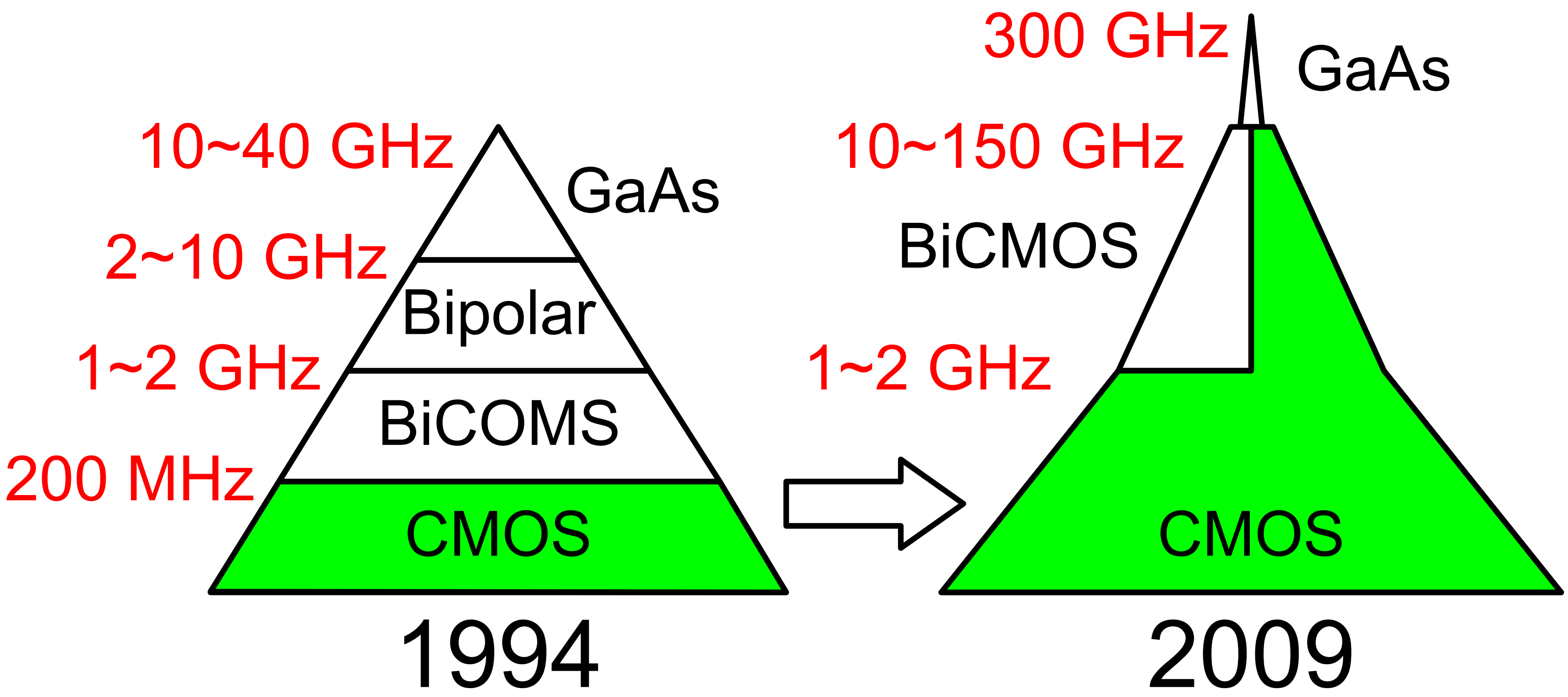
从双极型到MOS晶体管



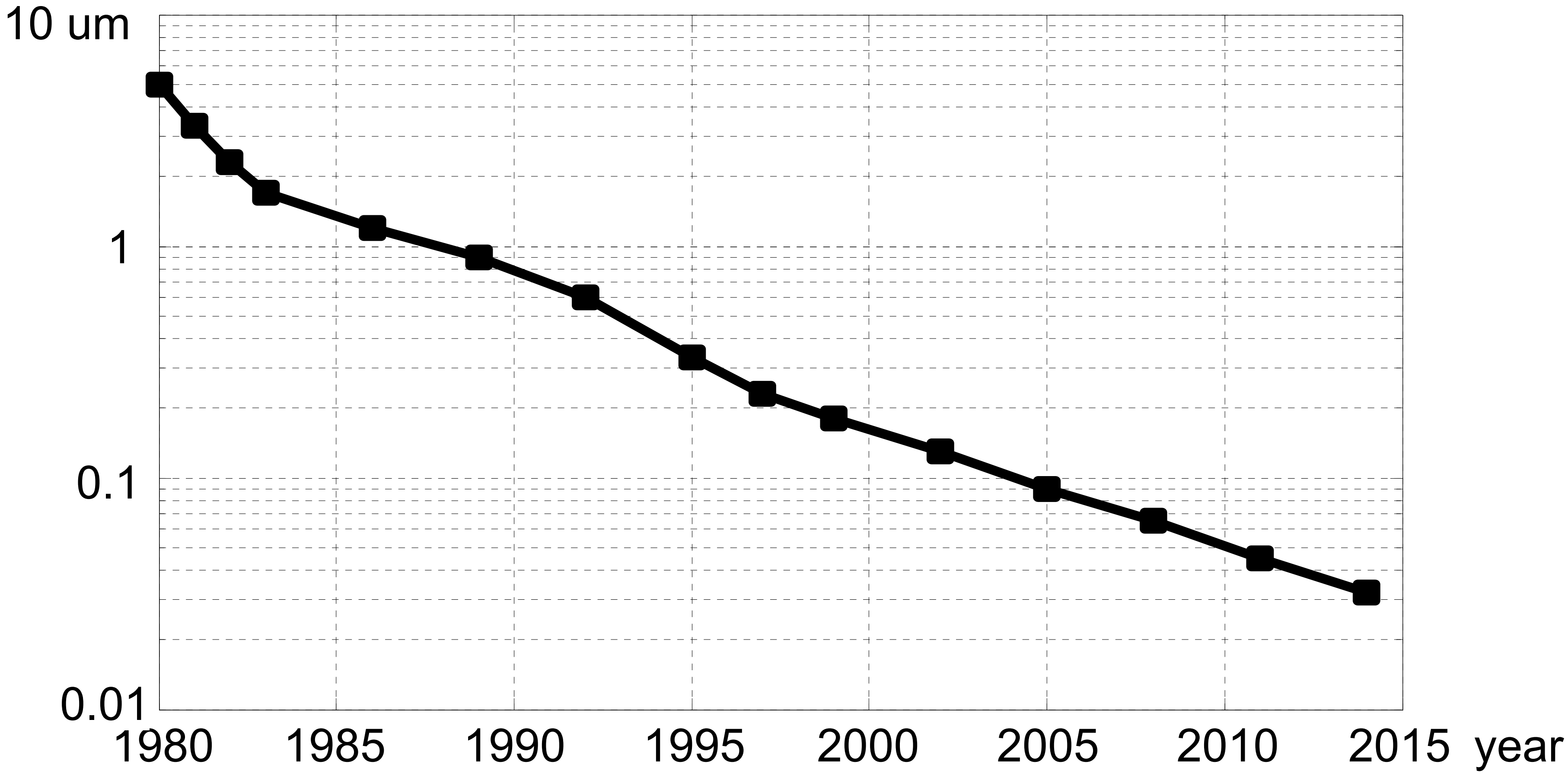
Ref.: Toshiba & ISSCC2009

SIA线路图

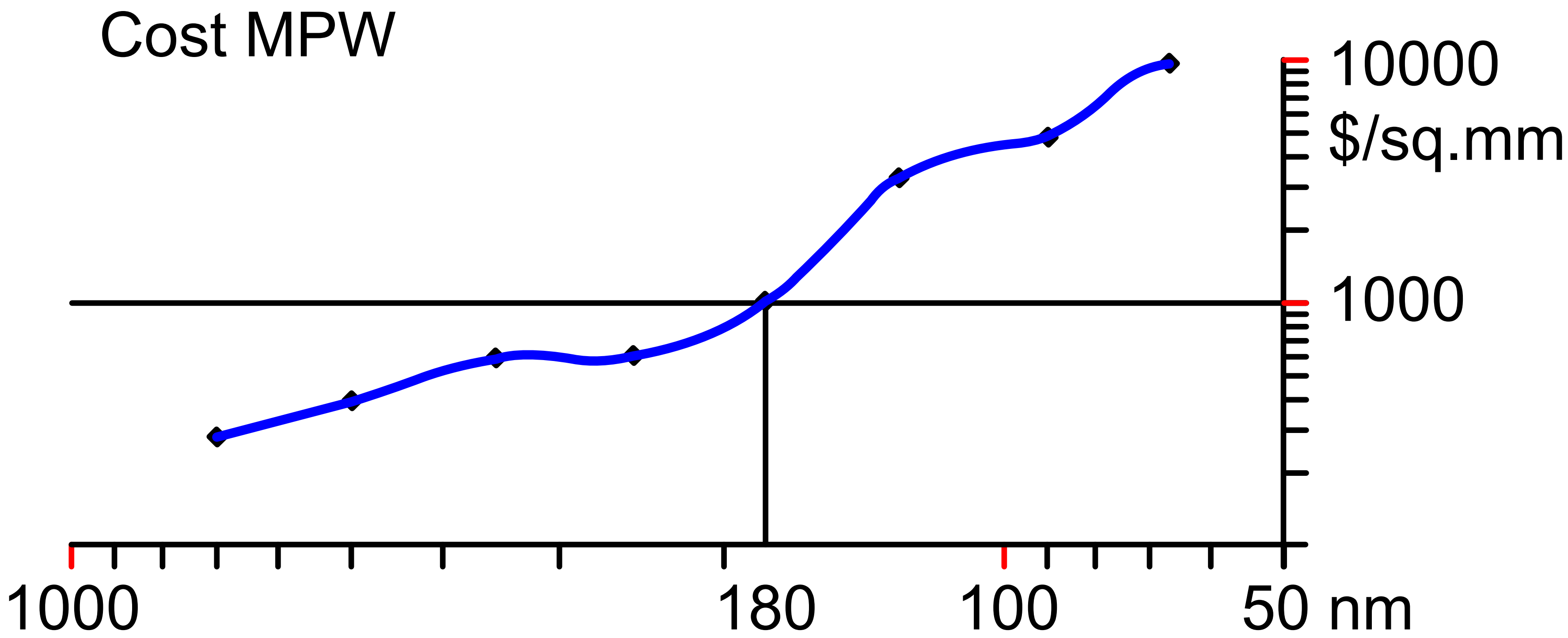
Year	L_{min} μm	Bits/chip Gb/chip	Trans/chip millions/chip	Clock MHz	Wiring
1995	0.35	0.064	4	300	4-5
1998	0.25	0.256	7	450	5
2001	0.18	1	13	600	5-6
2004	0.13	4	25	800	6
2007	0.09	16	50	1000	6-7
2010	0.065	64	90	1100	7-8
2013	0.045				
2016	0.032				

Semiconductor Industry Association

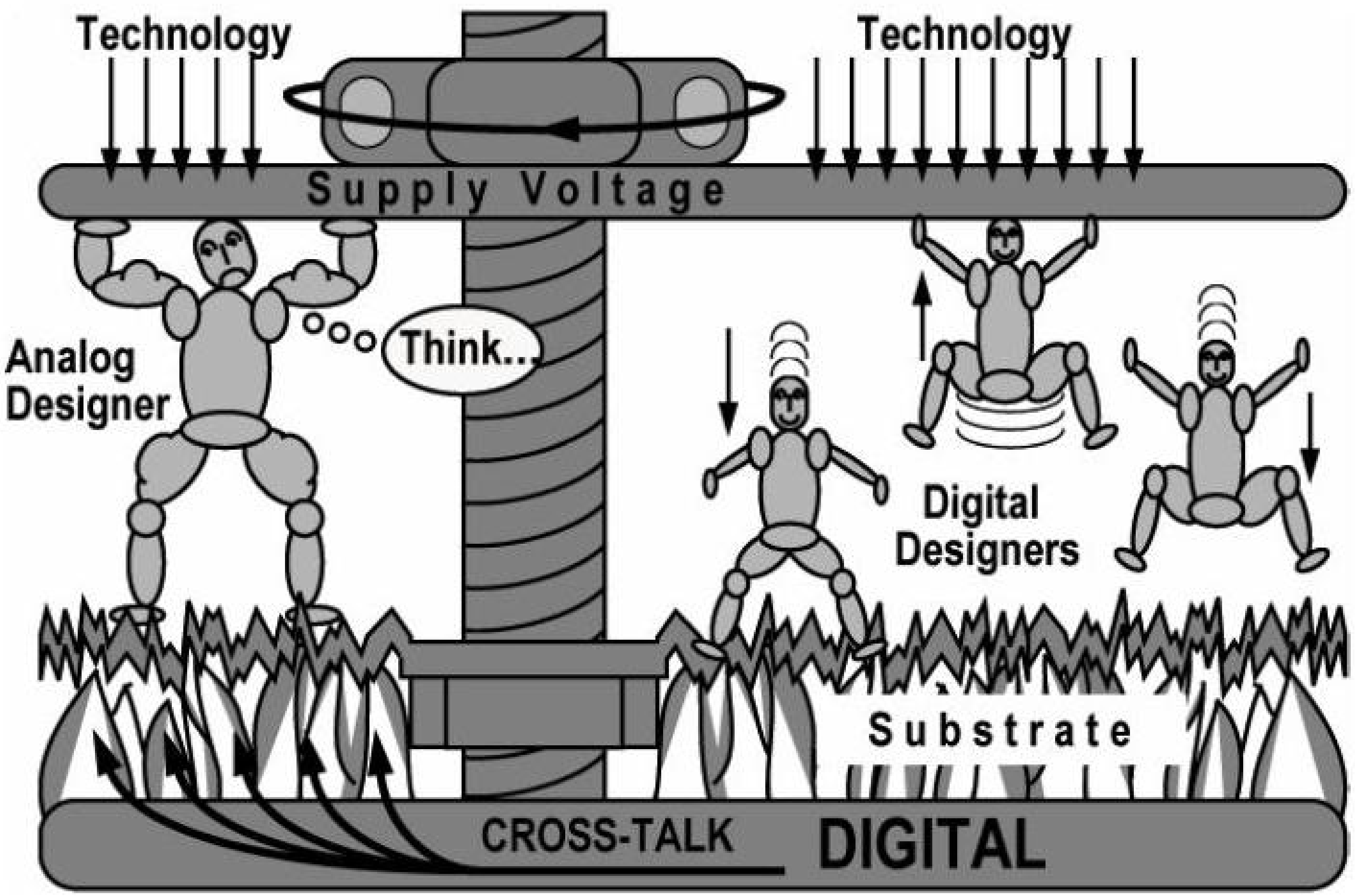
摩尔定律(The law of Moore)



使用不同特征尺寸的MPW价格

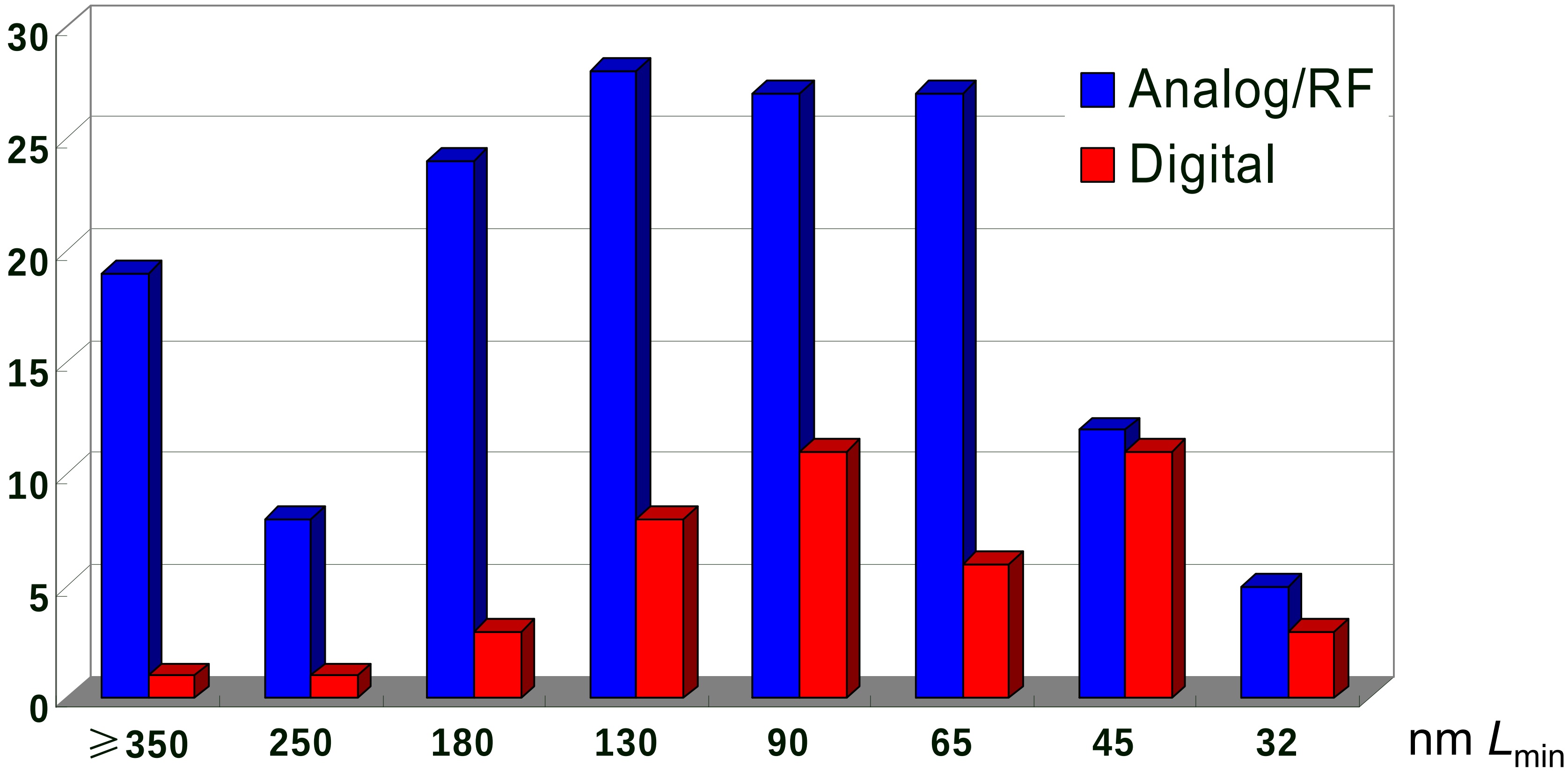


在深亚微米工艺下模拟设计的挑战

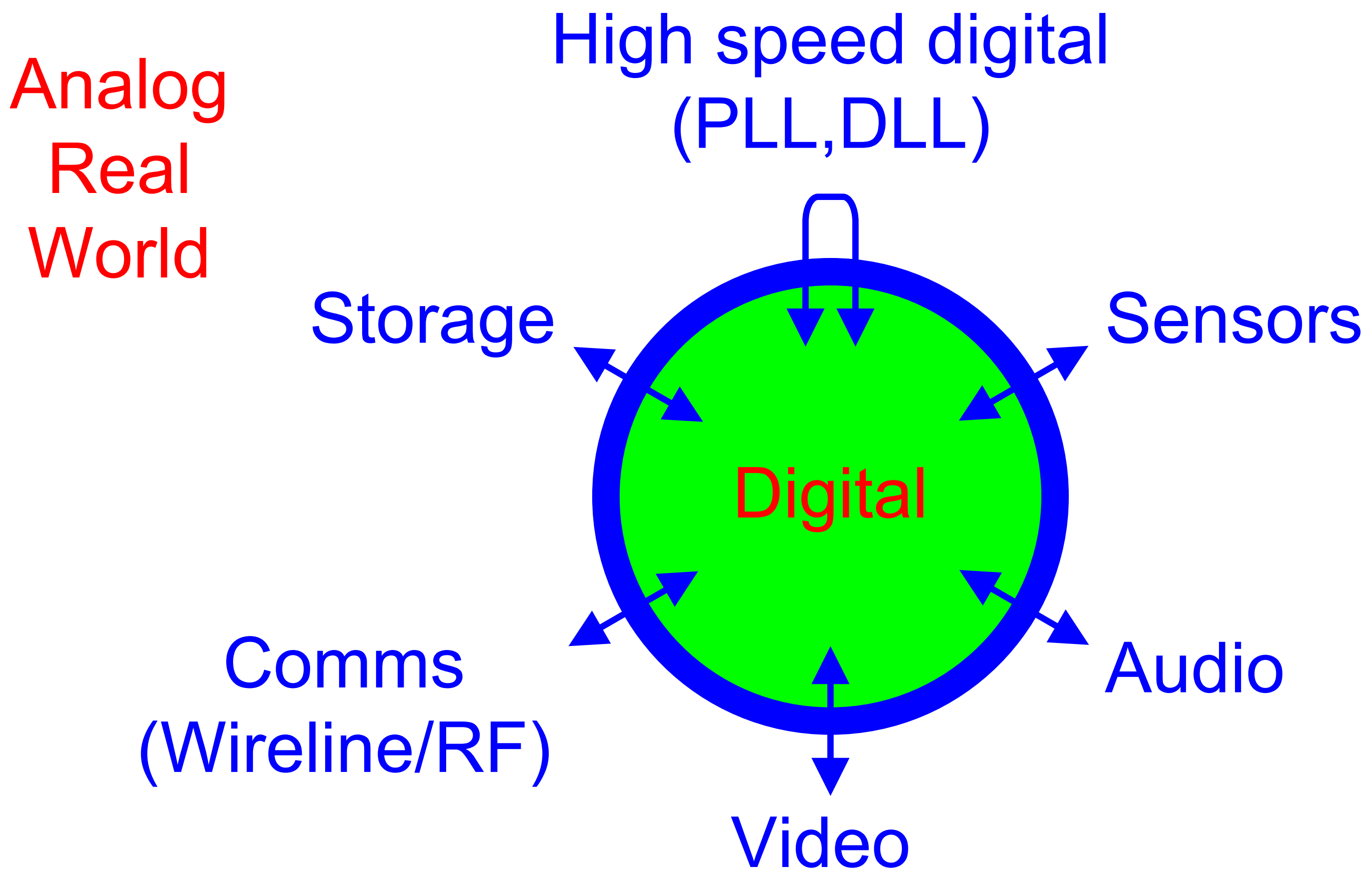


Ref.: SNUG2004, San Jose

ISSCC 2009论文分布情况



混合信号“蛋壳”



Ref.: SNUG2004, San Jose

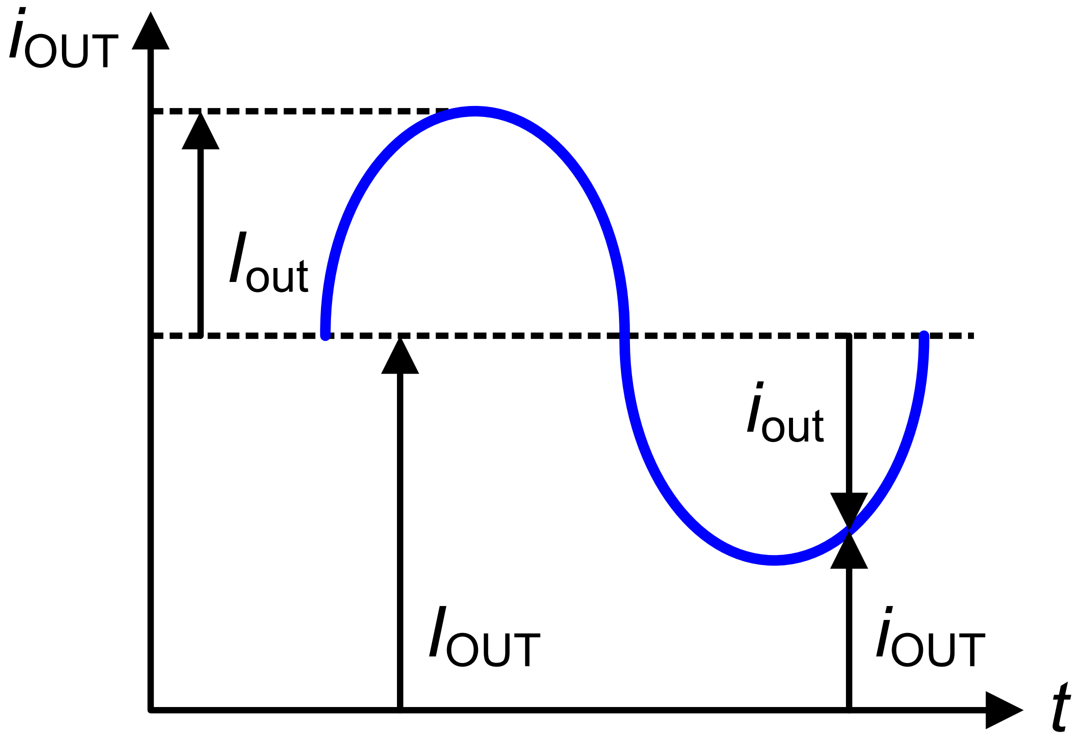
符号说明

i_{OUT} total instantaneous value

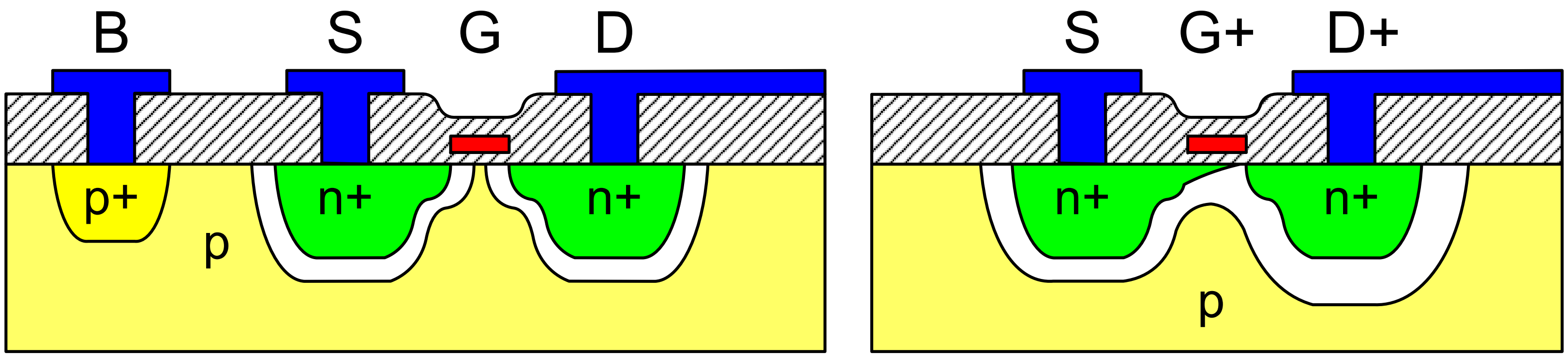
I_{OUT} DC or average value

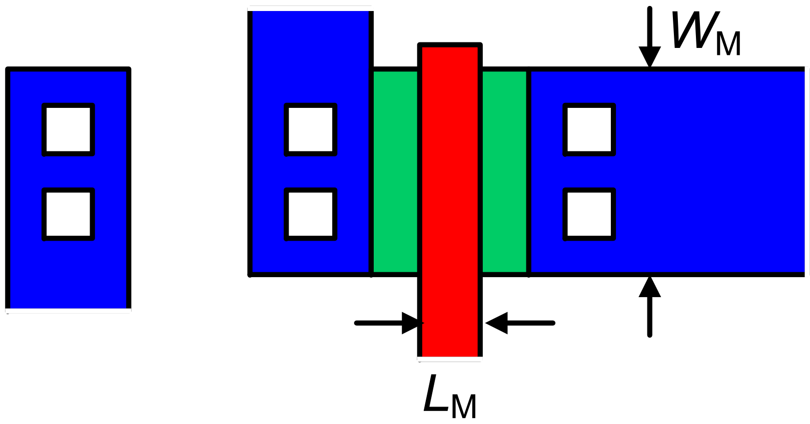
I_{out} amplitude of AC value

i_{out} instantaneous value of AC component

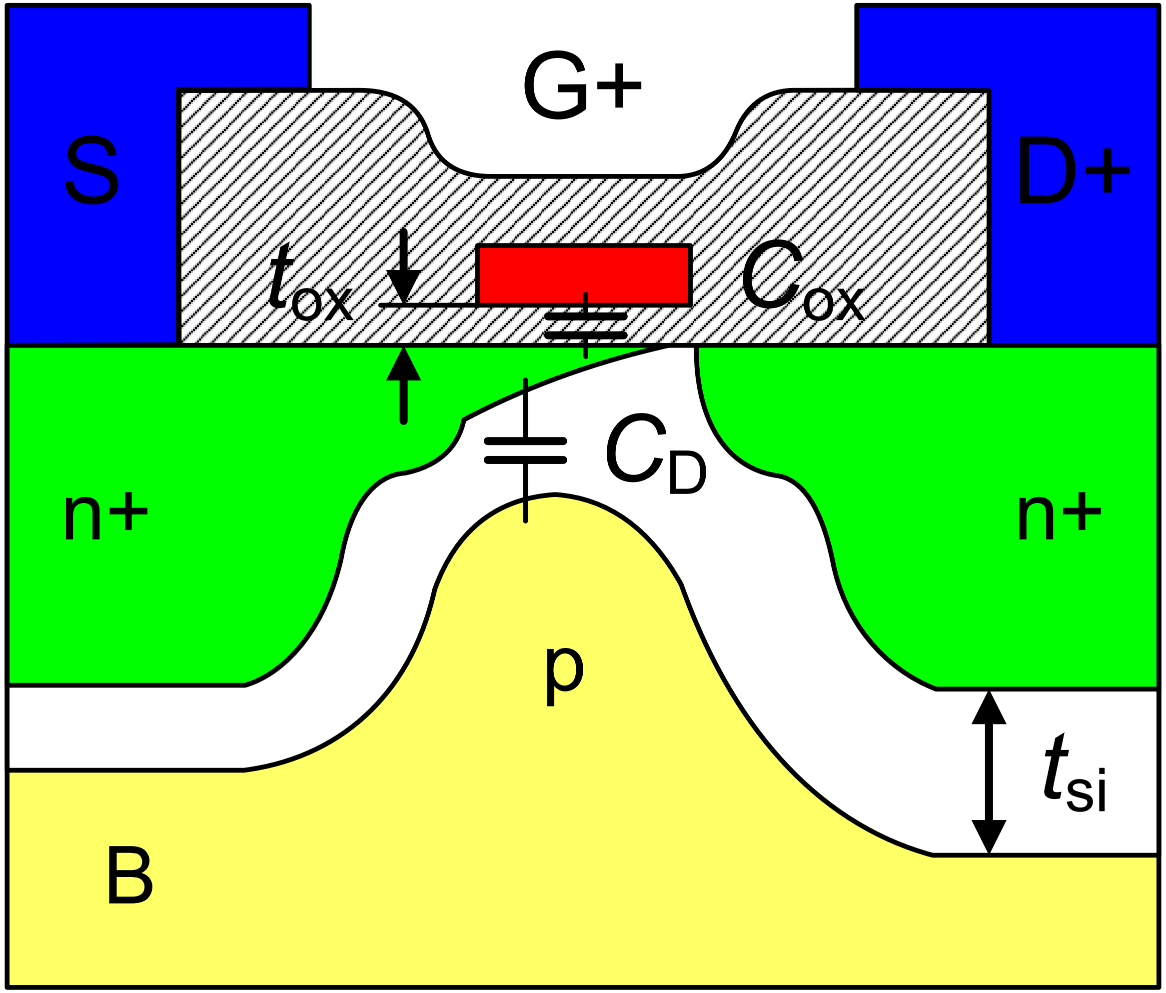


MOST版图





MOST版图：C_{ox}和C_D



$$C_D = \frac{\varepsilon_{si}}{t_{si}}$$

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}$$

$$\frac{C_D}{C_{ox}} = n\text{-}1$$

MOST版图：C_{ox}和C_D的值

$$C_D = \frac{\varepsilon_{si}}{t_{si}} \qquad t_{si} = \sqrt{\frac{2\varepsilon_{si}(\varphi - V_{BD})}{qN_B}}$$

$\varepsilon_{si} = 1$ pF/cm

$\varepsilon_{ox} = 0.34$ pF/cm

$N_B = 4\times10^{17}$ cm^{-3}

$\varphi \approx 0.6$ V

$q = 1.6\times10^{-19}$ C

例如：$L = 0.35\ \mu m \quad W/L = 8$

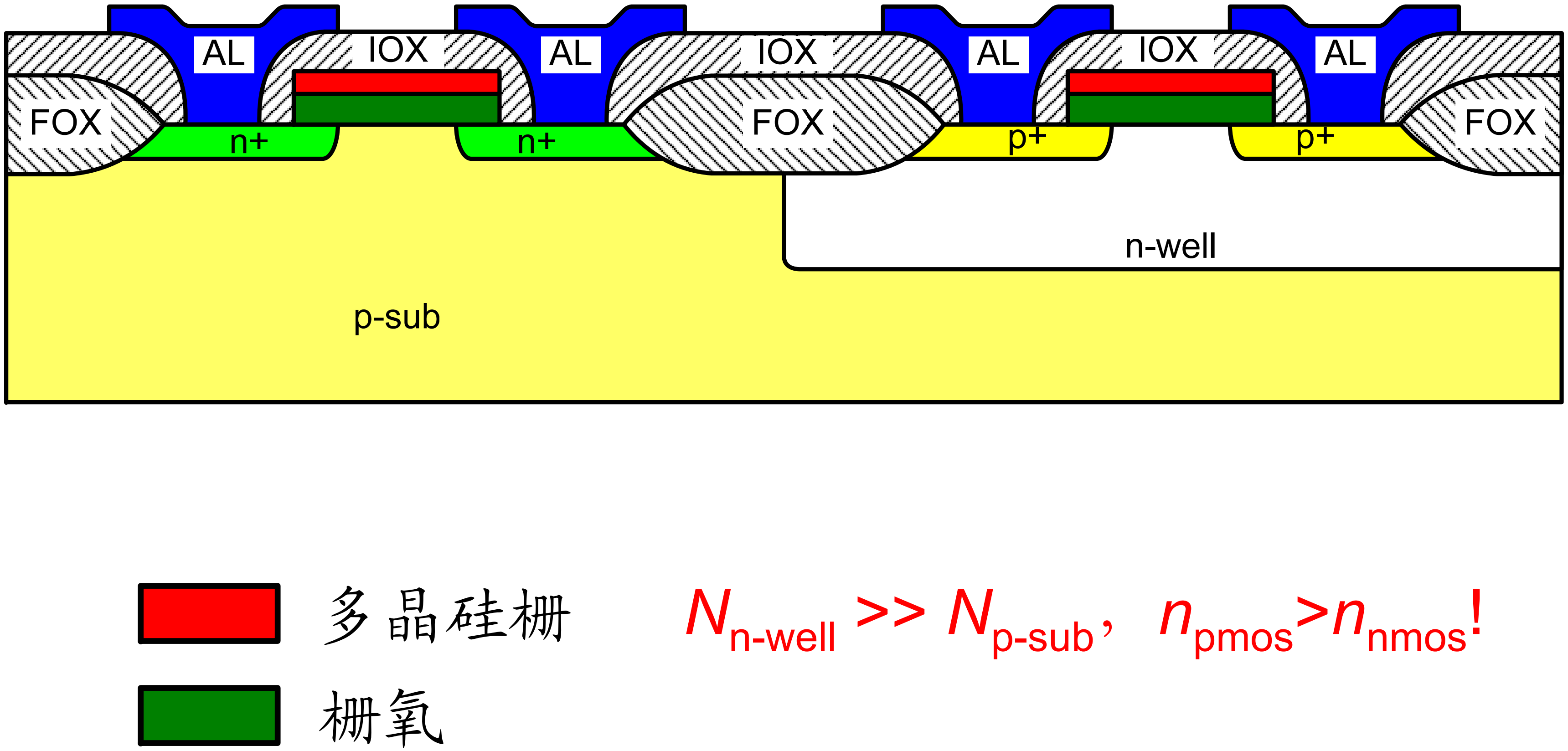
$V_{BD} = -3.3$ V

$$t_{si} = 0.11\ \mu m \Rightarrow C_D \approx 1\times10^{-7}\ \text{F/cm}^2 = 1\ \text{fF}/\mu\text{m}^2$$

$$t_{ox} = \frac{L_{min}}{50} \Rightarrow t_{ox} = 7\ \text{nm} \Rightarrow C_{ox} = 5\times10^{-7}\ \text{F/cm}^2 = 5\ \text{fF}/\mu\text{m}^2$$

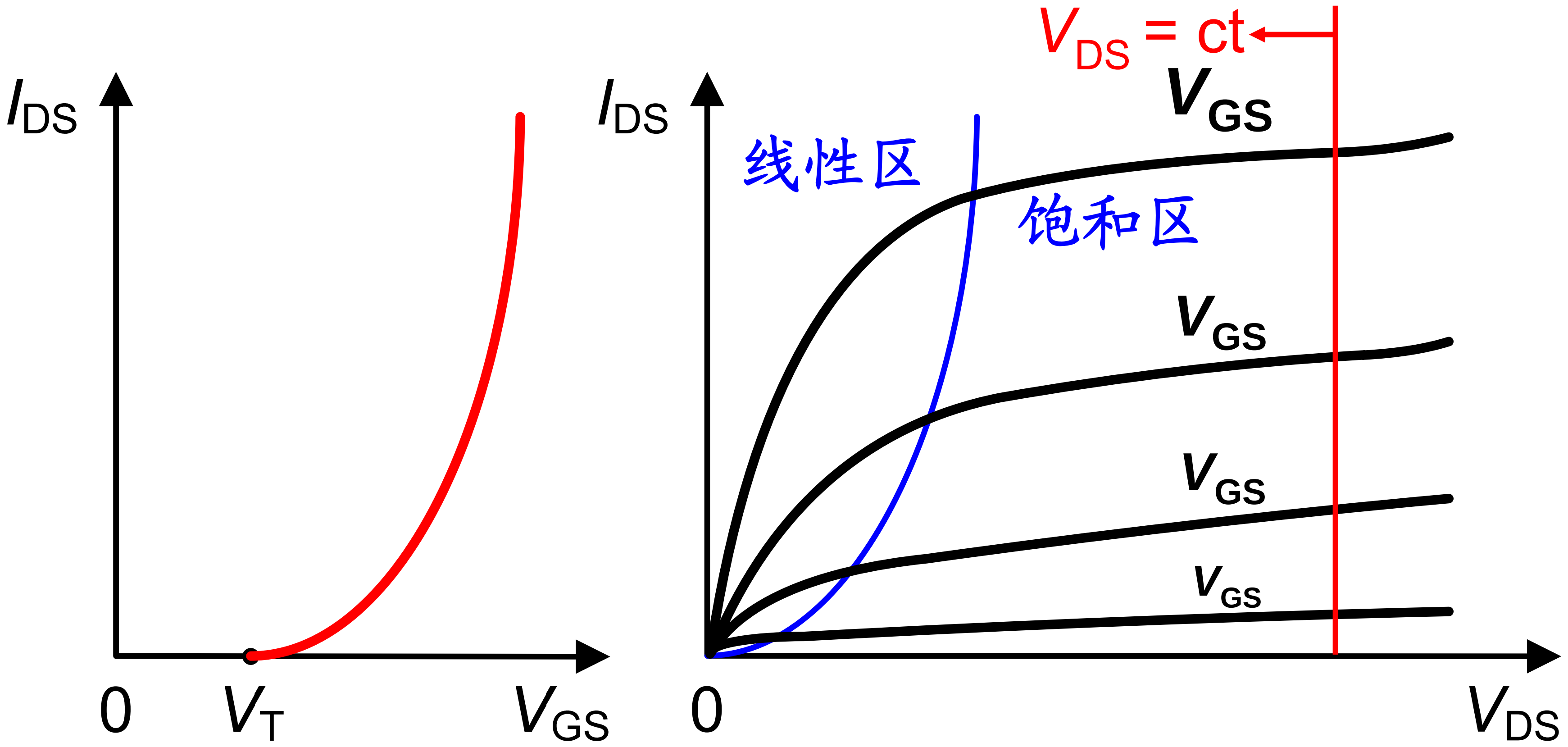
$$\frac{C_D}{C_{ox}} = n\text{-}1 \approx 0.2$$

N阱CMOS工艺



$N_{n\text{-}well} >> N_{p\text{-}sub}$， $n_{pmos} > n_{nmos}$!

MOST的I_{DS}与V_{GS}和V_{DS}的关系



高V_{DS}使MOST进入饱和区

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  - ❑强反型与速度饱和的转换点
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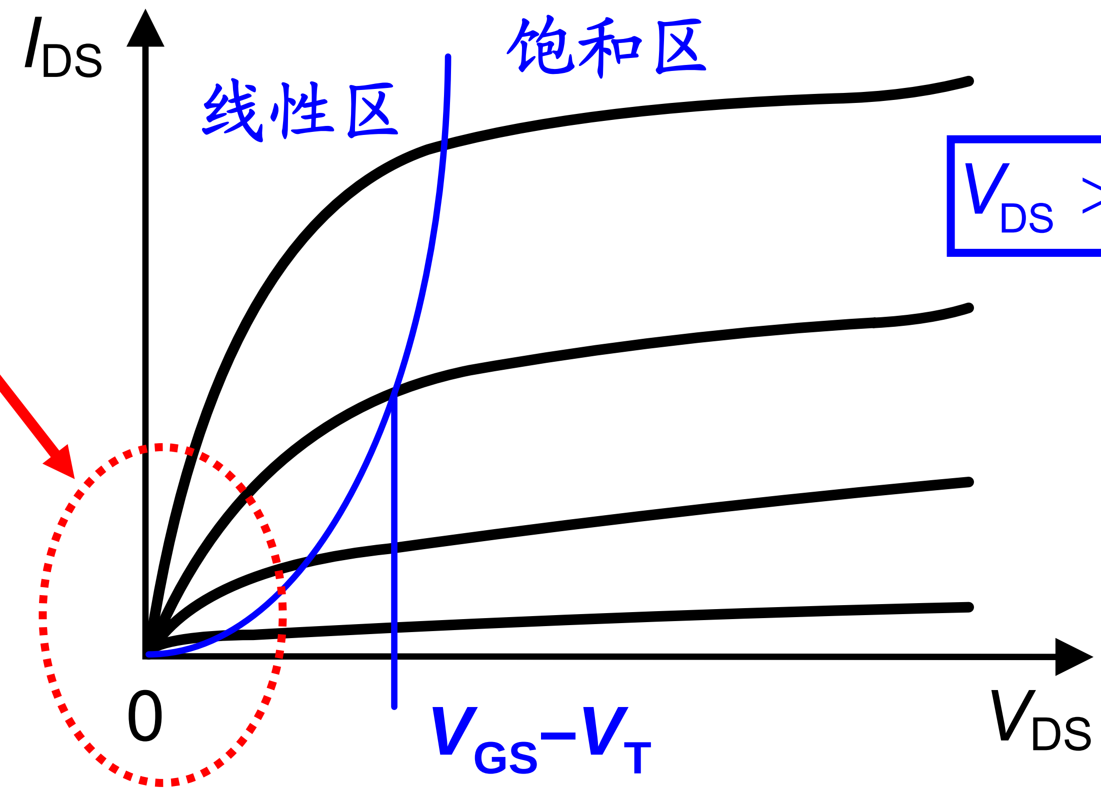
MOST的V_{DS}与I_{DS}的关系

线性电阻区



$$\boxed{V_{DS} > V_{GS} - V_T}$$

$$\frac{V_{GS} - V_T}{n}$$

$$R_{on} = \frac{1}{\beta(V_{GS} - V_T)}$$

$$\beta = KP\frac{W}{L}$$

MOST的参数β、KP、C_{ox}等

$$\beta = KP\frac{W}{L}$$

$$\Downarrow$$

$$KP = \mu C_{ox}$$

$$\Downarrow$$

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}$$

$$\Downarrow$$

$$t_{ox} = \frac{L_{min}}{50}$$

$KP_p \approx 125\ \mu\text{A/V}^2$

$KP_n \approx 300\ \mu\text{A/V}^2$

$C_{ox} \approx 5\times10^{-7}\ \text{F/cm}^2$

$\varepsilon_{si} = 1\ \text{pF/cm}$

$\varepsilon_{ox} = 0.34\ \text{pF/cm}$

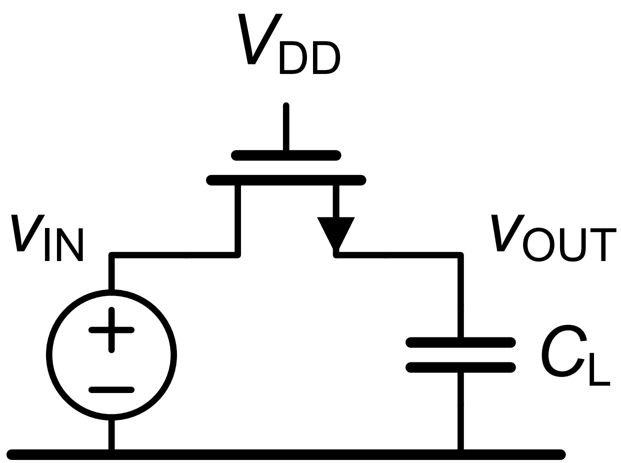
$t_{ox} = 7\ \text{nm}$

$L = 0.35\ \mu\text{m}$

$\mu_p = 250\ \text{cm}^2/\text{Vs}$

$\mu_n = 600\ \text{cm}^2/\text{Vs}$

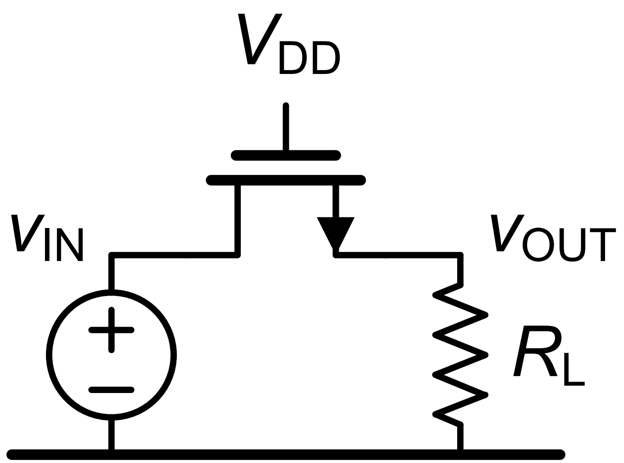
例：连接电容C_L的模拟开关



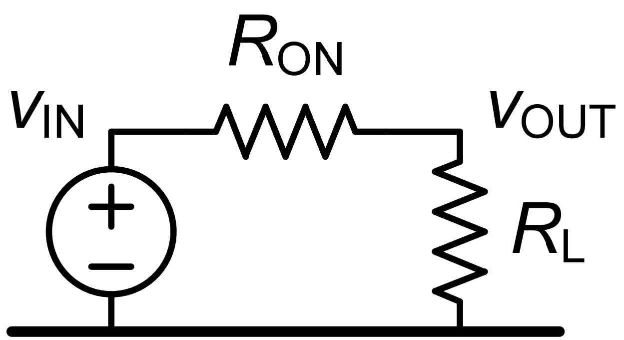
将0.6 V电压源连接到4 pF负载电容C_L。希望转换速度较快，时间常数为 0.5 ns。V_{DD}=2.5 V，V_T=0.5 V。使用0.35 μm标准CMOS工艺。

选择最小栅长，求v_{GS}平均值 。

例：连接电阻R_L的模拟开关



将0.6 V电压源连接到5 kΩ负载电阻R_L。W/L=8，V_{DD}=2.5 V，V_T=0.5 V。使用0.35 μm标准CMOS工艺。



选择最小栅长，求v_{OUT}，R_{ON}。

体效应：寄生的结型场效应管(JFET)

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

$$\gamma = \frac{\sqrt{2\varepsilon_{si} q N_{SUB}}}{C_{ox}} = \frac{C_D}{C_{ox}} 2\sqrt{|2\Phi_F| - V_{BS}}$$

$$|2\Phi_F| \approx 0.6\ \mathrm{V}$$

$$n - 1 = \frac{C_D}{C_{ox}} = \frac{\gamma}{2\sqrt{|2\Phi_F| - V_{BS}}}$$

$$n \approx 1.2 \sim 1.5$$

$$\gamma \approx 0.5 \sim 0.8\ \mathrm{V}^{1/2}$$

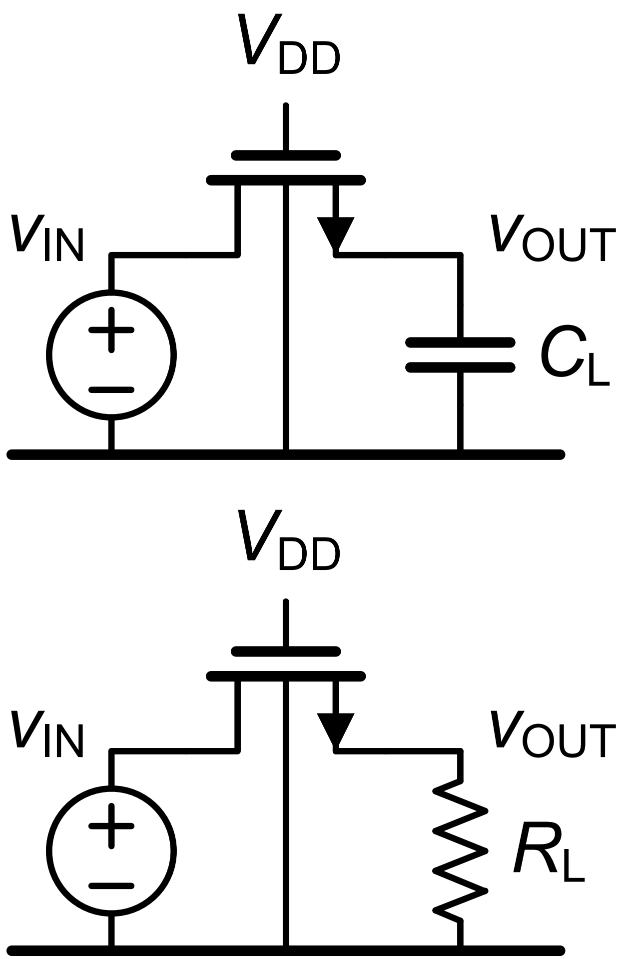
$$\varphi = 2\Phi_F$$

反向偏置V_{BS}增加，$|V_T|$增加，$|i_{DS}|$减小。

$n = 1/\kappa$ 为亚阈值栅耦合系数。

Ref.: Tsividis

例：$V_{BS}\neq 0$的模拟开关



将0.6 V电压源连接到4 pF负载电容C_L或5 kΩ负载电阻R_L。W/L=8(V_{BS}=0 V时，R_{on}为125Ω)。V_{DD}=2.5 V，V_{T0}=0.5 V，γ=0.5 V^{-1}。使用0.35 μm标准CMOS工艺。

求v_{OUT}。

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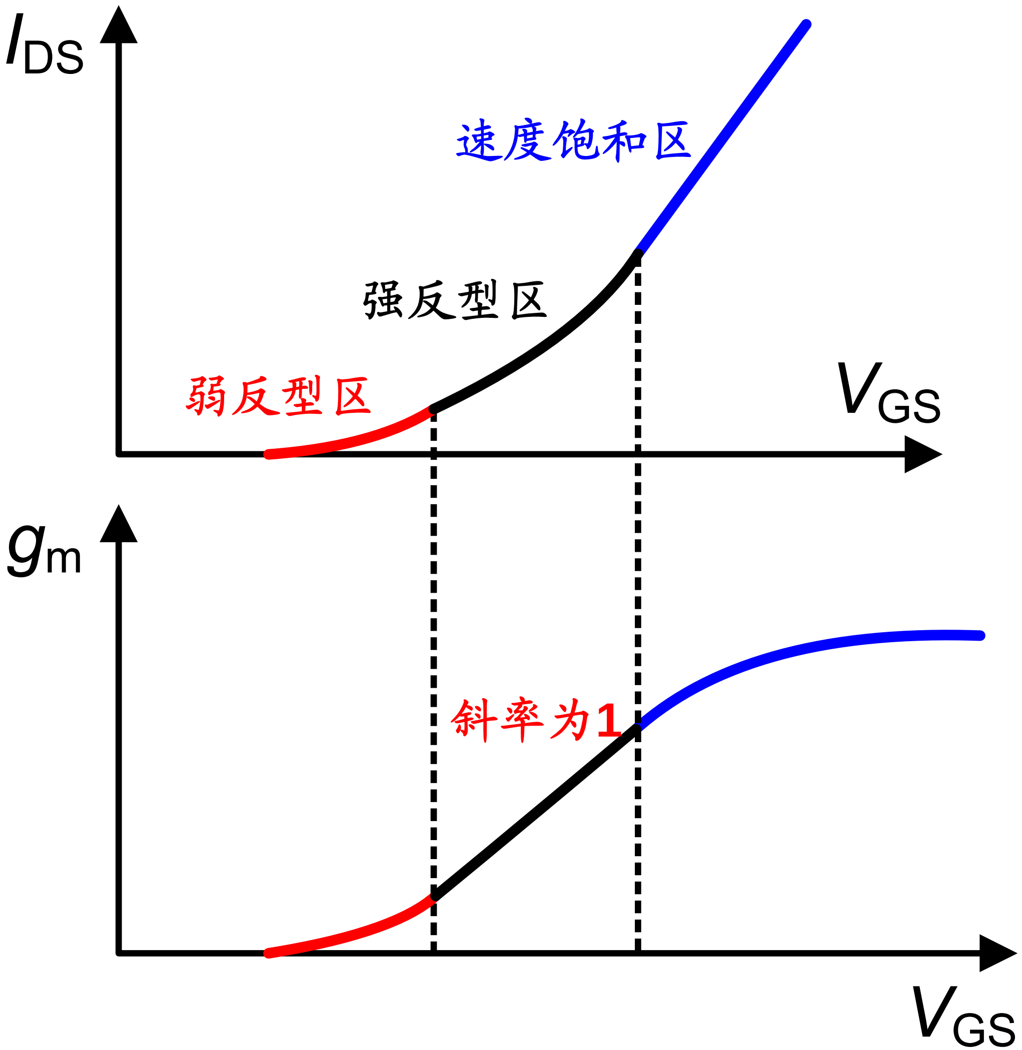
MOST I_{DS}与V_{GS}的关系：强反型区



$$I_{DS} \sim (V_{GS} - V_T)$$

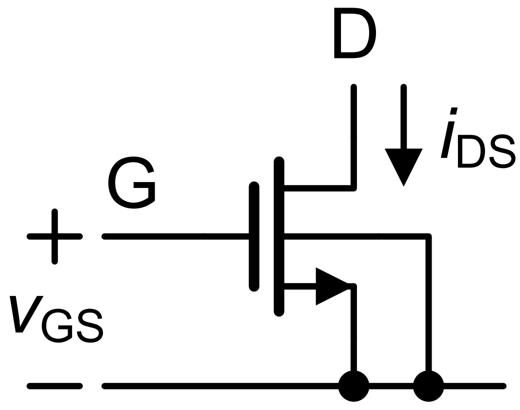
$$I_{DS} = K' \frac{W}{L}(V_{GS} - V_T)^2$$

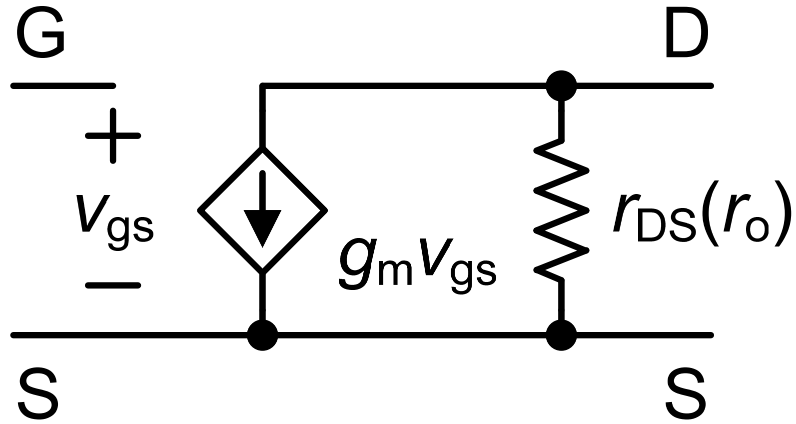
$$K' = \frac{KP}{2n}$$ $\boxed{n\,??}$

$$K_n' \approx 100\ \mu A/V^2$$

$$K_p' \approx 40\ \mu A/V^2$$

MOST的小信号模型：g_m和r_{DS}





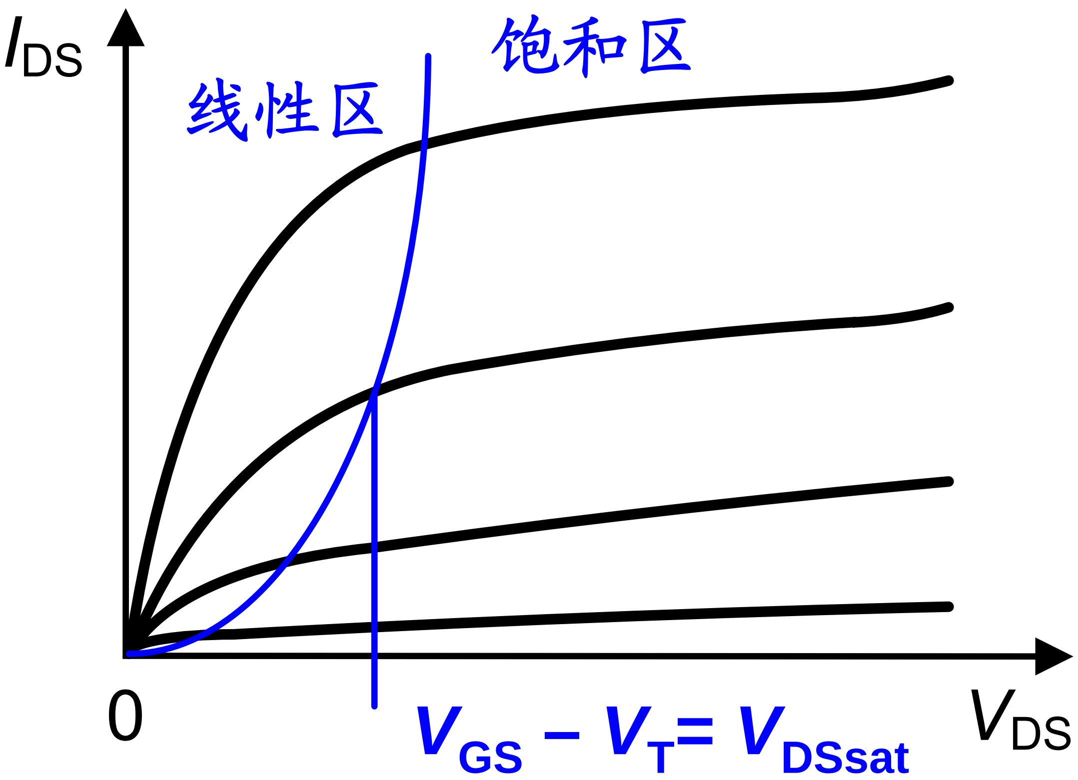
$$g_m = \frac{\mathrm{d}i_{DS}}{\mathrm{d}v_{GS}}$$

$$g_m = 2K_n^{'}\frac{W}{L}(V_{GS}-V_T) = 2\sqrt{K_n^{'}\frac{W}{L}I_{DS}} = \frac{2I_{DS}}{V_{GS}-V_T}$$

跨导g_m

g_m正比于$\sqrt{I_{DS}}$，还是I_{DS}？

MOST的小信号模型：r_{DS}



$$r_{DS}=r_o=\frac{V_E L}{I_{DS}}$$

$$\lambda=\frac{1}{V_E L}$$

$$V_{En}=4\ \text{V}/\mu\text{m}$$

$$L=1\ \mu\text{m}$$

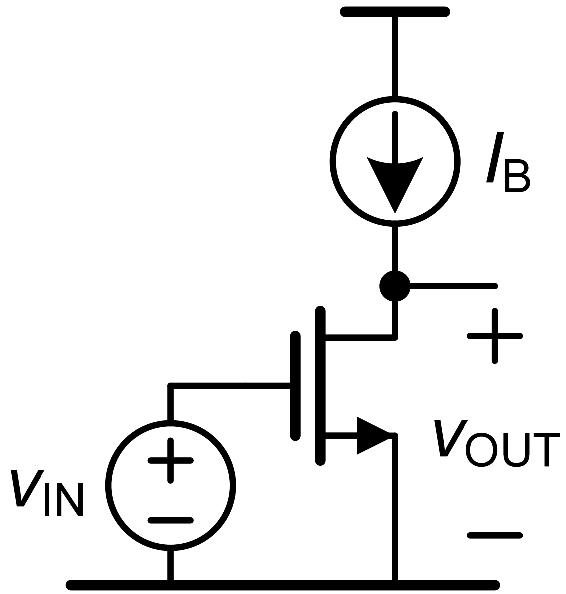
$$I_{DS}=100\ \mu\text{A}$$

$$r_{DS}=40\ \text{k}\Omega$$

$$I_{DS}=K_n'\frac{W}{L}(V_{GS}-V_T)^2(1+\lambda_n V_{DS})$$

$$\frac{1}{r_{DS}}=\frac{di_{DS}}{dv_{DS}}\doteq\lambda I_{DS}$$

MOST单管增益A_V



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

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

高增益设计

	高增益	高速
$V_{GS}-V_T$	低(0.2 V)	
L	高	

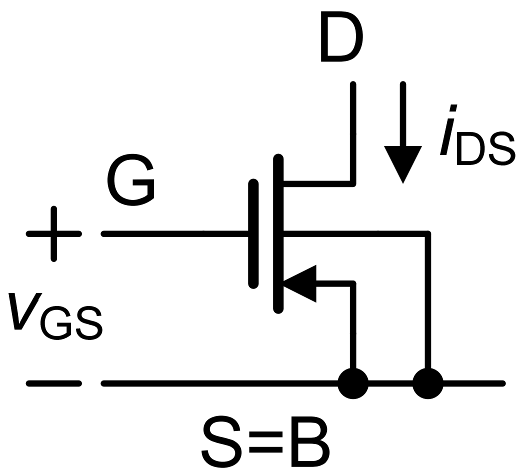
$V_{GS}-V_T$ 决定 g_m/I_{DS} 的比率，能效比!

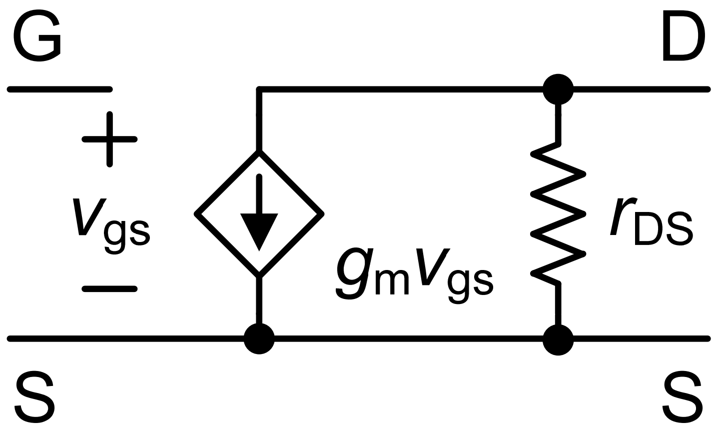
例：单管放大器

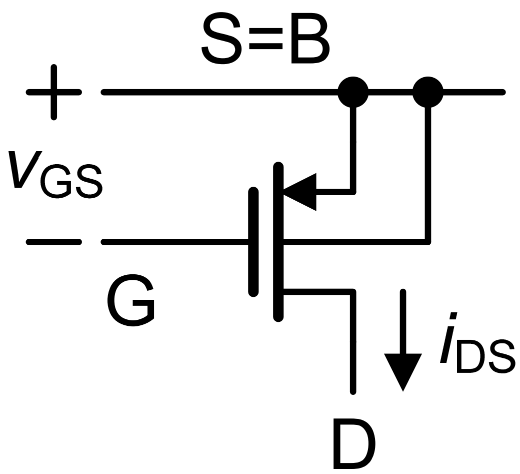
用三个单管串联的结构，实现总增益为10,000的三级放大器。$V_{GS}-V_{T}=0.2\ \mathrm{V}$。

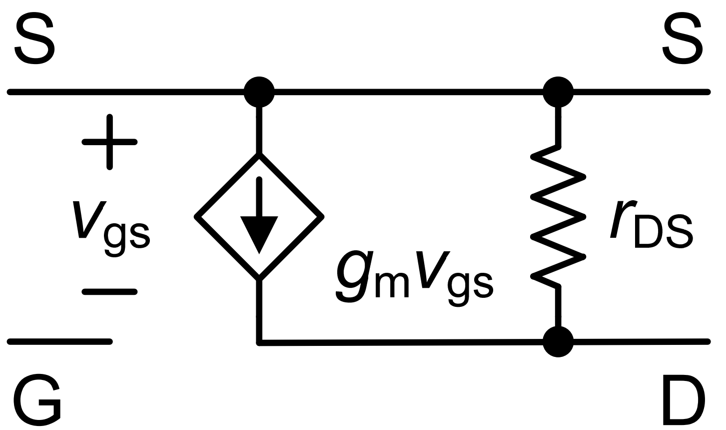
使用先进的65 nm CMOS工艺($V_{En}=4\ \mathrm{V/\mu m}$)，求最小栅长。

pMOST的小信号模型

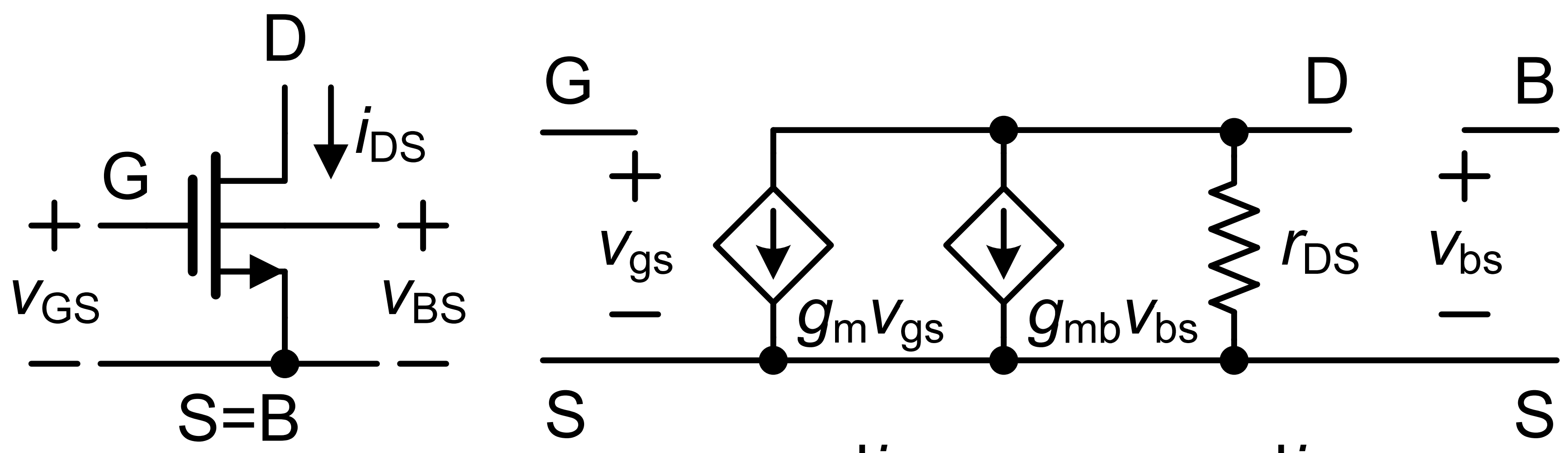








MOST的小信号模型：g_m和g_{mb}



$$g_m = \frac{di_{DS}}{dv_{GS}} \qquad g_{mb} = \frac{di_{DS}}{dv_{BS}}$$

$$\boxed{\frac{g_{mb}}{g_m} = \frac{C_D}{C_{ox}} = n - 1}$$

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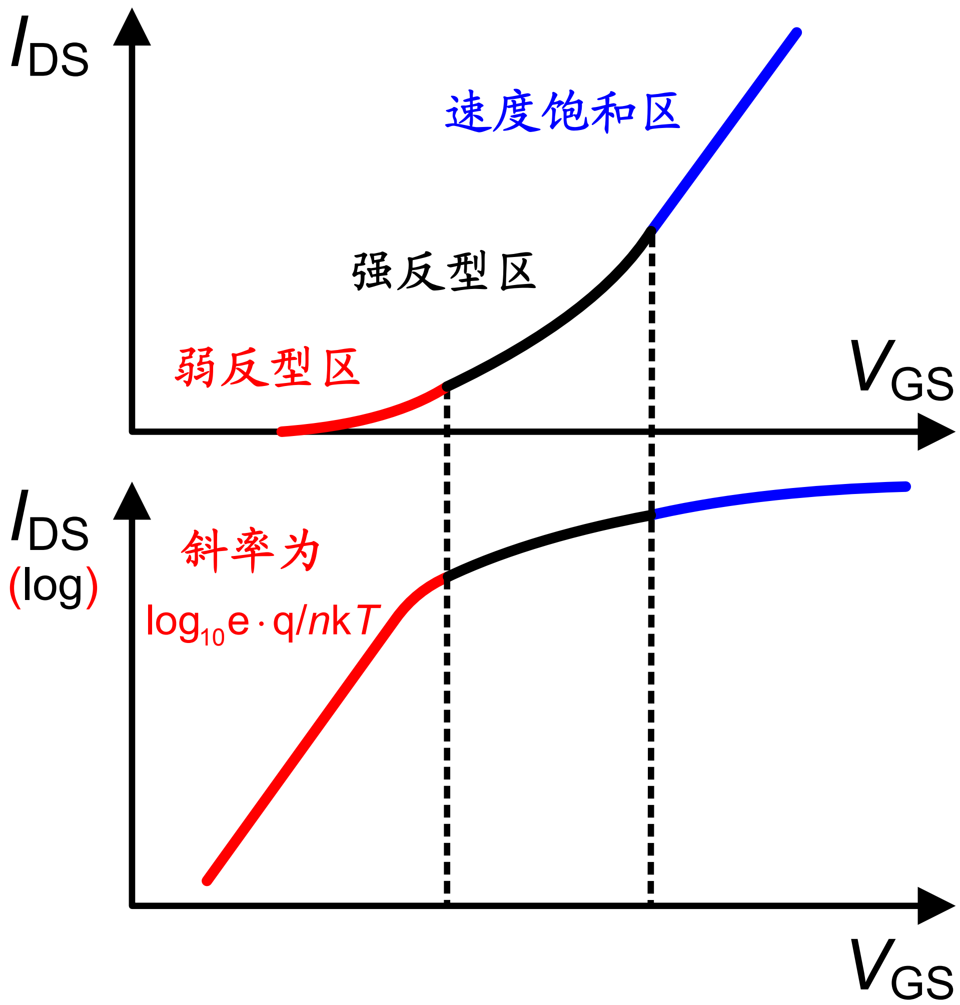
I_{DS}和g_m与V_{GS}的关系：弱反型区



wi：弱反型区

$$I_{DSwi} = I_{D0}\frac{W}{L}e^{\frac{V_{GS}}{nkT/q}}$$

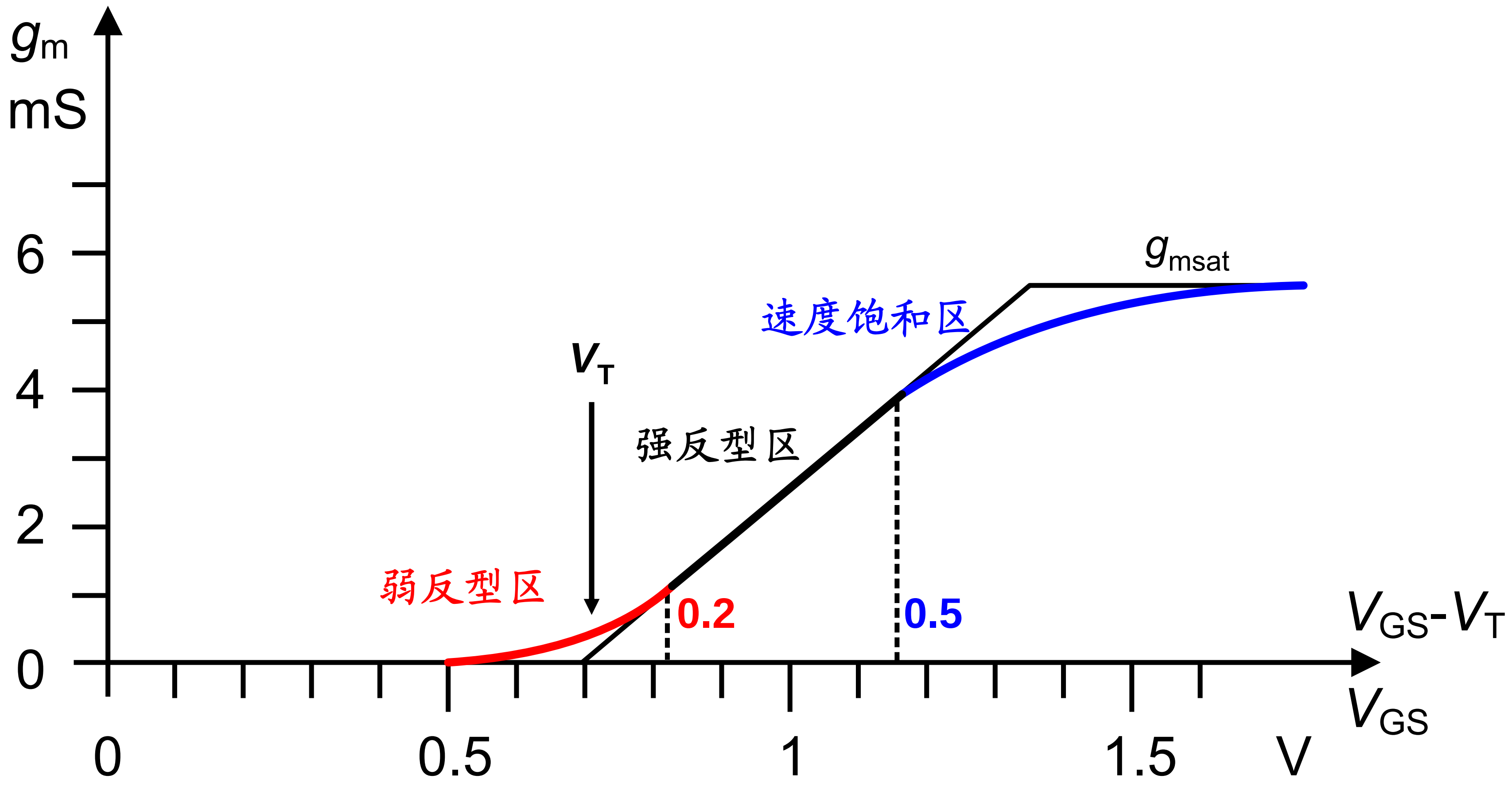
$$g_{mwi} = \frac{I_{DSwi}}{nkT/q}$$

$$k = 1.38 \times 10^{-23}\ \mathrm{J/K}$$

$$q = 1.6 \times 10^{-19}\ \mathrm{C}$$

$$kT/q = 26\ \mathrm{mV} @ T = 300\ \mathrm{K}$$

跨导g_m与V_{GS}的关系



wi与si转换点电压V_{GSt}

$$I_{DSwi} = I_{D0}\frac{W}{L}e^{\frac{V_{GS}}{nkT/q}}$$

$$g_{mwi} = \frac{I_{DSwi}}{nkT/q}$$

$$\frac{g_{mwi}}{I_{DSwi}} = \frac{1}{nkT/q}$$

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

$$g_m = \frac{2I_{DS}}{V_{GS} - V_T}$$

$$\frac{g_m}{I_{DS}} = \frac{2}{V_{GS} - V_T}$$

$$\boxed{(V_{GS} - V_T)_t = 2n\frac{kT}{q}}$$

转换点电压V_{GSt}：与沟道长度L无关

$$\boxed{(V_{GS}-V_T)_t = 2n\frac{kT}{q}}$$

$$(V_{GS}-V_T)_t = 2n\frac{kT}{q} \approx 70\ \mathrm{mV}$$

与沟道长度L无关，

很长时间内仍然遵循这一规律！

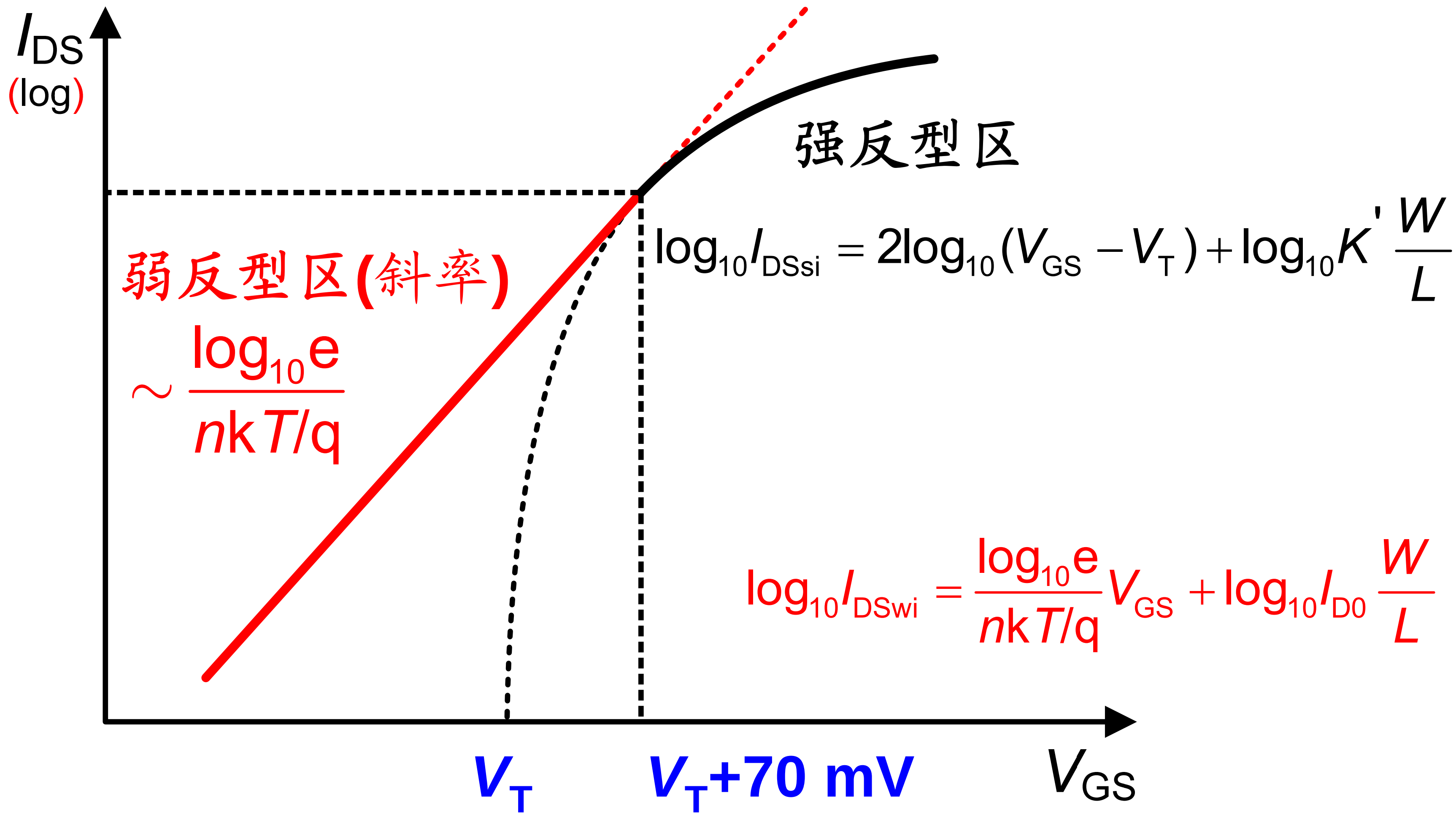
$$K_n^{'} \approx 100\ \mu A/V^2$$

$$K_p^{'} \approx 40\ \mu A/V^2$$

例如，当 $\dfrac{W}{L} = 10$ 时，NMOS的 $I_{DSt} \approx 5\ \mu A$ ；

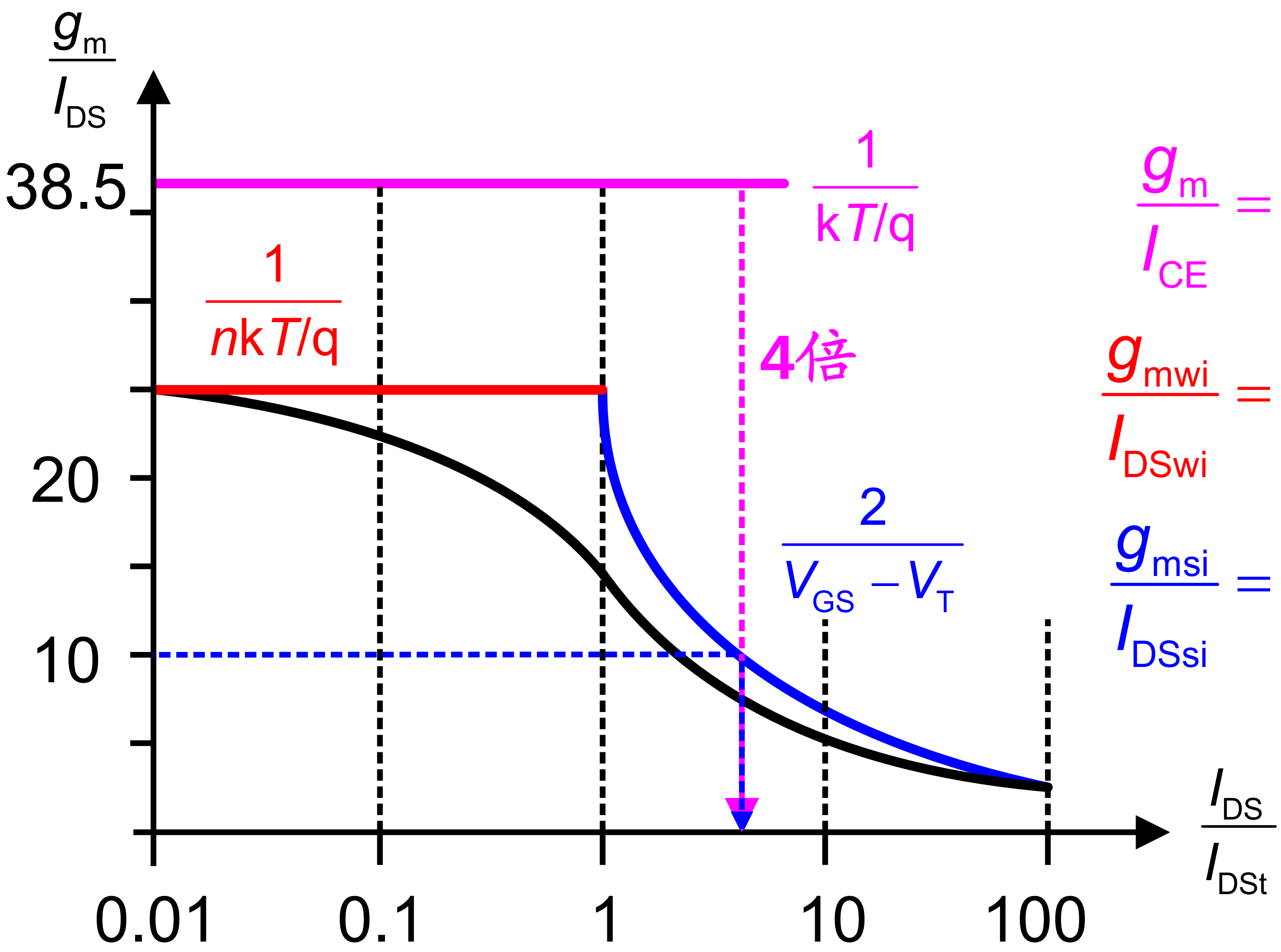
PMOS的 $I_{DSt} \approx 2\ \mu A$ 。

wi与si的转换点



I_{DS}
(log)
强反型区
$\log_{10} I_{DSsi} = 2\log_{10}(V_{GS} - V_T) + \log_{10} K' \frac{W}{L}$
弱反型区(斜率)
$\sim \frac{\log_{10} e}{nkT/q}$
$\log_{10} I_{DSwi} = \frac{\log_{10} e}{nkT/q} V_{GS} + \log_{10} I_{D0} \frac{W}{L}$
V_T
V_T+70 mV
V_{GS}

wi与si转换点的能效比g_m/I_{DS}



$$\frac{g_m}{I_{CE}}=\frac{1}{kT/q}$$

$$\frac{g_{mwi}}{I_{DSwi}}=\frac{1}{nkT/q}$$

$$\frac{g_{msi}}{I_{DSsi}}=\frac{2}{V_{GS}-V_T}$$

wi与si平滑过渡的EKV模型

$$\boxed{I_{DS} = K'\frac{W}{L}V_{GSTt}^2[\ln(1+e^v)]^2}$$

$$V_{GST} = V_{GS} - V_T \quad K' = \frac{KP}{2n}$$

$$v = \frac{V_{GST}}{V_{GSTt}} \quad V_{GSTt} = (V_{GS} - V_T)_t = 2n\frac{kT}{q} \approx 70\text{ mV}$$

当v较小时: $\ln(1+e^v) \approx e^v$

$$I_{DS} = K'\frac{W}{L}V_{GSTt}^2 e^{2v} = K'\frac{W}{L}V_{GSTt}^2 e^{\frac{V_{GS}-V_T}{nkT/q}} = I_{DSt}e^{\frac{V_{GS}-V_T}{nkT/q}}$$

当v较大时: $\ln(1+e^v) \approx v$

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

Ref.: Enz, AICSP ‘95,83-114
Cunha, JSSC Oct.98
1510-1519

wi与si转换点电流I_{DSt}

$$\boxed{I_{DSt} = K'\frac{W}{L}V_{GSTt}^2}$$

$$i = \frac{I_{DS}}{I_{DSt}} = [\ln(1+e^{v})]^2 \quad \text{反型系数}$$

$$v = \ln(e^{\sqrt{i}} - 1)$$

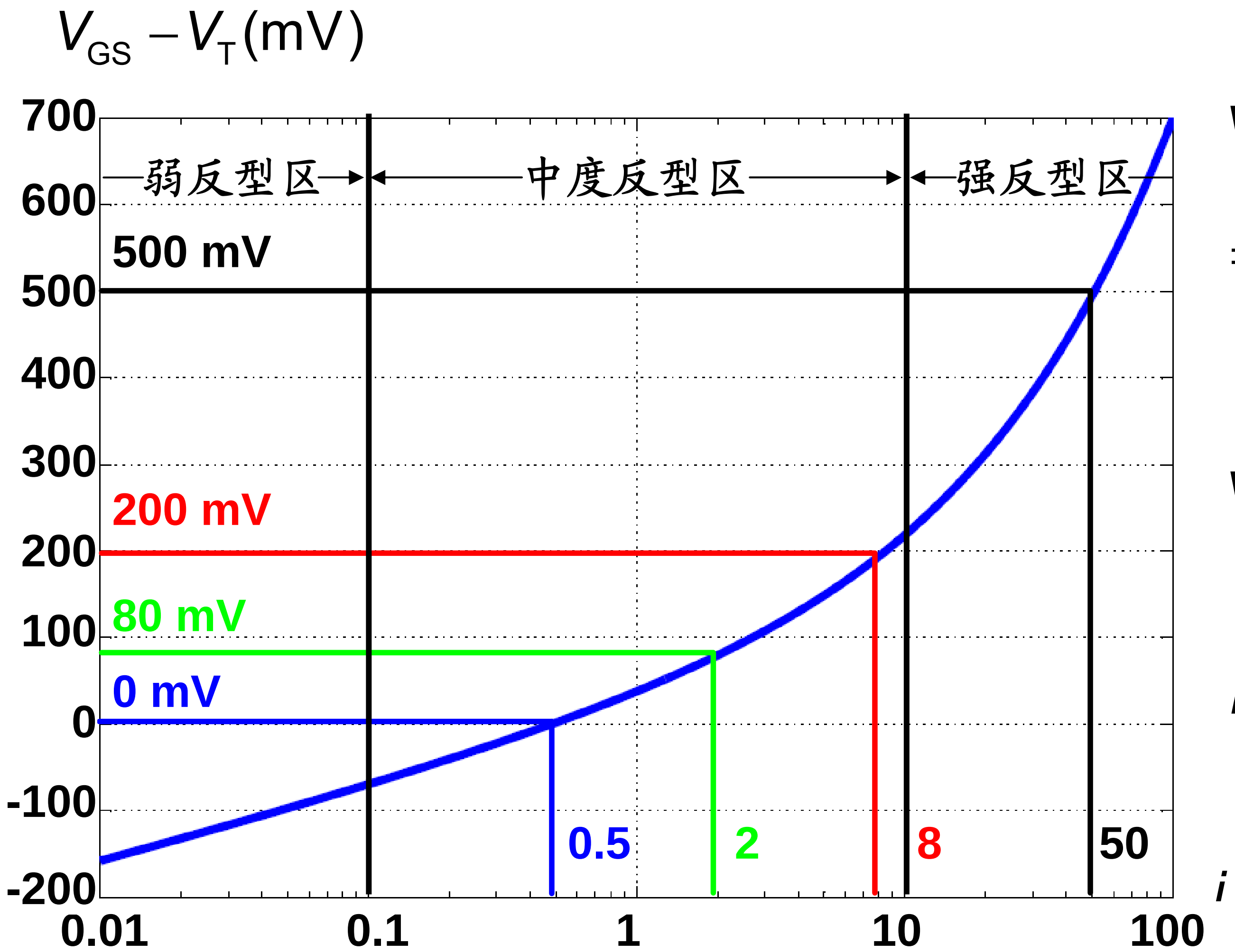
$$V_{GS} - V_T = V_{GSTt}\ln(e^{\sqrt{i}} - 1) \qquad V_{GSTt} = 2n\frac{kT}{q} \approx 70\ \text{mV}$$

$$i = 1 \quad v = \ln(e^{\sqrt{1}} - 1) = 0.54 \qquad V_{GS} - V_T \approx 38\ \text{mV}$$

$$v = 1 \quad i = [\ln(1+e^{1})]^2 = 1.72$$

$$v = 0 \quad i = [\ln(1+e^{0})]^2 = 0.48$$

V_{GS}-V_T与反型系数 i 的关系



$$V_{GS}-V_T = V_{GSTt}\ln(e^{\sqrt{i}}-1)$$

$$V_{GSTt} = 2n\frac{kT}{q}$$

$$i = \frac{I_{DS}}{I_{DSt}}$$

wi与si之间的跨导g_m：归一化GM

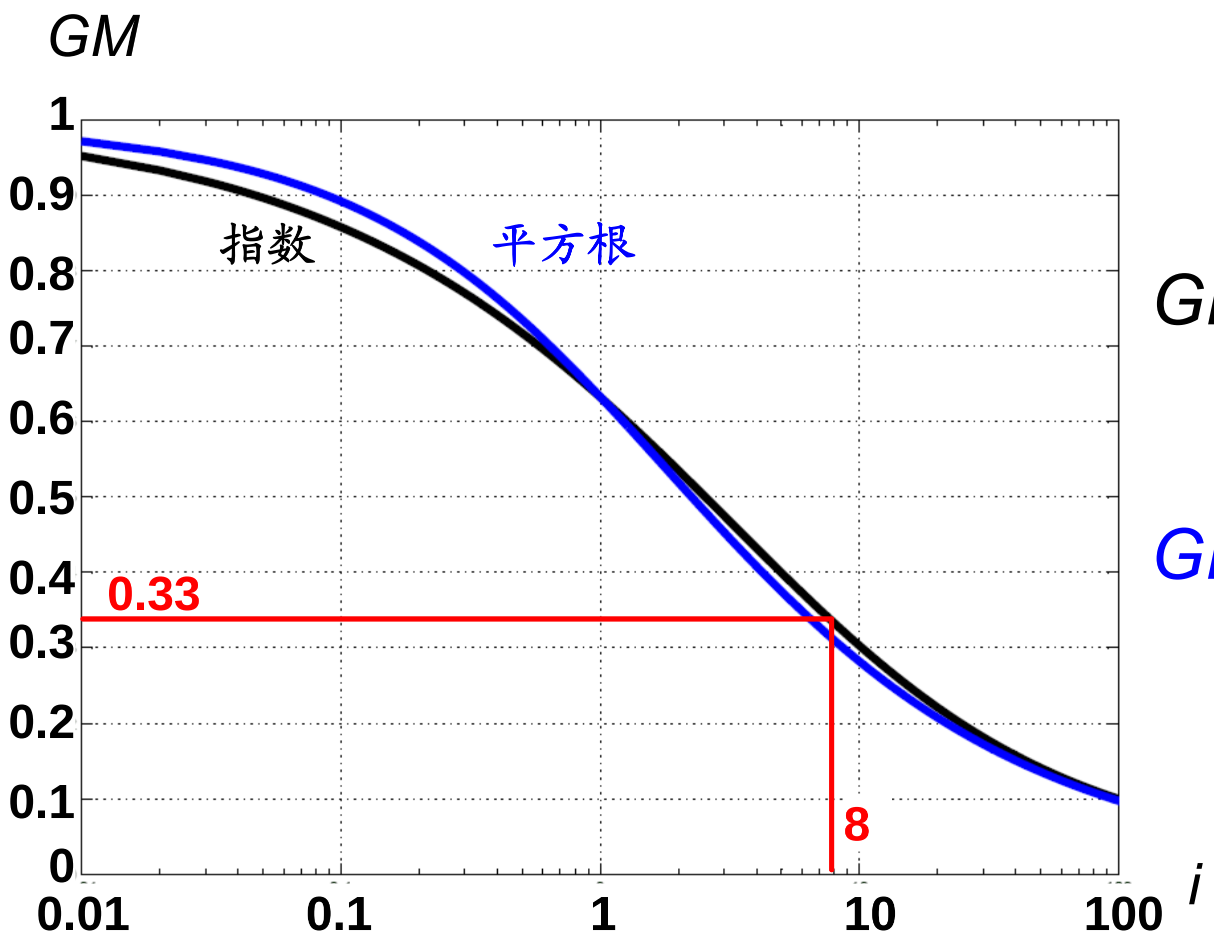
$$i=\frac{I_{DS}}{I_{DSt}}=[\ln(1+e^{v})]^2 \qquad g_m\approx\ldots$$

$$\boxed{GM=\frac{\dfrac{g_m}{I_{DS}}}{\dfrac{1}{nkT/q}}=\frac{g_m}{I_{DS}}\frac{nkT}{q}}$$

$$(1)GM=\frac{1-e^{-\sqrt{i}}}{\sqrt{i}} \qquad 大\ i:GM=\frac{1}{\sqrt{i}} \quad 小\ i:GM=1-\frac{\sqrt{i}}{2}$$

$$(2)GM=\frac{1}{\sqrt{1+0.5\sqrt{i}+i}} \qquad 大\ i:GM=\frac{1}{\sqrt{i}} \quad 小\ i:GM=1-\frac{\sqrt{i}}{4}$$

