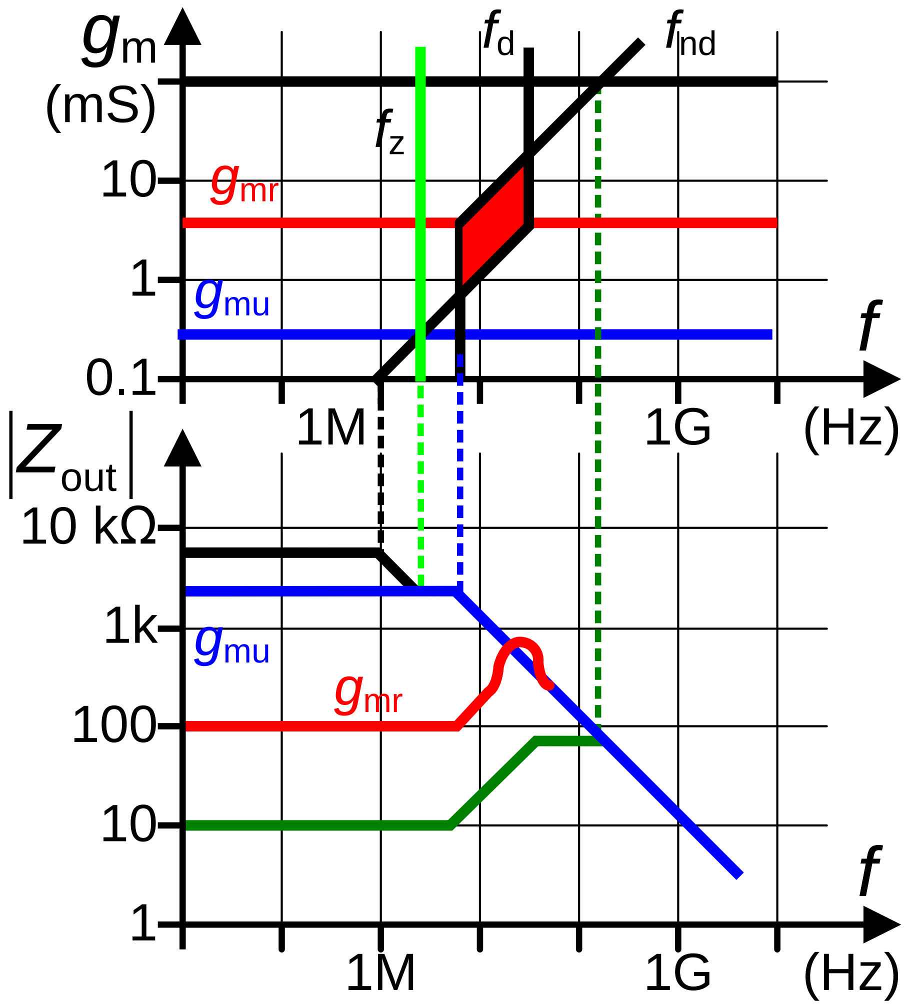
$$g_{mr}=\frac{1}{R_S}\frac{C_L+C_{sb}+C_{gs}}{C_{gd}}$$

$$\Delta g_{mr}=(1+\frac{C_{gdt}}{C_{gd}})^2$$

$$C_{gdt}=\frac{C_{gs}C'_{sb}}{C_{gs}+C'_{sb}}$$

$$g_{mu}\approx\frac{1}{R_S}$$

源极跟随器：输出阻抗随g_m的变化



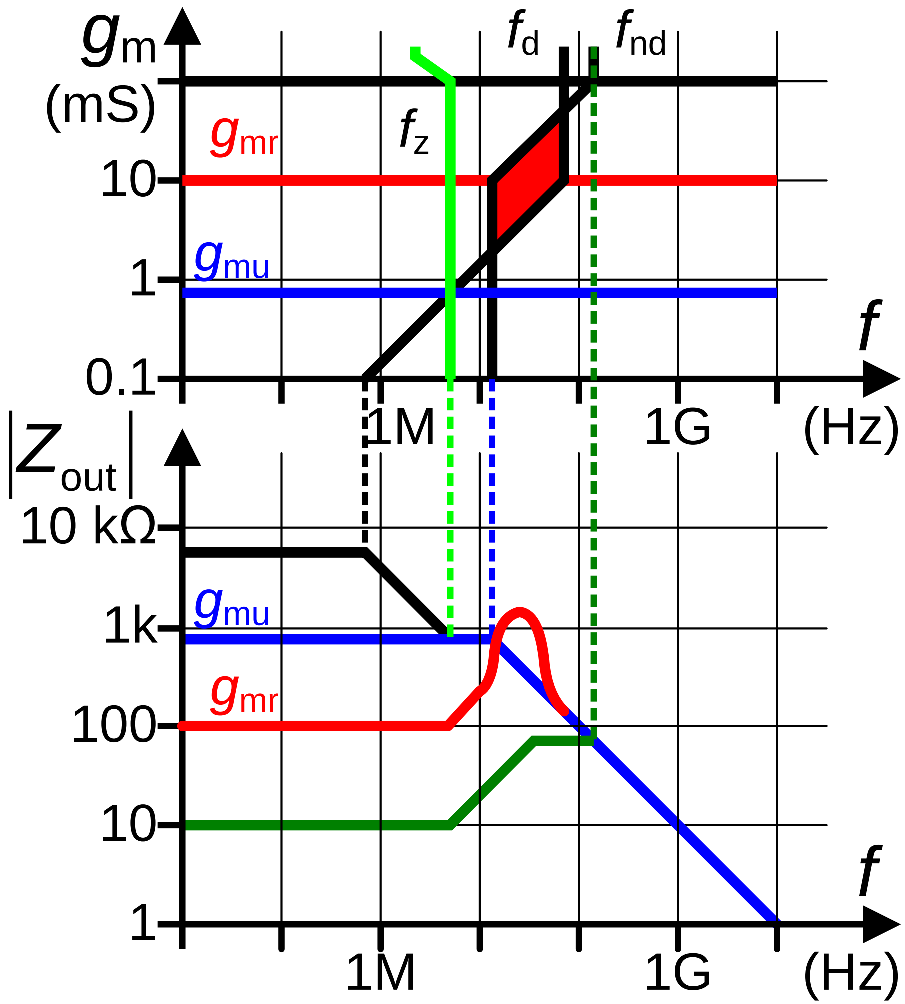
$$g_{mr} = \frac{1}{R_S}\frac{C_{gs} + C'_{sb}}{C_{gd}}$$

$$g_{mu} \approx \frac{1}{R_S}\frac{C_{gs} + C'_{sb}}{C_{gd} + C_{gs}}$$

$$f_z = \frac{1}{2\pi R_S (C_{gd} + C_{gs})}$$

$$f_{d,higm} = \frac{1}{2\pi R_S C_{gd}}$$

射极跟随器：输出阻抗随g_m的变化

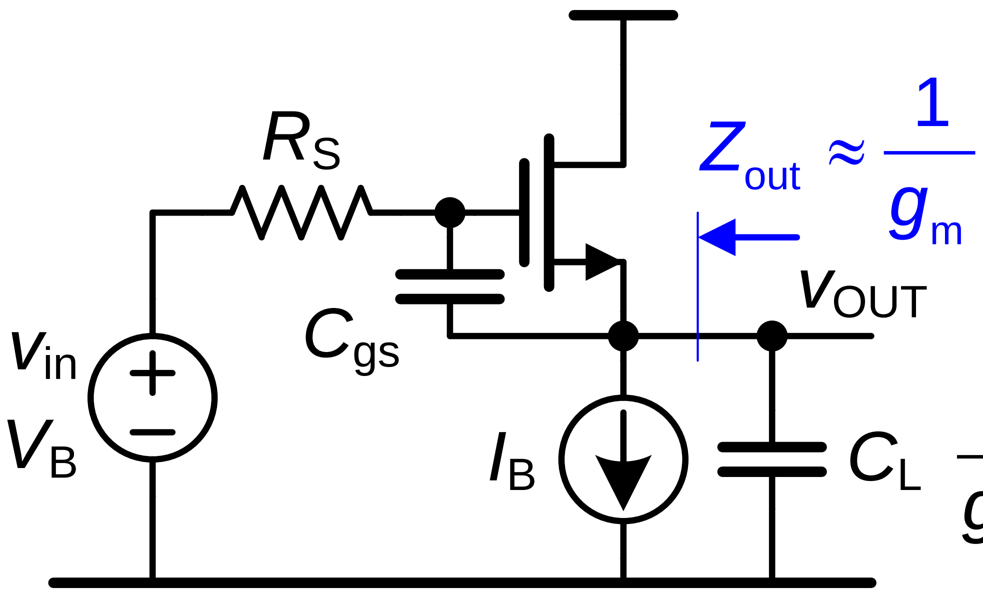


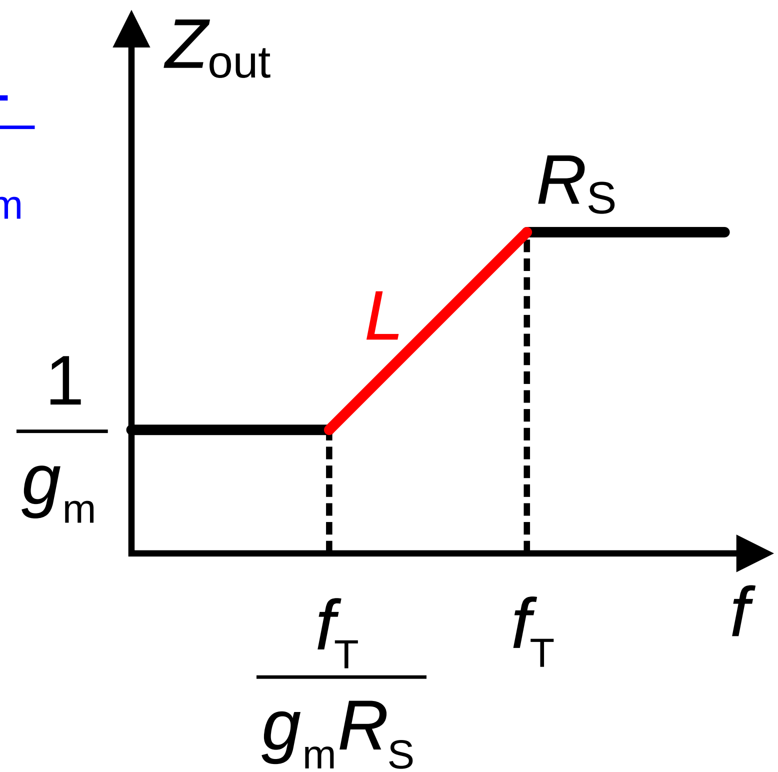
$$g_{mr} = \frac{C_{jE} + C_L}{\tau_F + R'_S C_\mu}$$

$$g_{mu} \approx \frac{1}{R'_S} \frac{C_{jE} + C_L}{C_{jE} + C_\mu}$$

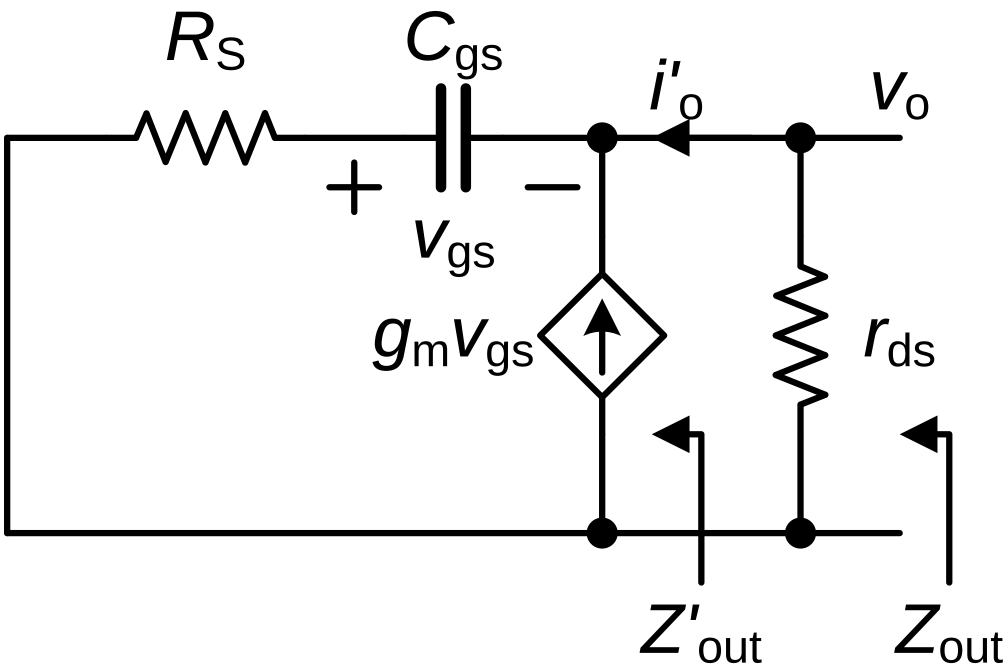
$$f_z = \frac{1}{2\pi (R'_S \parallel r_\pi)(C_\pi + C_\mu)}$$

做为有源电感的源极跟随器 1





$$Z_{out} \approx \frac{1}{g_m}(1 + R_S C_{gs} s) \qquad L \approx \frac{R_S}{2\pi f_T} \qquad f_T = \frac{g_m}{2\pi C_{gs}}$$

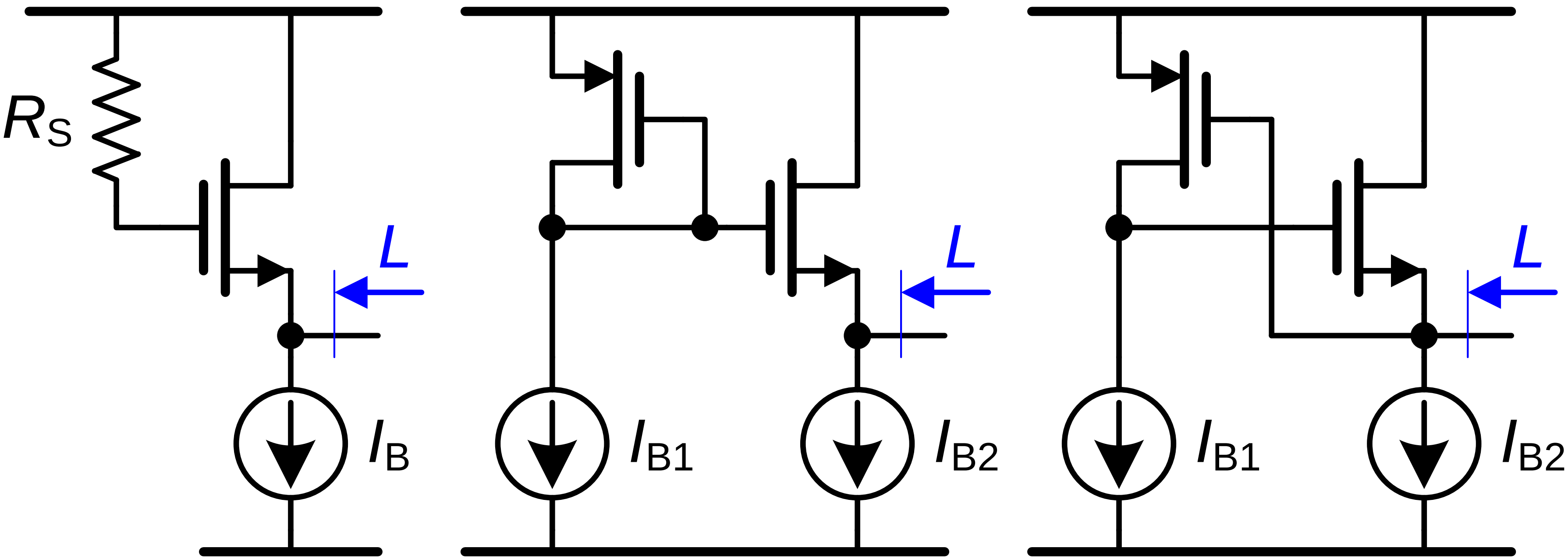


$$i'_o = -g_m\left(-\frac{1/sC_{gs}}{R_S + 1/sC_{gs}} v_o\right) + \frac{v_o}{R_S + 1/sC_{gs}}$$

$$Z'_{out} = \frac{v_o}{i'_o} = \frac{1}{g_m}\frac{1 + sR_S C_{gs}}{1 + s(C_{gs}/g_m)}$$

$$Z_{out} = Z'_{out} \,||\, r_{ds}$$

做为有源电感的源极跟随器 2



$$L \approx \frac{R_S}{2\pi f_T}$$

$$L \approx \frac{1/g_{mp}}{2\pi f_{Tn}}$$

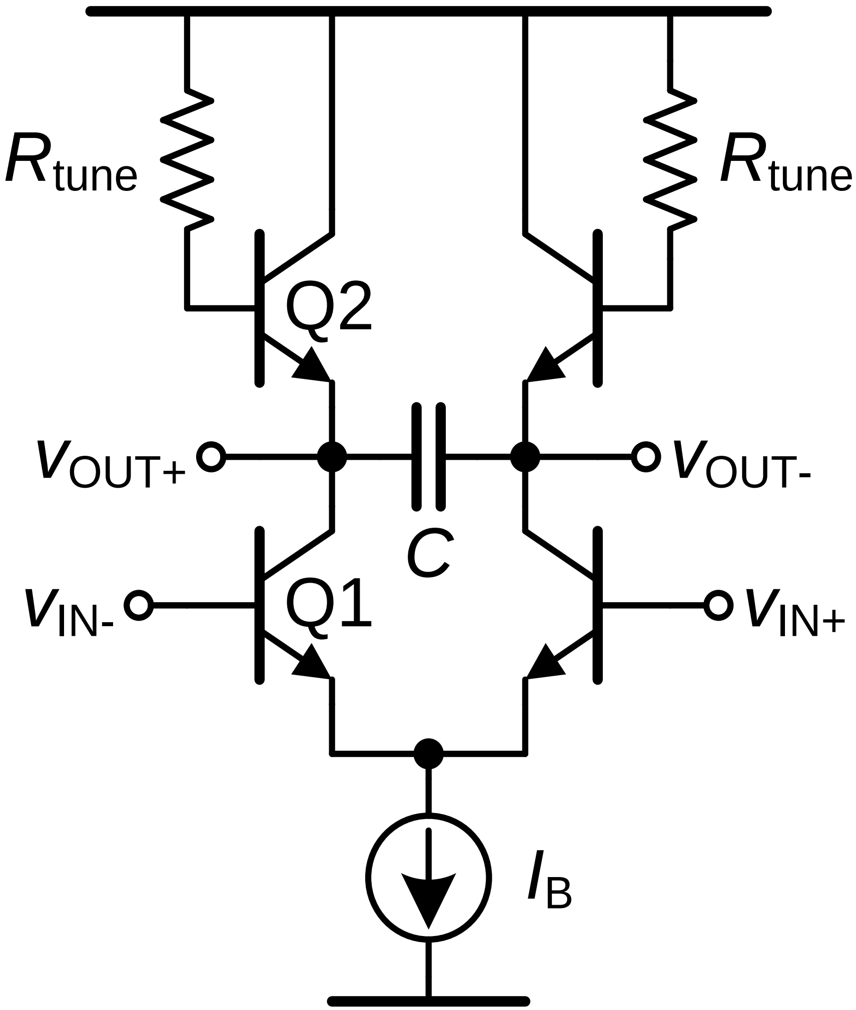
$$L \approx \frac{1/g_{mp}}{2\pi f_{Tn}}$$

$$V_{DSn} = V_{GSn}$$

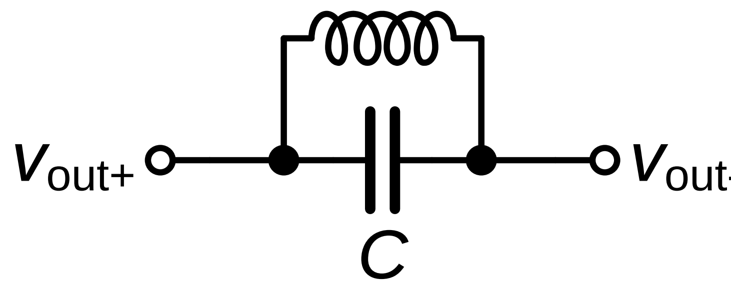
$$V_{DSn} = V_{GSn} + V_{GSp}$$

$$V_{DSn} = V_{GSp}$$

与电容并联的两端悬浮电感



$$L = \frac{R_{tune}}{\omega_{T_2}}$$



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

抬升高频特性！

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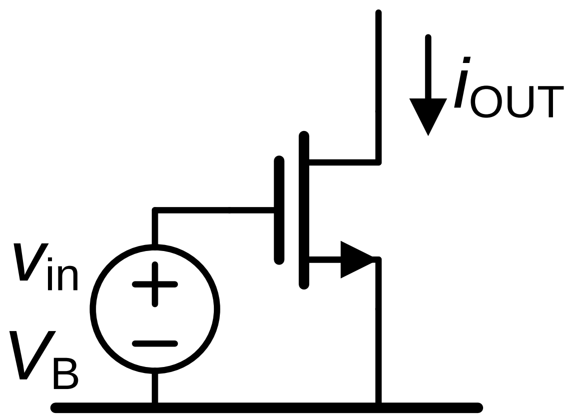
单晶体管级

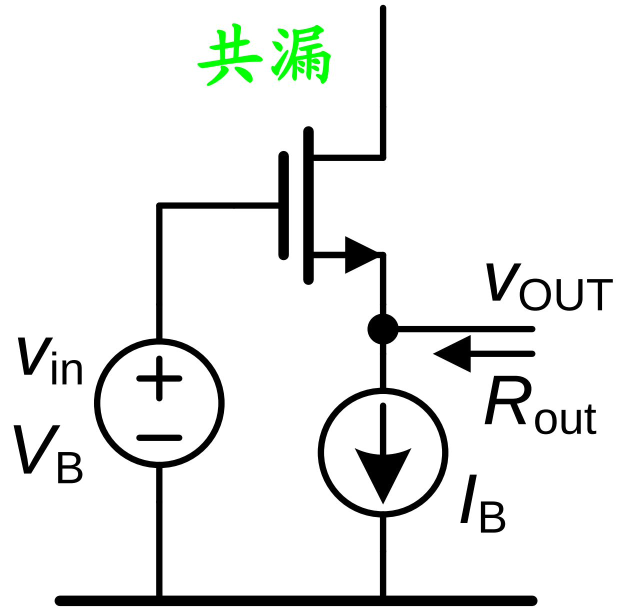
共源



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

共源放大器

共漏



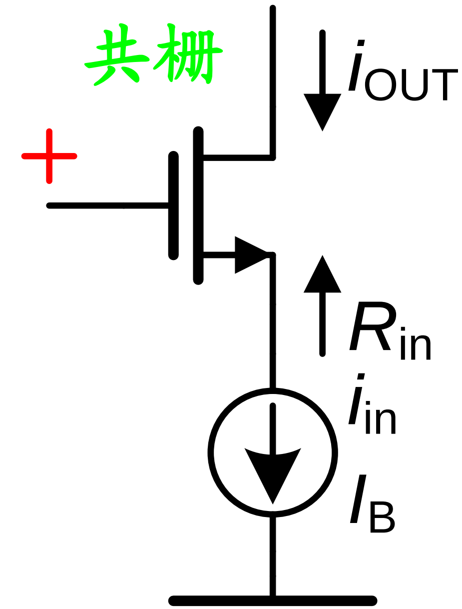
$$v_{out} = v_{in}$$

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

源极跟随器

电压缓冲器

共栅



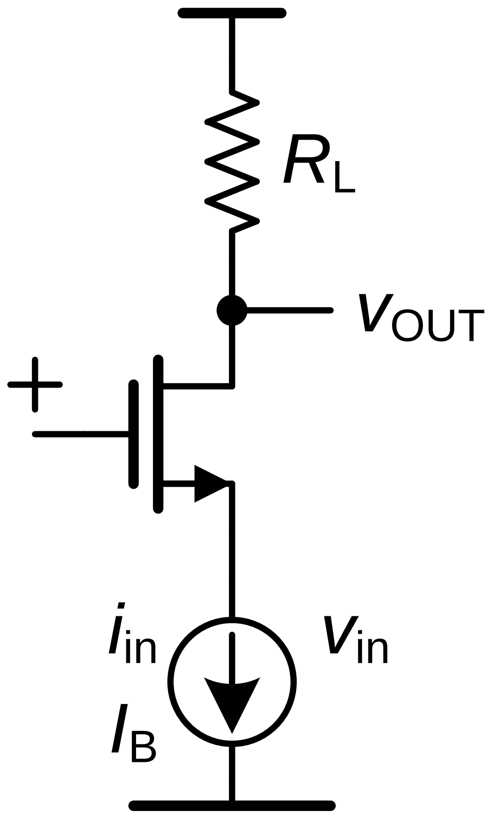
$$i_{out} = i_{in}$$

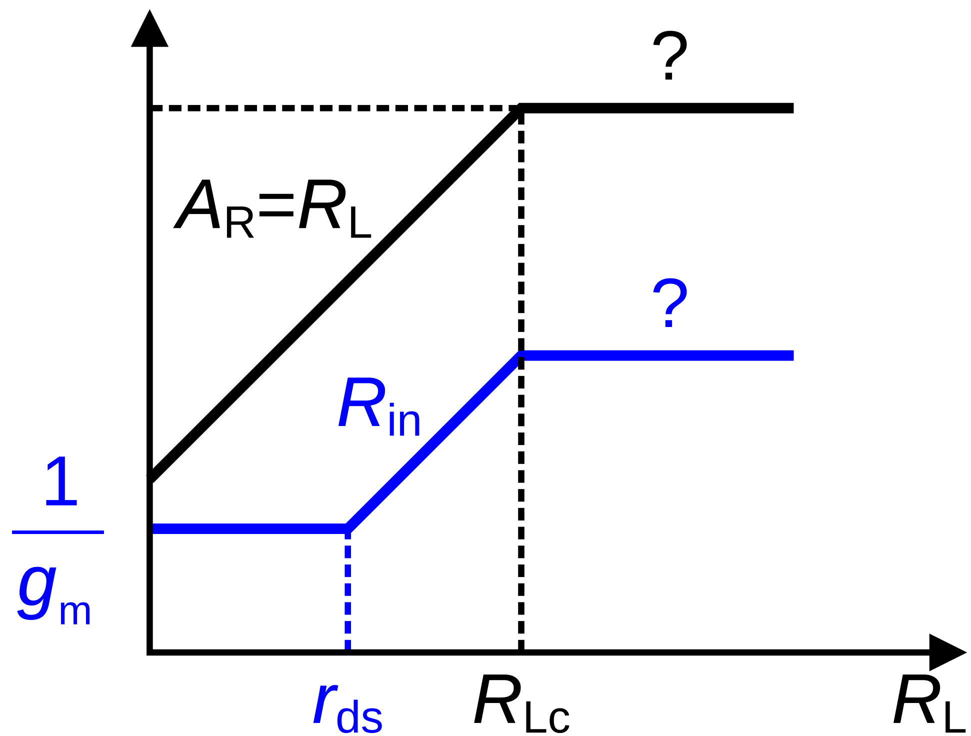
$$R_{in} \approx 1/g_m$$

共栅放大器

电流缓冲器

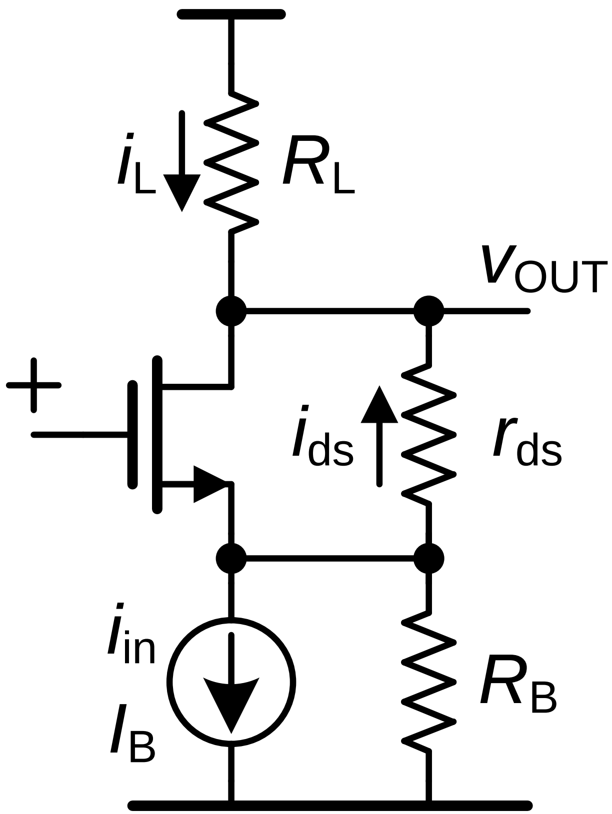
接电阻负载的共栅放大器





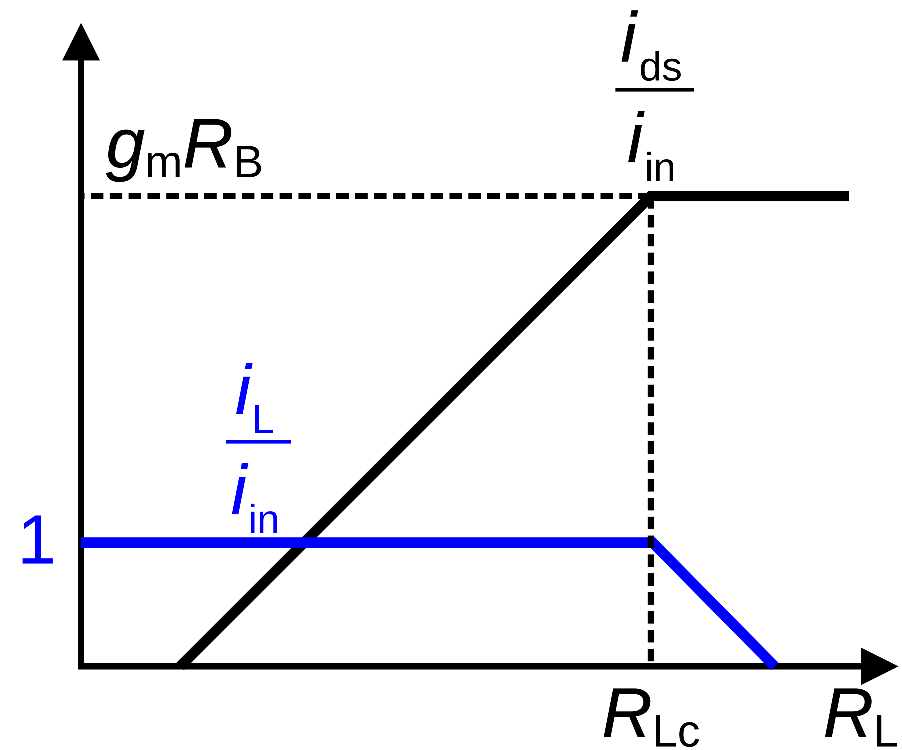
$$A_R = \frac{v_{out}}{i_{in}} \qquad R_{in} = \frac{v_{in}}{-i_{in}}$$