归一化跨导GM与反型系数 *i* 的关系



$$GM=\frac{g_m}{I_{DS}}\frac{nkT}{q}$$

$$GM=\frac{1-e^{-\sqrt{i}}}{\sqrt{i}}$$

(指数)

$$GM=\frac{1}{\sqrt{1+0.5\sqrt{i}+i}}$$

(平方根)

$$i=\frac{I_{DS}}{I_{DSt}}$$

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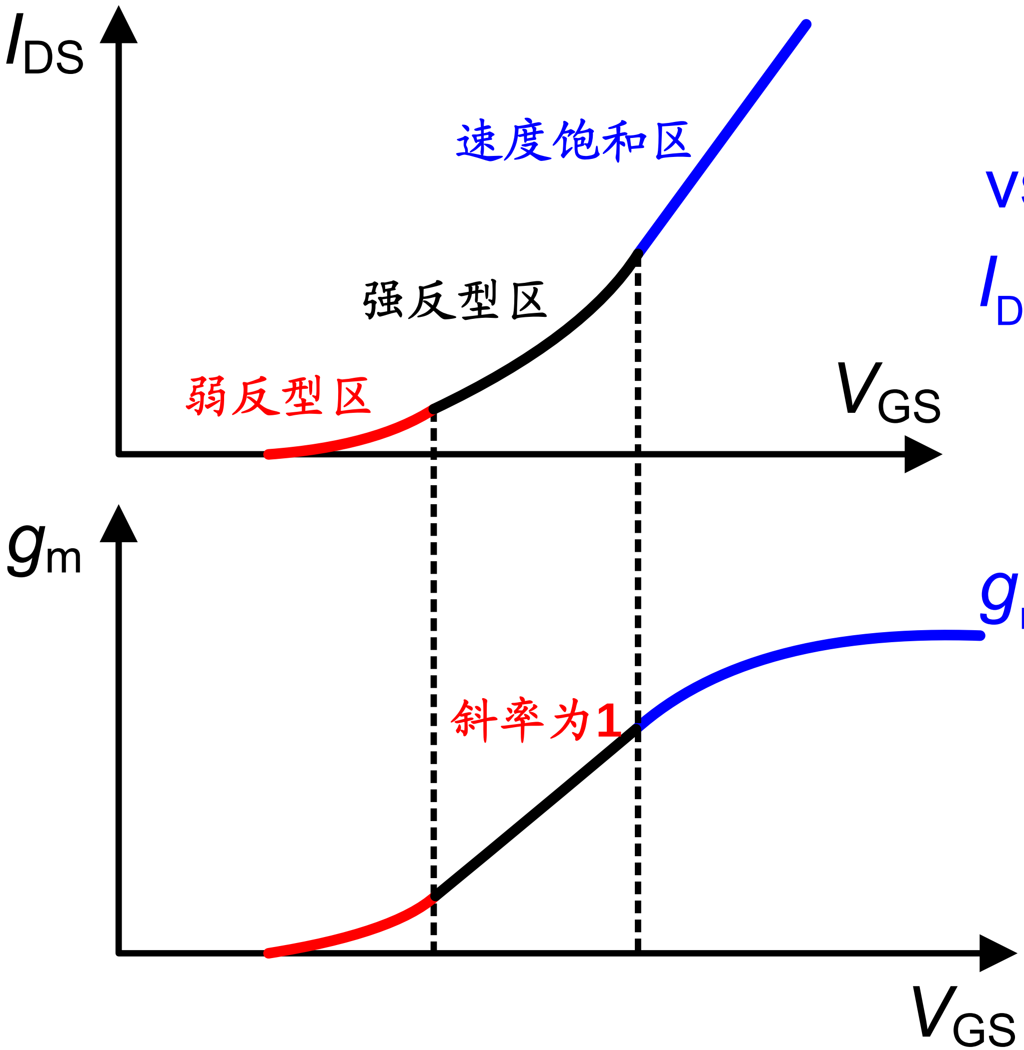
- MOS晶体管模型
  - ❑线性区：MOST线性电阻和模拟开关
  - ❑强反型区：MOST放大器
  - ❑弱反型与强反型的转换点
  - ❑强反型与速度饱和的转换点
  - ❑寄生电容与特征频率f_T
- 双极型晶体管模型
- MOST与双极型晶体管的比较

I_{DS}和g_m与V_{GS}的关系：速度饱和区



vs：速度饱和区

$$I_{DSvs} = WC_{ox}v_{sat}(V_{GS} - V_T)$$

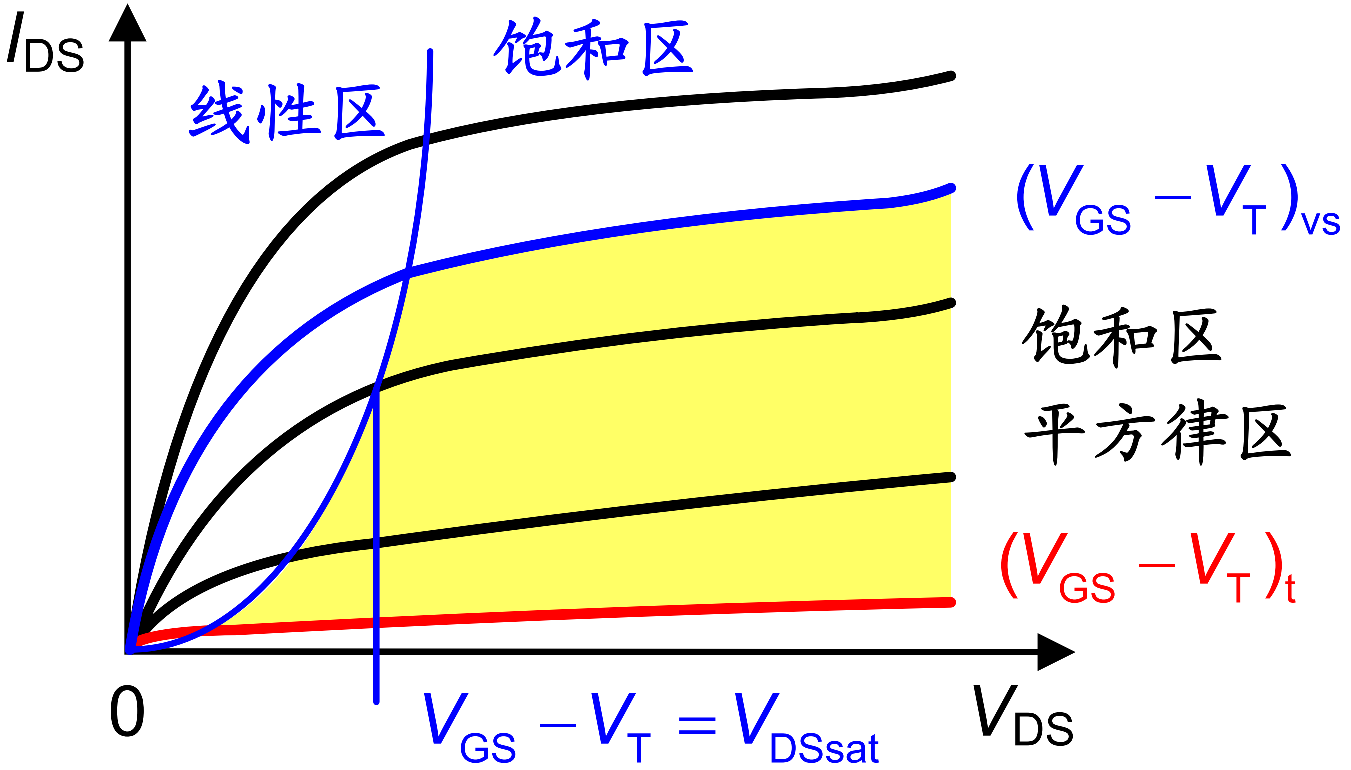
$$v_{sat} \approx 10^7 \text{ cm/s}$$

$$g_{msat} = WC_{ox}v_{sat}$$

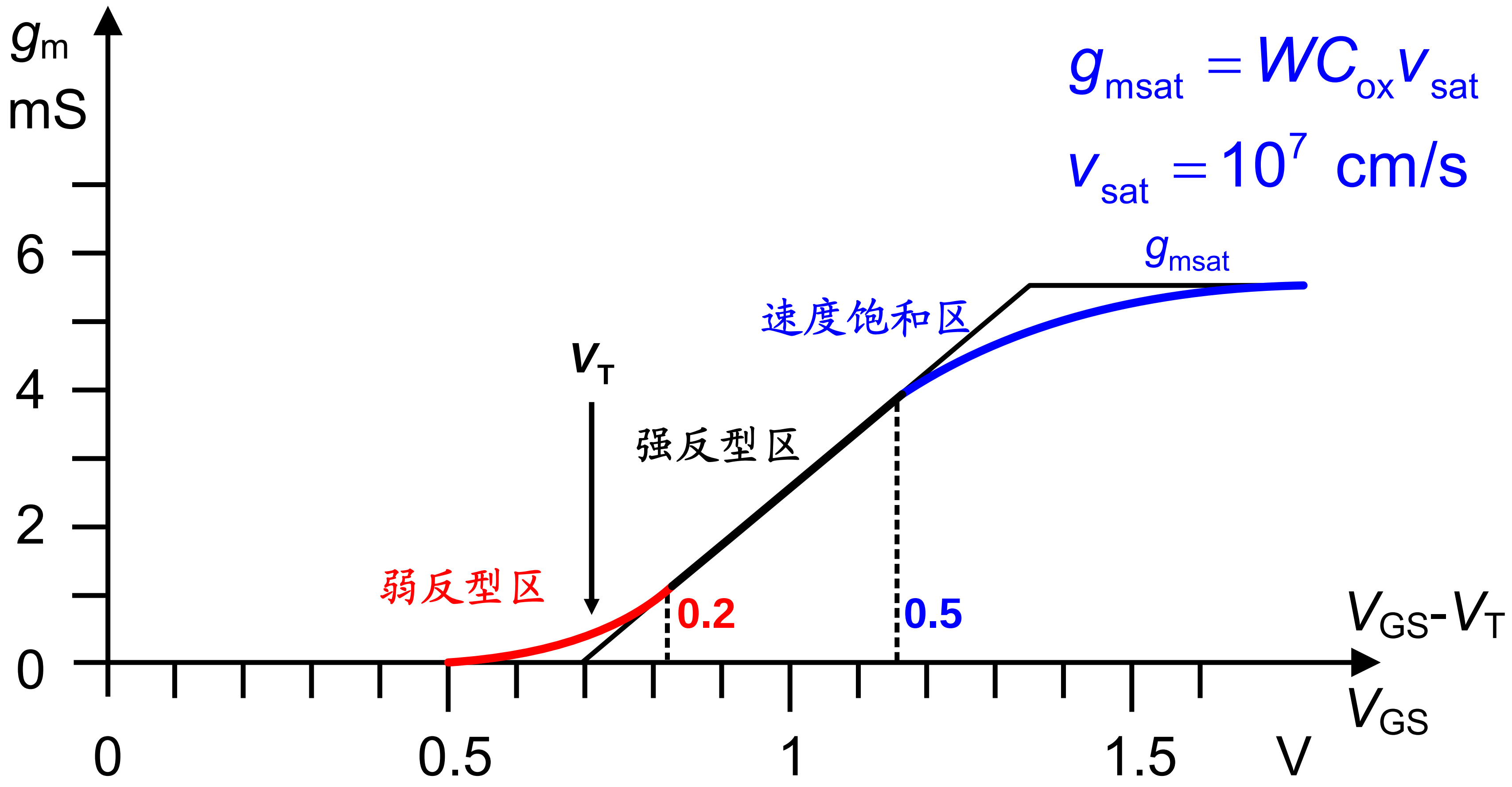
g_{msat}达到最大值，

不再增加。

饱和区和速度饱和区



跨导g_m与V_{GS}的关系



速度饱和区：v_{sat}和θ

$$\boxed{I_{DS}=\frac{K'\dfrac{W}{L}(V_{GS}-V_T)^2}{1+\theta(V_{GS}-V_T)}}$$

$$\approx\frac{K'}{\theta}\frac{W}{L}(V_{GS}-V_T)$$

$$\Downarrow$$

$$g_{msat}\approx 2K'\frac{W}{L}(V_{GS}-V_T)\frac{1+\dfrac{\theta}{2}(V_{GS}-V_T)}{[1+\theta(V_{GS}-V_T)]^2}\approx\frac{K'}{\theta}\frac{W}{L}$$

$$=WC_{ox}v_{sat}$$

$$\boxed{\theta L=\frac{\mu}{2n}\frac{1}{v_{sat}}}=\frac{1}{E_c}$$

E_c垂直临界场强

$$\theta_n L\approx 0.200\ \mu m/V$$
$$\theta_p L\approx 0.083\ \mu m/V$$

当 $L=0.13\ \mu m$，

$$\theta_n\approx 1.54\ V^{-1}$$
$$\theta_p\approx 0.64\ V^{-1}$$

速度饱和区：v_{sat}、R_S和θ

$$I_{DS} = \frac{K^{'}\frac{W}{L}(V_{GS}-V_T)^2}{1+\theta(V_{GS}-V_T)}$$

$$g_{msat} \approx \frac{K^{'}}{\theta}\frac{W}{L} \qquad g_{mRs} = \frac{g_m}{1+g_m R_S} \approx \frac{1}{R_S}$$

$$R_S = \frac{\theta}{K^{'}W/L} \qquad R_S \approx \frac{\mu}{2n}\frac{1}{WK^{'}v_{sat}} \approx \frac{1}{WC_{ox}v_{sat}}$$

si与vs转换点电压V_{GSTvs}

$$I_{DS}=\frac{K'\frac{W}{L}(V_{GS}-V_T)^2}{1+\theta(V_{GS}-V_T)}$$

$$I_{DS}=WC_{ox}v_{sat}(V_{GS}-V_T)$$

$$g_{msat}=WC_{ox}v_{sat}\approx\frac{K'}{\theta}\frac{W}{L}$$

$$(V_{GS}-V_T)_{vs}=\frac{1}{\theta}\approx 2nL\frac{v_{sat}}{\mu_n}$$

正比于沟道长度*L*！！！

$$\approx 5L$$

$$v_{sat}=10^7\ \text{cm/s}$$

$$n=1.4$$

当 $L=0.13\ \mu\text{m}$ 时，$(V_{GS}-V_T)_{vs}\approx 0.65\ \text{V}$

$$\mu_n=500\ \text{cm}^2/\text{Vs}$$

si与vs转换点电流I_{DSvs}

$$I_{DSvs} \approx K_n^{'} \frac{W}{L} \left(\frac{2nLv_{sat}}{\mu_n}\right)^2 \approx 100 n \varepsilon_{ox} W \frac{v_{sat}^2}{\mu_n}$$

$$K_n^{'} = \frac{\mu_n C_{ox}}{2n} \quad C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} \quad t_{ox} = \frac{L_{min}}{50}$$

$$\frac{I_{DSvs}}{W} \approx 10\ \text{A/cm}$$

$$\varepsilon_{ox} = 0.34\ \text{pF/cm}$$

$$v_{sat} = 10^7\ \text{cm/s}$$

$$n = 1.4$$

$$\mu_n = 500\ \text{cm}^2/\text{Vs}$$

当$W = 2.6\ \mu\text{m}$，$L_{min} = 0.13\ \mu\text{m}$时，$I_{DSvs} \approx 2.6\ \text{mA}$。

si与vs转换点跨导g_m

$$g_{msat} = WC_{ox}v_{sat} = 50\varepsilon_{ox}v_{sat}\frac{W}{L_{min}} = 17\times10^{-5}W/L_{min}\ \ (S)\Big|_{cm}$$

$$g_{msi} = 2K_n'\frac{W}{L_{min}}(V_{GS}-V_T)$$

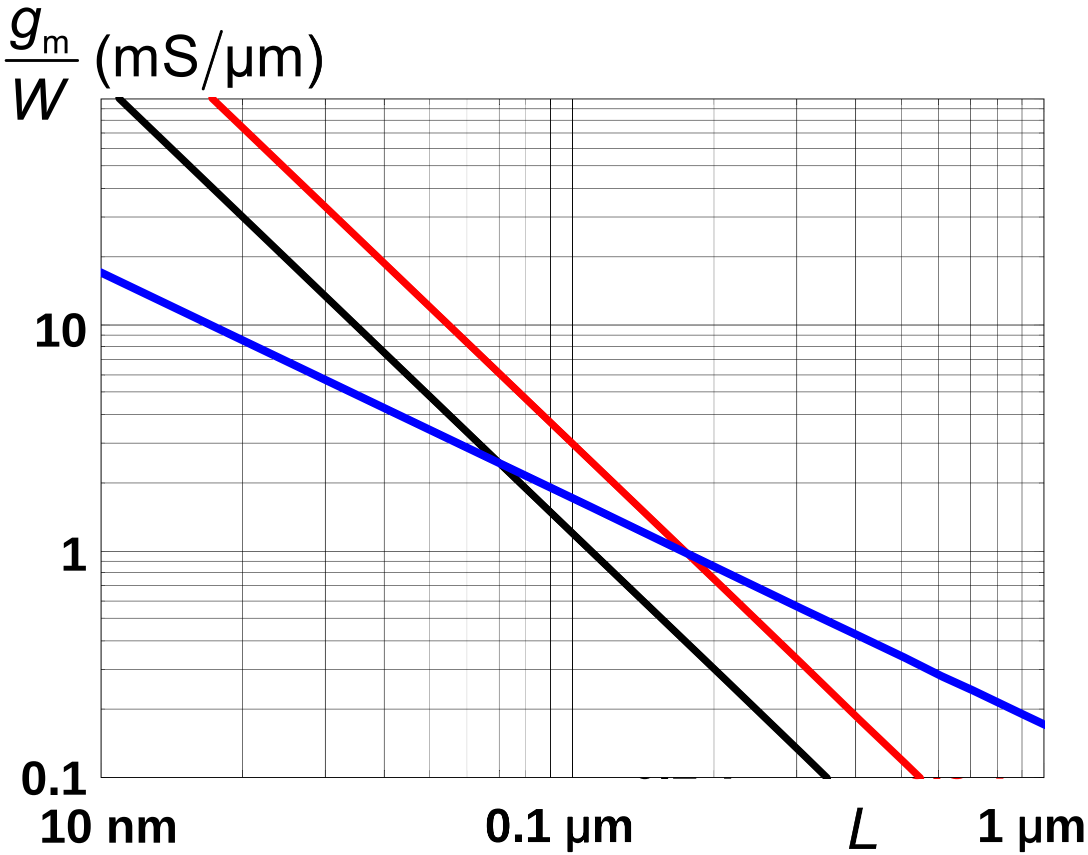
$$= \frac{50\mu_n\varepsilon_{ox}}{n}\frac{W}{L_{min}^2}V_{GST} = 6\times10^{-9}V_{GST}W/L_{min}^2\ \ (S)\Big|_{cm}$$

$$\frac{1}{g_m} = \frac{1}{g_{msat}} + \frac{1}{g_{msi}} \approx \frac{W}{L_{min}}\frac{17\times10^{-5}}{1+2.8\times10^4 L_{min}/V_{GST}}$$

L_{min}的单位为cm

$$g_{msat} = g_{msi} \qquad L_{min} = \frac{\mu_n V_{GST}}{nv_{sat}} \doteq 0.4V_{GST}(\mu m)$$

速度饱和区？强反型区？



$$V_{GS} - V_T \approx 0.2\ \text{V}$$

$$(0.5\ \text{V})$$

$$\frac{g_{msi}}{W} = \frac{2K_n'}{L_{min}}(V_{GS} - V_T)$$

$$\frac{g_{msi}}{W} \approx \frac{0.06V_{GST}}{L_{min}^2}$$

L的单位为μm

$$\frac{g_{msat}}{W} = C_{ox}v_{sat}$$

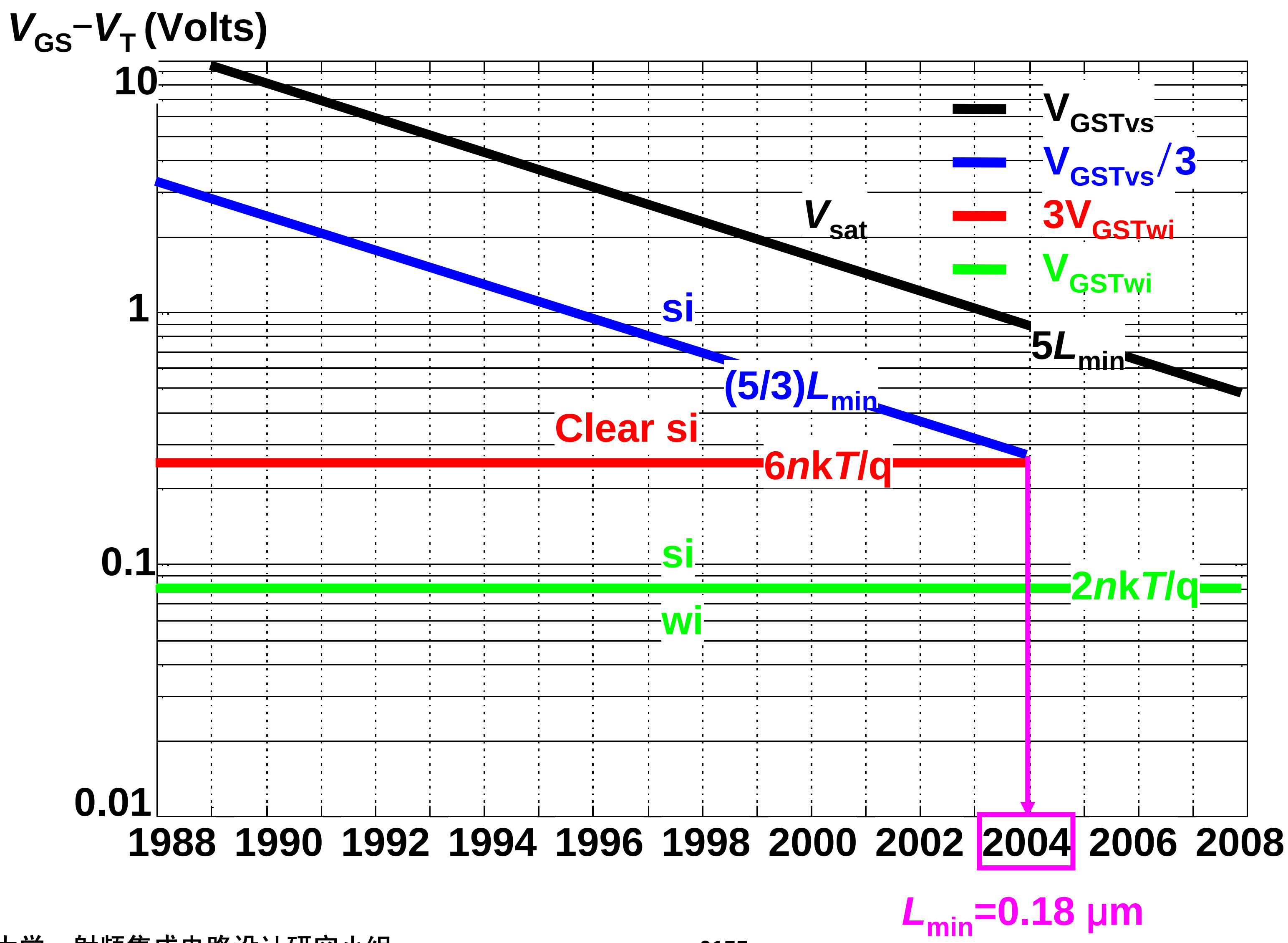
$$\frac{g_{msat}}{W} \approx \frac{0.17}{L_{min}}$$

L的单位为μm

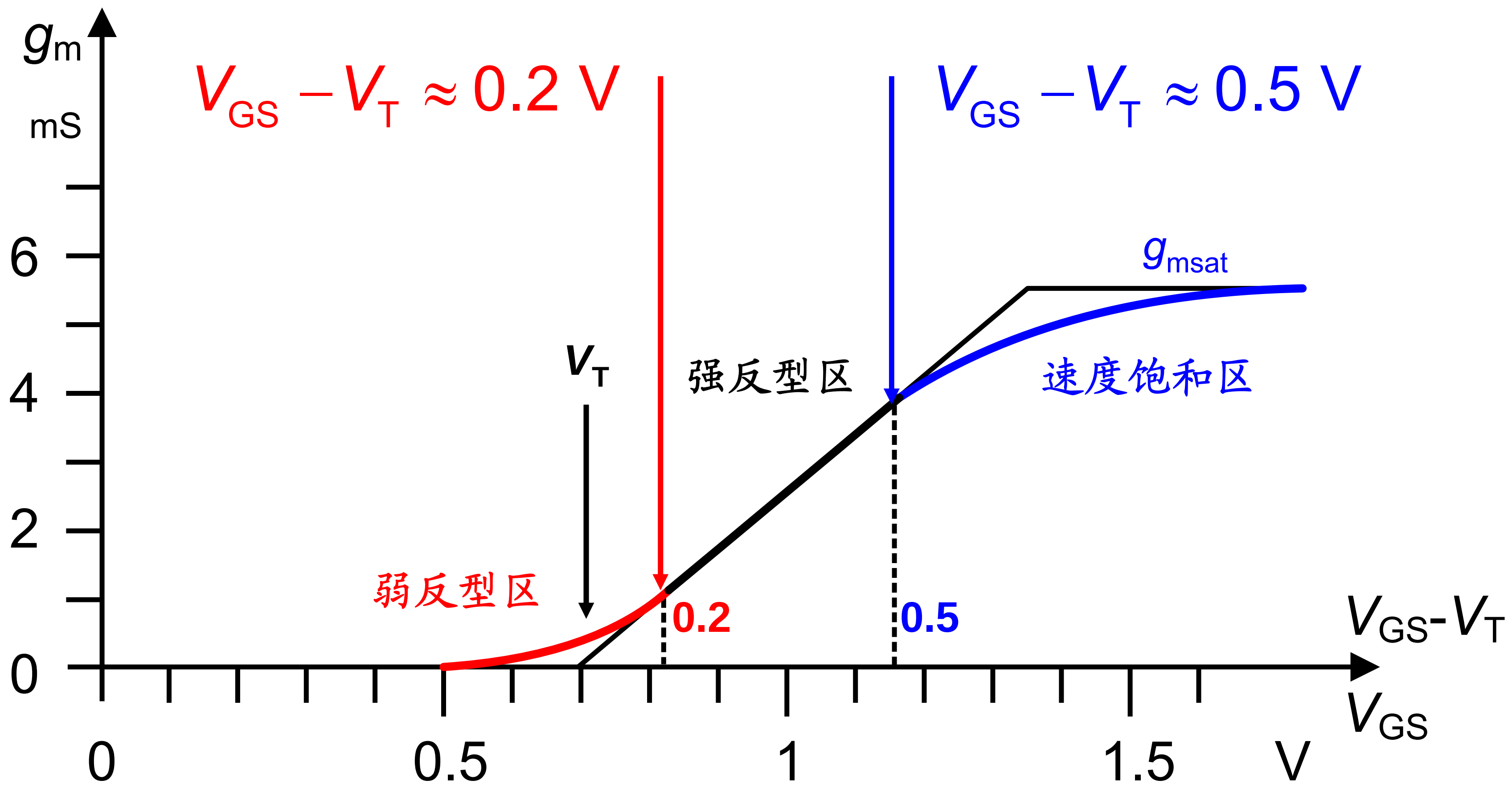
当V_{GST}=0.2 V，L_{min}<65 nm;

或V_{GST}=0.5 V，L_{min}<0.18 μm 时，晶体管进入速度饱和区

强反型区V_{GS}-V_T的有效范围

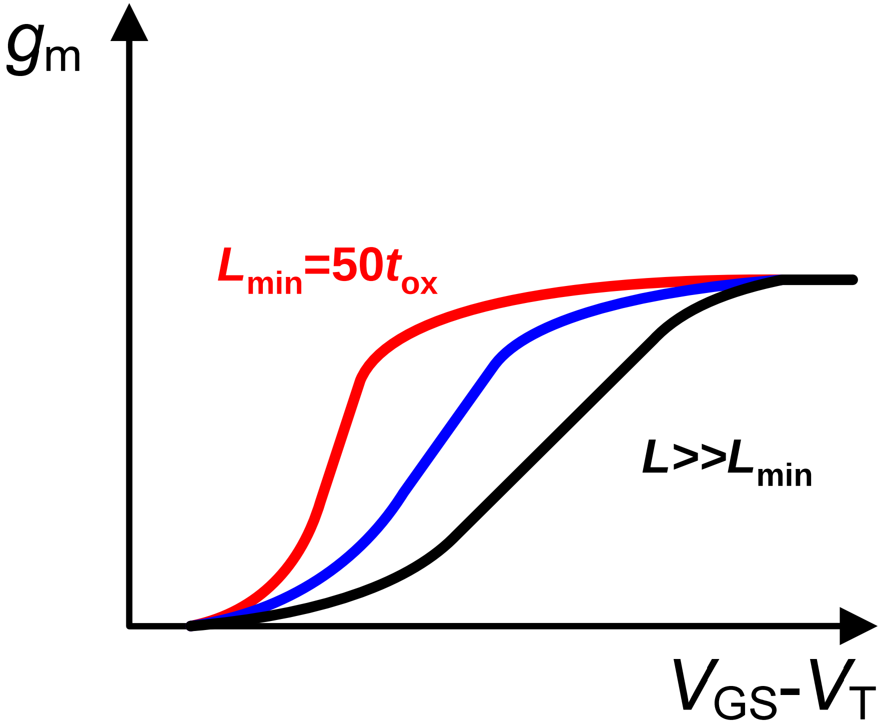


在强反型区MOST的工作范围

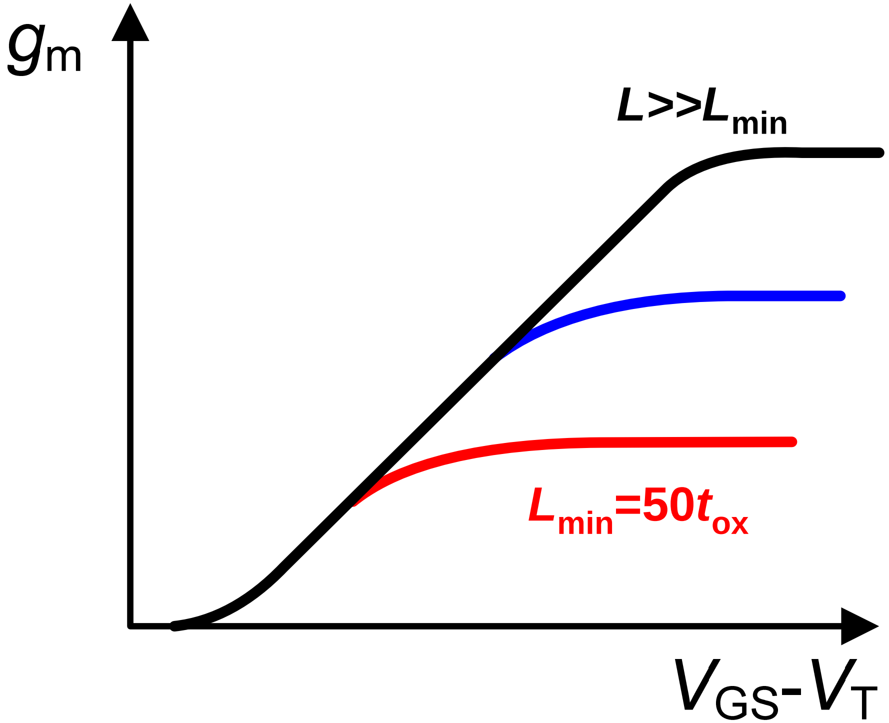


相同工艺下，不同L值，g_m vs. V_{GS}

相同t_{ox}值！



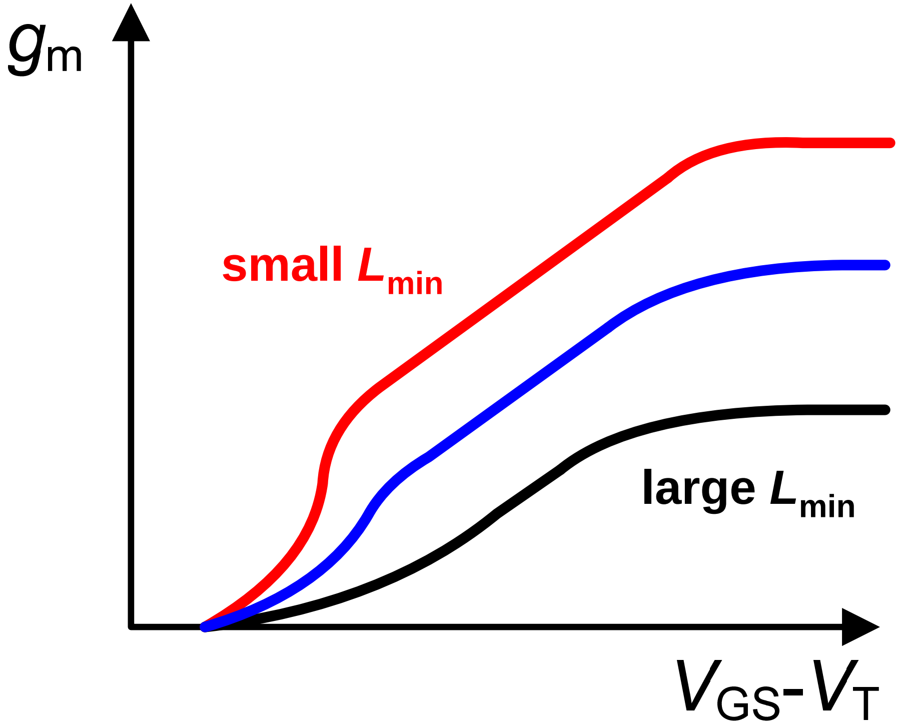
$W = \mathrm{ct}$



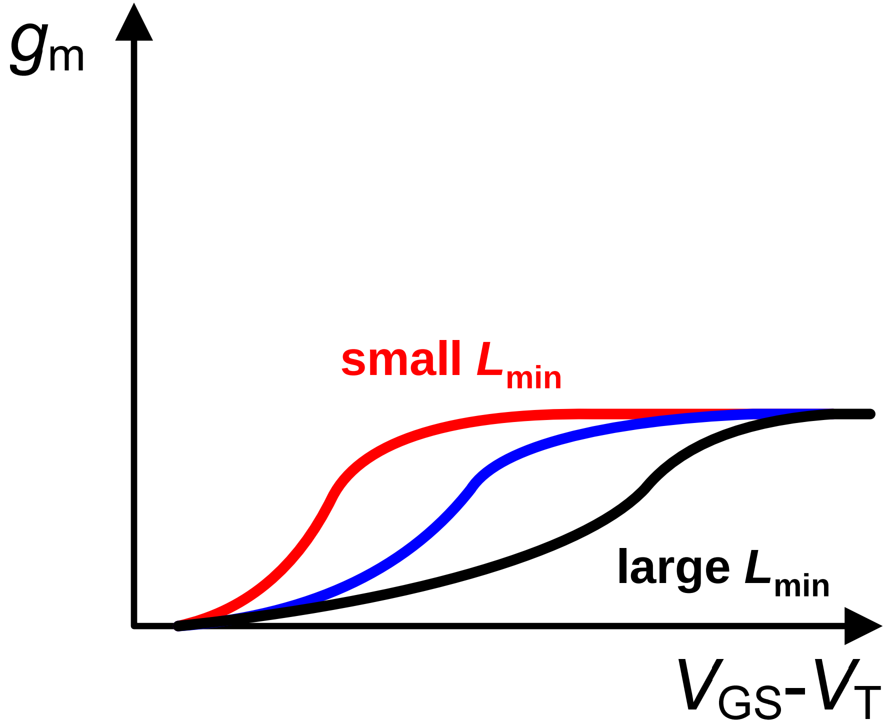
$\dfrac{W}{L} = \mathrm{ct}$

不同工艺下，L_{min}值，g_m vs. V_{GS}

不同t_{ox}值！



$W = \text{ct}$



$\frac{W}{L} = \text{ct}$

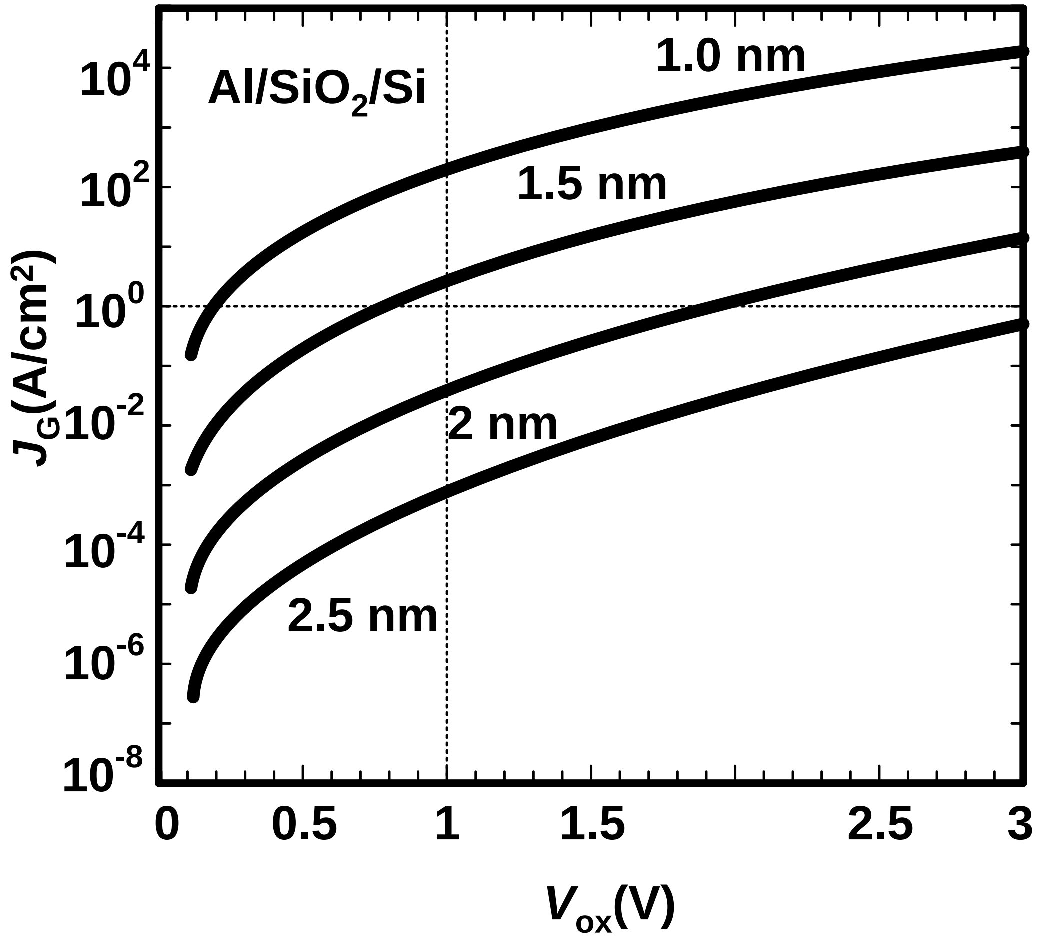
MOST的I_{DS}、g_m和g_m/I_{DS}

摘要：关于I_{DS}、g_m和g_m/I_{DS}的公式

	I_{DS}	g_m	$\frac{g_m}{I_{DS}}=f(V_{GS}-V_T)$	$\frac{g_m}{I_{DS}}=f(I_{DS})$
wi	$I_{D0}\frac{W}{L}e^{\frac{V_{GS}}{nkT/q}}$ (1-25a)	$\frac{I_{D0}}{nkT/q}\frac{W}{L}e^{\frac{V_{GS}}{nkT/q}}$ (1-25b)	$\frac{1}{nkT/q}$ (1-26b)	$\frac{1}{nkT/q}$ (1-26b)
ws			$(V_{GS}-V_T)_{ws}=2n\frac{kT}{q}$	$I_{DSws}=\frac{KP}{2n}\frac{W}{L}(2n\frac{kT}{q})^2$
si	$\frac{KP}{2n}\frac{W}{L}(V_{GS}-V_T)^2$ (1-18c)	$2\frac{KP}{2n}\frac{W}{L}(V_{GS}-V_T)$ (1-22a)	$\frac{2}{V_{GS}-V_T}$ (1-26a)	$2\sqrt{K_n'\frac{W}{L}\frac{1}{I_{DS}}}$ (1-26a)
sv	$I_{DSsi}=I_{DSvs}$ ⟶	⟶	$(V_{GS}-V_T)_{sv}=\frac{2nLC_{ox}v_{sat}}{KP}$	$I_{DSsv}=\frac{2nWLC_{ox}^2v_{sat}^2}{KP}$
		$g_{msi}=g_{mvs}$ ⟶	$(V_{GS}-V_T)_{sv}=\frac{2nLC_{ox}v_{sat}}{2KP}$	$I_{DSsv}=\frac{2nWLC_{ox}^2v_{sat}^2}{2KP}$
vs	$WC_{ox}v_{sat}(V_{GS}-V_T)$ (1-38b)	$WC_{ox}v_{sat}$ (1-39)	$\frac{1}{V_{GS}-V_T}$	$\frac{WC_{ox}v_{sat}}{I_{DSvs}}$

Ref.: Laker, Sansen : Design of analog …, MacGrawHill 1994; Table 1-4

栅极漏电流



0.1μm COMS:

$t_{ox} \approx 2$ nm

$J_G \approx 4 \times 10^{-2}$ A/cm^2

10×0.5 μm :

$I_G \approx 2$ nA

$$J_G(\text{A/cm}^2) \approx 4.5 \times 10^5 \exp(-\frac{L}{6.5})$$

L_{min}的单位为nm

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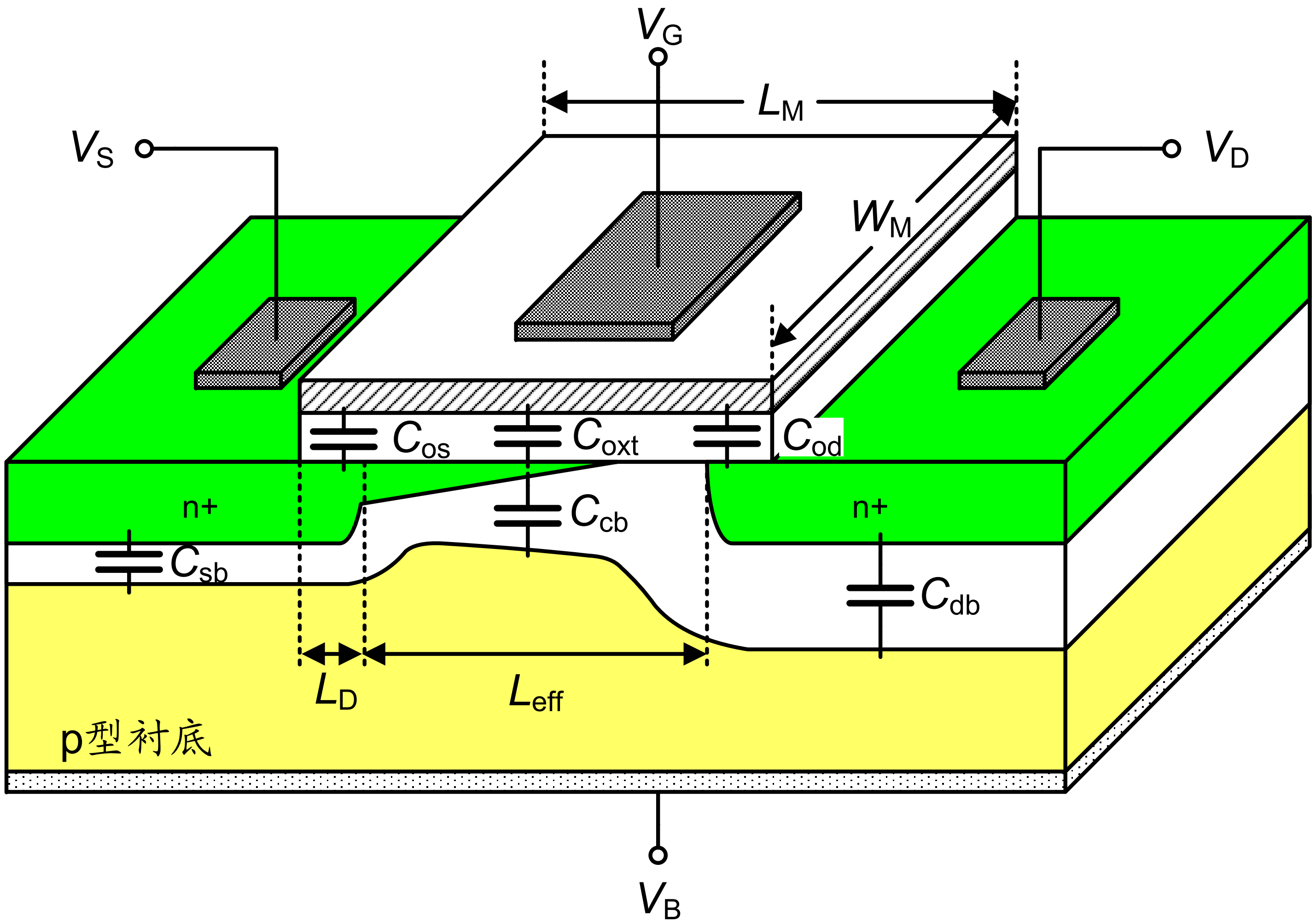
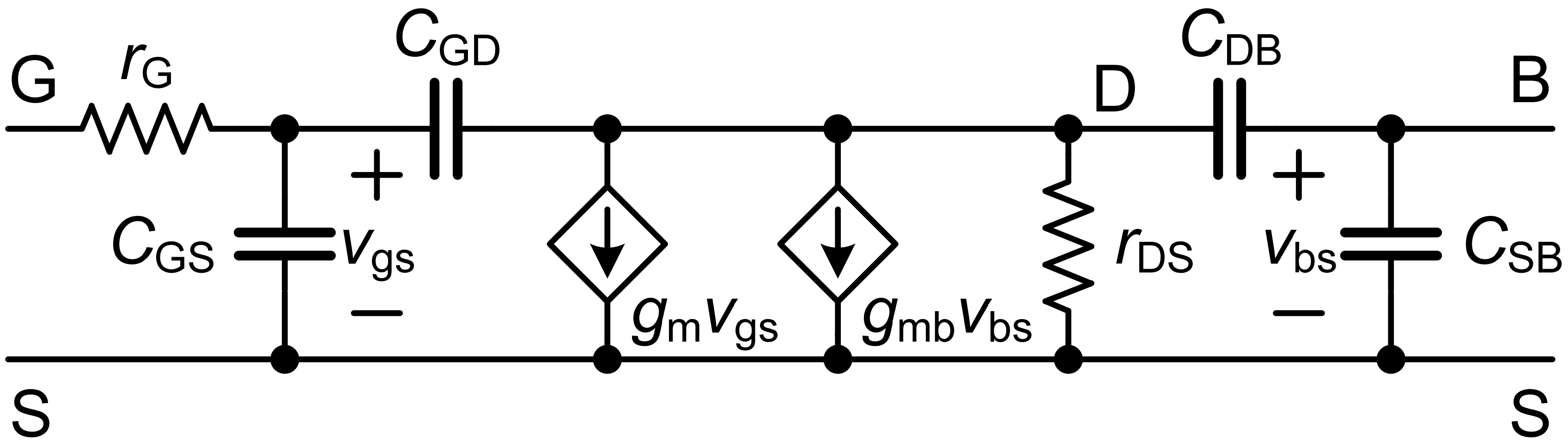
MOST电容



MOST电容C_{GS}和C_{GD}



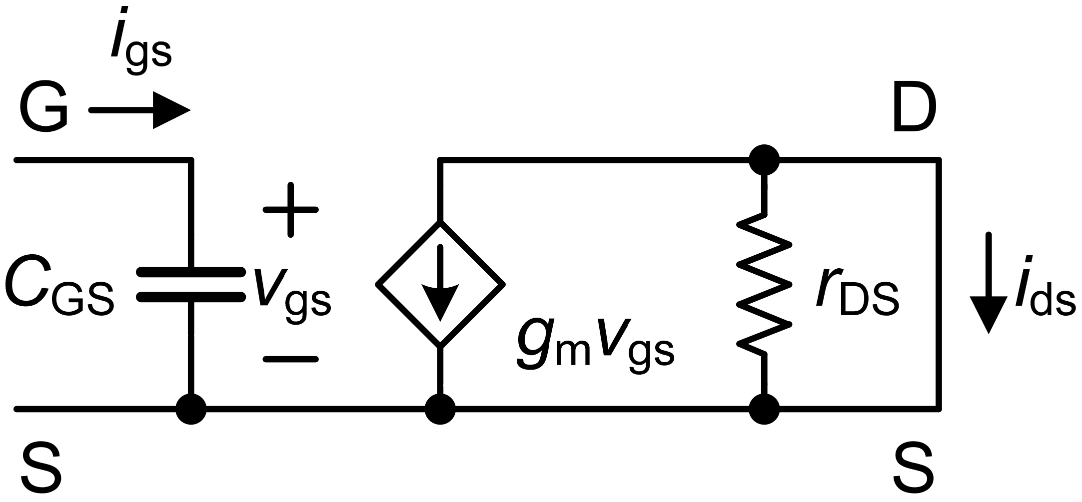
$$C_{GS} \approx \frac{2}{3} WLC_{ox}$$

当L=L_{min}时， $C_{GS} \approx 2W$ fF

$$L_{min}C_{ox} \approx L_{min}\frac{\varepsilon_{ox}}{t_{ox}} \approx 50\varepsilon_{ox} \approx 2 \text{ fF}/\mu\text{m}$$

$$C_{GD} = WC_{gdo}$$

当$i_{ds}=i_{gs}$时，MOST的特征频率f_T



$$\begin{cases} i_{gs} = v_{gs} C_{GS} s \\ i_{ds} = g_m v_{gs} \end{cases}$$

$$C_{GS} = \frac{2}{3} W L C_{ox} \qquad g_m = 2K' \frac{W}{L}(V_{GS} - V_T) \qquad K' = \frac{\mu C_{ox}}{2n}$$

$$\boxed{f_T = \frac{g_m}{2\pi C_{GS}} = \frac{1}{2\pi} \frac{3}{2n} \frac{\mu}{L^2}(V_{GS} - V_T)}$$

$$\frac{1}{2\pi \cdot L/v_{sat}} = \boxed{\frac{v_{sat}}{2\pi L}} \times \frac{3}{2}?$$

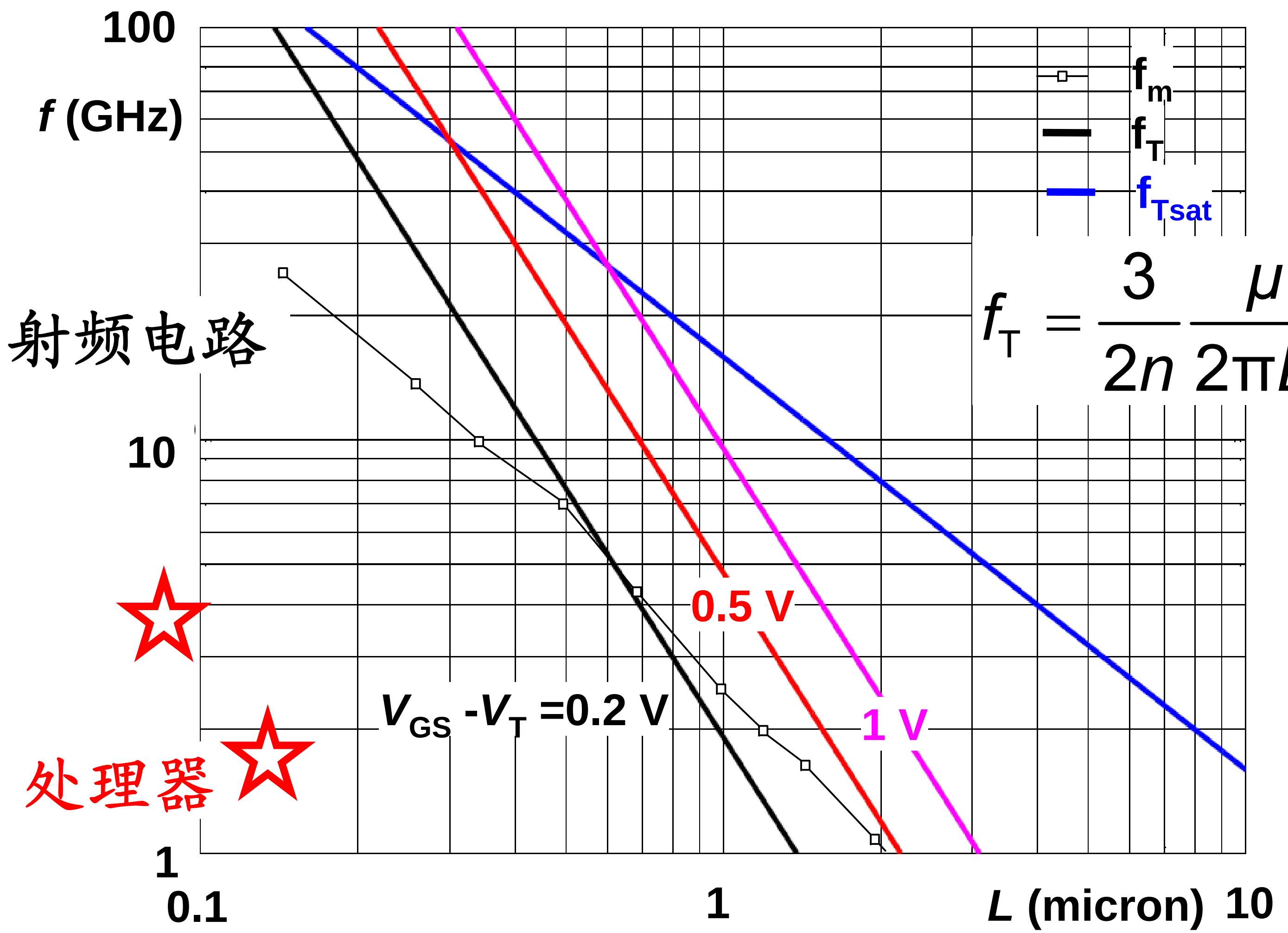
$$g_m = W C_{ox} v_{sat}$$

高速设计

	高增益	高速
$V_{GS}-V_T$	低(0.2 V)	高(0.5 V)
L	高	低

$V_{GS}-V_T$ 决定 g_m/I_{DS} 的比率，能效比!

最大特征频率f_T与沟道长度L的关系



$$f_T = \frac{3}{2n}\frac{\mu}{2\pi L^2}(V_{GS} - V_T)$$

$$f_{Tsat} = \frac{v_{sat}}{2\pi L}$$

$$f_m = \frac{f_T}{1+\alpha_{BD}}$$

$$\alpha_{BD} \approx \frac{C_{BD}}{C_{ox}}$$

强反型区和速度饱和区的特征频率f_T

$$f_T = \frac{g_m}{2\pi C_{GS}} \qquad C_{GS} = kW \qquad k = 2\ \text{fF/μm} = 2\times10^{-11}\ \text{F/cm}$$

$$g_m = \frac{W}{L_{min}} \frac{17\times10^{-5}}{1+2.8\times10^{4} L_{min}/V_{GST}} \quad L\text{的单位为cm}$$

$$\boxed{f_T = \frac{1}{L_{min}} \frac{13.5}{1+2.8 L_{min}/V_{GST}}\ \text{GHz}} \quad L\text{的单位为μm}$$

当V_{GST}=0.2 V，L_{min}<65 nm;

或V_{GST}=0.5 V，L_{min}<0.18 μm时，晶体管进入速度饱和区

强反型区和弱反型区的特征频率f_T

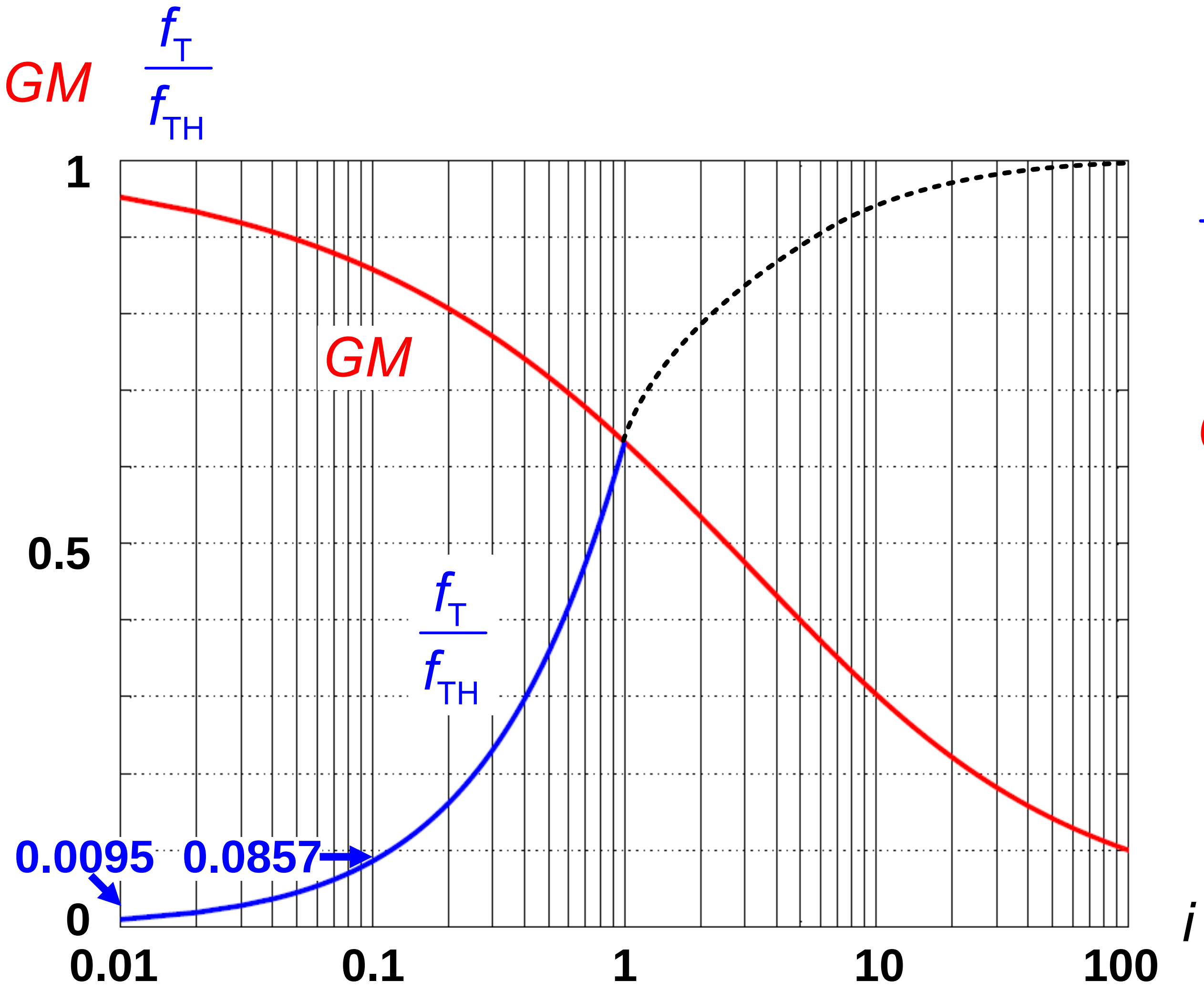
$$\left.\begin{aligned} GM &= \frac{1-e^{-\sqrt{i}}}{\sqrt{i}} \\ I_{DS} &= i \times I_{DSt} \end{aligned}\right\} \quad g_m = \frac{I_{DSt}}{nkT/q}\sqrt{i}\left(1-e^{-\sqrt{i}}\right)$$

$$\left.\begin{aligned} f_T &= \frac{g_m}{2\pi C_{GS}} \\ g_m &= \frac{I_{DSt}}{nkT/q}\sqrt{i}\left(1-e^{-\sqrt{i}}\right) \end{aligned}\right\} \quad \frac{f_T}{f_{TH}} = \sqrt{i}\left(1-e^{-\sqrt{i}}\right)$$

$$f_{TH} = \frac{I_{DSt}}{2\pi C_{GS} nkT/q} = \frac{K'\frac{W}{L}V_{GSTt}^2}{2\pi \frac{2}{3}WLC_{ox} nkT/q} = \frac{3}{2\pi}\frac{\mu kT/q}{L^2}$$

$$\boxed{\text{当}i\text{较小时：}\ \frac{f_T}{f_{TH}} = \sqrt{i}\left(1-e^{-\sqrt{i}}\right) \approx i}$$

特征频率f_T与反型系数 i 的关系



$$\frac{f_T}{f_{TH}} = \sqrt{i}\left(1 - e^{-\sqrt{i}}\right)$$

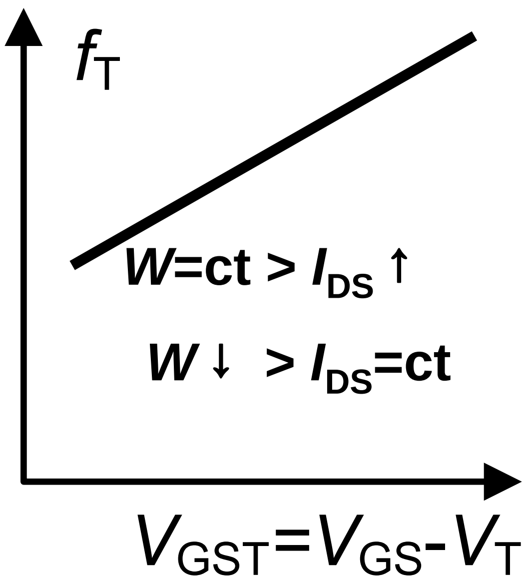
$$GM = \frac{1 - e^{-\sqrt{i}}}{\sqrt{i}}$$

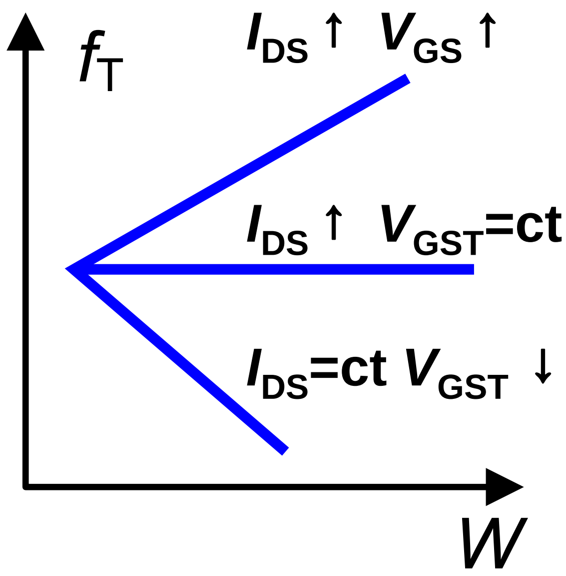
$$i = \frac{I_{DS}}{I_{DSt}}$$

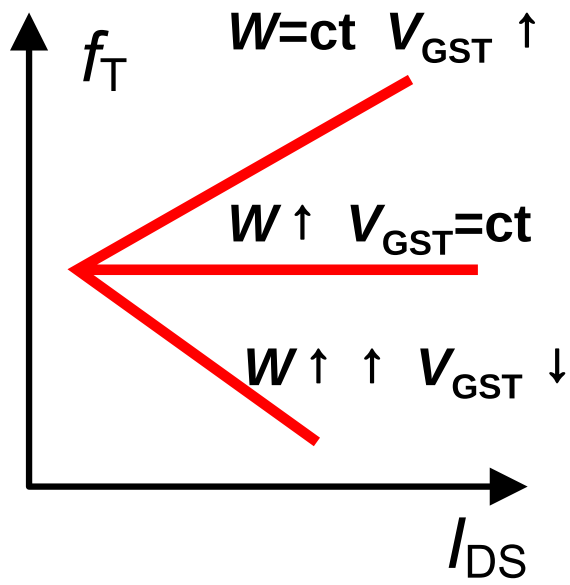
练习： MOST的特征频率f_T?

$\boxed{\text{所有} L=L_{min}}$

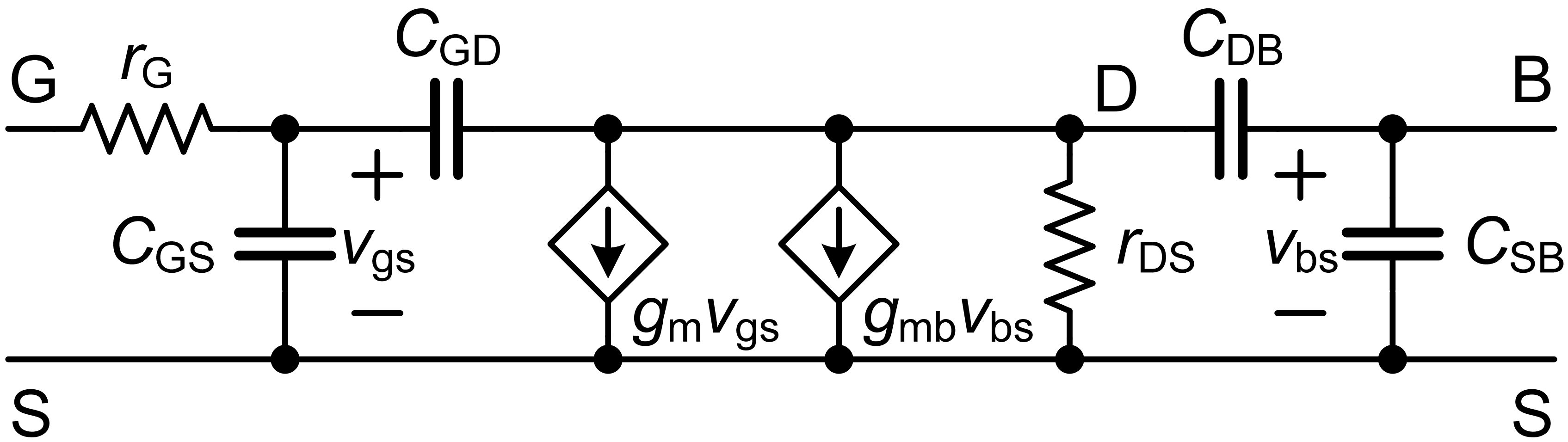
$$f_T = \frac{1}{2\pi}\frac{3}{2n}\frac{\mu}{L_{min}^2}(V_{GS}-V_T) = \frac{3}{2}\frac{\sqrt{K' I_{DS}}}{\pi C_{ox}\sqrt{WL_{min}^3}} = \frac{3}{2}\frac{I_{DS}}{\pi W L_{min} C_{ox}(V_{GS}-V_T)}$$







MOST的电容C_{SB}和C_{DB}

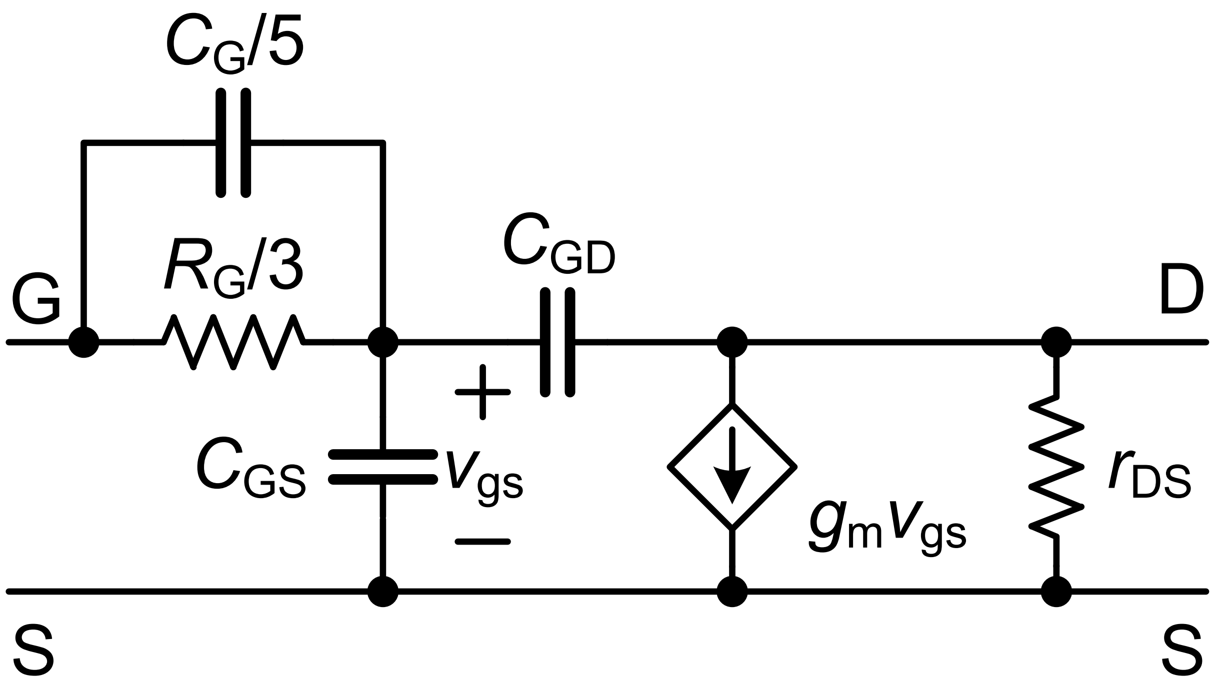


$$C_{SB} = \frac{C_{jSB0}}{\sqrt{1 + V_{SB}/\varphi_{jS}}}$$

$$C_{DB} = \frac{C_{jDB0}}{\sqrt{1 + V_{DB}/\varphi_{jD}}}$$

$$\varphi_{jS} \approx \varphi_{jD} \approx 0.5 \sim 0.7\ \text{V}$$

RF MOST模型



$$C_G = C_{GS} + C_{GD}$$

Ref.: Tin, Tr. CAD, April 1998, 372

Ref.: Sansen, etal, ACD, XDSL,RFMOS models, Kluwer 1999

“单页” MOST模型

$$V_{GS} - V_T \approx 0.2\ \text{V}$$

$$K_n^{'} \approx 100\ \mu\text{A/V}^2$$

$$K_p^{'} \approx 40\ \mu\text{A/V}^2$$

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

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

$$r_{DS} = r_o = \frac{V_E L}{I_{DS}}$$

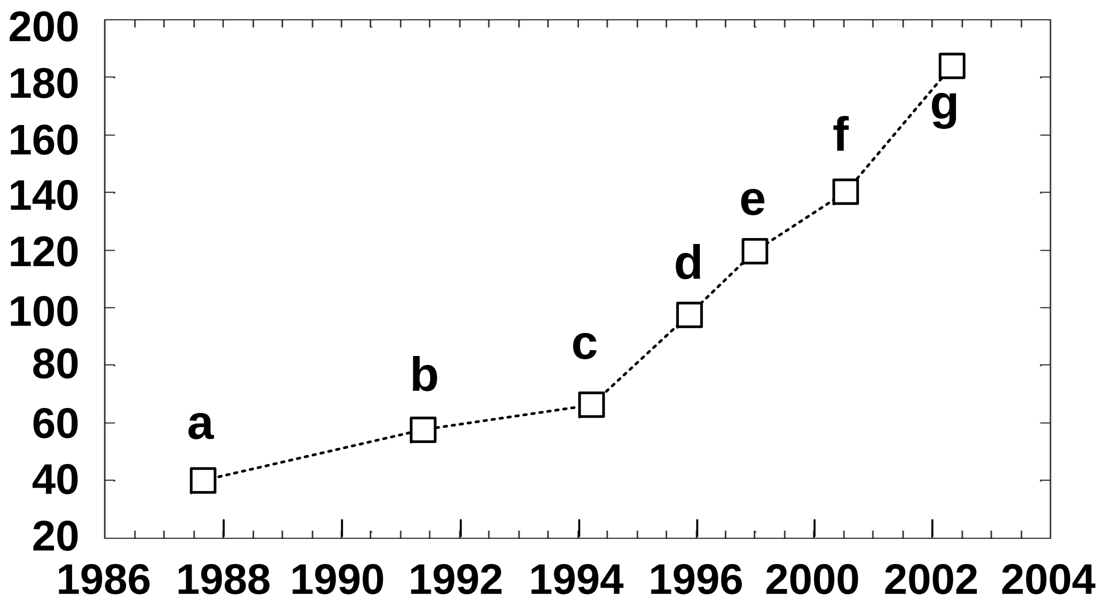
$$V_{En} \approx 5\ \text{V}/\mu\text{m}$$

$$V_{Ep} \approx 8\ \text{V}/\mu\text{m}$$

$$f_T = \frac{1}{2\pi}\frac{3}{2n}\frac{\mu}{L^2}(V_{GS} - V_T) \approx \frac{v_{sat}}{2\pi L}$$

$$v_{sat} \approx 10^7\ \text{cm/s}$$

参量数目的增加



a: BSIM1
b: BSIM2
c: BSIM3 version 2.0
d: BSIM3 version 3.0
e: BSIM3 version 3.1
f: BSIM3 version 3.2.2
g: BSIM4 4.0.0

BSIM4 : http://www-device.eecs.berkeley.edu/~bsim3/bsim_ent.html
Model 11 : http://en-origin.nxp.com/models/mos_models/model11/index.html
EKV : http://legwww.epfl.ch/ekv/model.html

基准测试

1. 弱反型转换点的I_{DS}和能效比g_m/I_{DS}
2. 速度饱和转换点的I_{DS}和能效比g_m/I_{DS}
3. 在V_{DSsat}附近的输出导纳
4. V_{DS}等于零时，电流和电容的连续性
5. 热噪声和1/*f* 噪声
6. 高频时的输入阻抗(s_{11})和跨导 (s_{21})

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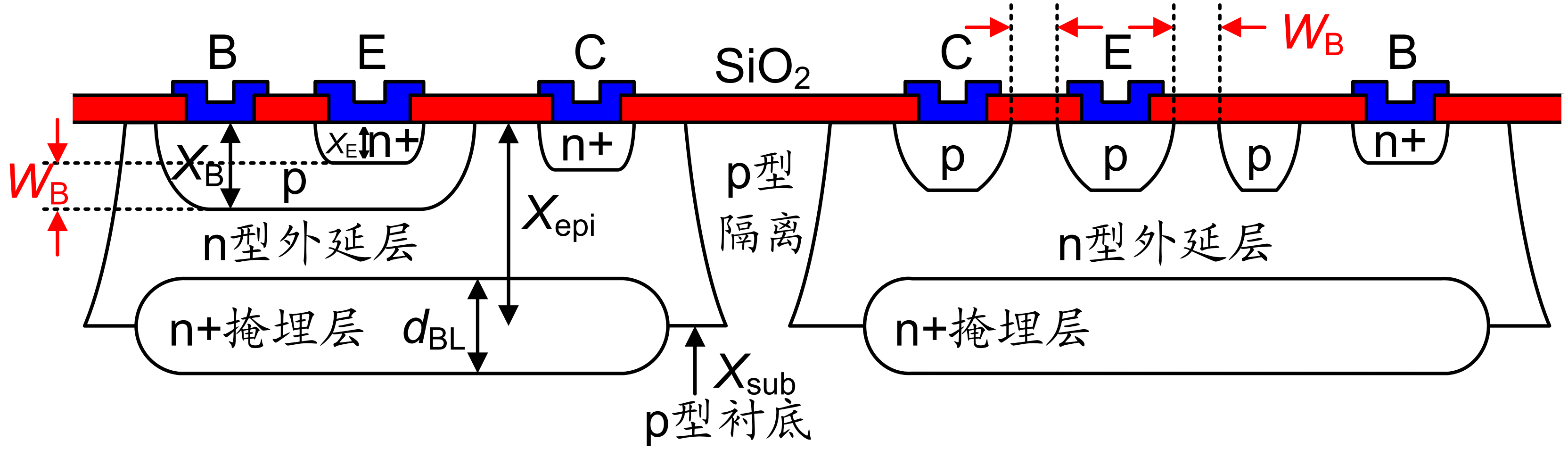
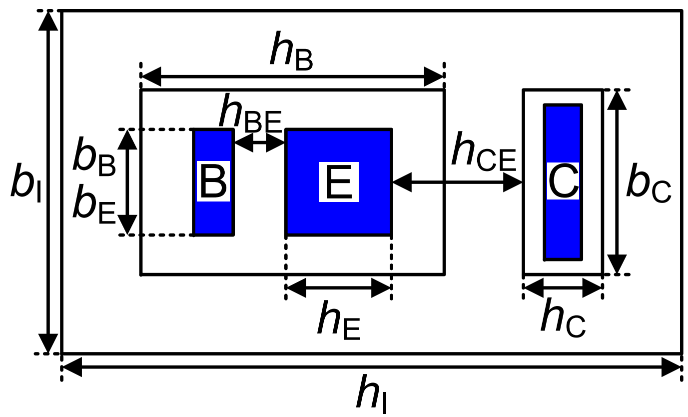
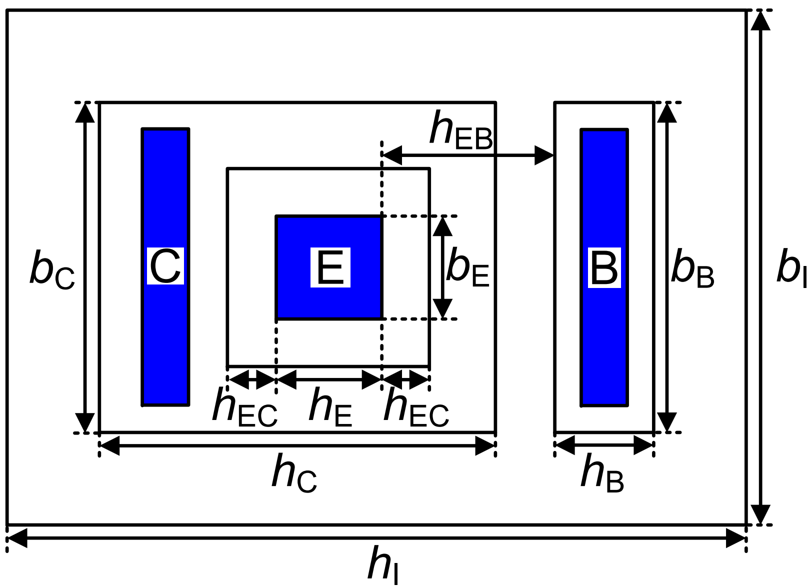
双极型晶体管



B
E
C
SiO2
C
E
WB
B
XB
XE
n+
n+
p
WB
Xepi
p型
隔离
p
p
p
n+
n型外延层
n型外延层
n+掩埋层
dBL
n+掩埋层
Xsub
p型衬底

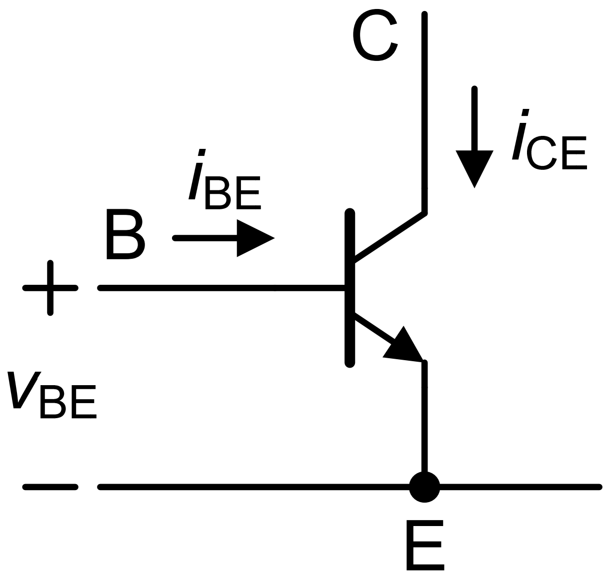


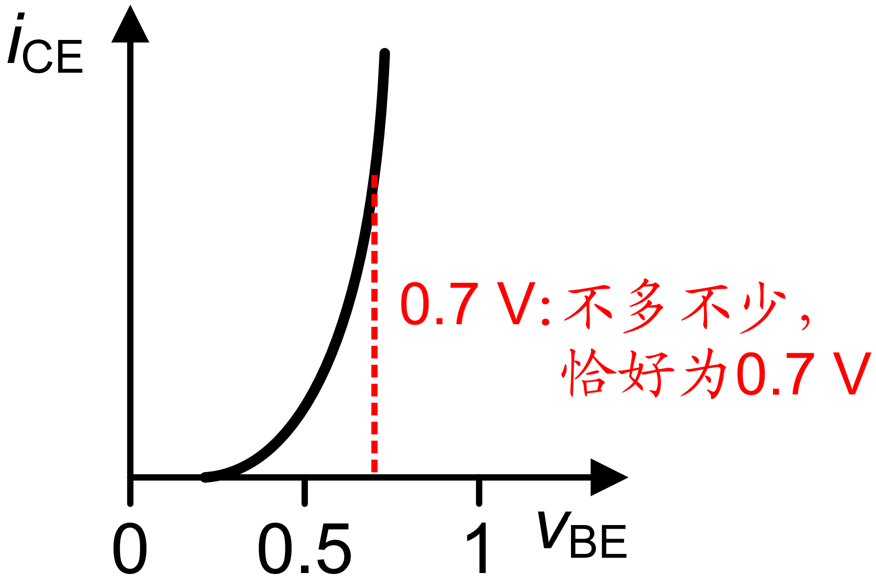
hB
hBE
bB
bE
bI
B
E
hCE
C
bC
hE
hC
hI



hEB
bC
C
E
bE
B
bB
bI
hEC
hE
hEC
hC
hB
hI

双极型晶体管的I_{CE}与V_{BE}的关系





$$\boxed{I_{CE}=I_S e^{\frac{V_{BE}}{kT/q}}}$$

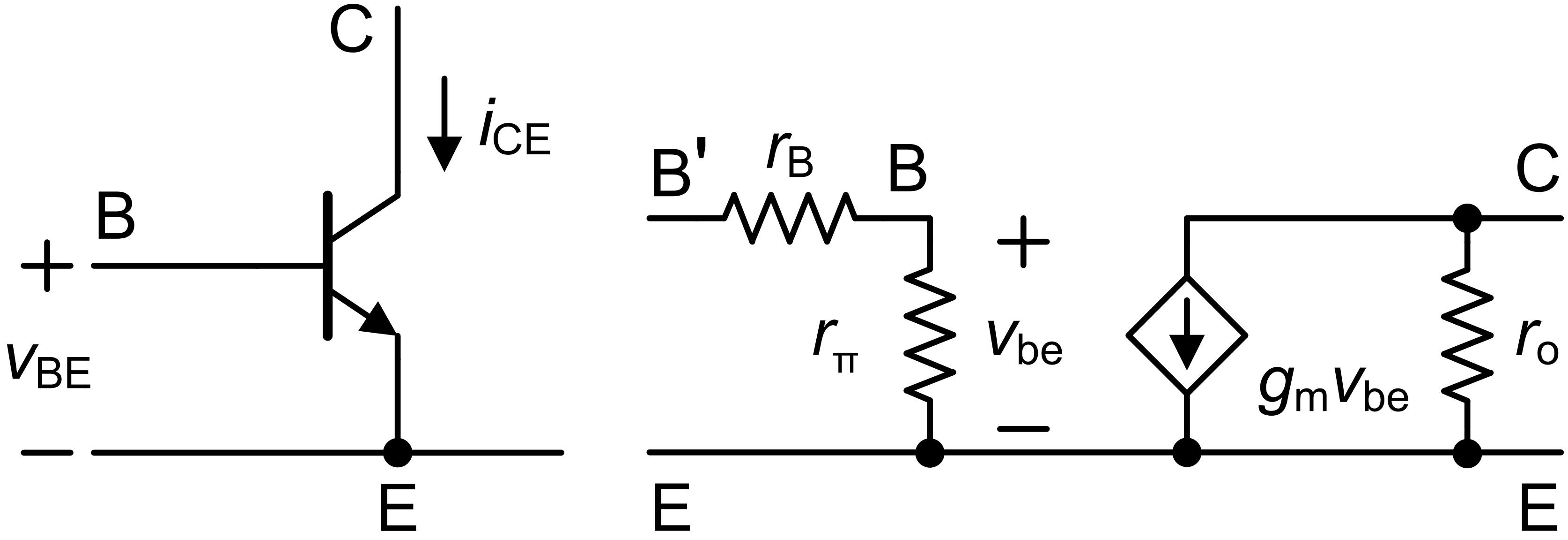
$$I_{BE}=\frac{I_{CE}}{\beta}$$

$I_S \approx 10^{-15}$ A

$\beta \approx 10 \sim 1000$

当$k=300$ K 时，kT/q$=26$ mV

双极型晶体管的小信号模型: g_m和r_o



$$g_m = \frac{di_{CE}}{dv_{BE}} = \frac{I_{CE}}{kT/q}$$

$$\frac{g_m}{I_{CE}} = \frac{1}{kT/q} \approx 40\ \mathrm{V}^{-1}$$

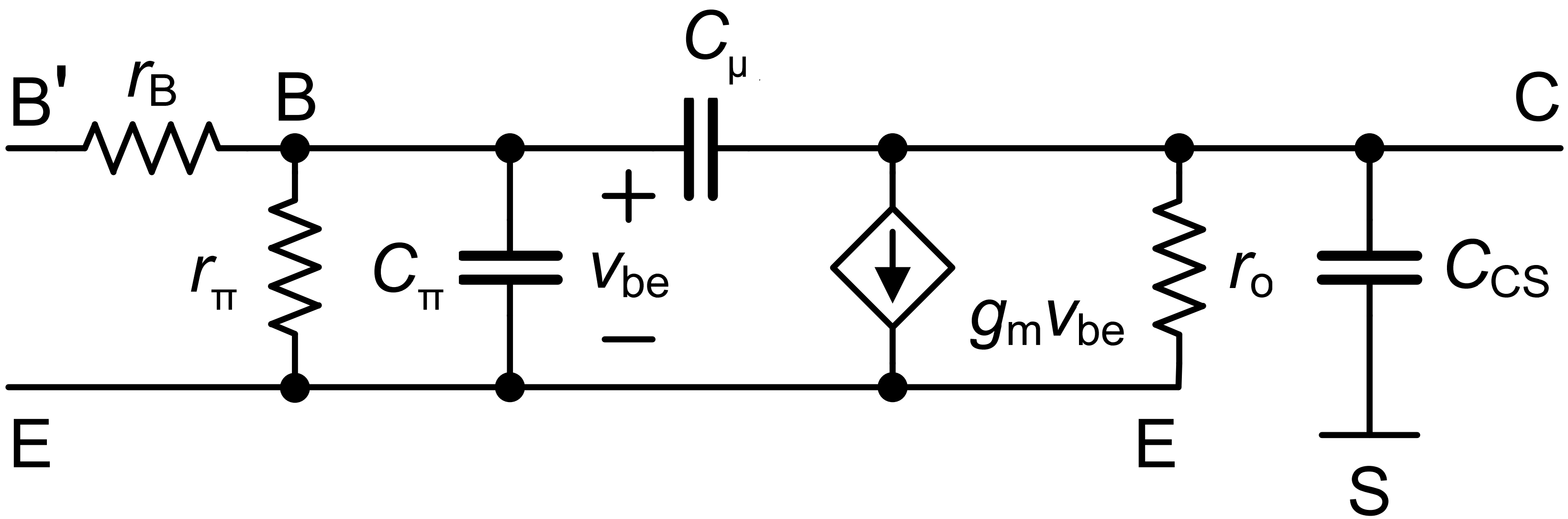
$$r_\pi = \frac{dv_{BE}}{di_{BE}} = \beta \frac{dv_{BE}}{di_{CE}} = \frac{\beta}{g_m}$$

$$r_o = \frac{V_E}{I_{CE}}$$

$$V_{En} \approx 20\ \mathrm{V}$$

$$V_{Ep} \approx 10\ \mathrm{V}$$

双极型晶体管的电容C_π

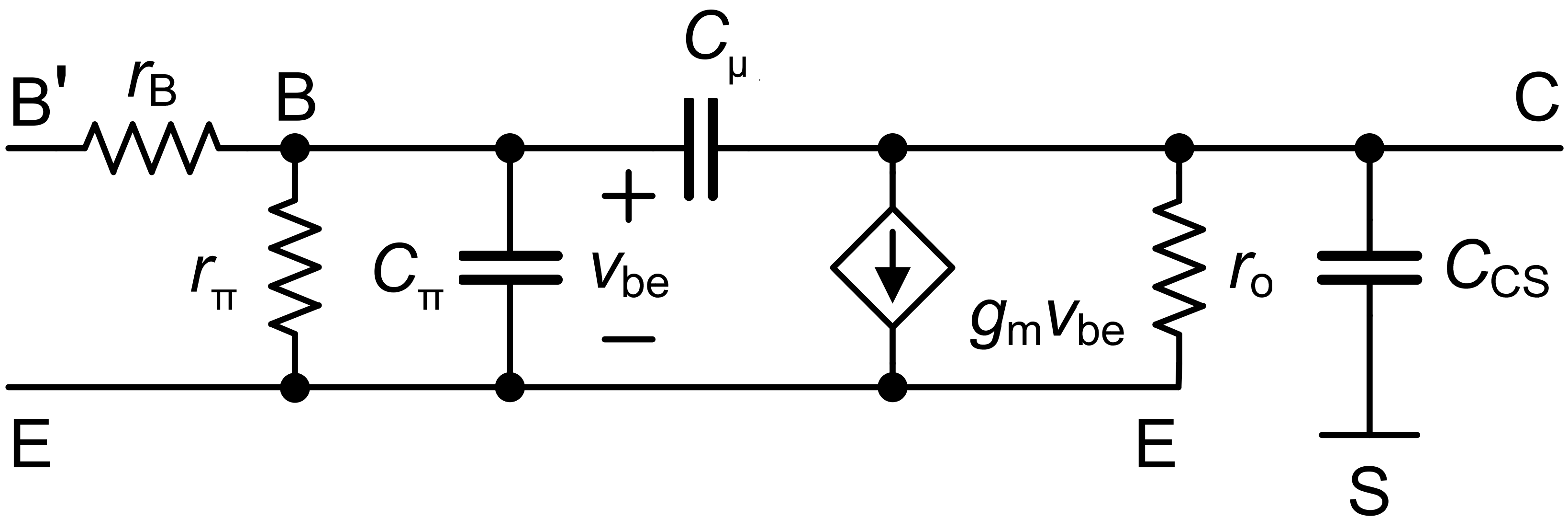


$$C_\pi = C_{jBE} + C_D$$

$$C_{jBE} = \frac{1}{\sqrt{1 - V_{BE}/\varphi_{jE}}} \qquad \varphi_{jE} \approx 0.7\ \mathrm{V}$$

C_D为扩散电容

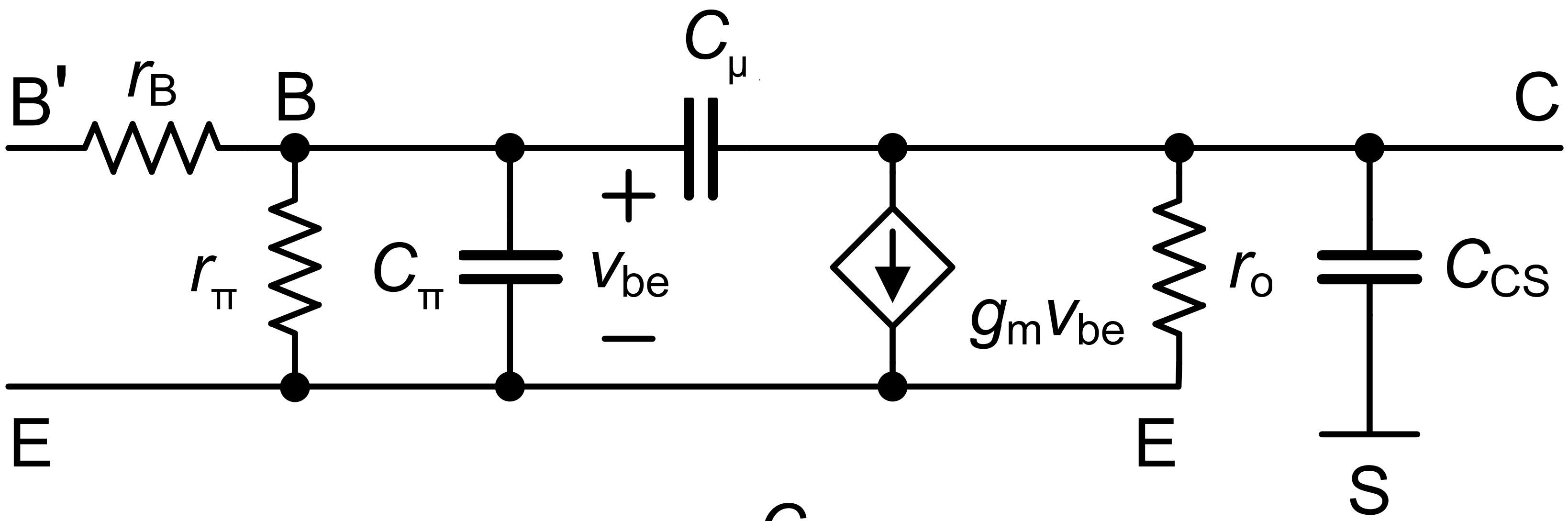
扩散电容C_D



$$C_D = \frac{Q_B}{v_{BE}} = \tau_F \frac{di_{CE}}{dv_{BE}} = \tau_F g_m = \tau_F \frac{I_{CE}}{kT/q}$$

基区穿越时间 $\tau_F = \dfrac{W_B^2}{2D_n}$ 现在 $\approx \dfrac{W_B}{v_{sat}} \approx 10 \sim 200\ \text{ps}$

双极型晶体管的电容C_μ和C_{CS}

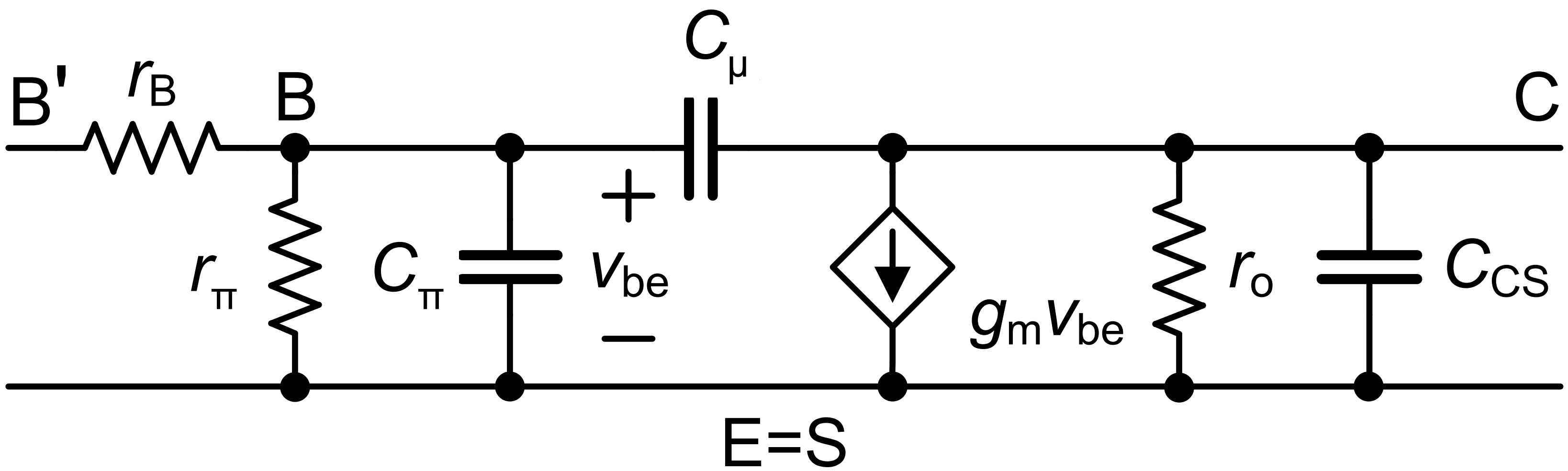


$$C_\mu = C_{jBC} \qquad C_{jBC} = \frac{C_{jBC0}}{\sqrt{1 - V_{BC}/\varphi_{jC}}}$$

$$C_{CS} = C_{jCS} \qquad C_{jCS} = \frac{C_{jCS0}}{\sqrt{1 + V_{CS}/\varphi_{jS}}}$$

$$\varphi_{jC} \approx \varphi_{jS} \approx 0.5\ \text{V}$$

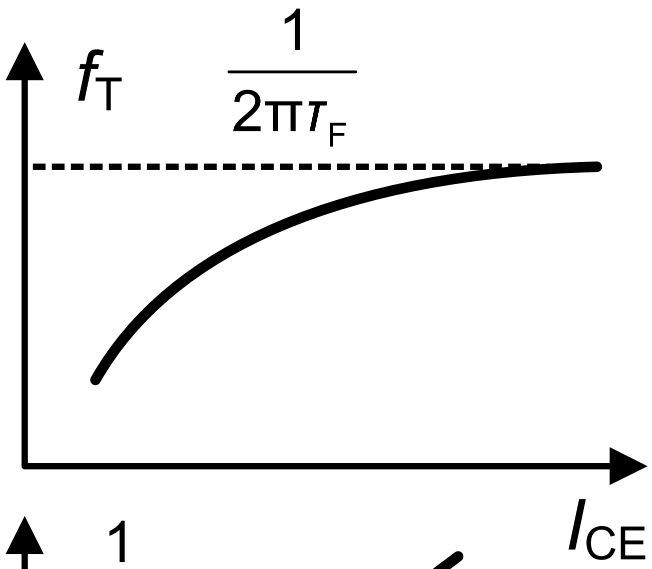
双极型晶体管的特征频率f_T



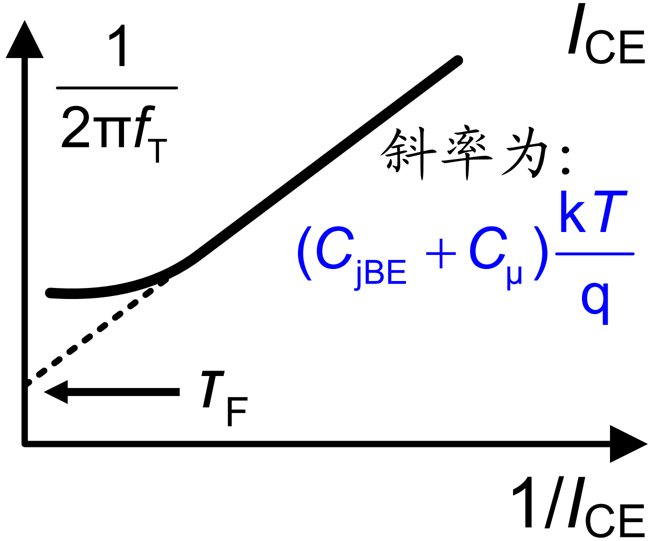
$$f_T = \frac{g_m}{2\pi(C_\pi + C_\mu)} = \frac{1}{2\pi}\frac{1}{\tau_F + \dfrac{C_{jBE} + C_\mu}{g_m}} \approx \frac{v_{sat}}{2\pi W_B}$$

电流增益为1!