共栅放大器：电流增益

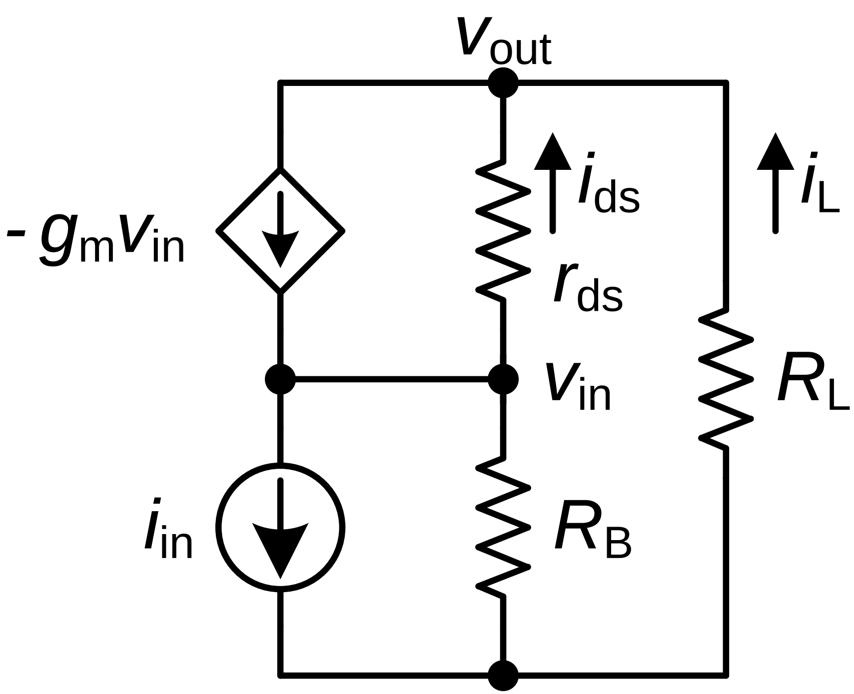


$$\frac{i_{ds}}{i_{in}}=\frac{R_B(g_m R_L-1)}{R_L+r_{ds}+R_B(1+g_m r_{ds})}$$

$$\frac{i_L}{i_{in}}=\frac{R_B(1+g_m r_{ds})}{R_L+r_{ds}+R_B(1+g_m r_{ds})}$$



$$R_{Lc}=g_m r_{ds} R_B$$



$$v_{in} = (i_L - i_{in})R_B \quad (1)$$

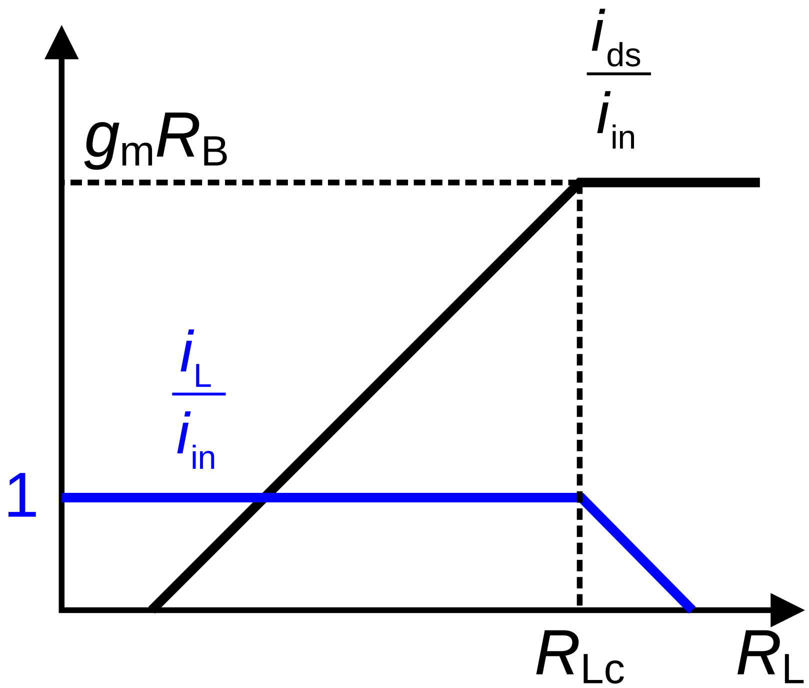
$$v_{out} = -R_L i_L \quad (2)$$

$$v_{out} - v_{in} = -r_{ds} i_{ds} \quad (3)$$

$$-i_{ds} = i_L - (-g_m v_{in}) \quad (4)$$

将(1)代入(4)得i_{ds}，再将i_{ds}、(1)、(2) 代入(3)得:

$$-R_L i_L - (i_L - i_{in})R_B = r_{ds}[i_L - (-g_m (i_L - i_{in})R_B)]$$

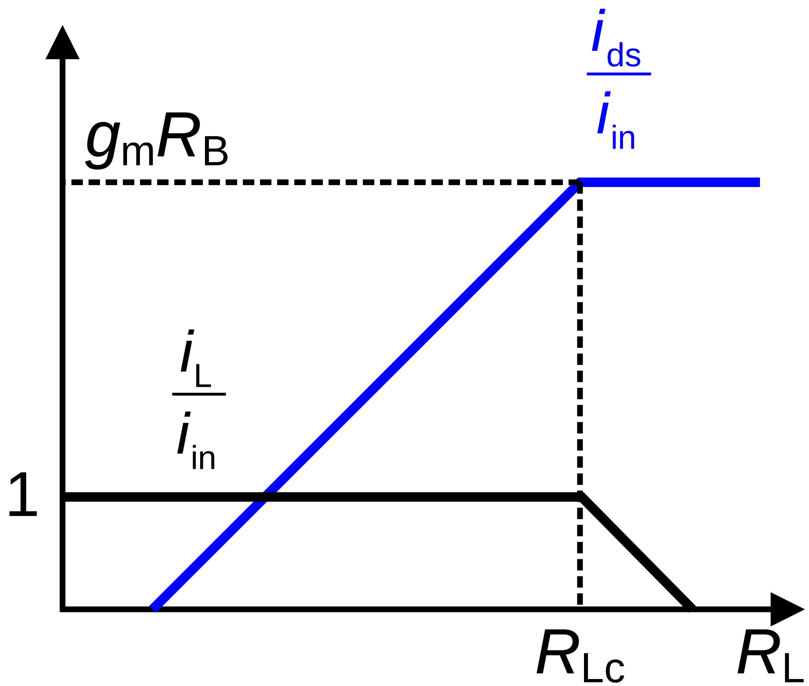


$$\frac{i_L}{i_{in}} = \frac{(1+g_m r_{ds})R_B}{R_L + r_{ds} + (1+g_m r_{ds})R_B}$$

$$R_L \ll g_m r_{ds} R_B \quad \frac{i_L}{i_{in}} = 1$$

$$R_L \gg g_m r_{ds} R_B \quad \frac{i_L}{i_{in}} = \frac{g_m r_{ds} R_B}{R_L}$$

$$-i_{ds} = i_L - (-g_m v_{in}) = i_L + g_m (i_L - i_{in}) R_B$$
$$= (1 + g_m R_B) i_L - g_m R_B i_{in}$$



$$\frac{i_{ds}}{i_{in}} = \frac{R_B (g_m R_L - 1)}{R_L + r_{ds} + (1 + g_m r_{ds}) R_B}$$

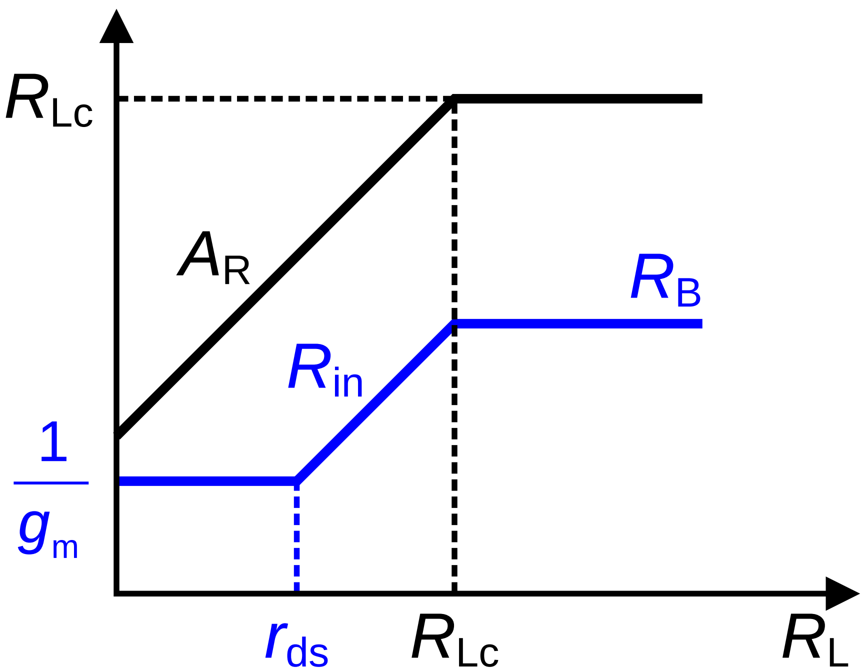
$$R_L \ll g_m r_{ds} R_B \qquad \frac{i_{ds}}{i_{in}} = \frac{R_L}{r_{ds}}$$

$$R_L \gg g_m r_{ds} R_B \qquad \frac{i_{ds}}{i_{in}} = g_m R_B$$

$$v_{in} = (i_L - i_{in})R_B$$

$$Z_{in} = \frac{v_{in}}{-i_{in}} = \frac{(R_L + r_{ds})R_B}{R_L + r_{ds} + (1 + g_m r_{ds})R_B}$$

$$= R_B \| \frac{R_L + r_{ds}}{1 + g_m r_{ds}}$$

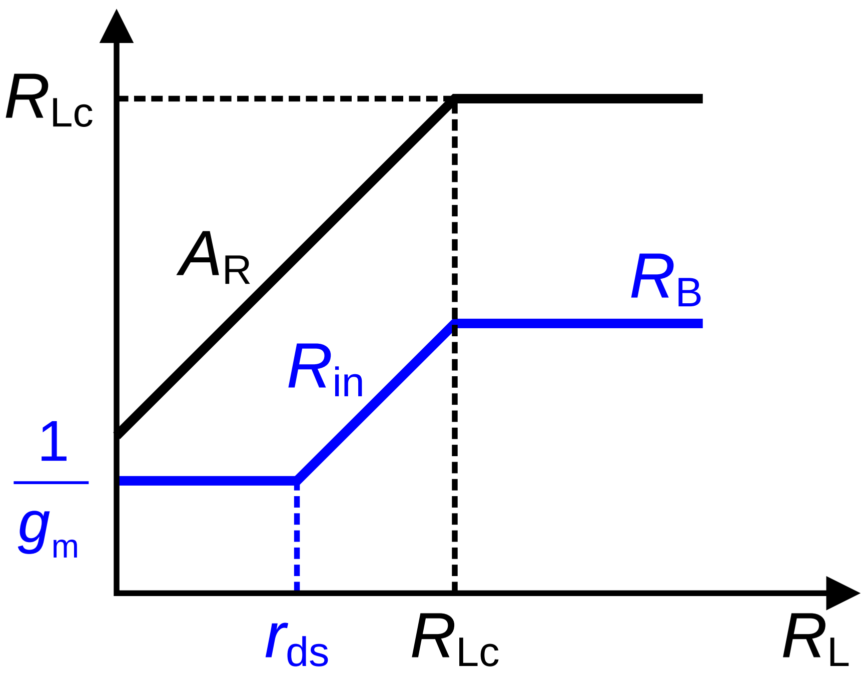


$$R_L \ll r_{ds} \qquad R_{in} = \frac{1}{g_m}$$

$$r_{ds} < R_L < g_m r_{ds} R_B \qquad R_{in} = \frac{R_L}{g_m r_{ds}}$$

$$R_L \gg g_m r_{ds} R_B \qquad R_{in} = R_B$$

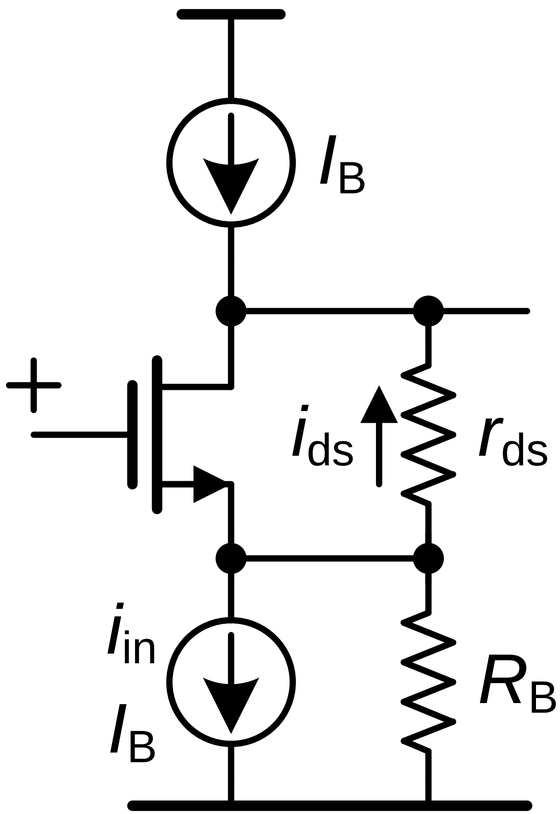
$$A_R = \frac{v_{out}}{i_{in}} = -\frac{R_L i_L}{i_{in}} = -R_L \frac{(1+g_m r_{ds})R_B}{R_L + r_{ds} + (1+g_m r_{ds})R_B}$$

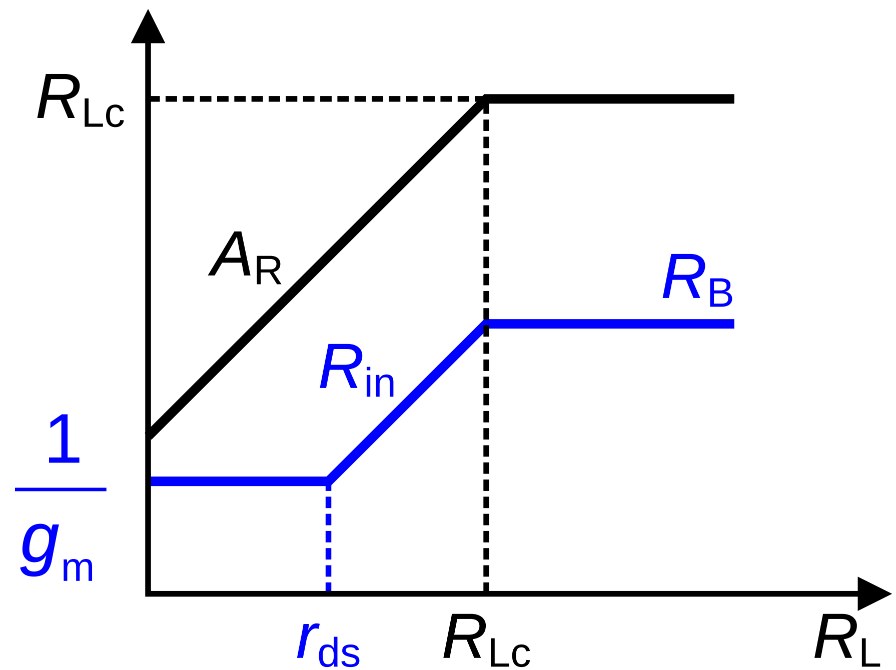


$$R_L \ll g_m r_{ds} R_B \quad |A_R| = R_L$$

$$R_L \gg g_m r_{ds} R_B \quad |A_R| = g_m r_{ds} R_B = R_{Lc}$$

共栅放大器：跨阻增益与输入阻抗

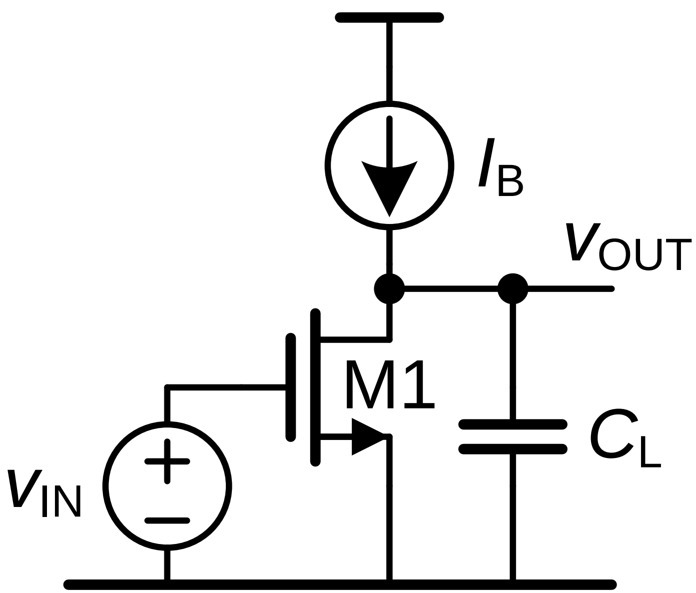




$$A_R = \frac{v_{out}}{i_{in}} \qquad R_{in} = \frac{v_{in}}{-i_{in}}$$

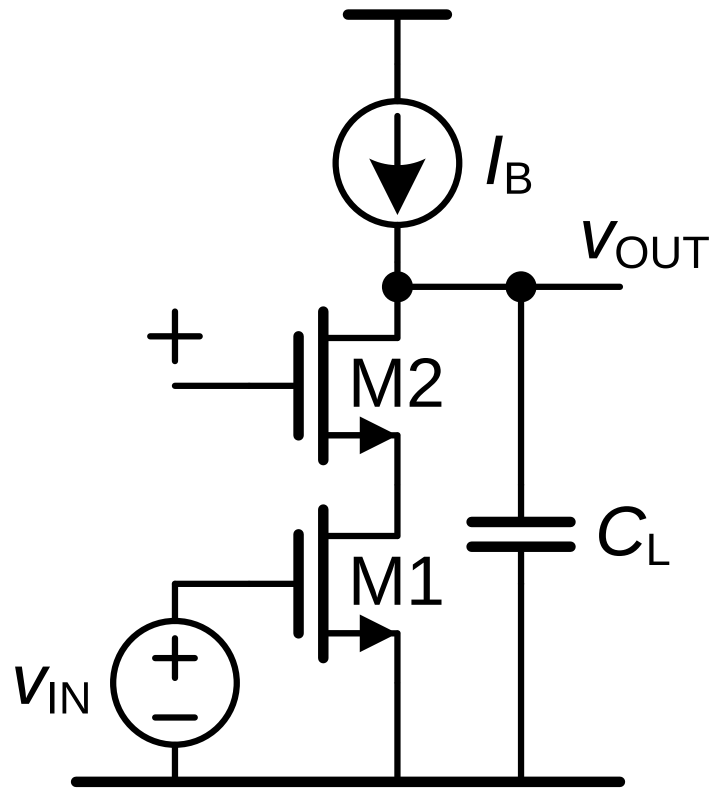
$$\boxed{R_{Lc} = g_m r_{ds} R_B} \approx 100 R_B$$