双极型晶体管的f_T与I_{CE}的关系



$$f_T = \frac{1}{2\pi(\tau_F + \frac{C_{jBE} + C_\mu}{g_m})}$$



$$\frac{1}{2\pi f_T} = \tau_F + (C_{jBE} + C_\mu)\frac{kT}{q}\frac{1}{I_{CE}}$$

“单页”双极型晶体管模型

$$I_{CE} = I_S e^{\frac{V_{BE}}{kT/q}}$$

$I_S \approx 10^{-15}$ A

当k=300 K时，$kT/q = 26$ mV

$$g_m = \frac{I_{CE}}{kT/q}$$

$$r_o = \frac{V_E}{I_{CE}}$$

$V_{En} \approx 20$ V

$V_{Ep} \approx 10$ V

$$f_T = \frac{1}{2\pi} \frac{1}{\tau_F + \dfrac{C_{jBE} + C_\mu}{g_m}}$$

或 $\approx \dfrac{v_{sat}}{2\pi W_B}$

目录

- MOS晶体管模型
- 双极型晶体管模型
- MOS与双极型晶体管的比较

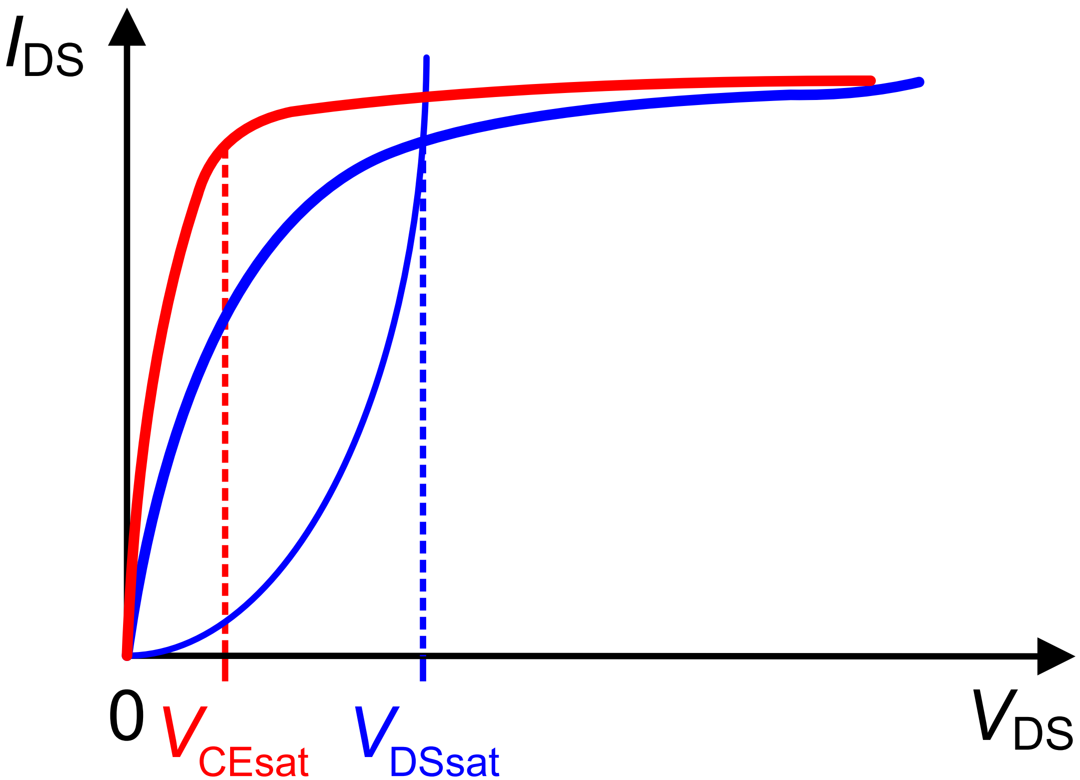
MOST与双极型晶体管的比较

表2-8 MOST与双极型晶体管的比较

Specification		MOST	Bipolar transistor	
1. I_{IN}		0	I_C/β	β ?
R_{IN}		∞	$r_\pi + r_B$	
2. V_{DSsat}		$V_{GS}-V_T=\sqrt{\dfrac{I_{DS}}{K'W/L}}$	few kT/q	
3. $\dfrac{g_m}{I}$	wi	$\dfrac{1}{nkT/q}$	$\dfrac{1}{kT/q}$	$n=1+\dfrac{C_D}{C_{ox}}$
	si	$\dfrac{2}{V_{GS}-V_T}$	$\dfrac{1}{kT/q}$	4…6 X
	vs	$\dfrac{1}{V_{GS}-V_T}$	$\dfrac{1}{kT/q}$	

Ref.: Laker Sansen Table 2-8

MOST-Bipolar的比较：最小V_{DS}



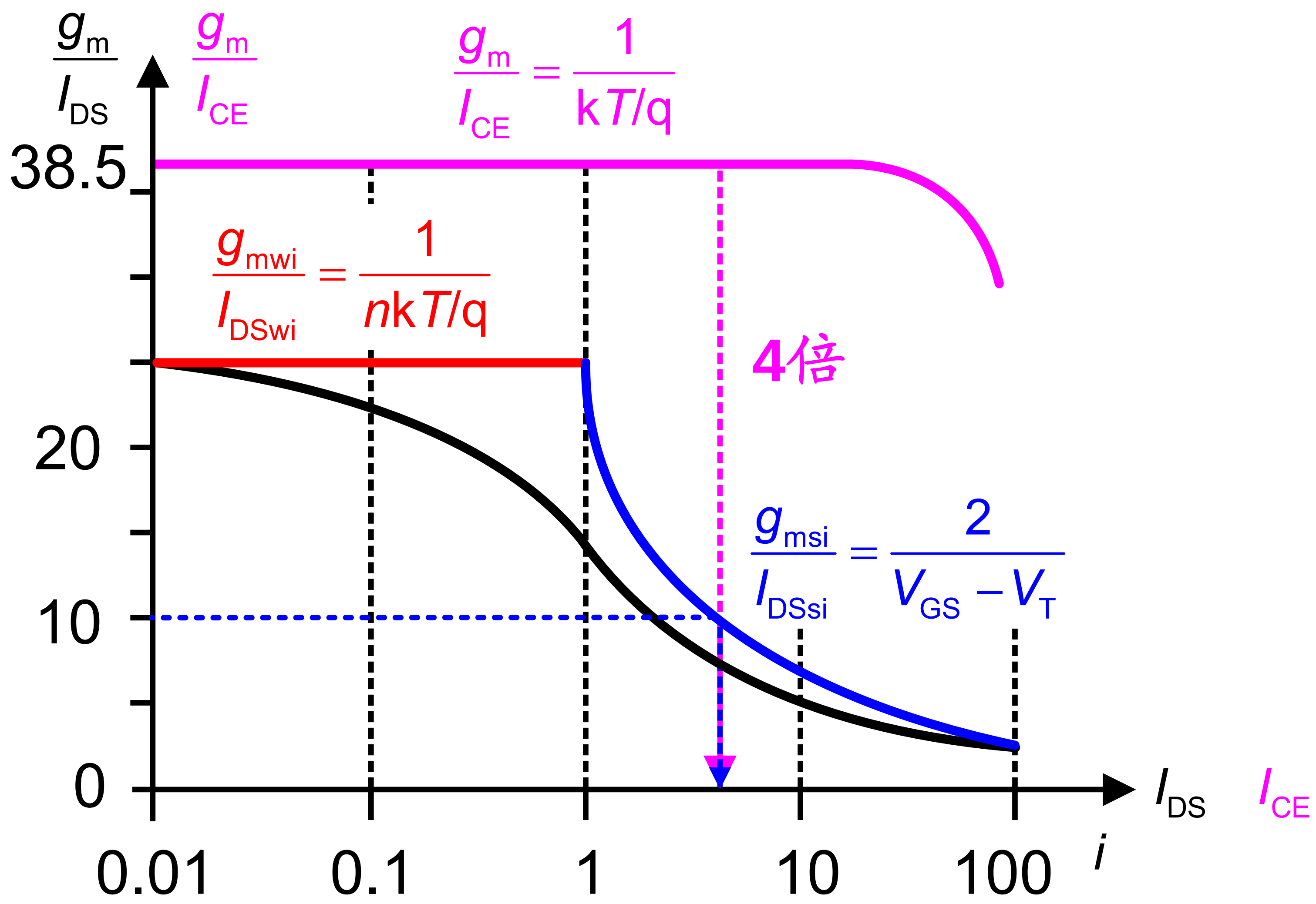
$$V_{DSsat} \approx V_{GS} - V_T$$

$$V_{GS} - V_T \approx \sqrt{\frac{I_{DS}}{K' \frac{W}{L}}}$$

$$V_{CEsat} \approx kT/q's$$

Ref.: Laker Sansen Table 2-8

MOST-Bipolar的比较：能效比g_m/I_{DS}



g_m的设计流程

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

$$g_m = 2K' \frac{W}{L}(V_{GS} - V_T) = 2\sqrt{K' \frac{W}{L} I_{DS}} = \frac{2I_{DS}}{V_{GS} - V_T}$$

2个方程，4个变量 >> 2个变量不受约束

选择V_{GS}-V_T和L！

MOST与双极型晶体管的比较

表2-8 MOST与双极型晶体管的比较

Specification		MOST	Bipolar transistor
4.Design planning		$\frac{W}{L}$, $V_{GS}-V_T$	kT/q
5. I-range		1 decade	7 decade
6. Max f_T	low I	C_{GS}, C_{GD}	C_{jBE}, C_μ
	high I	v_{sat}/L_{eff}	v_{sat}/W_B
7. Noise $\overline{dv_i^2}$	Therm.	$4kT(\frac{2/3}{g_m}+R_G)$	$4kT(\frac{1/2}{g_m}+R_B)$
	1/f	10X	
Offset		10X	$v_{sat}\approx 10^7$ cm/s

Ref.: Laker Sansen Table 2-8

关于晶体管模型的参考书目

- T. Fjeldly, T. Ytterdal, M. Shur, “*Introduction to Device Modeling and Circuit Simulation*”, Wiley 1998.
- D. Foty, “*MOSFET Modeling with SPICE”*, Prentice Hall
- K. Laker, W.Sansen, “*Design of Analog Integrated Circuits and Systems”*, MacGrawHill. NY., Febr.1994.
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- Y. Tsividis, “*Operation and modeling of the MOS transistor*”, McGraw-Hill, 2004.
- A. Vladimirescu “*The SPICE book*”, Wiley, 1994

关于模拟电路设计的参考书目

- P.Allen, D.Holberg, “*CMOS Analog Circuit Design”*, Holt, Rinehart and Winston. 1987,Oxford Press 2002
- P.Gray, P.Hurst, S. Lewis, R.Meyer, “*Analysis and Design of Analog Integrated Circuits”*, Wiley, 1977/84/93/01
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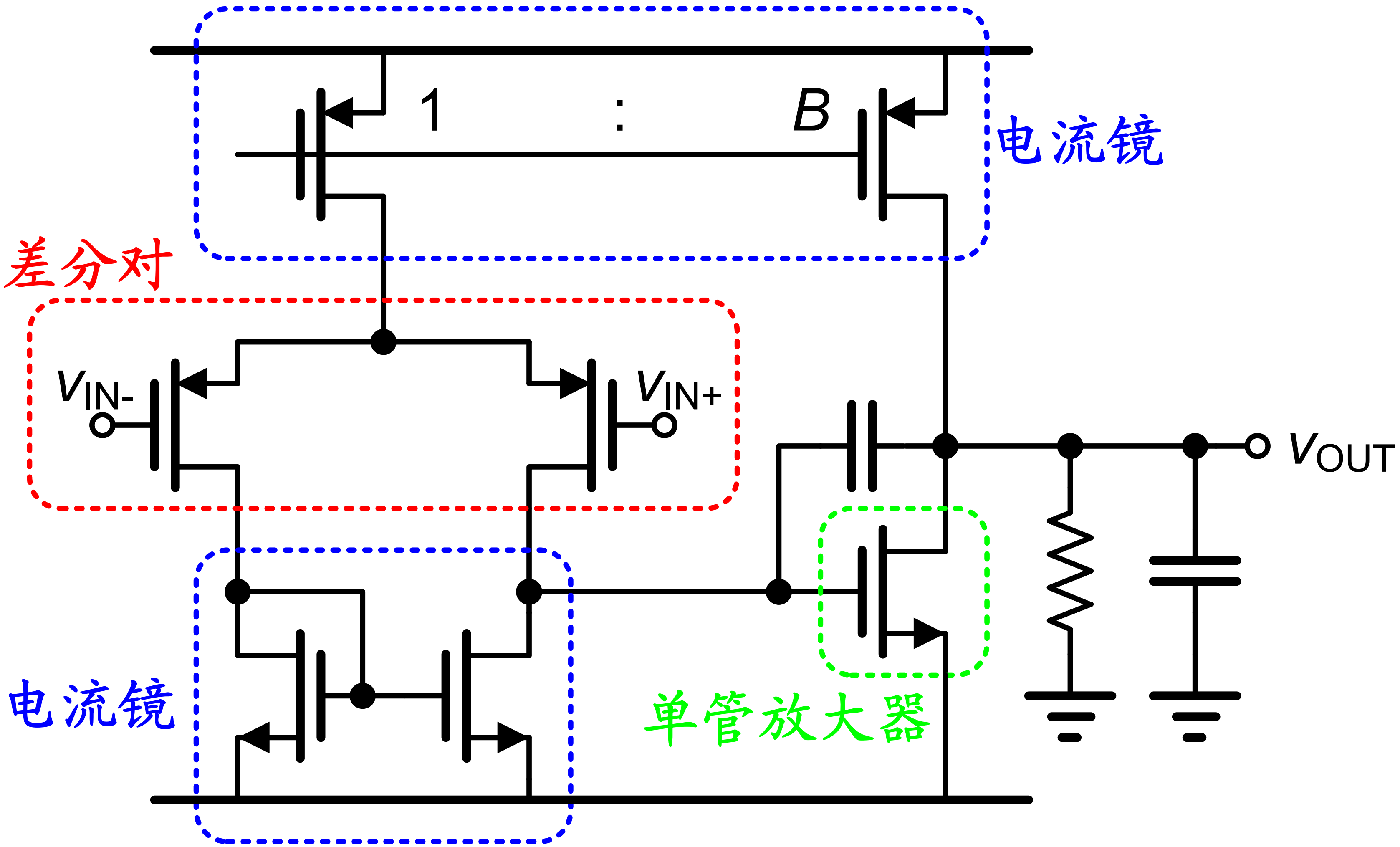
- A.Sedra, K.Smith, “*Microelectronic Circuits”*, CBS College Publishing, 1987.

共源放大器，
源极跟随器和共栅放大器

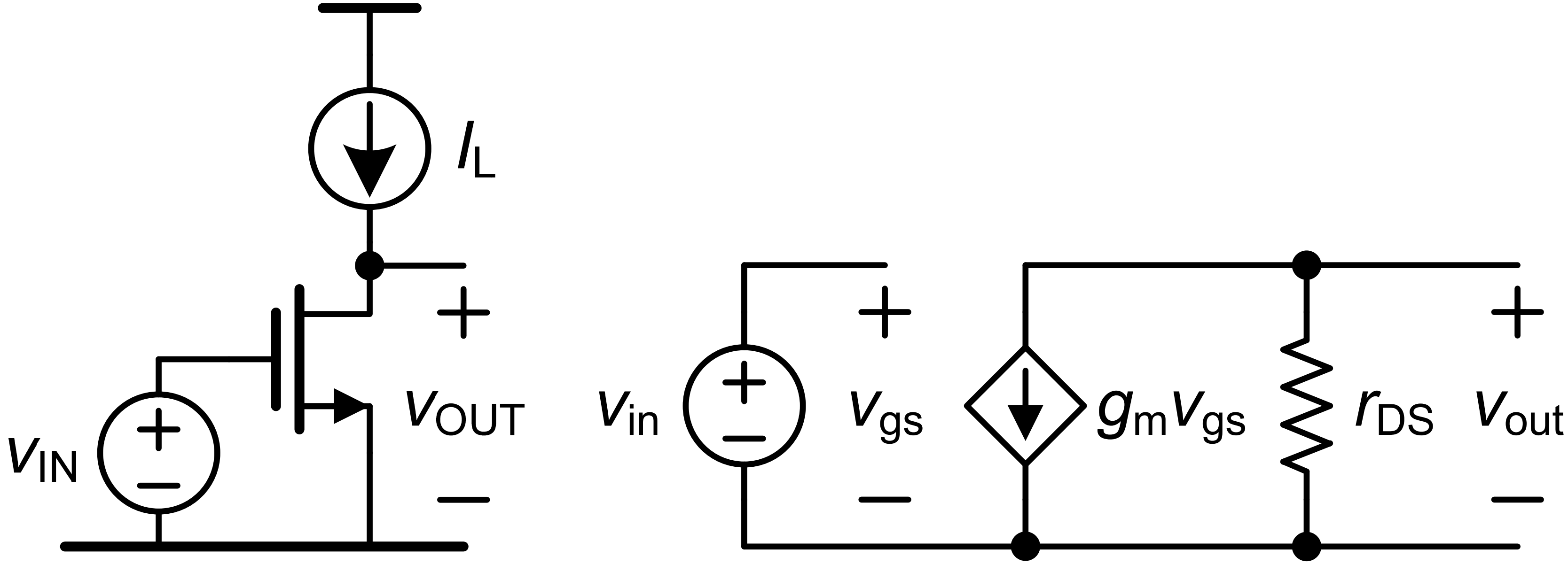
运算放大器(Opamp)



目录

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

共源放大器 1



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

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

共源放大器 2

高增益?

小$(V_{GS}-V_T)$，大L!!!

0.15~0.2 V　4~5L_{min}

MOST或双极型晶体管放大器?

MOST:

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

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

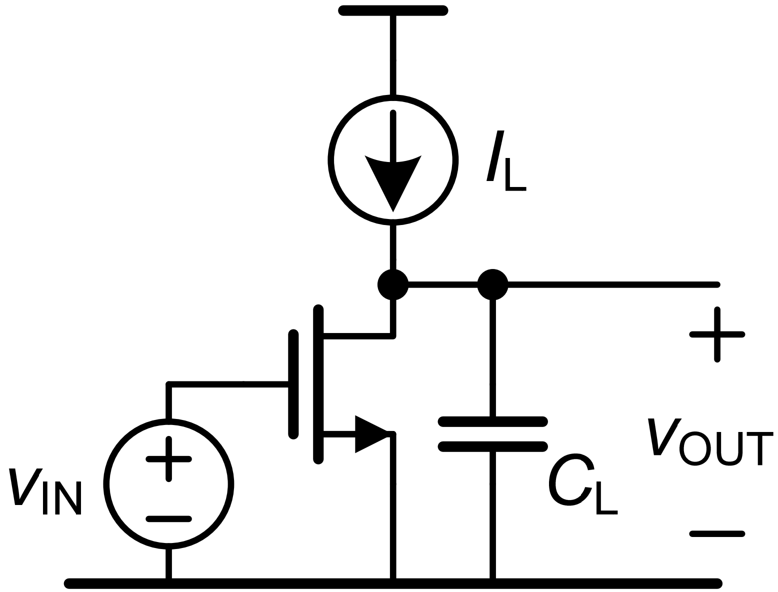
Bipolar:

$$A_V = \frac{V_E}{kT/q}$$

如果 $V_E \approx 26\ \text{V}$、$kT/q \approx 26\ \text{mV}$，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

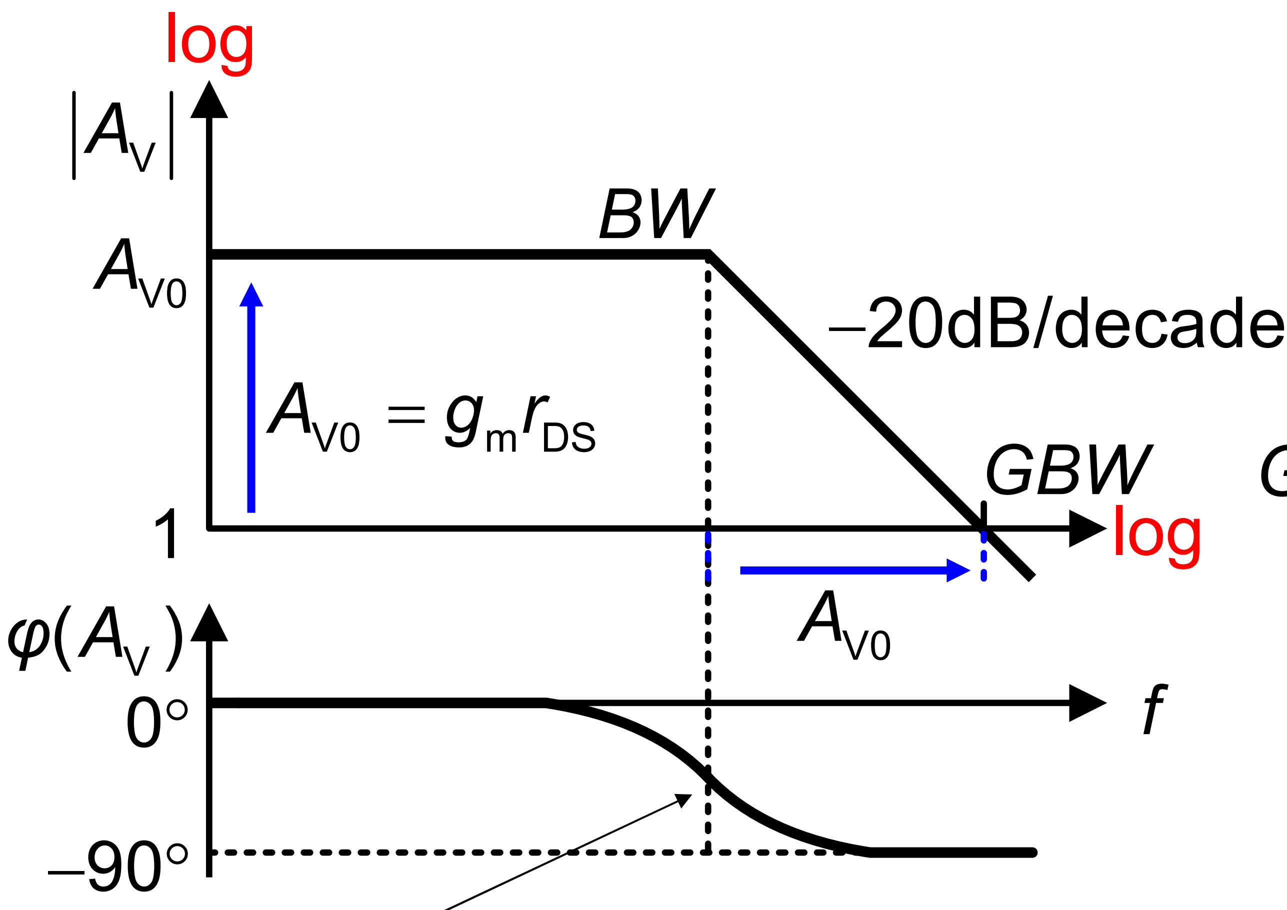


$$A_{V0} = g_m r_{DS}$$

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

适用于所有的单级运算放大器 →
$$\boxed{GBW = \frac{g_m}{2\pi C_L}}$$

增益A_{V0}、BW和GBW



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

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

在BW处 $\varphi(A_V)=-45°$

练习

已知：GBW=100 MHz，C_L=3 pF

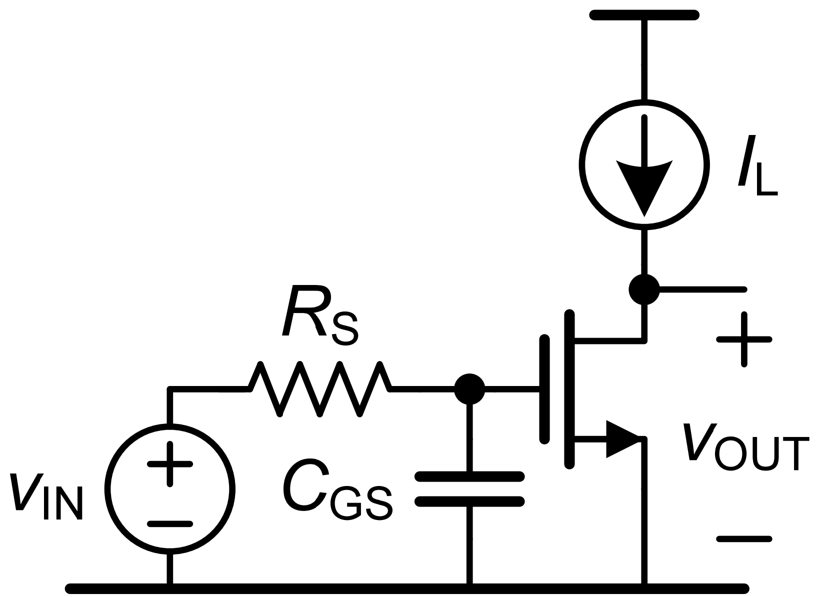
求：I_{DS}、L、W、$\dfrac{GBW \cdot C_L}{I_{DS}}$

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

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

$$\boxed{FOM = \frac{GBW \cdot C_L}{I_{DS}}}$$

增益带宽乘积：输入电容C_{GS}



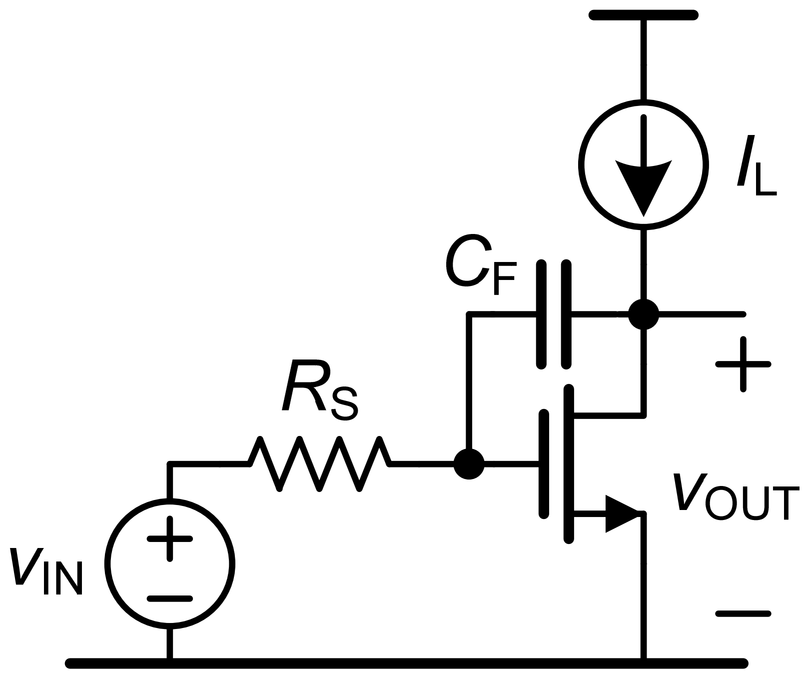
$$A_{V0} = g_m r_{DS}$$

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

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

W？ L？ V_{GS}–V_T？

增益带宽乘积：密勒电容C_F

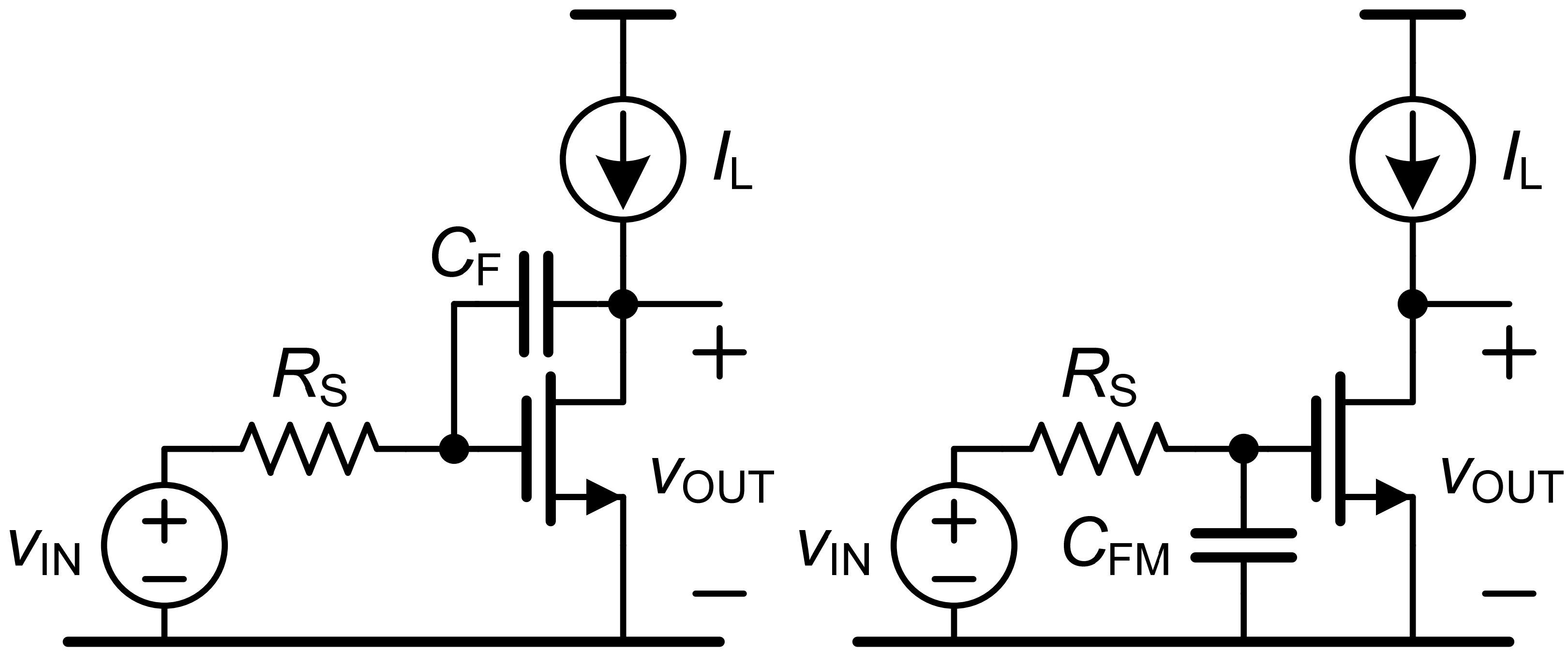


$$A_{V0} = g_m r_{DS}$$

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

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

密勒效应

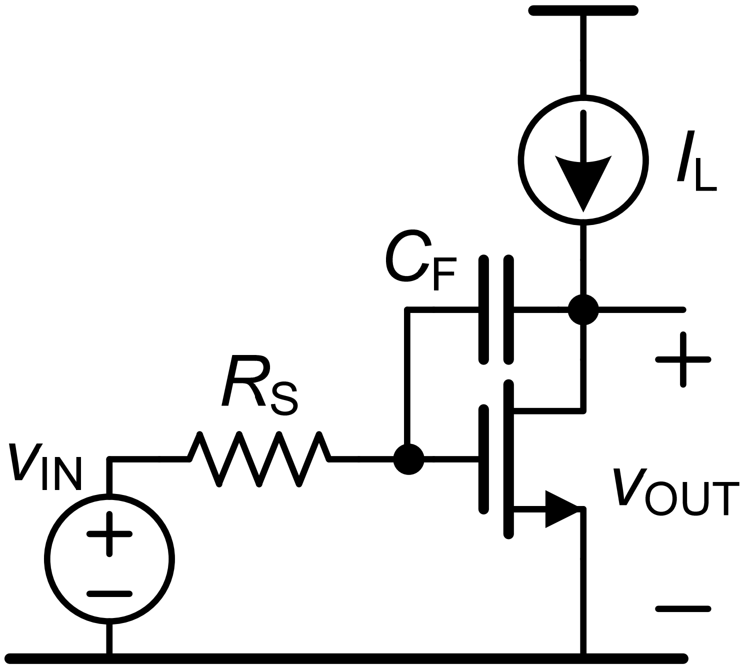


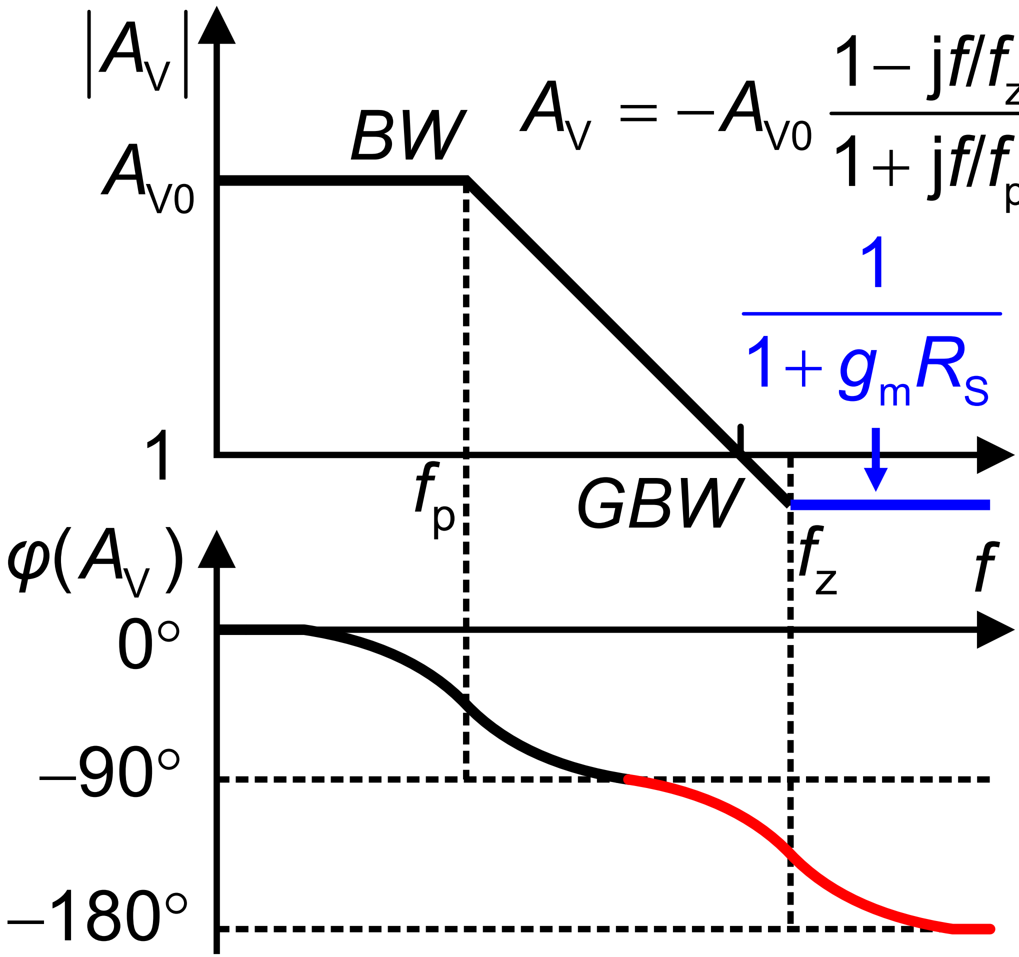
$$A_{V0} = g_m r_{DS}$$

$$C_{FM} = (1 + A_{V0}) C_F$$

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

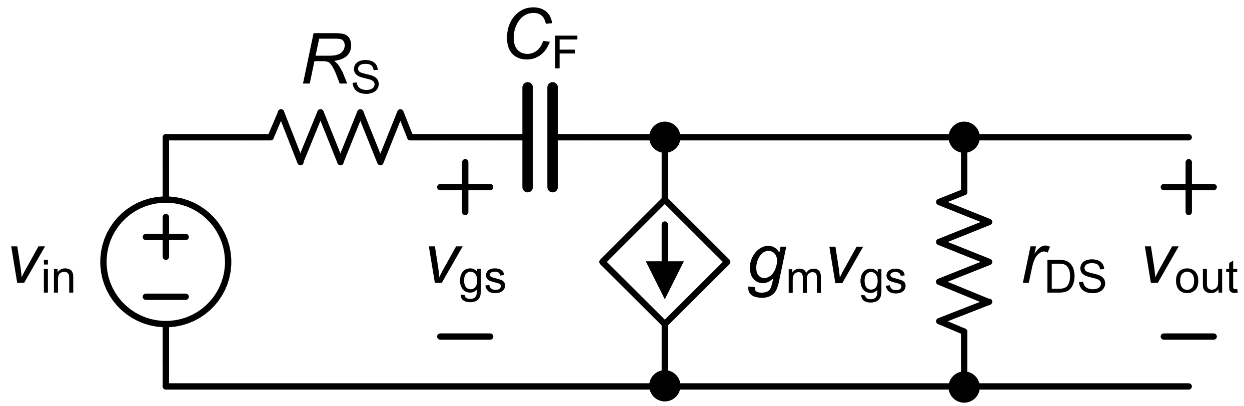




$$A_V = -A_{V0}\frac{1 - jf/f_z}{1 + jf/f_p}$$

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

就相位而言，一个正零点相当于一个负极点!!!



$$\frac{v_{in}-v_{gs}}{R_S}=\frac{v_{gs}-v_{out}}{\dfrac{1}{sC_F}} \quad \textbf{(1)} \qquad g_m v_{gs}=\frac{v_{gs}-v_{out}}{\dfrac{1}{sC_F}}-\frac{v_{out}}{r_{DS}} \quad \textbf{(2)}$$

由**(1)**得 $v_{gs}=\dfrac{\dfrac{1}{sC_F}v_{in}+R_S v_{out}}{R_S+\dfrac{1}{sC_F}}$，代入**(2)**得

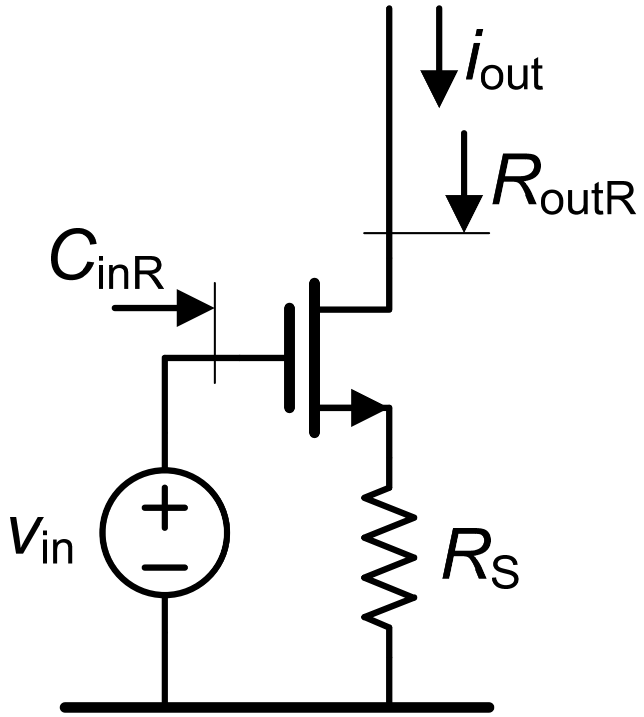
$$A_V = \frac{v_{out}}{v_{in}} = -g_m r_{DS} \frac{1 - \frac{C_F}{g_m} s}{1 + [r_{DS} + (1 + g_m r_{DS}) R_S] s C_F}$$

$$= -A_{V0} \frac{1 - \frac{C_F}{g_m} s}{1 + [r_{DS} + (1 + A_{V0}) R_S] s C_F}$$

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

$$f_p = -\frac{1}{2\pi R_S A_{V0} C_F}$$ 密勒效应

源极接电阻的退化共源放大器

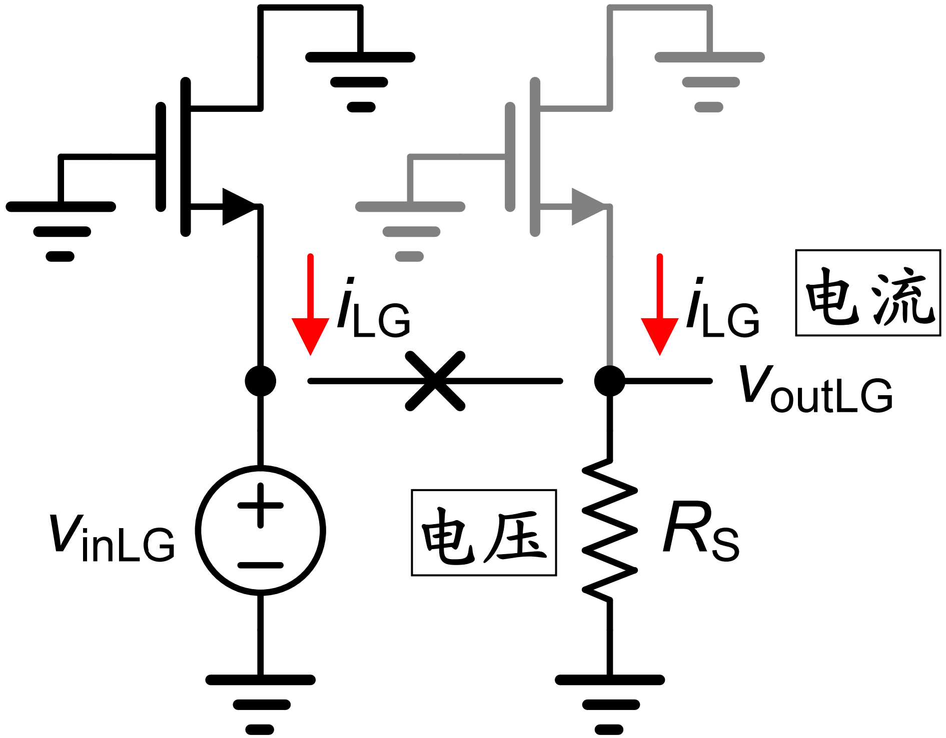


$$g_{mR} = \frac{g_m}{1+g_m R_S} \approx \frac{1}{R_S}$$

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

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

但是，R_S引入额外的噪声！



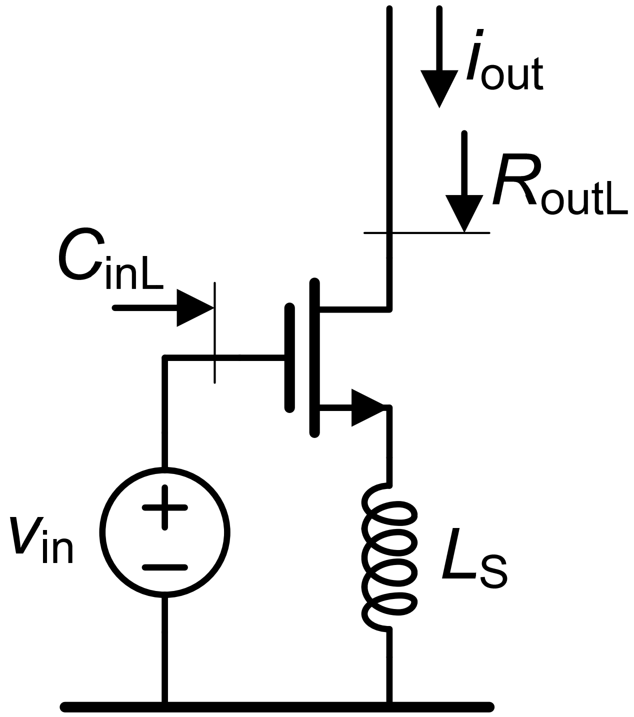
$$i_{LG} = -g_m v_{inLG}$$

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

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

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



$$g_{mL} = \frac{g_m}{1 + g_m L_S s}$$

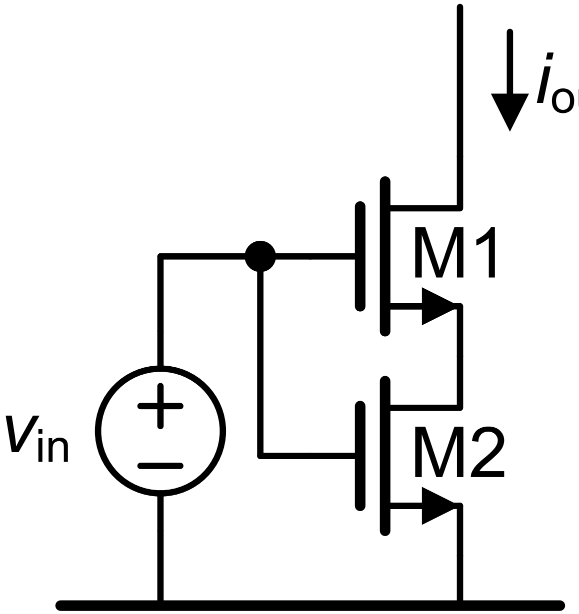
$$R_{outL} = (1 + g_m L_S s) r_{DS} + L_S s$$

$$Z_{inL} = g_m \frac{L_S}{C_{GS}} + \frac{1 + L_S C_{GS} s^2}{C_{GS} s}$$

$$Z_{inL} = L_S \omega_T + L_S s + \frac{1}{C_{GS} s}$$

没有额外的噪声！

源极接线性MOST的退化共源放大器



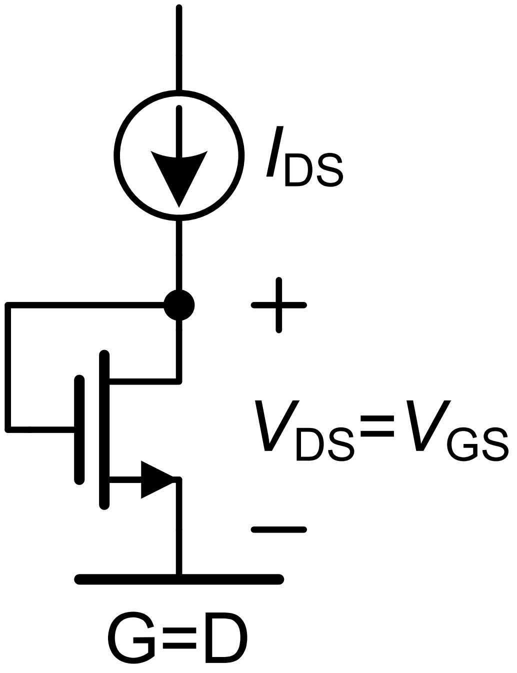
$$V_{\text{DS2}} = V_{\text{GS2}} - V_{\text{GS1}} \approx 0.2\ \text{V}$$

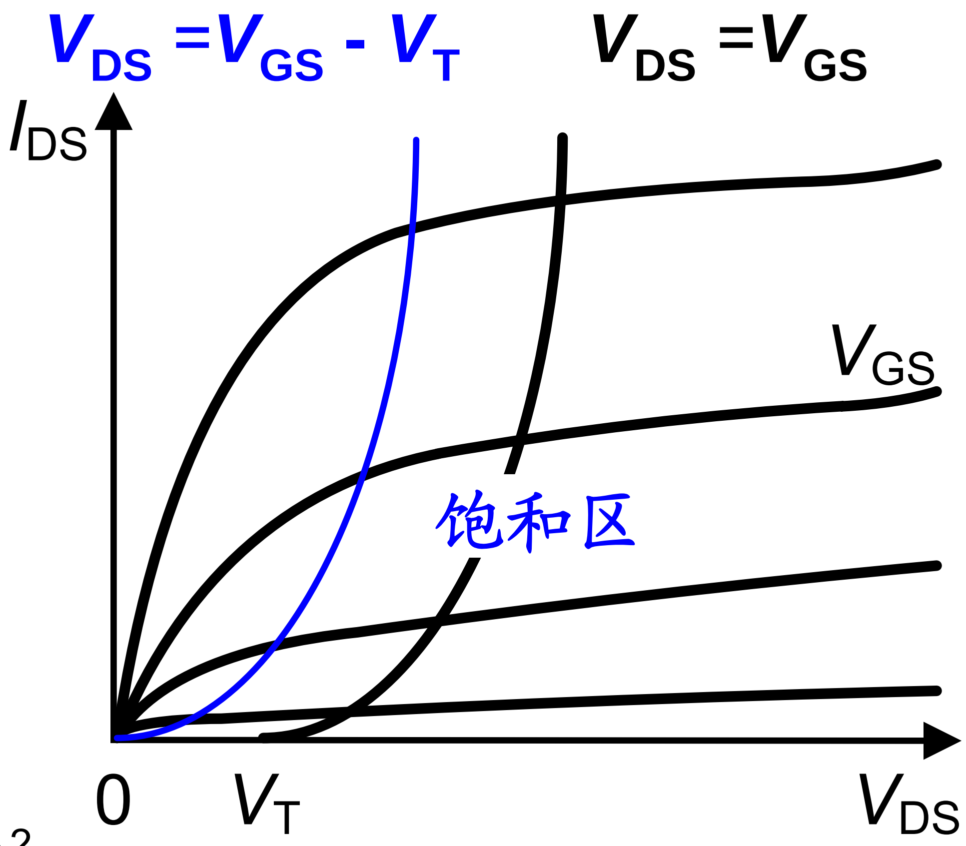
$$r_{\text{DS2}} = \frac{1}{KP \cdot W_2/L_2 \cdot (V_{\text{GS2}} - V_{\text{T}})}$$

$$R_{\text{outM}} = r_{\text{DS1}}(1 + g_{\text{m1}} r_{\text{DS2}}) + r_{\text{DS2}}$$

$$C_{\text{inM}} = \frac{C_{\text{GS1}}}{1 + g_{\text{m1}} r_{\text{DS2}}} + C_{\text{GS2}}$$

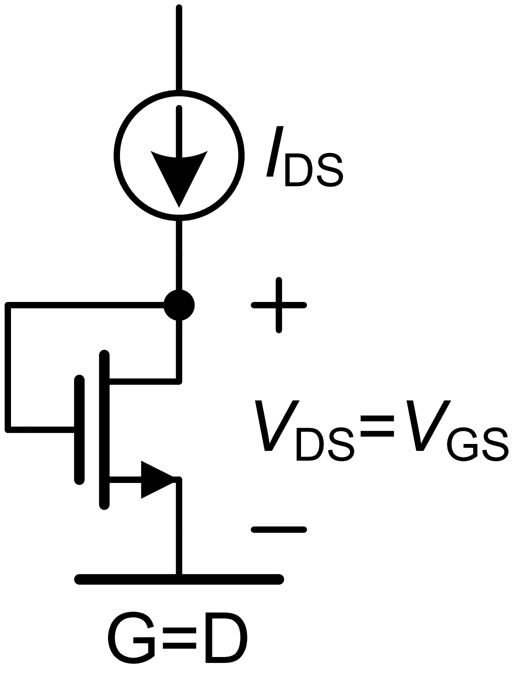
二极管连接MOST：并联反馈

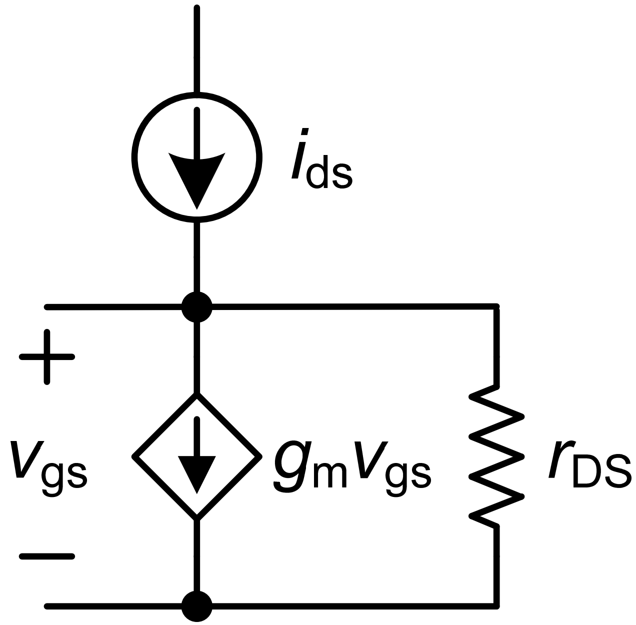




$$I_{DS}=K_n^{'}\frac{W}{L}(V_{DS}-V_T)^2$$

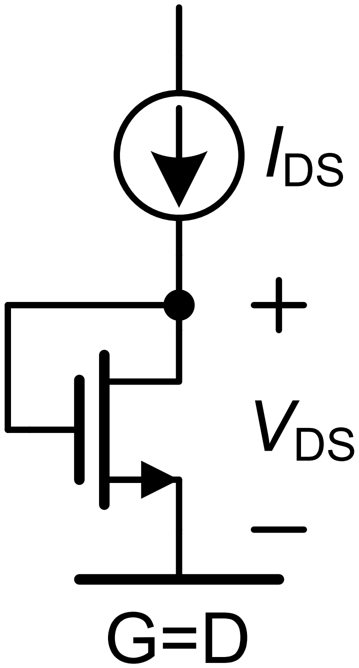
二极管连接MOST：小信号模型

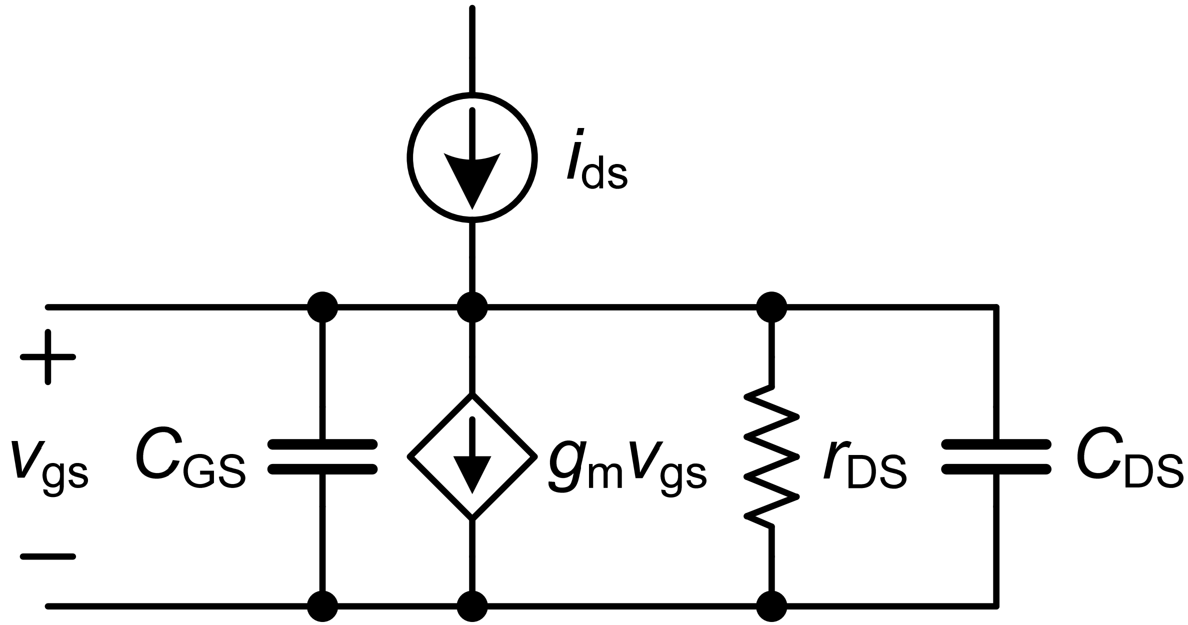




$$r_{out} = 1/g_m \,//\, r_{DS} \approx 1/g_m$$

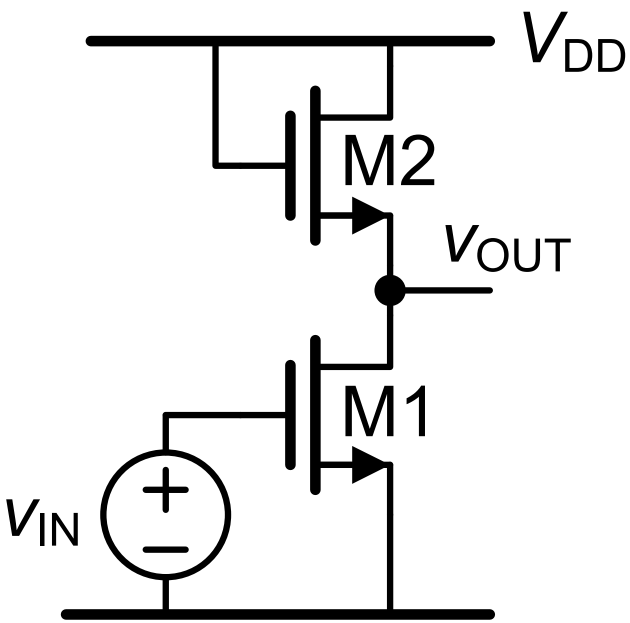
二极管连接MOST：高频特性





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

宽带放大器

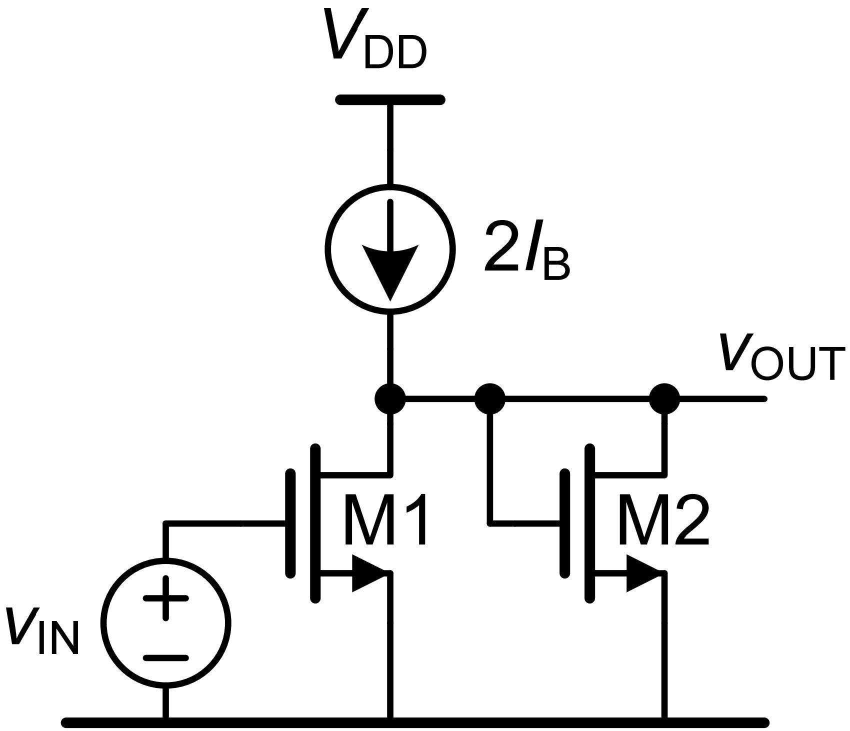


$$V_{OUT} = V_{DD} - V_{GS2}(V_{OUT})$$

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

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

线性宽带放大器



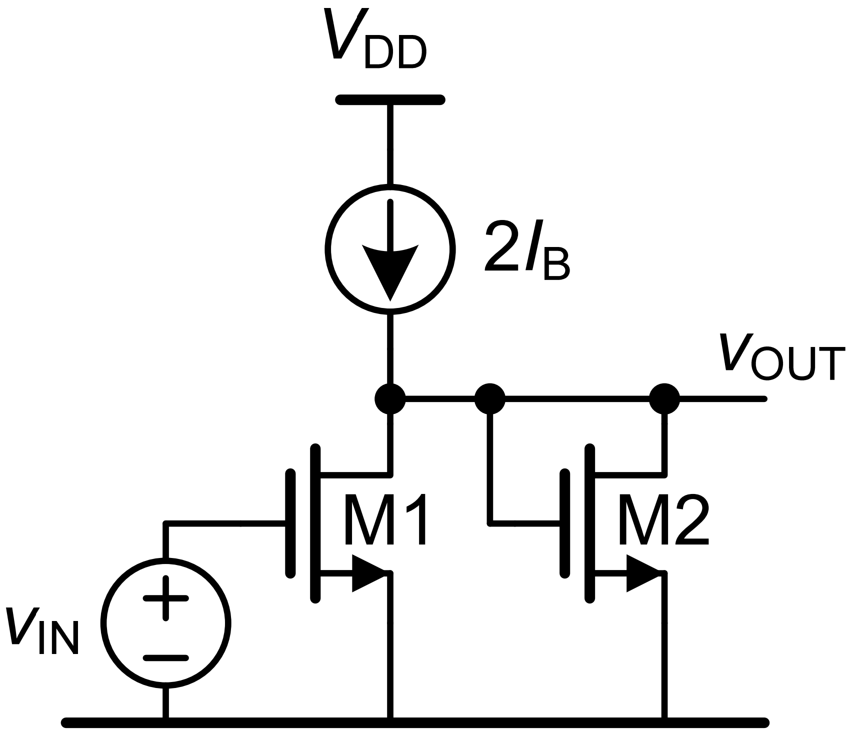
- 只有NMOS管+电流镜
- 输入/输出直流电平相同
- 无衬偏效应
- 高电源抑制比(PSRR)
- 双倍功耗!

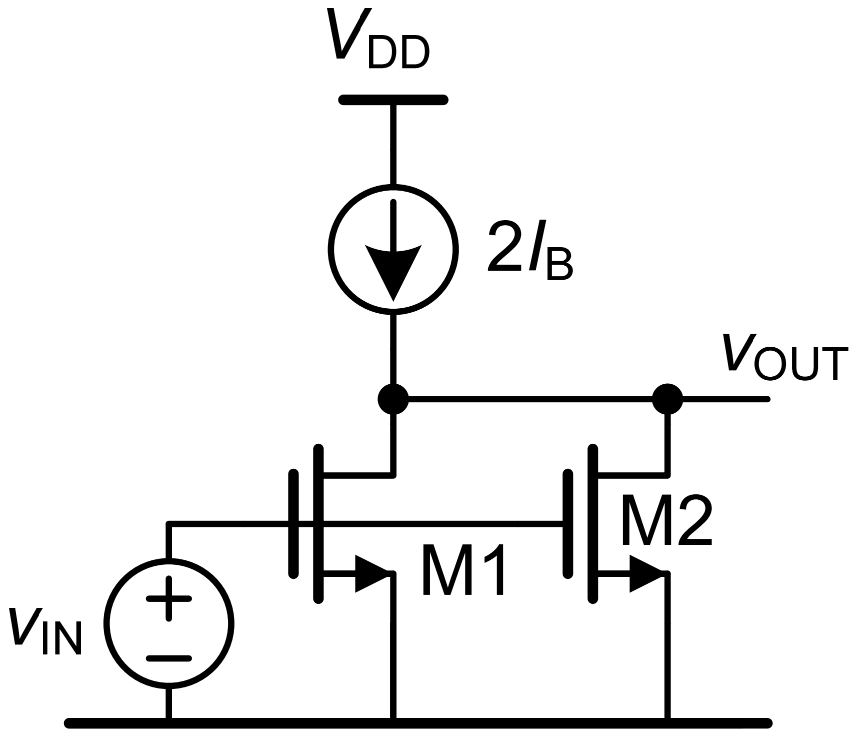
$$V_{OUT} = V_{GS2}$$

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

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

宽带放大器





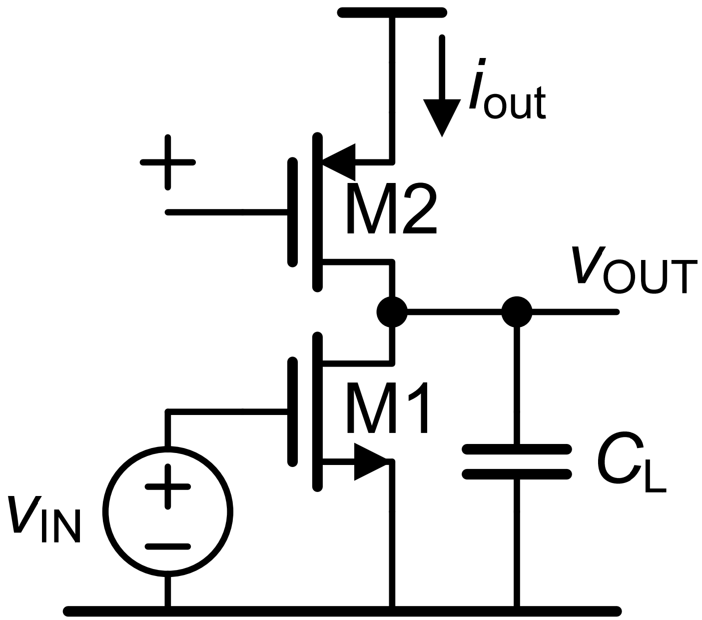
$$A_{V0} = \frac{g_{m1}}{g_{m2}} = \sqrt{\frac{(W/L)_1}{(W/L)_2}} = \frac{V_{GS2} - V_T}{V_{GS1} - V_T}$$

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

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

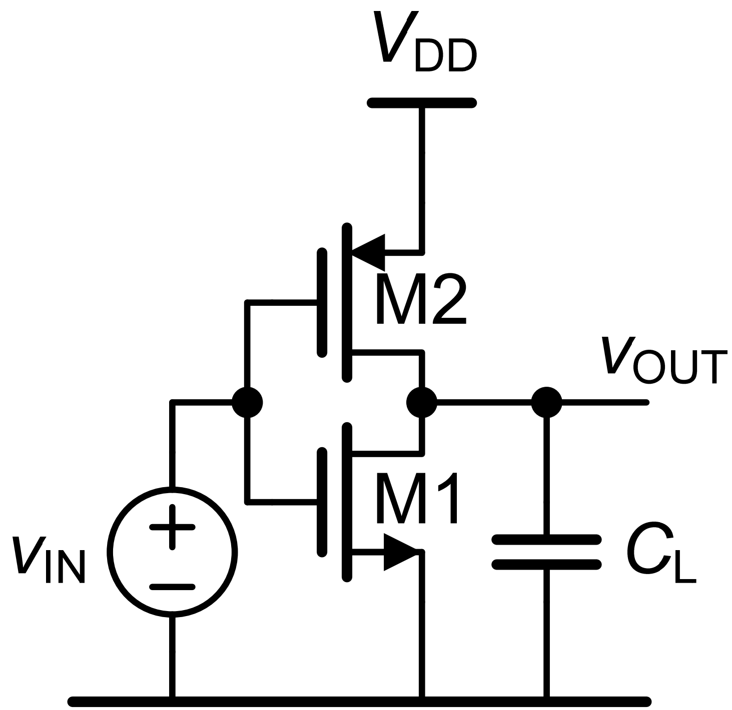
$$R_{out} = r_{DS1} // r_{DS2}$$

A类和AB类放大器



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

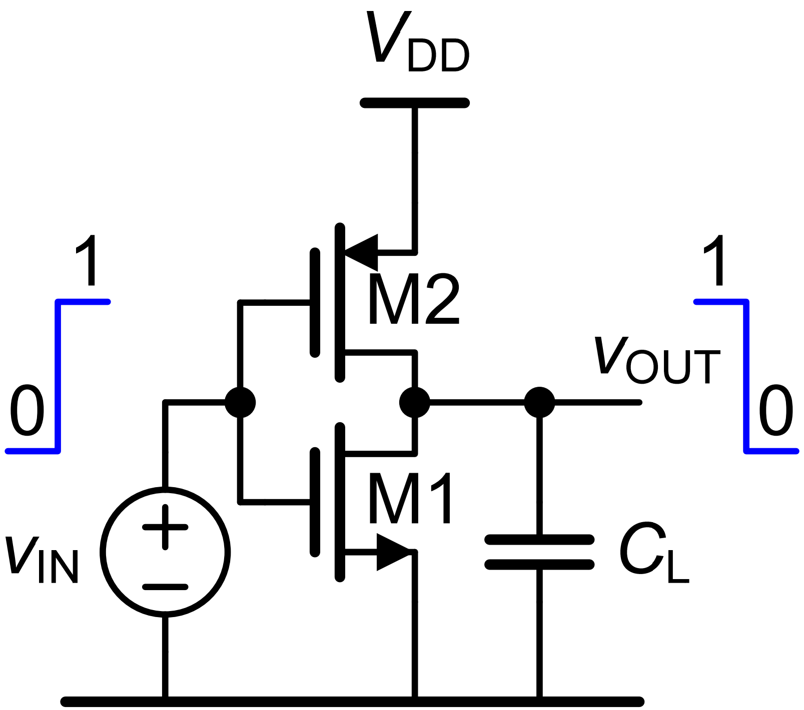
A类



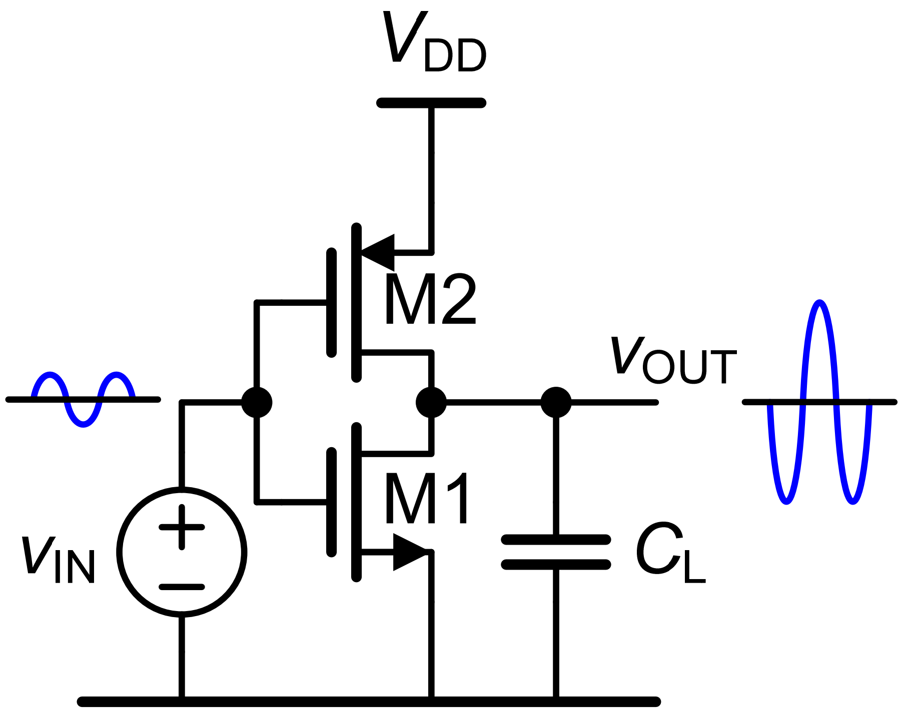
$$v_{out} = A_V v_{in}$$

AB类

CMOS反相放大器

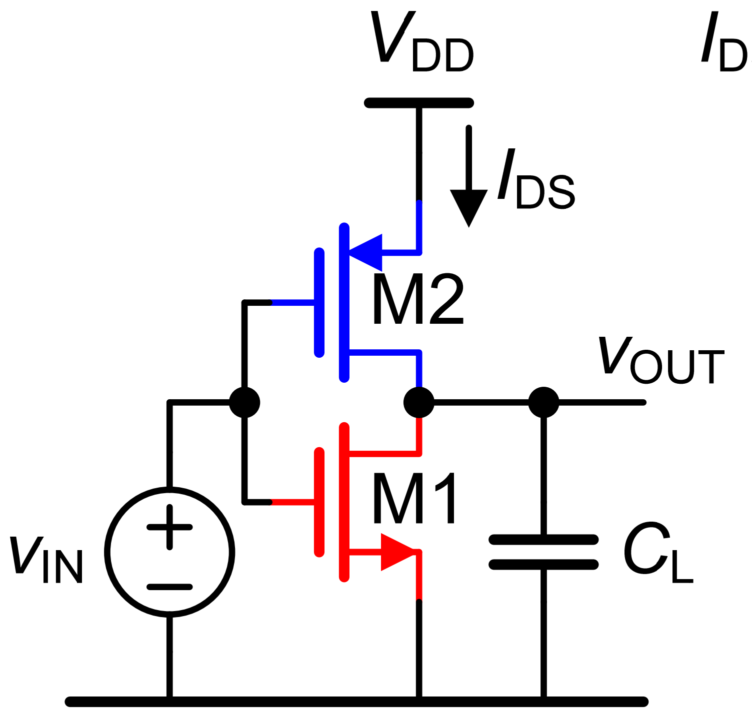


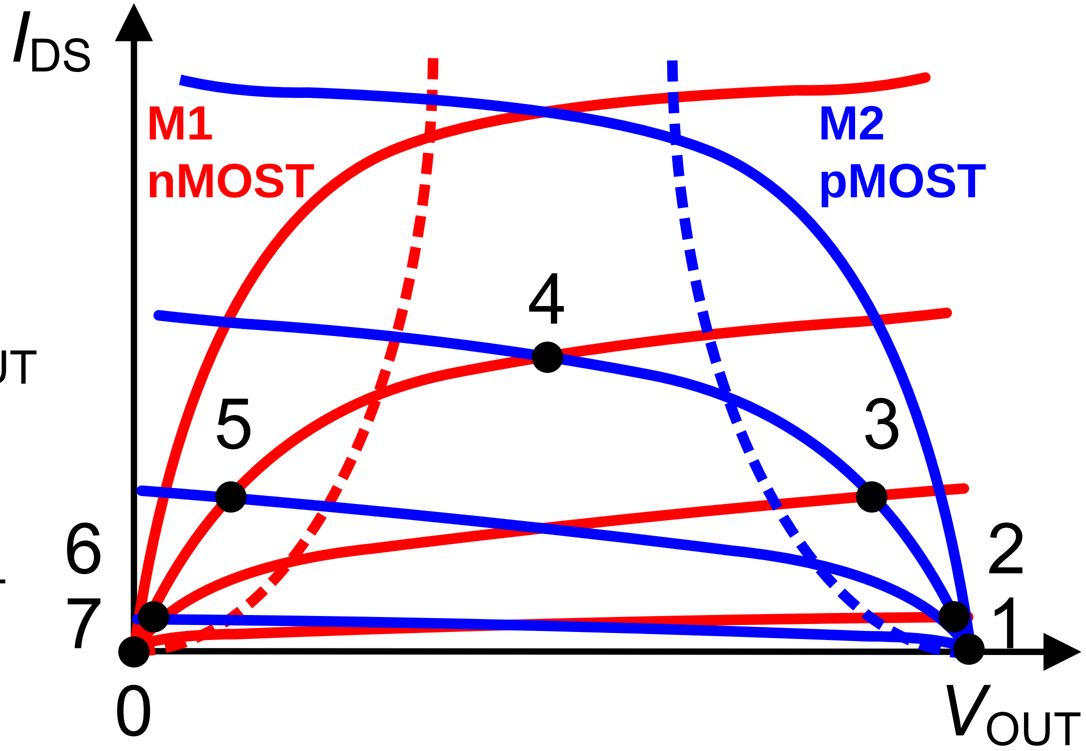
数字反相器



模拟放大器

nMOST和pMOST的工作点



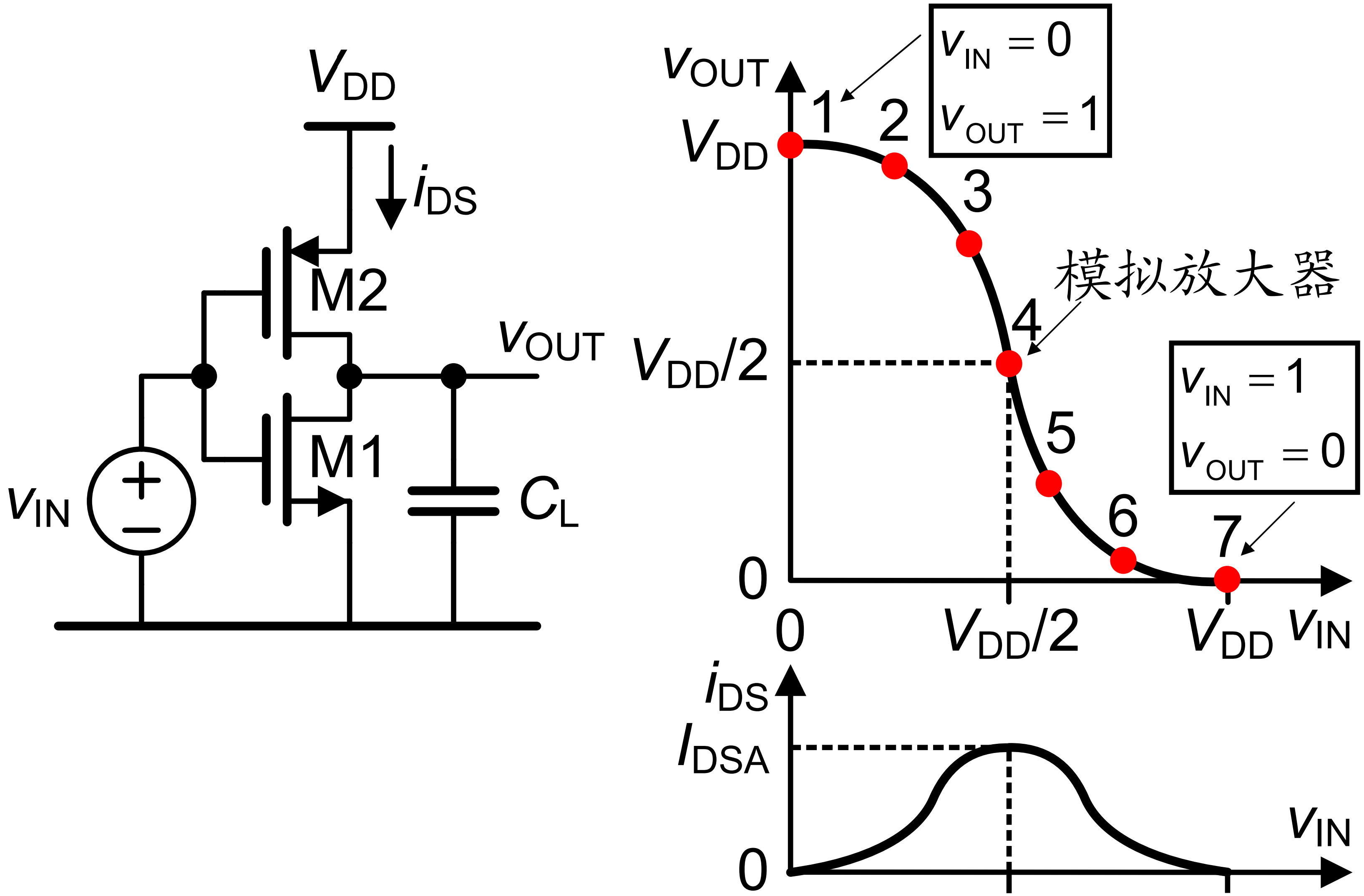


$$V_{DD} = V_{DSn} + V_{DSp}$$
$$= V_{GSn} + V_{GSp}$$

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

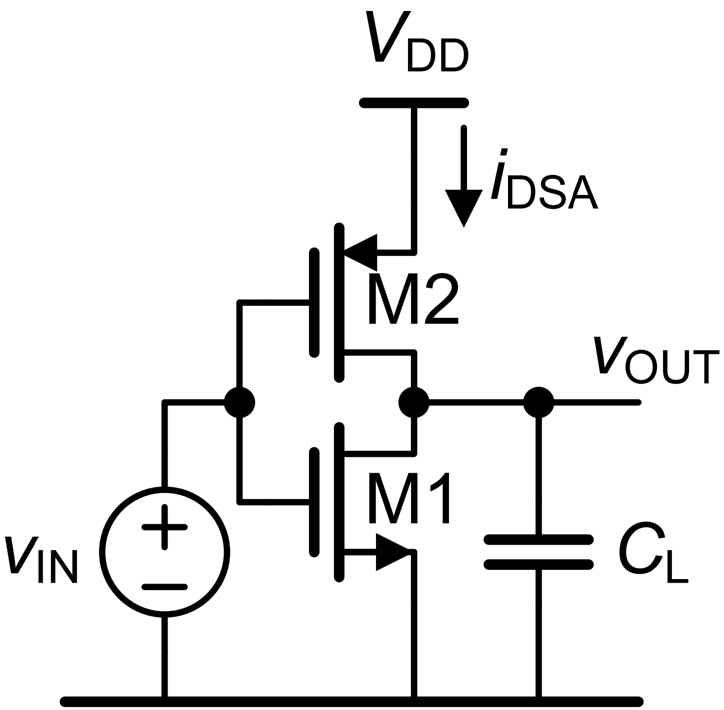
$$V_{GSn} = V_{IN} \qquad V_{GSp} = V_{DD} - V_{IN}$$

传输特性



V_{DD}
i_{DS}
M2
v_{OUT}
M1
v_{IN}
C_L
v_{OUT}
V_{DD}
$V_{DD}/2$
0
1
2
3
4
5
6
7
$v_{IN} = 0$
$v_{OUT} = 1$
模拟放大器
$v_{IN} = 1$
$v_{OUT} = 0$
0
$V_{DD}/2$
V_{DD}
v_{IN}
i_{DS}
I_{DSA}
0
v_{IN}

模拟放大器：直流工作点



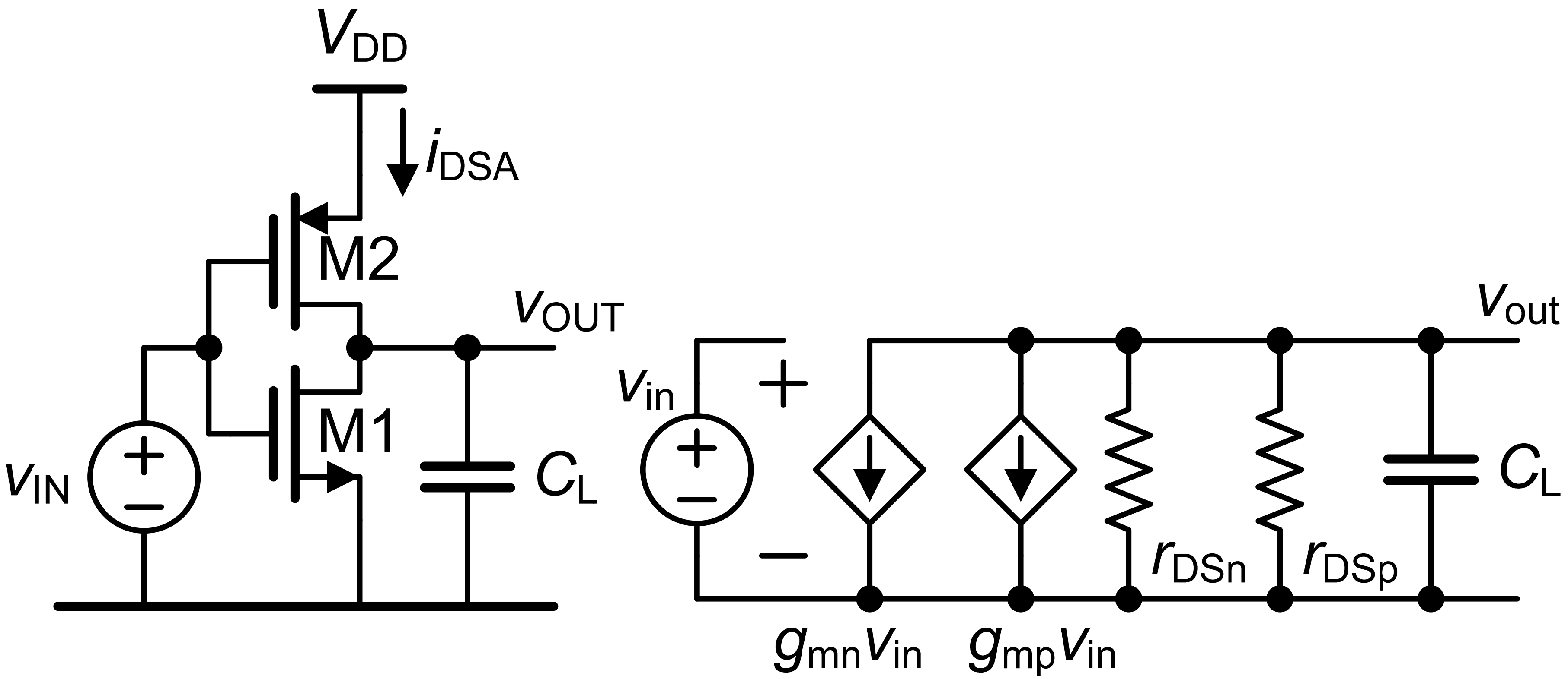
$$V_{in} = \frac{V_{DD}}{2} \Rightarrow V_{out} = \frac{V_{DD}}{2}$$

$$\left.\begin{aligned} I_{DSn} &= K_n' \frac{W_n}{L_n}(V_{in} - V_T)^2 \\ I_{DSp} &= K_p' \frac{W_p}{L_p}(V_{DD} - V_{in} - V_T)^2 \end{aligned}\right\}$$

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

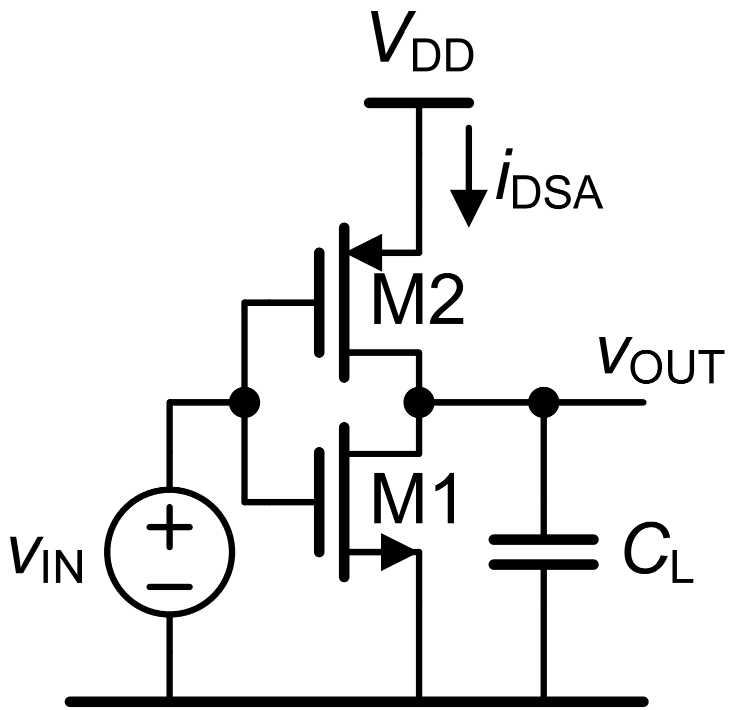
$$I_{DS} = K_n' \frac{W_n}{L_n}\left(\frac{V_{DD}}{2} - V_T\right)^2$$

模拟放大器：交流小信号模型



两个MOST的$V_{GS} - V_T$和I_{DS}相等，则： $g_{mn} = g_{mp} = g_m$

模拟放大器：增益A_V



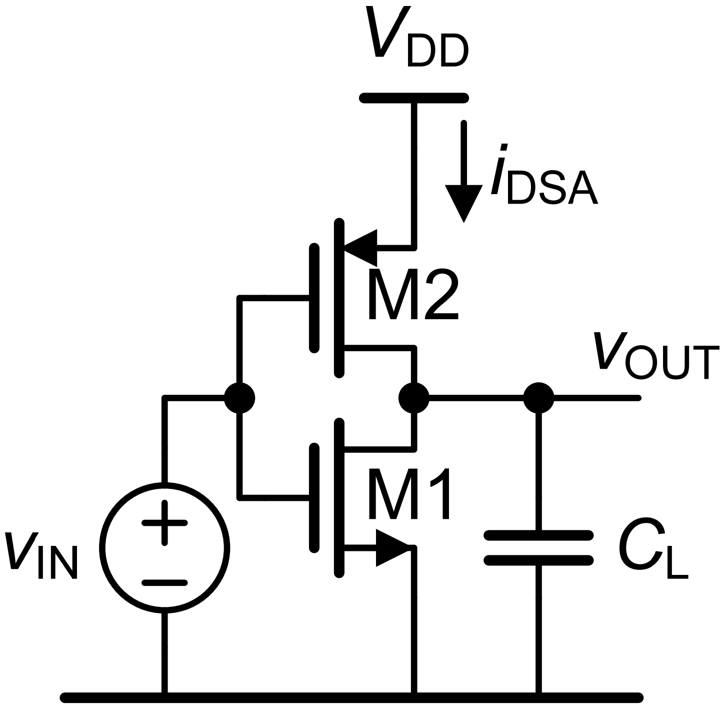
如果 $V_{En}L_n = V_{Ep}L_p = V_E$

$$g_{DSn} = g_{DSp} = g_{DS}$$

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

$$A_{V0} = -\frac{2g_m}{2g_{DS}} = -\frac{2V_E}{\frac{V_{DD}}{2} - V_T}$$

模拟放大器：BW & GBW



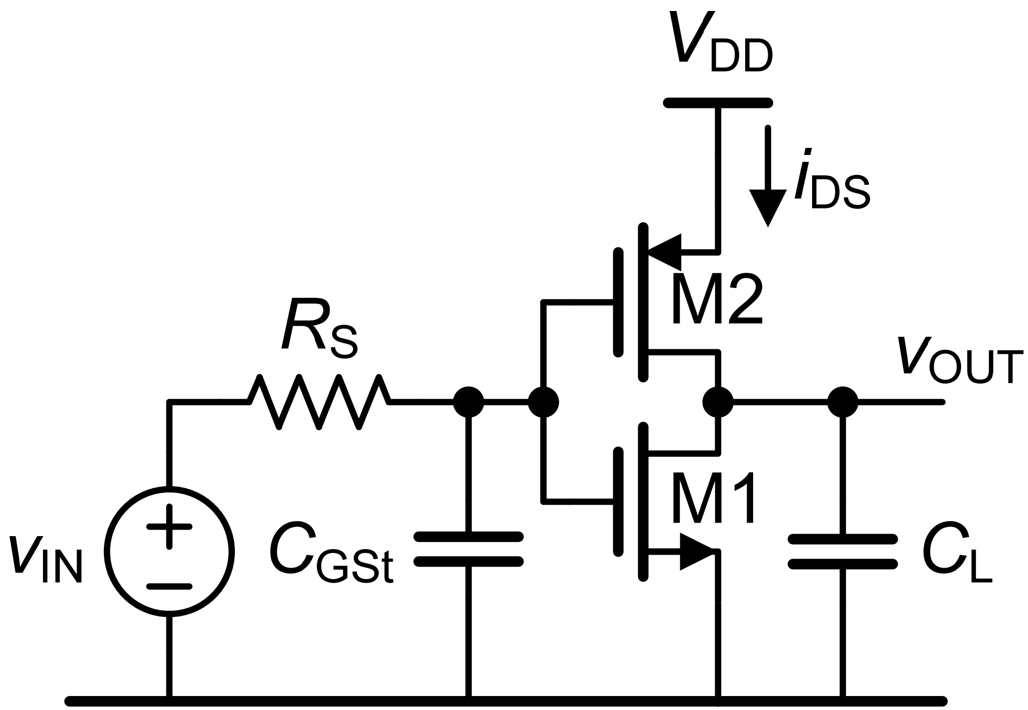
$$A_{V0} = 2g_m R_{out}$$

$$R_{out} = r_{DSn} // r_{DSp} = \frac{r_{DS}}{2}$$

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

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

模拟放大器：C_{GS}产生的极点



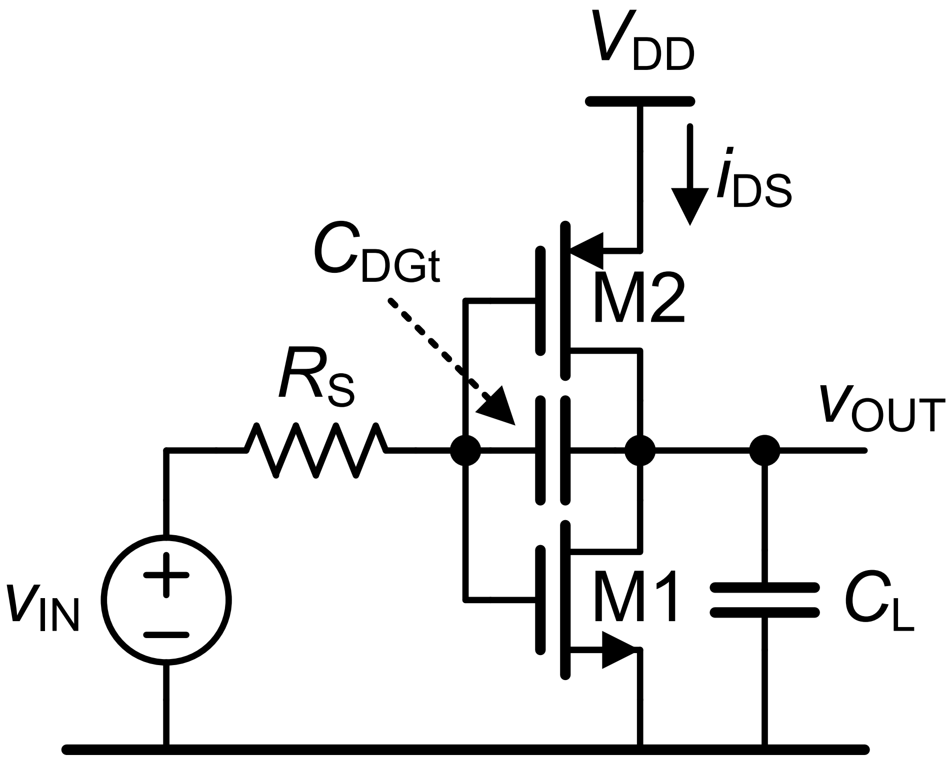
$$A_{V0} = 2g_m R_{out} = g_m r_{DS}$$

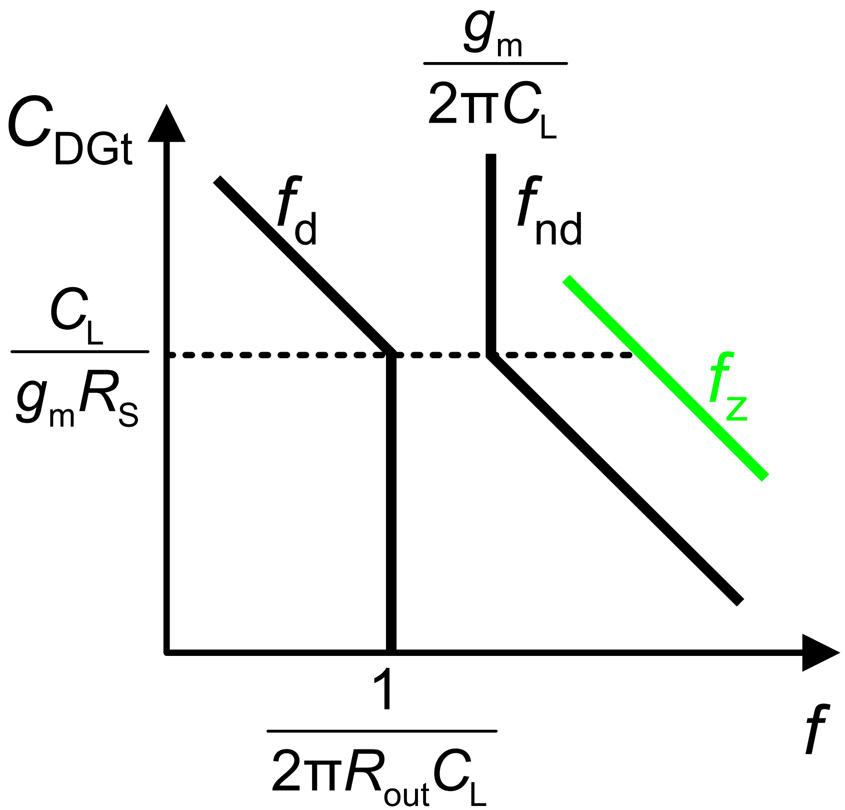
$$BW = \frac{1}{2\pi R_S C_{GSt}}$$

$$C_{GSt} = C_{GSn} + C_{GSp}$$

如果 $R_S C_{GSt} > r_{DS} C_L$ ： $GBW = \dfrac{f_T}{2}\dfrac{r_{DS}}{R_S}$

模拟放大器：C_{DG}产生的极点





$$A_V = \frac{v_{out}}{v_{in}} = -\frac{A_{V0}(1 - sC_{DGt}/g_m)}{1 + s[R_{out}C_L + R_{out}C_{DGt} + (1 + A_{v0})R_SC_{DGt}] + s^2R_SR_{out}C_{DGt}C_L}$$