共源共栅与单管共源放大器 1



$$A_V = (g_m r_{ds})_1$$

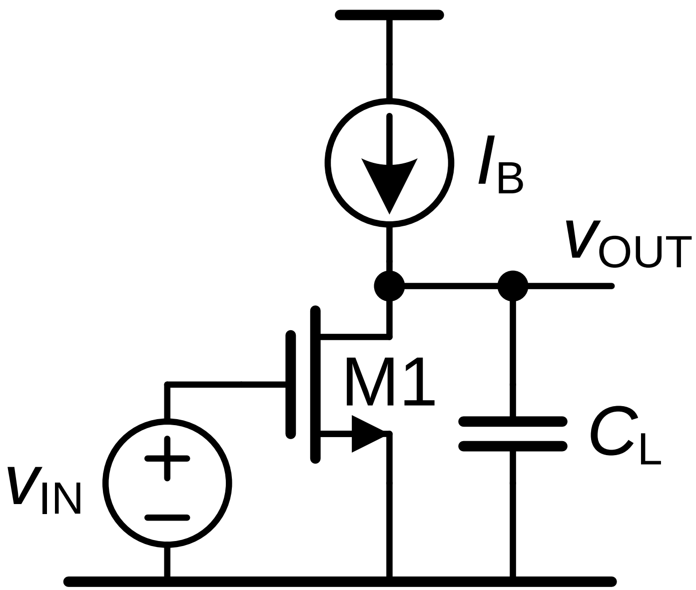
$$R_{out} = r_{ds1}$$

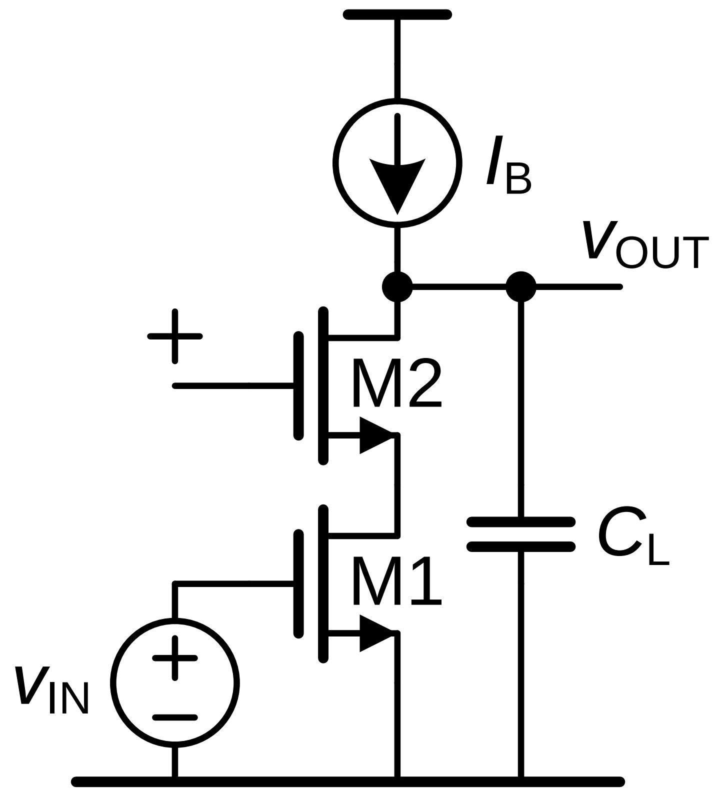


$$A_V = (g_m r_{ds})_1 (g_m r_{ds})_2$$

$$R_{out} = r_{ds1} (g_m r_{ds})_2$$

共源共栅与单管共源放大器 2

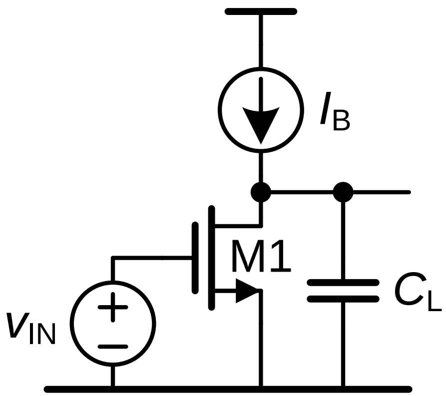


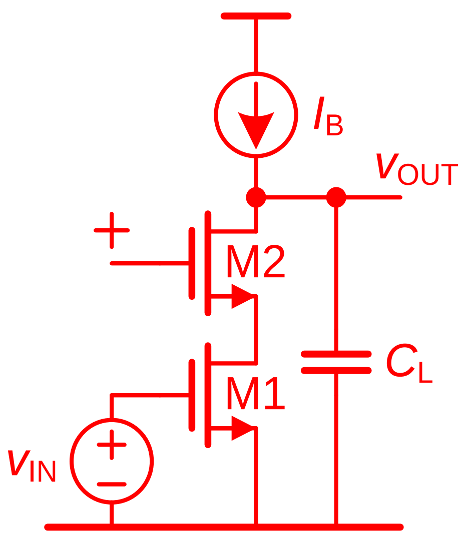


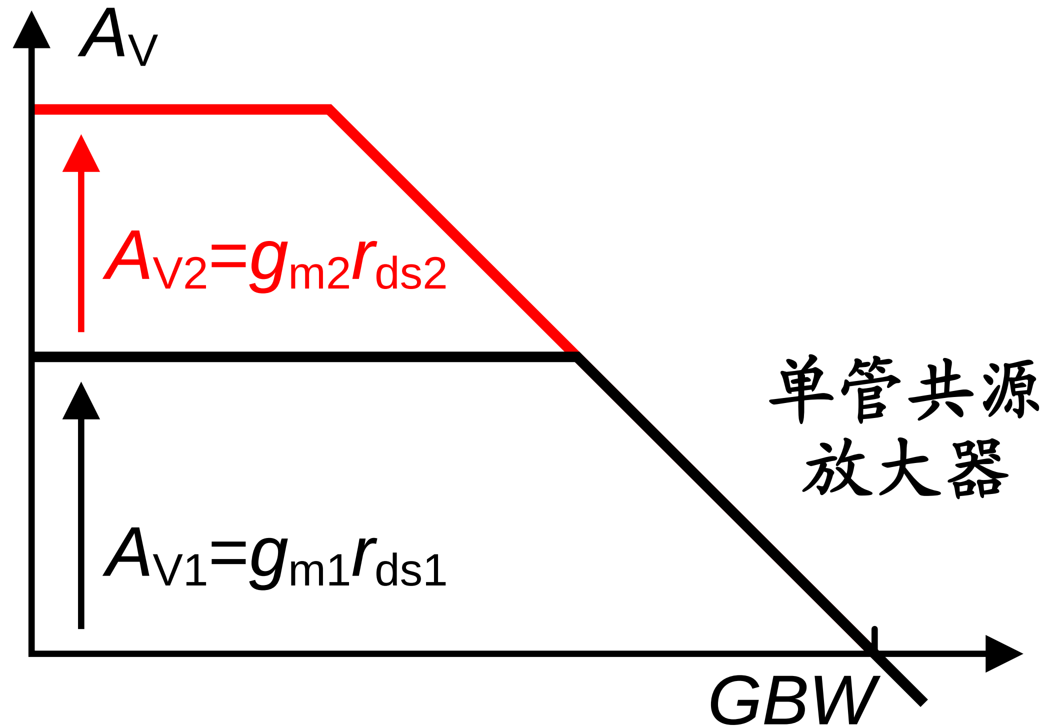
$$BW = \frac{1}{2\pi R_{out} C_L} \qquad GBW = \frac{g_{m1}}{2\pi C_L}$$

适用于两种结构！

共源共栅与单管共源放大器 3







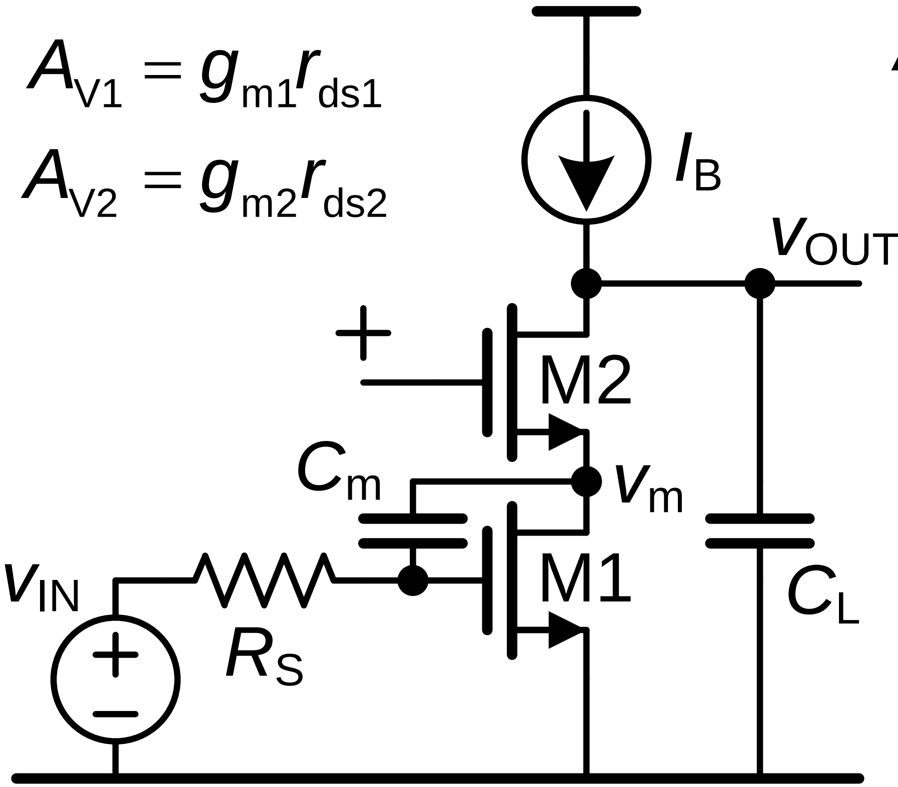
共源共栅:
低频时具有高增益

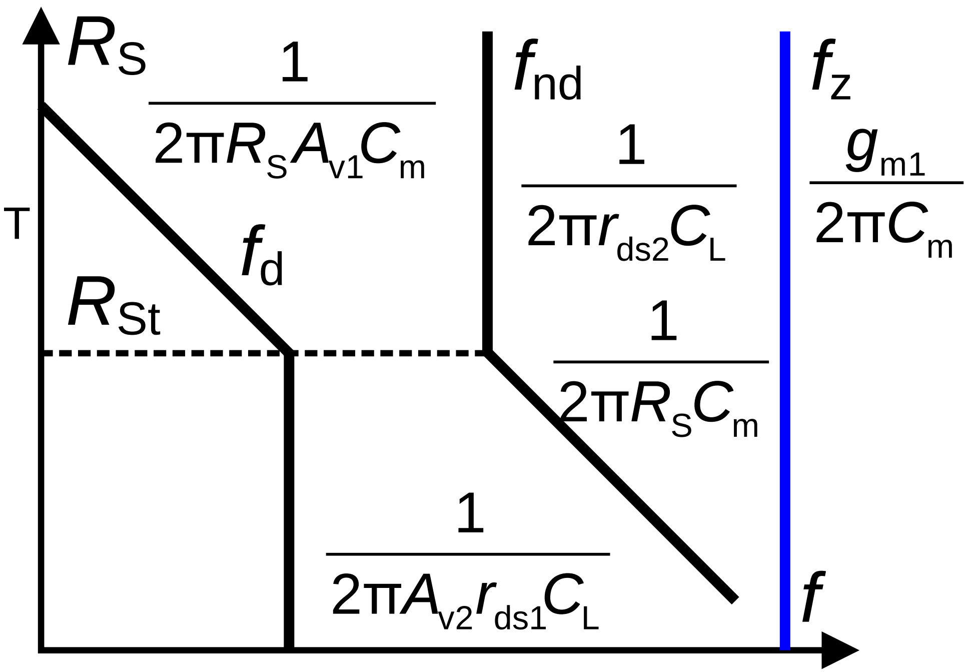
$$GBW = \frac{g_{m1}}{2\pi C_L}$$

共源共栅的密勒效应？

$$A_{V1} = g_{m1} r_{ds1}$$

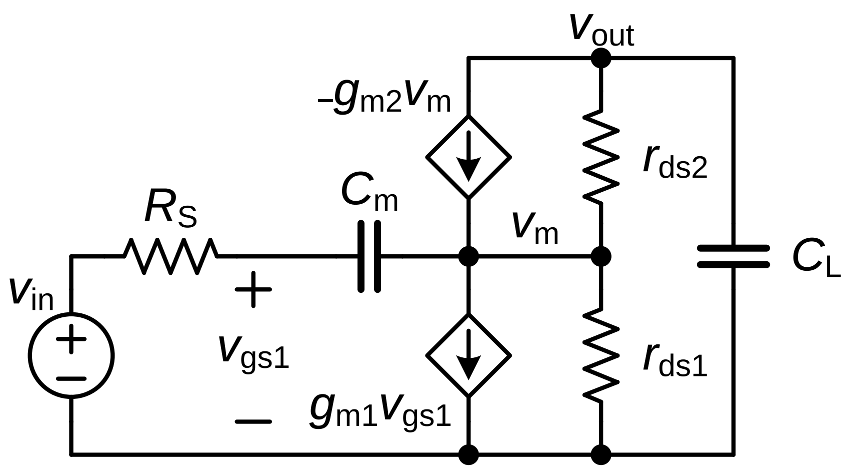
$$A_{V2} = g_{m2} r_{ds2}$$





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

如果$R_S < R_{St} = r_{ds2} \frac{C_L}{C_m} \frac{g_{m2}}{g_{m1}}$，没有密勒效应！



$$\frac{v_{out}-v_m}{r_{ds2}}+(-g_{m2}v_m)=-\frac{v_{out}}{1/sC_L} \quad \textbf{(1)}$$

$$\frac{v_m-v_{in}}{R_S+1/sC_m}+g_{m1}\left(\frac{v_m-v_{in}}{R_S+1/sC_m}R_S+v_{in}\right)+\frac{v_m}{r_{ds1}}=-\frac{v_{out}}{1/sC_L} \quad \textbf{(2)}$$

$$(g_{m2}+\frac{1}{r_{ds2}})v_m=\frac{v_{out}}{1/sC_L}+\frac{v_{out}}{r_{ds2}} \qquad v_m=\frac{1+sr_{ds2}C_L}{1+g_{m2}r_{ds2}}v_{out}$$

将(1) 求v_m代入(2)得:

$$\frac{g_{m1}/sC_m-1}{R_S+1/sC_m}v_{in}=-\frac{(g_{m1}R_S+1)v_m}{R_S+1/sC_m}-\frac{v_m}{r_{ds1}}-\frac{v_{out}}{1/sC_L}$$

$$A_V=\frac{v_{out}}{v_{in}}=-g_{m1}r_{ds1}(1+g_{m2}r_{ds2})\frac{(1-sC_m/g_{m1})}{1+as+bs^2}$$

$$a=[r_{ds1}+(1+g_{m1}r_{ds1})R_S]C_m+[r_{ds2}+(1+g_{m2}r_{ds2})r_{ds1}]C_L$$

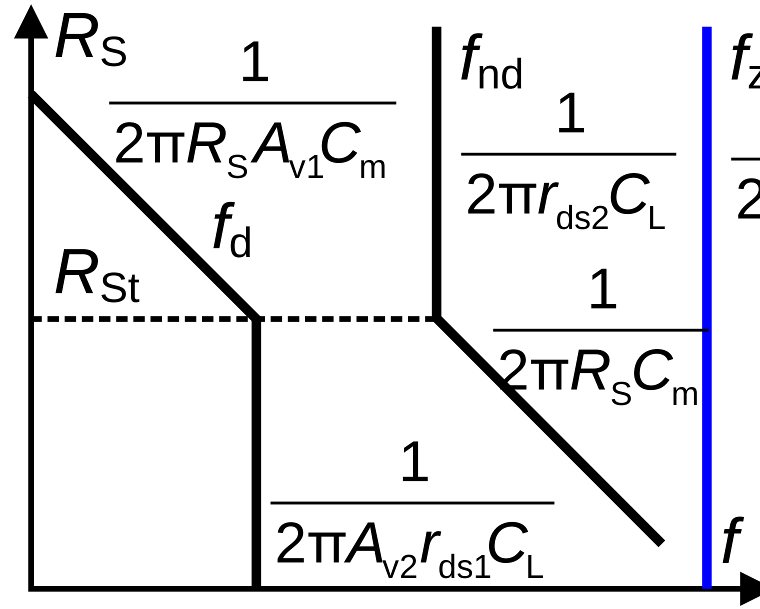
$$b=\{r_{ds1}r_{ds2}+R_S[(1+g_{m1}r_{ds1})r_{ds2}+(1+g_{m2}r_{ds2})r_{ds1}]\}C_mC_L$$

零极点与R_S的关系

$$A_{V2}r_{ds1}C_L = A_{V1}R_{St}C_m$$

$$\Rightarrow R_{St} = r_{ds2}\frac{C_L}{C_m}\frac{g_{m2}}{g_{m1}}$$

$$f_z = \frac{g_{m1}}{2\pi C_m}$$



当R_S较小时 $f_d = -\frac{1}{2\pi A_{v2} r_{ds1} C_L}$ $f_{nd} = -\frac{1}{2\pi R_S C_m}$

当R_S较大时 $f_d = -\frac{1}{2\pi R_S A_{v1} C_m}$ $f_{nd} = -\frac{1}{2\pi r_{ds2} C_L}$

$A_{V1} = g_{m1} r_{ds1}$

$A_{V2} = g_{m2} r_{ds2}$

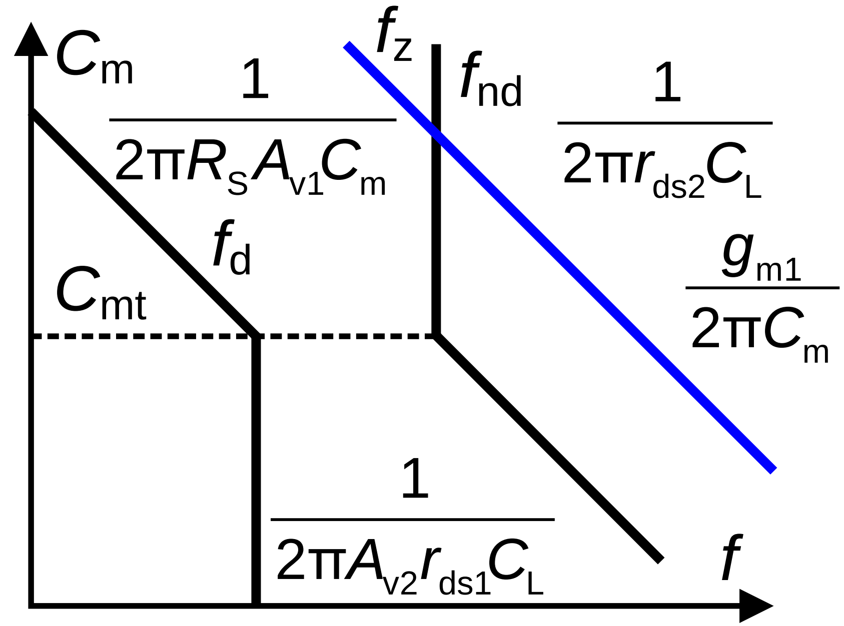
密勒效应

零极点与C_m的关系

$$A_{V2} r_{ds1} C_L = A_{V1} R_S C_{mt}$$

$$\Rightarrow \quad C_{mt} = C_L \frac{r_{ds2}}{R_S} \frac{g_{m2}}{g_{m1}}$$

$$f_z = \frac{g_{m1}}{2\pi C_m}$$



$$\frac{1}{2\pi R_S C_m}$$

当C_m较小时 $f_d = -\frac{1}{2\pi A_{v2} r_{ds1} C_L}$ $\quad f_{nd} = -\frac{1}{2\pi R_S C_m}$

当C_m较大时 $f_d = -\frac{1}{2\pi R_S A_{v1} C_m}$ $\quad f_{nd} = -\frac{1}{2\pi r_{ds2} C_L}$

$A_{V1} = g_{m1} r_{ds1}$

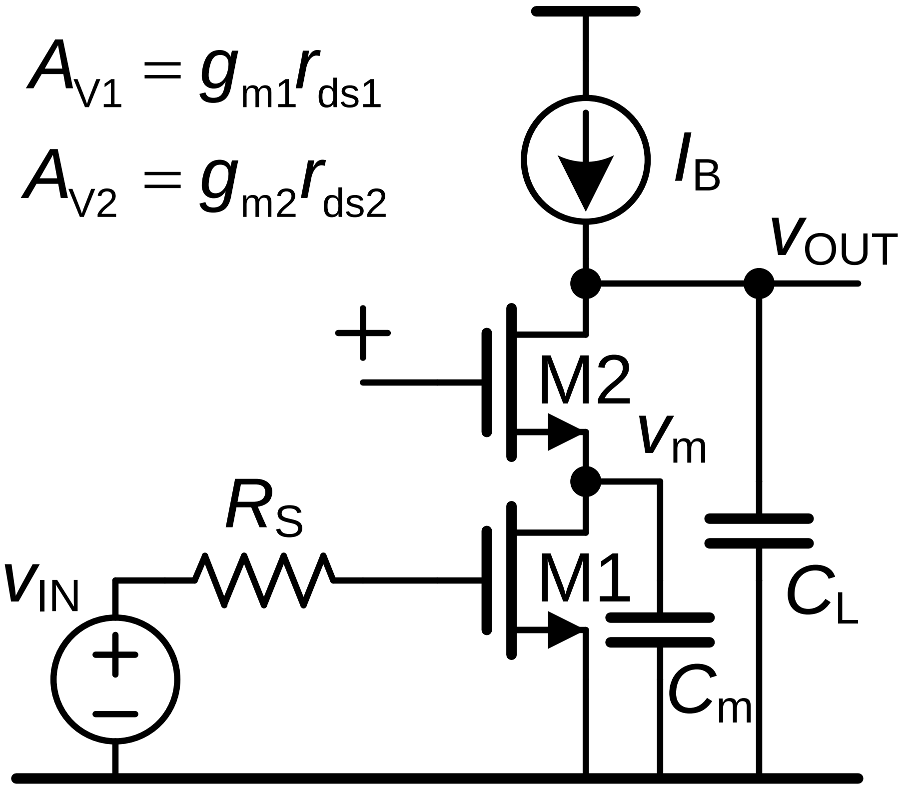
$A_{V2} = g_{m2} r_{ds2}$

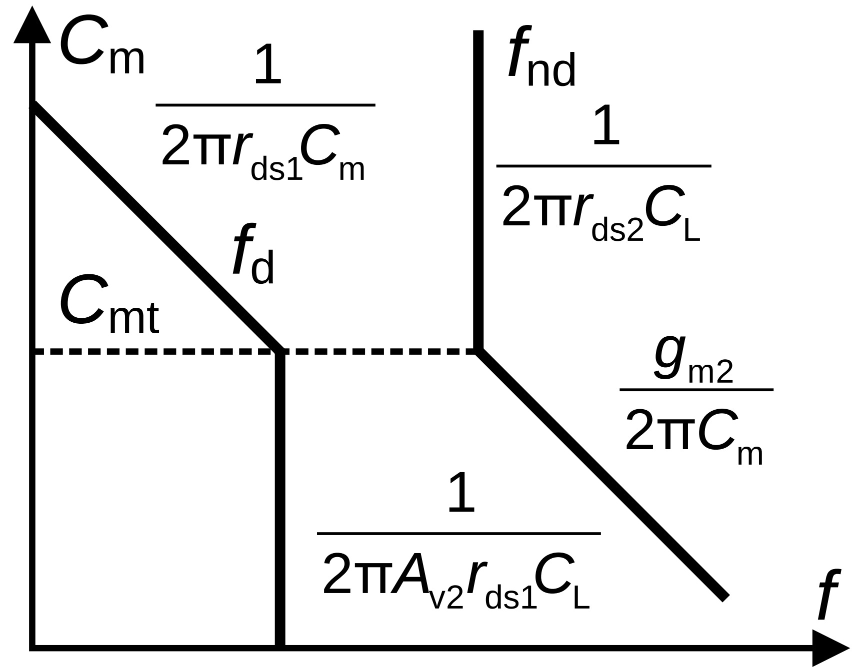
密勒效应

具有中间节点电容C_m的共源共栅

$$A_{V1} = g_{m1} r_{ds1}$$

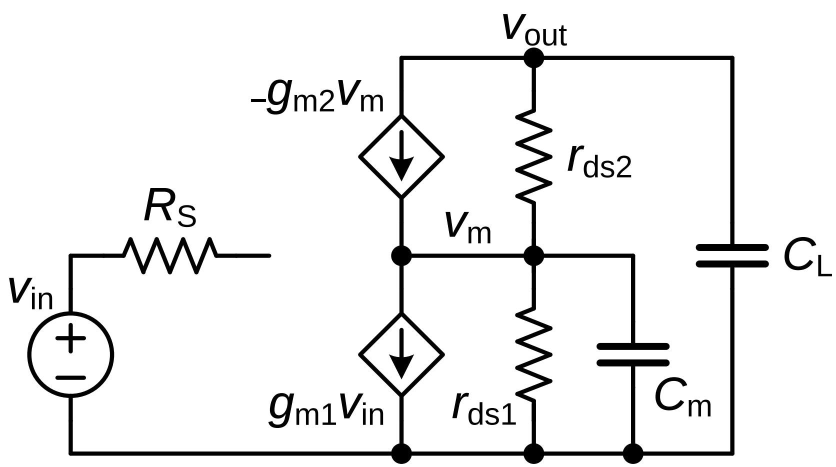
$$A_{V2} = g_{m2} r_{ds2}$$





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

$$C_{mt} = g_{m2} r_{ds2} C_L = A_{V2} C_L$$



$$\frac{v_{out}-v_m}{r_{ds2}}+(-g_{m2}v_m)=-\frac{v_{out}}{1/sC_L} \qquad \textbf{(1)}$$

$$g_{m1}v_{in}+\frac{v_m}{r_{ds1}}+\frac{v_m}{1/sC_m}=-\frac{v_{out}}{1/sC_L} \qquad \textbf{(2)}$$

$$(g_{m2}+\frac{1}{r_{ds2}})v_m=\frac{v_{out}}{1/sC_L}+\frac{v_{out}}{r_{ds2}} \qquad v_m=\frac{1+sr_{ds2}C_L}{1+g_{m2}r_{ds2}}v_{out}$$

由(1) 求v_m， 代入(2)得:

$$g_{m1}v_{in}=-\frac{v_m}{1/sC_m}-\frac{v_m}{r_{ds1}}-\frac{v_{out}}{1/sC_L}$$

$$A_V=-g_{m1}r_{ds1}(1+g_{m2}r_{ds2})\frac{1}{1+as+bs^2}$$

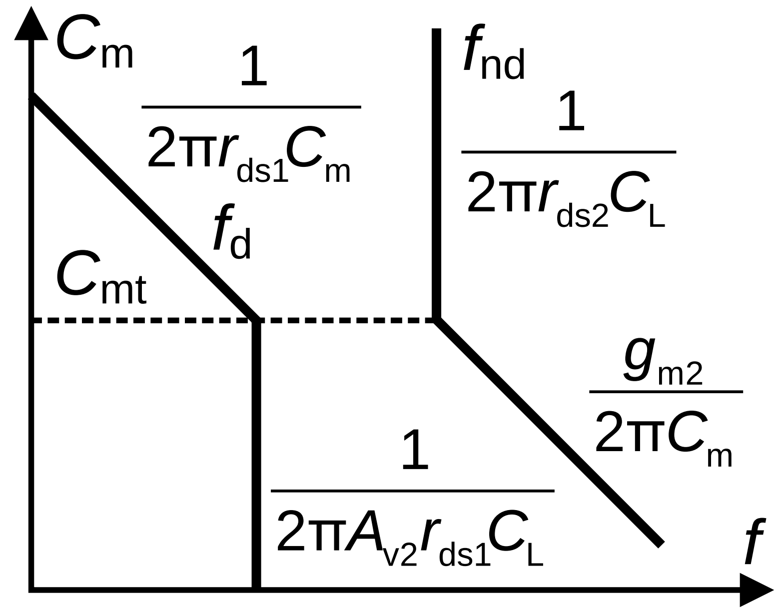
$$a=r_{ds1}C_m+[r_{ds2}+(1+g_{m2}r_{ds2})r_{ds1}]C_L$$

$$b=r_{ds1}r_{ds2}C_mC_L$$

极点与C_m的关系

$$r_{ds1}C_{mt} = A_{V2}r_{ds1}C_L$$

$$\Rightarrow C_{mt} = A_{V2}C_L$$

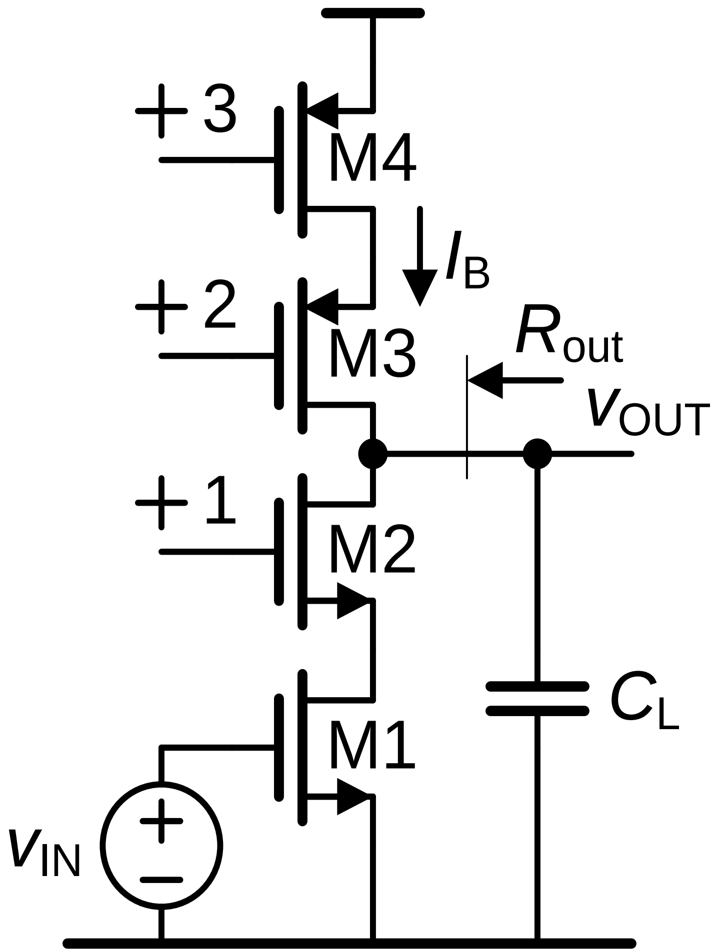


当C_m较小时 $f_d = -\frac{1}{2\pi A_{V2}r_{ds1}C_L}$ $f_{nd} = -\frac{g_{m2}}{2\pi C_m}$