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

零点 $z = \frac{1}{c}$

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

如果 $s_2 \gg s_1$ ：

s很小

$$\Downarrow$$

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

$$\Downarrow$$

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

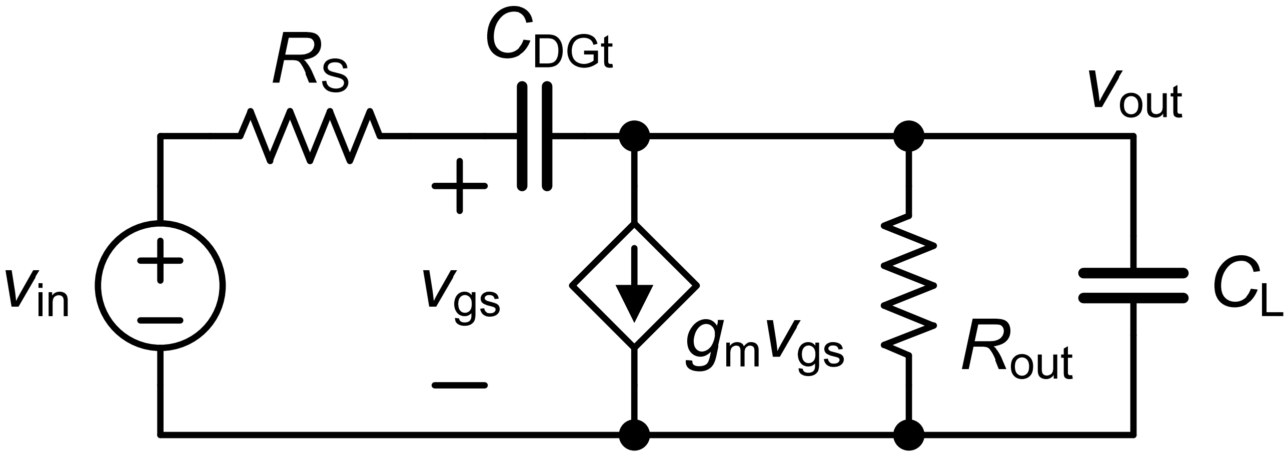
s很大

$$\Downarrow$$

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

$$\Downarrow$$

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



$$\frac{v_{in}-v_{out}}{R_S+\dfrac{1}{sC_{DGt}}}\frac{1}{sC_{DGt}}+v_{out}=v_{gs} \qquad \textbf{(1)}$$

$$\frac{v_{in}-v_{out}}{R_S+\dfrac{1}{sC_{DGt}}}=g_m v_{gs}+\frac{v_{out}}{R_{out}\,//\,\dfrac{1}{sC_L}} \qquad \textbf{(2)}$$

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

$$R_{out}=r_{DS1}\,//\,r_{DS2}$$

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

将(1) 代入(2)得:

$$A_{\mathrm{V}}=\frac{v_{\mathrm{out}}}{v_{\mathrm{in}}}=-\frac{A_{\mathrm{V0}}(1-sC_{\mathrm{DGt}}/g_{\mathrm{m}})}{1+s[R_{\mathrm{out}}C_{\mathrm{L}}+R_{\mathrm{out}}C_{\mathrm{DGt}}+(1+A_{\mathrm{v0}})R_{\mathrm{S}}C_{\mathrm{DGt}}]+s^{2}R_{\mathrm{S}}R_{\mathrm{out}}C_{\mathrm{DGt}}C_{\mathrm{L}}}$$

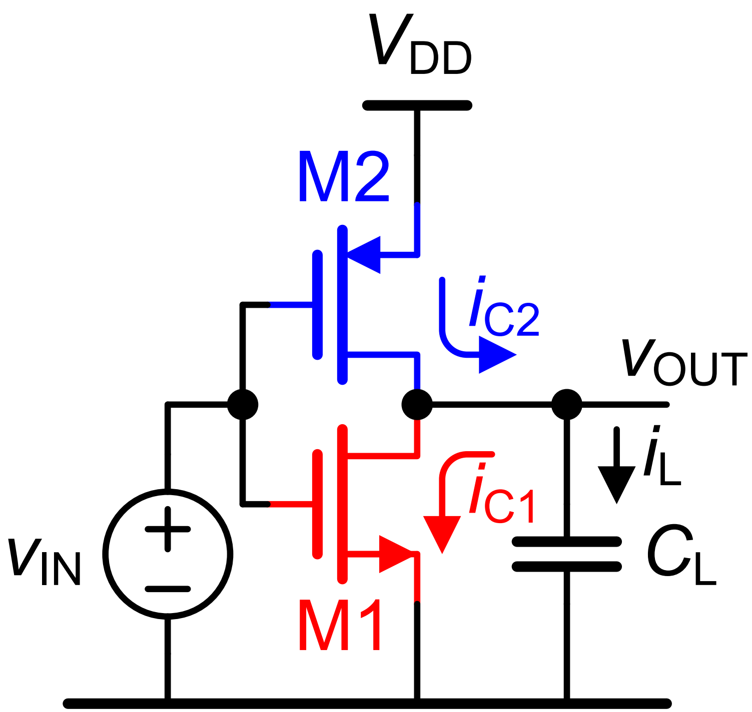
$$f_{\mathrm{z}}=\frac{g_{\mathrm{m}}}{2\pi C_{\mathrm{DGt}}},\quad f_{\mathrm{d}},\quad f_{\mathrm{nd}}$$

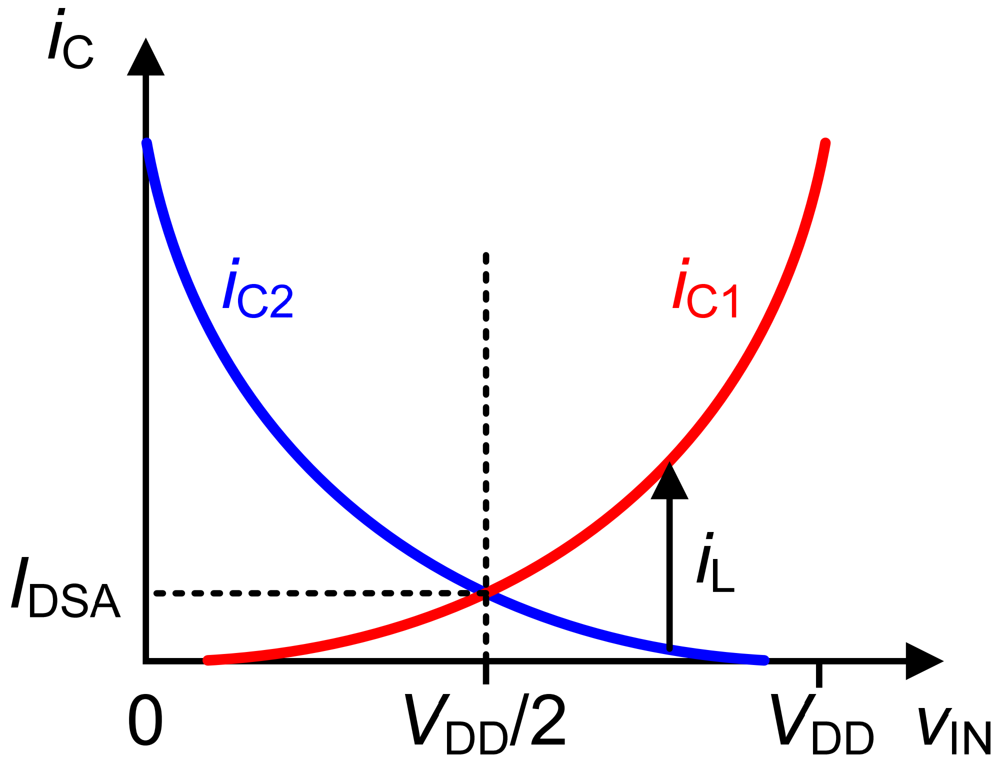
$$R_{\mathrm{out}}C_{\mathrm{L}}=A_{\mathrm{v0}}R_{\mathrm{S}}C_{\mathrm{DGt}}\quad\Rightarrow\quad C_{\mathrm{DGt}}=\frac{C_{\mathrm{L}}}{g_{\mathrm{m}}R_{\mathrm{S}}}$$

$$C_{\mathrm{DGt}}\ll\frac{C_{\mathrm{L}}}{g_{\mathrm{m}}R_{\mathrm{S}}}\qquad f_{\mathrm{d}}=-\frac{1}{2\pi R_{\mathrm{out}}C_{\mathrm{L}}}\qquad f_{\mathrm{nd}}=-\frac{1}{2\pi R_{\mathrm{S}}C_{\mathrm{DGt}}}$$

$$C_{\mathrm{DGt}}\gg\frac{C_{\mathrm{L}}}{g_{\mathrm{m}}R_{\mathrm{S}}}\qquad f_{\mathrm{d}}=-\frac{1}{2\pi R_{\mathrm{S}}A_{\mathrm{V0}}C_{\mathrm{DGt}}}\qquad f_{\mathrm{nd}}=-\frac{g_{\mathrm{m}}}{2\pi C_{\mathrm{L}}}$$

AB类放大器



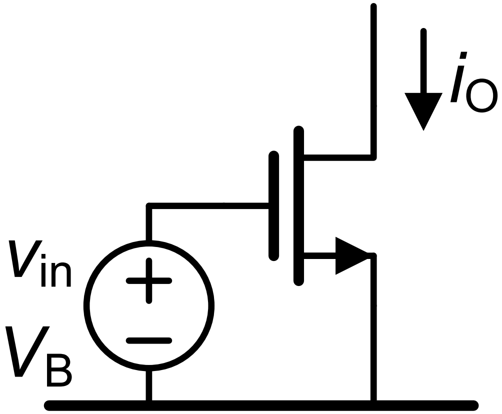


$$\boxed{i_L = i_{C2} - i_{C1}}$$

目录

单晶体管级

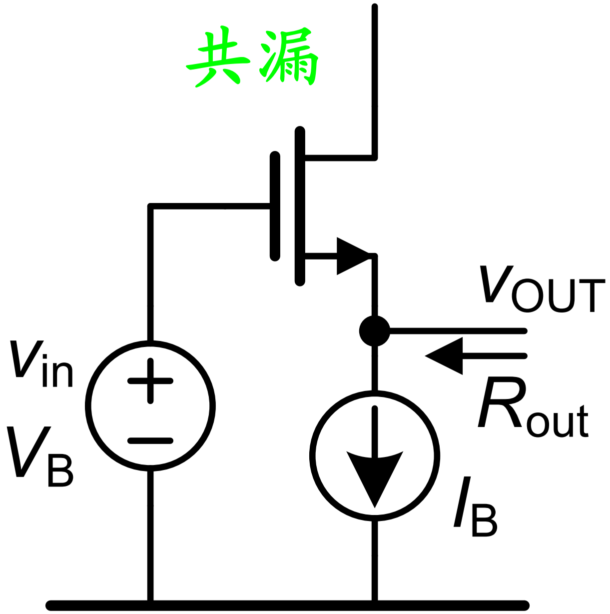
共源



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

共源放大器

共漏



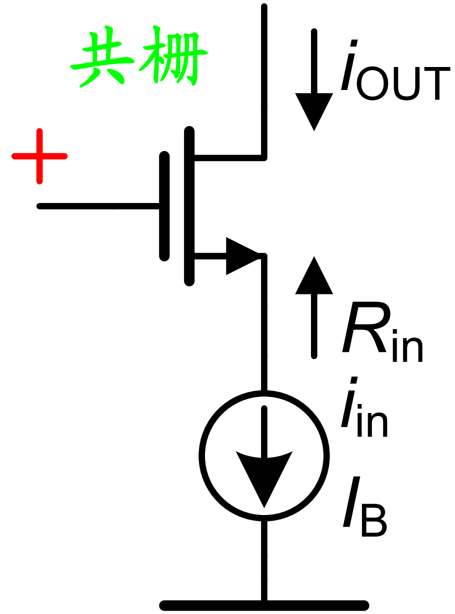
$$v_{out} = v_{in}$$

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

源极跟随器

电压缓冲器

共栅



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

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

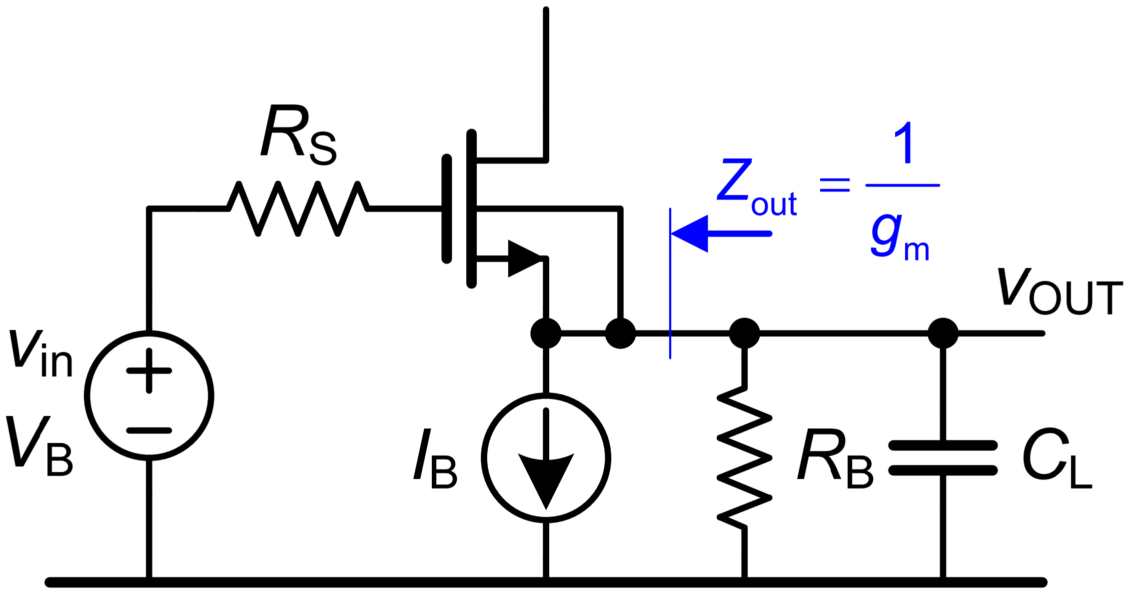
共栅放大器

电流缓冲器

源极跟随器： V_{BS}=0 V (p阱)

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

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

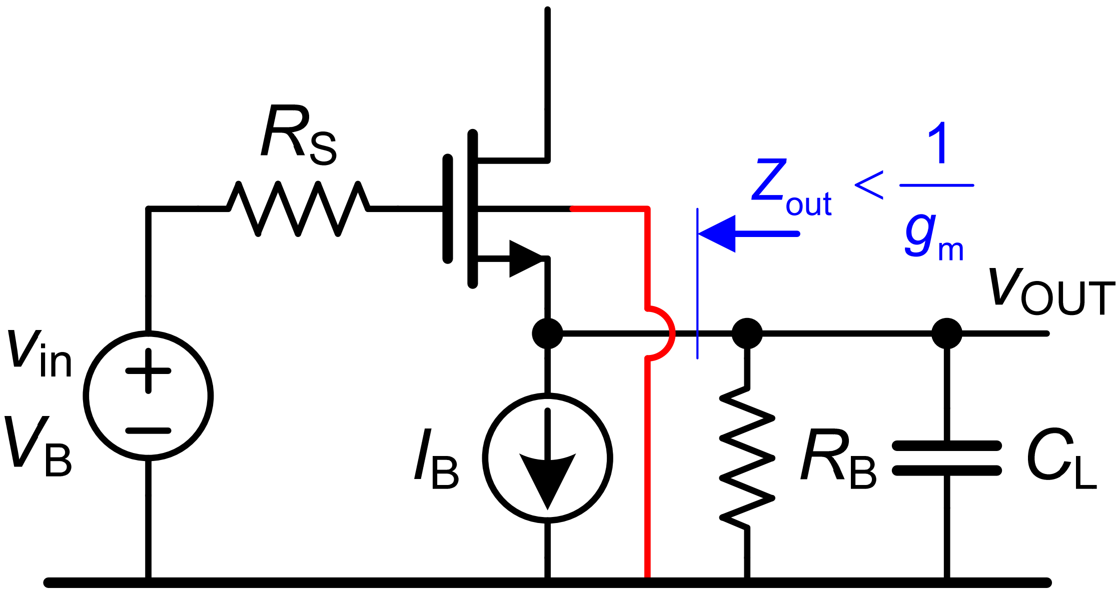


如果 $I_B=\text{ct}$， 则 $V_{GS}=\text{ct}$

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

源极跟随器： $V_{BS} \neq 0$ V (n阱)

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

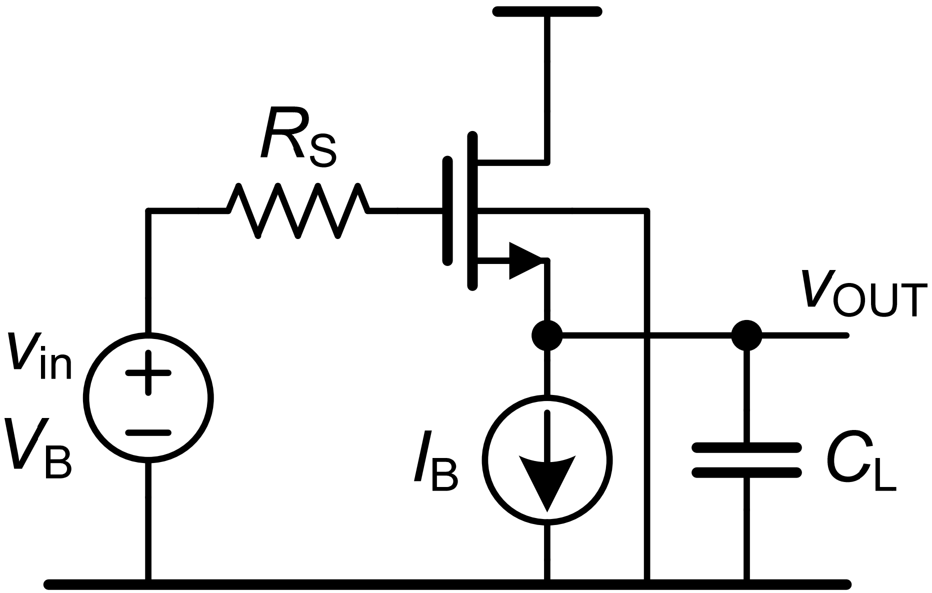


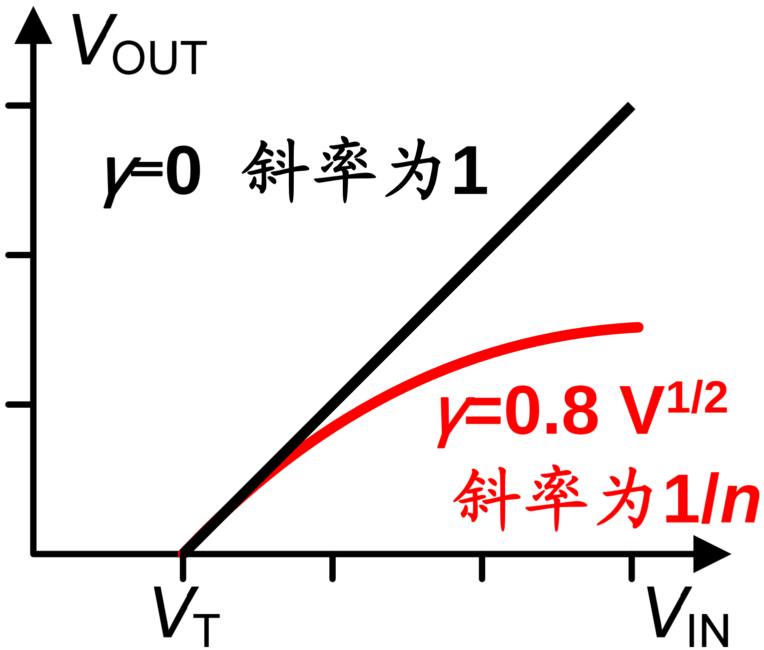
$$V_{GS} = V_T + \sqrt{\frac{I_B}{K'W/L}}$$

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

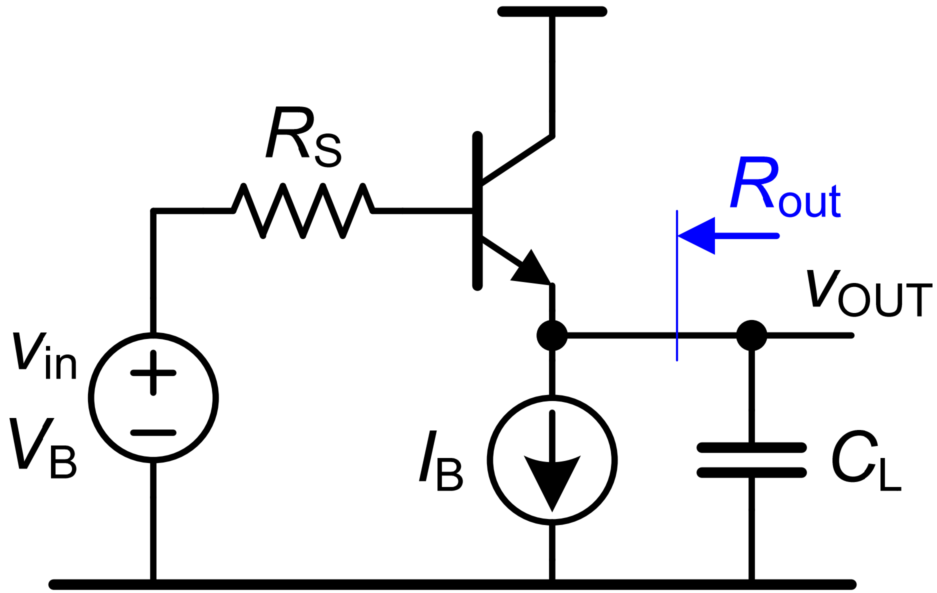
$V_{OUT} = V_{IN} - V_{GS}$ $\Rightarrow \Delta V_{OUT} \neq \Delta V_{IN} \Rightarrow \boxed{A_V = \frac{1}{n}}$

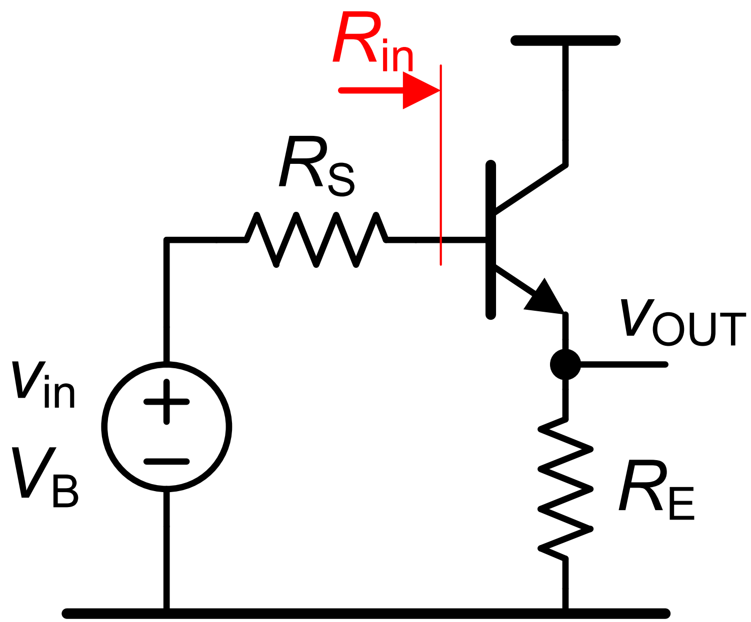
源极跟随器：非线性





射极跟随器



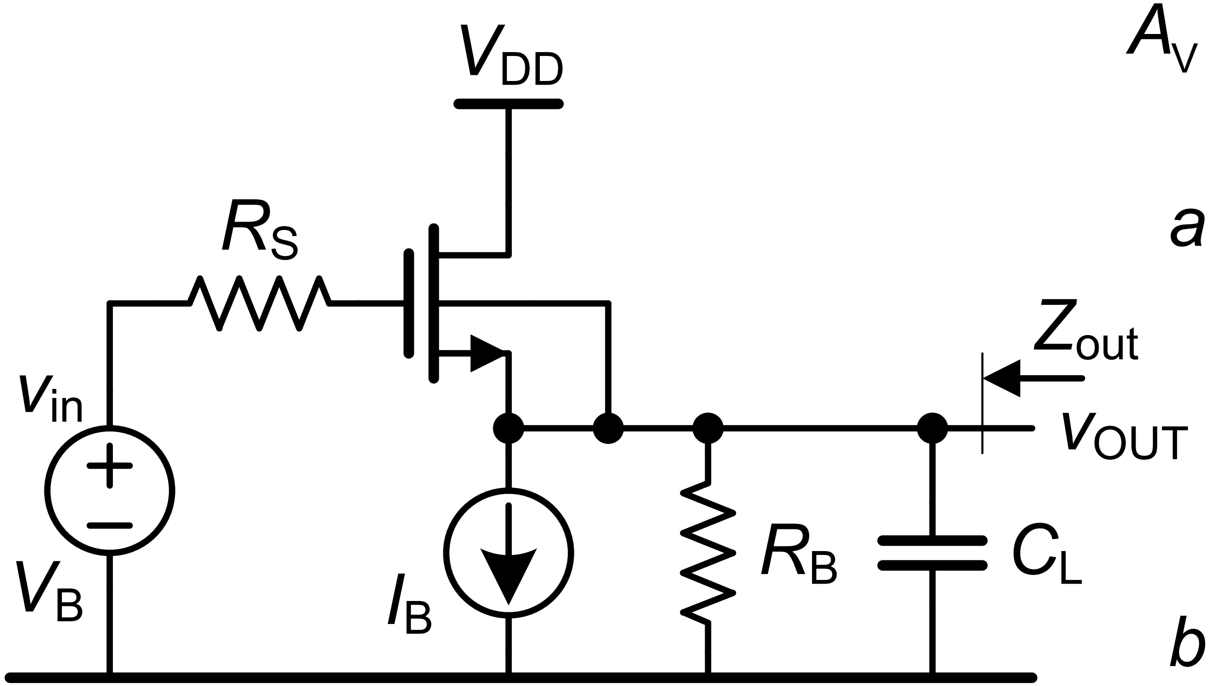


$$A_V = 1 \qquad R_{out} = \frac{1}{g_m} + \frac{R_S + r_B}{\beta+1}$$

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

隔离度受限！

接负载电容C_L的源极跟随器



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

$$a = R_S C_{DG} + \frac{C'_{DS}}{g_m} + \frac{C_{GS}}{g_m}\left(1 + \frac{R_S}{r'_{DS}}\right)$$

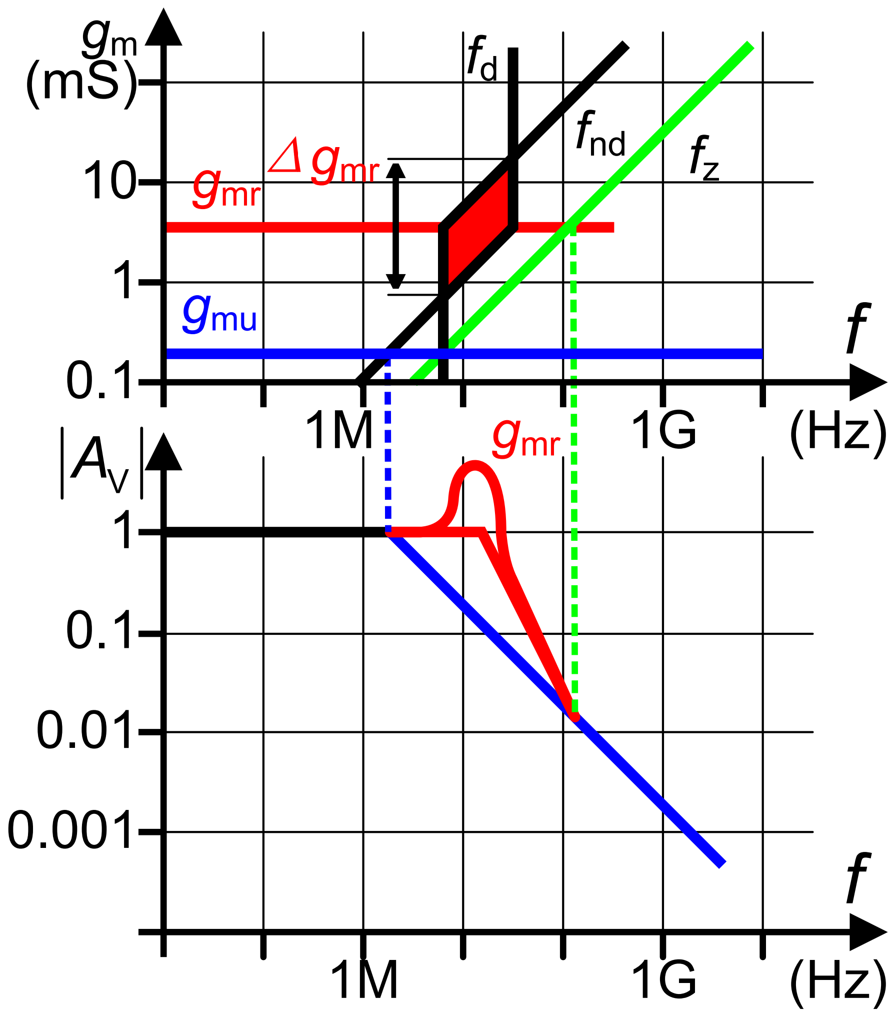
$$b = \frac{R_S C'C'}{g_m}$$

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

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

$$C'C' = C'_{DS}C_{DG} + C'_{DS}C_{GS} + C_{DG}C_{GS}$$

源极跟随器：频响特性随g_m的变化



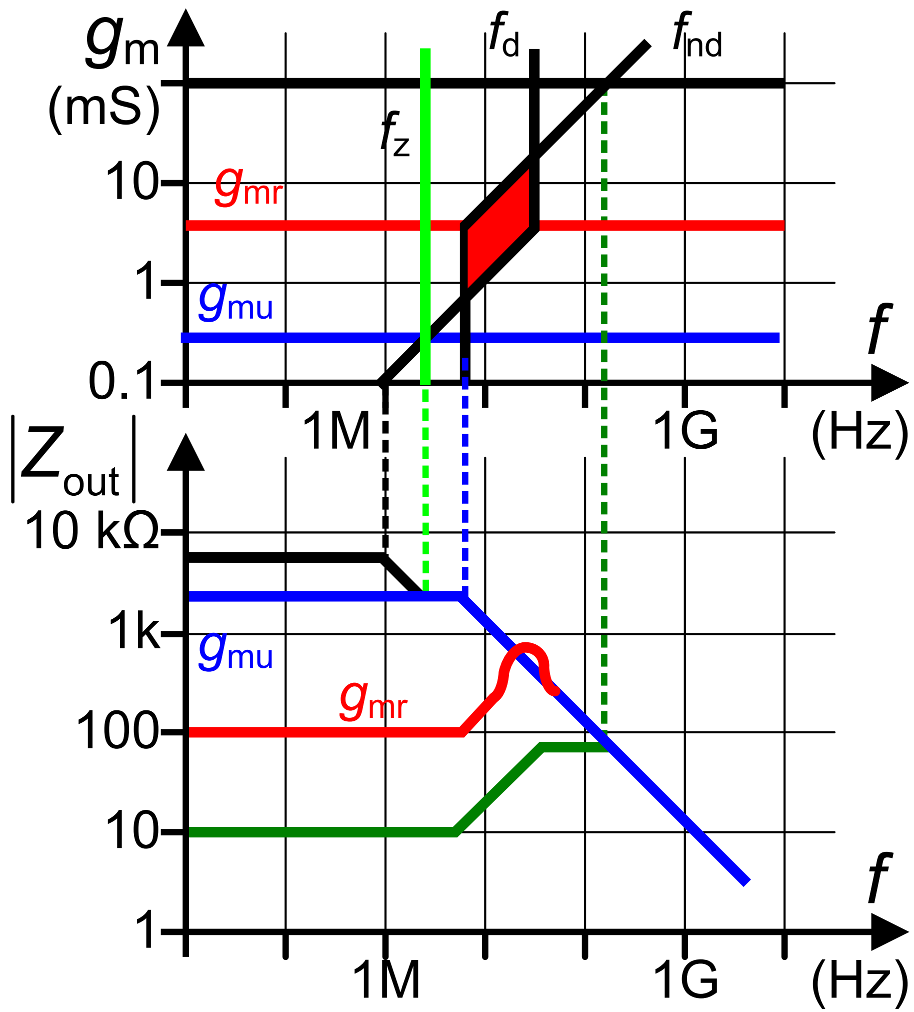
$$g_{mr} = \frac{1}{R_S} \frac{C_L + C_{DS} + C_{GS}}{C_{DG}}$$

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

$$C_{DGt} = \frac{C_{GS} C'_{DS}}{C_{GS} + C'_{DS}}$$

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

源极跟随器：输出阻抗随g_m的变化



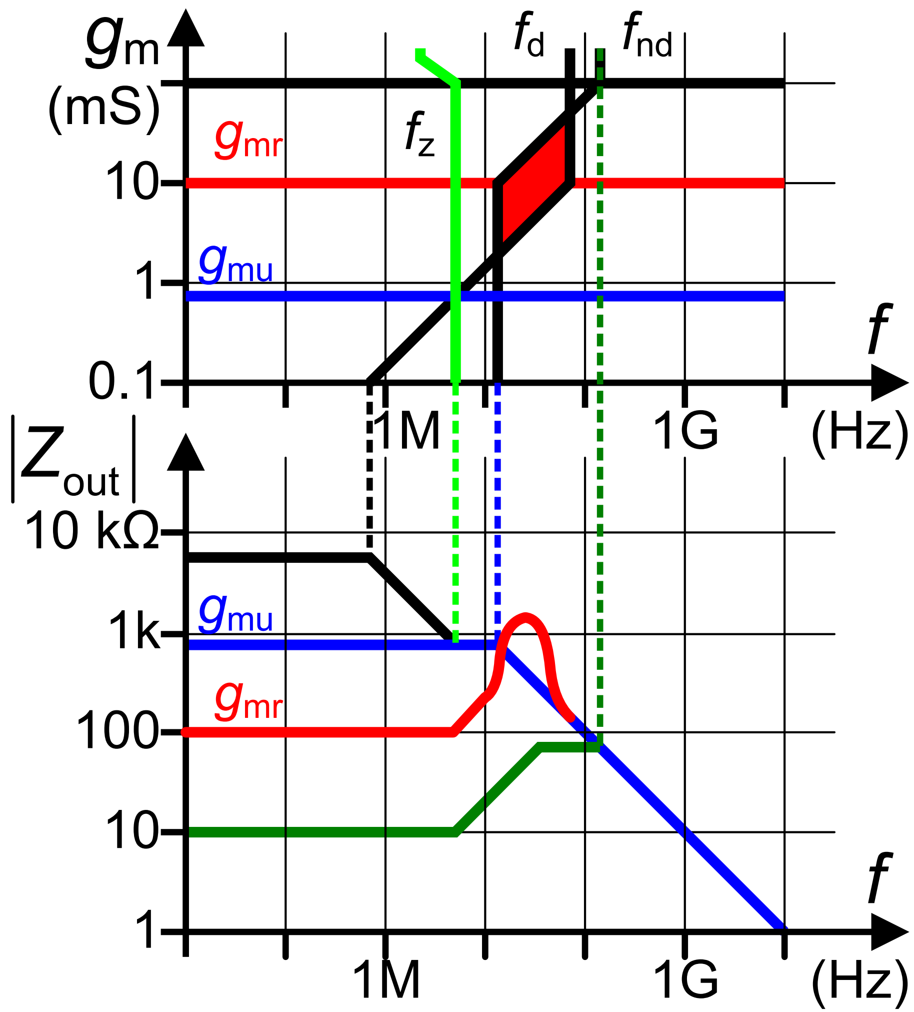
$$g_{mr} = \frac{1}{R_S} \frac{C_{GS} + C'_{DS}}{C_{DG}}$$

$$g_{mu} \approx \frac{1}{R_S} \frac{C_{GS} + C'_{DS}}{C_{DG} + C_{GS}}$$

$$f_z = \frac{1}{2\pi R_S (C_{DG} + C_{GS})}$$

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

射极跟随器：输出阻抗随g_m的变化

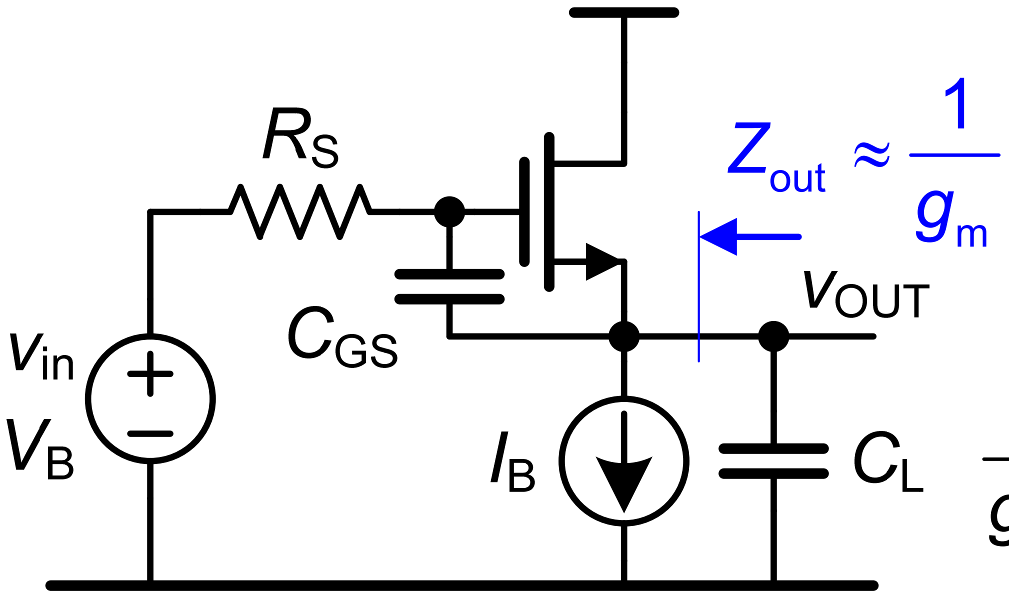


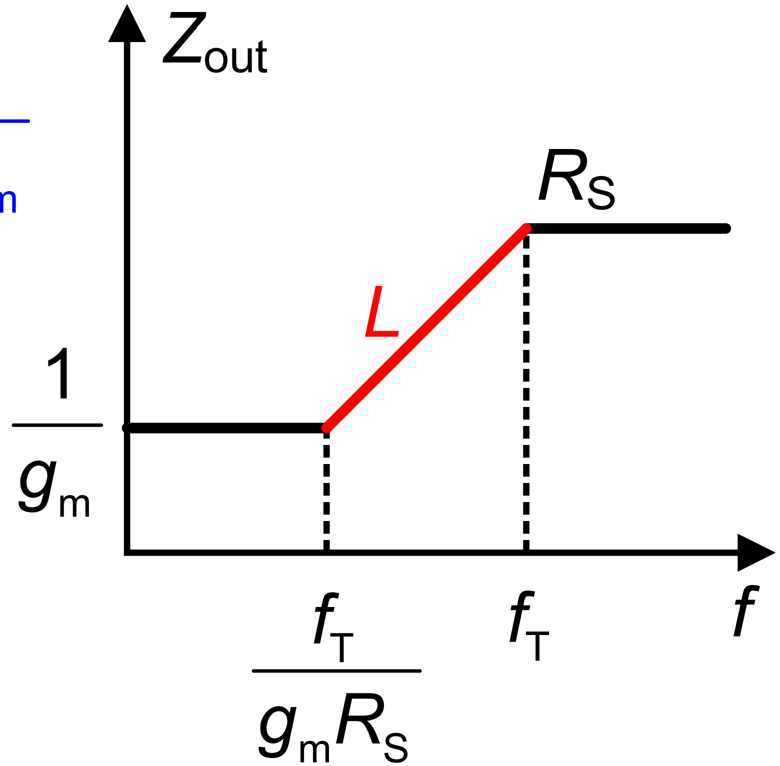
$$g_{mr} = \frac{C_{jE} + C_L}{\tau_F + R'_S C_\mu}$$

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

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

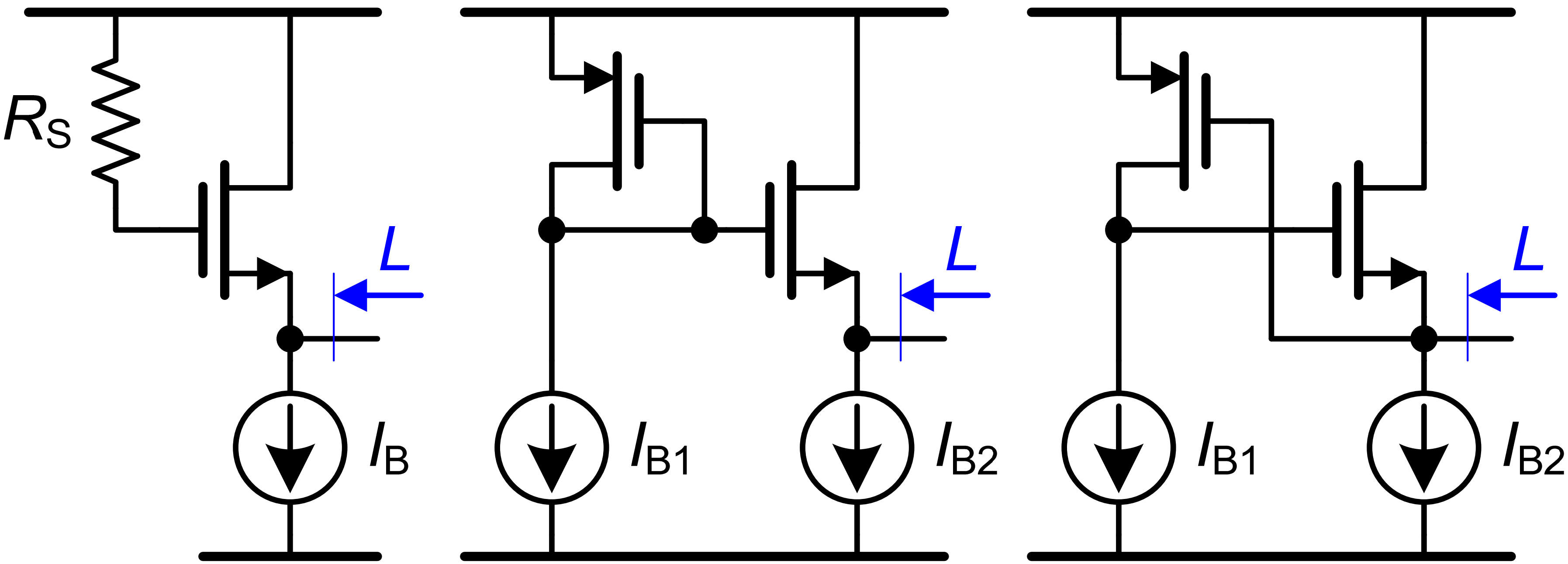
做为有源电感的源极跟随器 1





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

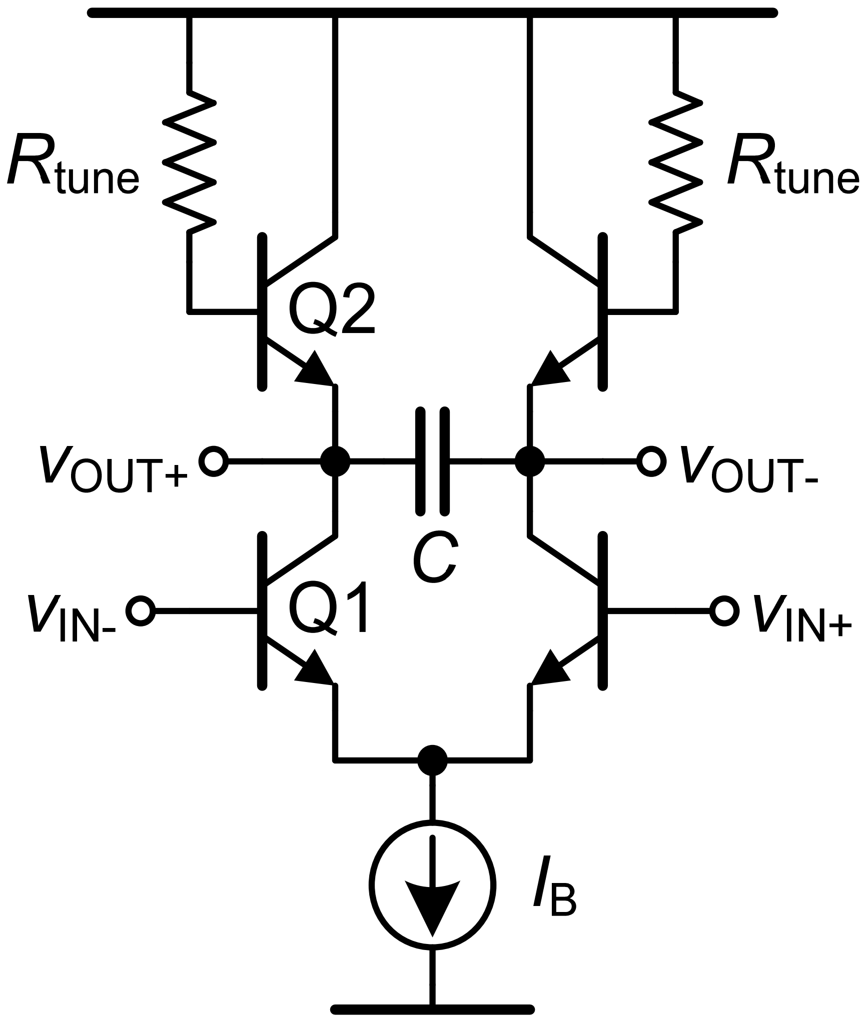
做为有源电感的源极跟随器 2



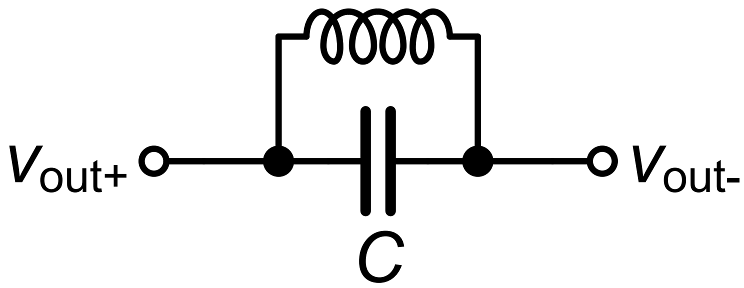
$$L \approx \frac{R_S}{2\pi f_T} \qquad L \approx \frac{1/g_{mp}}{2\pi f_{Tn}} \qquad L \approx \frac{1/g_{mp}}{2\pi f_{Tn}}$$

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

与电容并联的两端悬浮电感



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



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

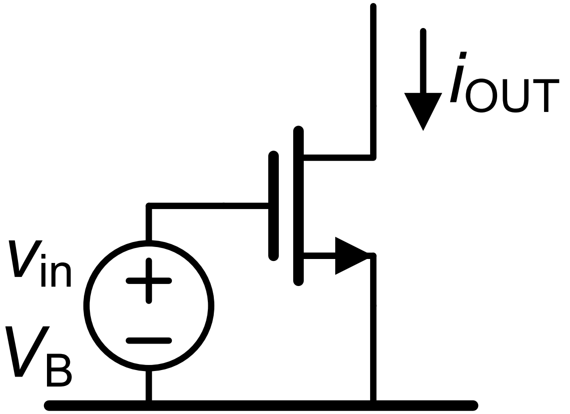
抬升高频特性！

目录

- 共源放大器
- 源极跟随器
- 共栅放大器

单晶体管级

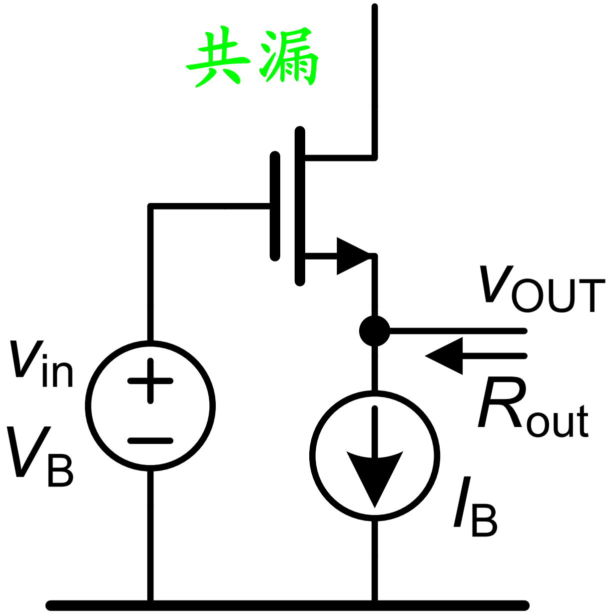
共源



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

共源放大器

共漏



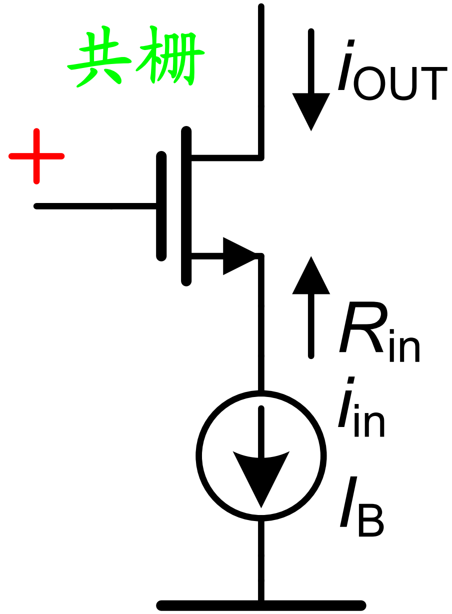
$$v_{out} = v_{in}$$

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

源极跟随器

电压缓冲器

共栅



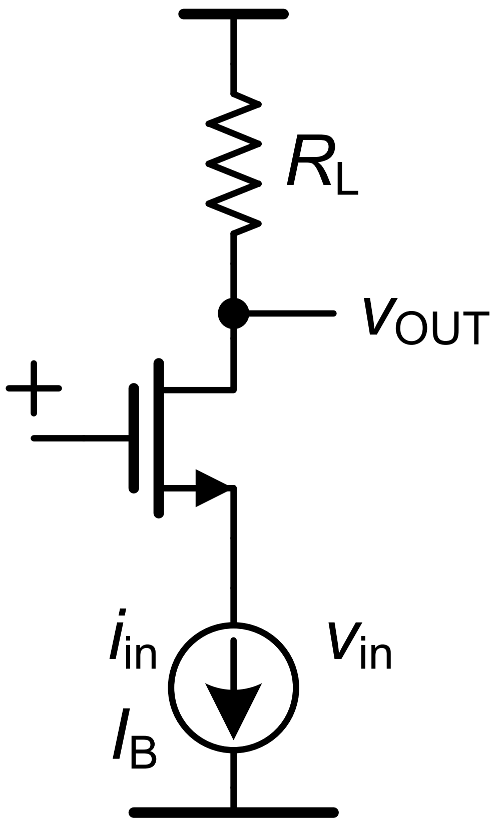
$$i_{out} = i_{in}$$

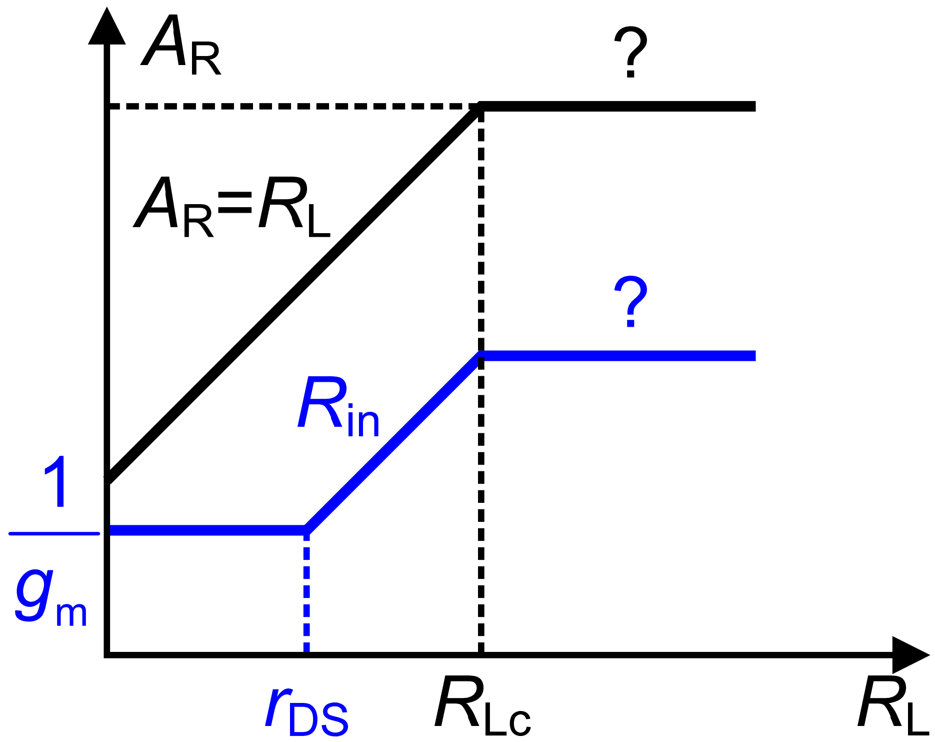
$$R_{in} \approx 1/g_m$$

共栅放大器

电流缓冲器

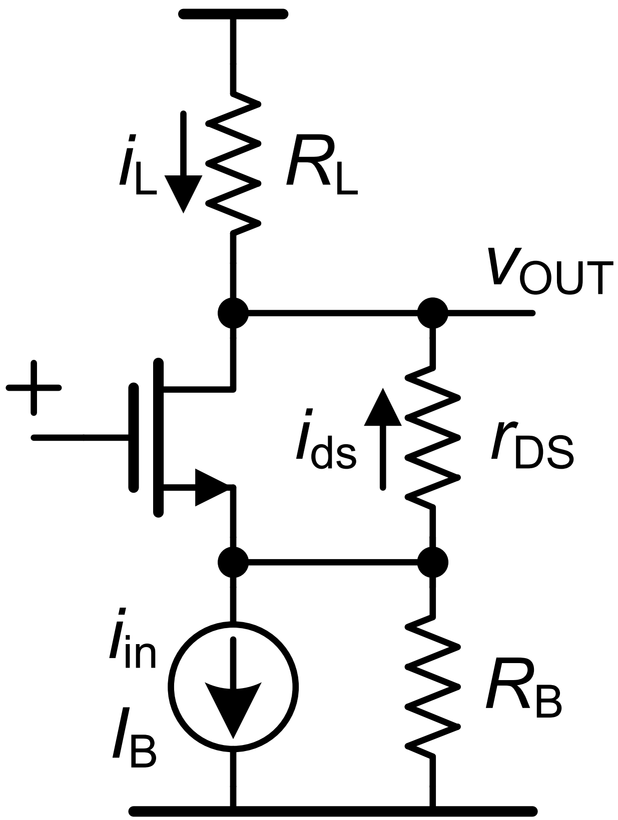
接电阻负载的共栅放大器





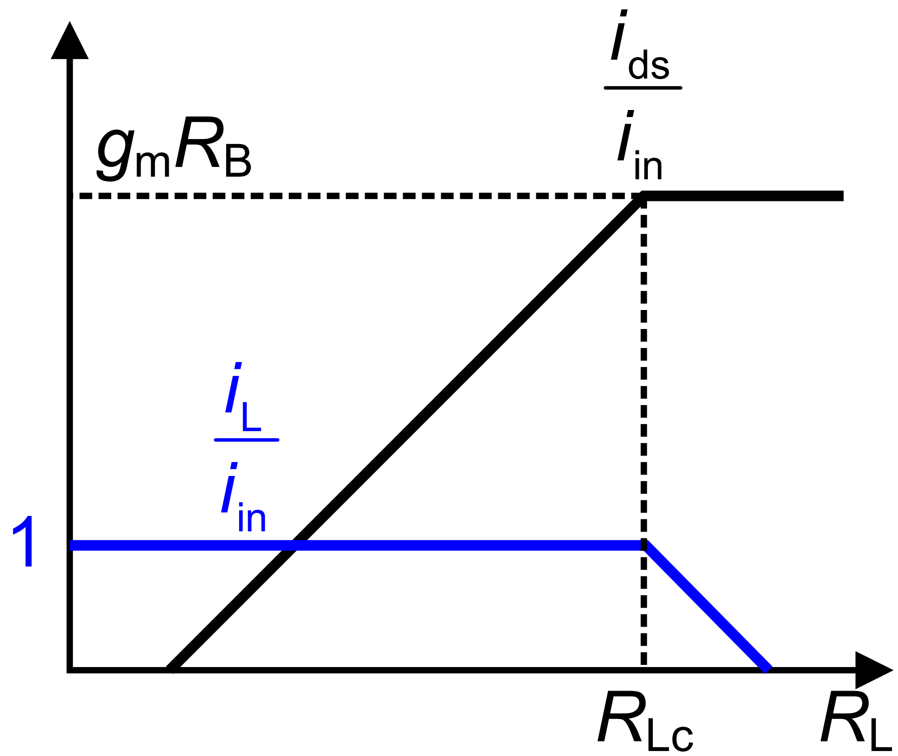
$$A_R = \frac{v_{out}}{i_{in}} \qquad R_{in} = \frac{v_{in}}{-i_{in}}$$

共栅放大器：电流增益

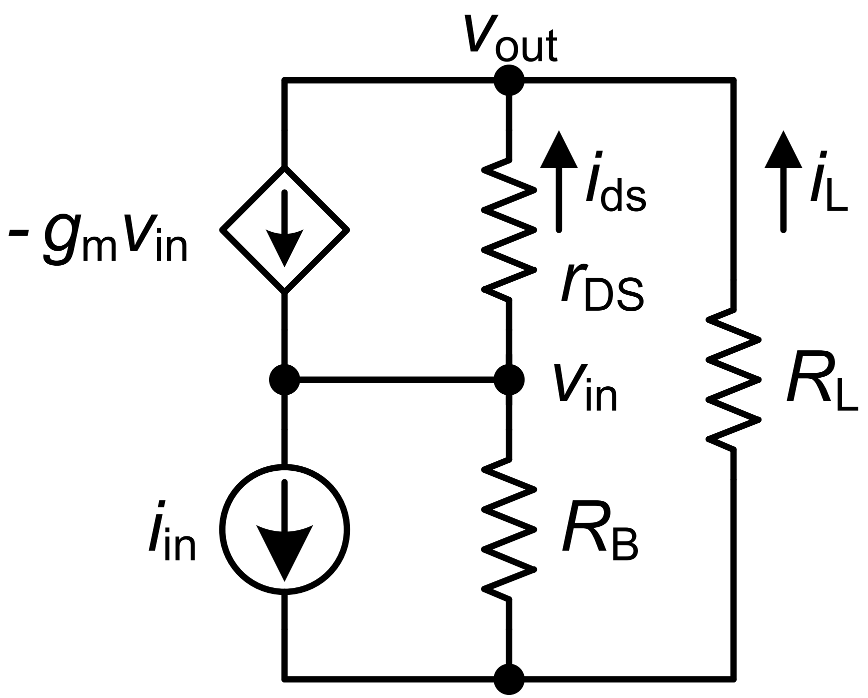


$$\frac{i_{ds}}{i_{in}} = \frac{R_B(g_m R_L - 1)}{R_L + r_{DS} + R_B(1 + g_m r_{DS})}$$

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



$$\boxed{R_{Lc} = g_{m1} r_{DS} R_B}$$



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

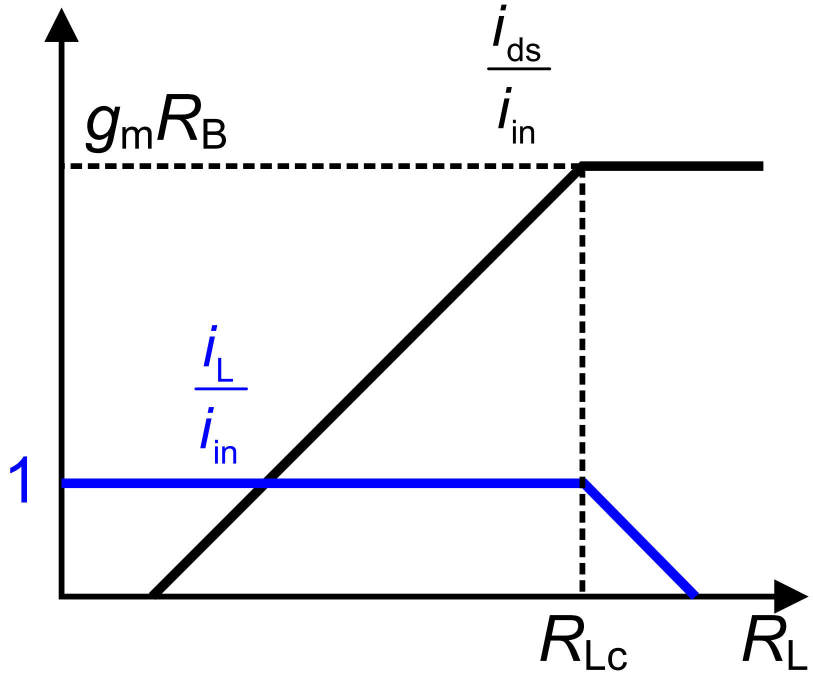
$$v_{out} = -R_L i_L \quad \textbf{(2)}$$

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

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

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

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

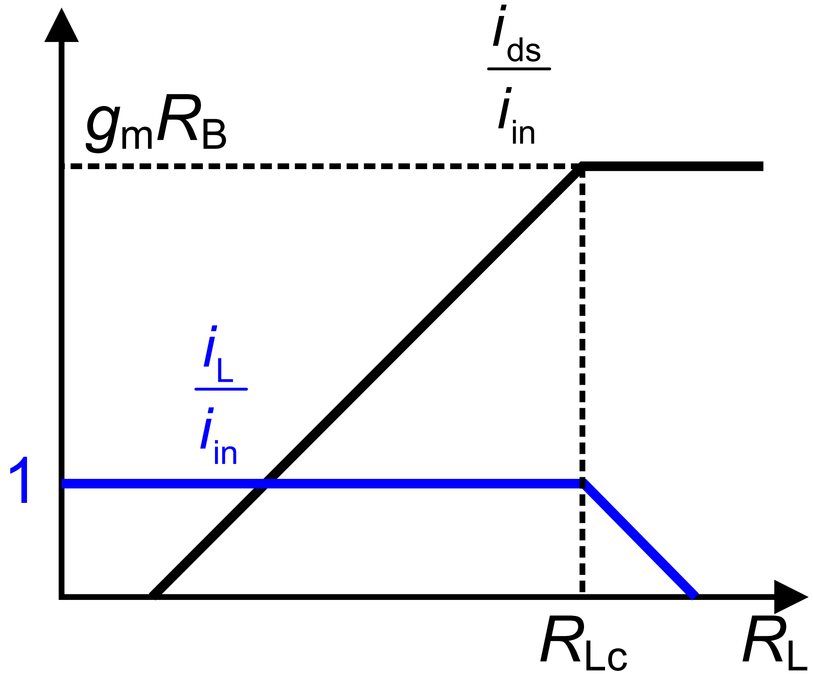


$$\frac{i_L}{i_{in}} = \frac{R_B(1+g_m r_{DS})}{R_L + r_{DS} + R_B(1+g_m r_{DS})}$$

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

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

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

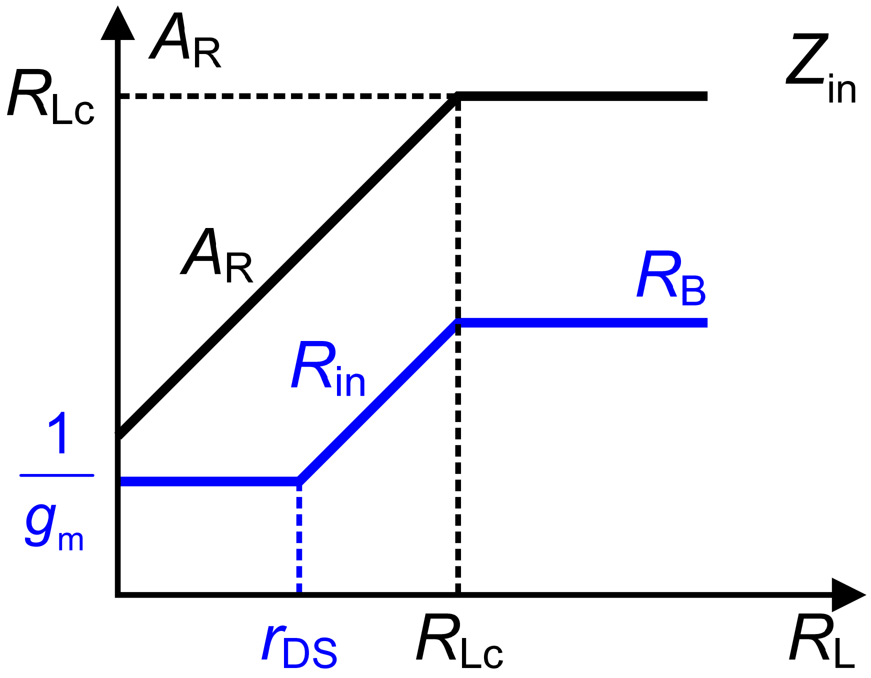


$$\frac{i_{ds}}{i_{in}} = \frac{R_B (g_m R_L - 1)}{R_L + r_{DS} + R_B (1 + g_m r_{DS})}$$

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

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

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



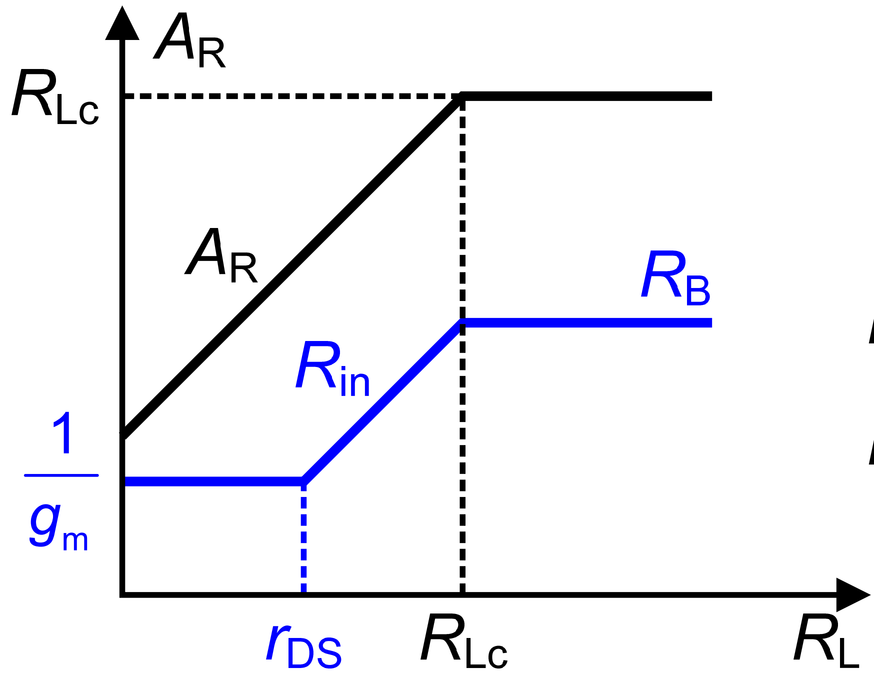
$$Z_{in} = \frac{v_{in}}{-i_{in}} = \frac{R_B(R_L + r_{DS})}{R_L + r_{DS} + R_B(1 + g_m r_{DS})}$$

$$R_L \ll r_{DS} \qquad Z_{in} = \frac{1}{g_m}$$

$$r_{DS} < R_L < g_m r_{DS} R_B \qquad Z_{in} = \frac{R_L}{g_m r_{DS}}$$

$$R_L \gg g_m r_{DS} R_B \qquad Z_{in} = R_B$$

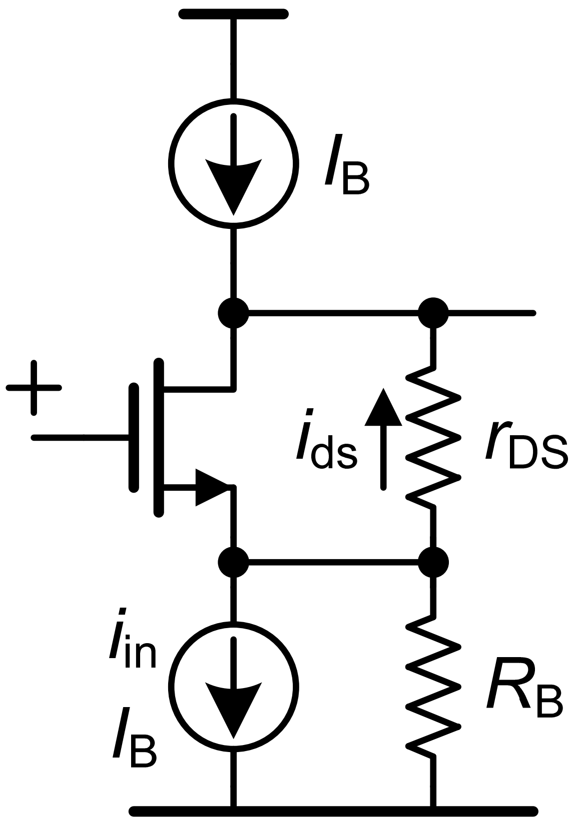
$$A_R = \frac{v_{out}}{i_{in}} = -\frac{R_L i_L}{i_{in}} = -R_L \frac{R_B(1+g_m r_{DS})}{R_L + r_{DS} + R_B(1+g_m r_{DS})}$$

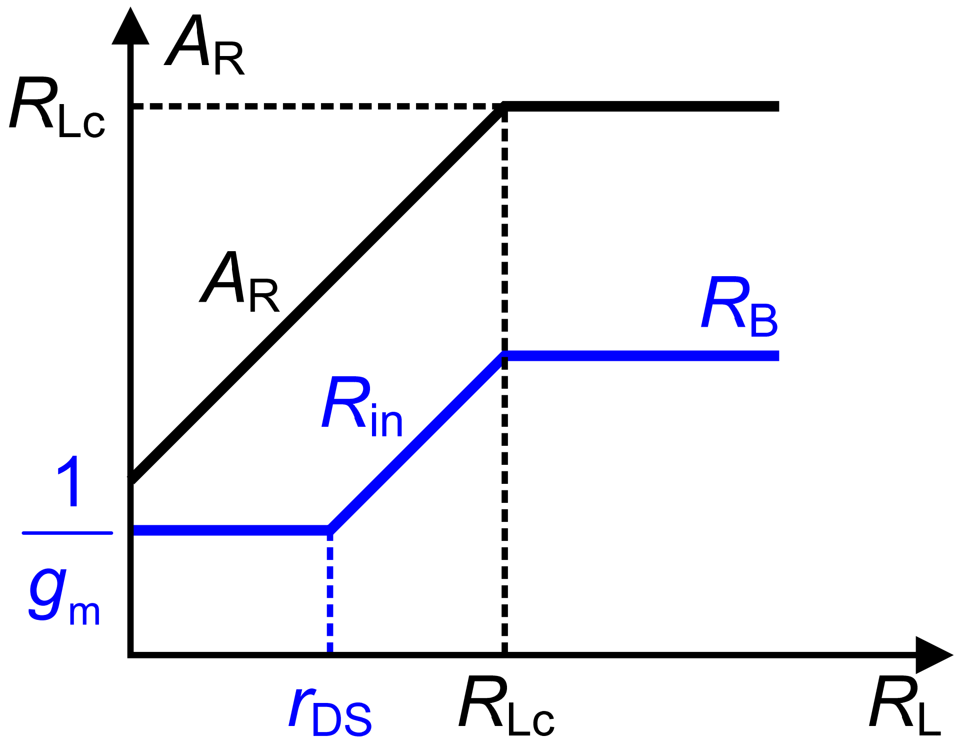


$$R_L \ll g_m r_{DS} R_B \quad |A_R| = R_L$$

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

共栅放大器：跨阻增益与输入阻抗

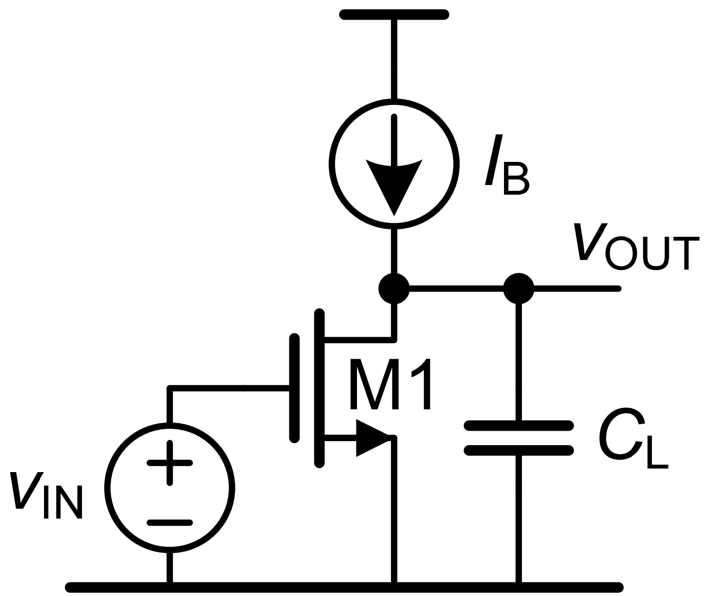


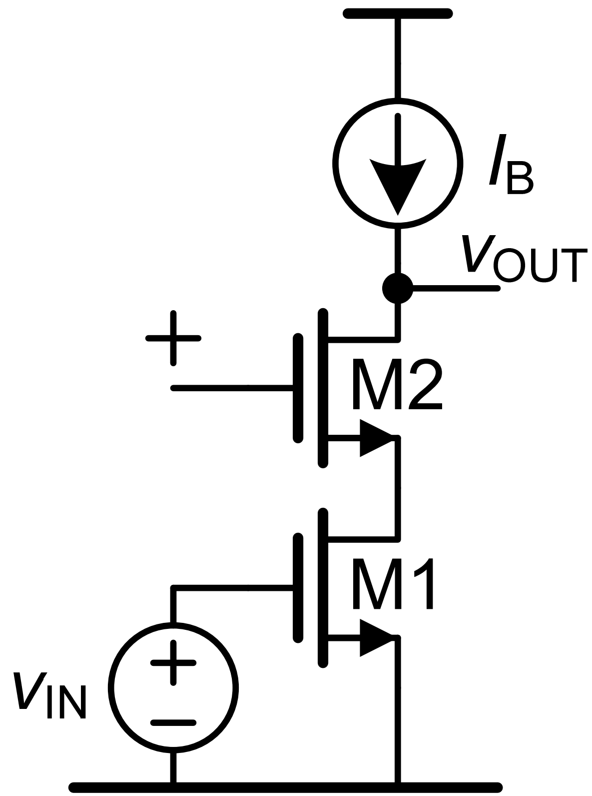


$$A_R = \frac{v_{out}}{i_{in}} \qquad R_{in} = \frac{v_{in}}{-i_{in}}$$

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

共源共栅与单管共源放大器 1





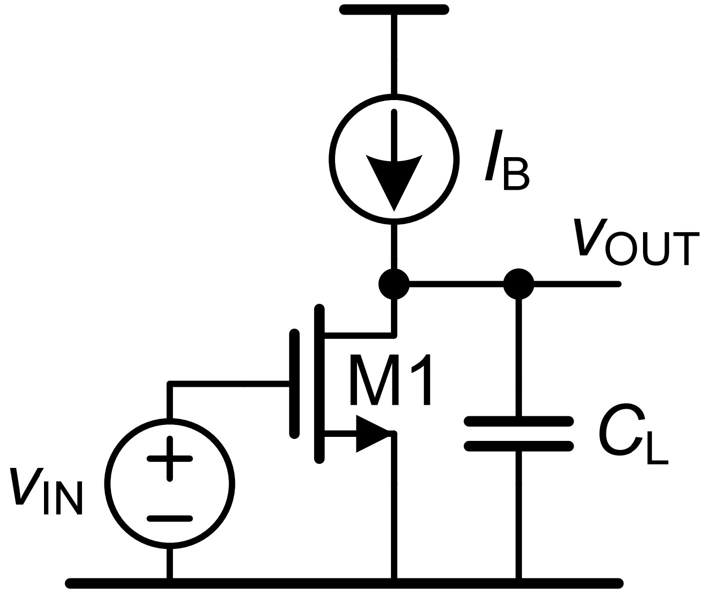
$$A_V = (g_m r_{DS})_1$$

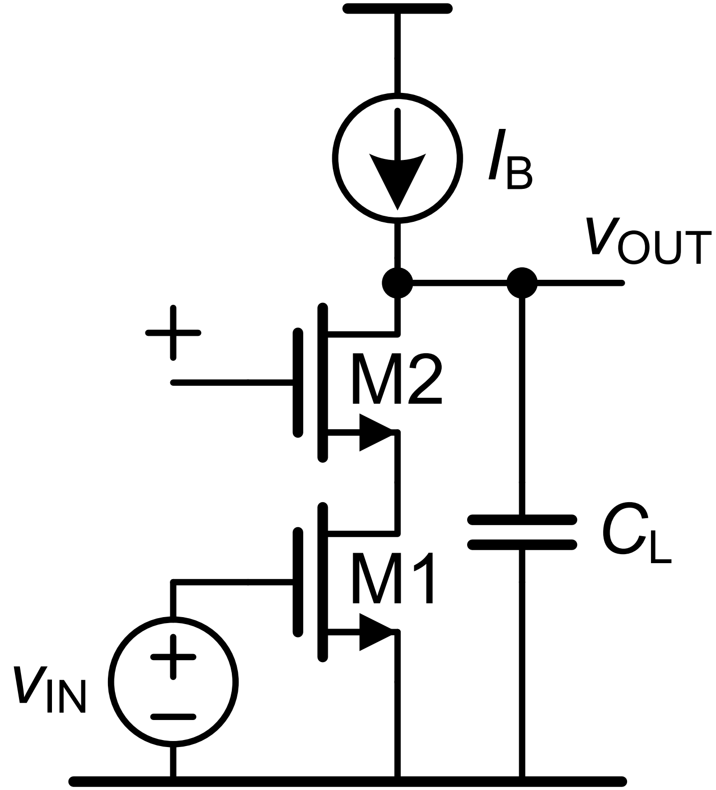
$$R_{out} = r_{DS1}$$

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

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

共源共栅与单管共源放大器 2

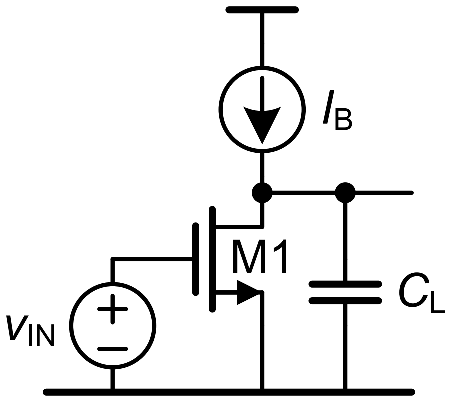


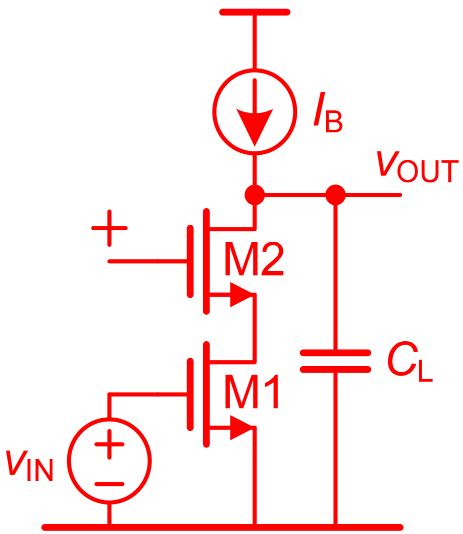


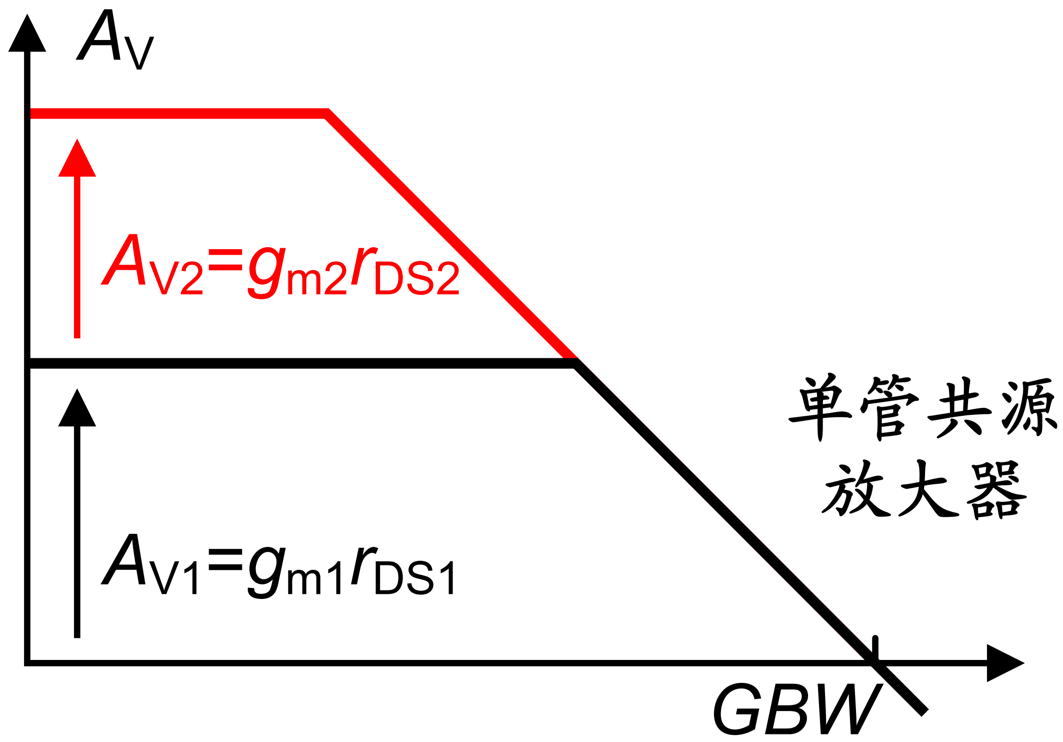
$$BW = \frac{1}{2\pi R_{out} C_L} \qquad GBW = \frac{g_{m1}}{2\pi C_L}$$

适用于两种结构！

共源共栅与单管共源放大器 3







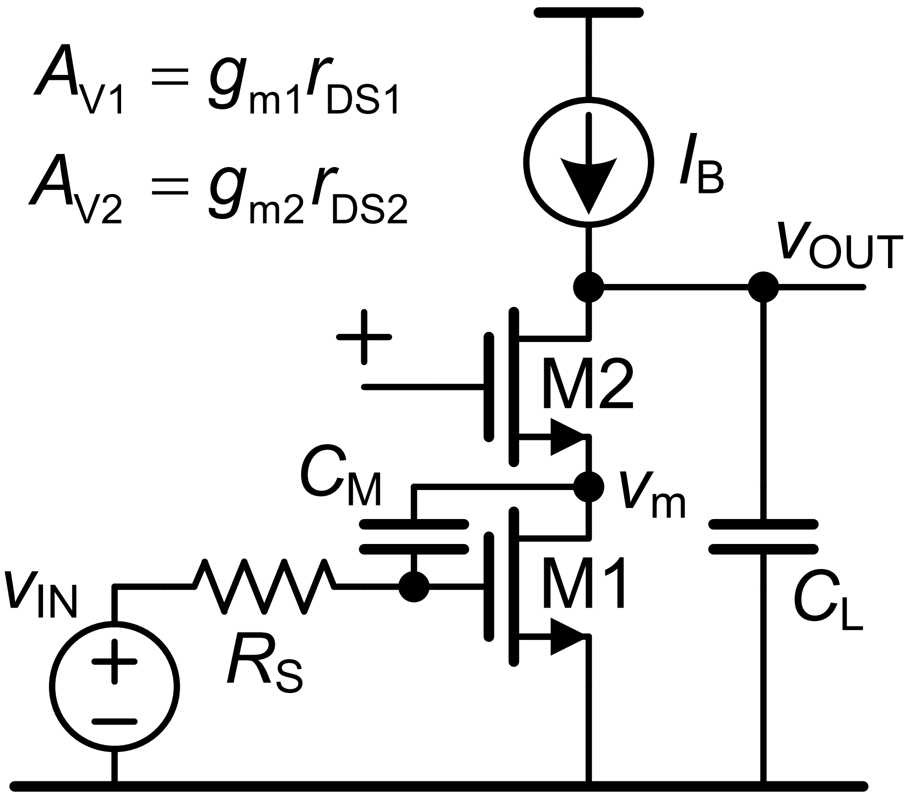
共源共栅:
低频时具有高增益

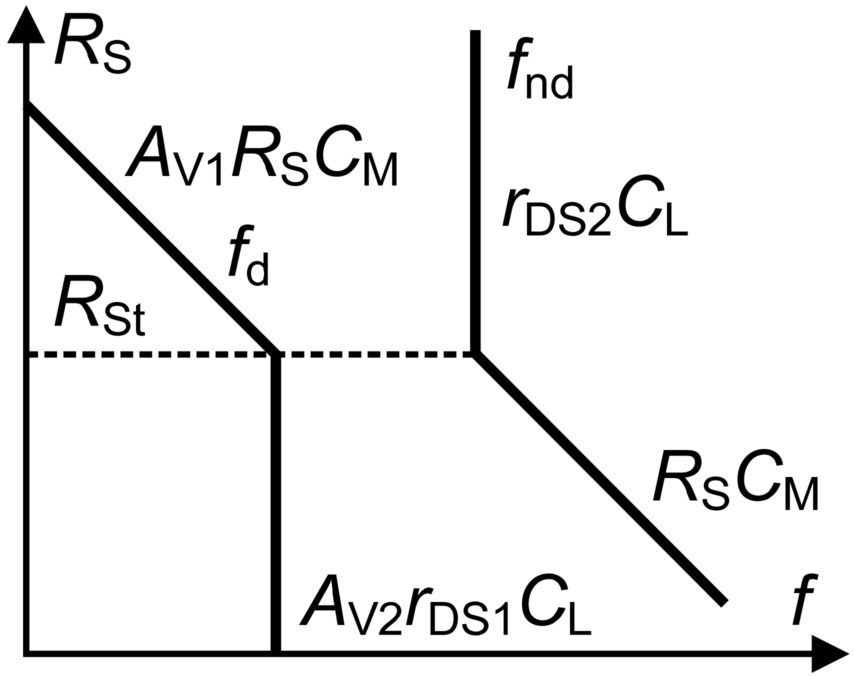
$$GBW = \frac{g_{m1}}{2\pi C_L}$$

共源共栅的密勒效应？

$$A_{V1}=g_{m1}r_{DS1}$$

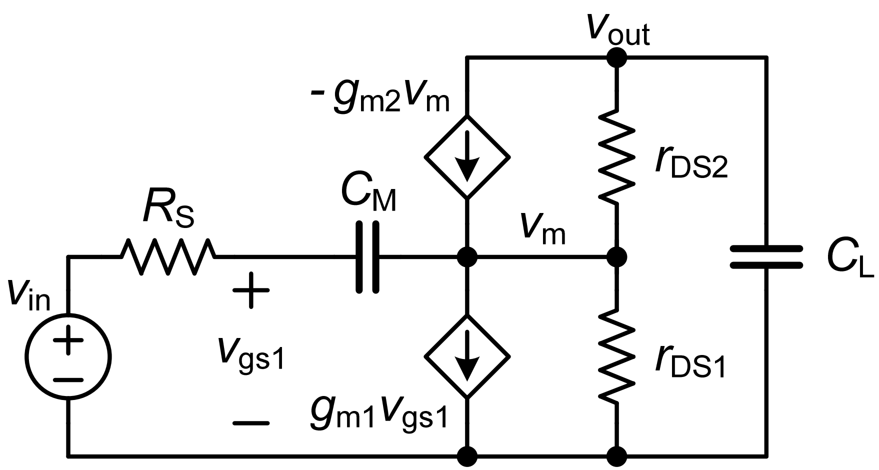
$$A_{V2}=g_{m2}r_{DS2}$$





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

如果$R_S<R_{St}=r_{DS2}\dfrac{C_L}{C_M}\dfrac{g_{m2}}{g_{m1}}$，没有密勒效应！



$$\frac{v_{out}-v_m}{r_{DS2}}+(-g_{m2}v_m)=-\frac{v_{out}}{\frac{1}{sC_L}} \quad \textbf{(1)}$$

$$\left(\frac{v_m-v_{in}}{R_S+\frac{1}{sC_M}}R_S+v_{in}\right)g_{m1}+\frac{v_m}{r_{DS1}}+\frac{v_m-v_{in}}{R_S+\frac{1}{sC_M}}=-\frac{v_{out}}{\frac{1}{sC_L}} \quad \textbf{(2)}$$

将(1) 求v_m代入(2)得:

$$A_V = \frac{v_{out}}{v_{in}} = -\frac{g_{m1}r_{DS1}(1+g_{m2}r_{DS2})(1-sC_M/g_{m1})}{1+as+bs^2}$$

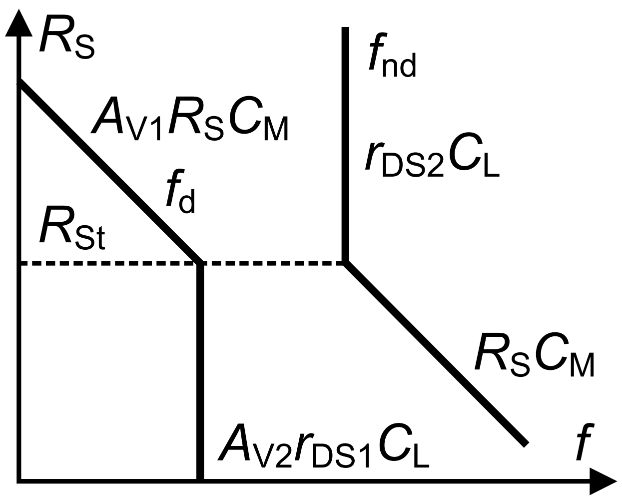
$$a = [r_{DS2} + (1+g_{m2}r_{DS2})r_{DS1}]C_L + [r_{DS1} + (1+g_{m1}r_{DS1})R_S]C_M$$

$$b = \{r_{DS1}r_{DS2} + R_S[(1+g_{m1}r_{DS1})r_{DS2} + (1+g_{m2}r_{DS2})r_{DS1}]\}C_L C_M$$

$$A_{V2}r_{DS1}C_L = A_{V1}R_{St}C_M$$

$$\Rightarrow R_{St} = r_{DS2}\frac{C_L}{C_M}\frac{g_{m2}}{g_{m1}}$$

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



当R_S较小时 $f_d = -\dfrac{1}{2\pi A_{v2}r_{DS1}C_L}$ $\quad f_{nd} = -\dfrac{1}{2\pi r_{DS2}C_L}$

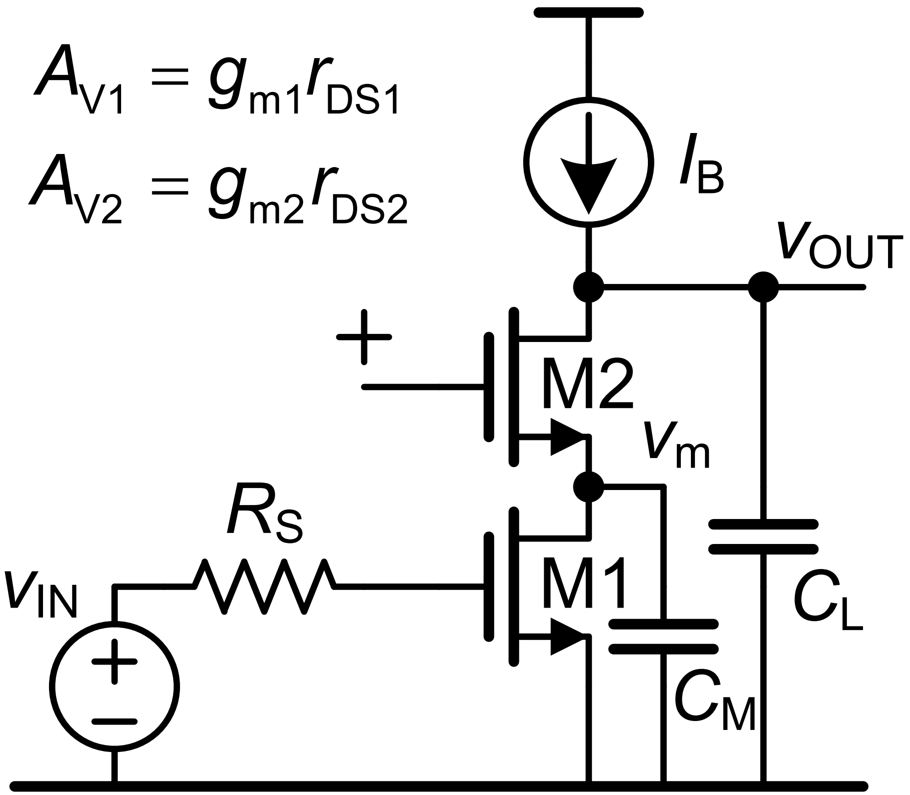
当R_S较大时 $f_d = -\dfrac{1}{2\pi A_{v1}R_SC_M}$ $\quad f_{nd} = -\dfrac{1}{2\pi R_SC_M}$ $\quad A_{V1} = g_{m1}r_{DS1}$ $\quad A_{V2} = g_{m2}r_{DS2}$

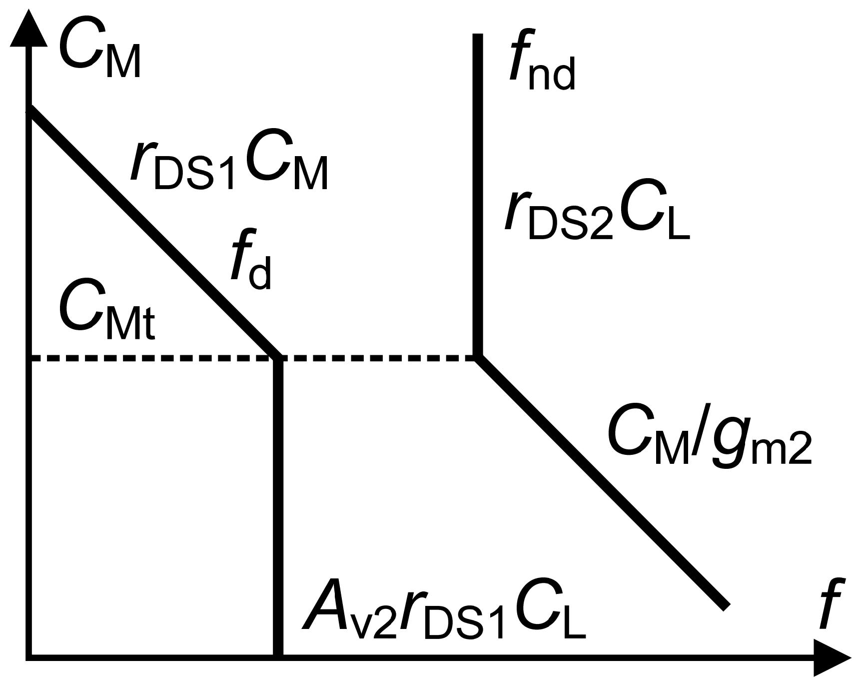
密勒效应

具有中间节点电容C_M的共源共栅

$$A_{V1} = g_{m1} r_{DS1}$$

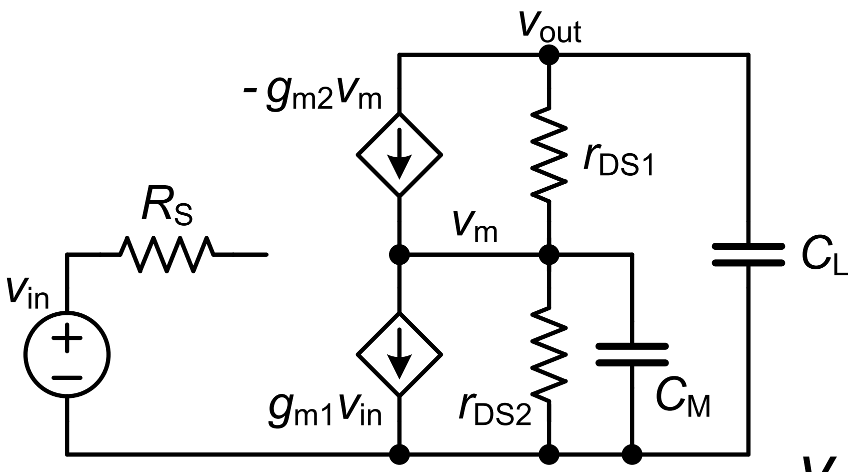
$$A_{V2} = g_{m2} r_{DS2}$$





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

$$C_{Mt} = g_{m2} r_{DS2} C_L = A_{V2} C_L$$



$$\frac{v_{out}-v_m}{r_{DS2}}+(-g_{m2}v_m)=-\frac{v_{out}}{\frac{1}{sC_L}} \quad \textbf{(1)}$$

$$g_{m1}v_{in}+\frac{v_m}{r_{DS1}/\!/\frac{1}{sC_M}}=-\frac{v_{out}}{\frac{1}{sC_L}} \quad \textbf{(2)}$$

由(1) 求v_m，代入(2)得:

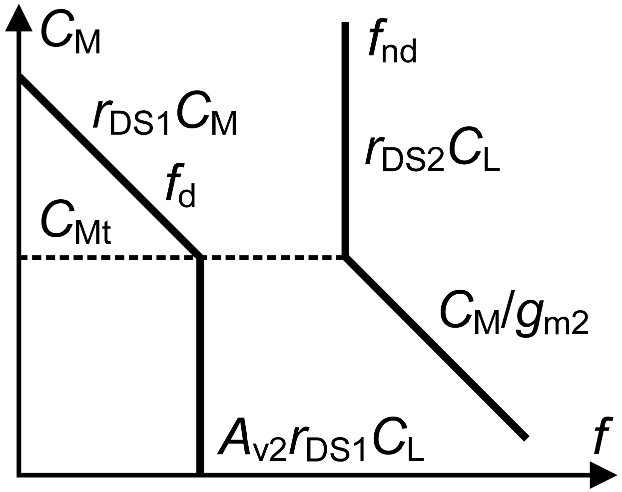
$$A_V = -\frac{g_{m1}r_{DS1}(1+g_{m2}r_{DS2})}{1+as+bs^2}$$

$$a = r_{DS2}C_L + r_{DS1}C_M + (1+g_{m2}r_{DS2})r_{DS1}C_L$$

$$b = r_{DS2}C_L r_{DS1}C_M$$

$$r_{DS1}C_{Mt} = A_{V2}r_{DS1}C_L$$

$$\Rightarrow \quad C_{Mt} = A_{V2}C_L$$

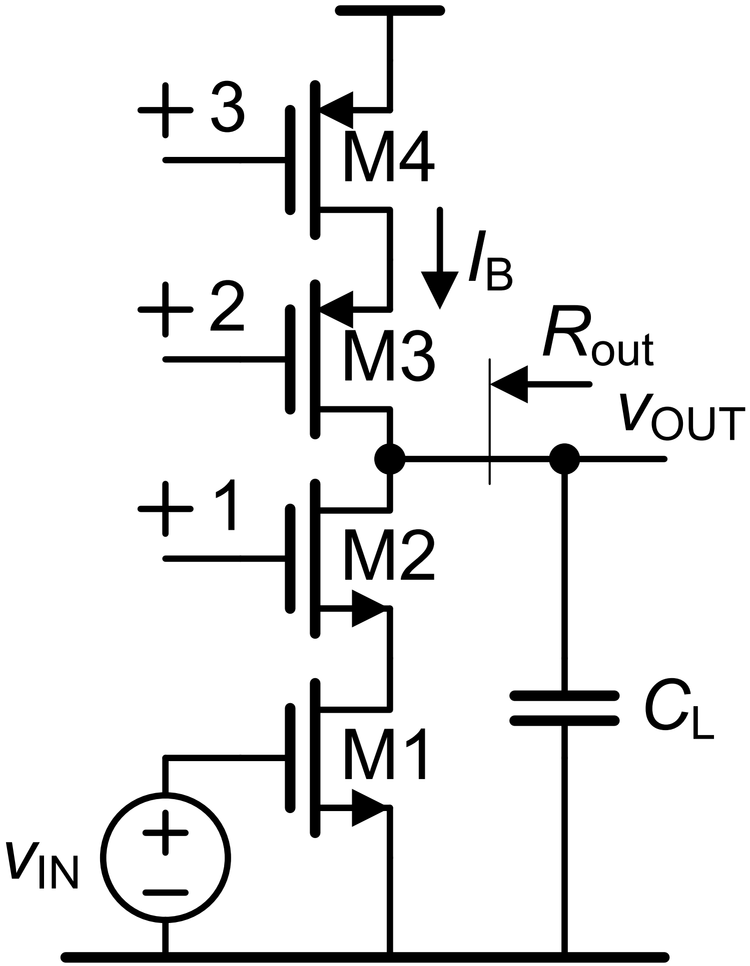


当C_M较小时 $f_d = \dfrac{1}{2\pi A_{v2}r_{DS1}C_L}$ $\quad f_{nd} = \dfrac{g_{m2}}{2\pi C_M}$

当C_M较大时 $f_d = \dfrac{1}{2\pi r_{DS1}C_M}$ $\quad f_{nd} = \dfrac{1}{2\pi r_{DS2}C_L}$

$$A_{V1} = g_{m1}r_{DS1}$$
$$A_{V2} = g_{m2}r_{DS2}$$

套筒式共源共栅



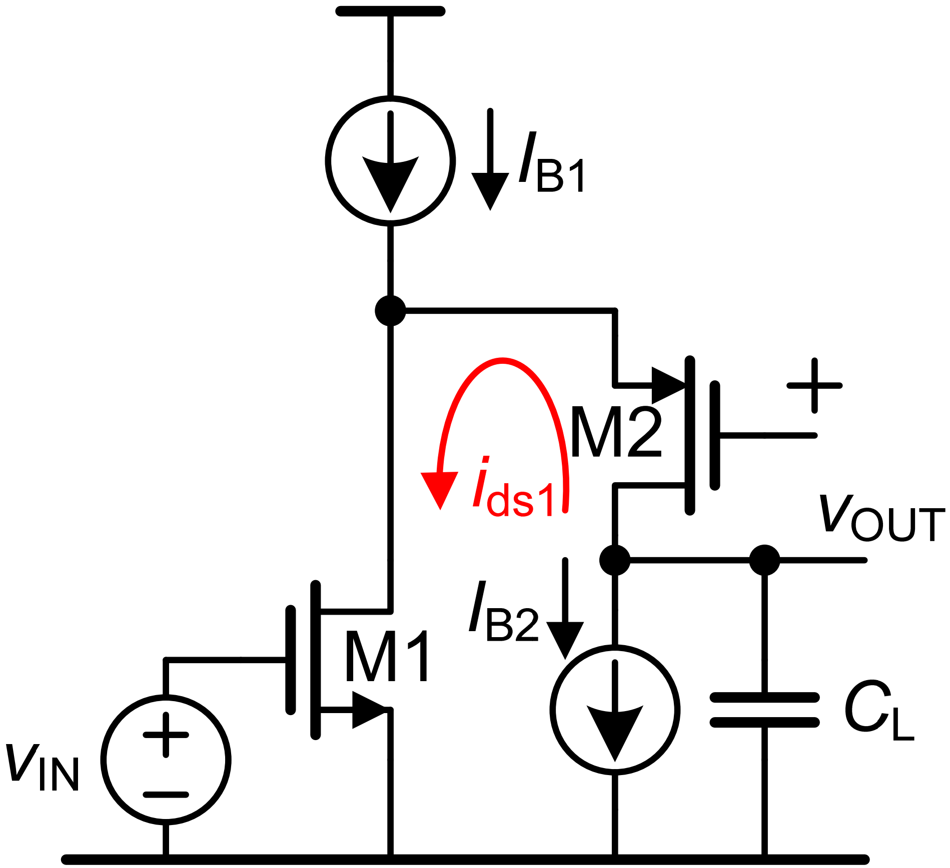
$$A_V = g_{m1} R_{out}$$

$$R_{out} = \frac{1}{2} r_{DS1} g_{m2} r_{DS2}$$

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

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

折叠共源共栅



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

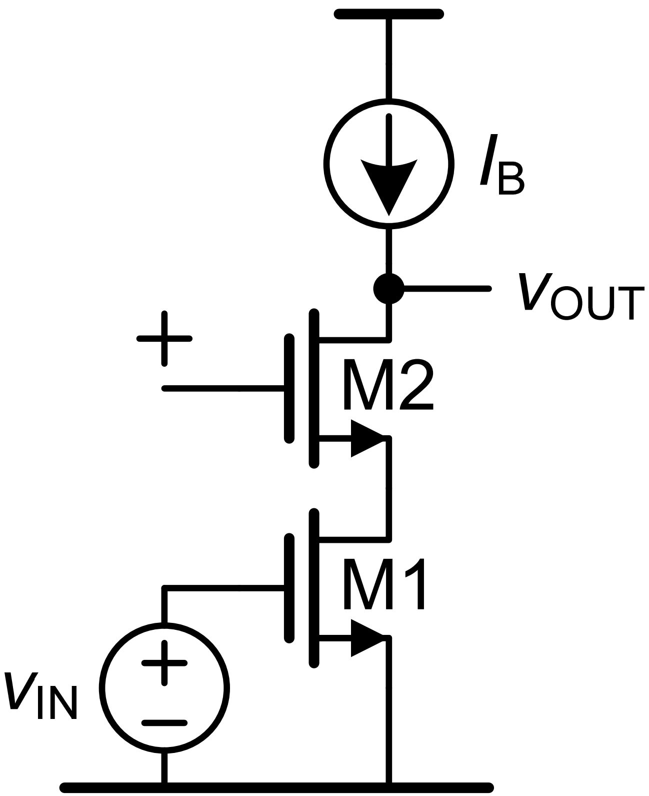
$$A_V = g_{m1} R_{out}$$

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

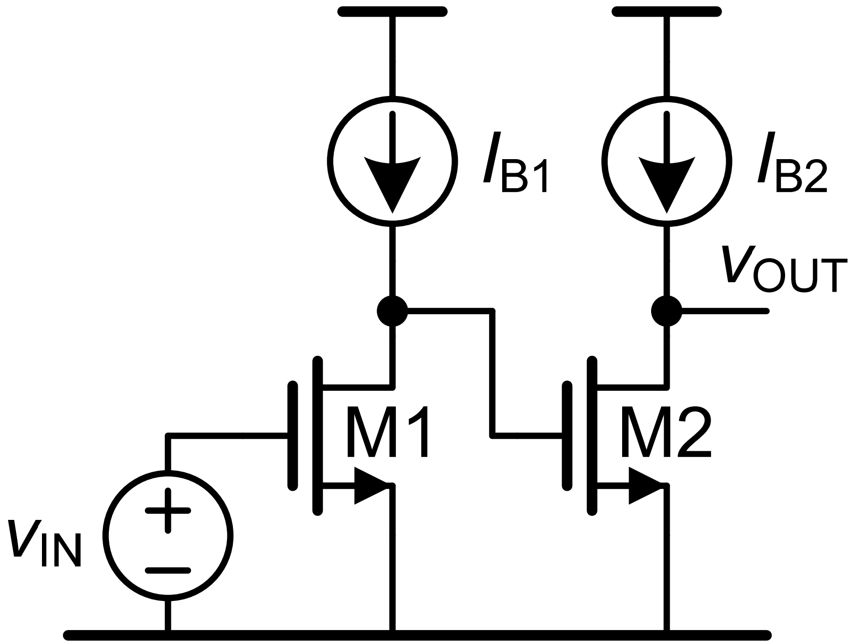
$$BW = \frac{1}{2\pi R_{out} C_L}$$

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

共源共栅与级联

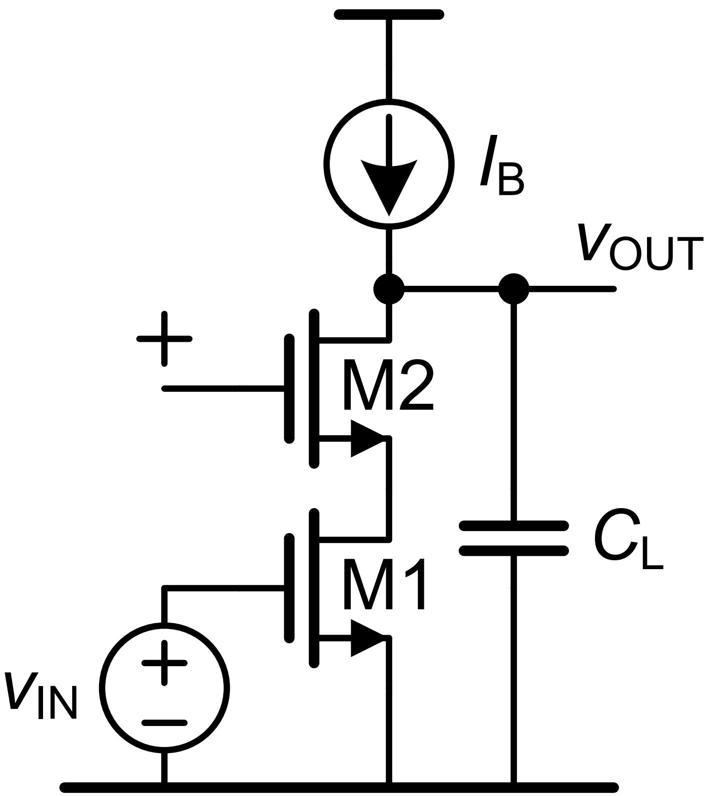


$$A_V = (g_m r_{DS})_1 (g_m r_{DS})_2$$



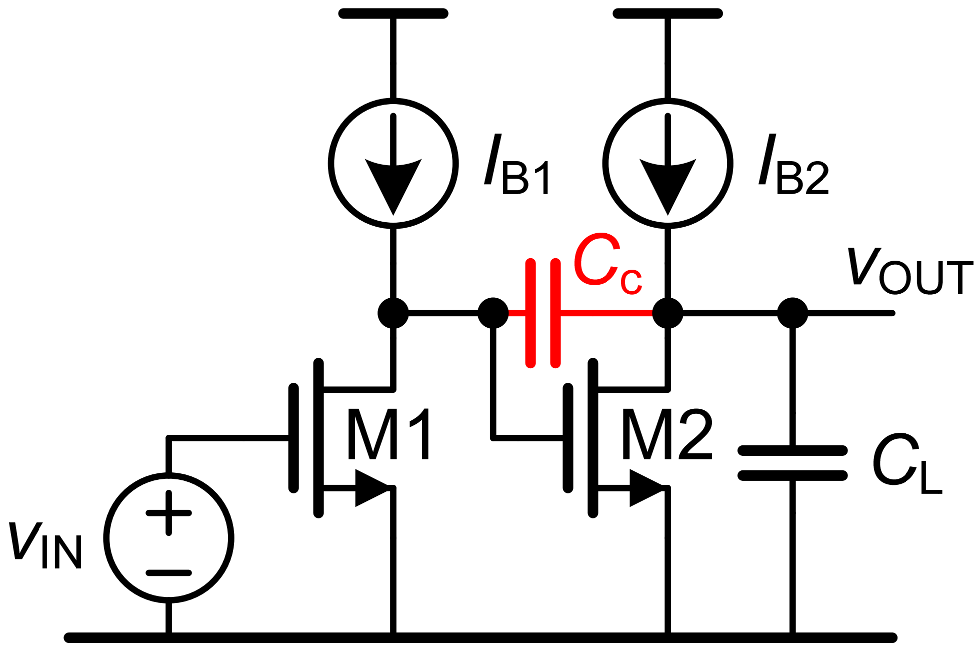
$$A_V = (g_m r_{DS})_1 (g_m r_{DS})_2$$

共源共栅与级联



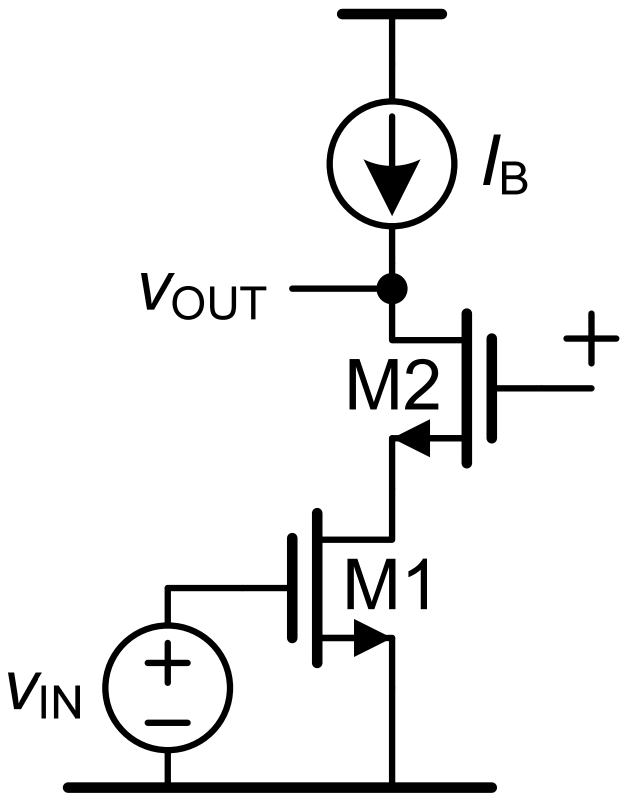
$$GBW = \frac{g_{m1}}{2\pi C_L}$$

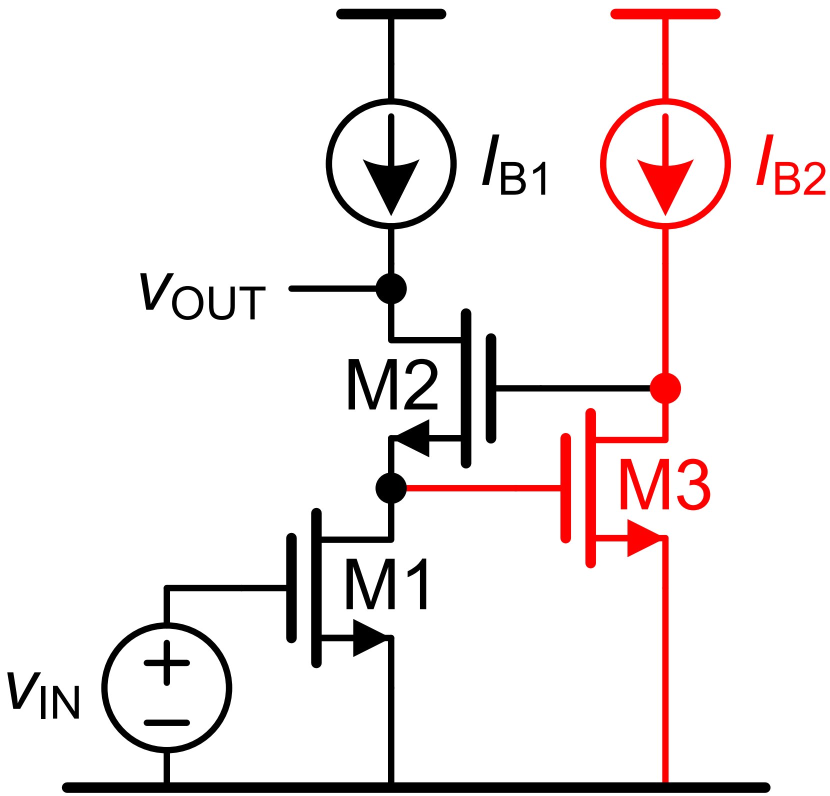
两级密勒放大器



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

调节共源共栅/增益抬升

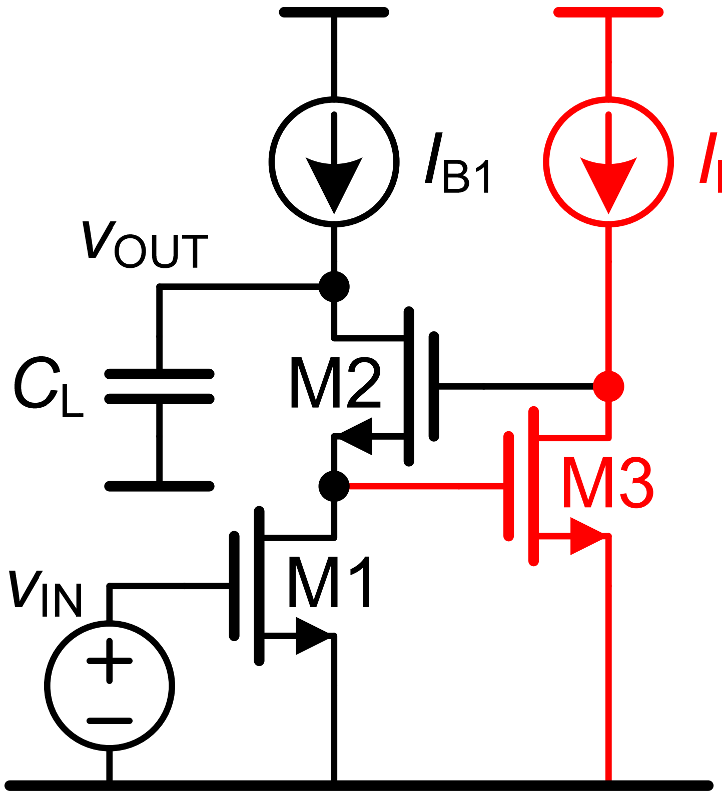


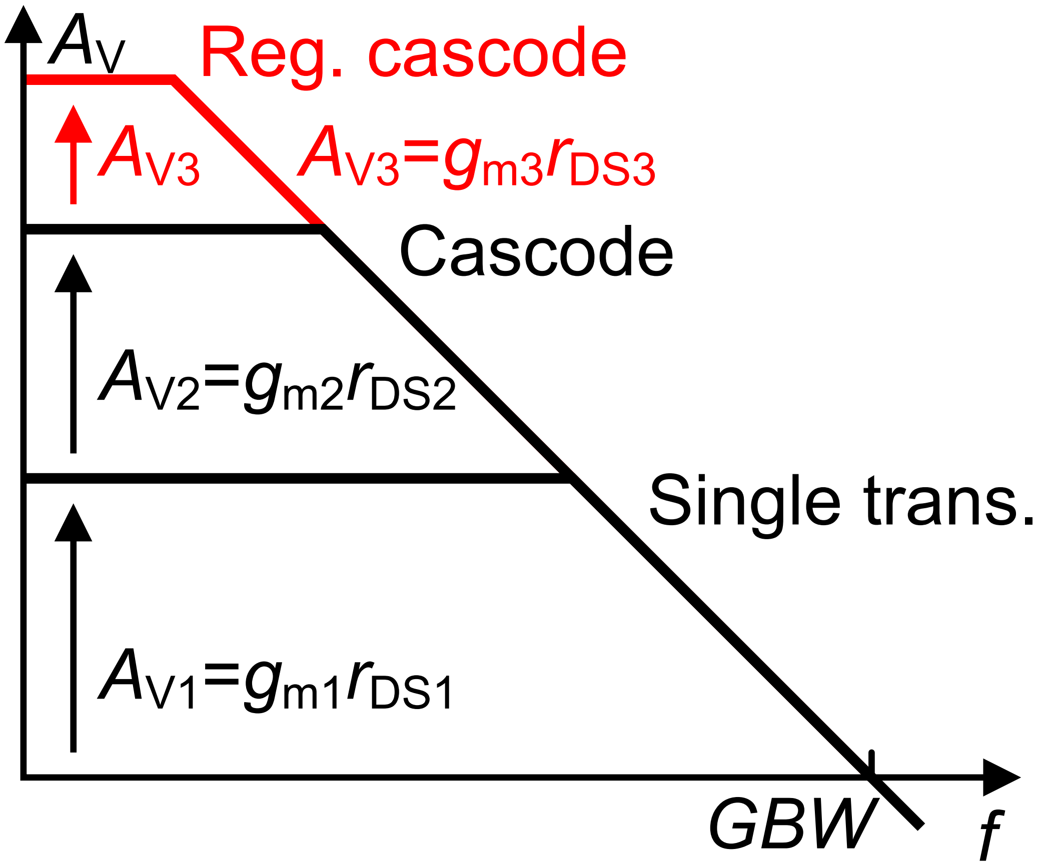


$$A_V = (g_m r_{DS})_1 (g_m r_{DS})_2 \qquad A_V = (g_m r_{DS})_1 (g_m r_{DS})_2 (g_m r_{DS})_3$$

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

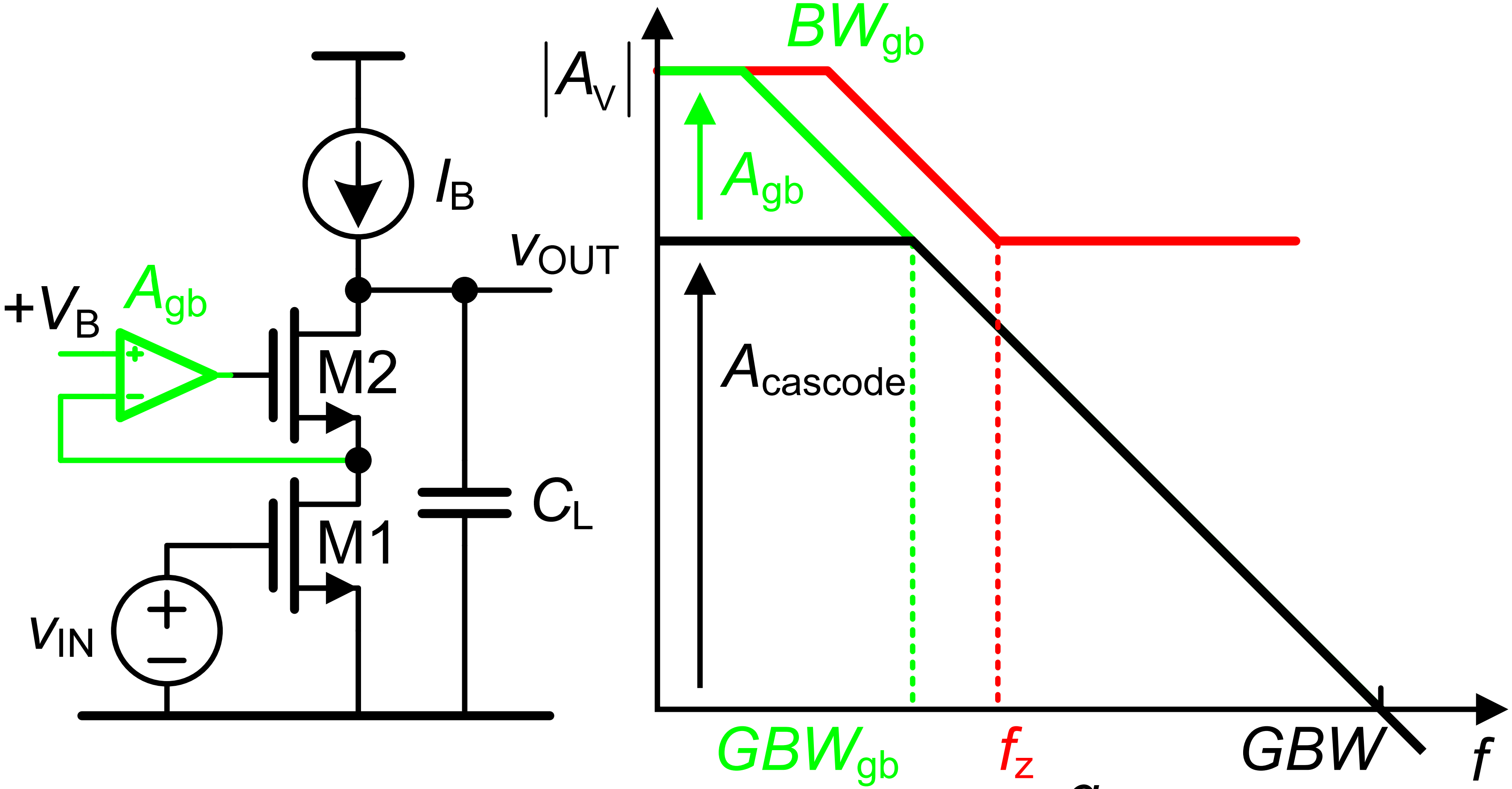
增益抬升，共源共栅和单管放大器





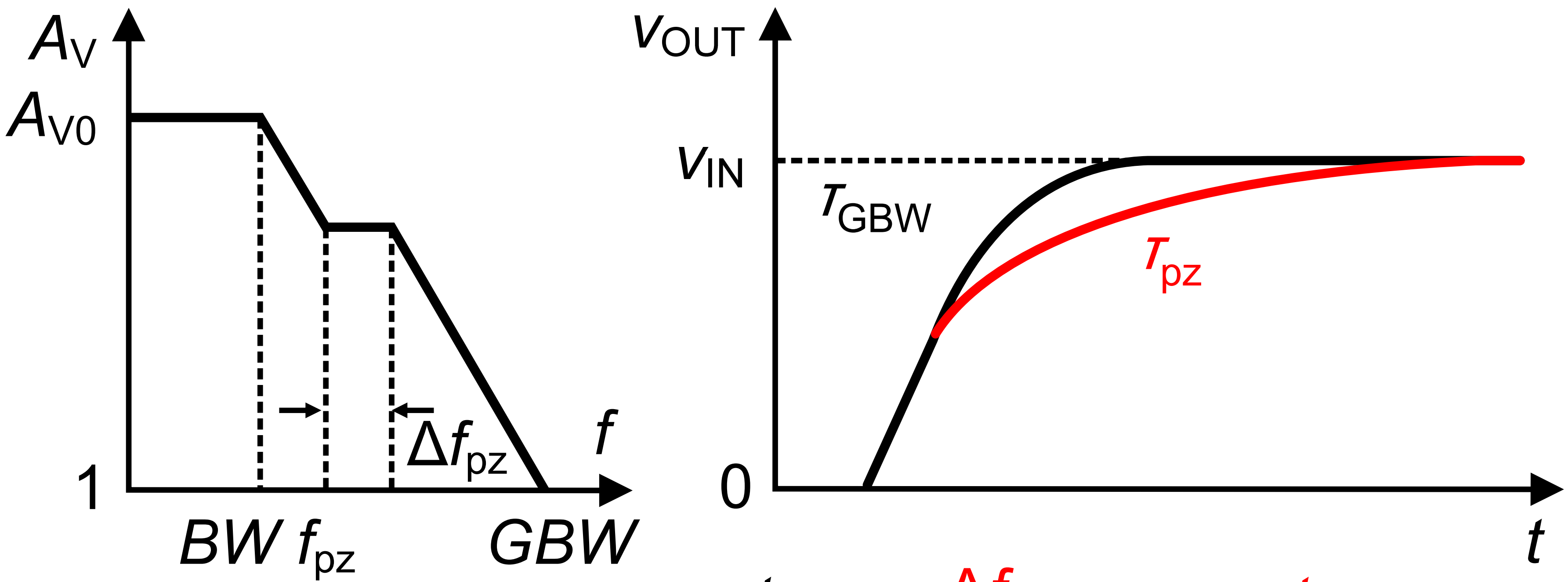
$$GBW = \frac{g_{m1}}{2\pi C_L}$$

增益抬升



$$A_V = A_{gb}(g_m r_{DS})_1 (g_m r_{DS})_2 \qquad GBW = \frac{g_{m1}}{2\pi C_L}$$

零极点对和建立时间

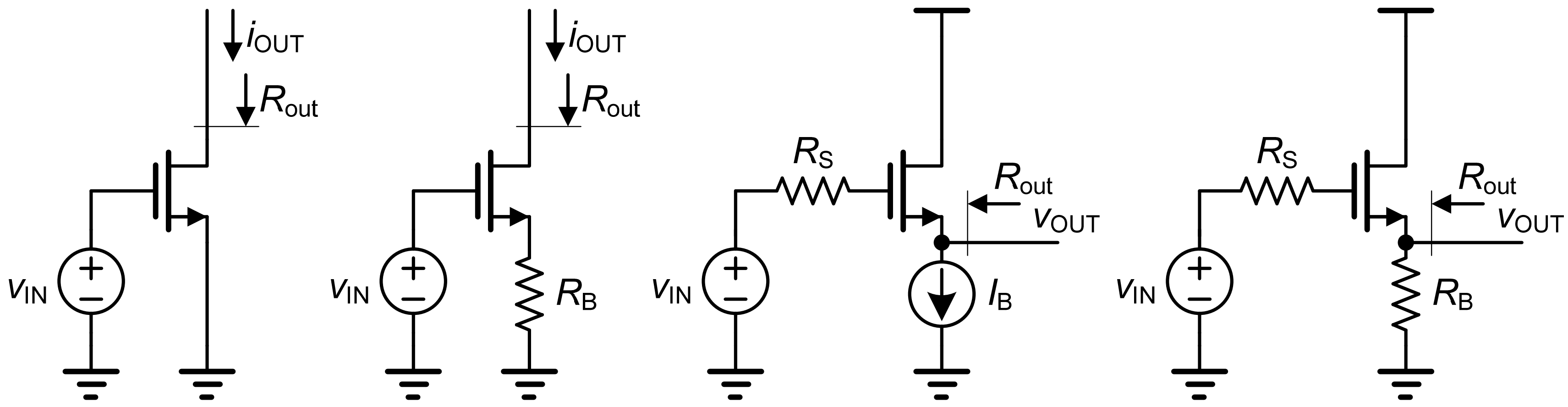


$$v_{OUT} = v_{IN}\left[1 - \exp\left(-\frac{t}{\tau_{GBW}}\right) - \frac{\Delta f_{pz}}{GBW}\exp\left(-\frac{t}{\tau_{pz}}\right)\right]$$

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

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

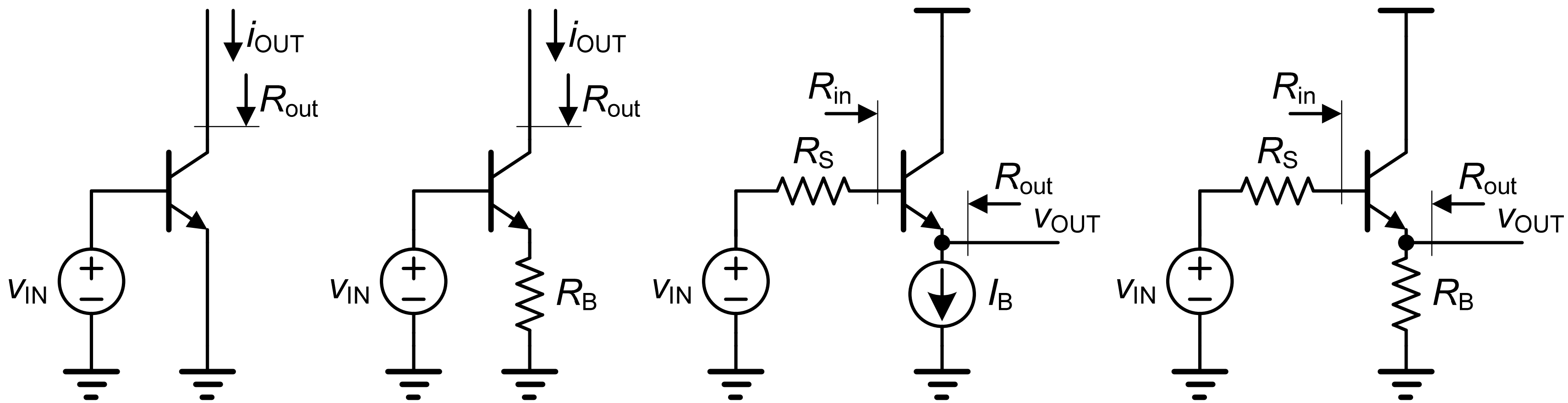
MOST共源放大器和源极跟随器



$R_B > 1/g_m$ $R_B > 1/g_m$

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

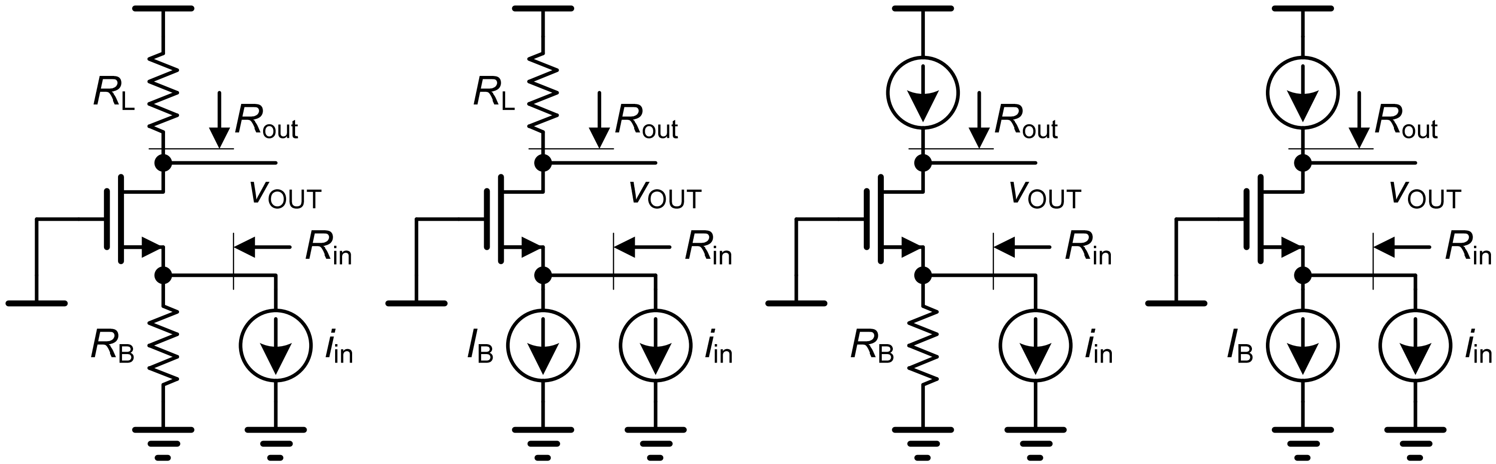
双极型共射放大器和射极跟随器



$R_B > 1/g_m$ $R_B > 1/g_m$

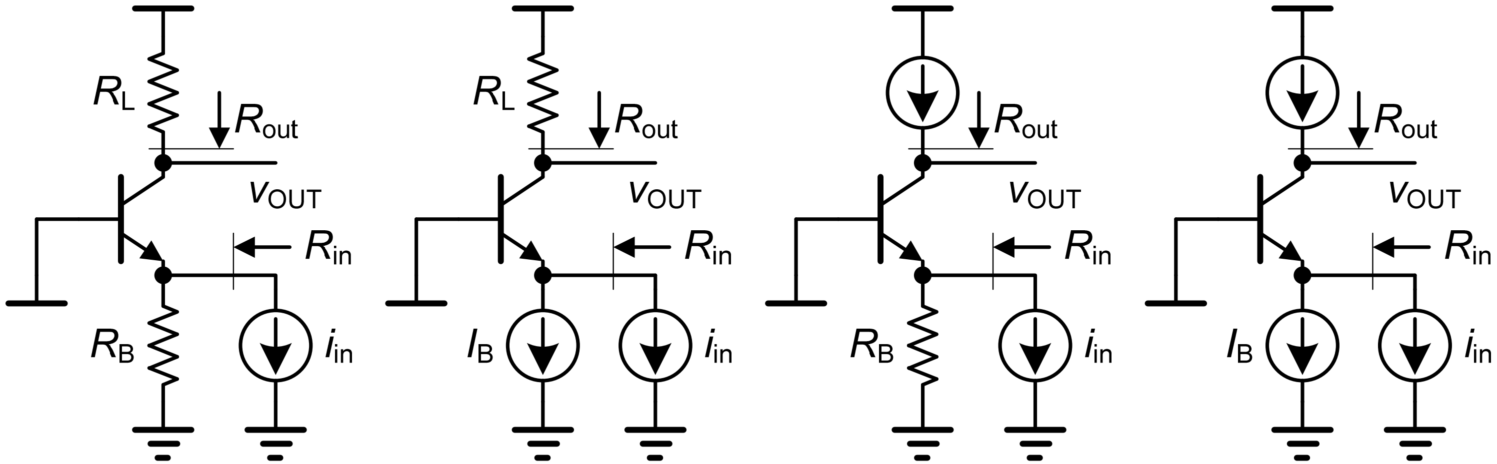
A_G	g_m	$1/R_B$	A_V	1	1
R_{in}	$r_B + r_\pi$	$r_B + r_\pi + (\beta+1)R_B$		$r_B + r_\pi + (\beta+1)r_o$	$r_B + r_\pi + (\beta+1)R_B$
R_{out}	r_o	$g_m R_B r_o$		$\dfrac{1}{g_m} + \dfrac{R_S + r_B}{\beta+1}$	$\dfrac{1}{g_m} + \dfrac{R_S + r_B}{\beta+1}$

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}	$g_m r_{DS} R_B$	∞	$g_m r_{DS} R_B$	∞

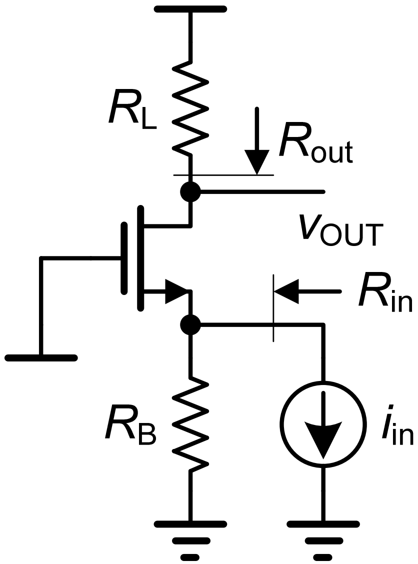
双极型共基放大器

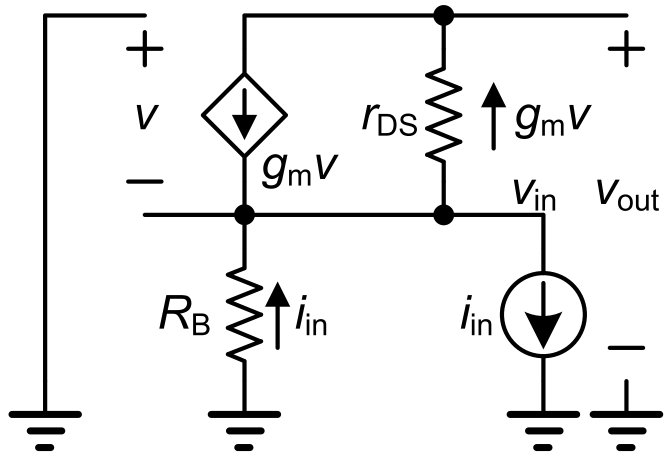


$R_B > 1/g_m$ $\qquad\qquad\qquad\qquad$ $R_B > 1/g_m$

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





$$R_B > 1/g_m$$

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

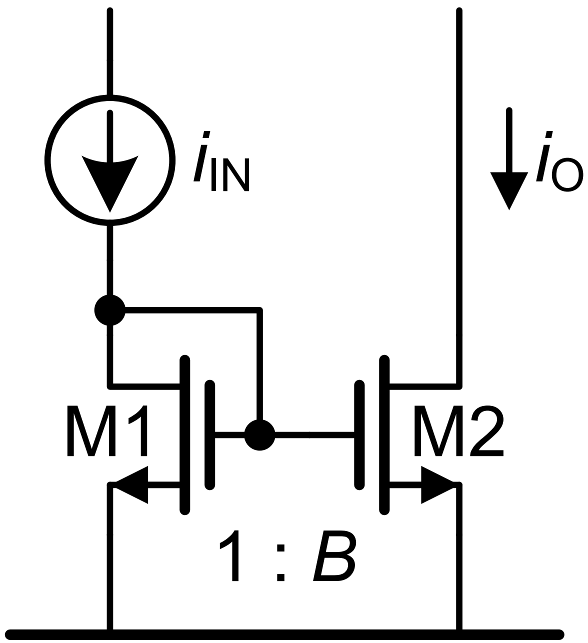
$$\begin{cases} v_{in} = -R_B i_{in} \\ v_{out} = v_{in} - g_m v r_{DS} \\ v = -v_{in} \end{cases}$$

$\Downarrow$

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

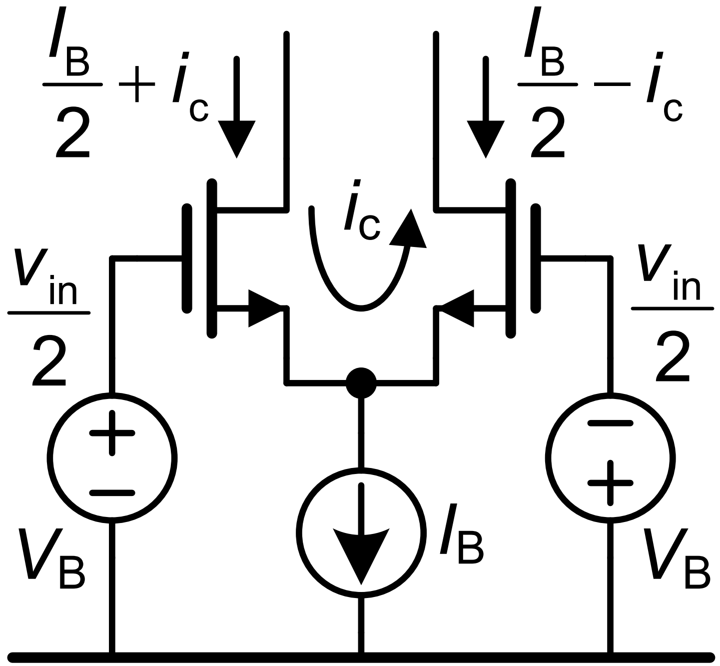
差分电压放大器
差分电流放大器

双晶体管电路



$$i_{OUT} = Bi_{IN}$$

电流镜/放大器



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

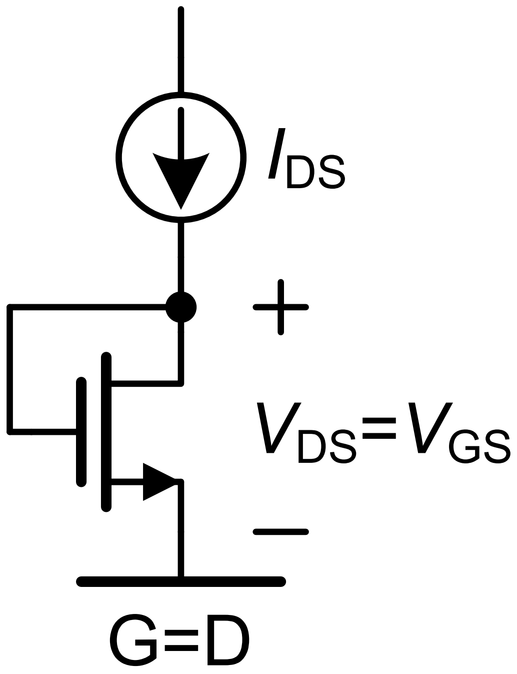
差分电压放大器

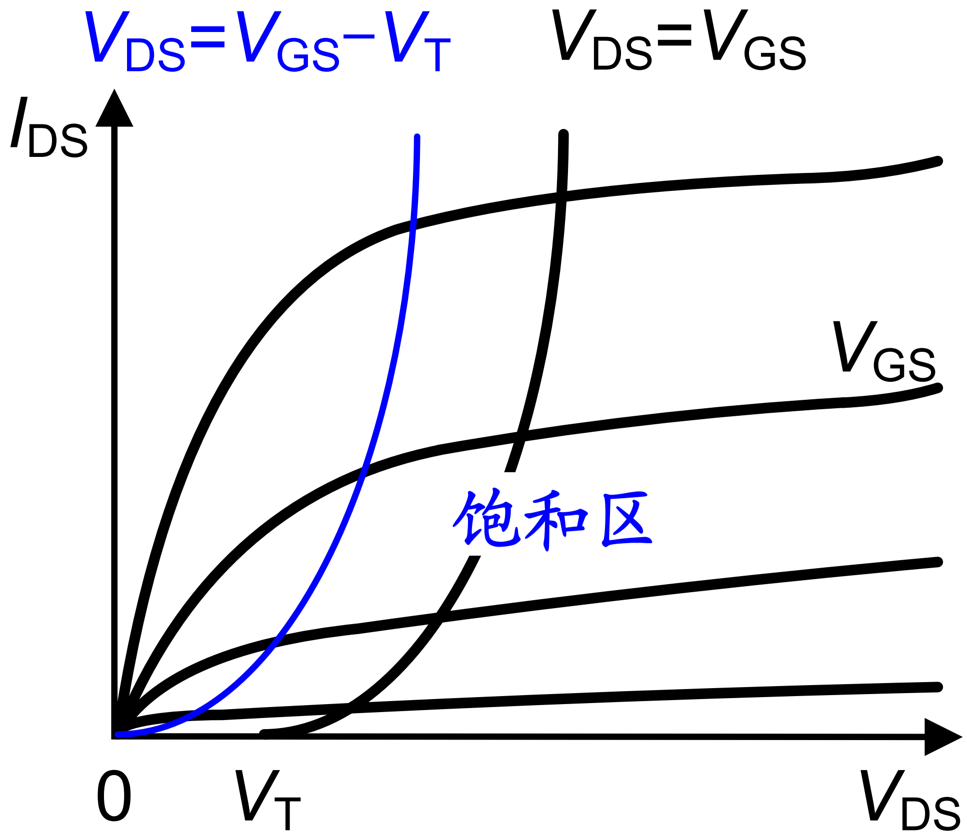
目录

- 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

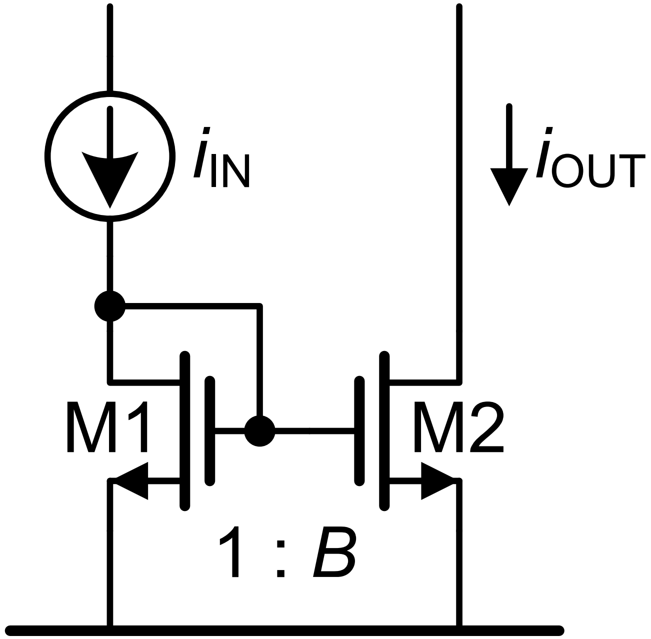


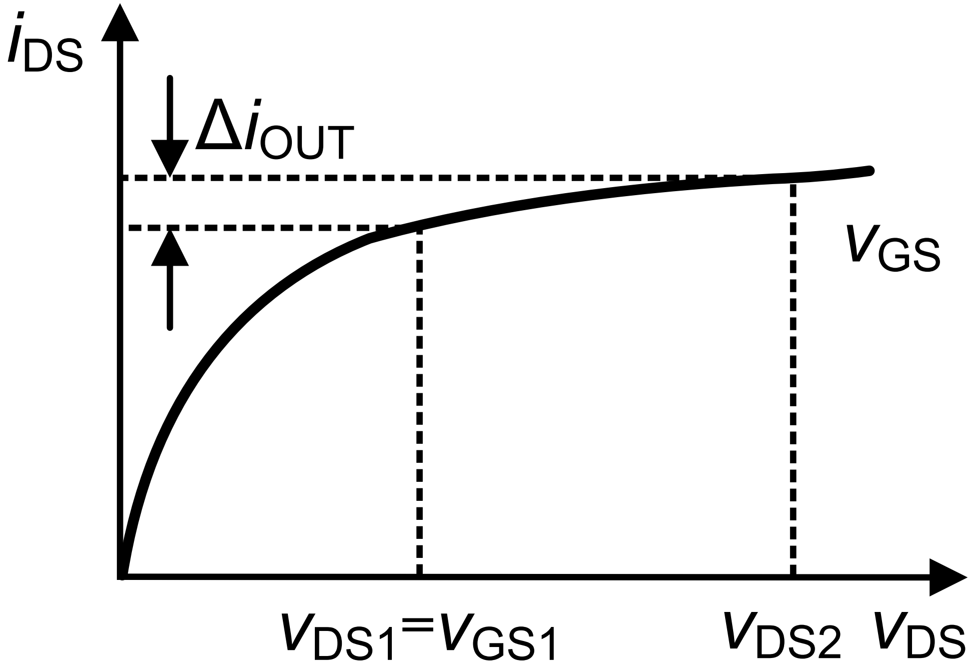


$$I_{DS}=K_n'\frac{W}{L}(V_{GS}-V_T)^2$$

$$g_m=\frac{\mathrm{d}i_{DS}}{\mathrm{d}v_{GS}}$$

电流镜

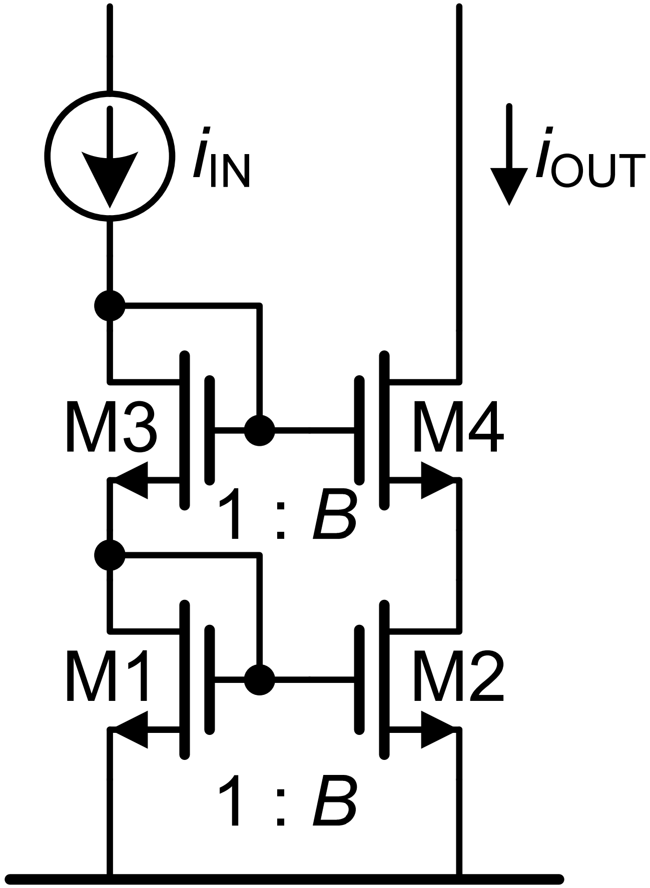


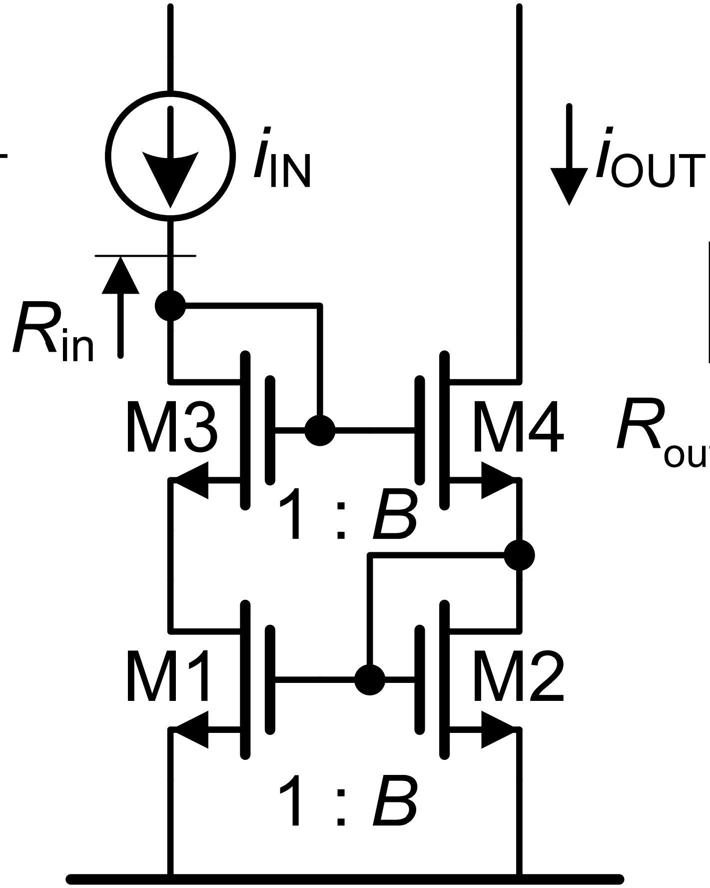


$$i_{OUT} = Bi_{IN}$$

$$\frac{\Delta i_{OUT}}{i_{OUT}} = \frac{v_{DS2} - v_{DS1}}{V_E L_2}$$

改进的电流镜





$$\boxed{v_{DS2} = v_{DS1}}$$

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

$$v_{OUTmin}$$

$$= v_{GS} + v_{DS}$$

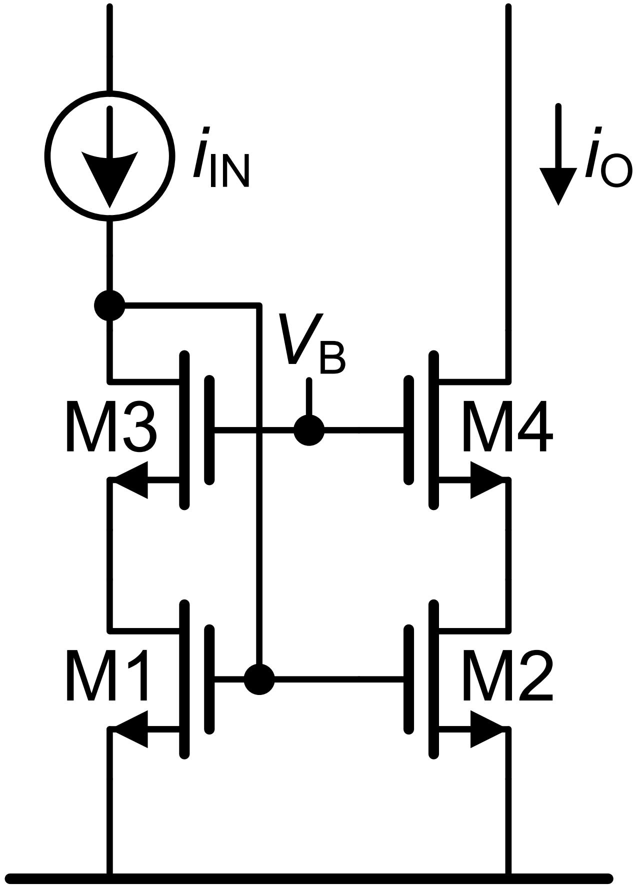
$$\approx 0.9 + 0.2$$

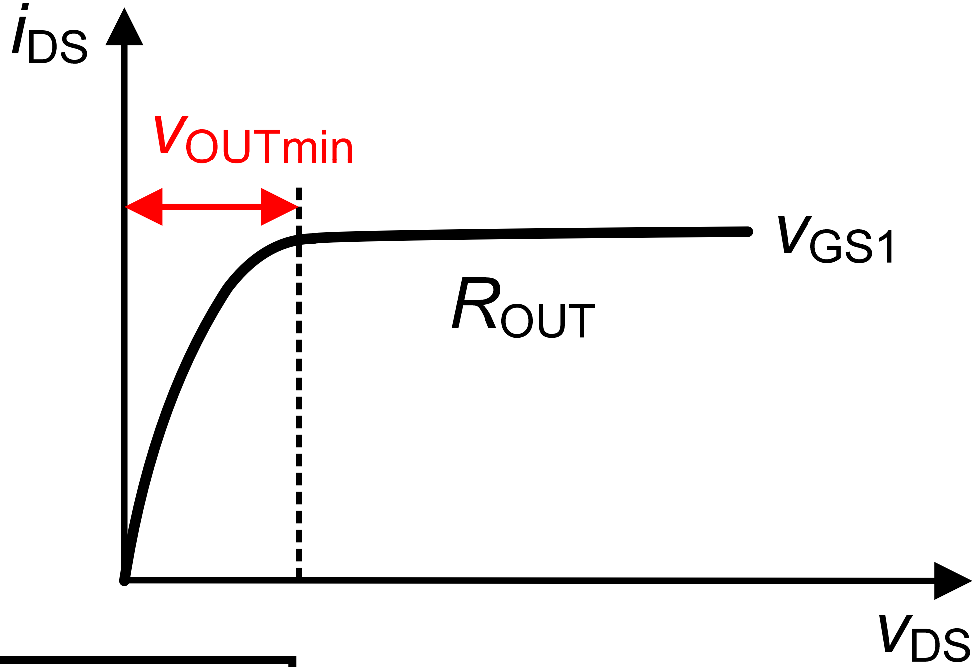
$$= 1.1\ \text{V}$$

太大！！！

反馈 $T = g_{m1} R_{in}$

低电压电流镜



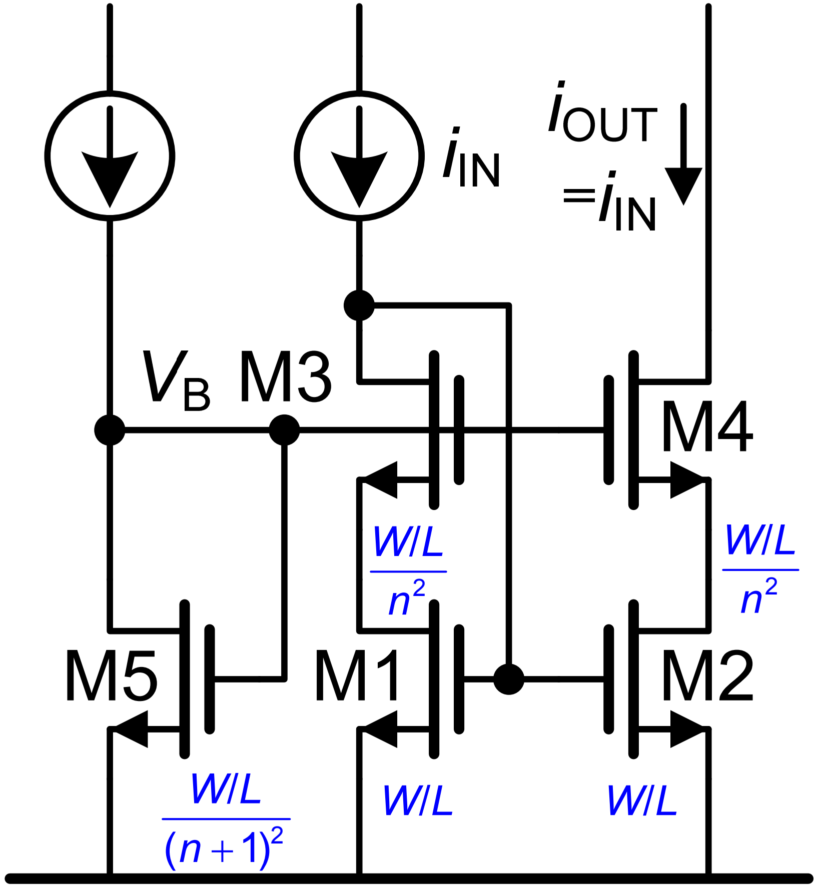


$$\boxed{v_{DS2} = v_{DS1}} \qquad R_{out} = r_{DS2} g_{m4} r_{DS4}$$

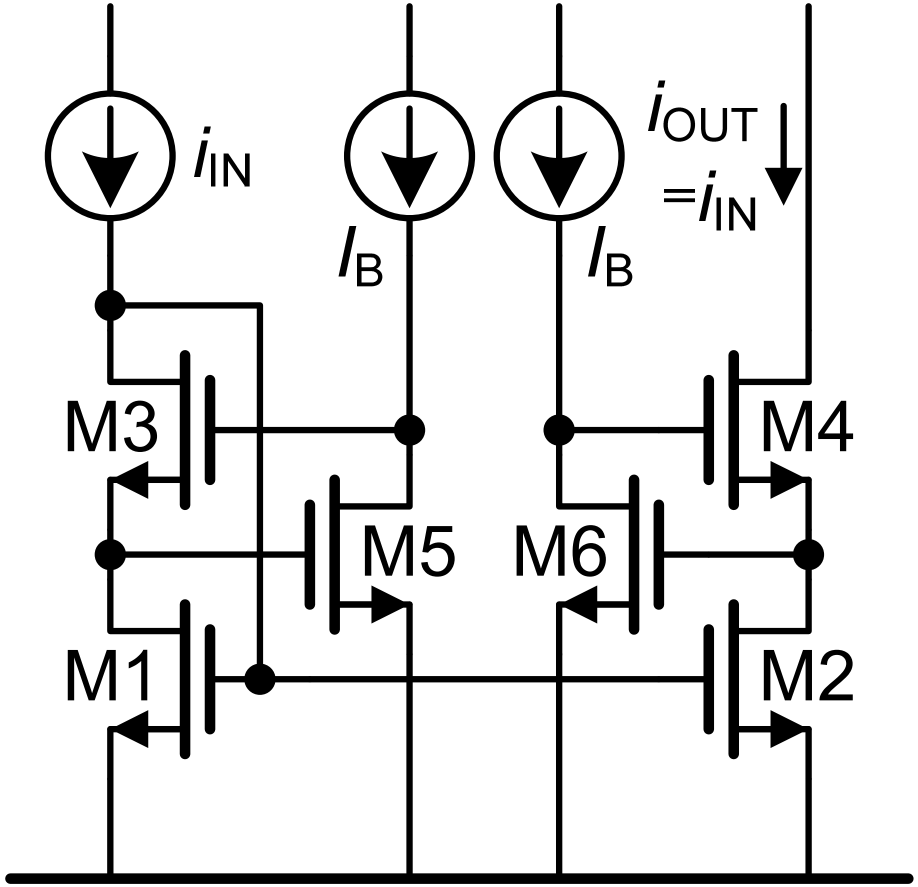
$$v_{OUTmin} = v_{DS2} + v_{DS4}$$

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

低电压电流镜

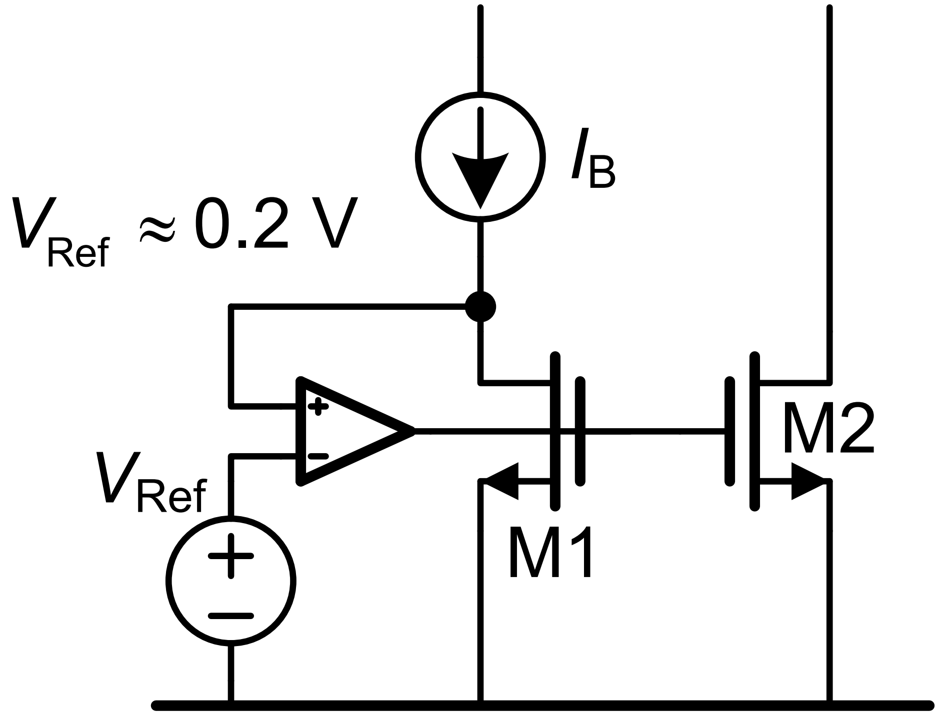


i_{IN}
i_{OUT}
$=i_{IN}$
V_B
M3
M4
$W/L \over n^2$
$W/L \over n^2$
M5
M1
M2
$W/L \over (n+1)^2$
W/L
W/L



i_{IN}
i_{OUT}
$=i_{IN}$
I_B
I_B
M3
M4
M5
M6
M1
M2

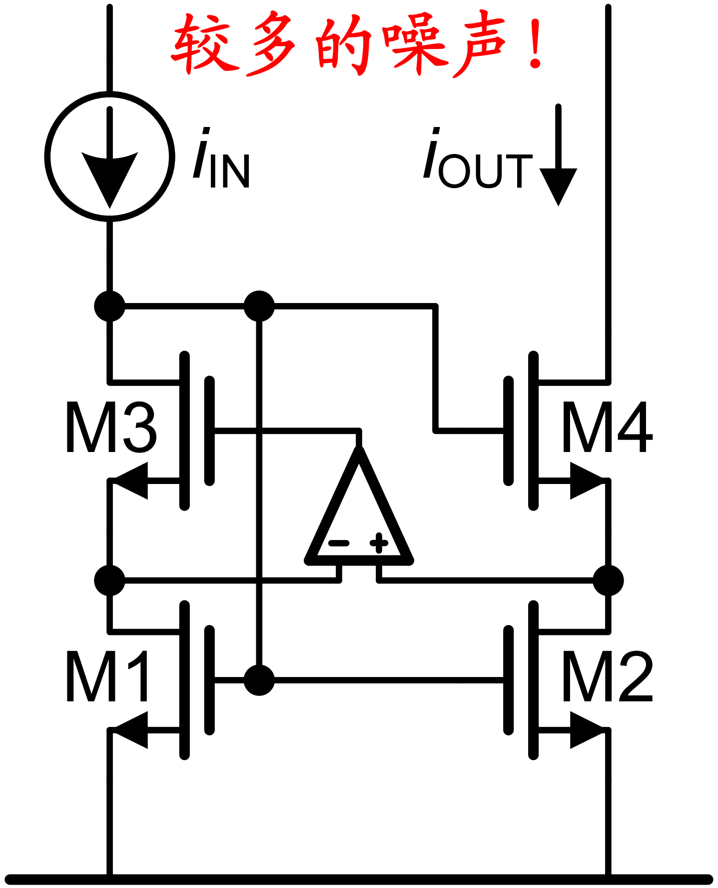
低电压二极管连接的MOST

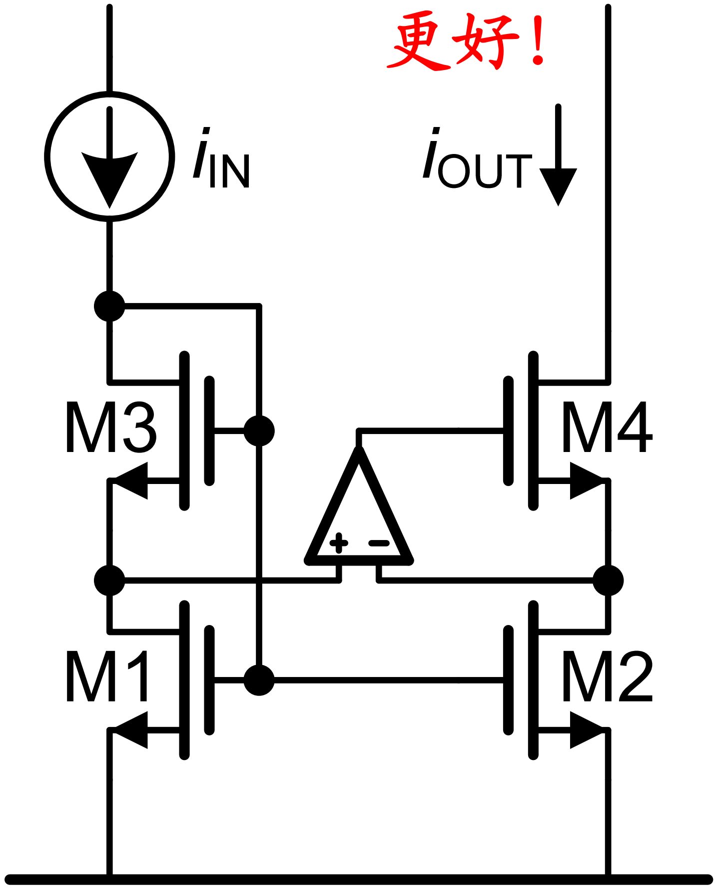


$v_{DSmin} \approx 0.2$ V

$R_{out} = r_{DS2}$

低电压电流镜

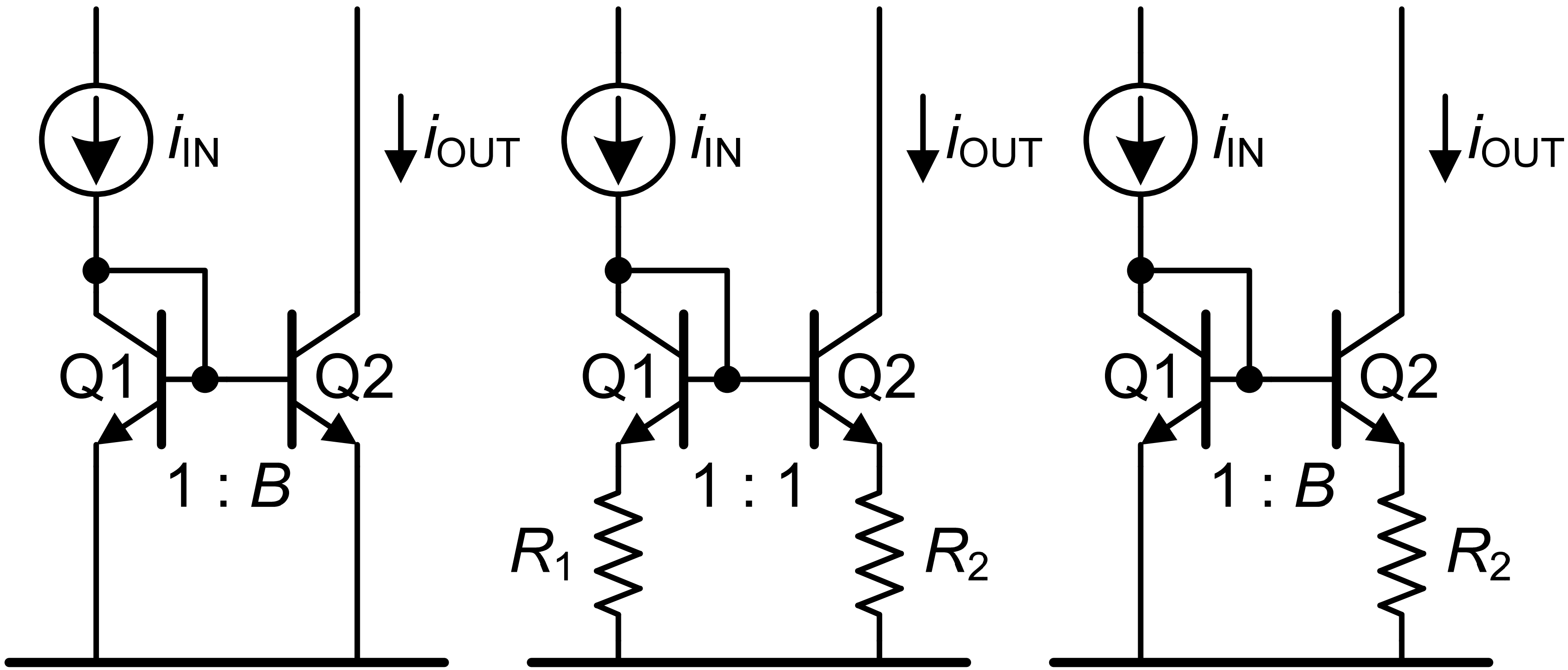




$v_{OUTmin} \approx 50\ \text{mV}$

Ref.: Charlon, .., ESSCIRC 2004

电流镜



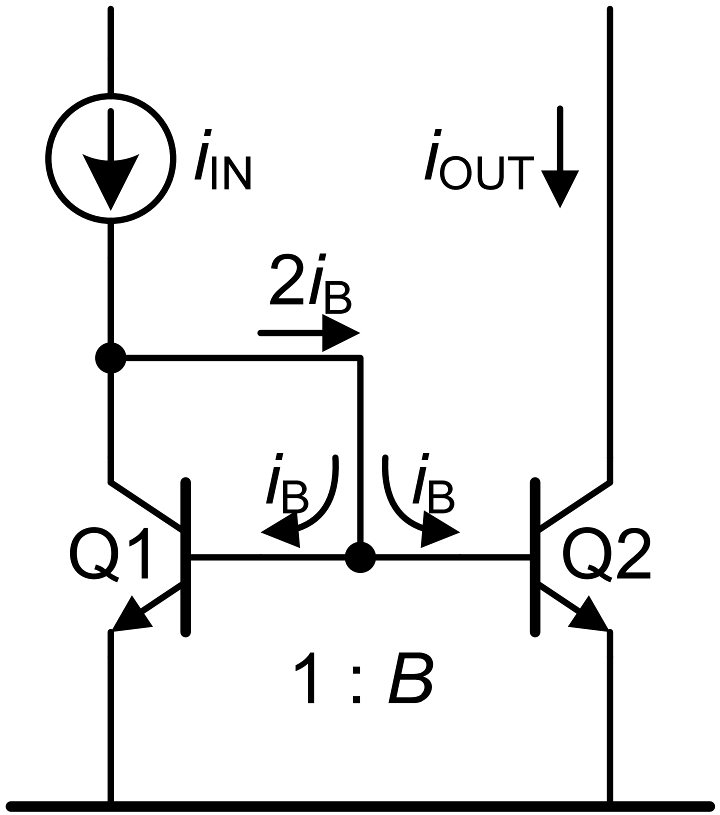
$$i_{OUT} = B i_{IN}$$

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

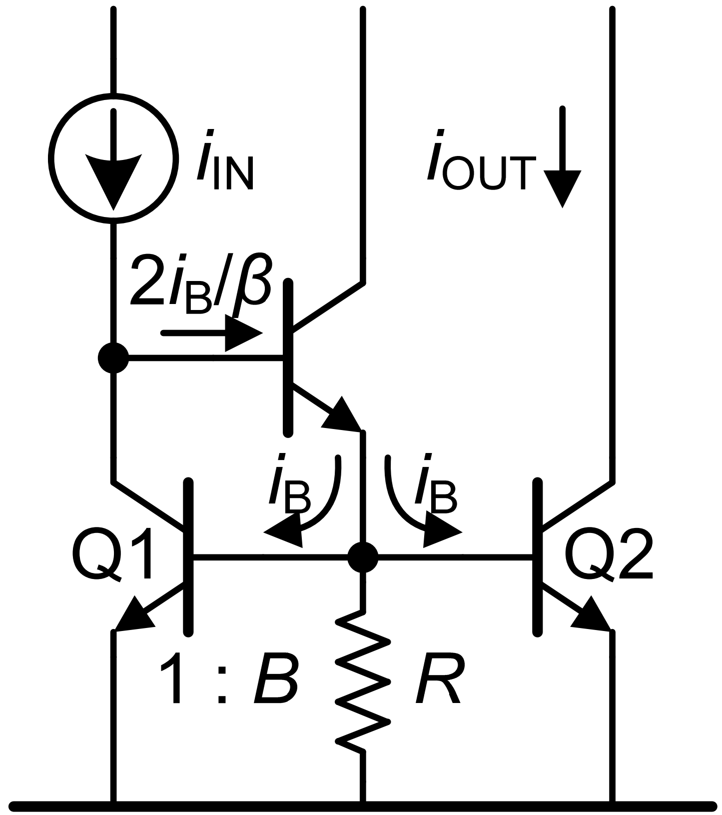
$$i_{OUT} = \frac{kT/q}{R} \ln B \frac{i_{IN}}{i_{OUT}}$$

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

改进的电流镜

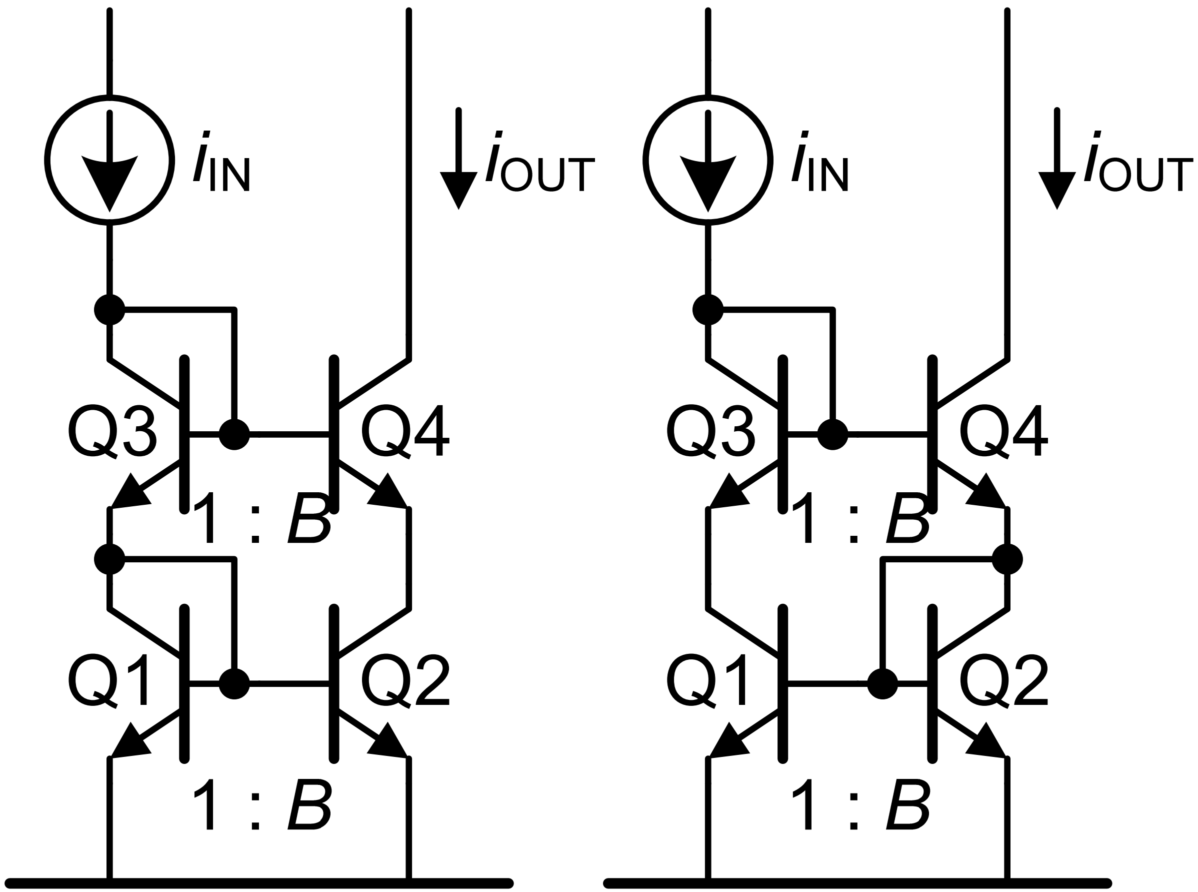


$$误差 \propto \frac{2}{\beta}$$



$$误差 \propto \frac{2}{\beta^2}$$

改进的电流镜



$$\boxed{V_{CE2} = V_{CE1}}$$

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

V_{OUTmin}

$= V_{BE} + V_{CE}$

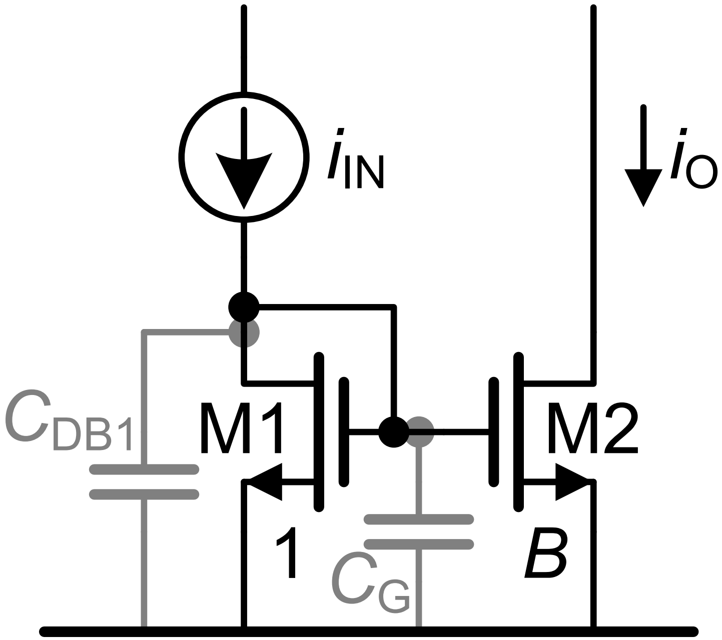
$\approx 0.7 + 0.1$

$= 0.8\ \mathrm{V}$

太大！！！

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

高频时的电流镜



$$i_{OUT} = Bi_{IN}$$

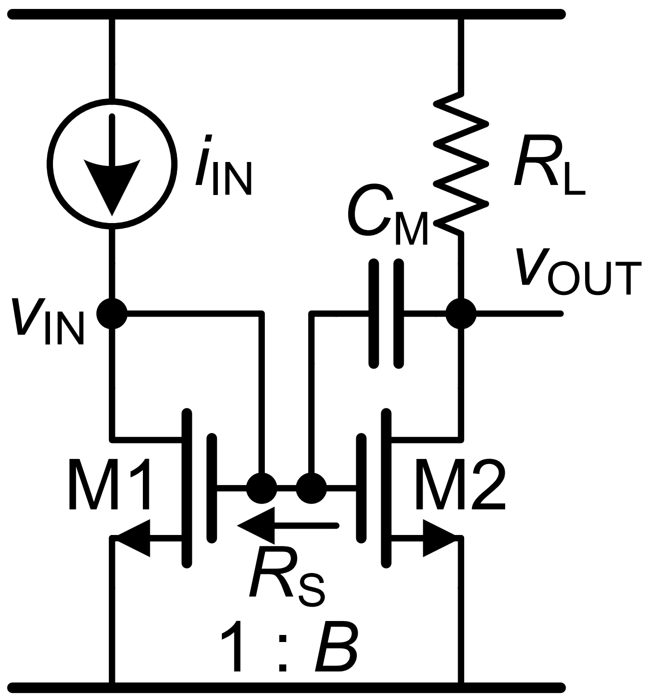
$$R_{out} = r_{DS}$$

$$C_G = (1+B)C_{GS1} + C_{DB1}$$

$$BW = \frac{g_{m1}}{2\pi(C_G + C_{DS1})} \approx f_T \frac{1}{2+B}$$

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

电流密勒效应



$$A_I = B$$

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

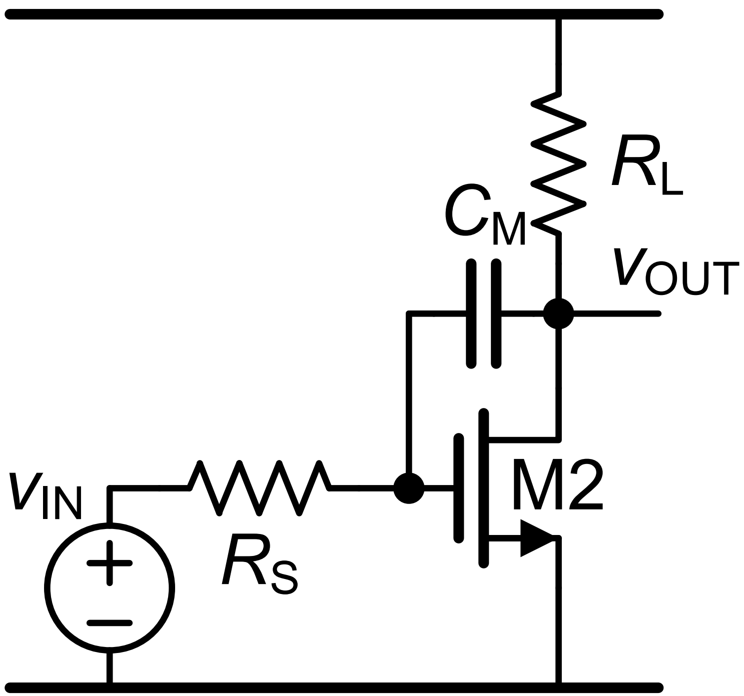
$$R_S = \frac{1}{g_{m1}}$$

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

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

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

电流密勒效应的等效电路



密勒效应:

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

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

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

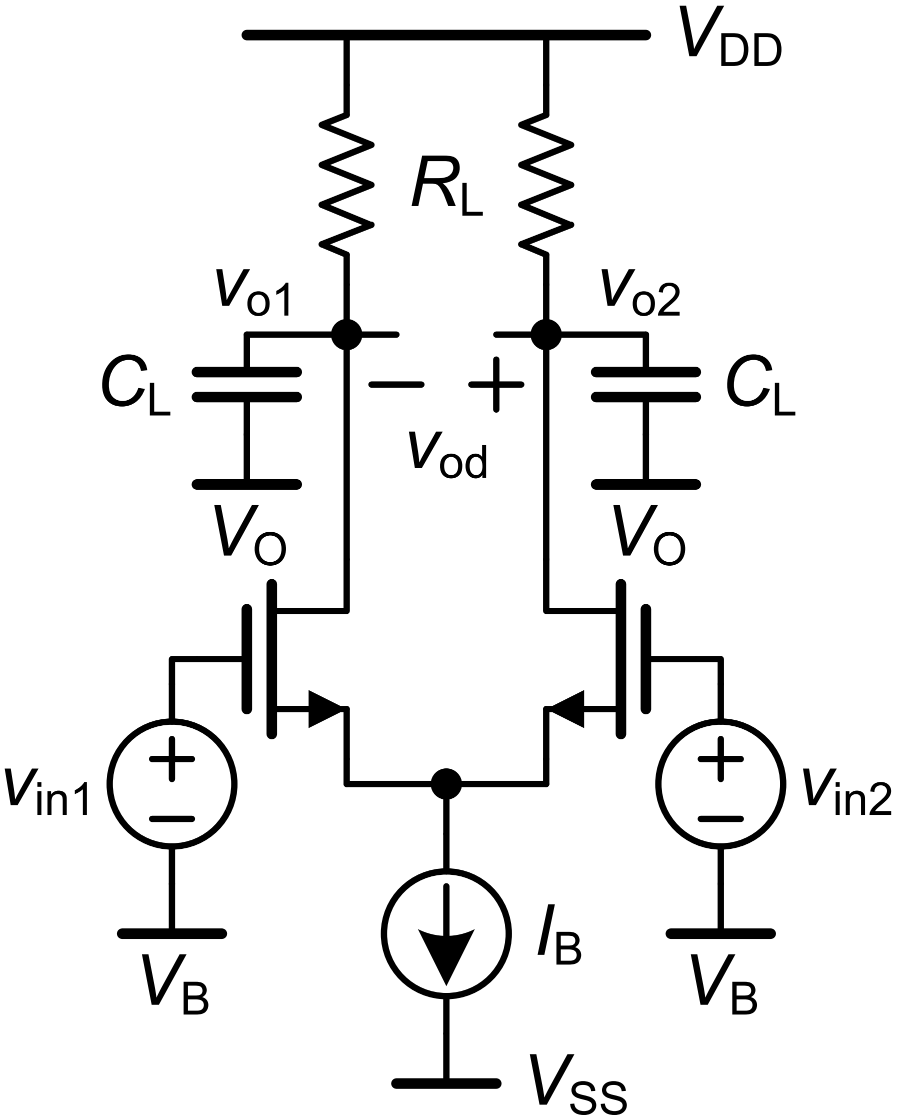
$$f_{-3dB} = \frac{1}{2\pi(1+B)C_M R_L}$$

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

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



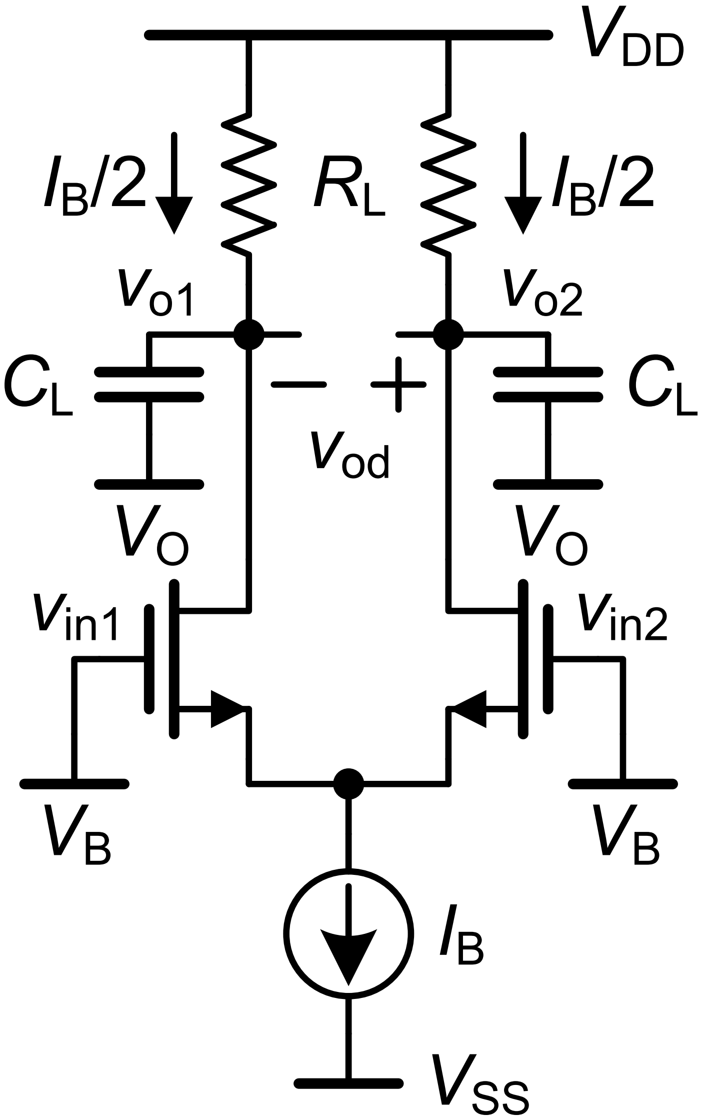
两个相同的晶体管

重新定义v_{in} 和 v_o：

$$\begin{cases} v_{ind} = v_{in1} - v_{in2} \\ v_{inc} = \dfrac{v_{in1} + v_{in2}}{2} \end{cases}$$

$$\begin{cases} v_{od} = v_{o1} - v_{o2} \\ v_{oc} = \dfrac{v_{o1} + v_{o2}}{2} \end{cases}$$

差分电压放大器：直流

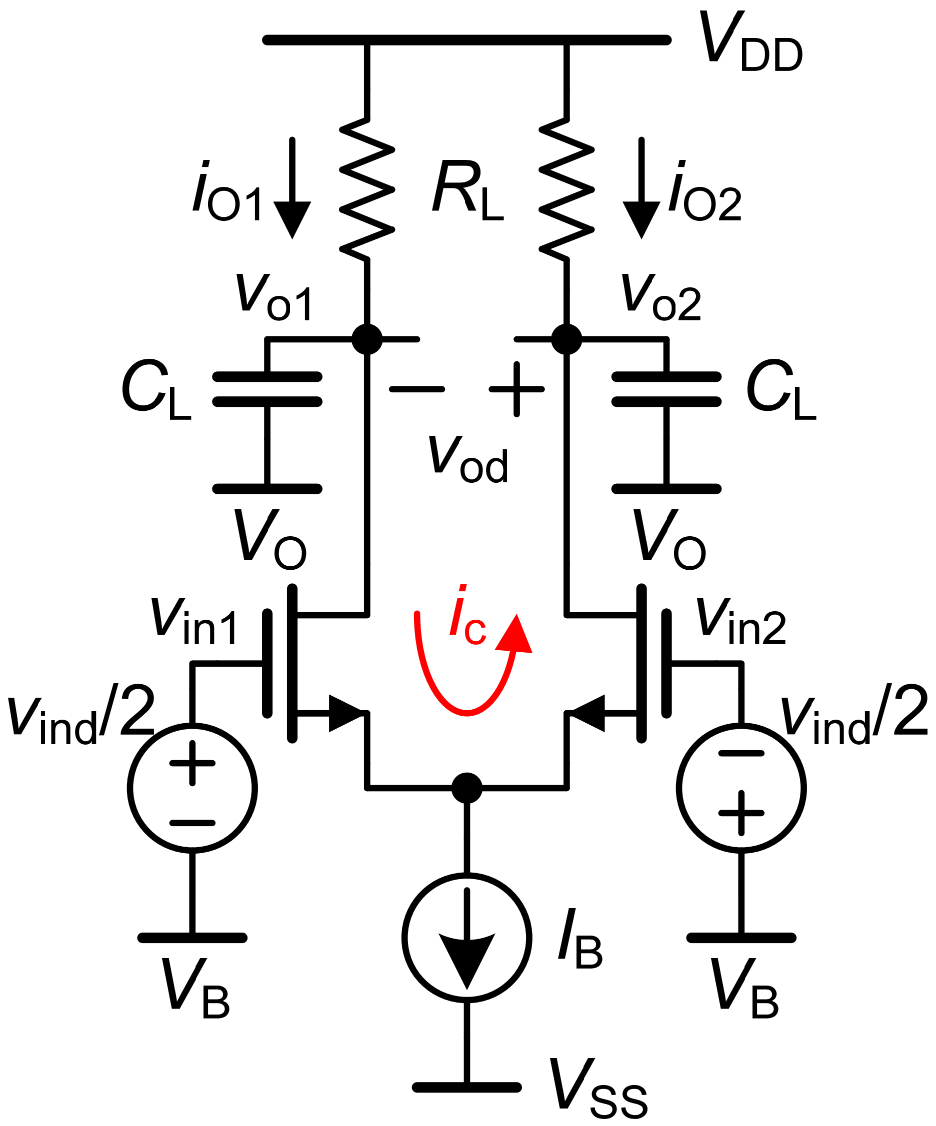


$$v_{in1} = v_{in2} = 0$$

$$v_{o1} = v_{o2} = V_{DD} - R_L I_B/2$$

$$v_{od} = v_{o1} - v_{o2} = 0$$

差分电压放大器: 交流增益



差分输入电压：

$$v_{ind} = v_{in1} - v_{in2}$$

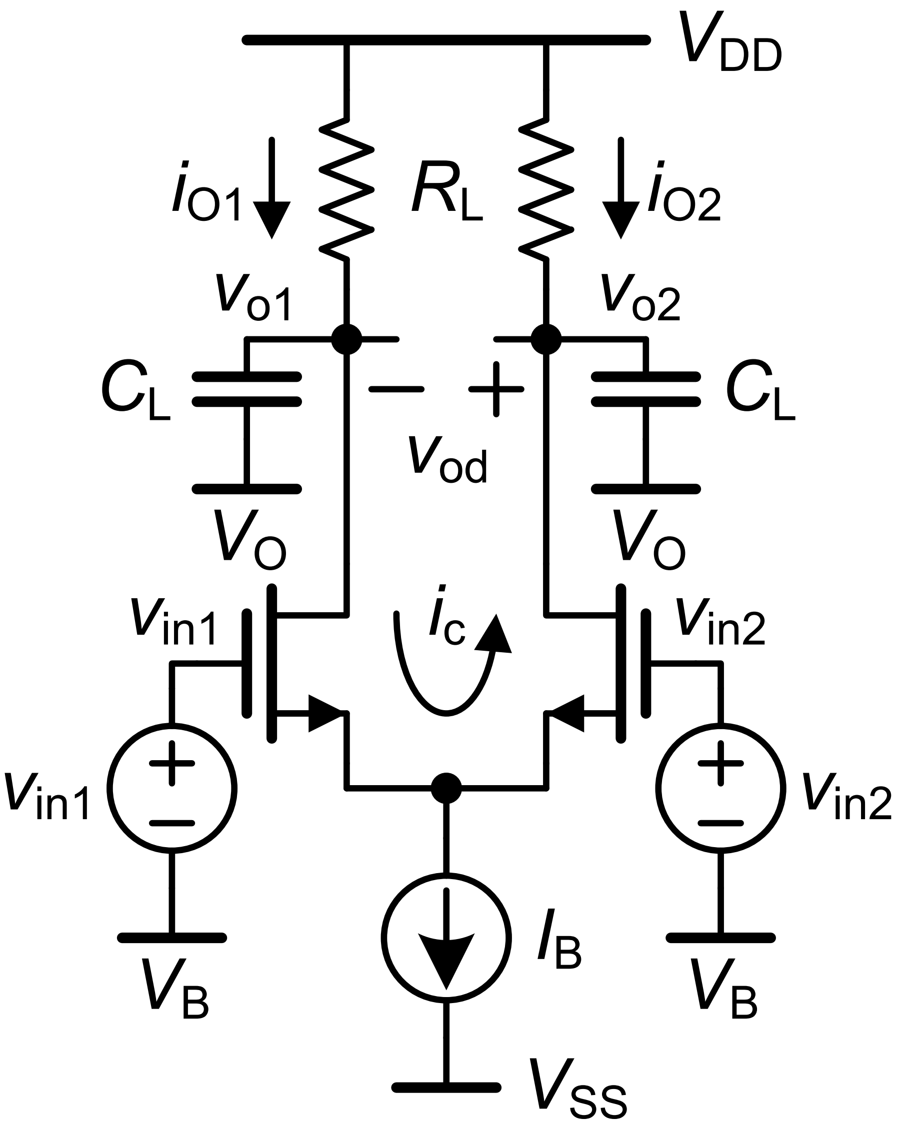
环路电流：

$$i_c = g_m \frac{v_{ind}}{2}$$

$$v_{od} = 2R_L i_c$$

$$\boxed{A_V = \frac{v_{od}}{v_{ind}} = g_m R_L}$$

差分电压放大器



$$\boxed{A_V = g_m R_L}$$

与单个晶体管相同 !!