当C_m较大时 $f_d = -\frac{1}{2\pi r_{ds1}C_m}$ $f_{nd} = -\frac{1}{2\pi r_{ds2}C_L}$

$$A_{V1} = g_{m1}r_{ds1}$$
$$A_{V2} = g_{m2}r_{ds2}$$

套筒式共源共栅



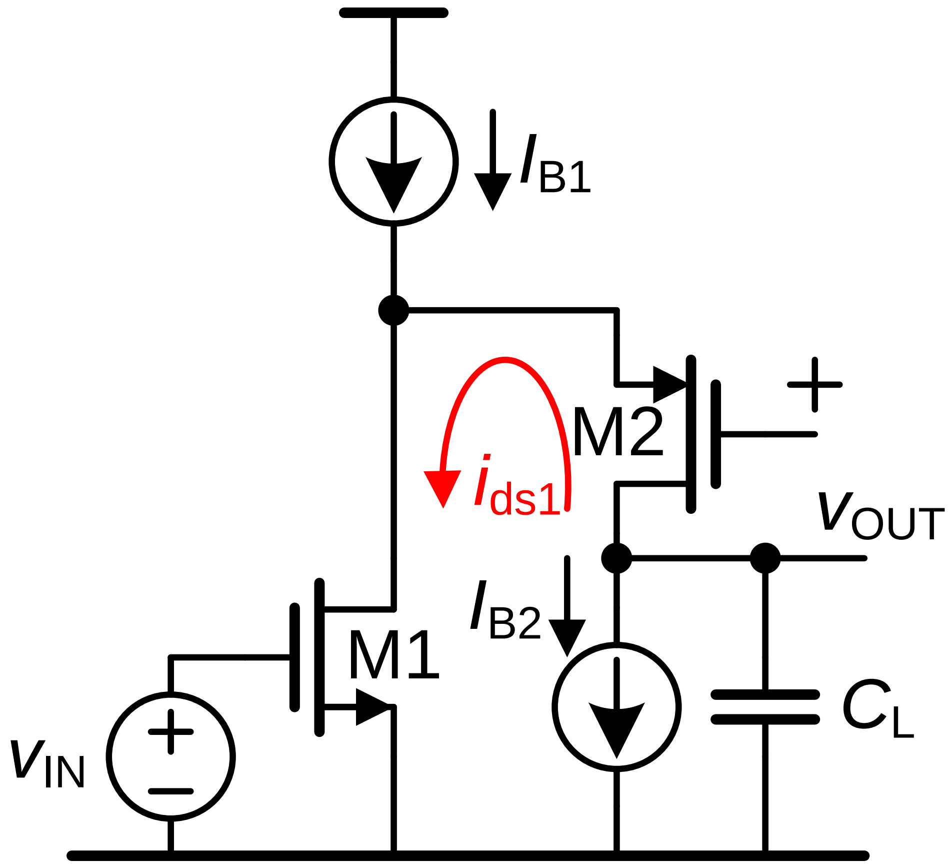
$$A_V = g_{m1} R_{out}$$

$$R_{out} = \frac{1}{2} r_{ds1} g_{m2} r_{ds2}$$

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

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

折叠共源共栅



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

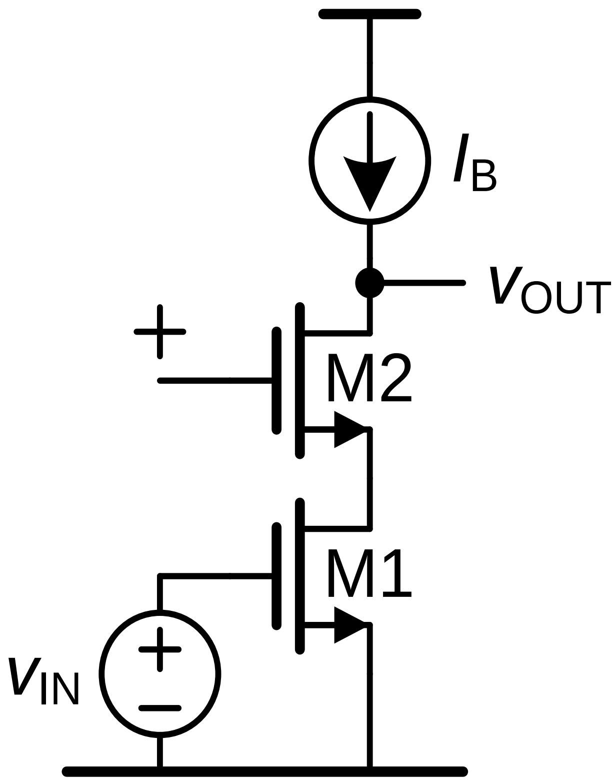
$$A_V = g_{m1} R_{out}$$

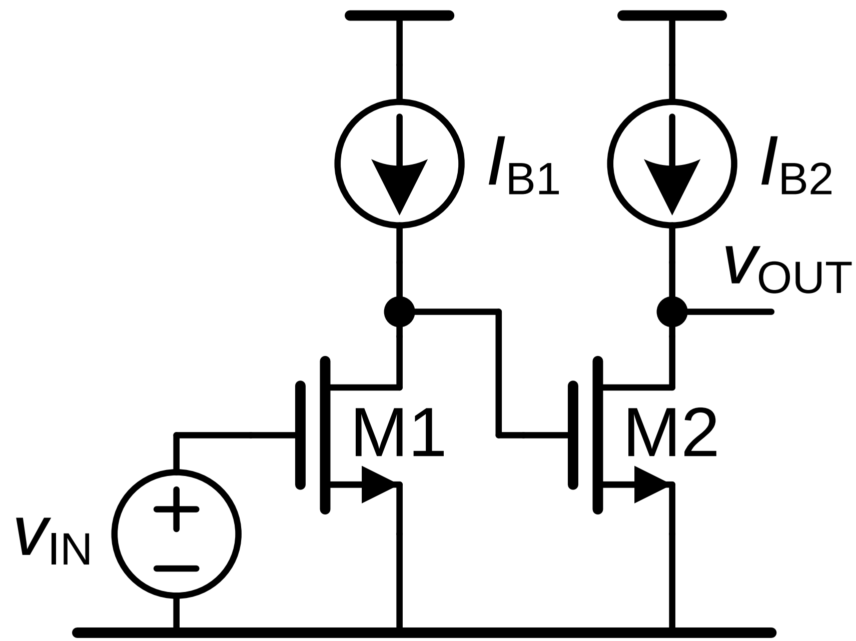
$$R_{out} = r_{ds1} g_{m2} r_{ds2}$$

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

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

共源共栅与级联

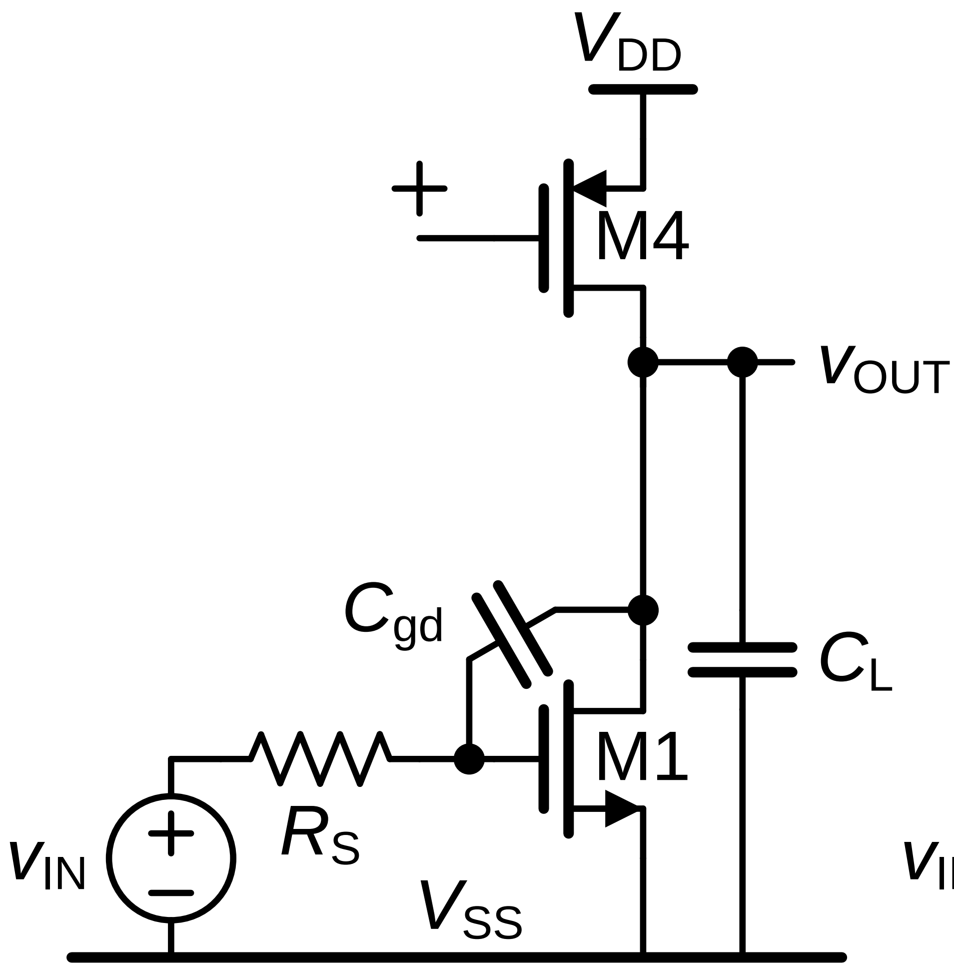




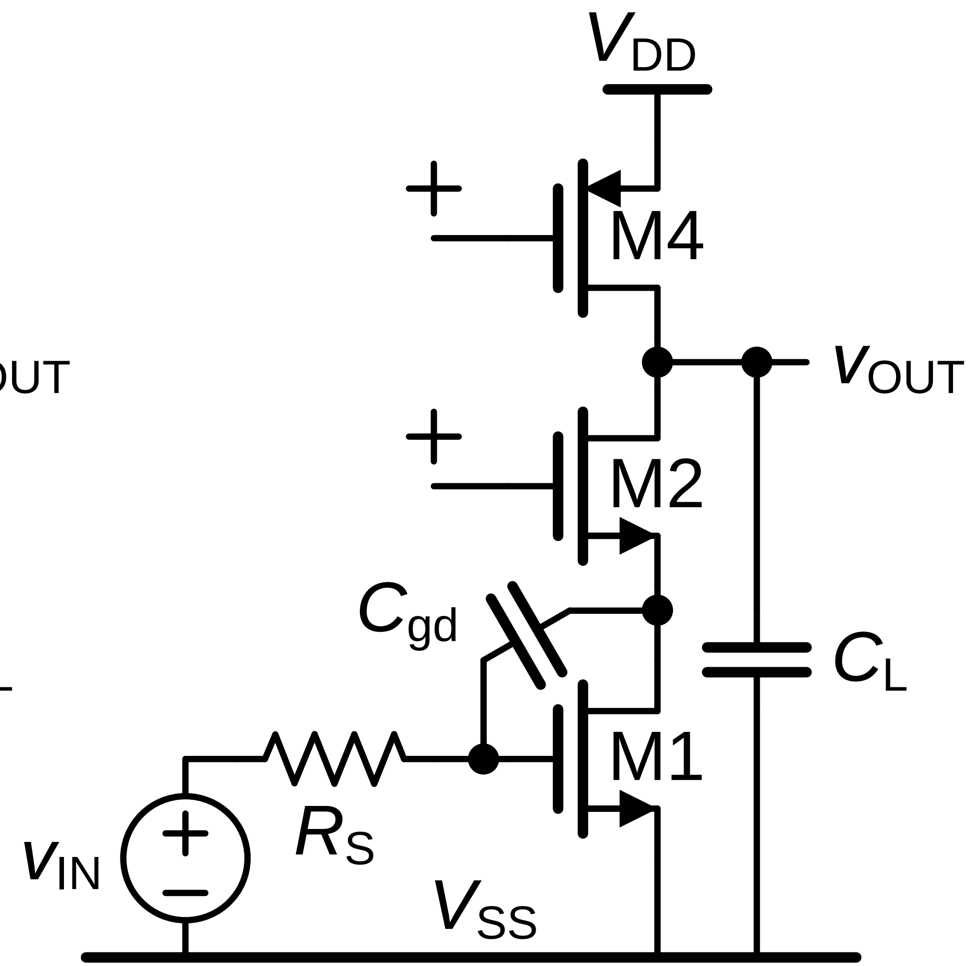
$$A_V = (g_m r_{ds})_1 (g_m r_{ds})_2$$

$$A_V = (g_m r_{ds})_1 (g_m r_{ds})_2$$

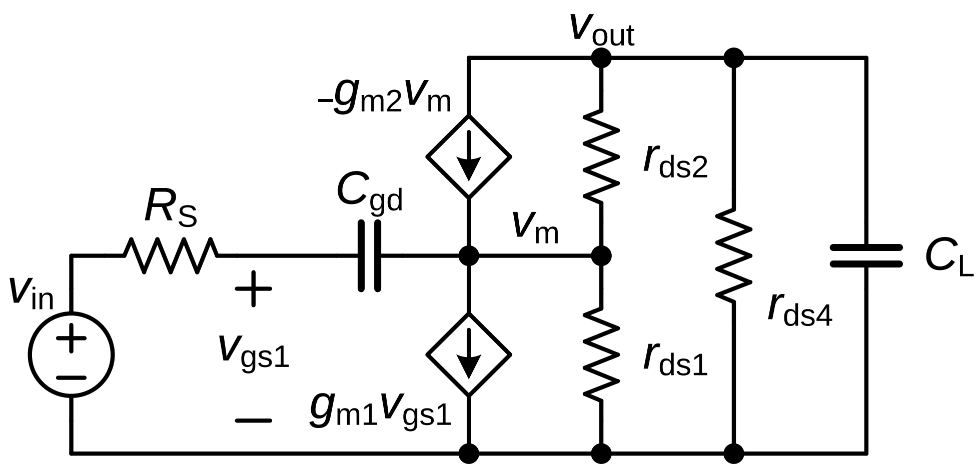
弥天大谎: Cascode管减小密勒效应?!



CS amplifier



Cascode amplifier



$$\frac{v_{out}-v_m}{r_{ds2}}+(-g_{m2}v_m)=-\frac{v_{out}}{r_{ds4}}-\frac{v_{out}}{1/sC_L} \quad \textbf{(1)}$$

$$\frac{v_m-v_{in}}{R_S+1/sC_{gd}}+g_{m1}\left(\frac{v_m-v_{in}}{R_S+1/sC_{gd}}R_S+v_{in}\right)+\frac{v_m}{r_{ds1}}=-\frac{v_{out}}{r_{ds4}}-\frac{v_{out}}{1/sC_L} \quad \textbf{(2)}$$

$$\left(g_{m2}+\frac{1}{r_{ds2}}\right)v_m=\frac{v_{out}}{r_{ds4}}+\frac{v_{out}}{1/sC_L}+\frac{v_{out}}{r_{ds2}}$$

$$v_m=\frac{r_{ds2}+r_{ds4}+sr_{ds2}r_{ds4}C_L}{(1+g_{m2}r_{ds2})r_{ds4}}v_{out}$$

将(1) 求v_m代入(2)得:

$$\frac{g_{m1}/sC_{gd}-1}{R_S+1/sC_{gd}}v_{in}=-\frac{(g_{m1}R_S+1)v_m}{R_S+1/sC_{gd}}-\frac{v_m}{r_{ds1}}-\frac{v_{out}}{r_{ds4}}-\frac{v_{out}}{1/sC_L}$$

$$A_V=\frac{v_{out}}{v_{in}}=-g_{m1}r_{ds1}(1+g_{m2}r_{ds2})r_{ds4}\frac{(1-sC_{gd}/g_{m1})}{c+as+bs^2}$$

$$=-G_m[r_{ds4}\,||\,(r_{ds2}+(1+g_{m2}r_{ds2})r_{ds1})]\frac{(1-sC_{gd}/g_{m1})}{1+\frac{a}{c}s+\frac{b}{c}s^2}$$

$$G_m=\frac{g_{m1}(1+g_{m2}r_{ds2})r_{ds1}}{r_{ds2}+(1+g_{m2}r_{ds2})r_{ds1}}$$

$$c=r_{ds4}+r_{ds2}+(1+g_{m2}r_{ds2})r_{ds1}$$

Cascode放大器: $g_{m2}\neq 0$, $r_{ds2}\neq 0$

$$a=\{r_{ds4}[r_{ds1}+(1+g_{m1}r_{ds1})R_S]+r_{ds1}r_{ds2}+R_S[(1+g_{m1}r_{ds1})r_{ds2}+(1+g_{m2}r_{ds2})r_{ds1}]\}C_{gd}$$
$$+r_{ds4}[r_{ds2}+(1+g_{m2}r_{ds2})r_{ds1}]C_L$$

$$b=r_{ds4}\{r_{ds1}r_{ds2}+R_S[(1+g_{m1}r_{ds1})r_{ds2}+(1+g_{m2}r_{ds2})r_{ds1}]\}C_{gd}C_L$$

当C_{gd}小, C_L大时

$$f_d=-\frac{1}{2\pi R_{out}C_L}\qquad f_{nd}=-\frac{1}{2\pi R_S C_{gd}}$$

当C_{gd}大, C_L小, r_{ds4}大时

$$f_d=-\frac{1}{2\pi R_S A_{v1}C_{gd}}\qquad f_{nd}=-\frac{1}{2\pi r_{ds2}C_L}$$

$$A_{V1}=g_{m1}r_{ds1}$$
$$A_{V2}=g_{m2}r_{ds2}$$

$$R_{out}=r_{ds4}\,||\,(r_{ds2}+(1+g_{m2}r_{ds2})r_{ds1})$$

CS放大器: g_{m2}=0, r_{ds2}=0

$$A_V = \frac{v_{out}}{v_{in}} = -g_m(r_{ds4} \| r_{ds1}) \frac{(1 - sC_{gd}/g_{m1})}{1 + \frac{a}{c}s + \frac{b}{c}s^2}$$

$$c = r_{ds4} + r_{ds1}$$

$$a = \{r_{ds4}[r_{ds1} + (1 + g_{m1}r_{ds1})R_S] + R_S r_{ds1}\}C_{gd} + r_{ds4}r_{ds1}C_L$$

$$b = R_S r_{ds4} r_{ds1} C_{gd} C_L$$

$$R_{out} = r_{ds4} \| r_{ds1}$$

当C_{gd}小，C_L大时

$$f_d = -\frac{1}{2\pi R_{out} C_L} \qquad f_{nd} = -\frac{1}{2\pi R_S C_{gd}}$$

当C_{gd}大，C_L小，r_{ds4}大时

$$f_d = -\frac{1}{2\pi R_S A_{v1} C_{gd}} \qquad f_{nd} = -\frac{g_{m1}}{2\pi C_L}$$