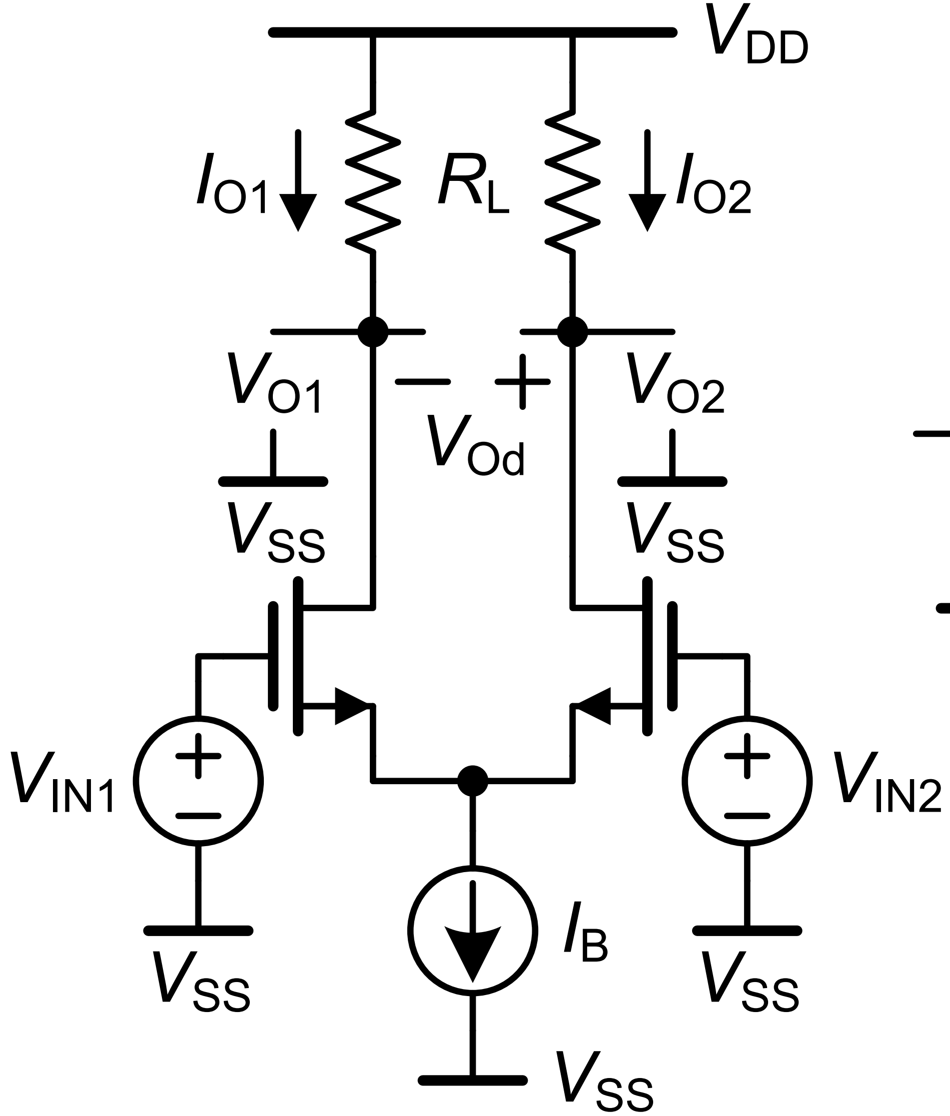
优点：

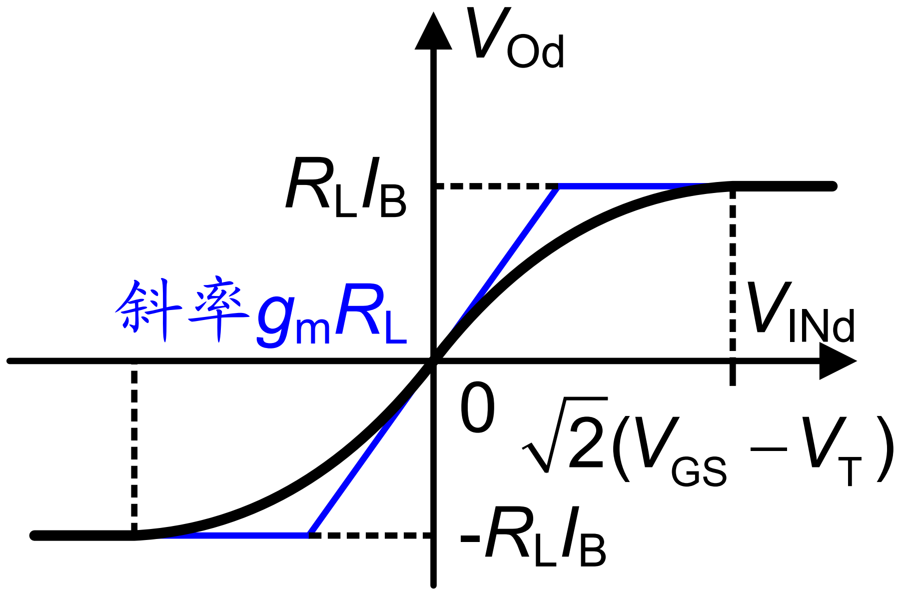
V_{DD}的噪声： $PSRR_{DD}$

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_T决定斜率、范围...增益！

CMOS差分电压放大器：大信号输入

$$\frac{I_{\mathrm{Od}}}{I_{\mathrm{B}}}=\frac{V_{\mathrm{INd}}}{V_{\mathrm{GS}}-V_{\mathrm{T}}}\sqrt{1-\frac{1}{4}\left(\frac{V_{\mathrm{INd}}}{V_{\mathrm{GS}}-V_{\mathrm{T}}}\right)^{2}}$$

V_{INd}为差分输入电压

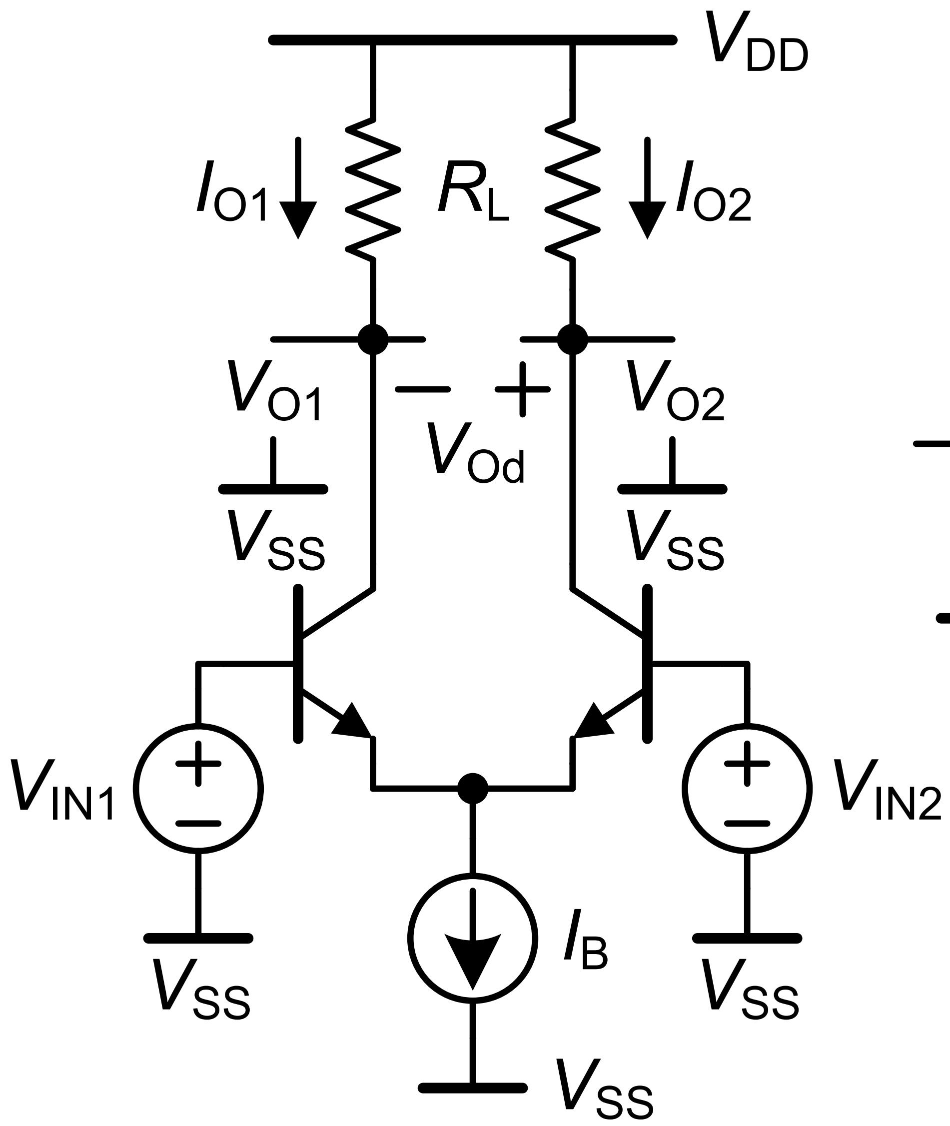
I_{Od}为差分输出电流

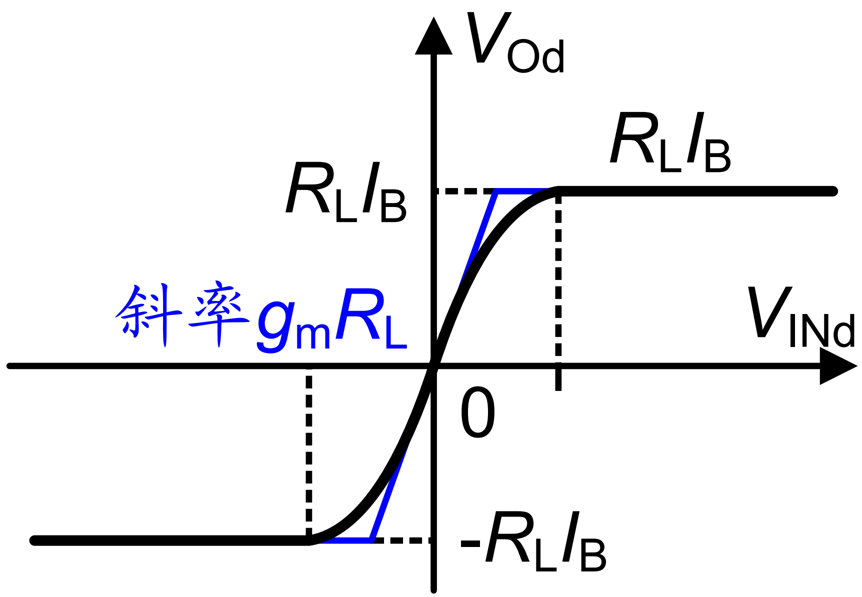
i_{od}为差分小信号输出电流($g_m v_{\mathrm{ind}}$)
  或两倍的环路电流($g_m v_{\mathrm{ind}}/2$)

I_{B}为差分对的总的直流电流

注意：$g_m=\dfrac{I_{\mathrm{B}}}{V_{\mathrm{GS}}-V_{\mathrm{T}}}=2K'\dfrac{W}{L}(V_{\mathrm{GS}}-V_{\mathrm{T}})$

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

$$\frac{I_{\mathrm{Od}}}{I_{\mathrm{B}}}=\tanh\frac{V_{\mathrm{INd}}}{2\mathrm{k}T/\mathrm{q}} \qquad \tanh x=\frac{\mathrm{e}^{x}-\mathrm{e}^{-x}}{\mathrm{e}^{x}+\mathrm{e}^{-x}}=\frac{2\mathrm{e}^{x}-1}{2\mathrm{e}^{x}+1}$$

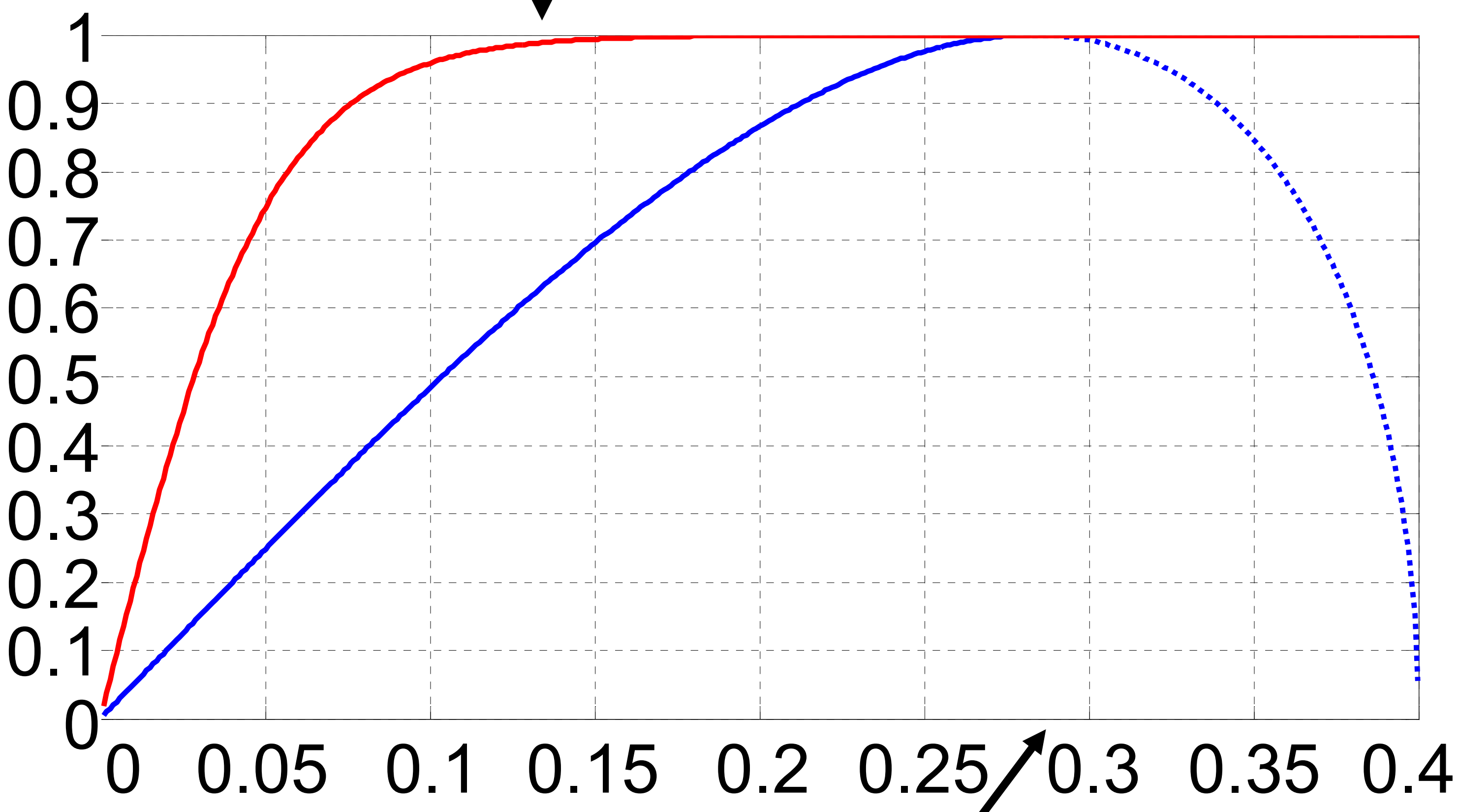
V_{INd}为差分输入电压
I_{Od}为差分输出电流
i_{od}为差分小信号输出电流($g_{\mathrm{m}}v_{\mathrm{ind}}$)
或两倍的环路电流($g_{\mathrm{m}}v_{\mathrm{ind}}/2$)
I_{B}为差分对的总的直流电流

注意： $g_{\mathrm{m}}=\dfrac{I_{\mathrm{B}}}{2\mathrm{k}T/\mathrm{q}}$

差分电压放大器：转移曲线

$$\frac{I_{\mathrm{Od}}}{I_{\mathrm{B}}}=\tanh\frac{V_{\mathrm{INd}}}{2kT/q}$$

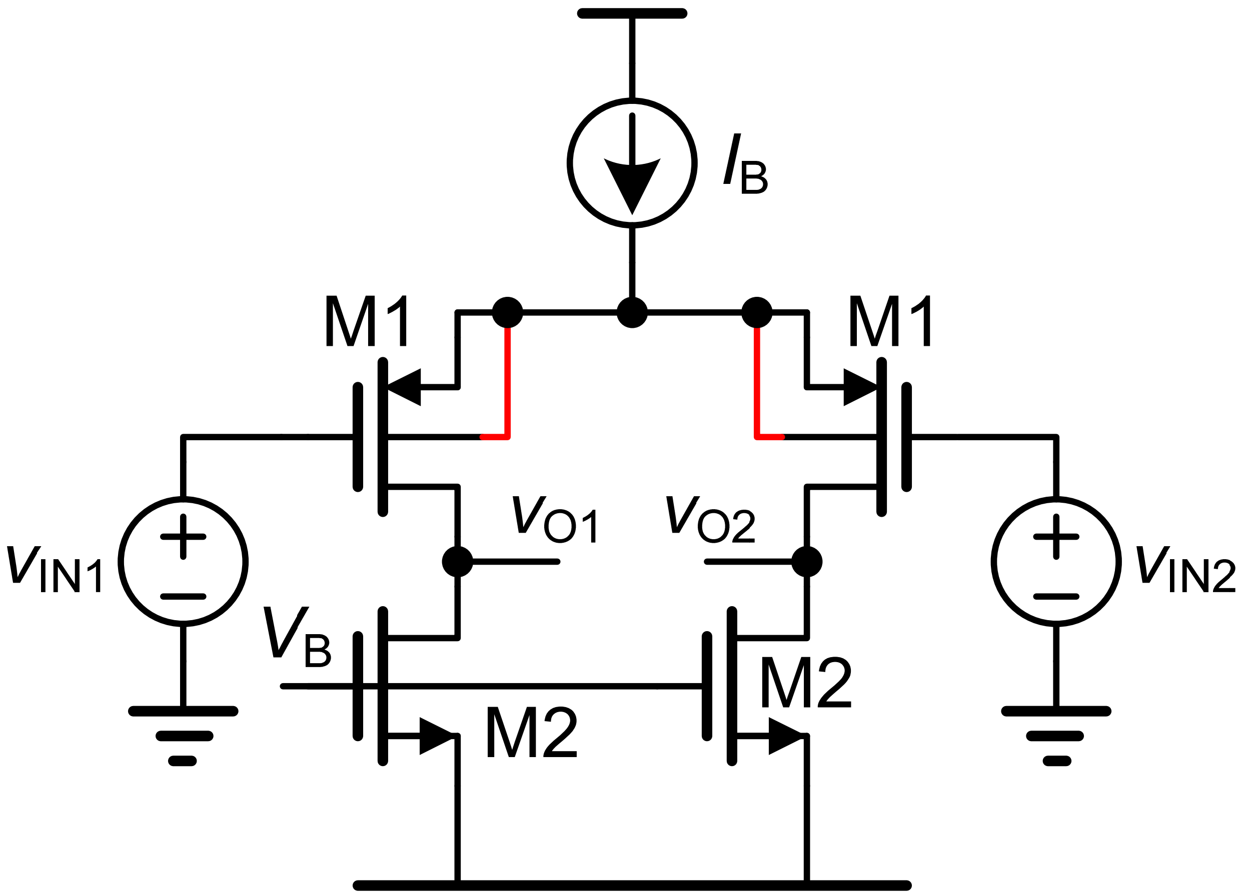
$$-1\% \quad V_{\mathrm{INd}}\approx 2.67\times 2kT/q=0.14\ \mathrm{V}$$



$$\frac{I_{\mathrm{Od}}}{I_{\mathrm{B}}}=\frac{V_{\mathrm{INd}}}{V_{\mathrm{GS}}-V_{\mathrm{T}}}\sqrt{1-\frac{1}{4}\left(\frac{V_{\mathrm{INd}}}{V_{\mathrm{GS}}-V_{\mathrm{T}}}\right)^2}$$

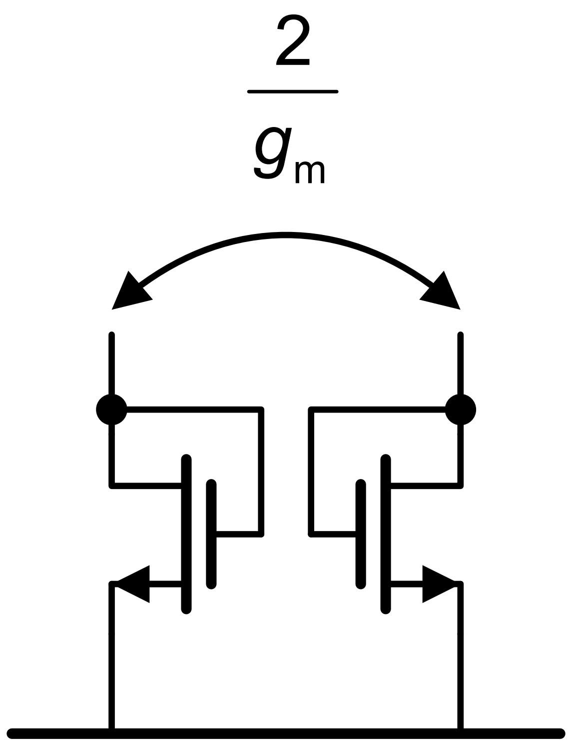
$$V_{\mathrm{INd}}=\sqrt{2}(V_{\mathrm{GS}}-V_{\mathrm{T}})=\sqrt{2}\times 0.2\ \mathrm{V}$$

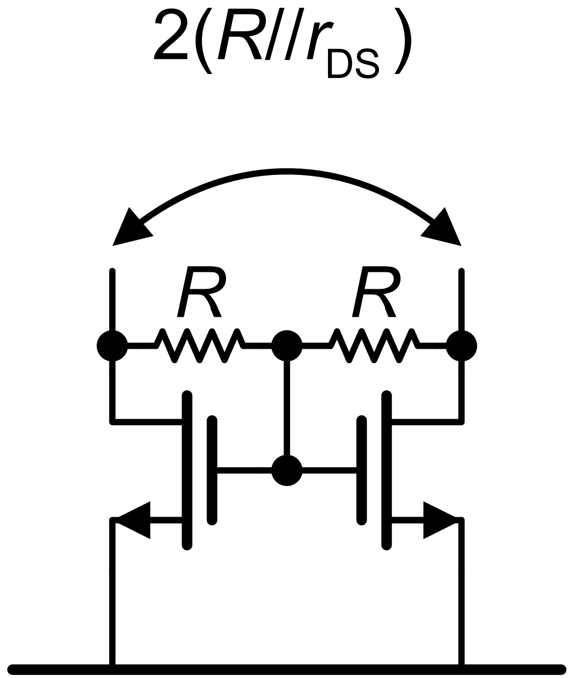
增益为$g_m r_{DS}$的差分电压放大器



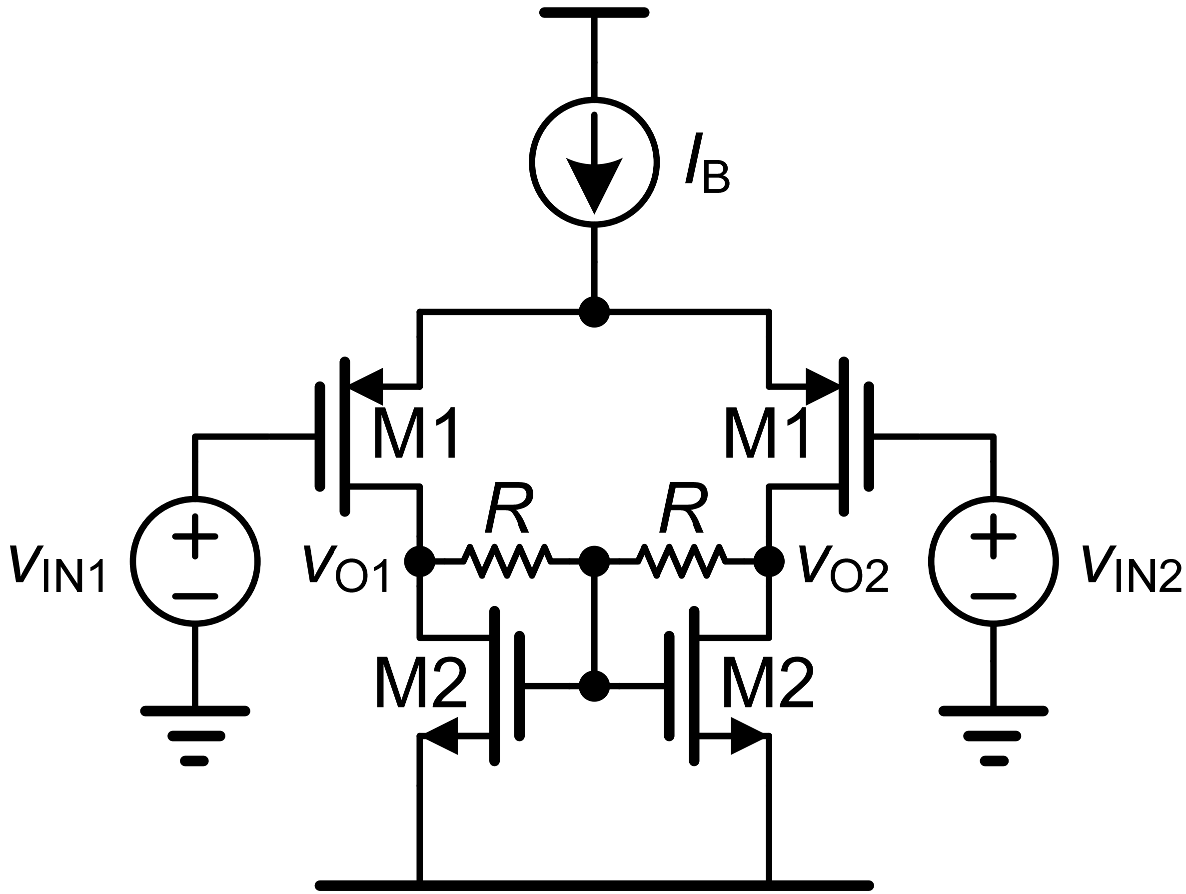
$$A_V = g_{m1}(r_{DS1} // r_{DS2})$$

接电阻的二极管连接MOST





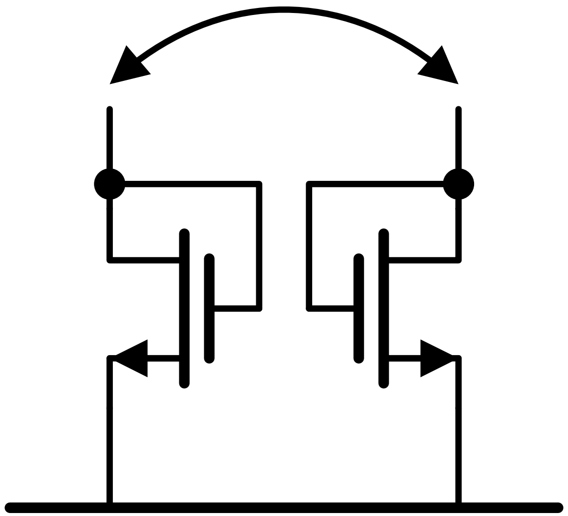
高增益差分电压放大器



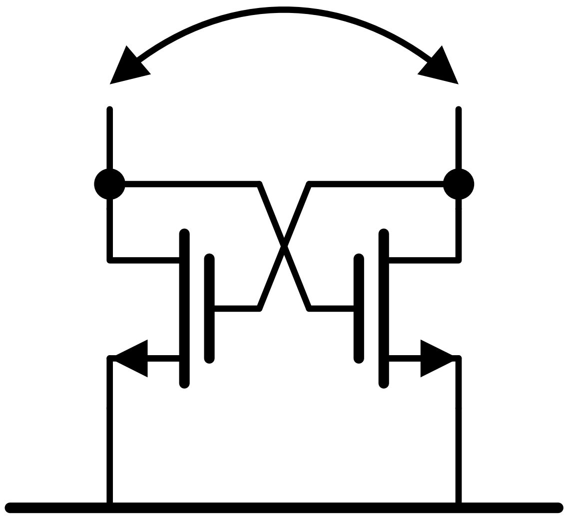
$$A_V = g_{m1}(R // r_{DS}) \qquad r_{DS} = r_{DS1} // r_{DS2}$$

差分二极管连接MOST 1

$$\frac{2}{g_m}$$

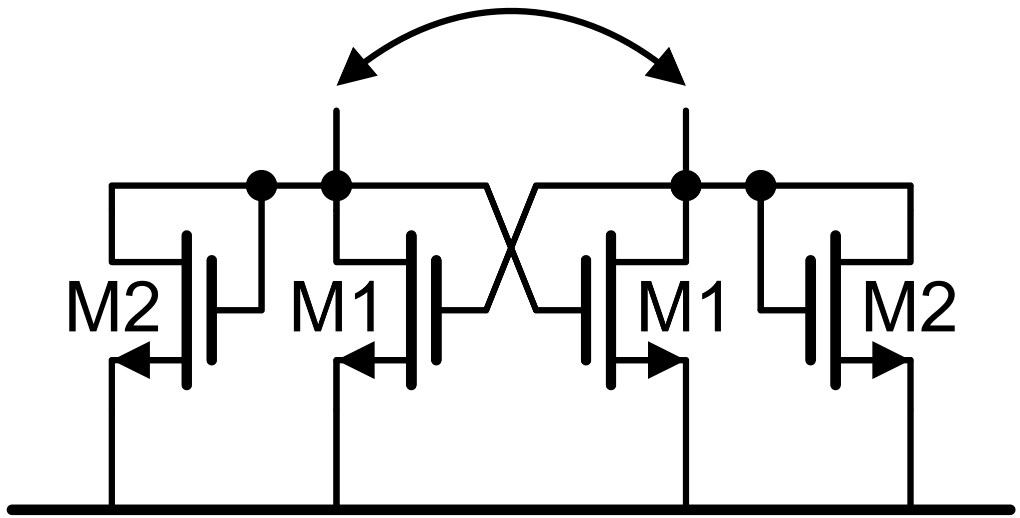


$$-\frac{2}{g_m}$$



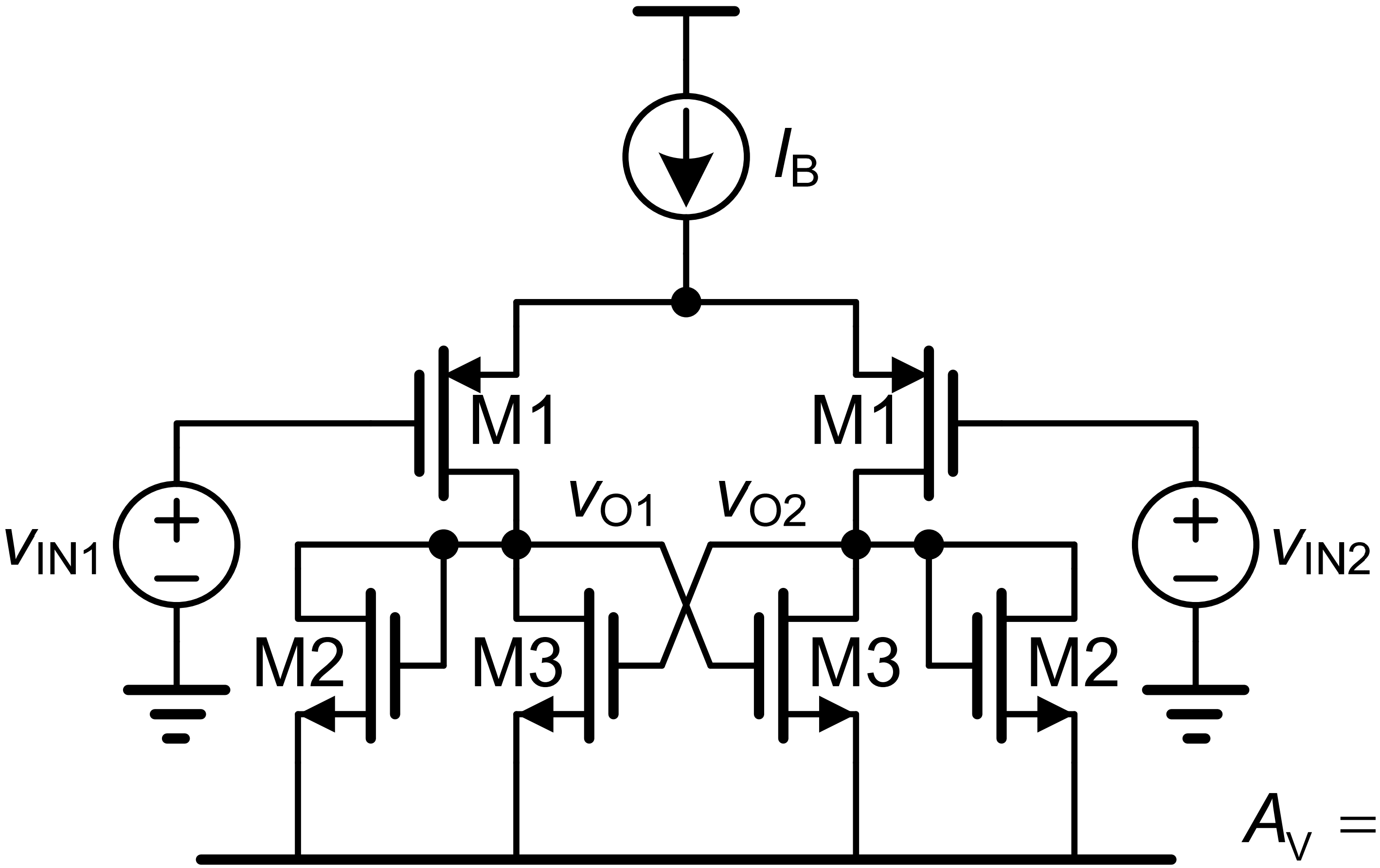
差分二极管连接MOST 2

$$\frac{2}{g_{m2}-g_{m1}}$$



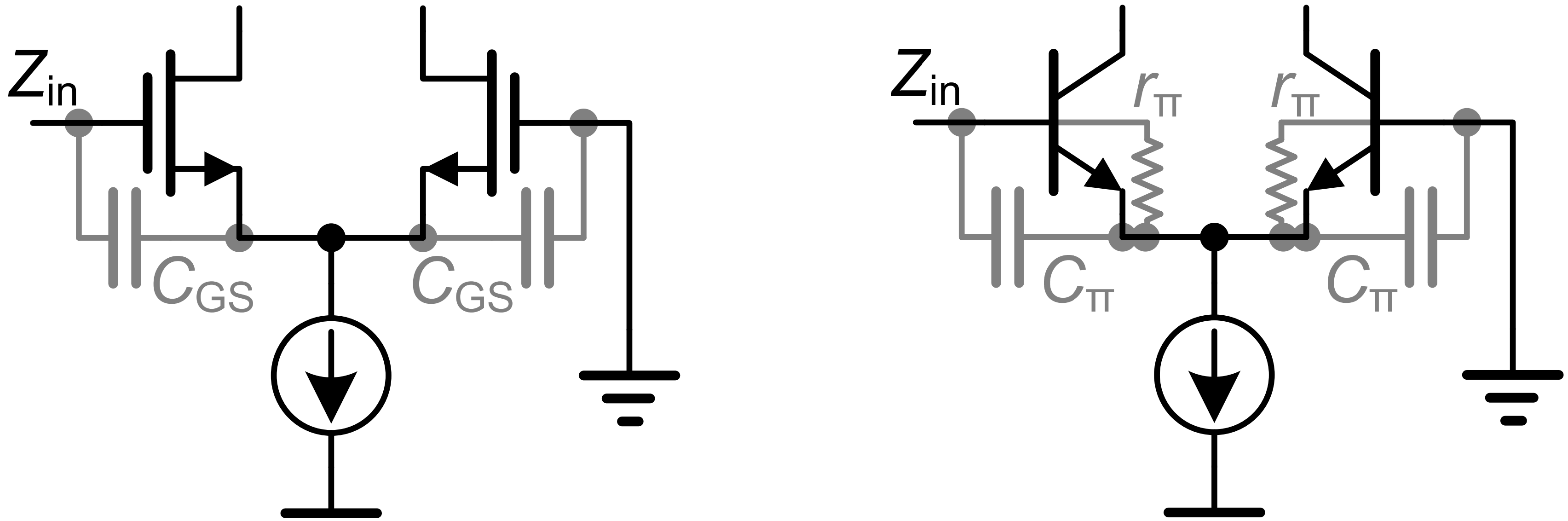
值接近 ∞！

高增益电流抵消技术



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

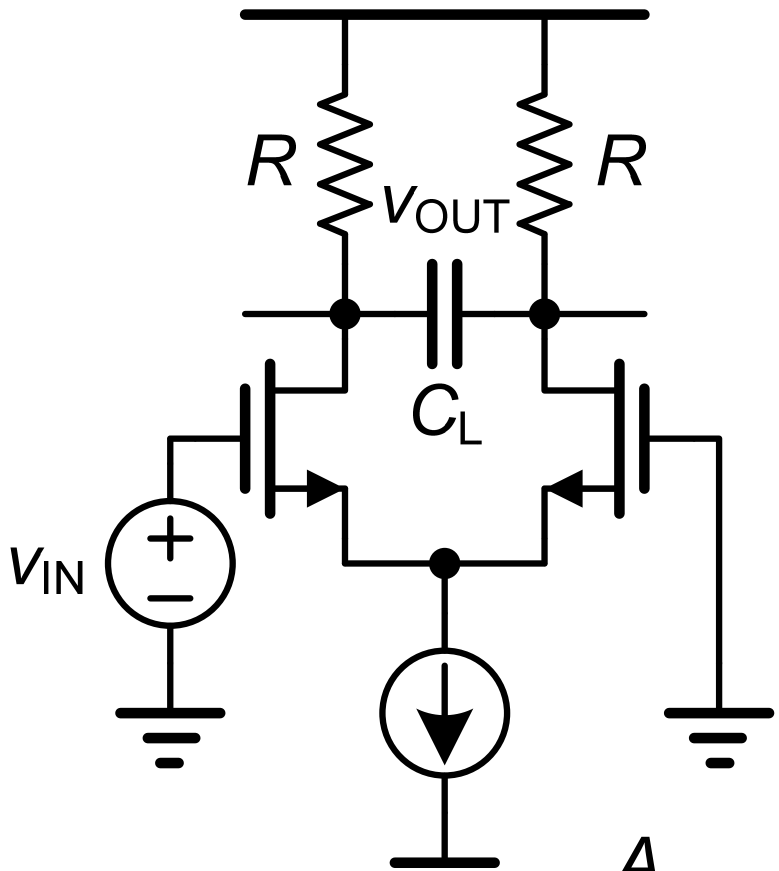
输入阻抗

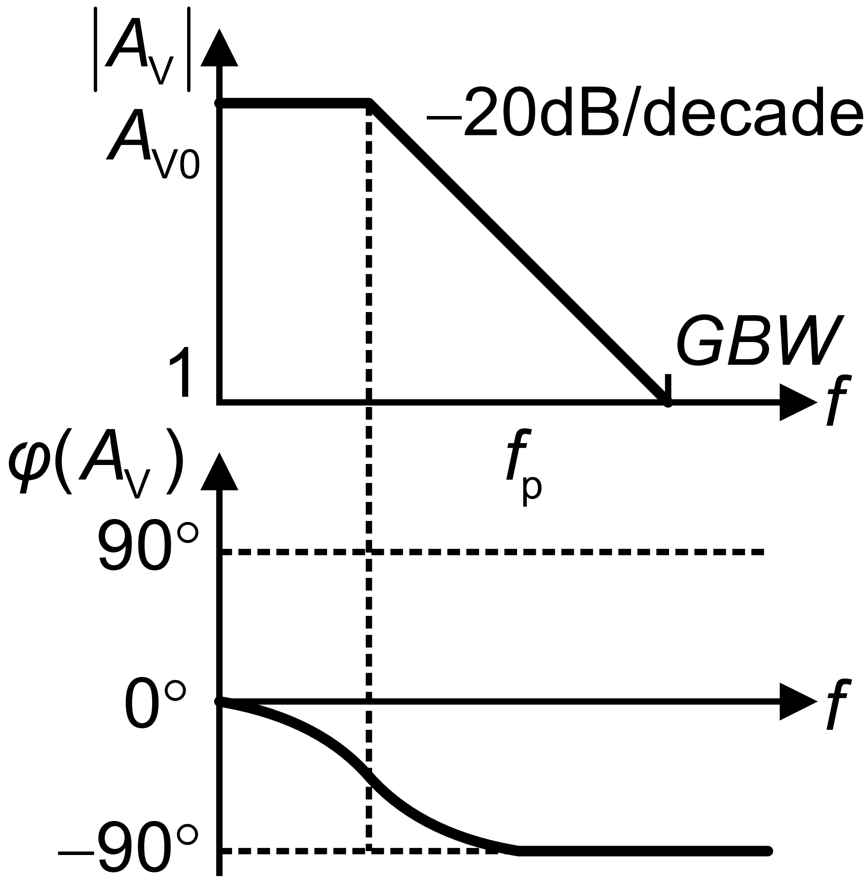


$$C_{in} = \frac{C_{GS}}{2}$$

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

低通电压差分放大器

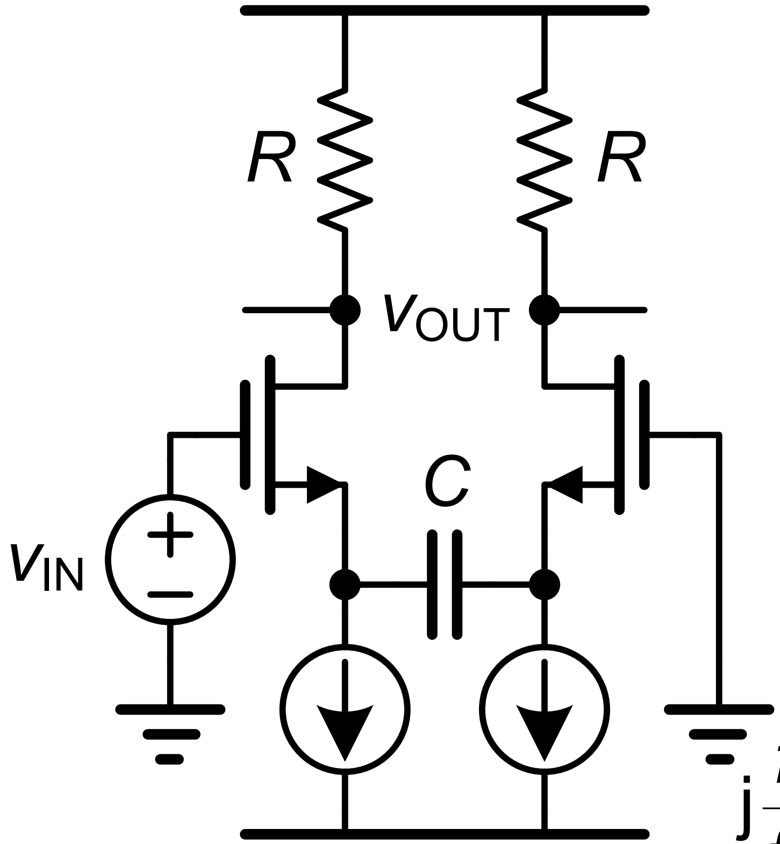


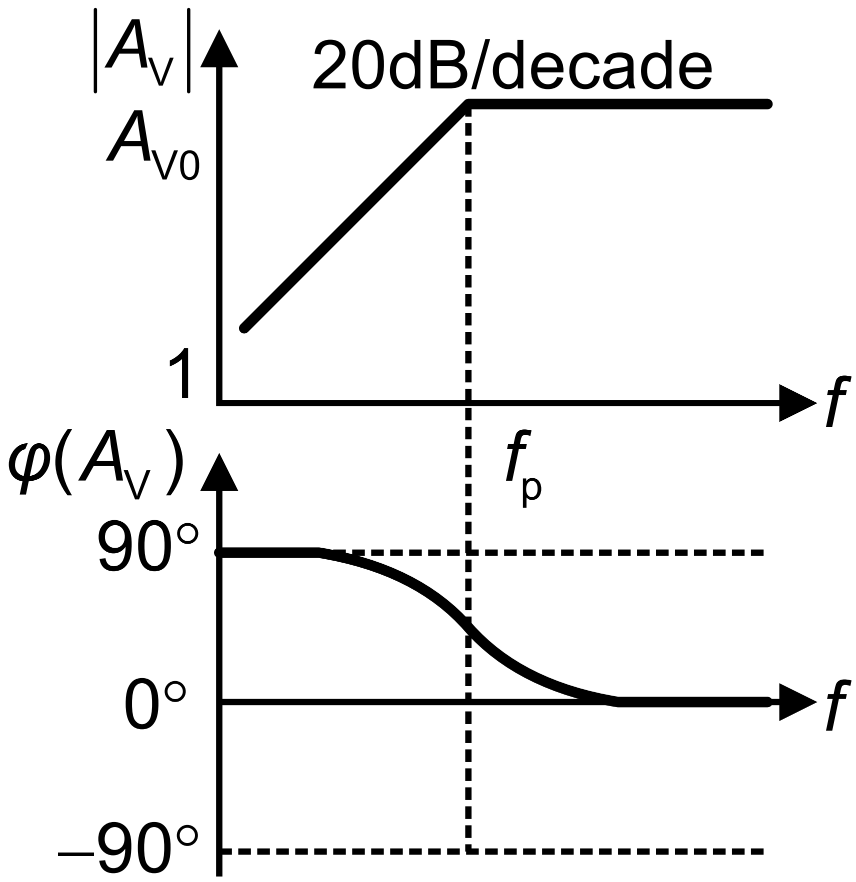


$$A_{V0} = g_m R \quad A_V = \frac{A_{V0}}{(1 + j\frac{f}{f_p})}$$

$$f_p = \frac{1}{2\pi 2RC_L} \quad GBW = \frac{g_m}{2\pi 2C_L}$$

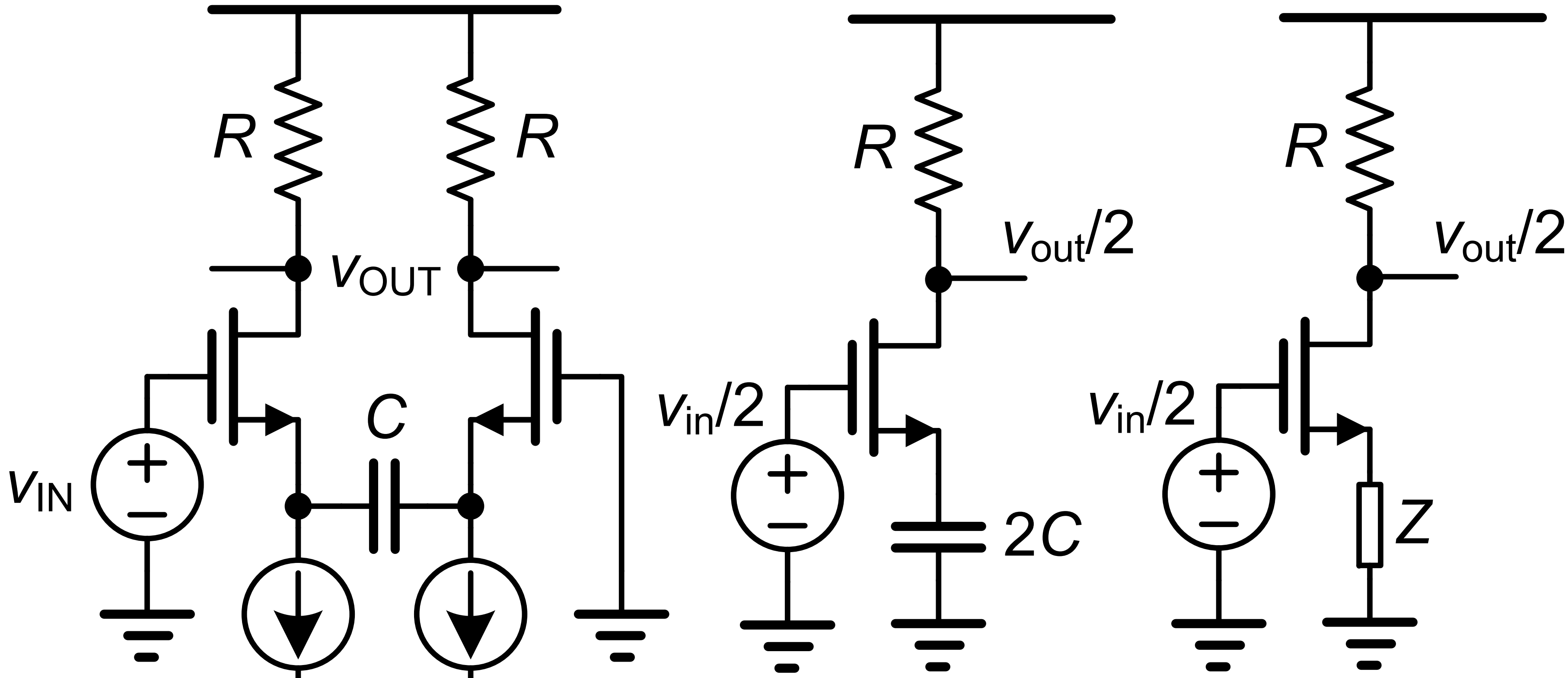
高通电压差分放大器





$$A_{V0}=g_mR \quad A_V=A_{V0}\frac{j\frac{f}{f_p}}{(1+j\frac{f}{f_p})} \quad f_p=\frac{1}{2\pi 2C}$$

高通差分放大器的计算



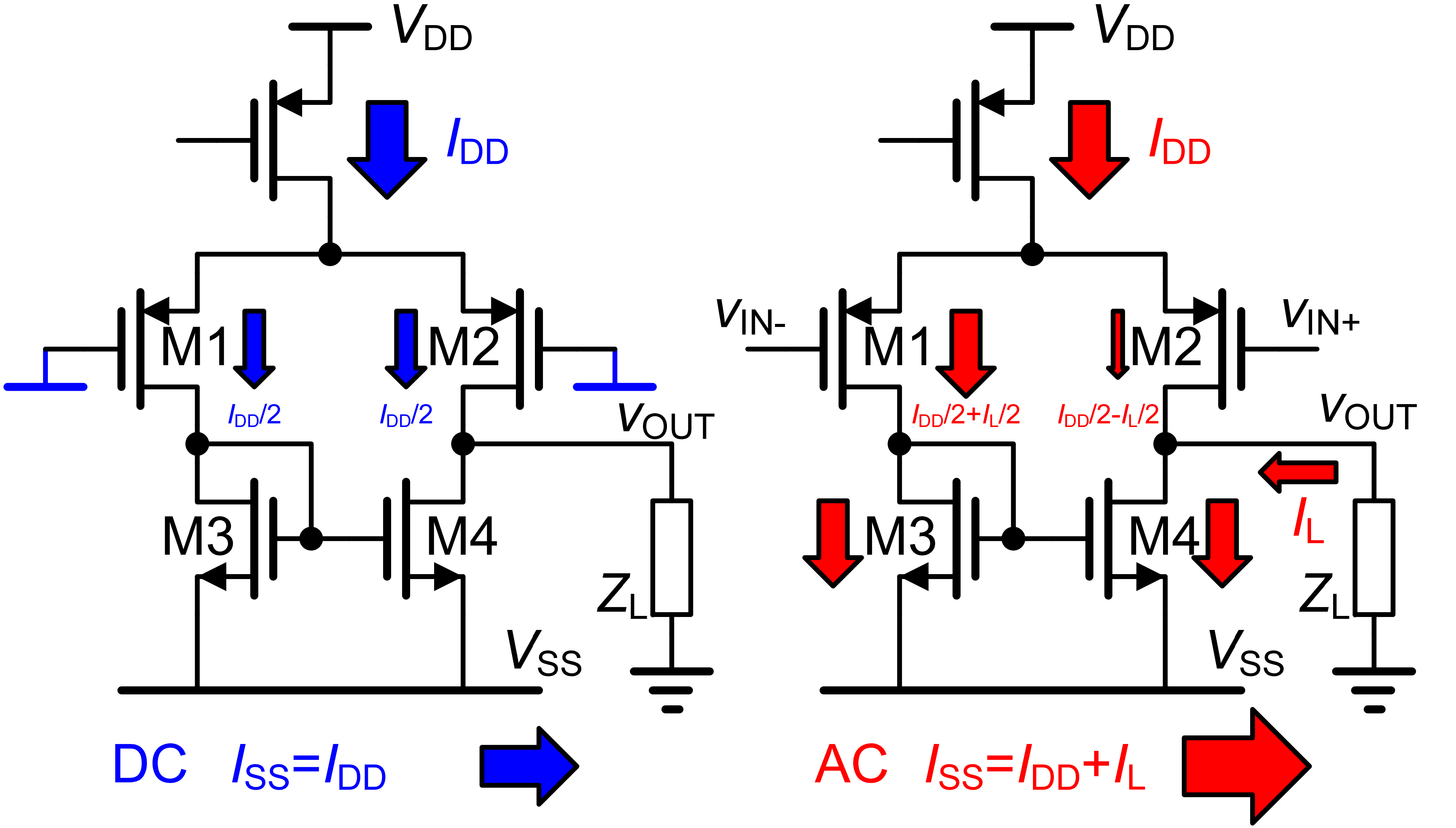
$$A_V = \frac{-g_m R}{(1+\frac{g_m}{2C_S})}$$

$$A_V = \frac{-g_m R}{(1+g_m Z)}$$

目录

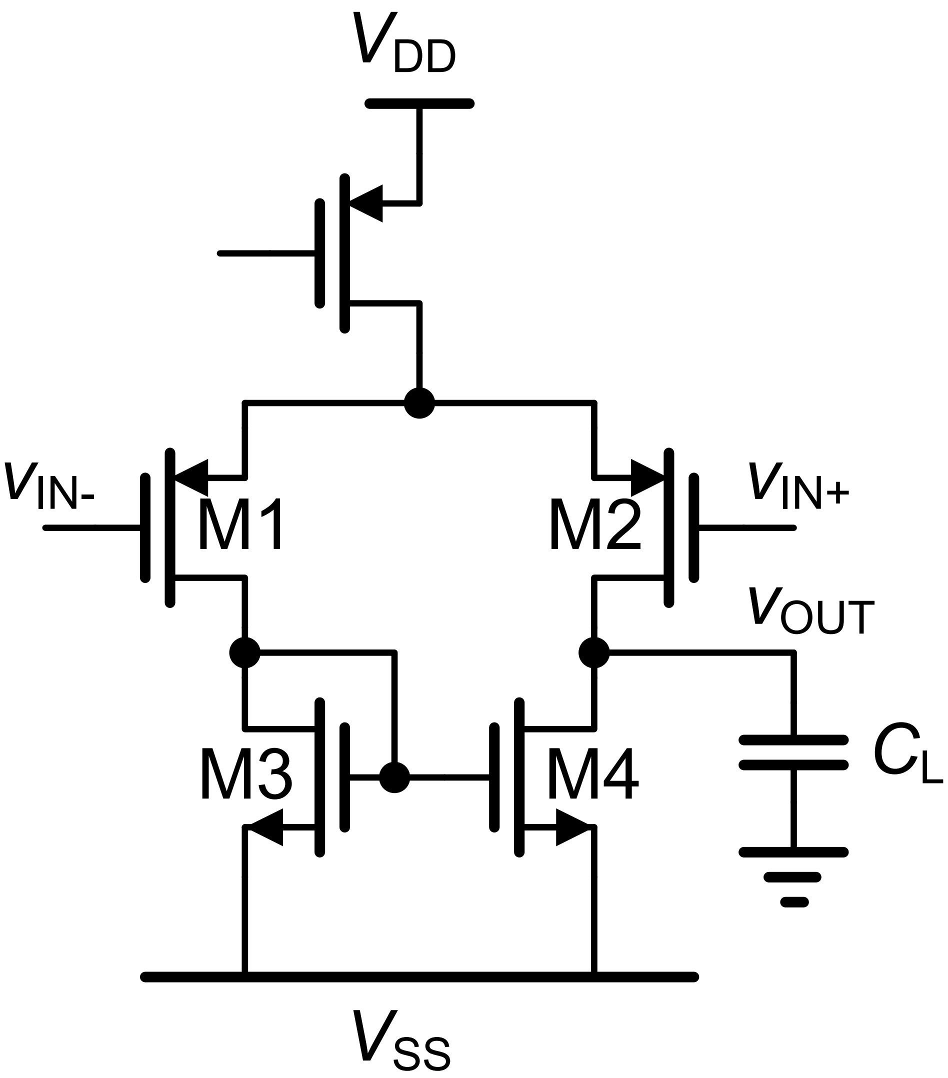
- 电流镜
- 差分对
- 差分电压放大器和差分电流放大器

运算跨导放大器(OTA)



V_{DD}
I_{DD}
M1
M2
$I_{DD}/2$
$I_{DD}/2$
V_{OUT}
M3
M4
Z_L
V_{SS}
DC $I_{SS}=I_{DD}$
V_{DD}
I_{DD}
V_{IN-}
V_{IN+}
M1
M2
$I_{DD}/2+I_L/2$
$I_{DD}/2-I_L/2$
V_{OUT}
I_L
M3
M4
Z_L
V_{SS}
AC $I_{SS}=I_{DD}+I_L$

单级OTA



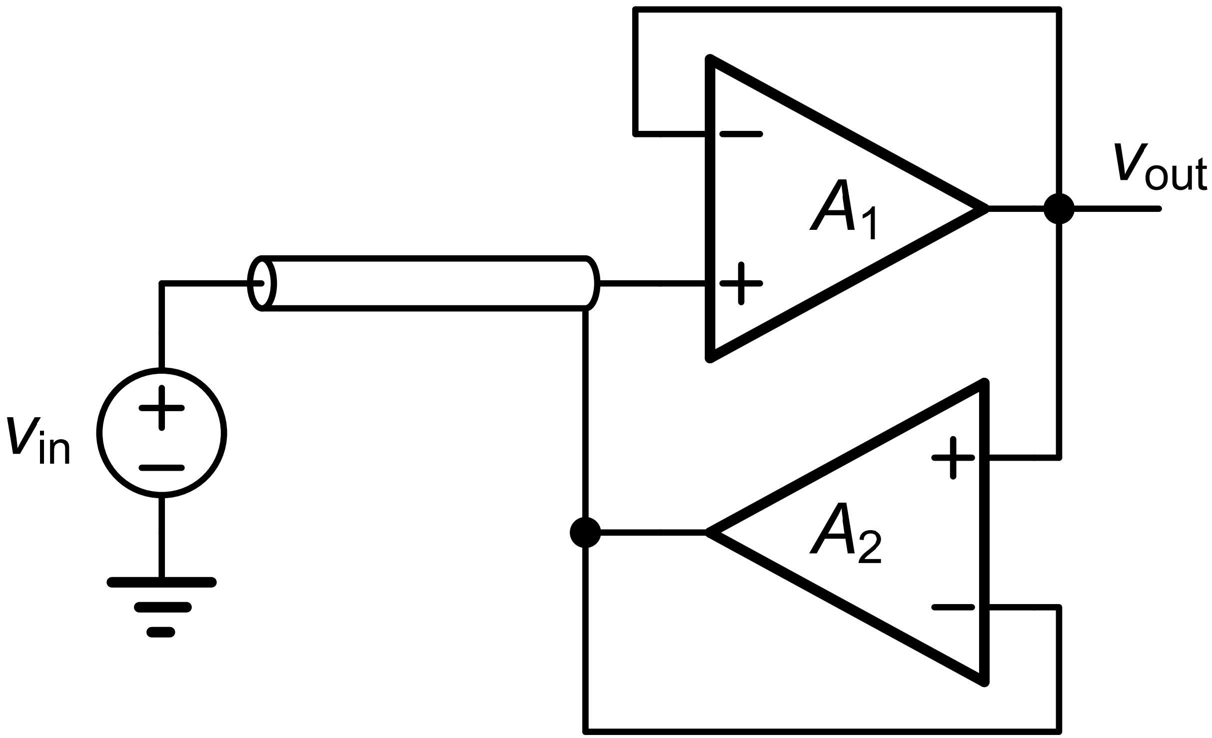
$$A_V = g_{m1} R_{out}$$

$$R_{out} = r_{DS2} // r_{DS4}$$

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

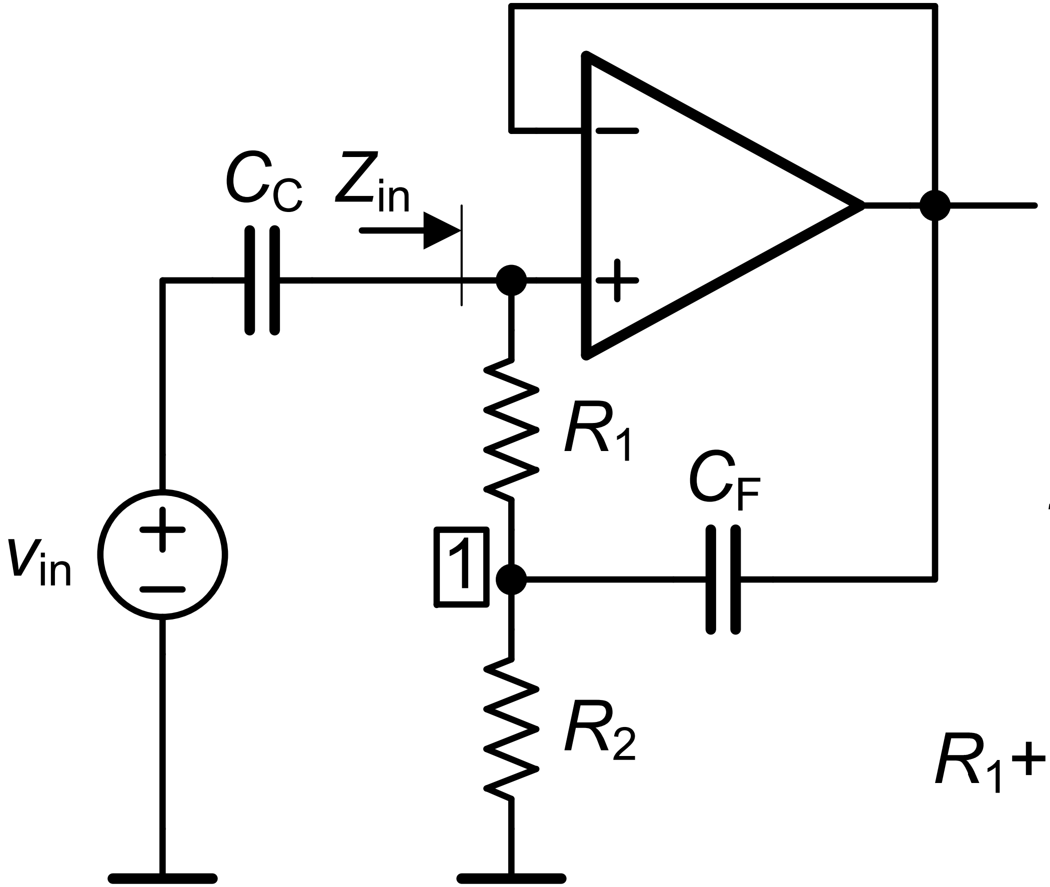
$$GBW = \frac{g_{m1}}{2\pi C_L}$$

电容自举电路



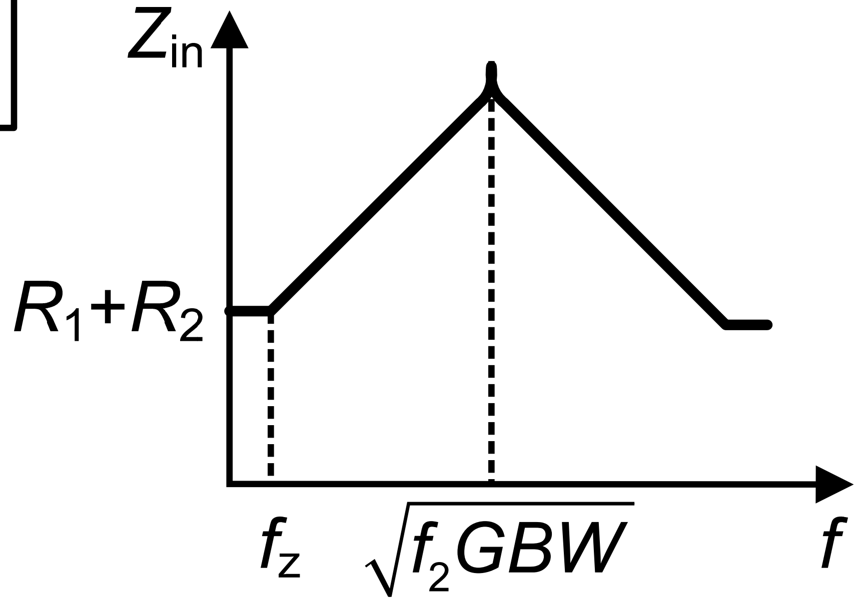
$C_{coax} \approx 0$!!!

电阻自举电路 1

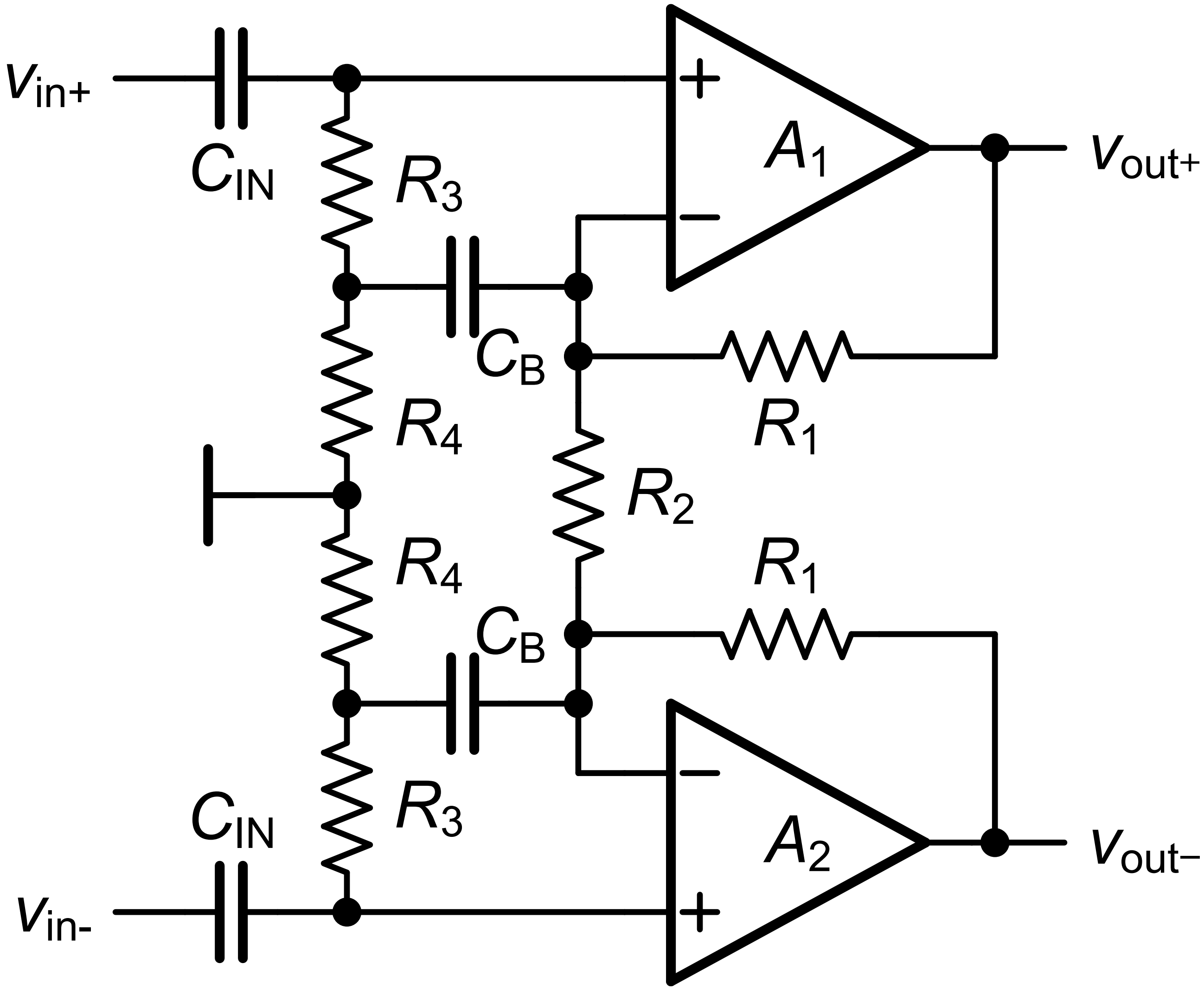


$$f_z = \frac{1}{2\pi(R_1 /\!/ R_2)C_F}$$

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

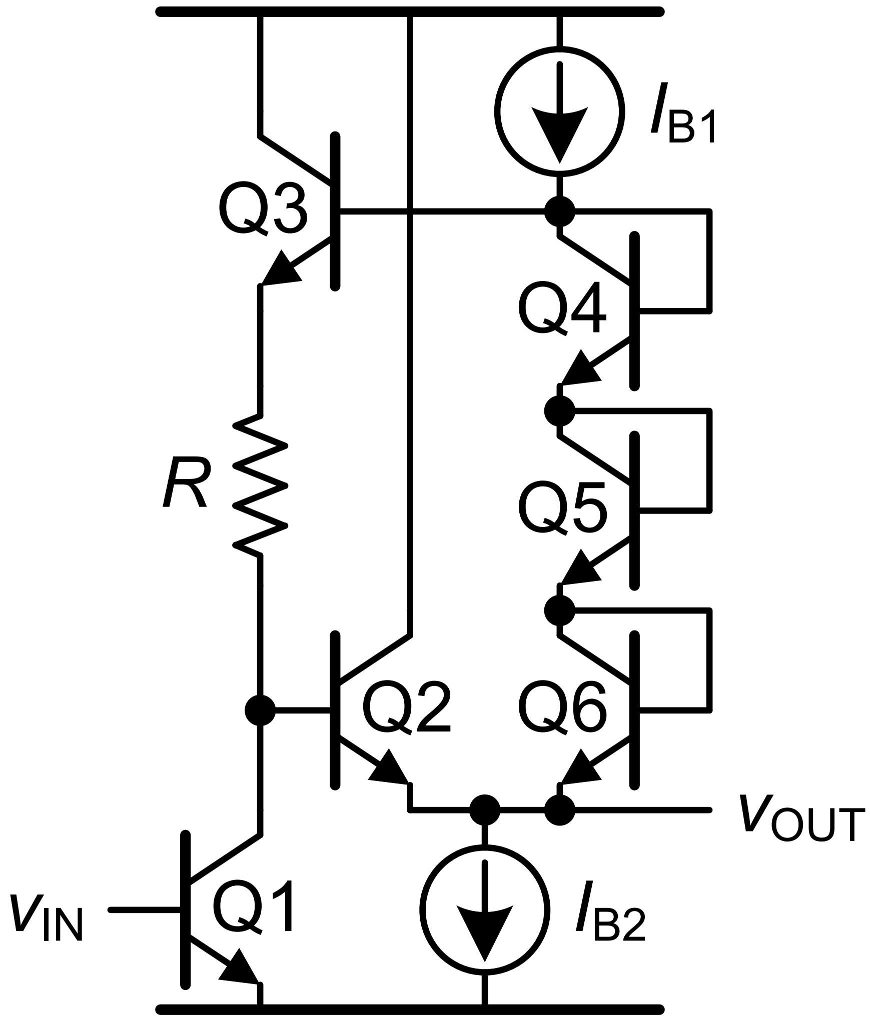


电阻自举电路 2



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

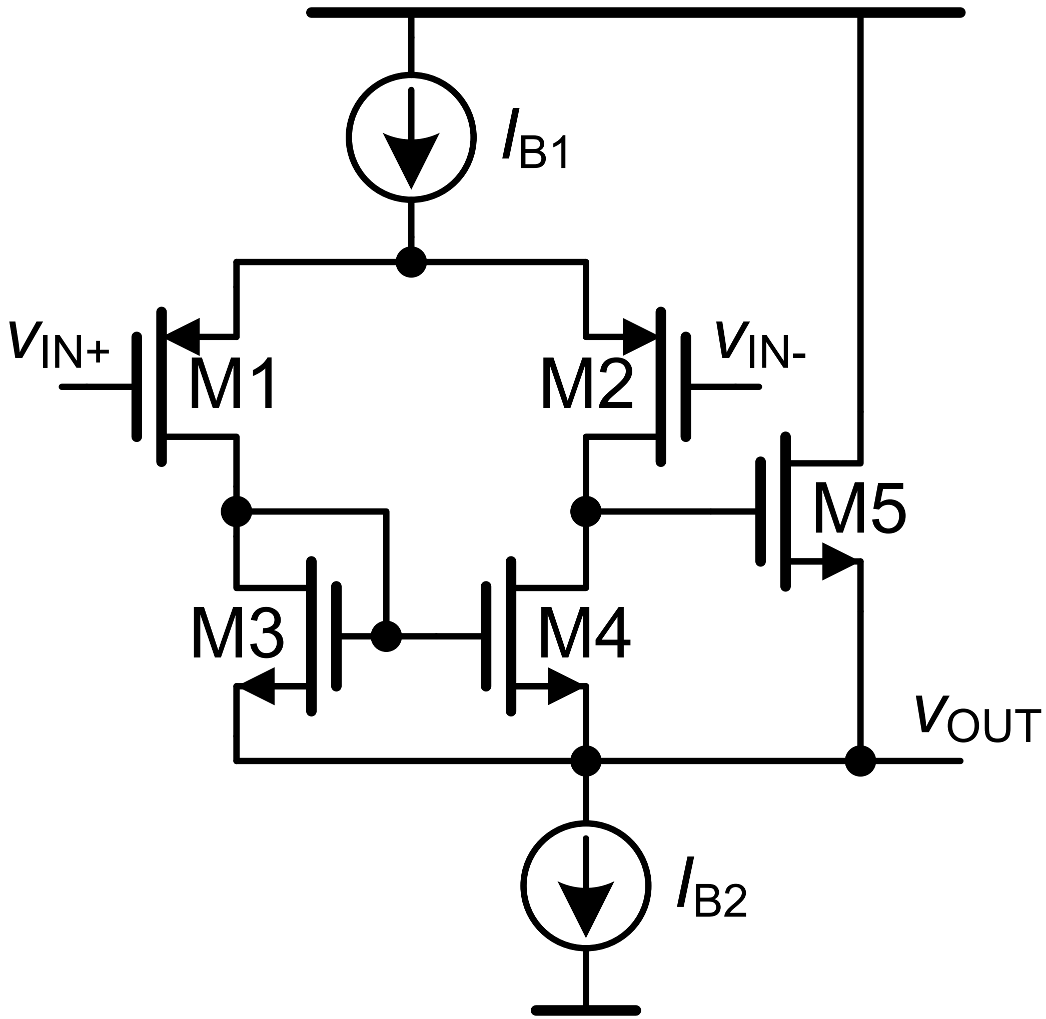
电阻自举电路 3



*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

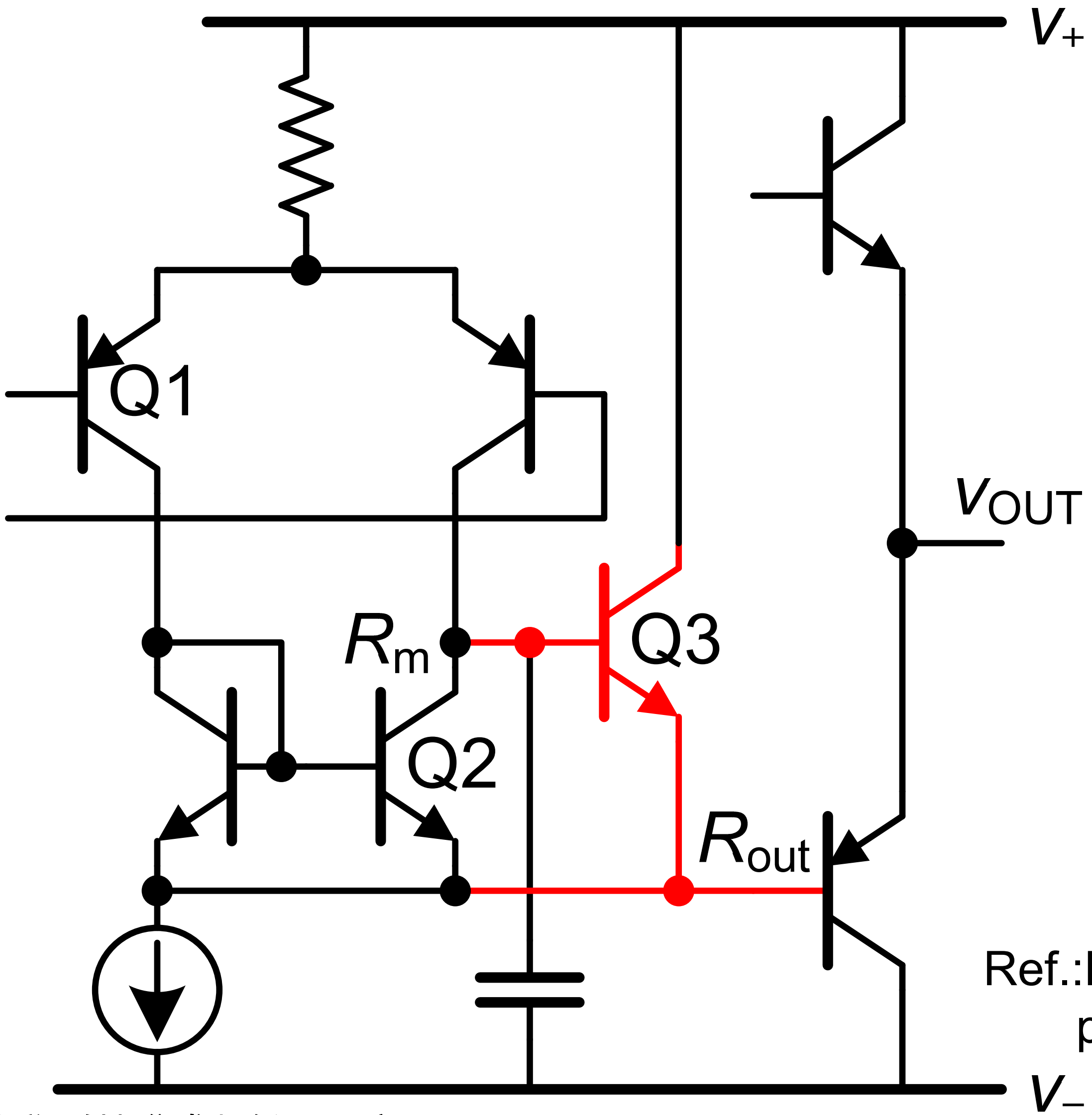


r_{DS4}被自举掉了！

$A_V \approx g_{m1} r_{DS2}$

*GBW*相同！

电阻自举电路 5



$$R_m \to x\beta_3$$

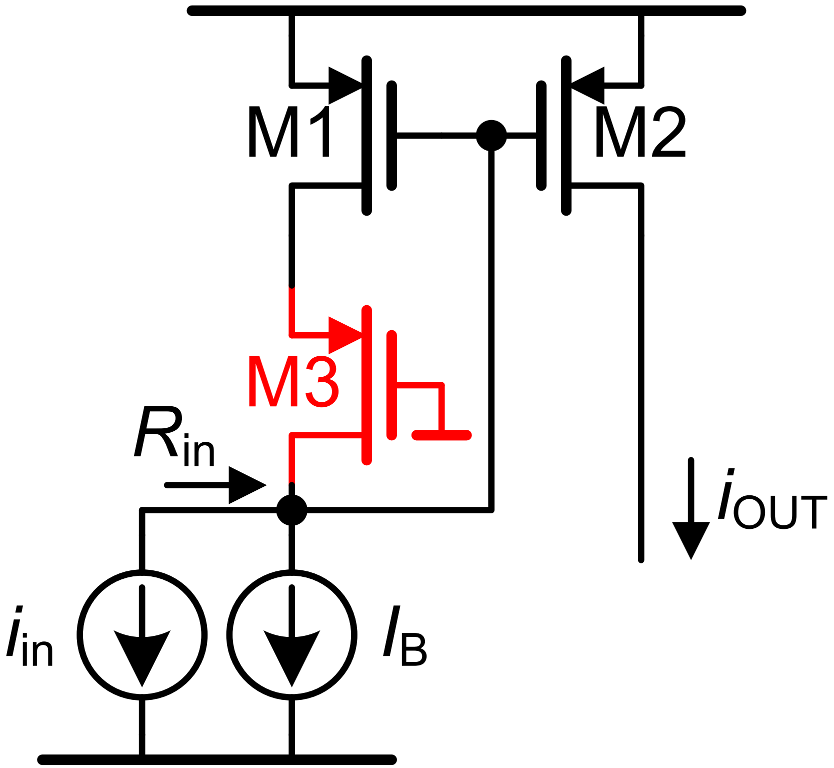
$$R_{out} \to x\frac{1}{\beta_3}$$

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

*GBW*相同！

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

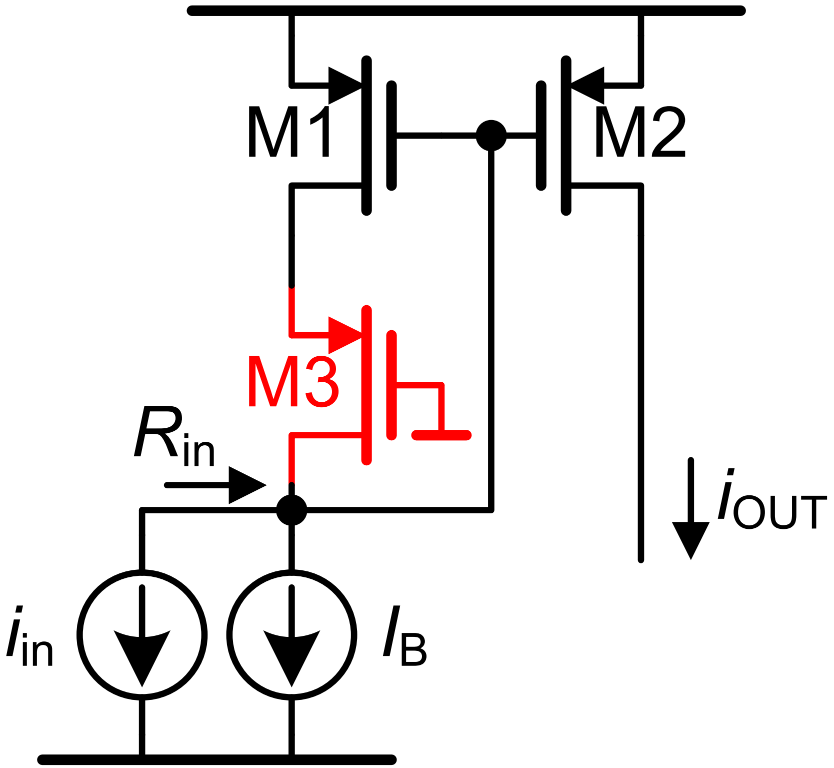
电流差分放大器



相同！ **M3**未影响其他参数。

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

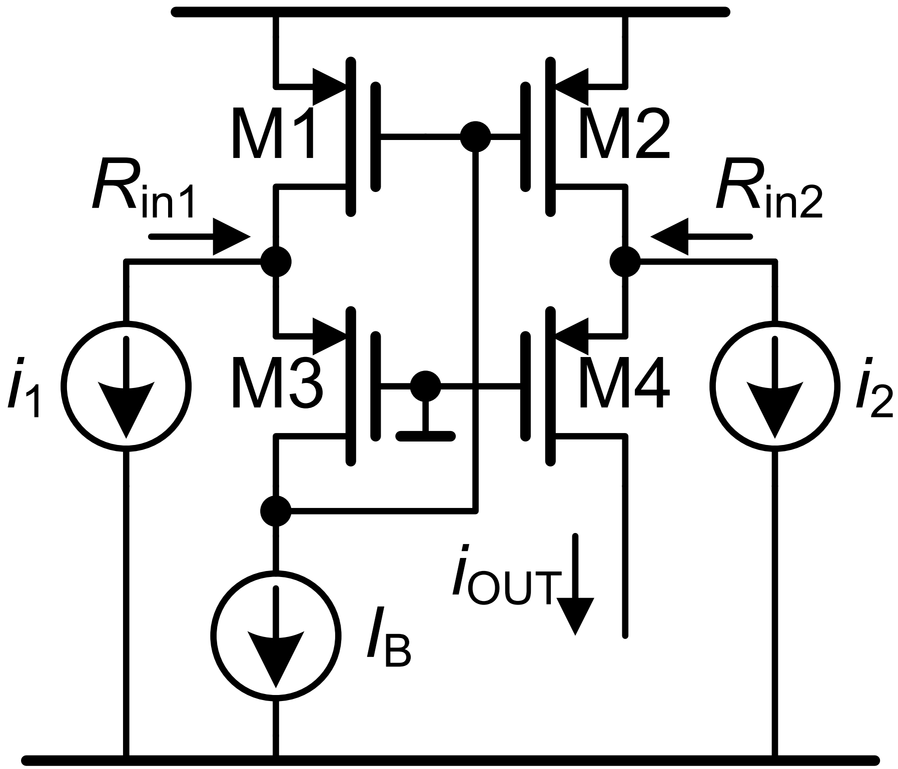
电流差分放大器



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

$$R_{in} = \frac{1}{g_{m1}} \frac{1}{g_{m3} r_{DS3}}$$

电流差分放大器



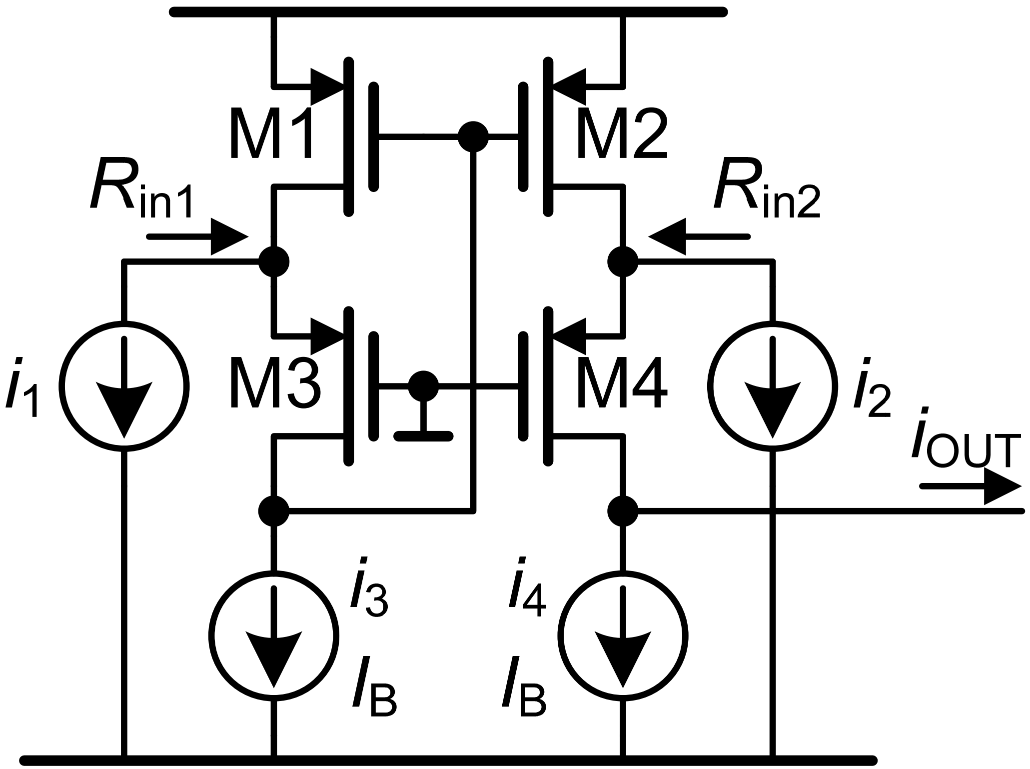
$$i_{OUT} = I_B + i_1 - i_2$$

$$R_{in1} = \frac{1}{g_{m1}} \frac{1}{g_{m3} r_{DS3}}$$

$$R_{in2} = \frac{1}{g_{m4}}$$

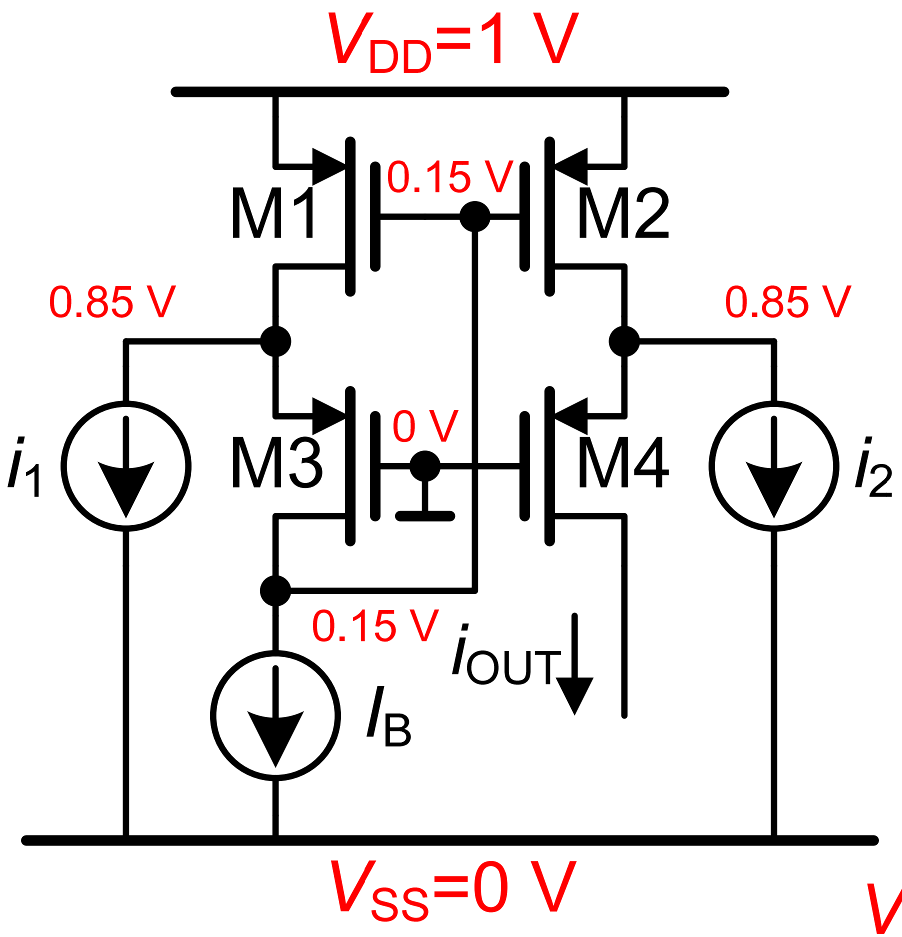
Ref.:Ref. Fischer, JSSC June 87, 330-340

4输入电流放大器



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

低电压放大器



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

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

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

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

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

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

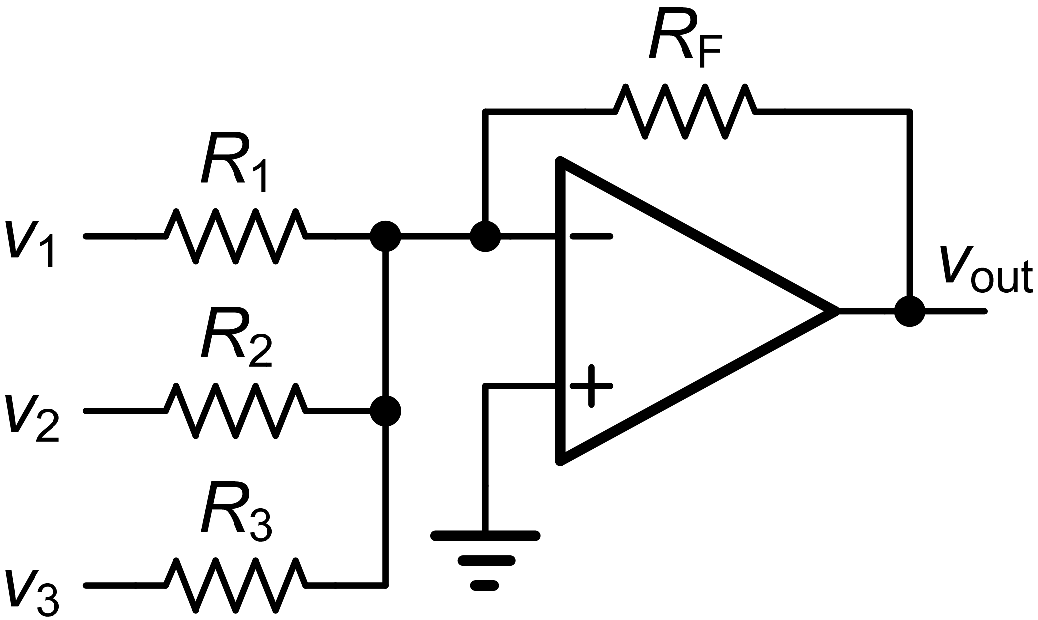
运算放大器的稳定性

目录

- 运算放大器的使用
- 两级运放的稳定性
- 极点分离
- 正零点的补偿
- 三级运放的稳定性

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

运算放大器的运算功能

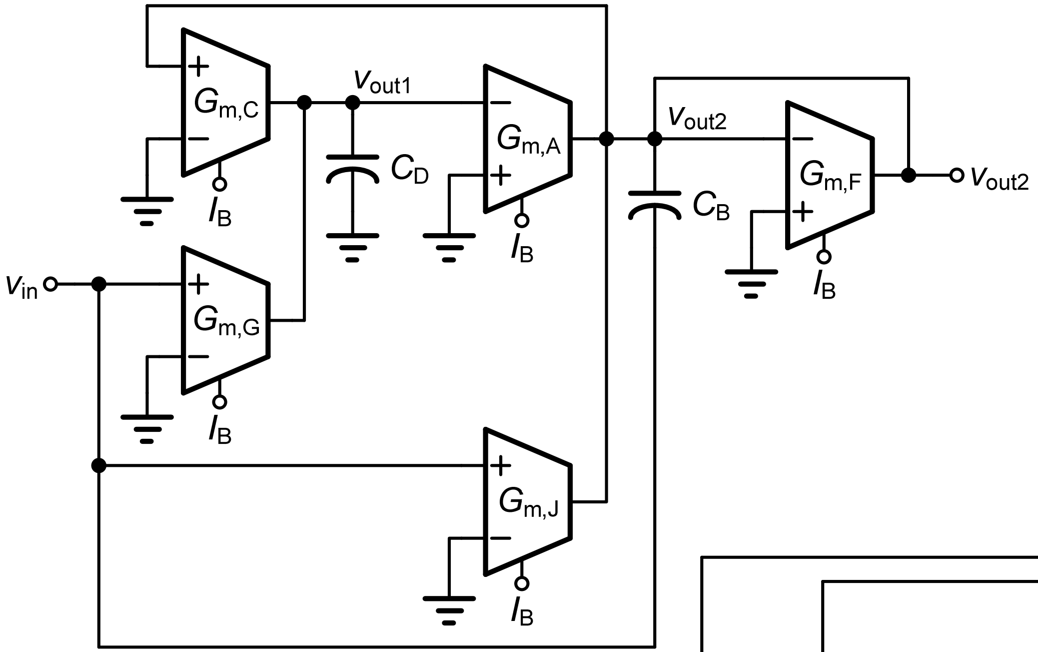


$$-\frac{v_{out}}{R_F}=\frac{v_1}{R_1}+\frac{v_2}{R_2}+\frac{v_3}{R_3}$$

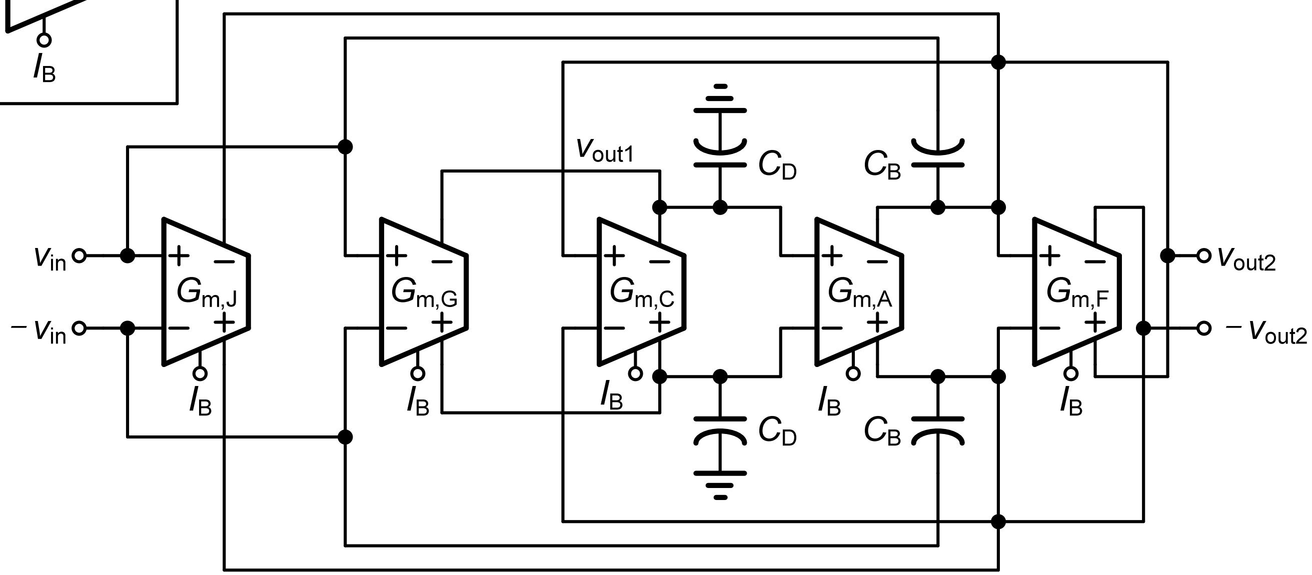
要求： 高增益
高速
低噪声
低功耗

运放性能指标： 高电压增益
差分输入电压≈0
输入电流 =0
高带宽
增益带宽乘积GBW非常，非常高！

单端？全差分？

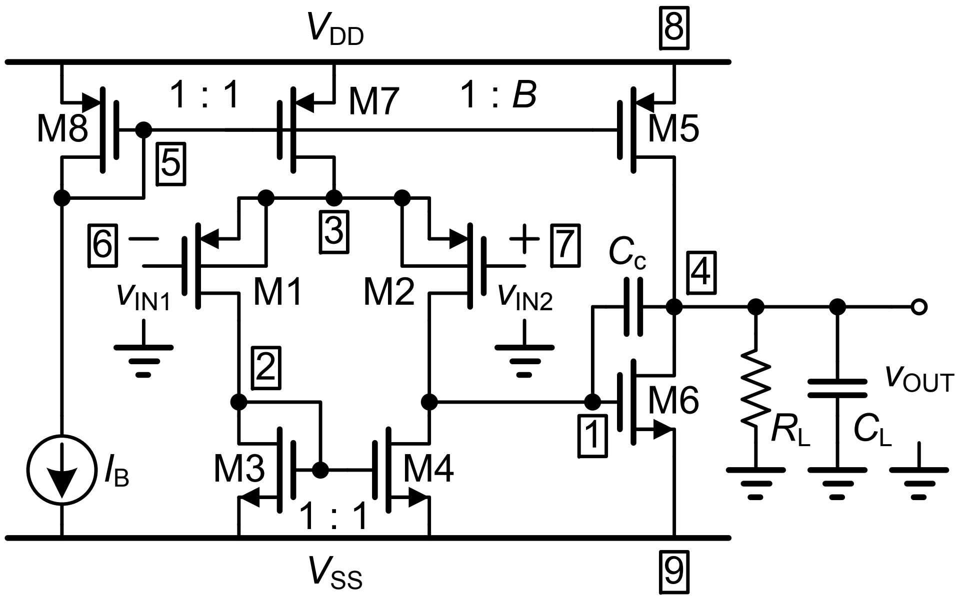


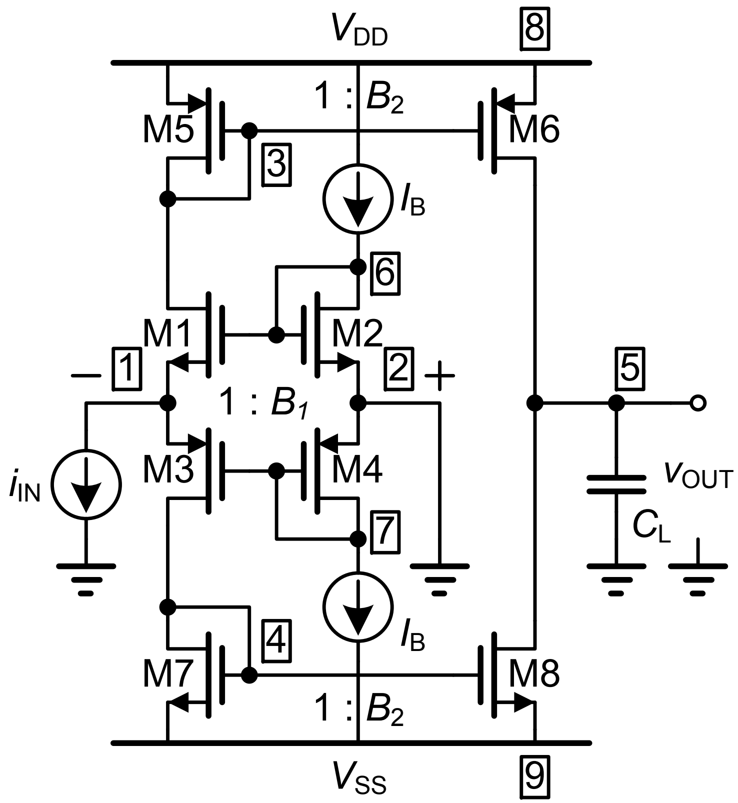
$G_{m,C}$
$G_{m,G}$
$G_{m,A}$
$G_{m,J}$
$G_{m,F}$
v_{out1}
v_{out2}
v_{in}
C_D
C_B
I_B



$G_{m,J}$
$G_{m,G}$
$G_{m,C}$
$G_{m,A}$
$G_{m,F}$
v_{in}
$-v_{in}$
v_{out1}
v_{out2}
$-v_{out2}$
C_D
C_B
I_B

电压输入？电流输入？





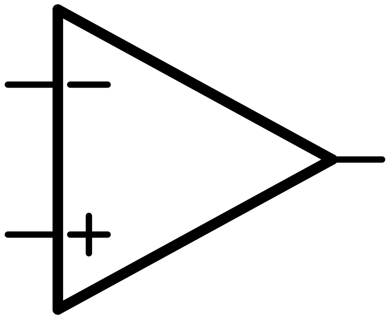
电压输入
电流输出

电流输入
电流输出

分类

Opamp

电压
放大器



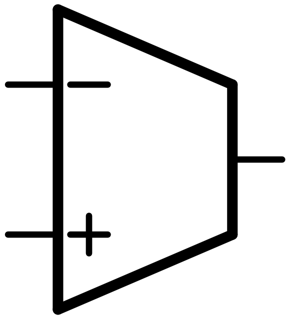
$$A_V = \frac{v_{out}}{v_{in}}$$

$A_V =$

GBW

OTA

跨导
放大器

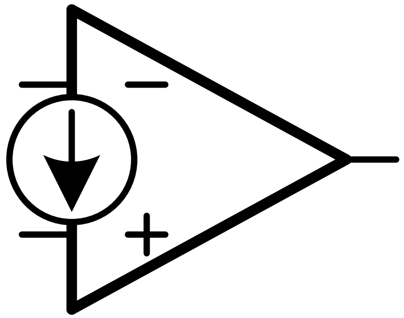


$$A_G = \frac{i_{out}}{v_{in}}$$

$$A_V = A_G R_L$$

OCA

电流
放大器

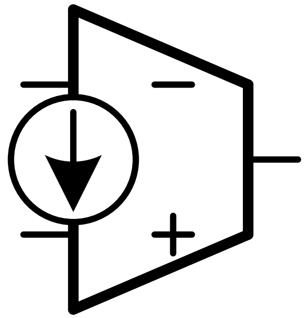


$$A_I = \frac{i_{out}}{i_{in}}$$

$$A_V = A_I \frac{R_L}{R_S}$$

CM amp

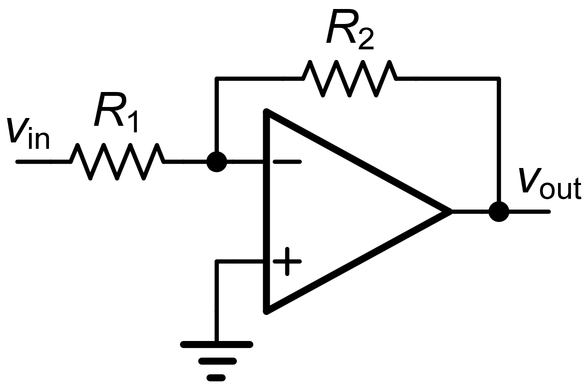
跨阻
放大器

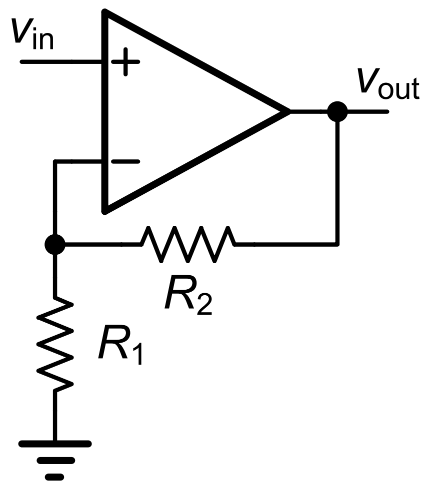


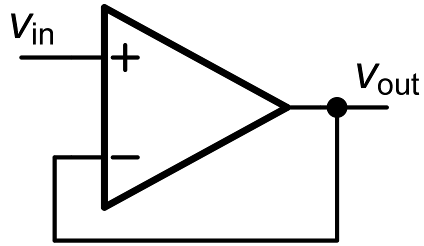
$$A_R = \frac{v_{out}}{i_{in}}$$

$$A_V = A_R \frac{1}{R_S}$$

反馈结构







$$A_V = -\frac{R_2}{R_1}$$

$$R_{IN} = R_1$$

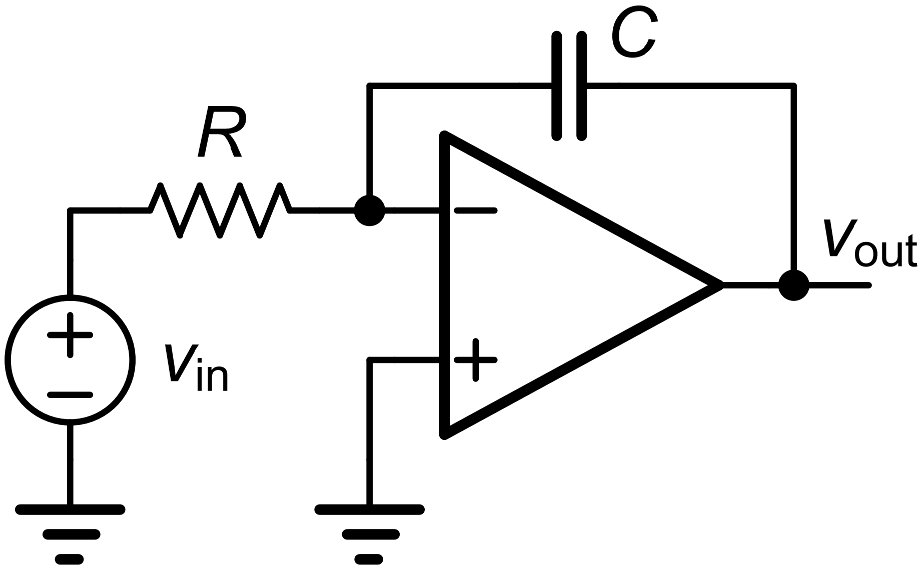
$$A_V = 1 + \frac{R_2}{R_1}$$

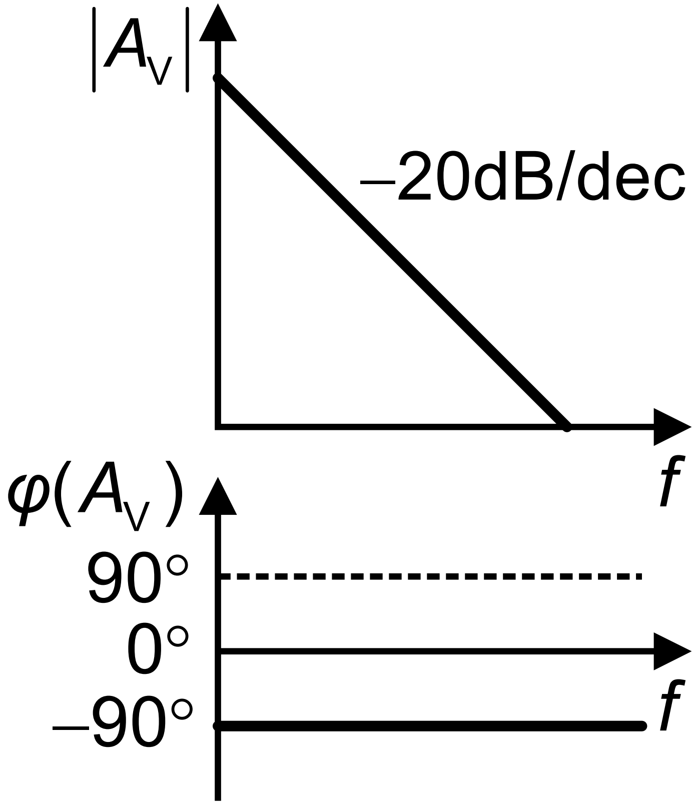
$$R_{IN} = \infty$$

$$A_V = 1$$

$$R_{IN} = \infty$$

积分器

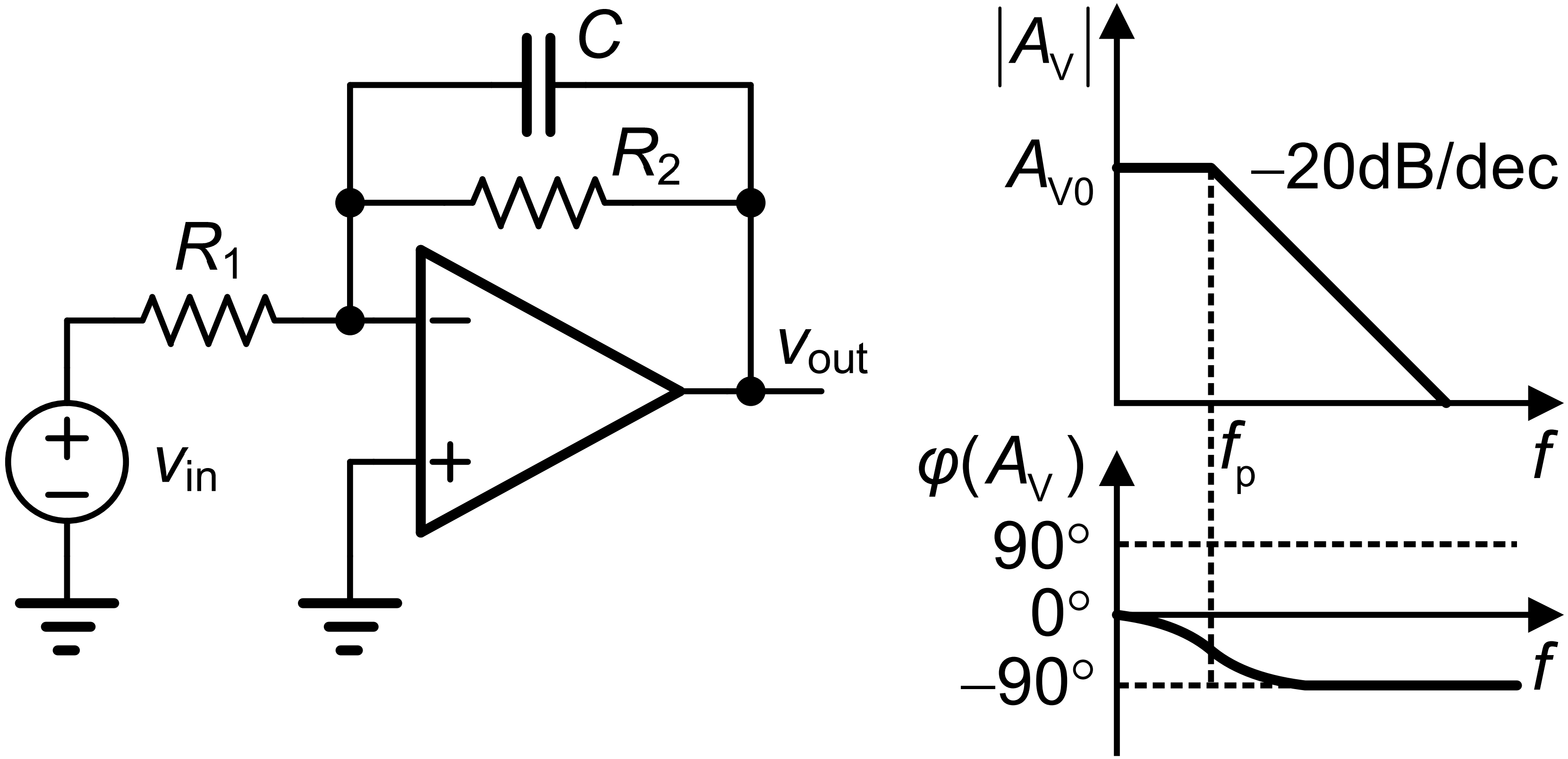




$$A_V = -\frac{1}{j\frac{f}{f_p}}$$

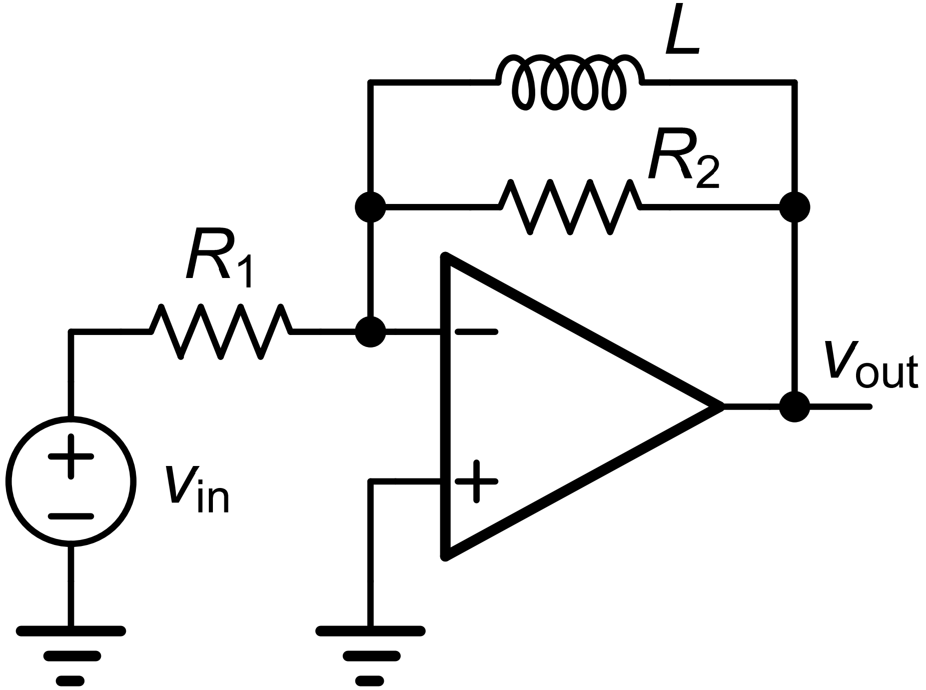
$$f_p = \frac{1}{2\pi RC}$$

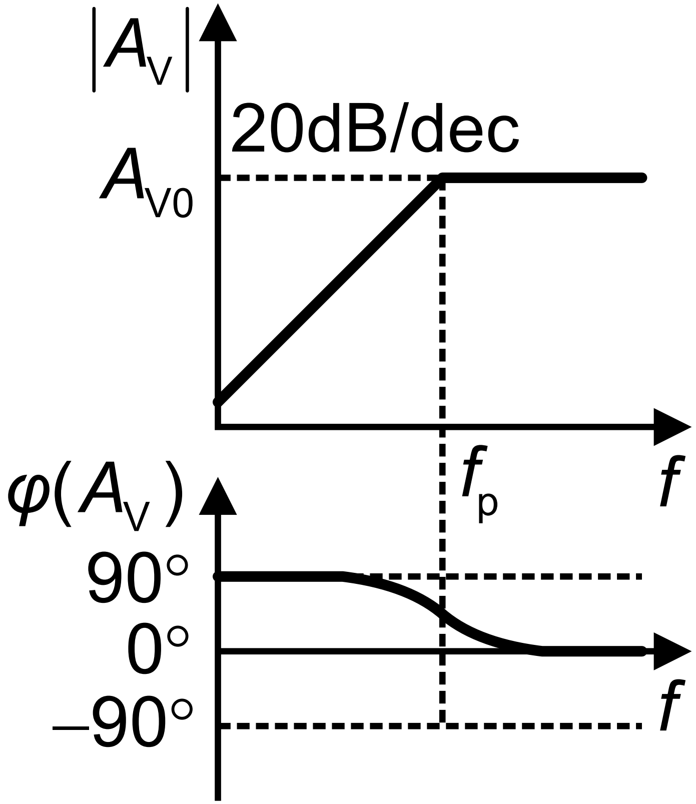
有损积分器：低通滤波器



$$A_{V0} = -\frac{R_2}{R_1} \qquad A_V = A_{V0}\frac{1}{1+\mathrm{j}\frac{f}{f_p}} \qquad f_p = \frac{1}{2\pi R_2 C}$$

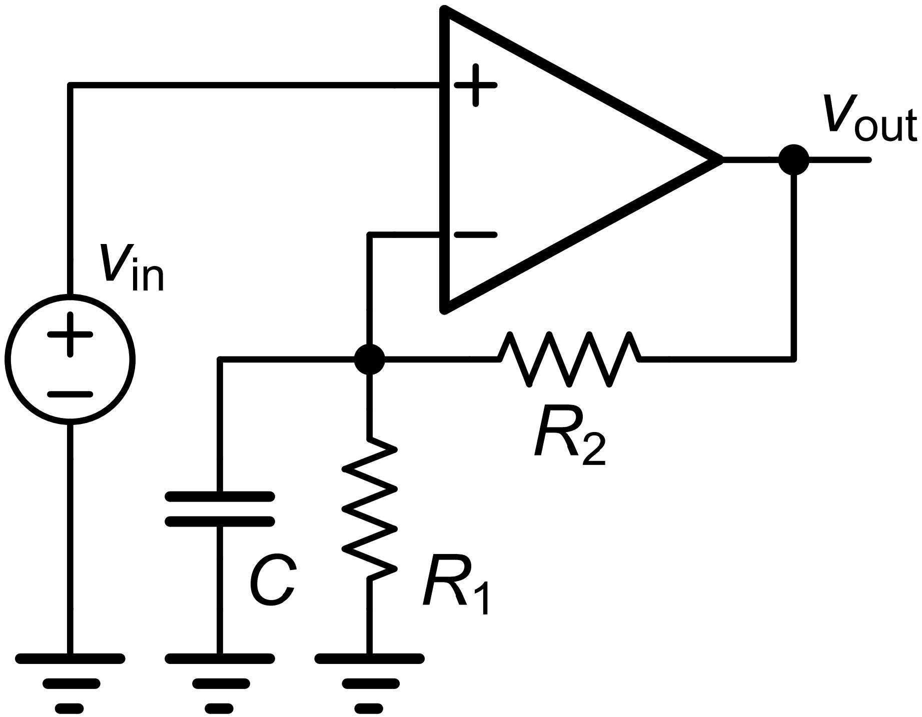
高通滤波器 1

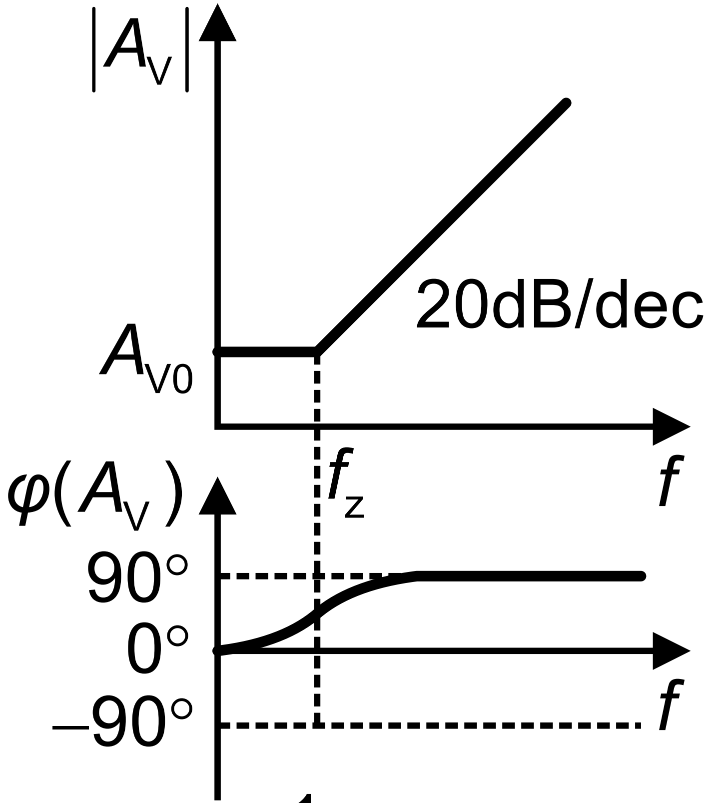




$$A_{V0} = -\frac{R_2}{R_1} \qquad A_V = A_{V0}\frac{\mathrm{j}\dfrac{f}{f_p}}{1+\mathrm{j}\dfrac{f}{f_p}} \qquad f_p = \frac{R_2}{2\pi L}$$

高通滤波器 2

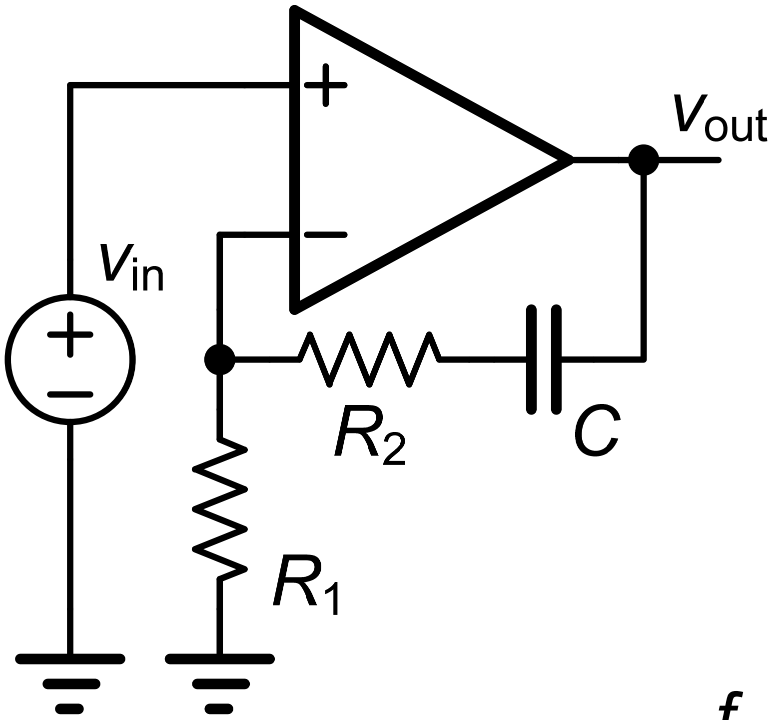


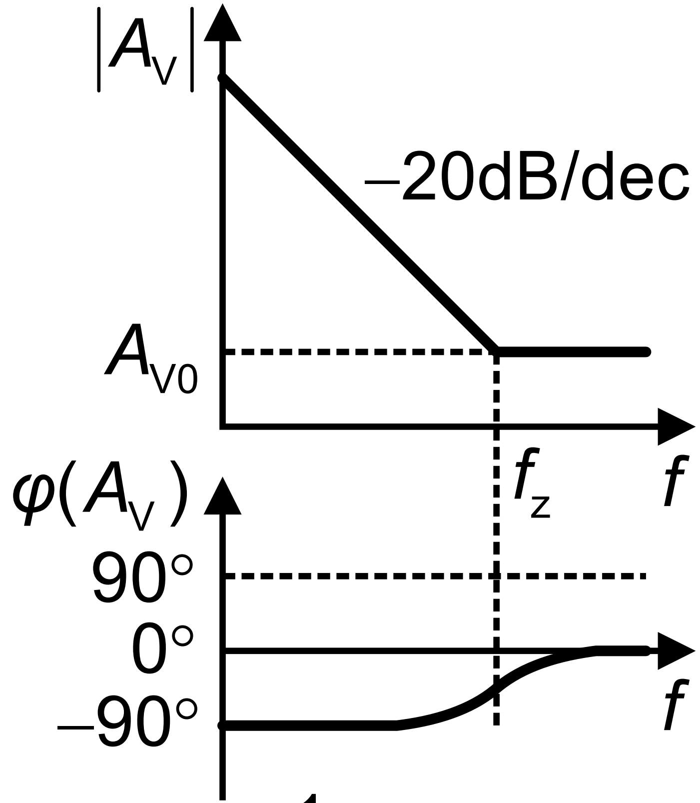


$$A_{V0} = 1 + \frac{R_2}{R_1} \qquad A_V = A_{V0}(1 + j\frac{f}{f_z}) \qquad f_z = \frac{1}{2\pi RC}$$

$$R = R_1 // R_2 = \frac{R_1 R_2}{R_1 + R_2}$$

有限衰减的低通滤波器

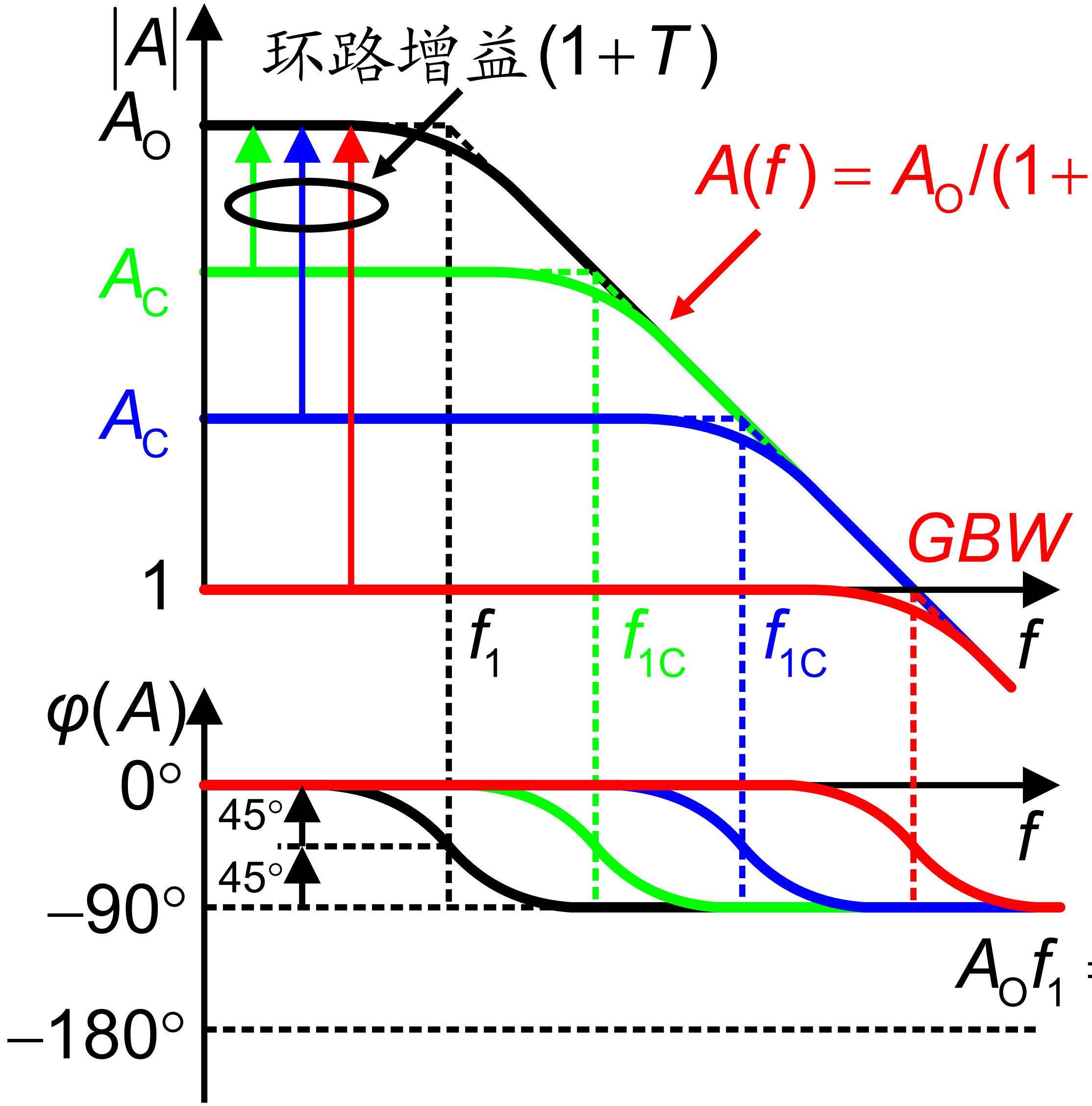




$$A_{\text{V0}} = 1 + \frac{R_2}{R_1} \qquad A_{\text{V}} = A_{\text{V0}} \frac{1 + \mathrm{j}\dfrac{f}{f_z}}{\mathrm{j}\dfrac{f}{f_z}} \qquad f_z = \frac{1}{2\pi RC}$$

$$R = R_1 + R_2$$

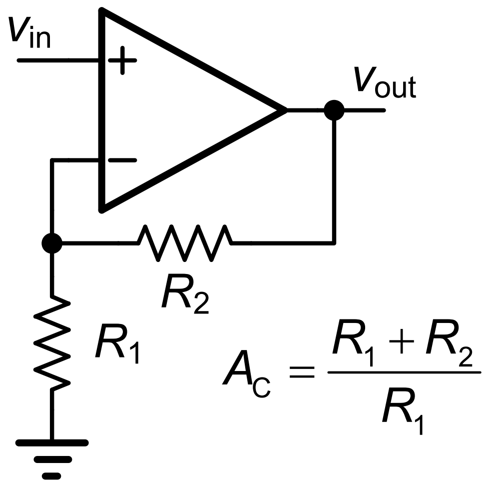
增益和带宽之间的交换



$A(f) = A_O/(1 + jf/f_1)$

A_O 开环增益

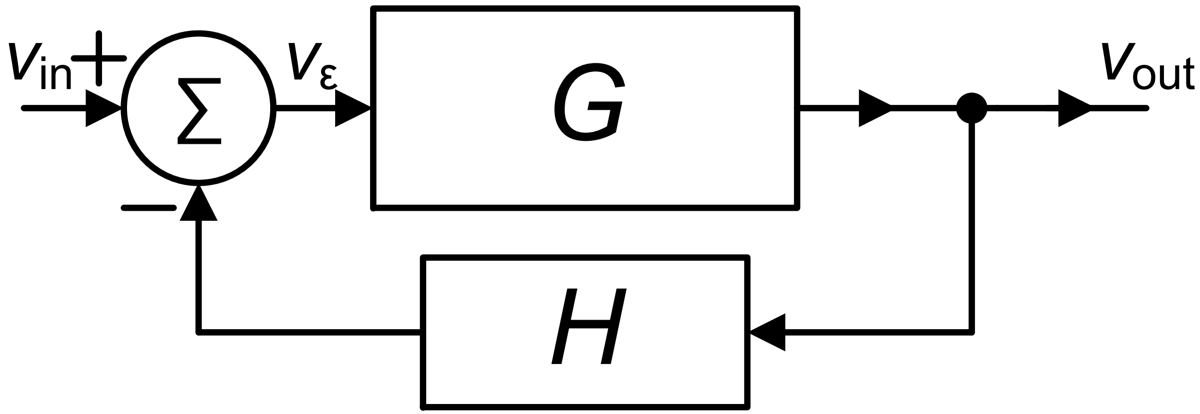
A_C 闭环增益



$$A_C = \frac{R_1 + R_2}{R_1}$$

$$A_O f_1 = A_C f_{1C} = A_C f_{1C} = GBW$$

开环增益和闭环增益

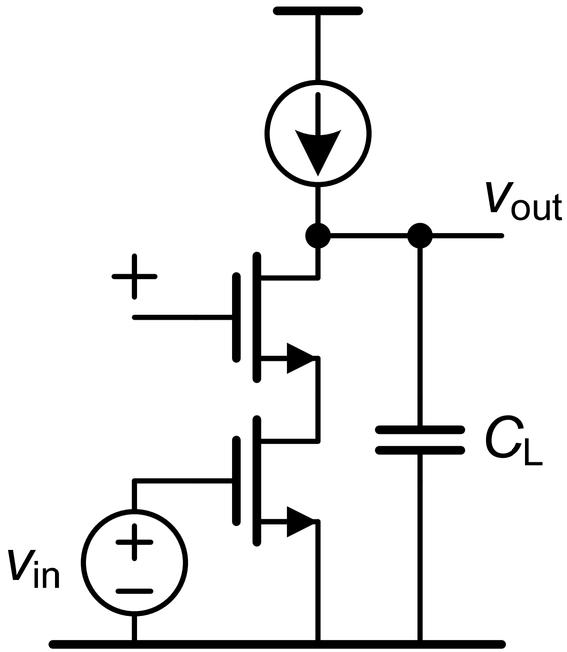


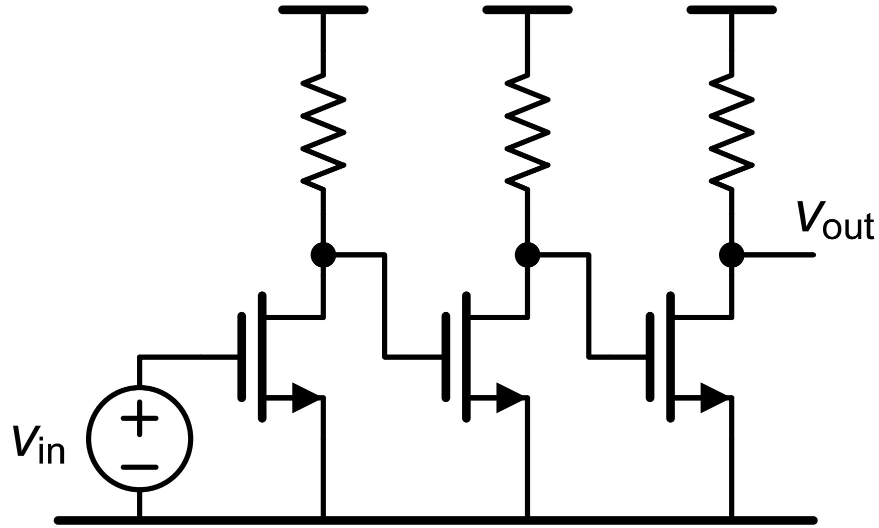
$$\left.\begin{aligned} v_\varepsilon &= v_{in} - Hv_{out} \\ v_{out} &= Gv_\varepsilon \end{aligned}\right\} \Rightarrow A_C = \frac{v_{out}}{v_{in}} = \frac{G}{1+GH} \approx \frac{1}{H}$$

如果环路增益 $GH = T \gg 1$

Ref.: P. Gray, P.Hurst, S.Lewis, R. Meyer: Design of analog integrated circuits, 4th ed., Wiley 2001

运放成为运放的原因？





运算放大器

单级点放大器

高阻抗=高增益

增益与带宽交换

任何增益下都稳定

宽带放大器

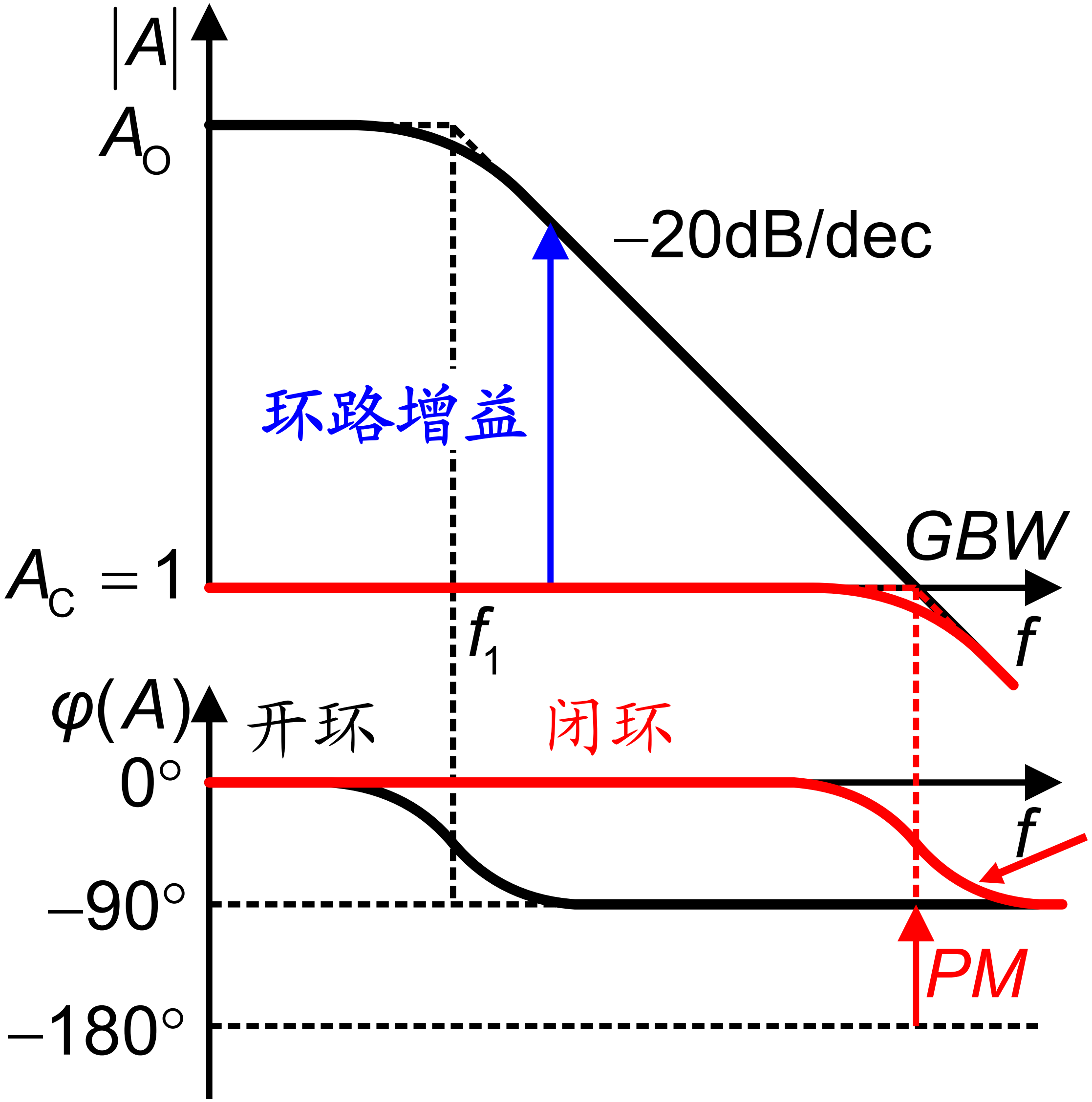
多级点放大器

低阻抗节点

高带宽

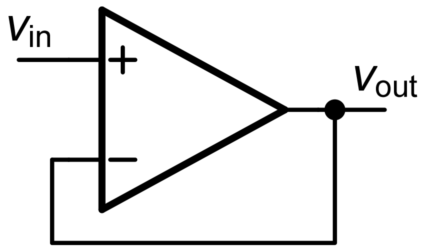
只在某些增益下稳定

单极点系统



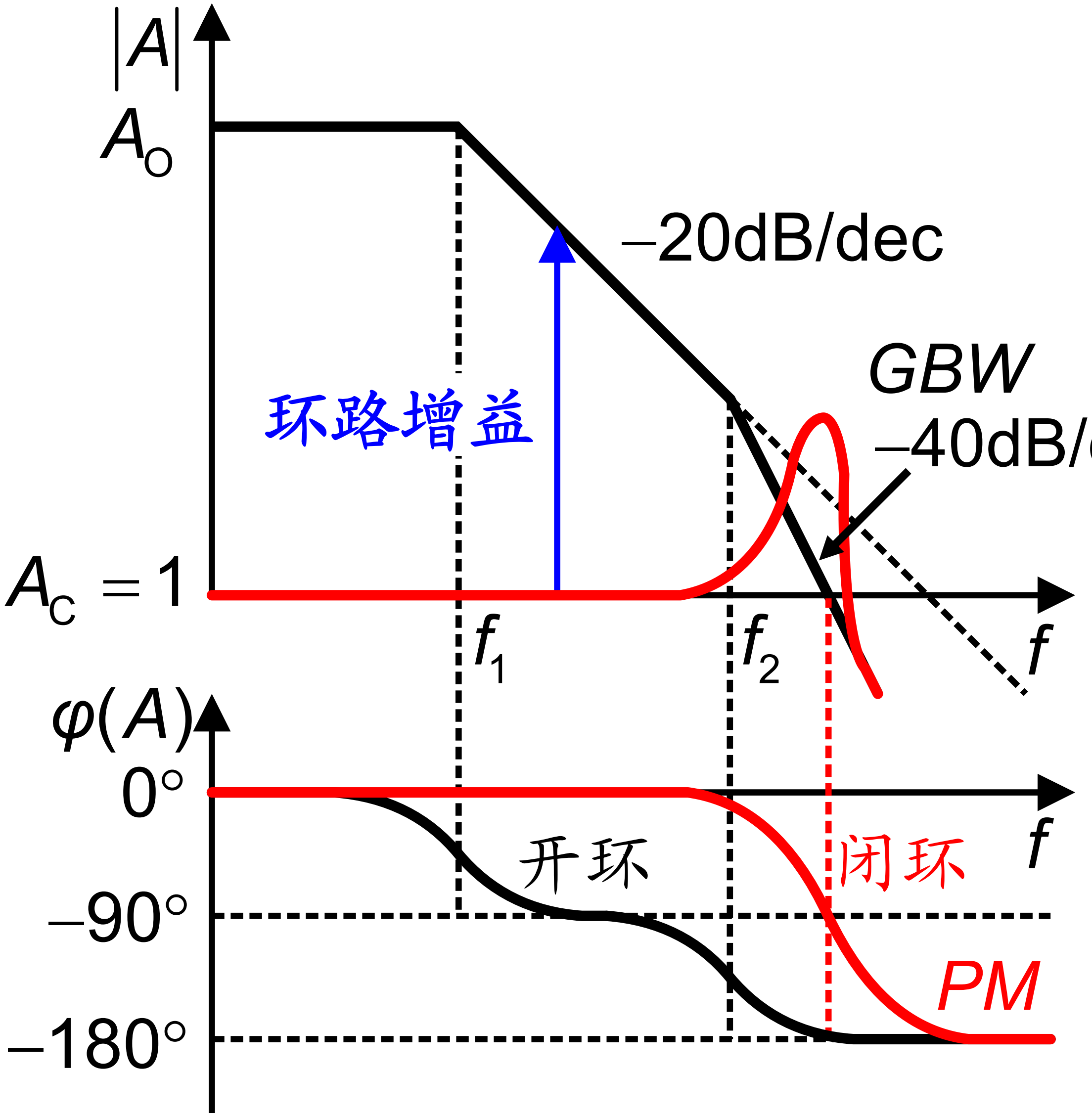
A_O 开环增益

闭环增益 $A_C = 1$



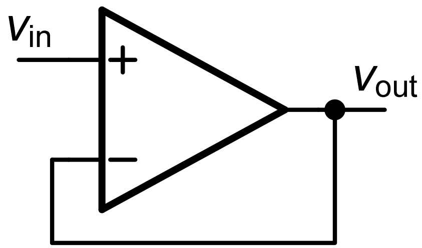
PM相位裕度

双极点系统



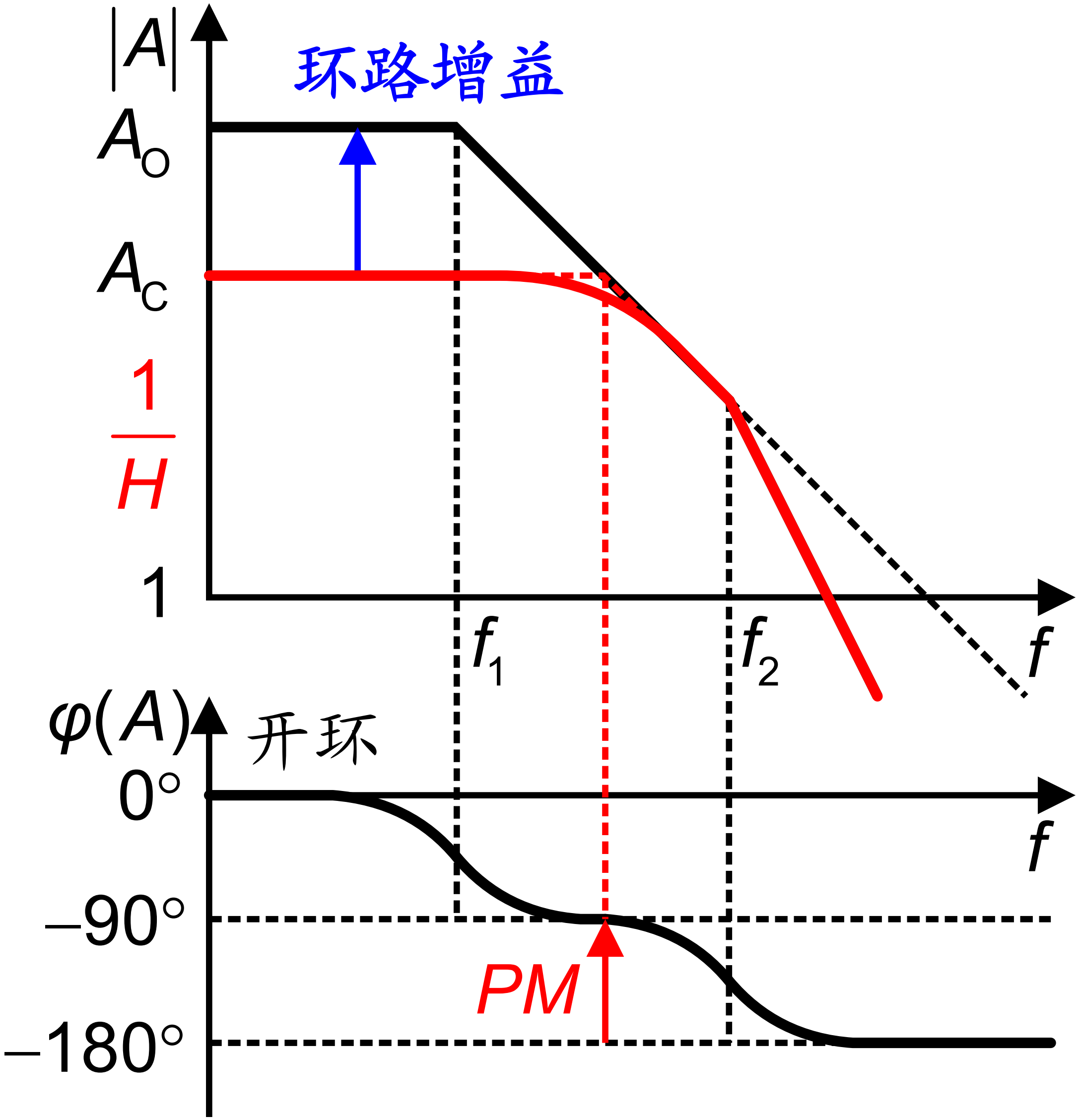
A_O 开环增益

闭环增益 $A_C = 1$



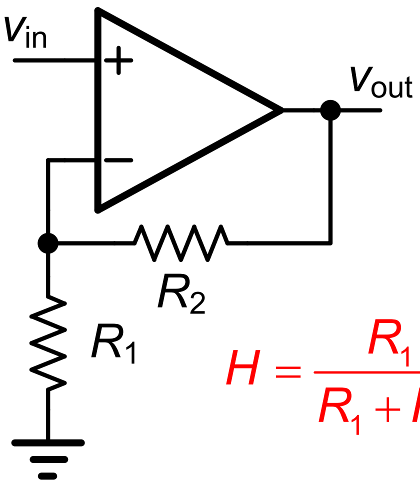
PM相位裕度

环路增益与相位裕度的关系 1



A_O 开环增益

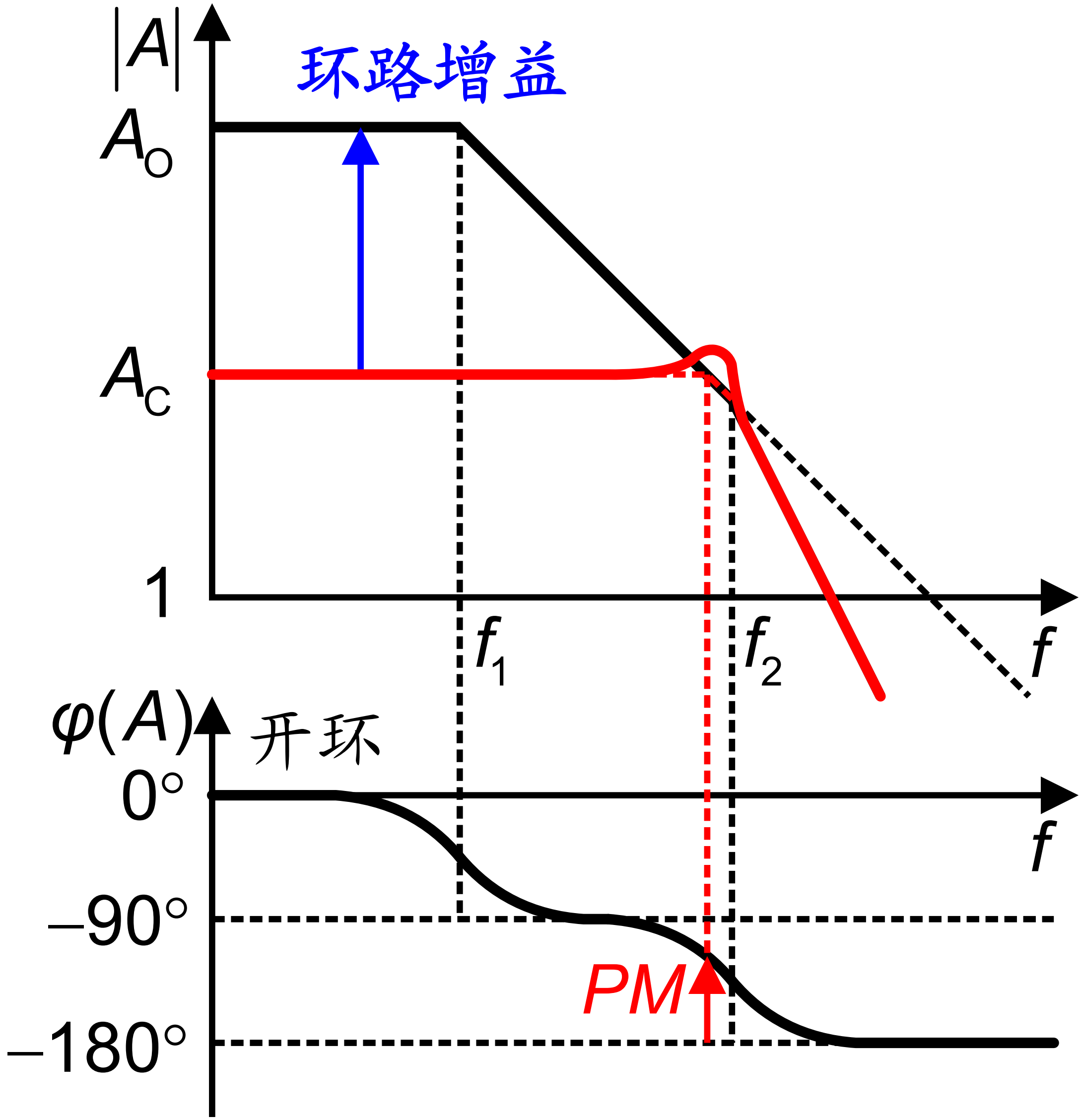
A_C 闭环增益



$$H = \frac{R_1}{R_1 + R_2}$$

PM相位裕度

环路增益与相位裕度的关系 2

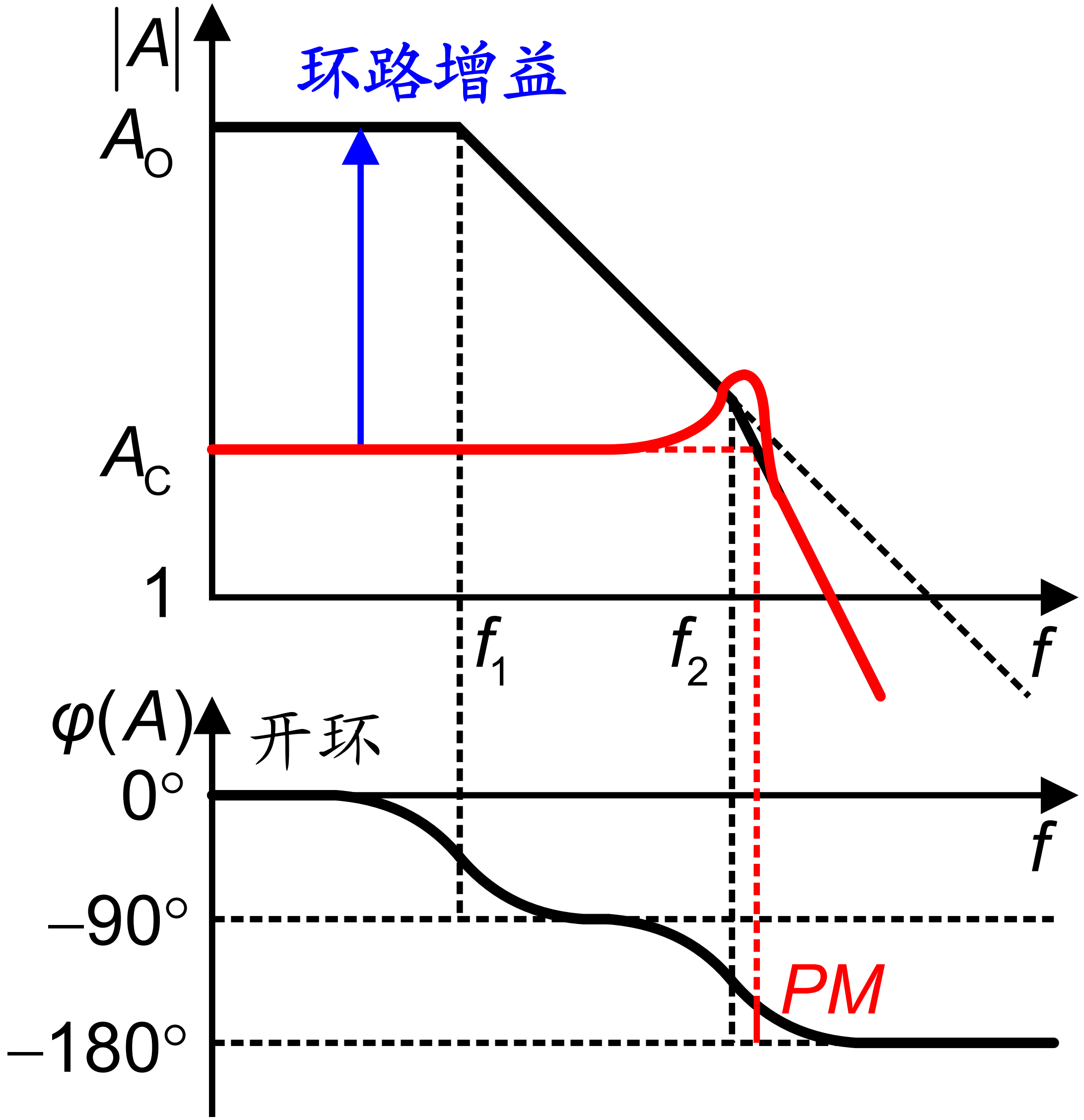


A_O 开环增益

A_C 闭环增益

*PM*相位裕度

环路增益与相位裕度的关系 3

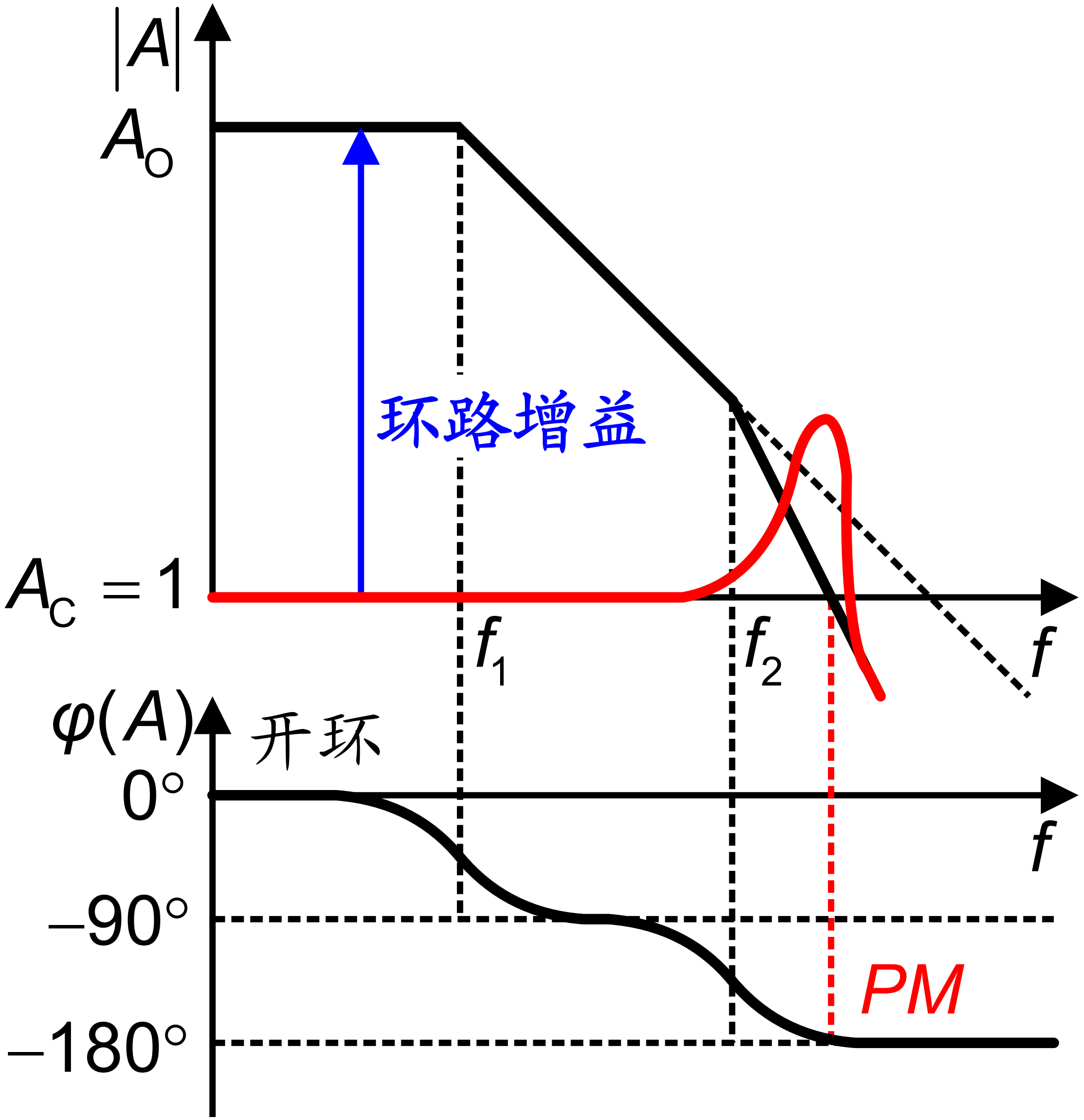


A_O 开环增益

A_C 闭环增益

PM相位裕度

环路增益与相位裕度的关系 4



A_O 开环增益

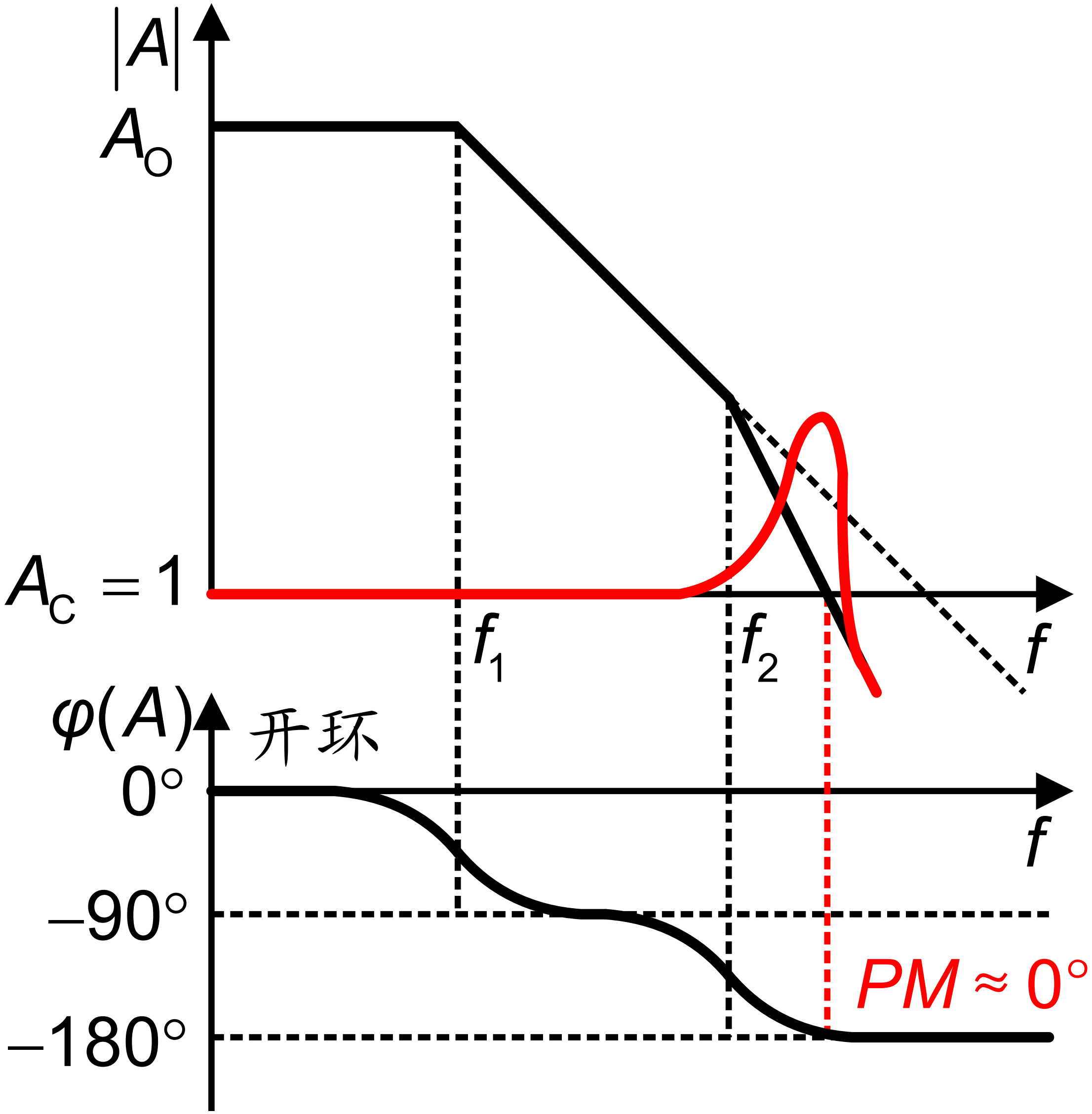
A_C 闭环增益

最坏情况

$A_C = 1$

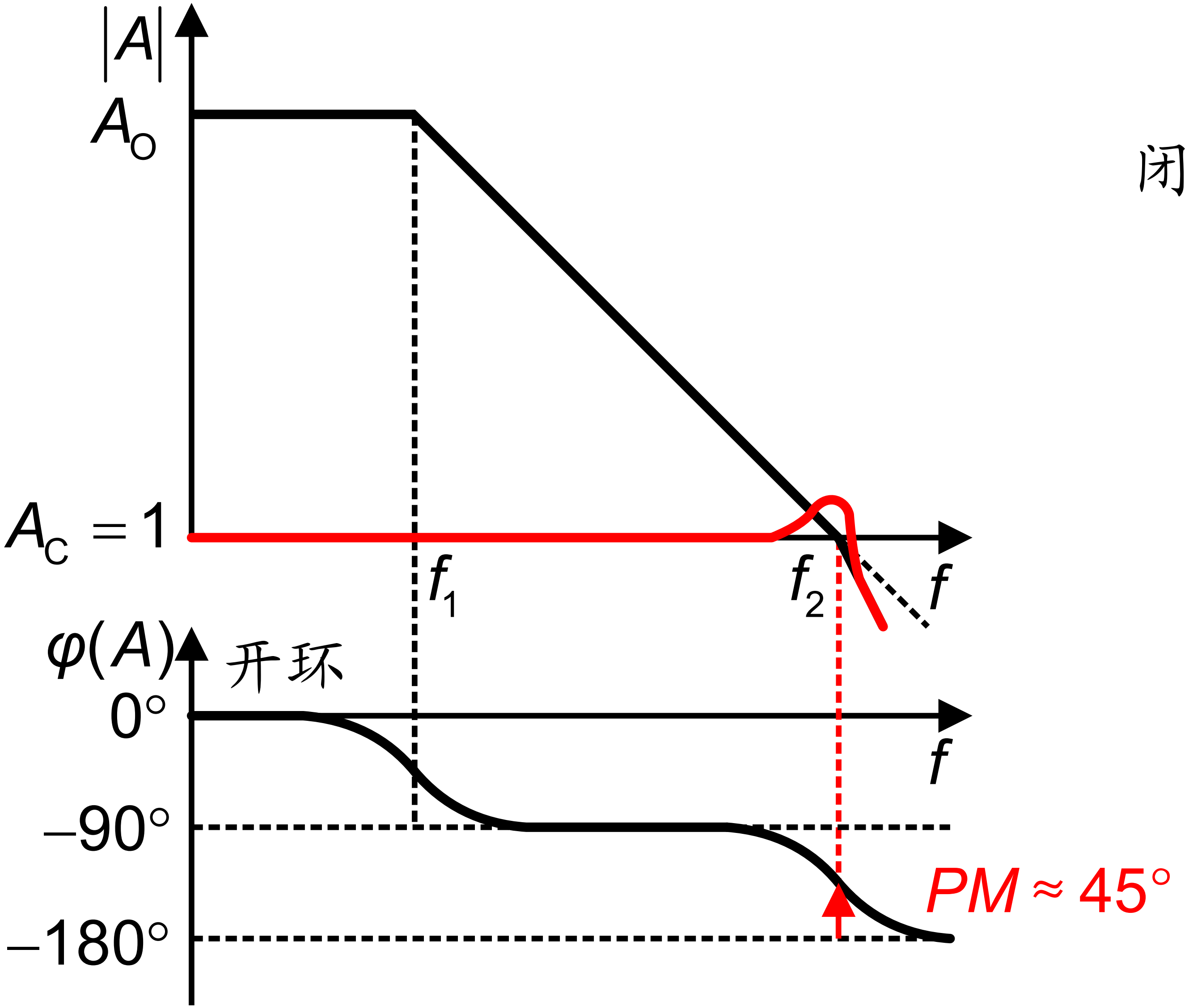
*PM*相位裕度

当f_2频率较低时



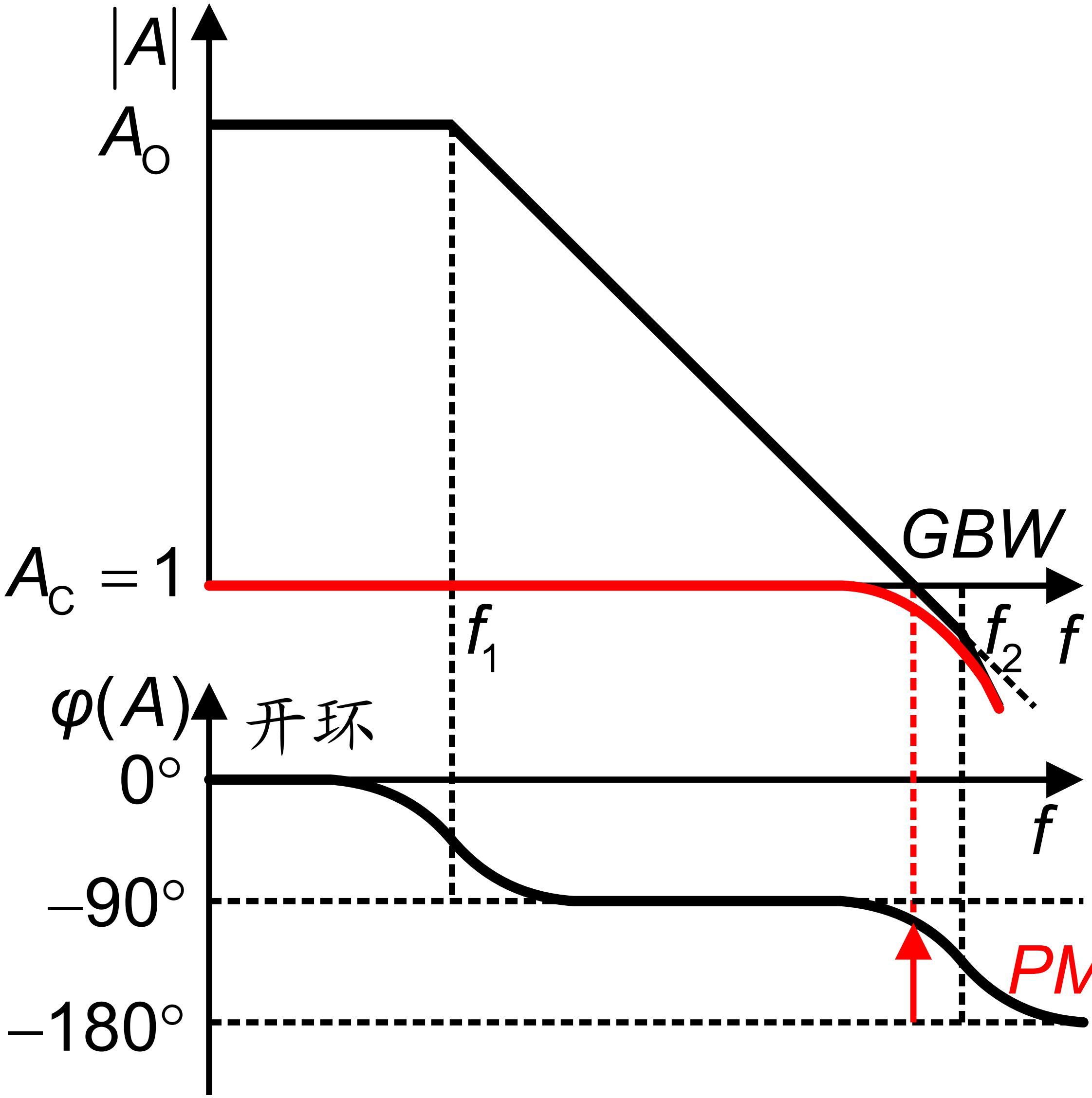
闭环增益 $A_C = 1$

通过增加f_2，提高PM。(f_2=GBW)



闭环增益 $A_C = 1$

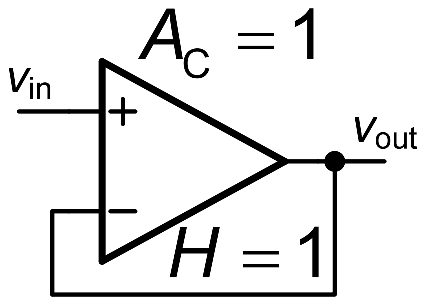
通过增加f_2，提高PM。(f_2=3GBW)



闭环增益 $A_C = 1$

$f_2 \approx 3GBW$

当$f_2 \approx 3GBW$时，计算PM



开环增益 $A = \dfrac{A_O}{(1+j\dfrac{f}{f_1})(1+j\dfrac{f}{f_2})}$

闭环增益 $A_C = \dfrac{A}{1+A} \approx \dfrac{1}{1+j\dfrac{f}{GBW}+j^2\dfrac{f^2}{GBWf_2}}$

$$\approx \frac{1}{1+j2\zeta\dfrac{f}{f_r}+j^2\dfrac{f^2}{f_r^2}}$$

$f_r = \sqrt{GBWf_2}$ 自激振荡频率

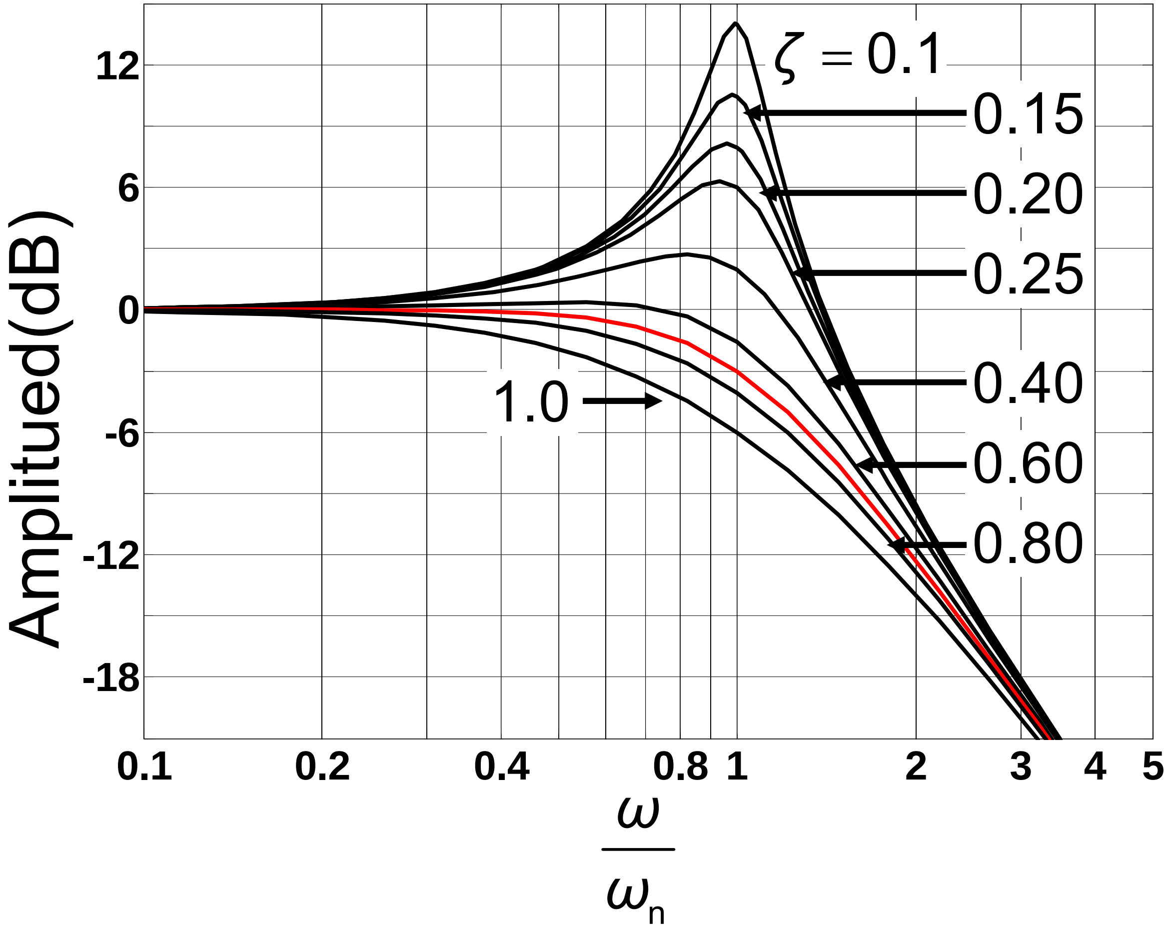
$\zeta = \dfrac{1}{2}\sqrt{\dfrac{f_2}{GBW}}$ 阻尼系数$(=1/2Q)$

PM, ζ, P_f和P_t

$$f_r = \sqrt{GBWf_2} \qquad PM(^\circ) = 90^\circ - \arctan\frac{GBW}{f_2} = \arctan\frac{f_2}{GBW}$$

$\frac{f_2}{GBW}$	$PM(^\circ)$	$\zeta = \frac{1}{2}\sqrt{\frac{f_2}{GBW}}$	$P_f(\mathrm{dB})$	$P_t(\mathrm{dB})$
0.5	27	0.35	3.6	2.3
1	45	0.5	1.25	1.3
1.5	56	0.61	0.28	0.73
2	63	$\sqrt{2}/2$	0	0.37
3	72	0.87	0	0.04
4	76	1		
5	79			