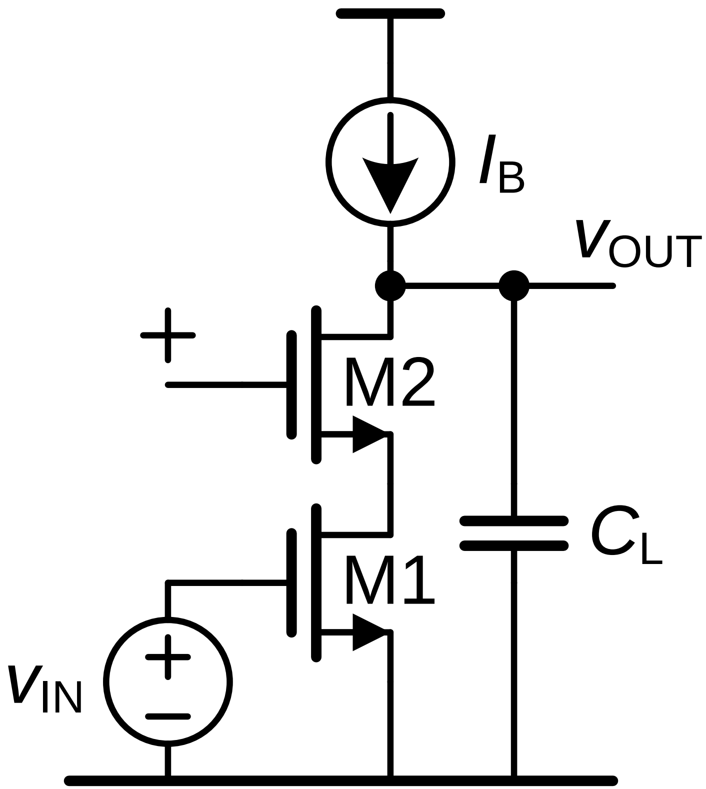
当C_{gd}大, C_L小时: 所有g_m, r_{ds}相等

Cascode放大器: $f_d=-\frac{1}{2\pi R_S C_{gd}}\times\frac{1}{3}$ $f_{nd}=-\frac{1}{2\pi r_{ds} C_L}\times\frac{3}{2}$

CS放大器: $f_d=-\frac{1}{2\pi R_S A_{V1} C_{gd}}\times 2$ $f_{nd}=-\frac{g_m}{2\pi C_L}$

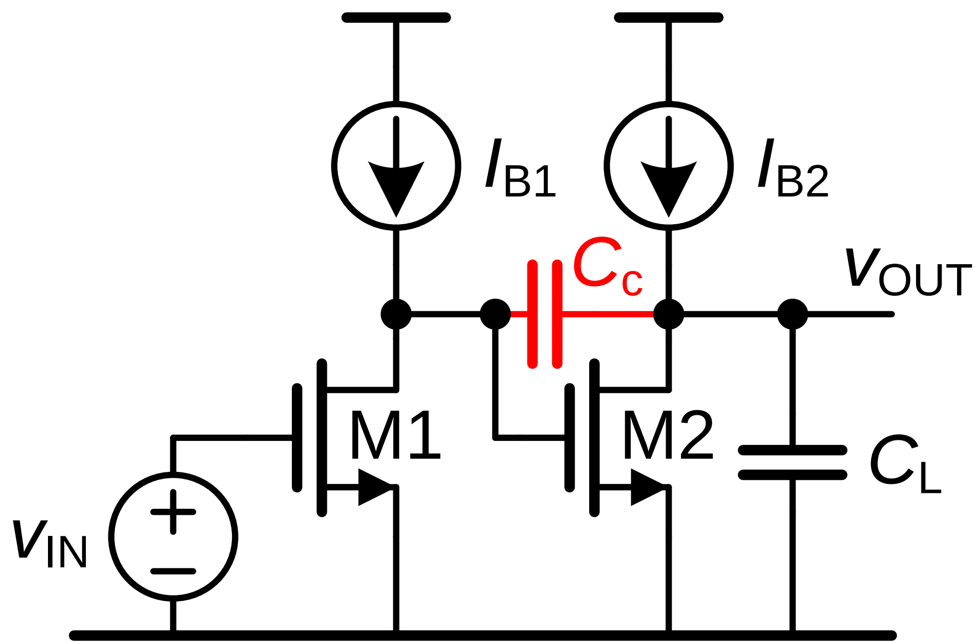
- C_L很大时， Cascode管不能减小密勒效应！
- $r_{ds4}\rightarrow\infty$时，Cascode管不能减小密勒效应！
- r_{ds4}很小(=r_{ds})，Cascode管能够减小密勒效应！

共源共栅与级联



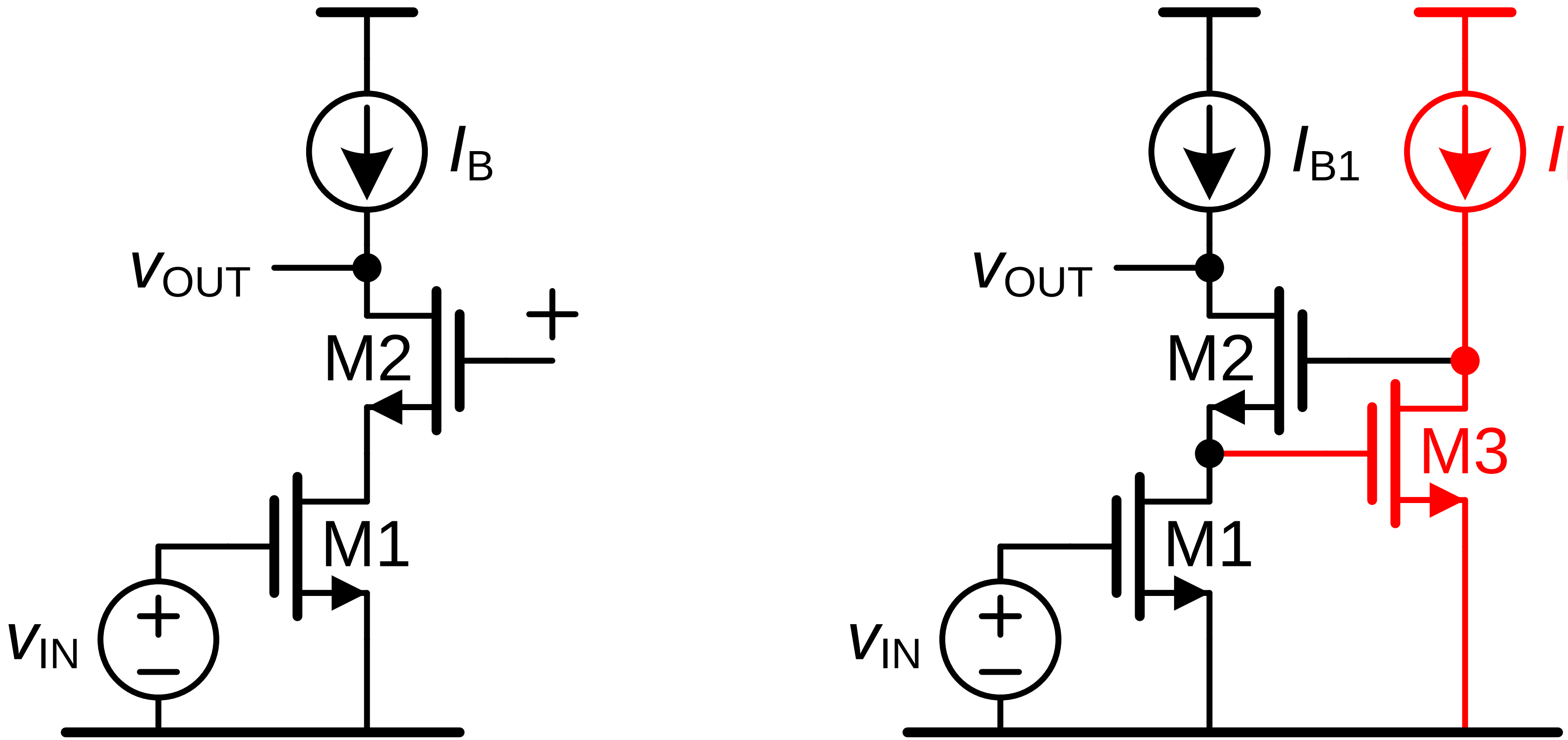
$$GBW = \frac{g_{m1}}{2\pi C_L}$$

两级密勒放大器



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

调节共源共栅/增益抬升

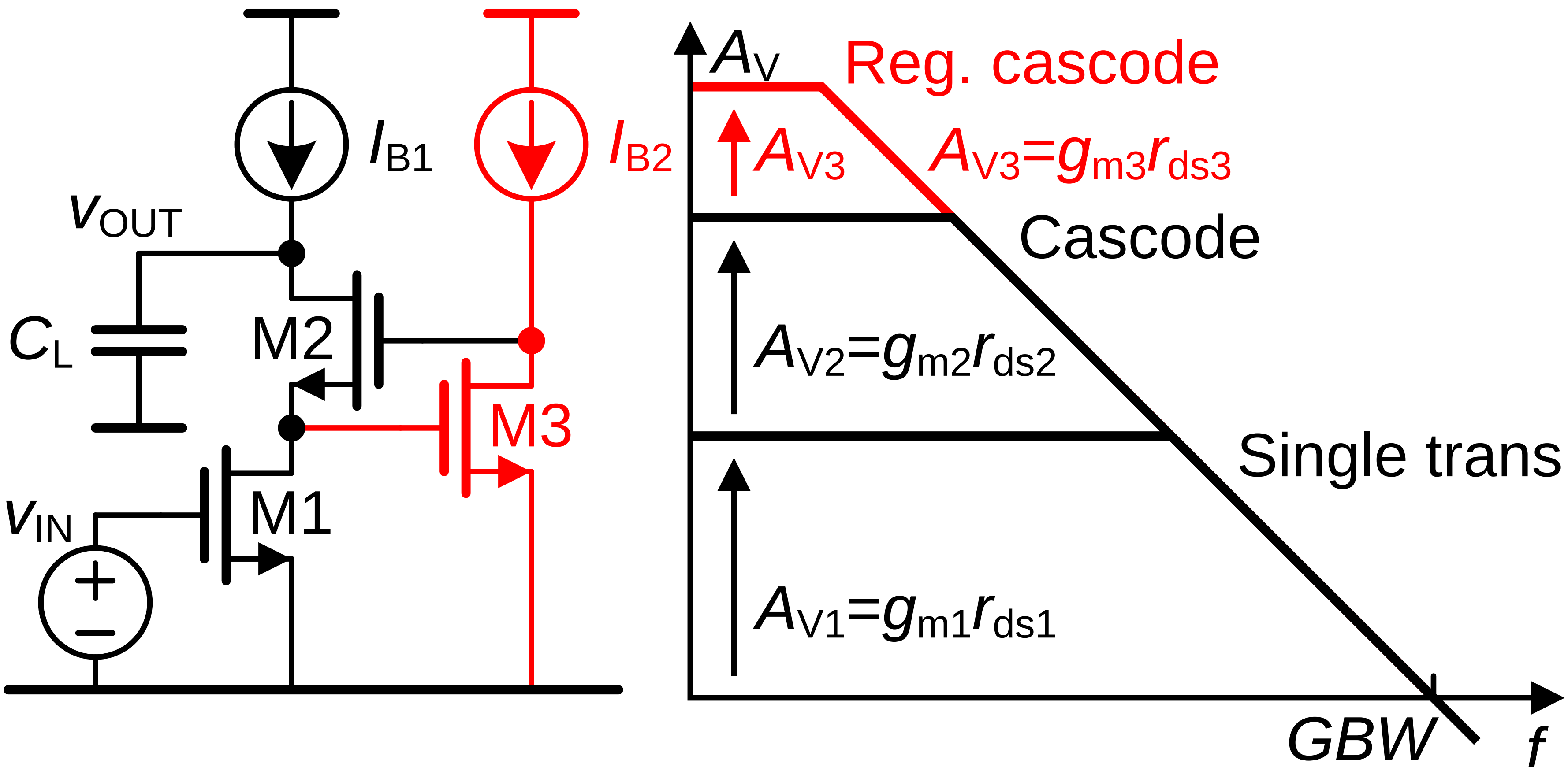


$$A_V = (g_m r_{ds})_1 (g_m r_{ds})_2$$

$$A_V = (g_m r_{ds})_1 (g_m r_{ds})_2 (g_m r_{ds})_3$$

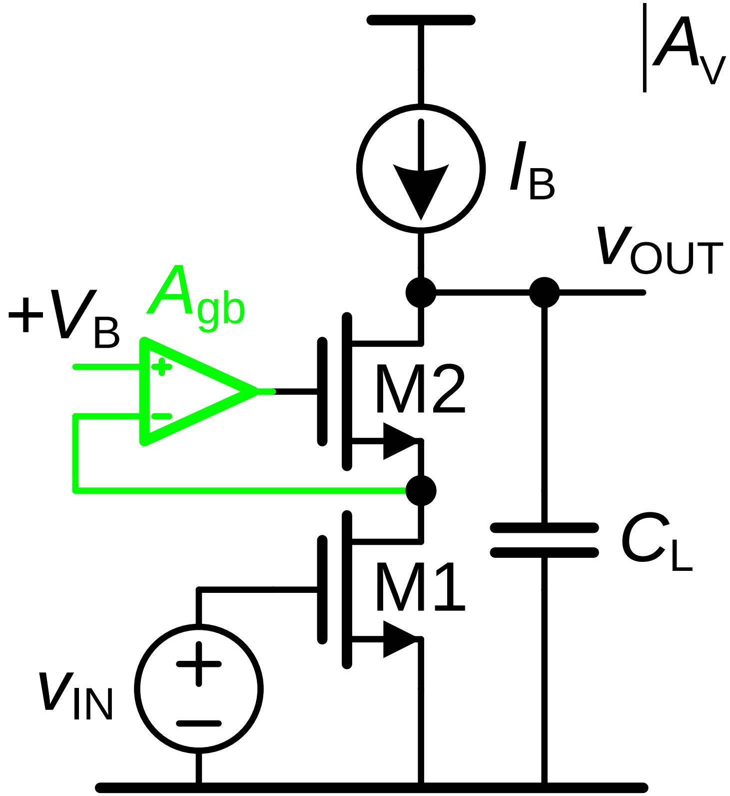
Ref.: Hosticka, JSSC Dec.79, pp. 1111-1114; Sackinger, JSSC Febr.90, pp. 289-298;
Bult JSSC Dec.90, pp. 1379-1384

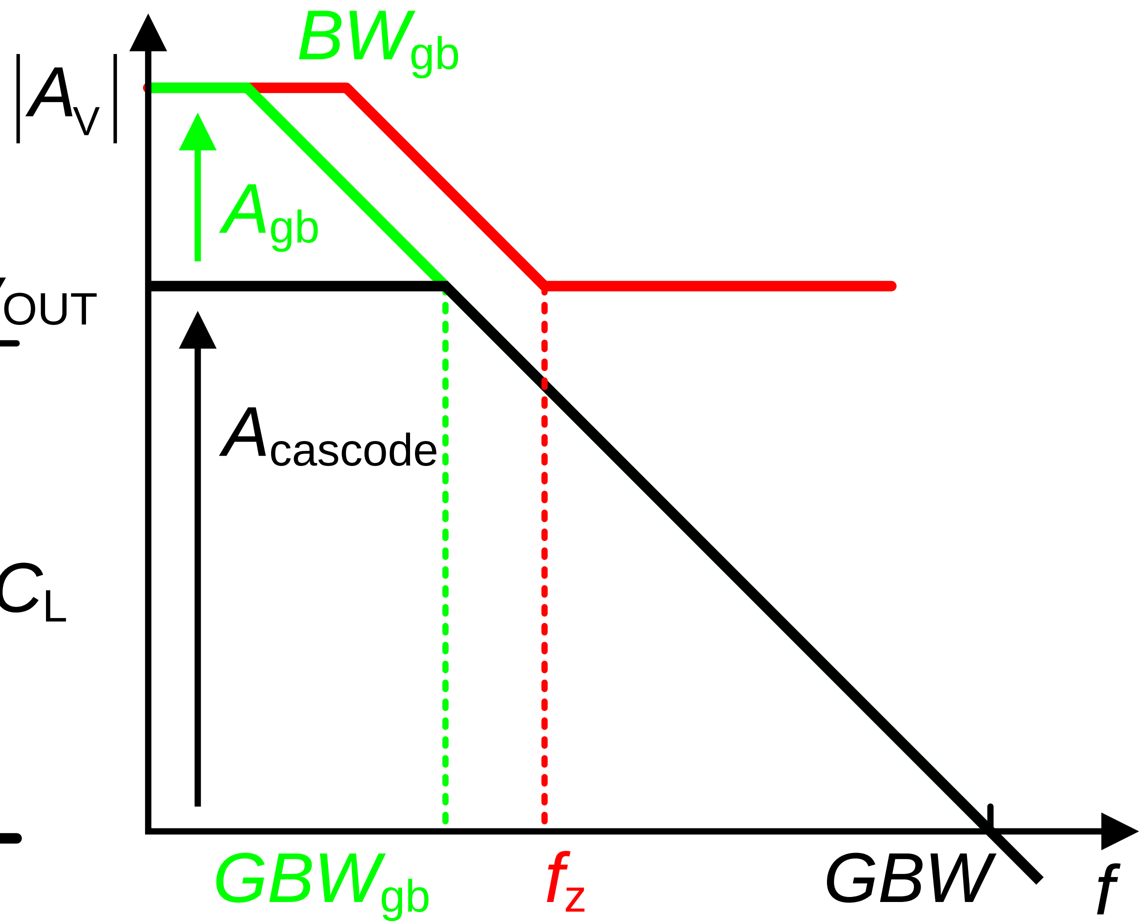
增益抬升，共源共栅和单管放大器



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

增益抬升

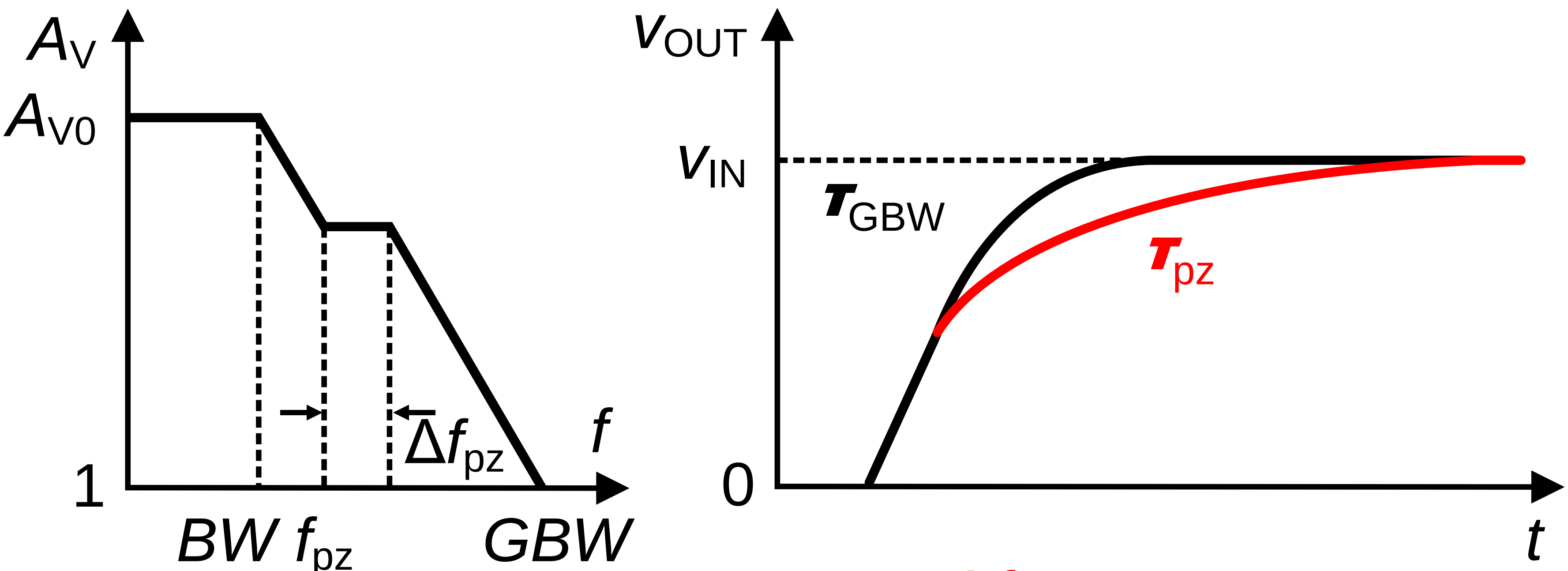




$$A_V = A_{gb}(g_m r_{ds})_1 (g_m r_{ds})_2$$

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

零极点对和建立时间

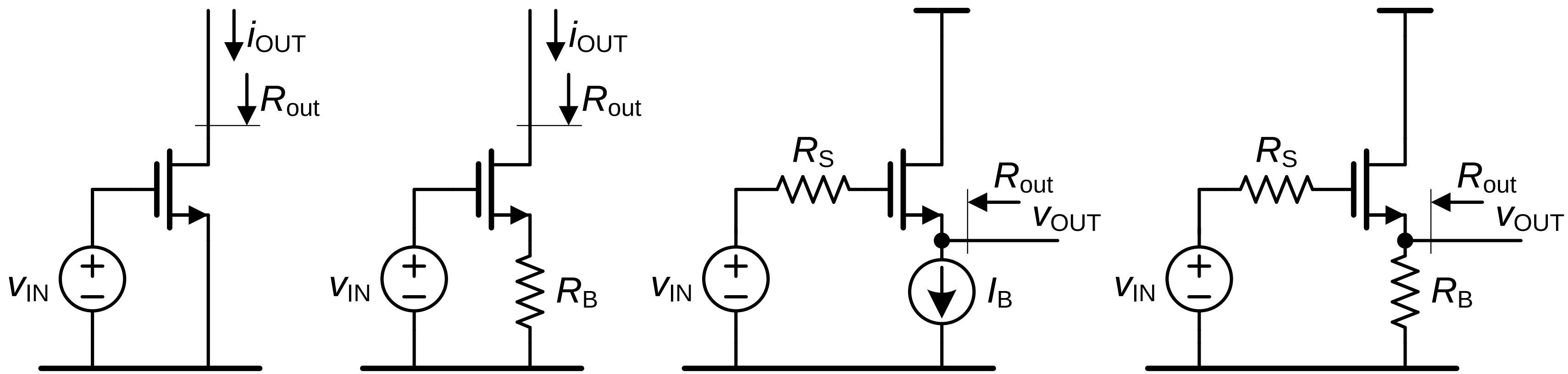


$$v_{OUT} = v_{IN}[1 - \exp(-\frac{t}{\tau_{GBW}}) - \frac{\Delta f_{pz}}{GBW}\exp(-\frac{t}{\tau_{pz}})]$$

$$f_{pz} = \frac{1}{2\pi\tau_{pz}} \qquad GBW = \frac{1}{2\pi\tau_{GBW}}$$

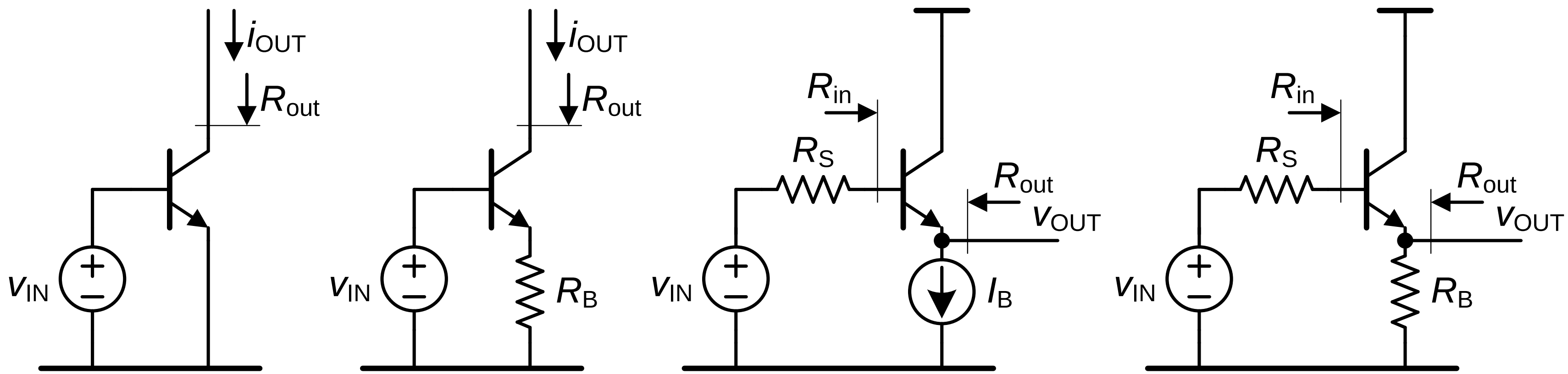
Ref.: Kamath, etal, JSSC Dec.74, pp. 347-352

MOST共源放大器和源极跟随器



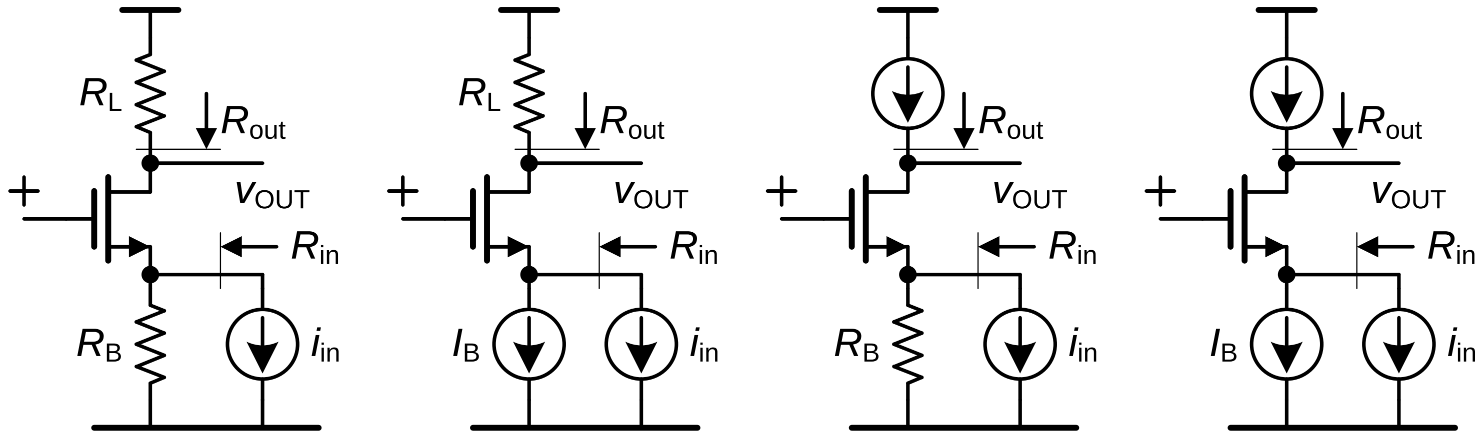
		$R_B > 1/g_m$			$R_B > 1/g_m$
A_G	g_m	$1/R_B$	A_V	1	1
R_{in}	∞	∞		∞	∞
R_{out}	r_{ds}	$g_m R_B r_{ds}$		$1/g_m$	$1/g_m$

双极型共射放大器和射极跟随器



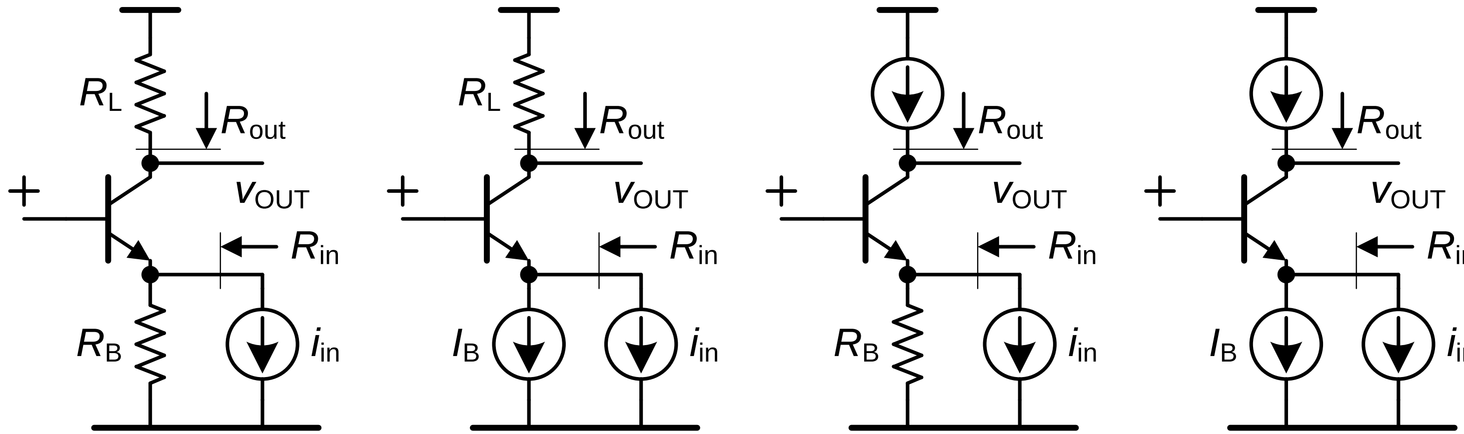
		$R_B > 1/g_m$			$R_B > 1/g_m$
A_G	g_m	$1/R_B$	A_V	1	1
R_{in}	$r_B + r_\pi$	$r_B + r_\pi + (\beta+1)R_B$		$r_B + r_\pi + (\beta+1)r_o$	$r_B + r_\pi + (\beta+1)R_B$
R_{out}	r_o	$g_m R_B r_o$		$\dfrac{1}{g_m} + \dfrac{R_S + r_B}{\beta+1}$	$\dfrac{1}{g_m} + \dfrac{R_S + r_B}{\beta+1}$

MOST共栅放大器



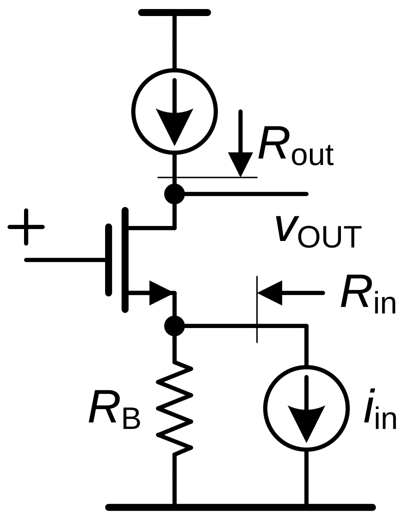
	$R_B > 1/g_m$		$R_B > 1/g_m$	
A_R	R_L	R_L	$g_m r_{ds} R_B$	-
R_{in}	$1/g_m$	$1/g_m$	R_B	∞
R_{out}	$g_m r_{ds} R_B$	∞	$g_m r_{ds} R_B$	∞

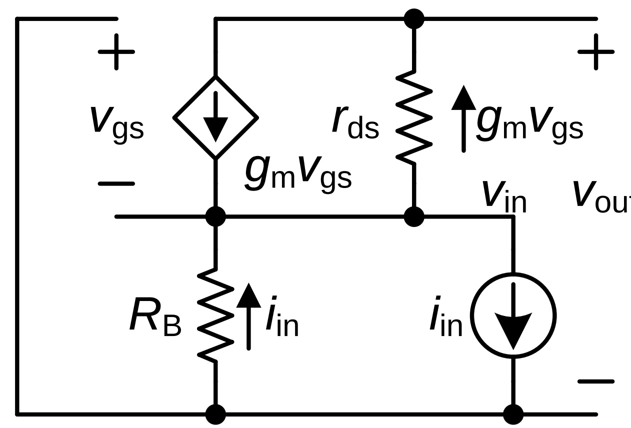
双极型共基放大器



	$R_B > 1/g_m$		$R_B > 1/g_m$	
A_G	R_L	R_L	$g_m r_o R_B$	βr_o
R_{in}	$1/g_m$	$1/g_m$	$R_B // (r_B + r_\pi)$	$r_B + r_\pi$
R_{out}	$g_m r_o R_B$	$\approx \beta r_o$	$g_m r_o [R_B // (r_B + r_\pi)]$	$\approx \beta r_o$

MOST共栅放大器的跨阻A_R





$$R_B > 1/g_m$$

$$A_R = g_m r_{ds} R_B$$

$$\begin{cases} v_{in} = -R_B i_{in} \\ v_{out} = v_{in} - g_m v_{gs} r_{ds} \\ v_{gs} = -v_{in} \end{cases}$$

$$\Downarrow$$

$$v_{out} = -i_{in}(1+g_m r_{ds})R_B \qquad g_m r_{ds} \gg 1$$