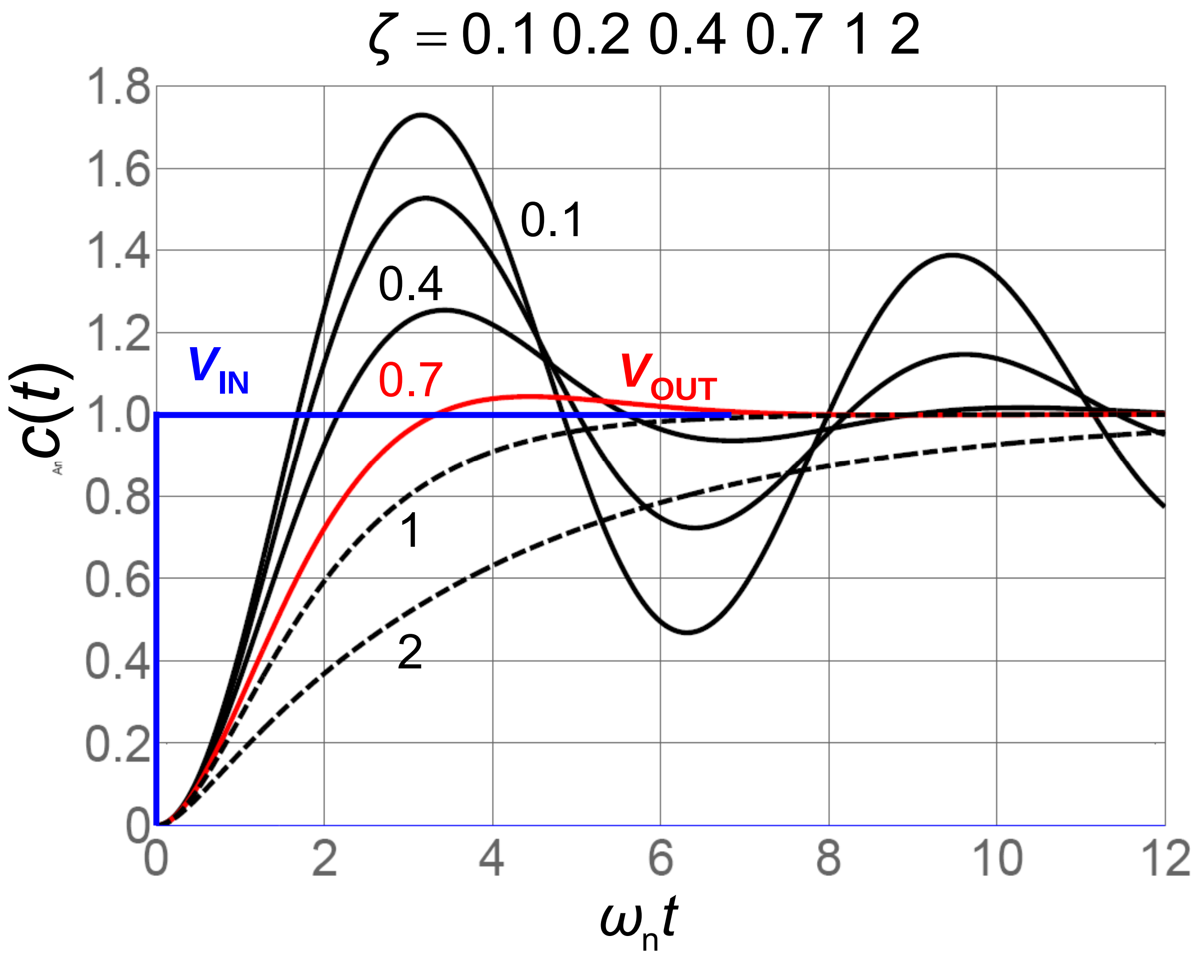
闭环幅度频率响应



$$\zeta = Q = \sqrt{2}/2$$

$$P_f = \frac{1}{2\zeta\sqrt{1-\zeta^2}}$$

闭环阶跃冲击响应



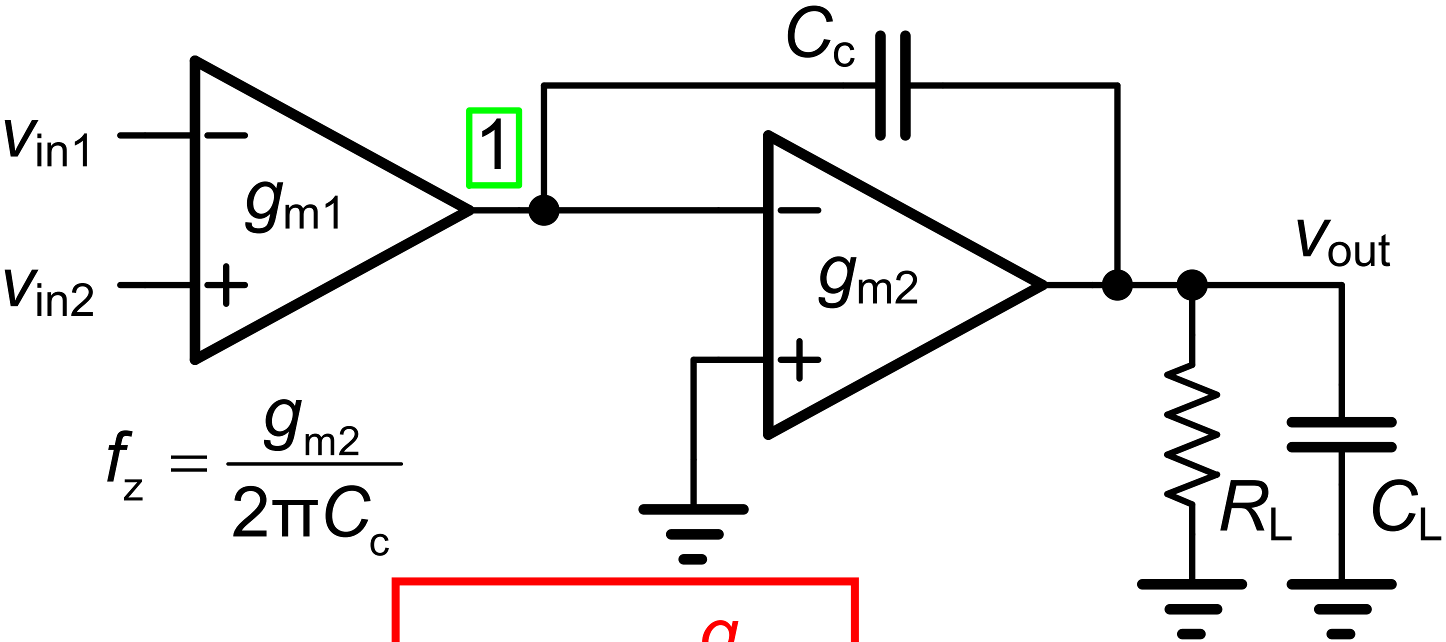
$$\zeta = Q = \sqrt{2}/2$$

$$P_t = 1 + e^{\frac{-\pi\zeta}{\sqrt{1-\zeta^2}}}$$

目录

- 运算放大器的使用
- 两级运放的稳定性
- 极点分离
- 正零点的补偿
- 三级运放的稳定性

通用两级放大器 1

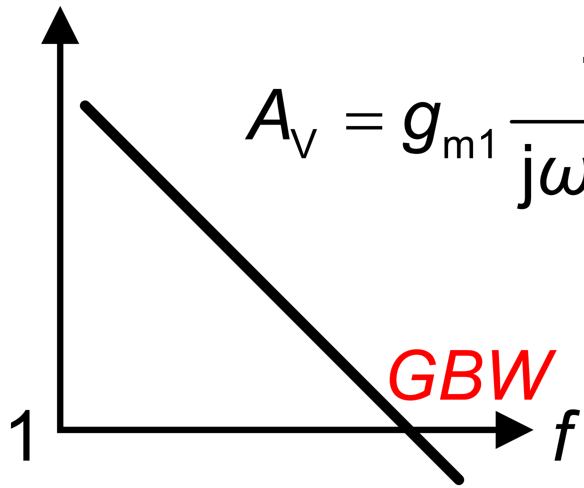


$$f_z = \frac{g_{m2}}{2\pi C_c}$$

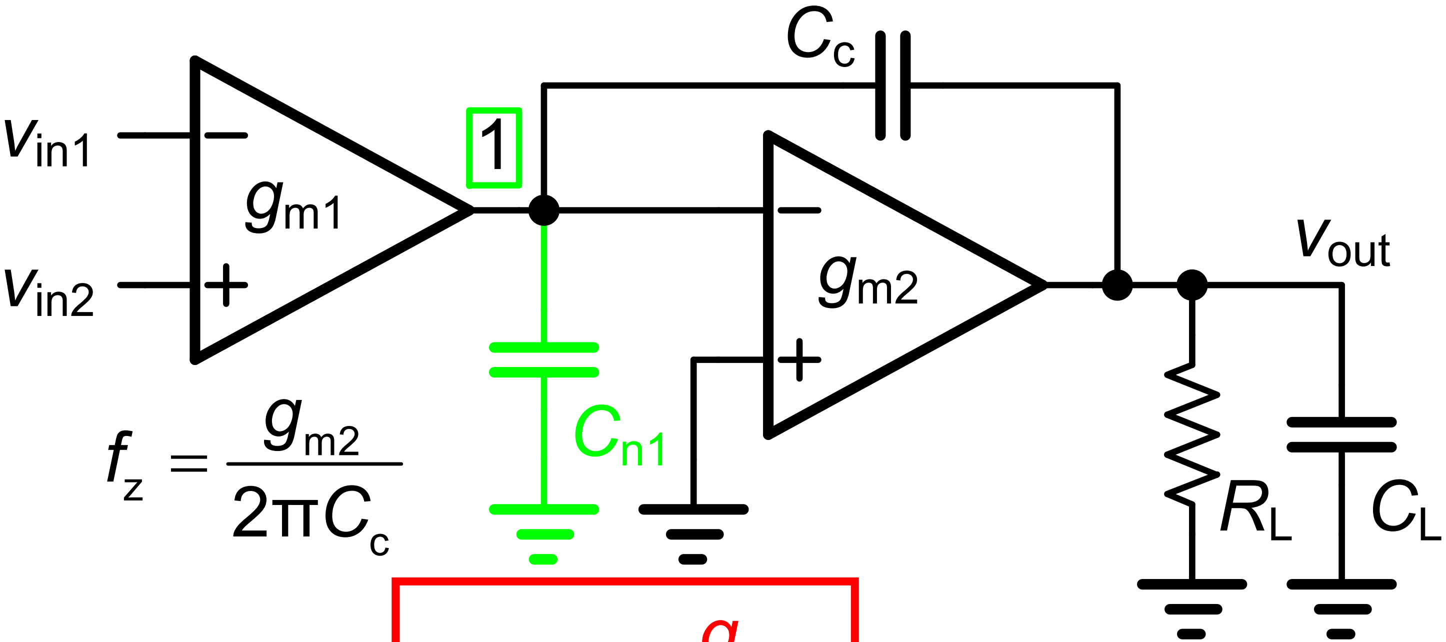
$$|A_V| = 1 \Rightarrow \boxed{GBW = \frac{g_{m1}}{2\pi C_c}}$$

$$\boxed{f_{nd} = \frac{g_{m2}}{2\pi C_L}}$$

$$A_V = g_{m1}\frac{1}{j\omega C_c}$$



通用两级放大器 2

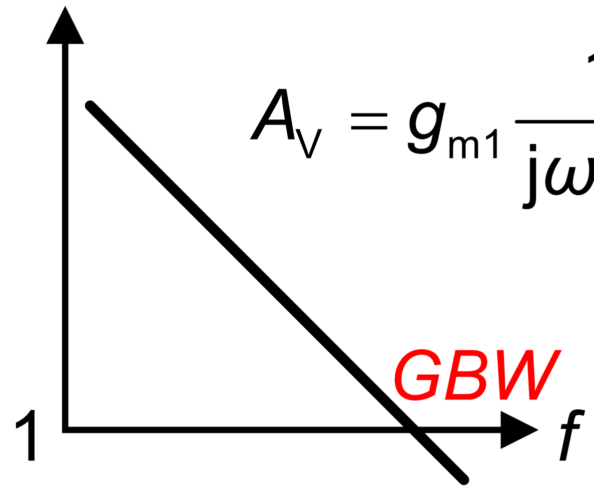


$$f_z = \frac{g_{m2}}{2\pi C_c}$$

$$\left|A_V\right| = 1 \quad \Rightarrow \quad \boxed{GBW = \frac{g_{m1}}{2\pi C_c}}$$

$$\boxed{f_{nd} = \frac{g_{m2}}{2\pi C_L}\frac{1}{1+\frac{C_{n1}}{C_c}}}$$

$$A_V = g_{m1}\frac{1}{j\omega C_c}$$



初步设计两级运放

$$GBW = \frac{g_{m1}}{2\pi C_c} \qquad f_{nd} = \frac{g_{m2}}{2\pi C_L} \frac{1}{1+\underbrace{\frac{C_{n1}}{C_c}}_{\approx 0.3}}$$

$$\left.\begin{aligned} f_{nd} &= 3GBW \\ \frac{C_{n1}}{C_c} &\approx 0.3 \end{aligned}\right\} \Rightarrow \boxed{\frac{g_{m2}}{g_{m1}} \approx 4\frac{C_L}{C_c}}$$

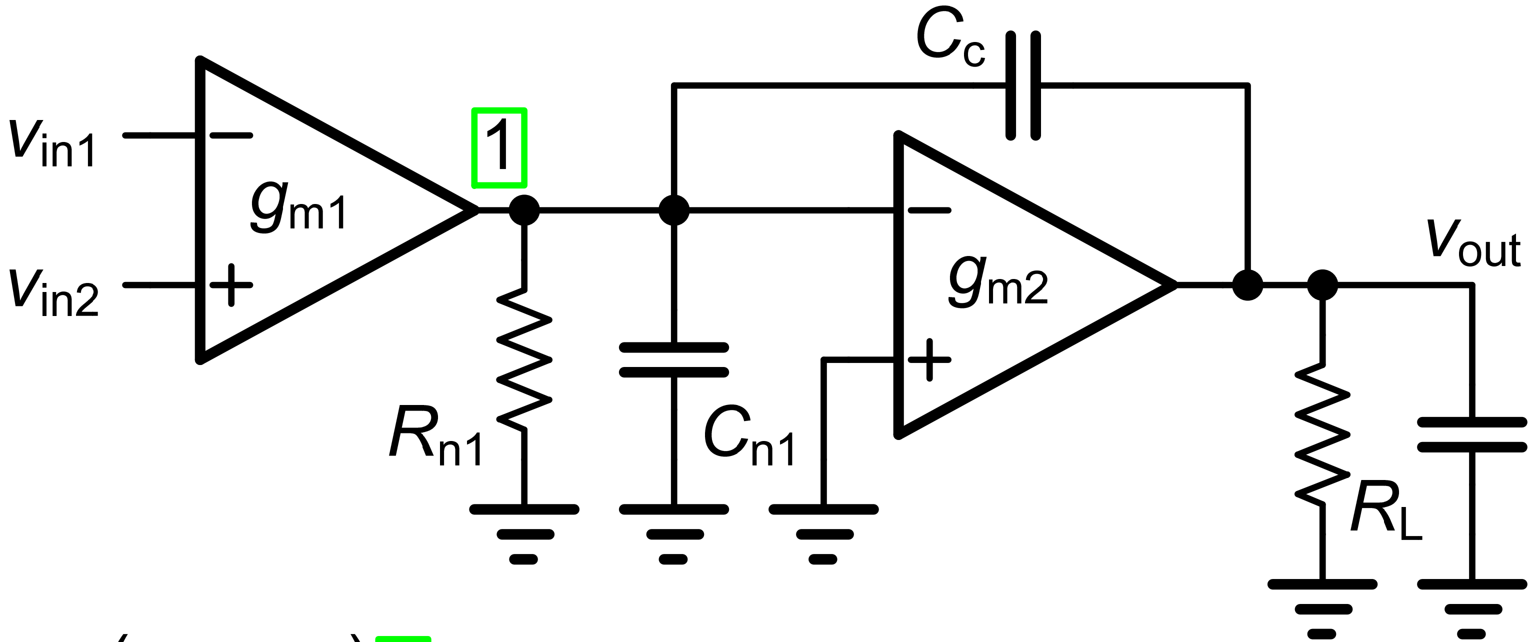
第二级需要很大的电流！

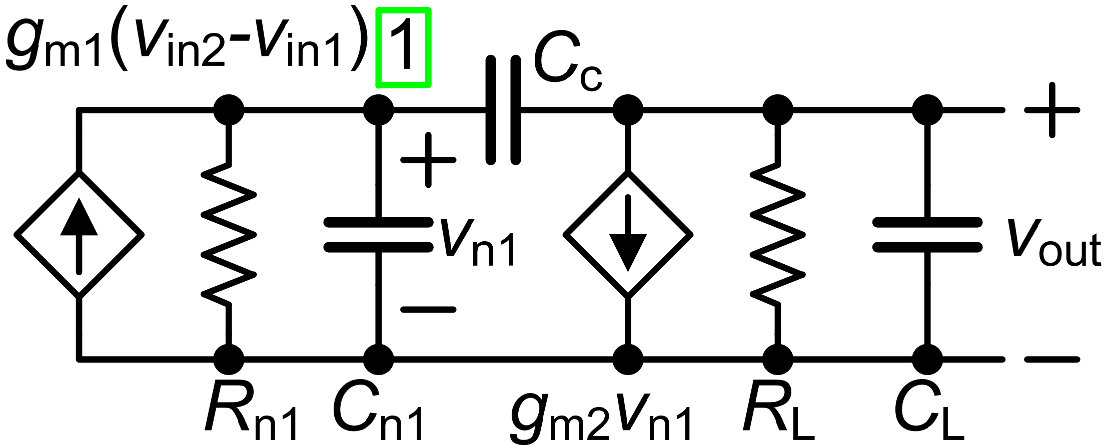
当 $GBW = 100\ \text{MHz}$、$C_L = 2\ \text{pF}$ 时

解：选择 $C_c = 1\text{pF}$

目录

通用两级运放：密勒OTA



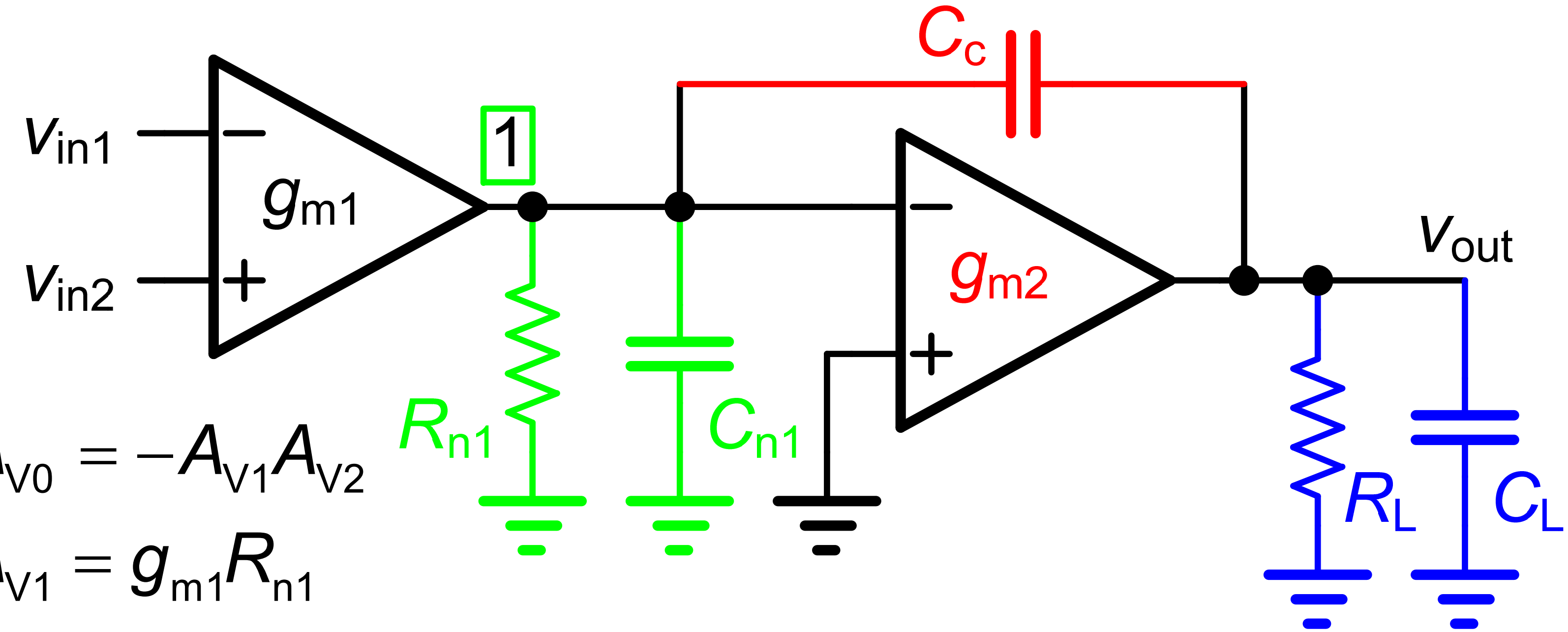


$$A_{V0} = -A_{V1}A_{V2}$$

$$A_{V1} = g_{m1}R_{n1}$$

$$A_{V2} = g_{m2}R_{L}$$

通用两级运放



$$A_{V0} = -A_{V1}A_{V2}$$

$$A_{V1} = g_{m1}R_{n1}$$

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

$$A_V = A_{V0}\frac{1-\dfrac{C_c}{g_{m2}}s}{1+(R_{n1}C_{n1}+R_{n1}C_c+A_{V2}R_{n1}C_c+R_LC_L+R_LC_c)s+R_{n1}R_LCCs^2}$$

$$CC = C_{n1}C_c + C_{n1}C_L + C_cC_L$$

零极点近似

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

零点 $z = \dfrac{1}{c}$

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

$$\boxed{a \uparrow \quad \Rightarrow \quad s_1 \downarrow \text{ and } s_2 \uparrow}$$

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

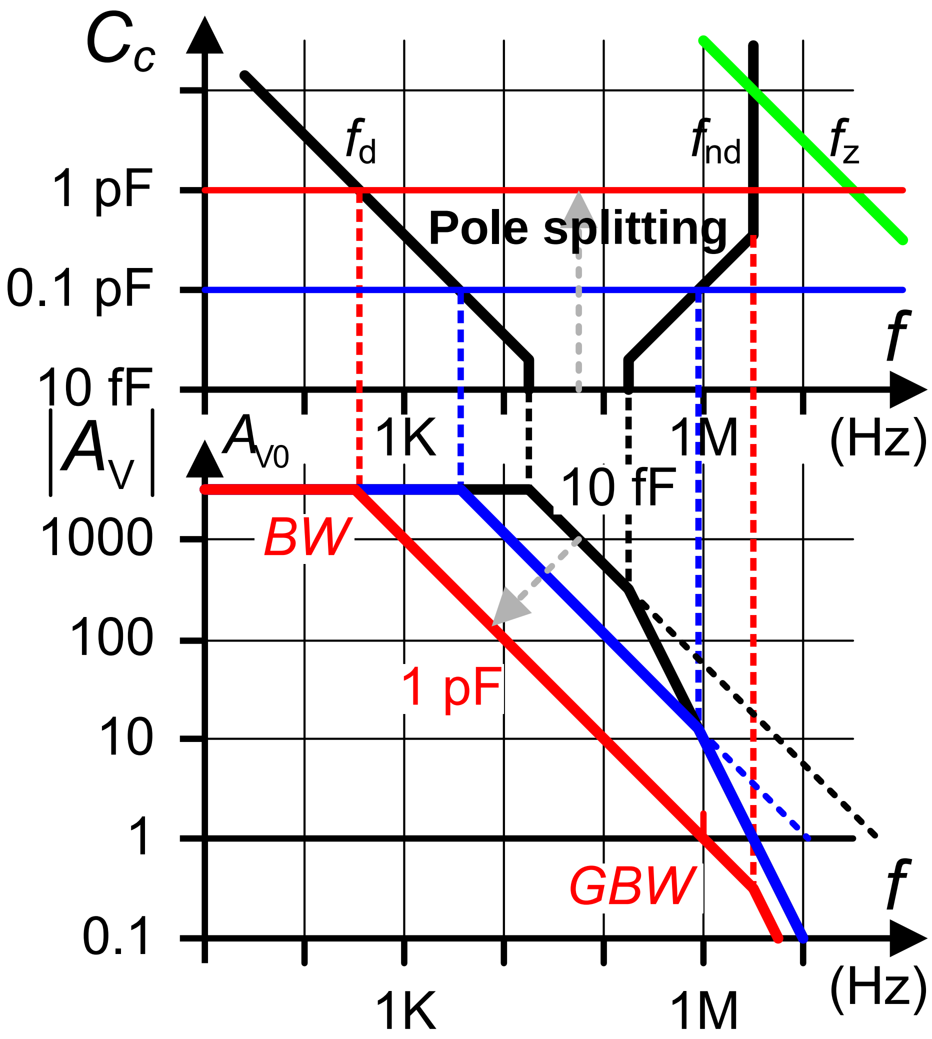
$$\Downarrow$$

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

$$\Downarrow$$

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

密勒OTA：用C_c进行极点分离



C_c取较大值，

进行极点分离：

$$f_d = \frac{1}{2\pi A_{V2} R_{n1} C_c}$$

$$f_z = \frac{g_{m2}}{2\pi C_c}$$ 为正零点！

$$\boxed{GBW = \frac{g_{m1}}{2\pi C_c}}$$

正零点的作用

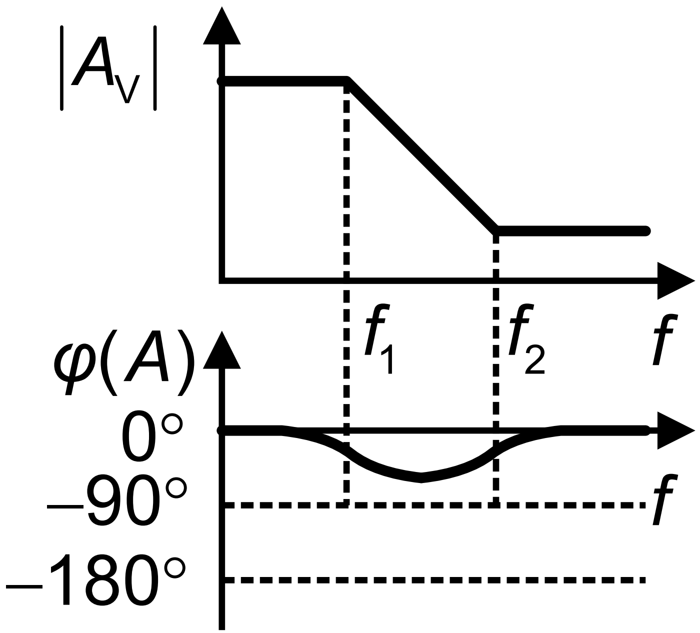
负零点

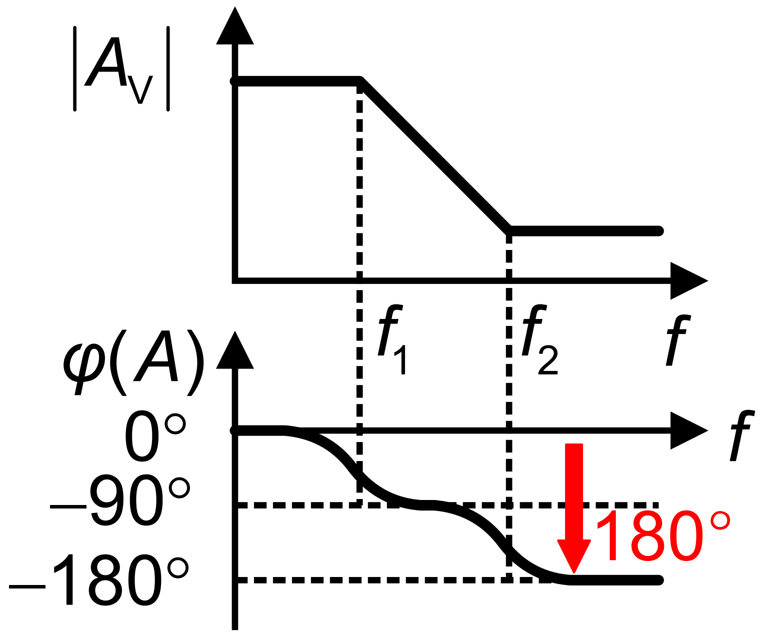
$$A_V = A_{V0}\frac{1+\mathrm{j}f/f_2}{1+\mathrm{j}f/f_1}$$

正零点

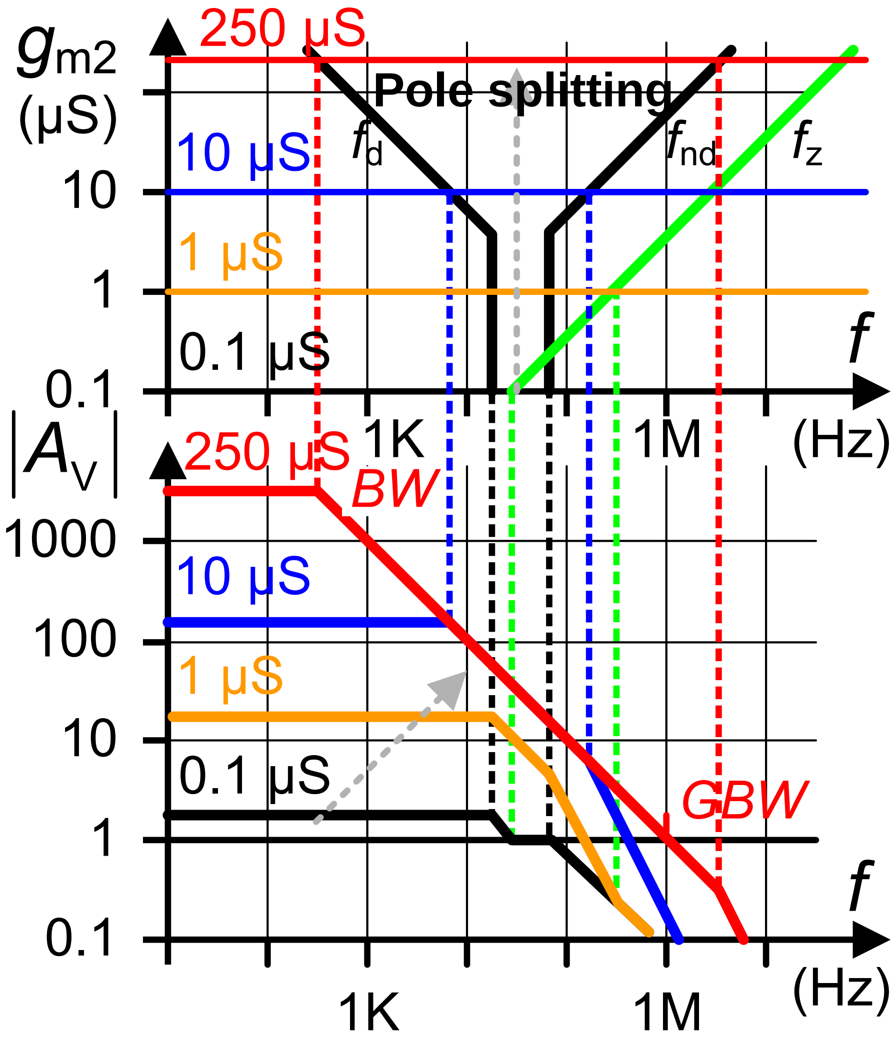
$$A_V = A_{V0}\frac{1-\mathrm{j}f/f_2}{1+\mathrm{j}f/f_1}$$

对于相位，正零点像一个负极点!!!





密勒OTA：用g_{m2}进行极点分离



g_{m2}取较大值，

进行极点分离：

$$f_d = \frac{1}{2\pi A_{V2} R_{n1} C_c}$$

$$f_z = \frac{g_{m2}}{2\pi C_c}$$ 为正零点！

$$\boxed{GBW = \frac{g_{m1}}{2\pi C_c}}$$

极点分离的方式

$$\boxed{\frac{g_{m2}}{g_{m1}} \approx 4\frac{C_L}{C_c}}$$ 或表示为 $$\boxed{g_{m2}C_c \approx 4g_{m1}C_L}$$

g_{m2} 和 C_c 二者均可

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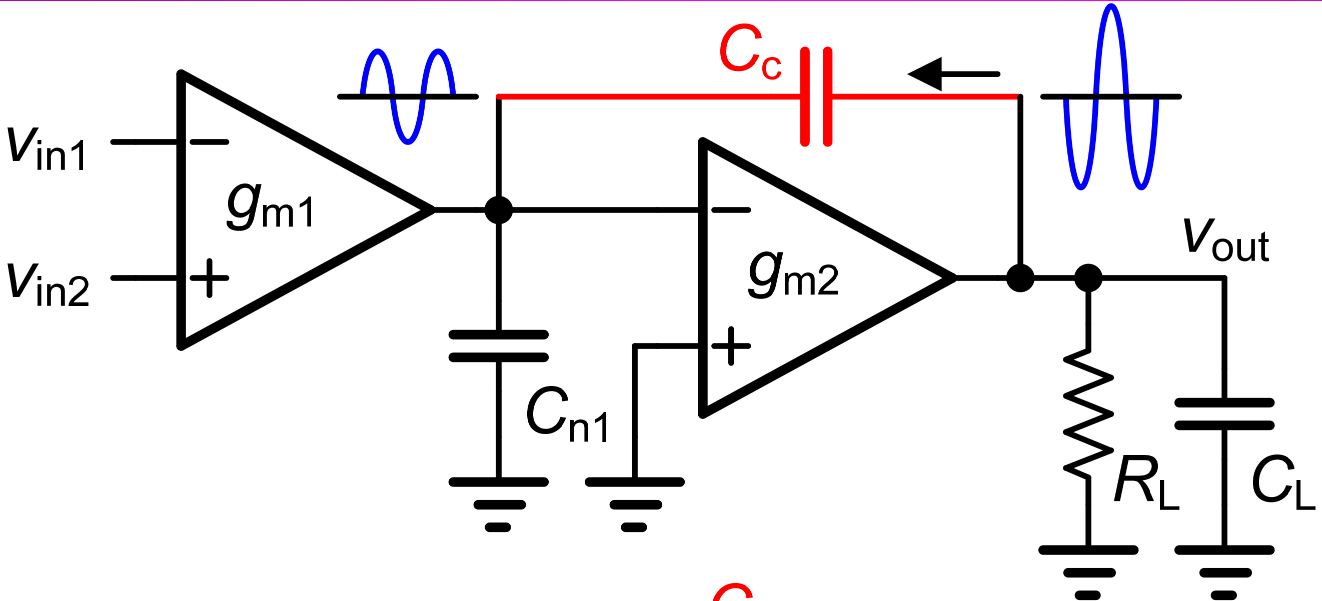
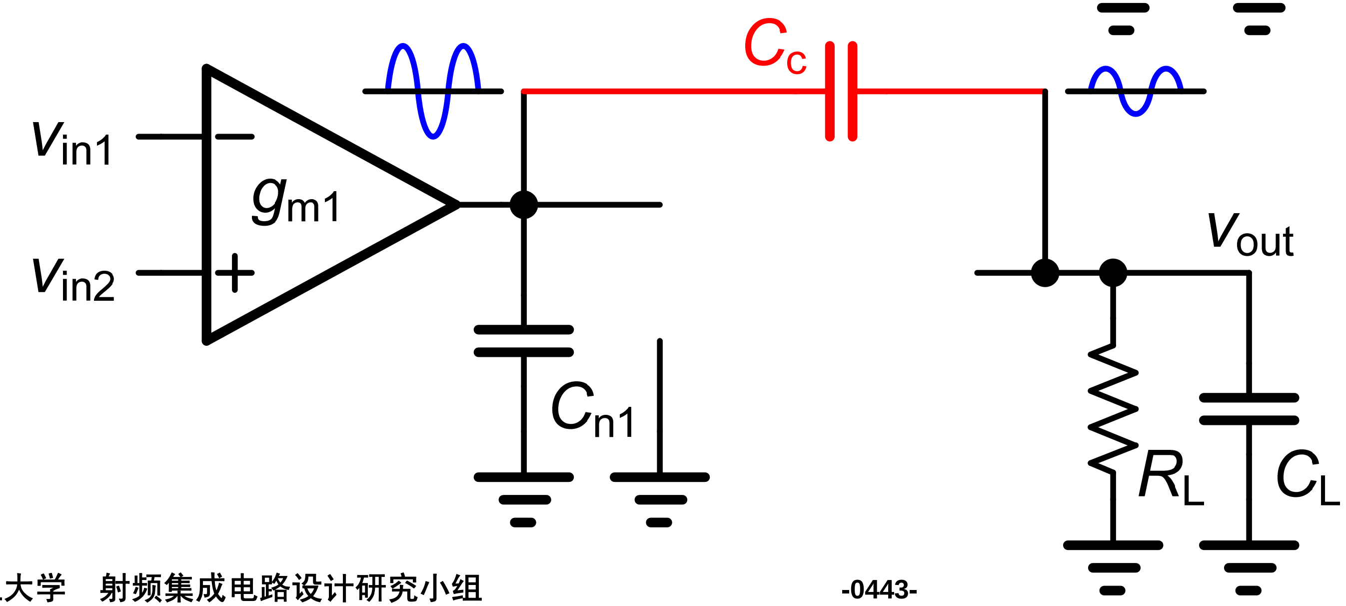
密勒效应的正反馈特性产生正零点



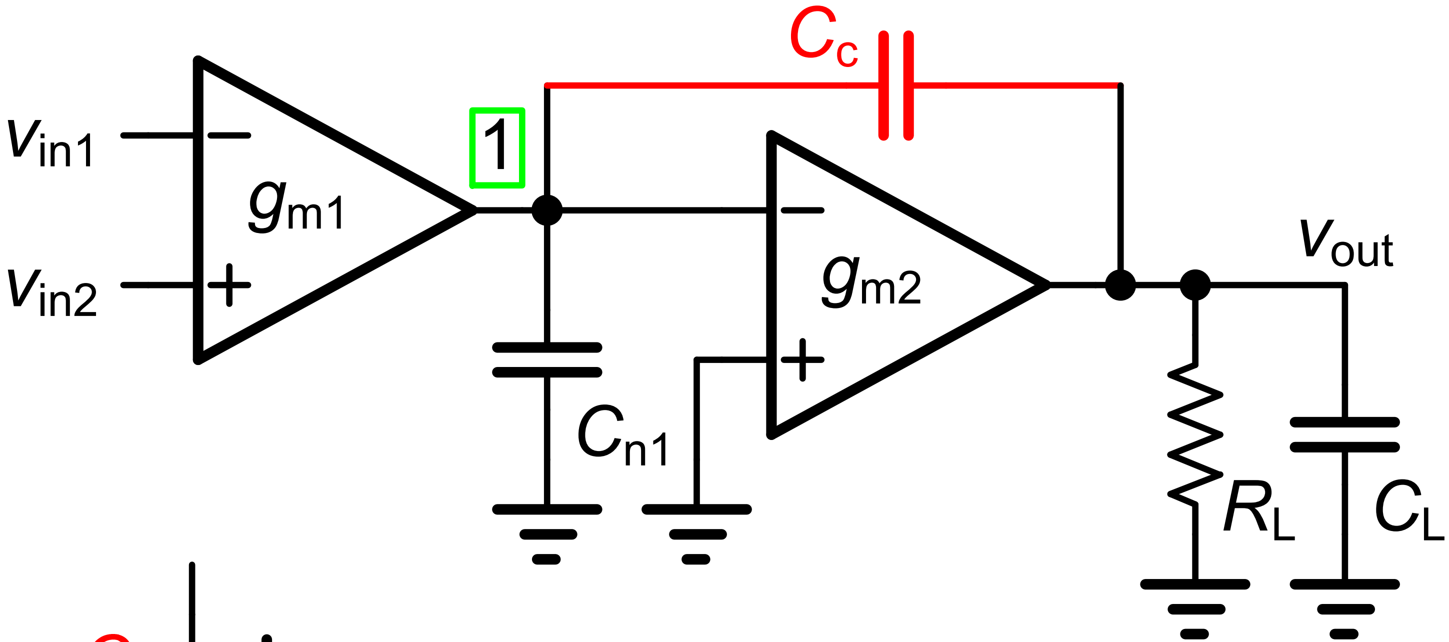
密勒效应为反馈

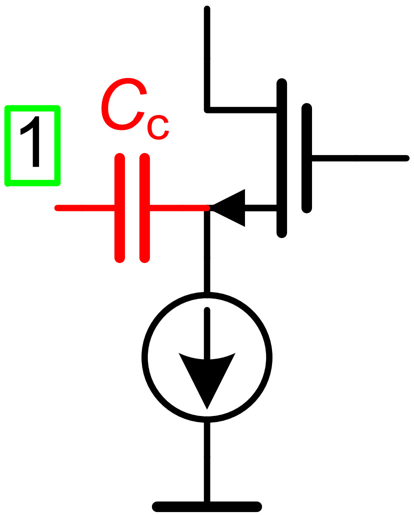


正馈

截断！

截断正馈通路 1

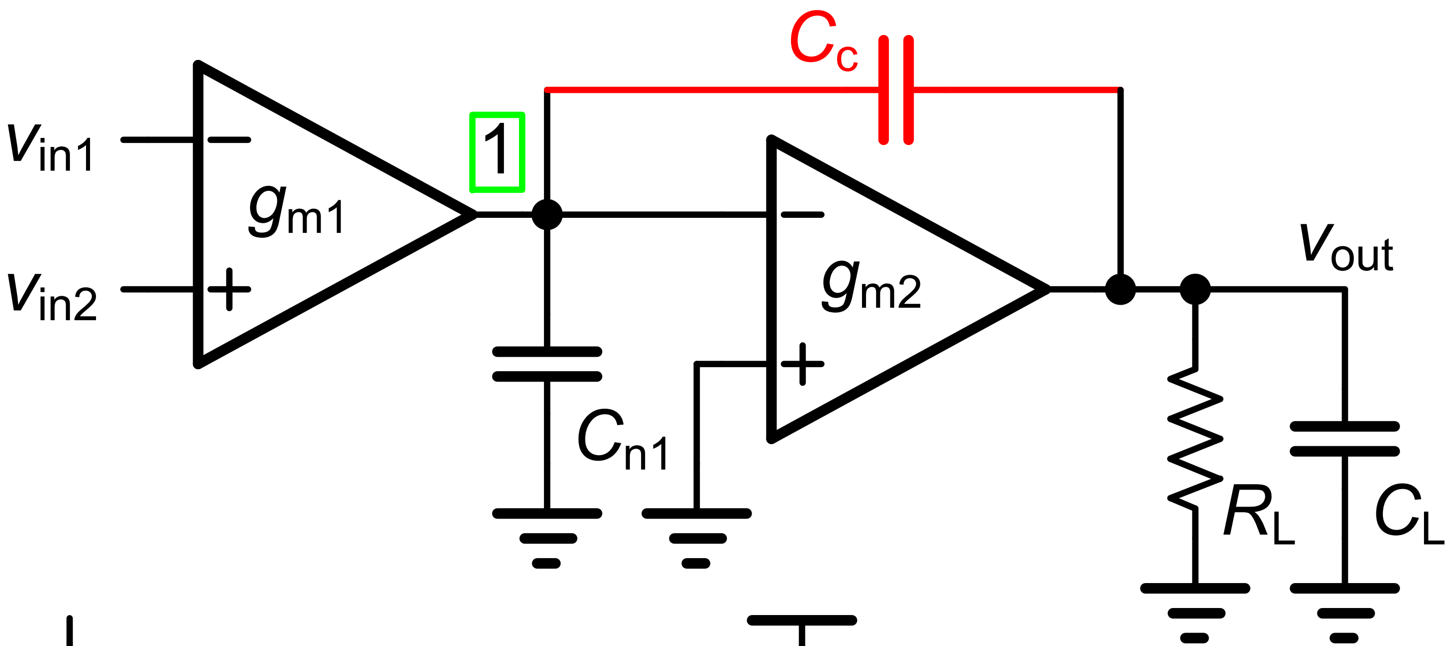


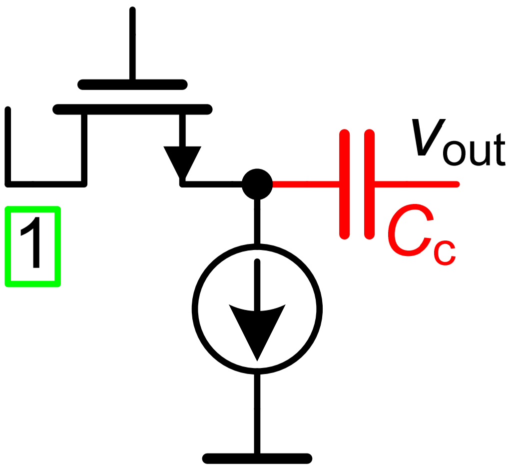


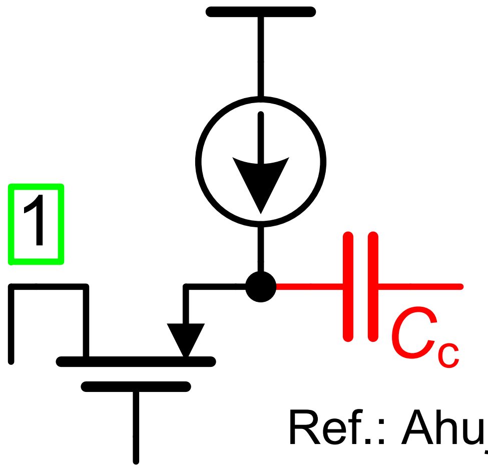
电压缓冲源极跟随器

Ref.: Tsividis, JSSC Dec.76, 748-753

截断正馈通路 2



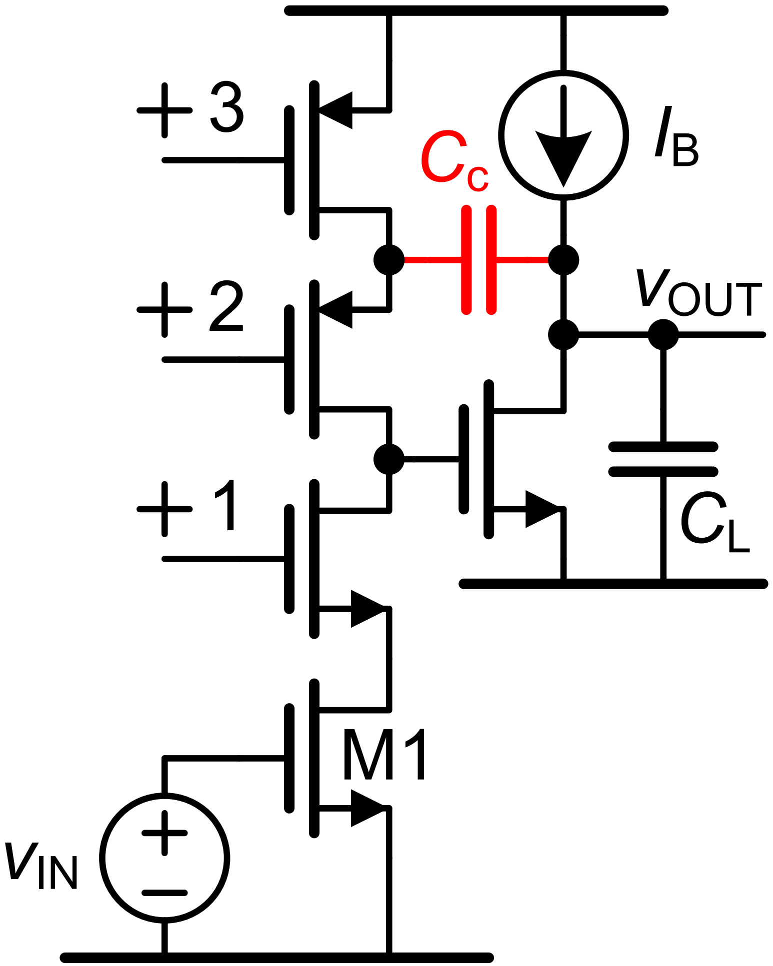


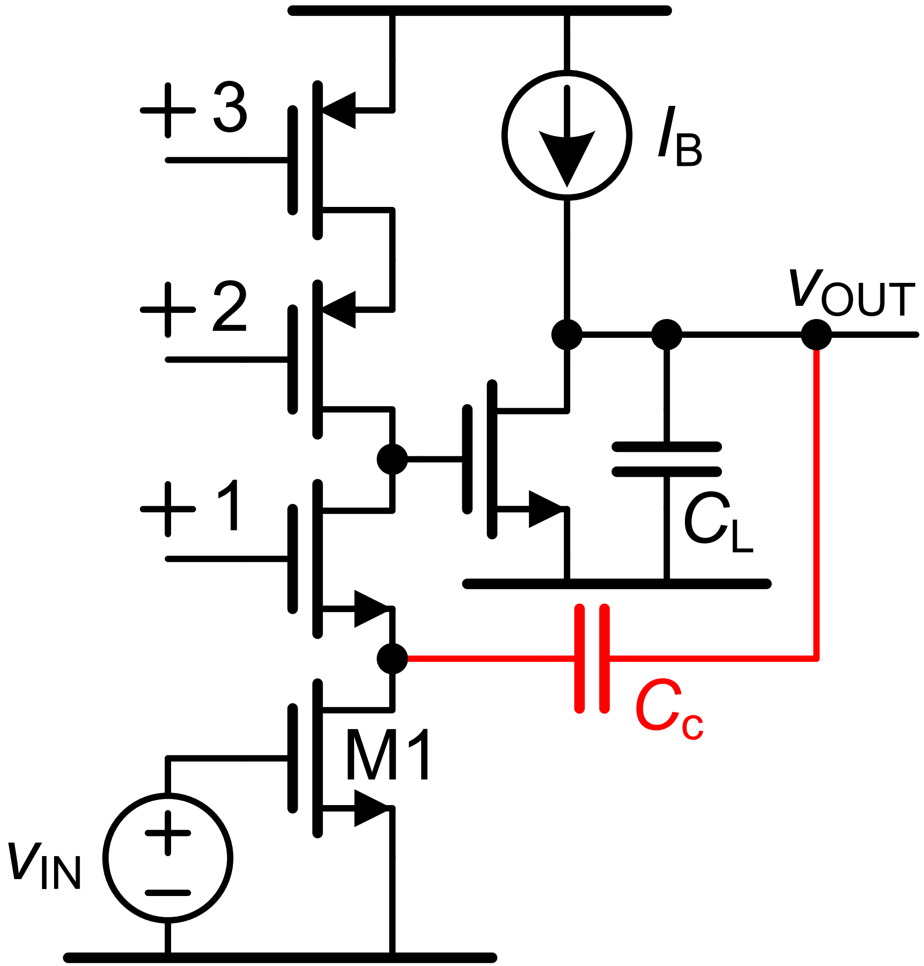


电流缓冲共源共栅

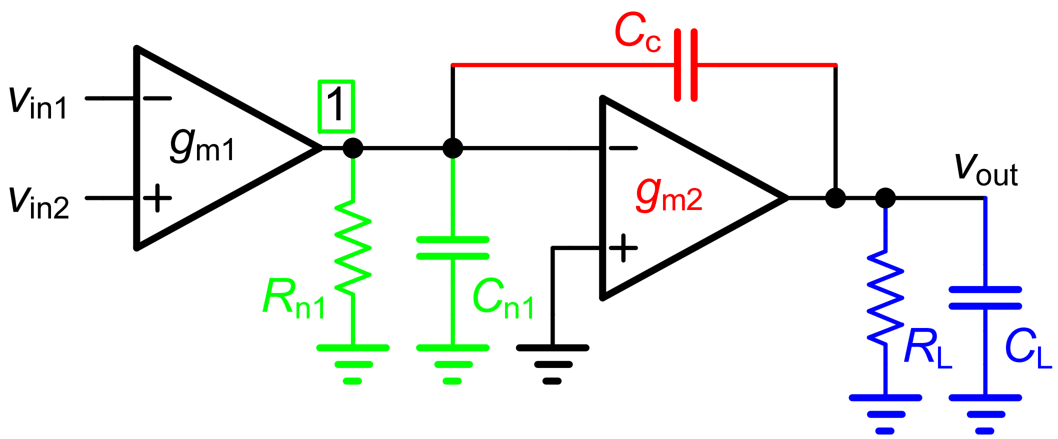
Ref.: Ahuja, JSSC Dec 83, 629-633

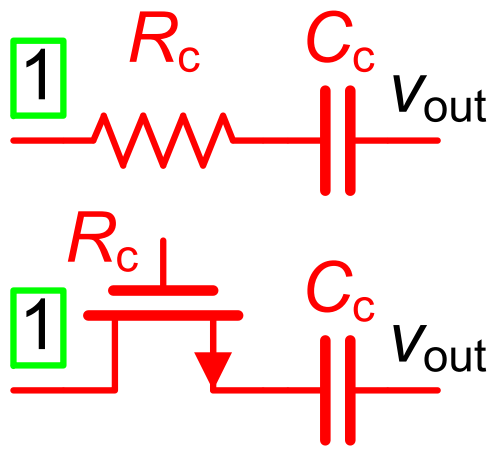
共源共栅密勒补偿





截断正馈通路 3





$$\boxed{f_z = \frac{1}{2\pi C_c (1/g_{m2} - R_c)}}$$

$R_c = 1/g_{m2}$ 无穷远处零点

$R_c > 1/g_{m2}$ 负零点

Ref.: Senderovics, JSSC Dec 78, 760-766

负零点补偿

$$R_c \gg 1/g_{m2} \quad \Rightarrow \quad f_z = -\frac{1}{2\pi C_c R_c}$$

$$f_z = 3GBW \quad \Rightarrow \quad R_c = \frac{1}{3g_{m1}}$$

选择 $\boxed{\frac{1}{g_{m2}} < R_c < \frac{1}{3g_{m1}}}$

练习：两级运放

已知: $GBW = 50\ \text{MHz}$、$C_L = 2\ \text{pF}$ 和 $V_{GS1} - V_T = 0.2\ \text{V}$

求: I_{DS1}、I_{DS2}、C_c 和 R_c

选择 $C_c = 1\ \text{pF} \Rightarrow g_{m1} = 2\pi C_c GBW = 315\ \mu\text{S}$

$$I_{DS1} = 31.5\ \mu\text{A} \quad 1/g_{m1} \approx 3.2\ \text{k}\Omega$$

$$f_{nd} = 150\ \text{MHz} \Rightarrow g_{m2} = 2\pi C_L 4GBW = 8g_{m1} = 2520\ \mu\text{S}$$

$$I_{DS2} = 252\ \mu\text{A} \quad 1/g_{m2} \approx 400\ \Omega$$

$$\frac{1}{g_{m2}} < R_c < \frac{1}{3g_{m1}} \Rightarrow 400\ \Omega < R_c < 1\ \text{k}\Omega$$

$$R_c \approx 400\sqrt{2.5} \approx 640\ \Omega \pm 60\%$$

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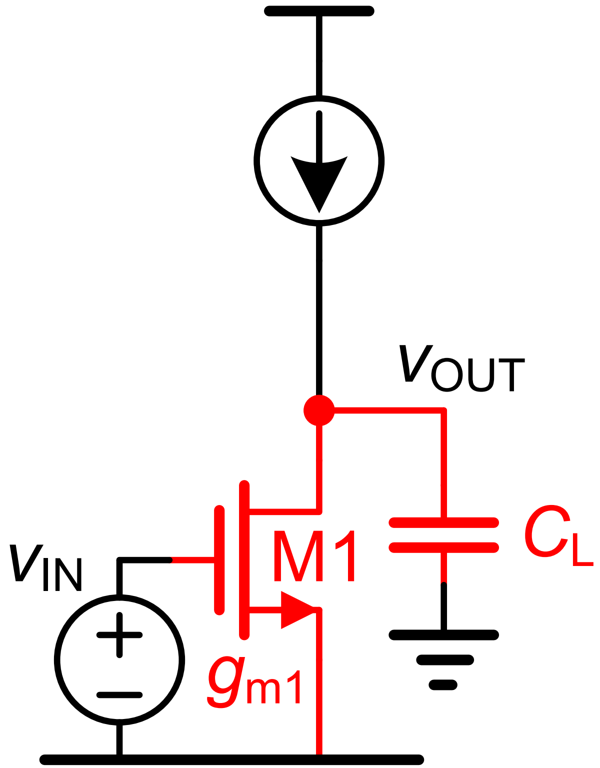
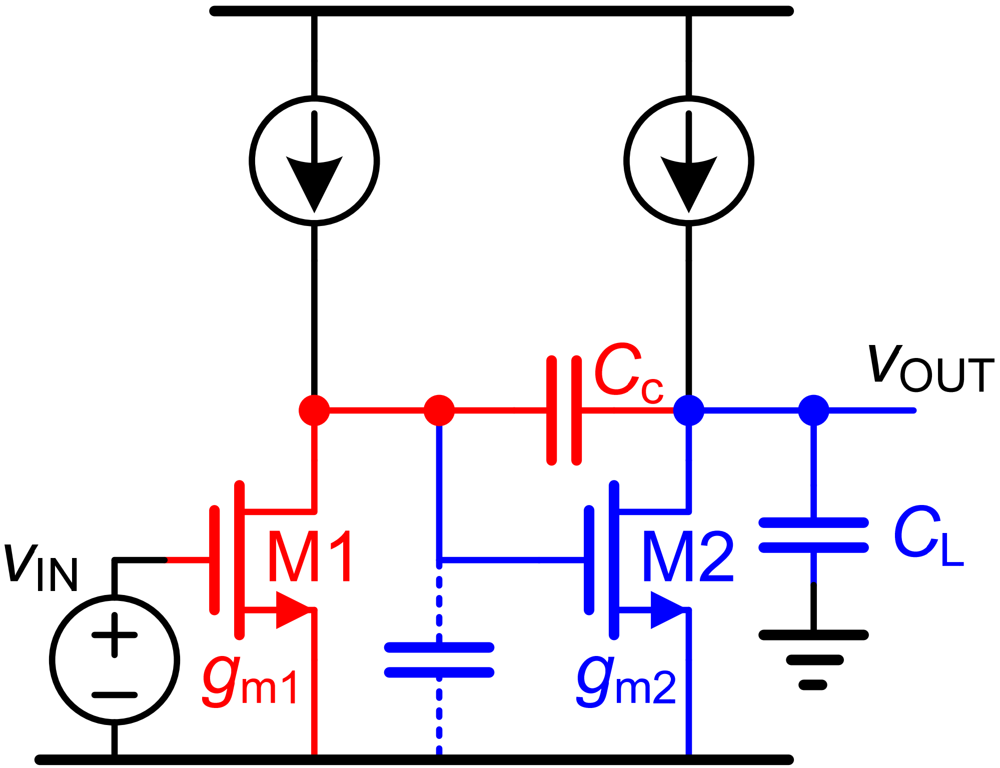
一级CMOS OTA



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

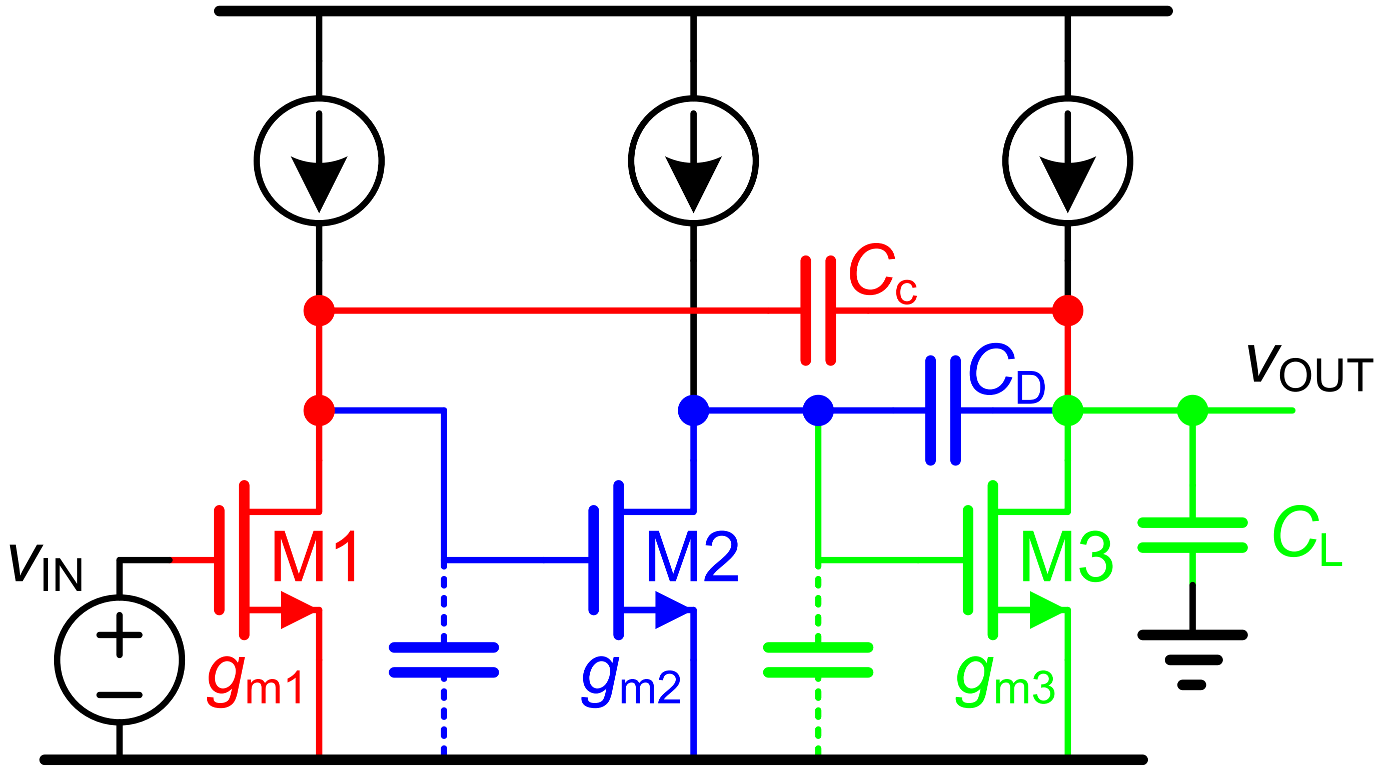
两级密勒CMOS OTA



$$GBW = \frac{g_{m1}}{2\pi C_c} \qquad f_{nd1} = \frac{g_{m2}}{2\pi C_L}$$

$$f_{nd1} = 3GBW$$

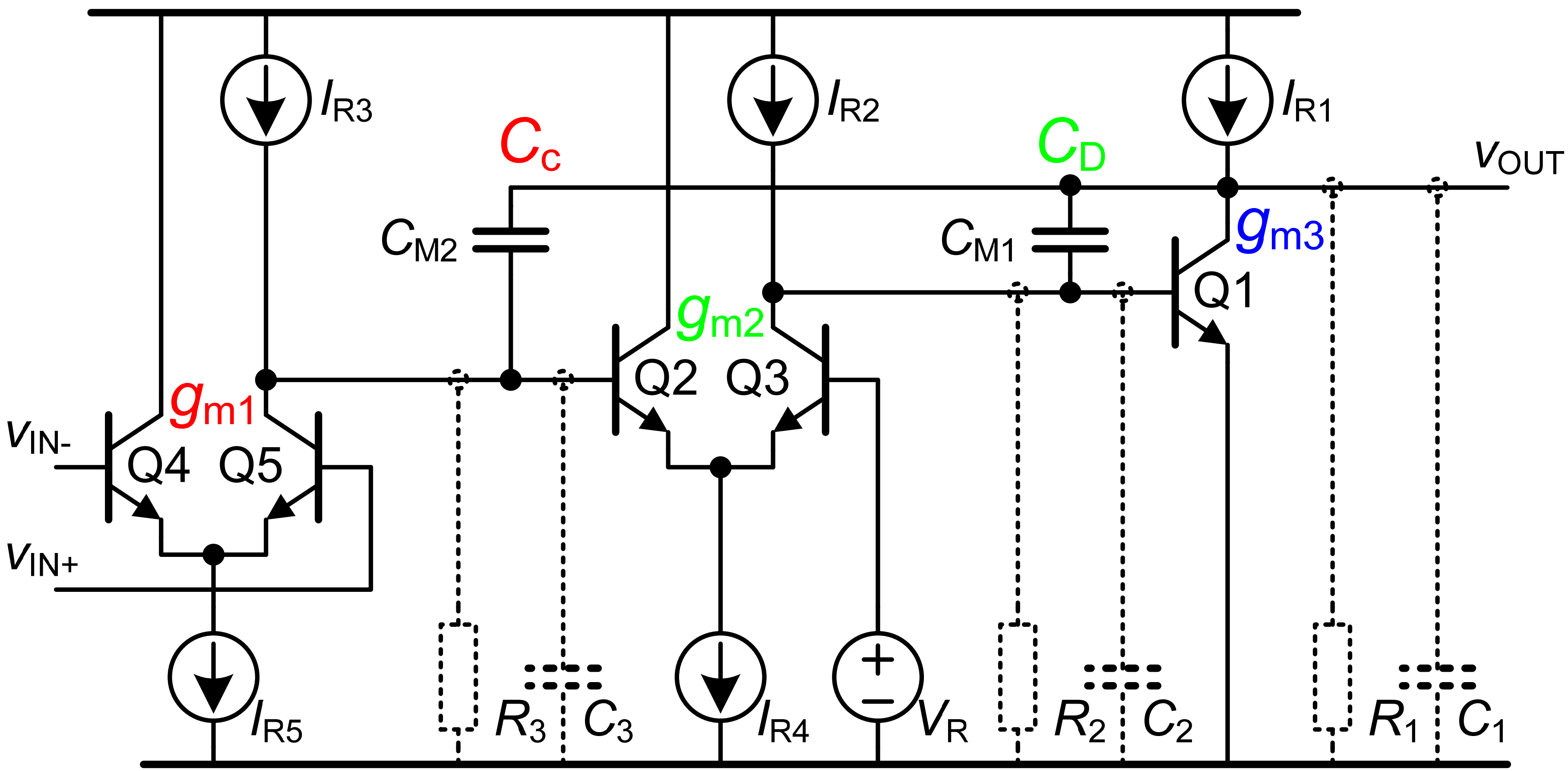
三级嵌套密勒CMOS OTA



$$GBW = \frac{g_{m1}}{2\pi C_c} \qquad f_{nd1} = \frac{g_{m2}}{2\pi C_D} \qquad f_{nd2} = \frac{g_{m3}}{2\pi C_L}$$

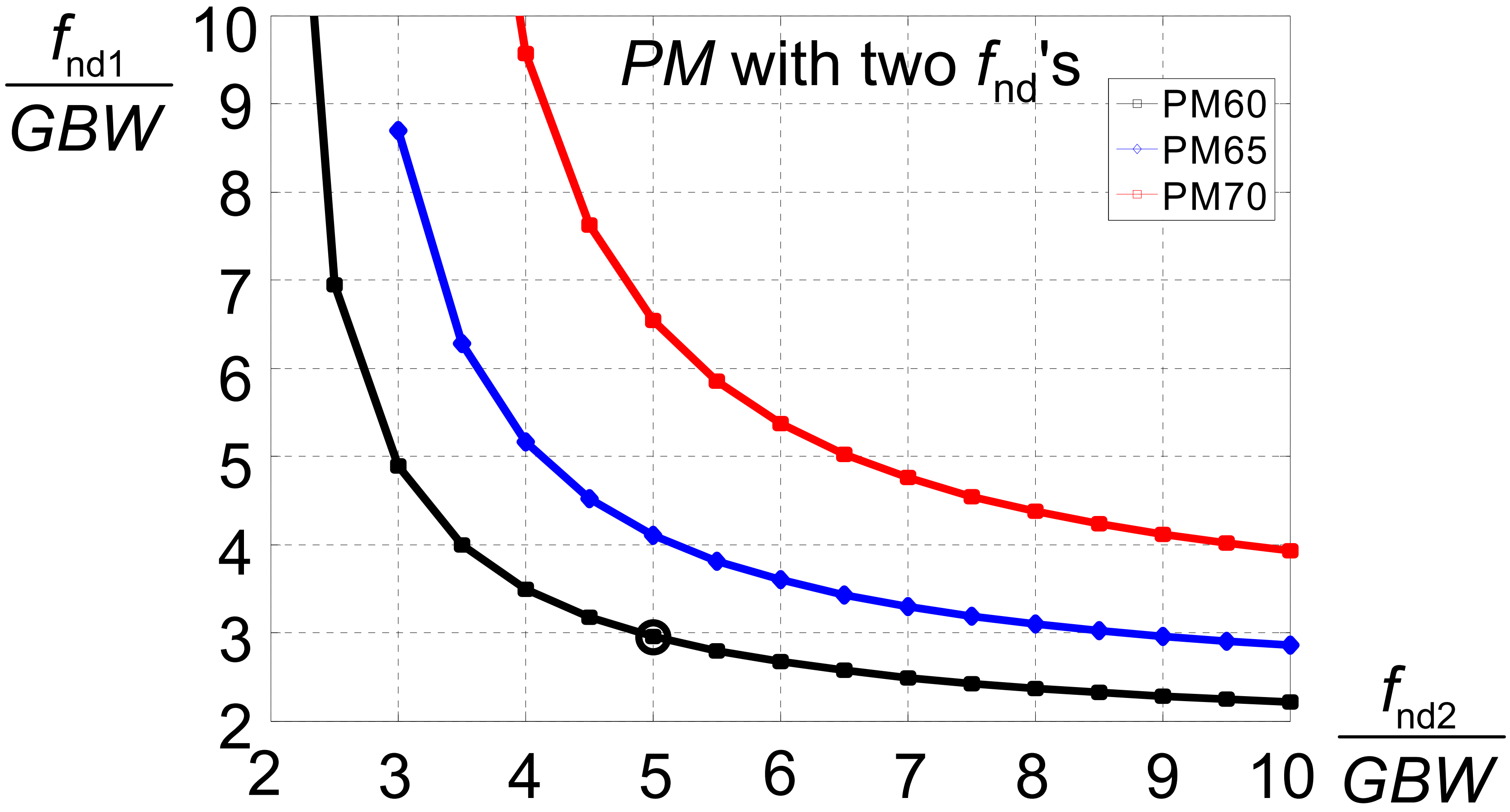
$$f_{nd1} = 3GBW \qquad f_{nd2} = 5GBW$$

差分对构建嵌套密勒OTA



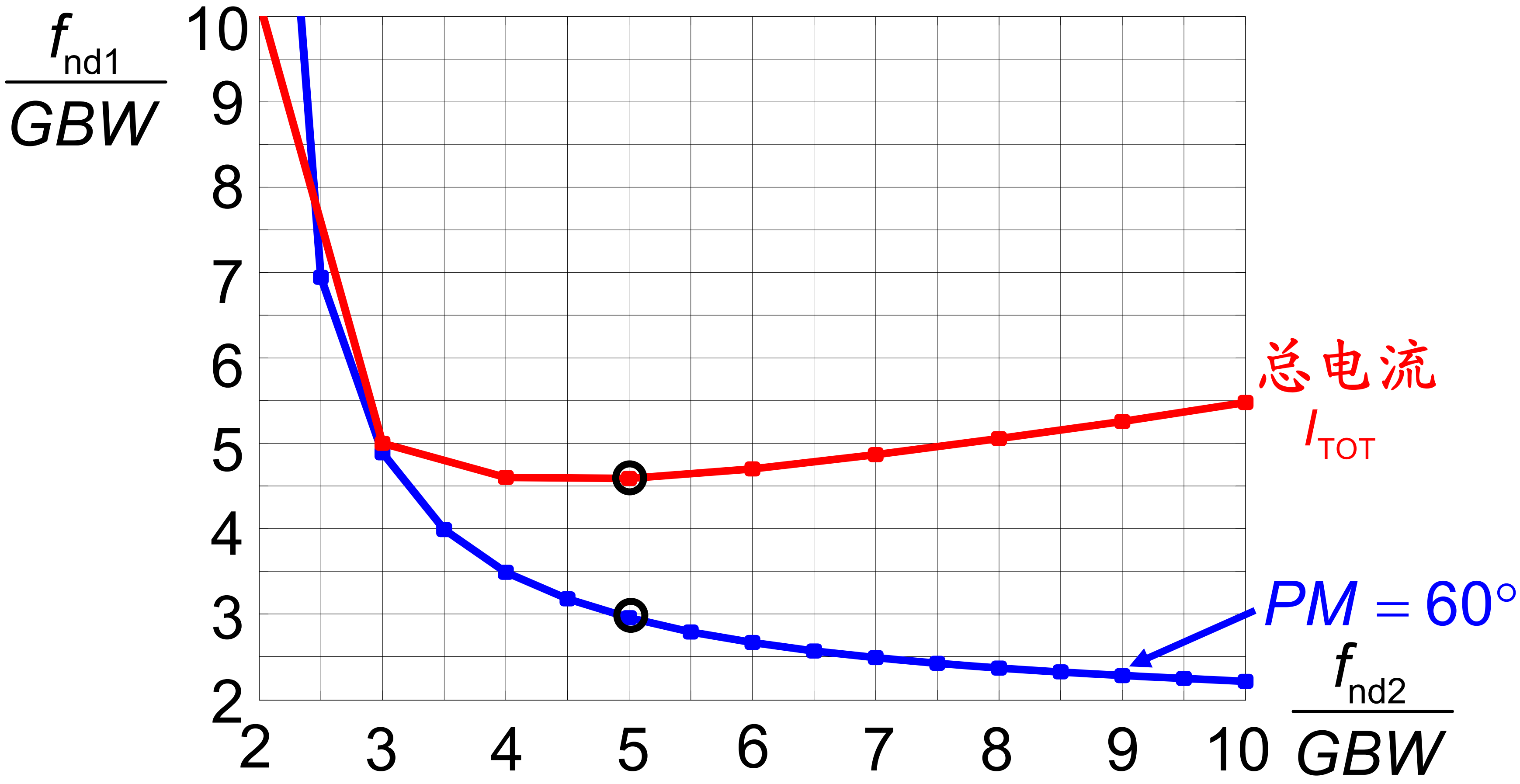
Ref.: Huijsing, JSSC Dec.85, pp.1144-1150

PM与两个非主极点的关系



$$PM = 90° - \arctan\left(\frac{GBW}{f_{nd1}}\right) - \arctan\left(\frac{GBW}{f_{nd2}}\right)$$

功耗与两个非主极点的关系



$$I_{TOT} = 2I_{DS1} + 2I_{DS2} + I_{DS3}$$

三级运放的初步设计

$$GBW = \frac{g_{m1}}{2\pi C_c} \qquad f_{nd1} = \frac{g_{m2}}{2\pi C_D} \qquad f_{nd2} = \frac{g_{m3}}{2\pi C_L}$$

$$f_{nd1} = 3GBW \qquad f_{nd2} = 5GBW$$

选择 $C_D \approx C_c$ $\Rightarrow$ $\frac{g_{m2}}{g_{m1}} \approx 3$ $\qquad \frac{g_{m3}}{g_{m1}} \approx 5\frac{C_L}{C_c}$

输出级需要大电流!

练习：三级运放设计

已知: $GBW = 50\ \text{MHz}$、$C_L = 2\ \text{pF}$ 和 $V_{GS} - V_T = 0.2\ \text{V}$

求: I_{DS1}、I_{DS2}、I_{DS3}、C_c 和 C_D

$$\text{选择}\ C_c = C_D = 1\ \text{pF} \Rightarrow g_{m1} = 2\pi C_c GBW = 315\ \mu\text{S}$$

$$I_{DS1} = 31.5\ \mu\text{A}$$

$$f_{nd1} = 150\ \text{MHz} \Rightarrow g_{m2} = 2\pi C_D 3GBW = 3g_{m1} = 945\ \mu\text{S}$$

$$I_{DS2} = 94.5\ \mu\text{A}$$

$$f_{nd2} = 250\ \text{MHz} \Rightarrow g_{m3} = 2\pi C_L 5GBW = 10g_{m1} = 3150\ \mu\text{S}$$

$$I_{DS3} = 315\ \mu\text{A}$$

一/两/三级运放的比较

$GBW = 50\ \text{MHz} \quad C_L = 2\ \text{pF}$

单级：$I_{DS1} = 31.5\ \mu\text{A}$

$I_{TOT} = 2I_{DS1} = 63\ \mu\text{A}$

两级：选择 $C_c = 1\ \text{pF} \quad I_{DS1} = 31.5\ \mu\text{A} \quad I_{DS2} = 252\ \mu\text{A}$

$I_{TOT} = 2I_{DS1} + I_{DS2} = 315\ \mu\text{A}$

三级：选择 $C_c = C_D = 1\ \text{pF}$

$I_{DS1} = 31.5\ \mu\text{A} \quad I_{DS2} = 94.5\ \mu\text{A} \quad I_{DS3} = 315\ \mu\text{A}$

$I_{TOT} = 2I_{DS1} + 2I_{DS2} + I_{DS3} = 576\ \mu\text{A}$

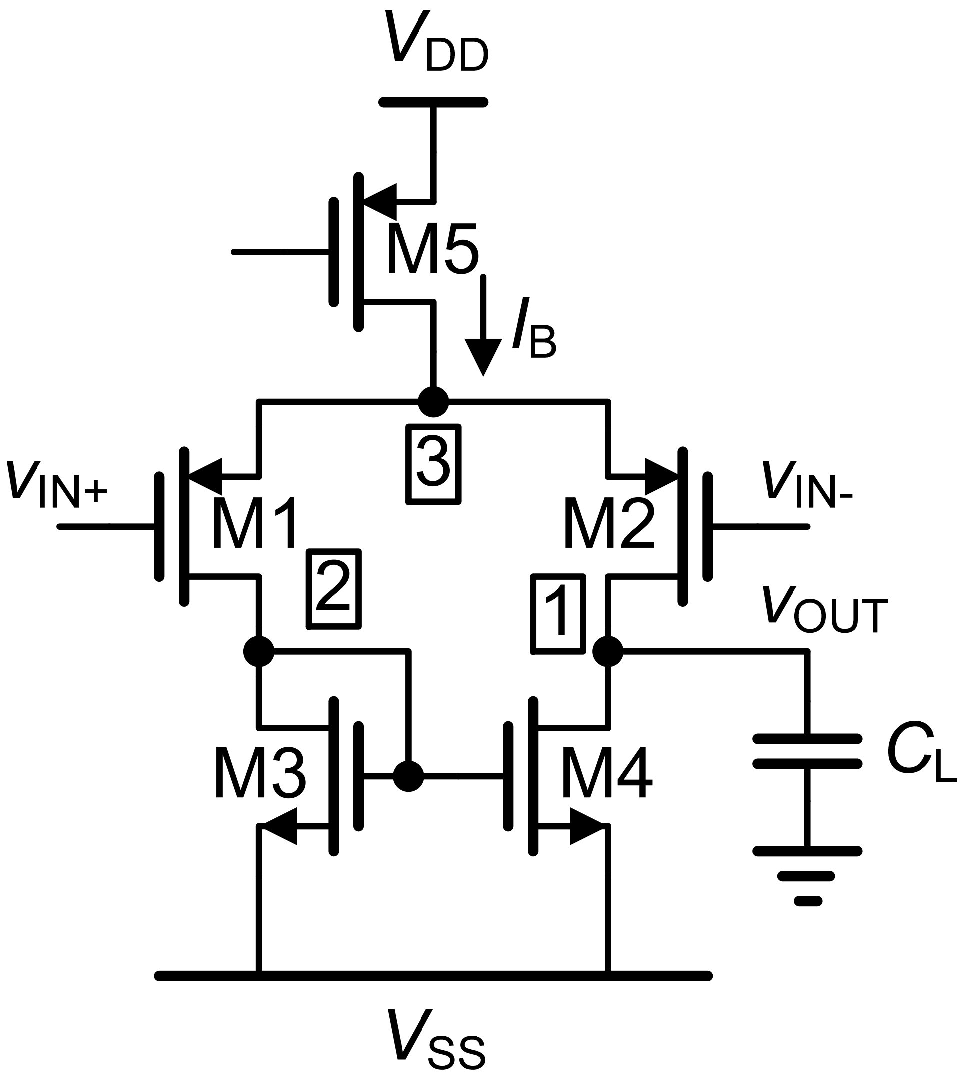
运算放大器的系统设计

目录

- 单级OTA的设计
- CMOS密勒OTA的设计
- *GBW*和相位裕度的设计
- 其他指标：输入范围、输出范围、*SR*…

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

CMOS单级OTA：*GBW*



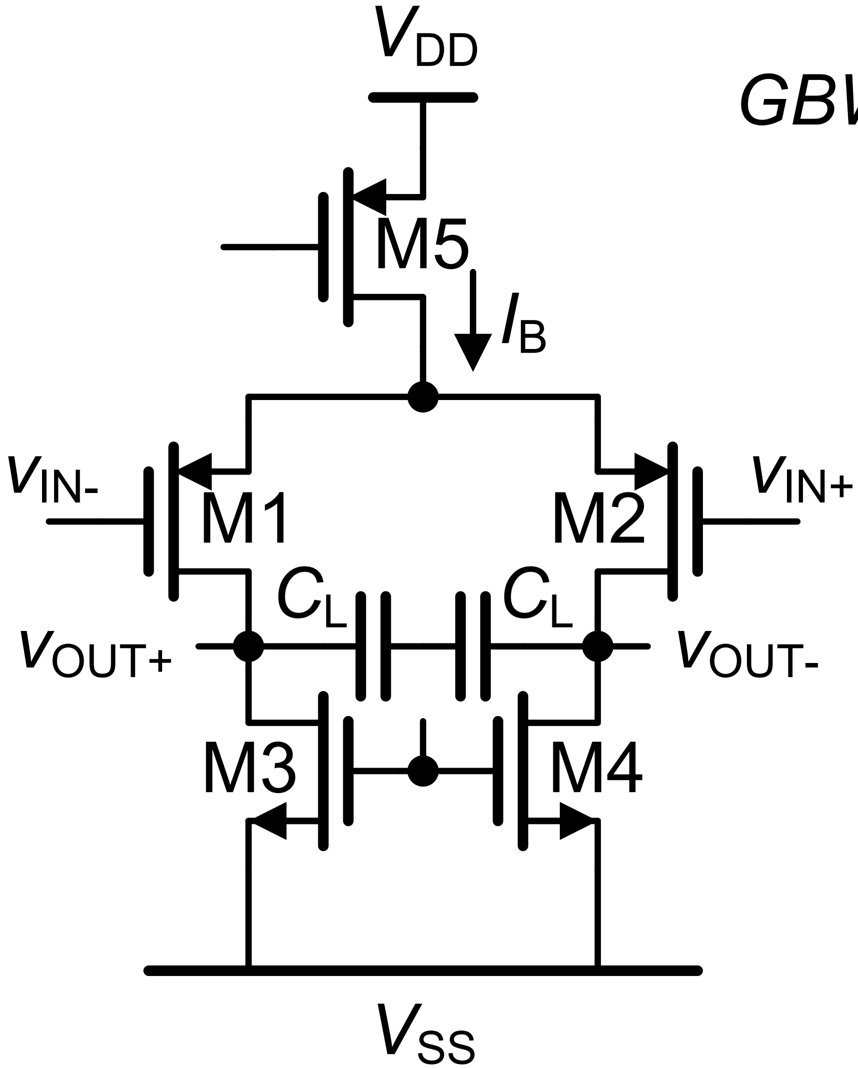
$$A_V = g_{m1}\frac{r_{DS}}{2}$$

如果：$r_{DS2} = r_{DS4} = r_{DS}$

$$BW = \frac{1}{2\pi\frac{r_{DS}}{2}(C_L + C_{n1})}$$

$$\boxed{GBW = \frac{g_{m1}}{2\pi(C_L + C_{n1})}}$$

CMOS OTA：最大GBW



$$GBW = \frac{g_{m1}}{2\pi C_L} \qquad g_{m1} = \frac{I_B}{V_{GS1} - V_T}$$

$$\boxed{GBW_{max} = \frac{I_B}{V_{GS1} - V_T} \frac{1}{2\pi C_L}}$$

$C_L = 1\ \text{pF}$

$I_B = 10\ \mu\text{A}$ $\Rightarrow GBW_{max} \approx 10\ \text{MHz}$

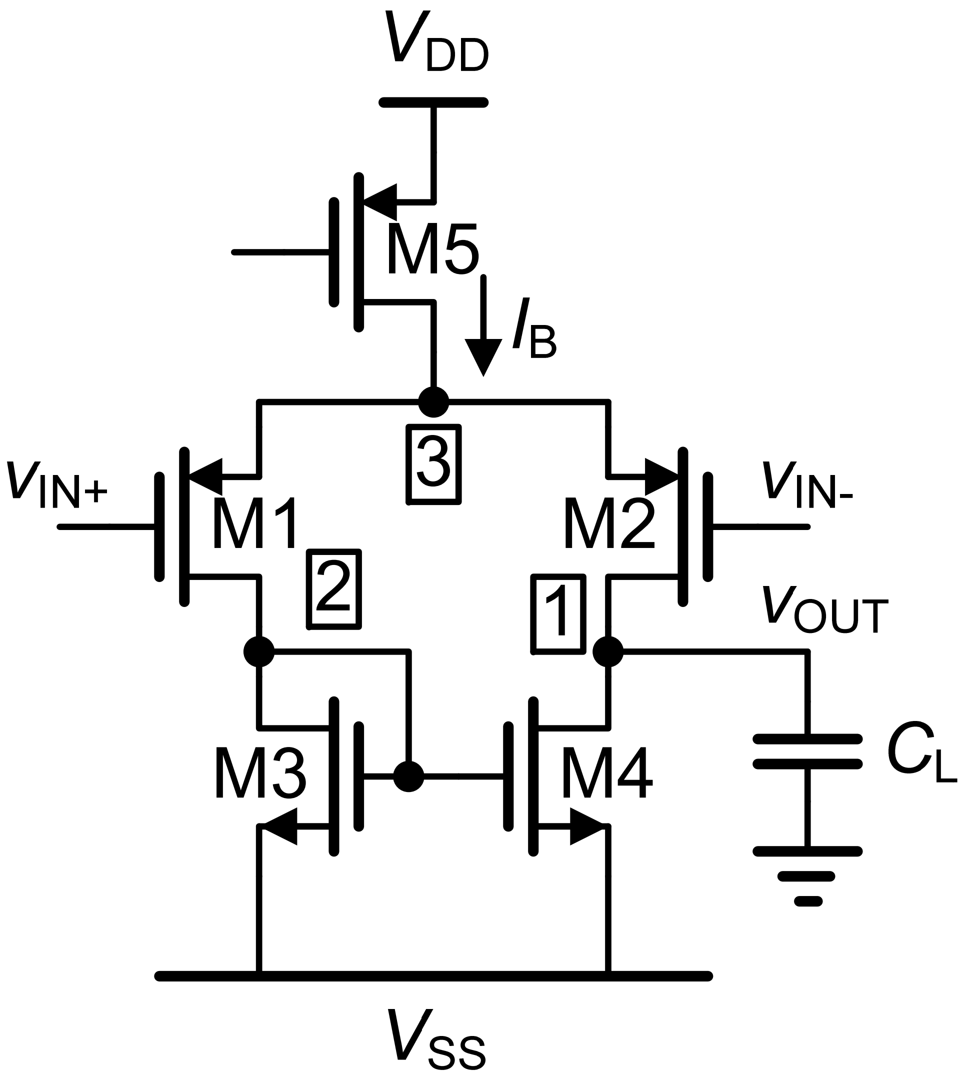
[8]

$$FOM = \frac{GBW \bullet C_L}{I_B}$$

$= 1000\ \text{MHzpF/mA}$

[800]

CMOS单级OTA：f_{nd}



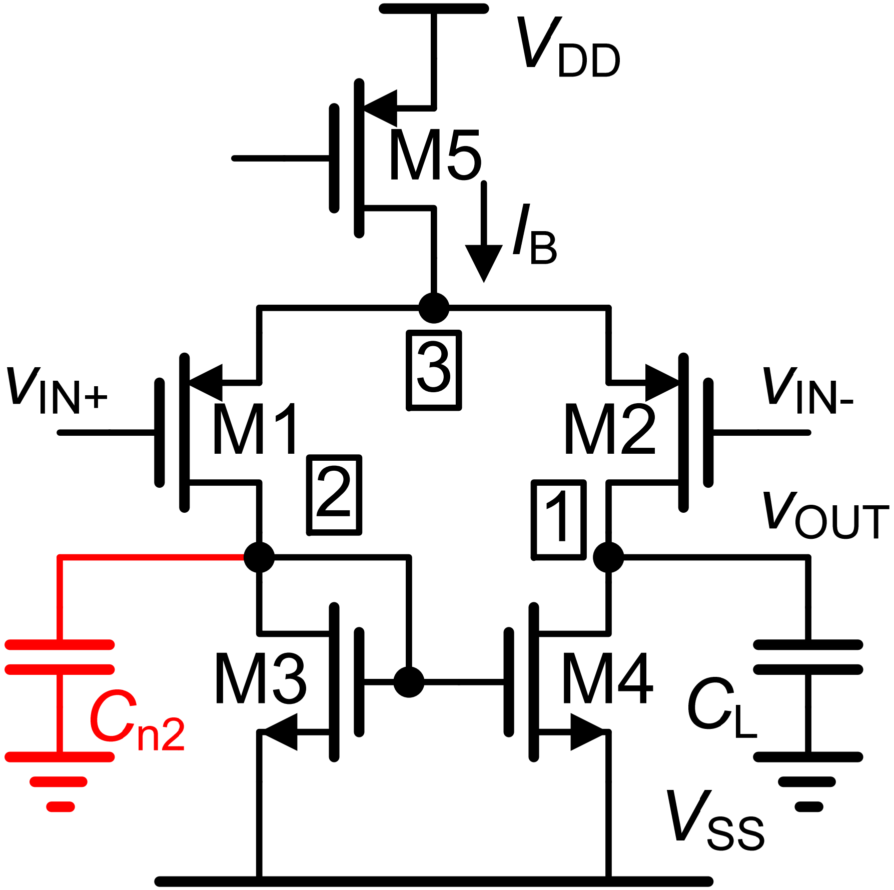
$$GBW = \frac{g_{m1}}{2\pi(C_L + C_{n1})}$$

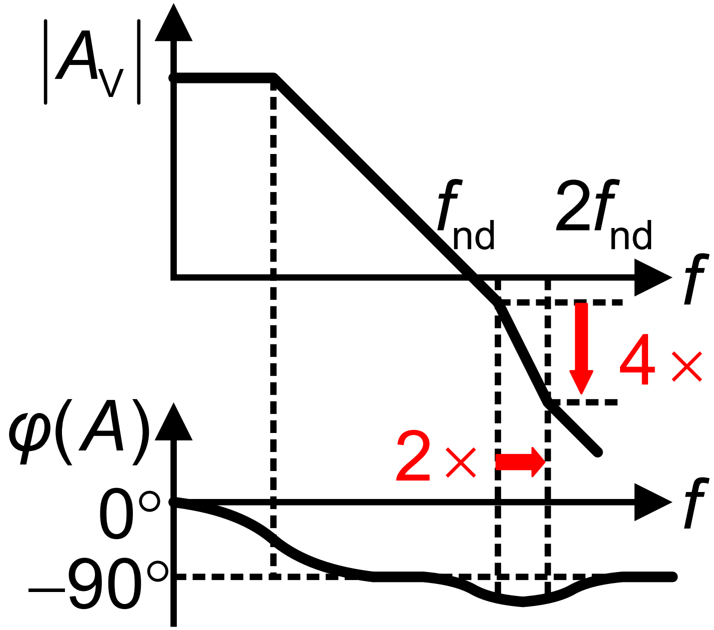
$$f_{nd} = \frac{g_{m3}}{2\pi C_{n2}}$$

$$C_{n2} \approx 2C_{GS3} + C_{DB3} + C_{DB1}$$
$$\approx 4C_{GS3}$$

$$\boxed{f_{nd} \approx \frac{f_{T3}}{4}}$$

CMOS OTA: f_{nd}





$$f_{nd} = \frac{g_{m3}}{2\pi C_{n2}}$$

$$PM = 90° - \arctan\left(\frac{GBW}{f_{nd}}\right) + \arctan\left(\frac{GBW}{2f_{nd}}\right) \approx 85°$$

CMOS单级OTA：设计 1

已知：$GBW = 100\ \text{MHz}$ 和 $C_L = 2\ \text{pF}$

工艺：$L_{min} = 0.35\ \mu\text{m}$、$K_n^{'} = 60\ \mu\text{A/V}^2$ 和 $K_p^{'} = 30\ \mu\text{A/V}^2$

求：I_{DS}、W、L

$$g_m = 2\pi C_L GBW = 1.2\ \text{mS} \qquad V_{GS} - V_T = 0.2\ \text{V}$$

$$I_{DS} = g_m \frac{V_{GS} - V_T}{2} = \frac{g_m}{10} = 0.12\ \text{mA}$$

$$\frac{W}{L} = \frac{I_{DS}}{K^{'}(V_{GS} - V_T)^2} = 100 \qquad L_p = L_n = 1\ \mu\text{m} \text{ 考虑增益！}$$

$$W_n = 50\ \mu\text{m}、W_p = 100\ \mu\text{m}$$

目录

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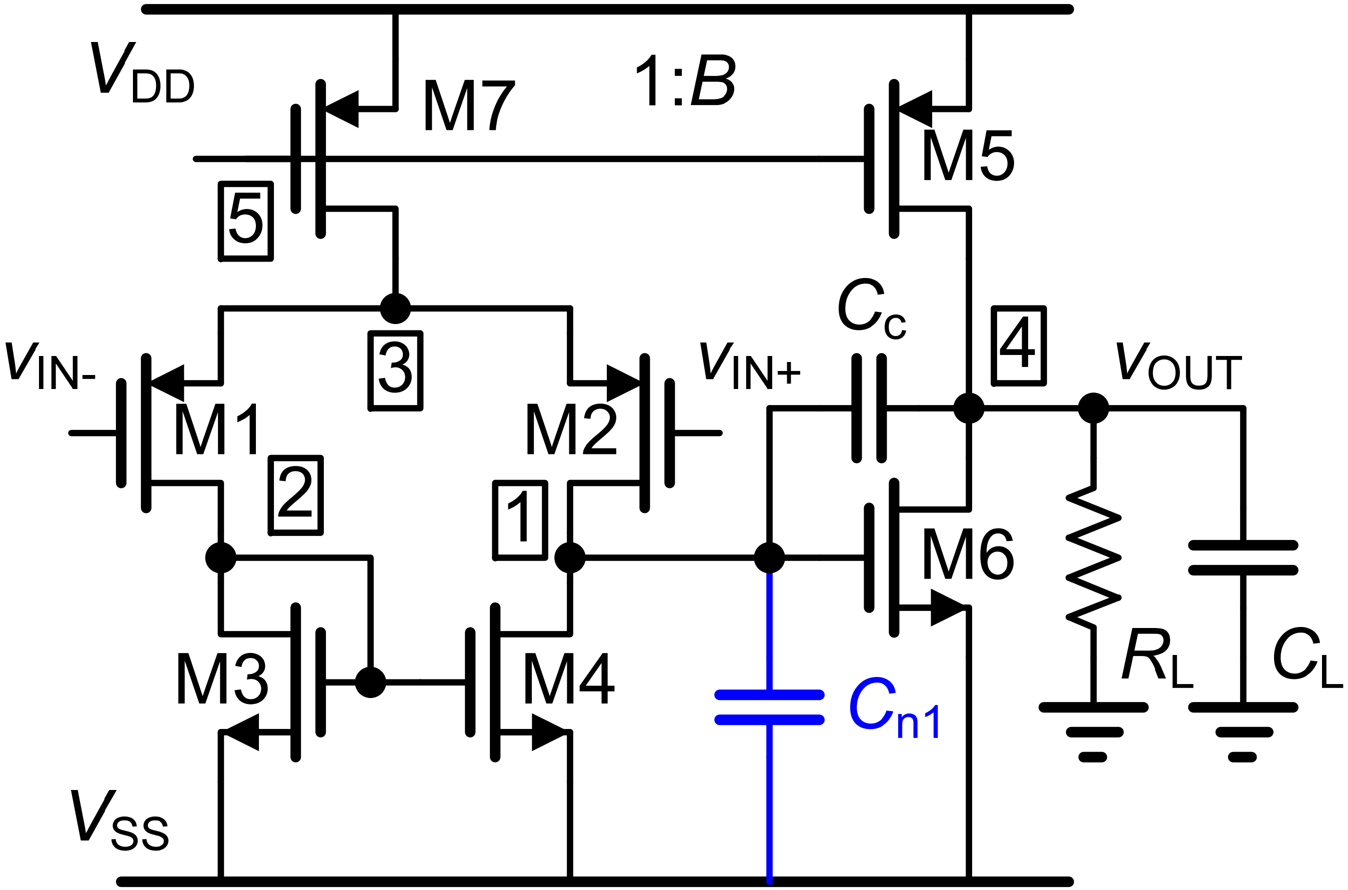
CMOS密勒OTA



两个节点

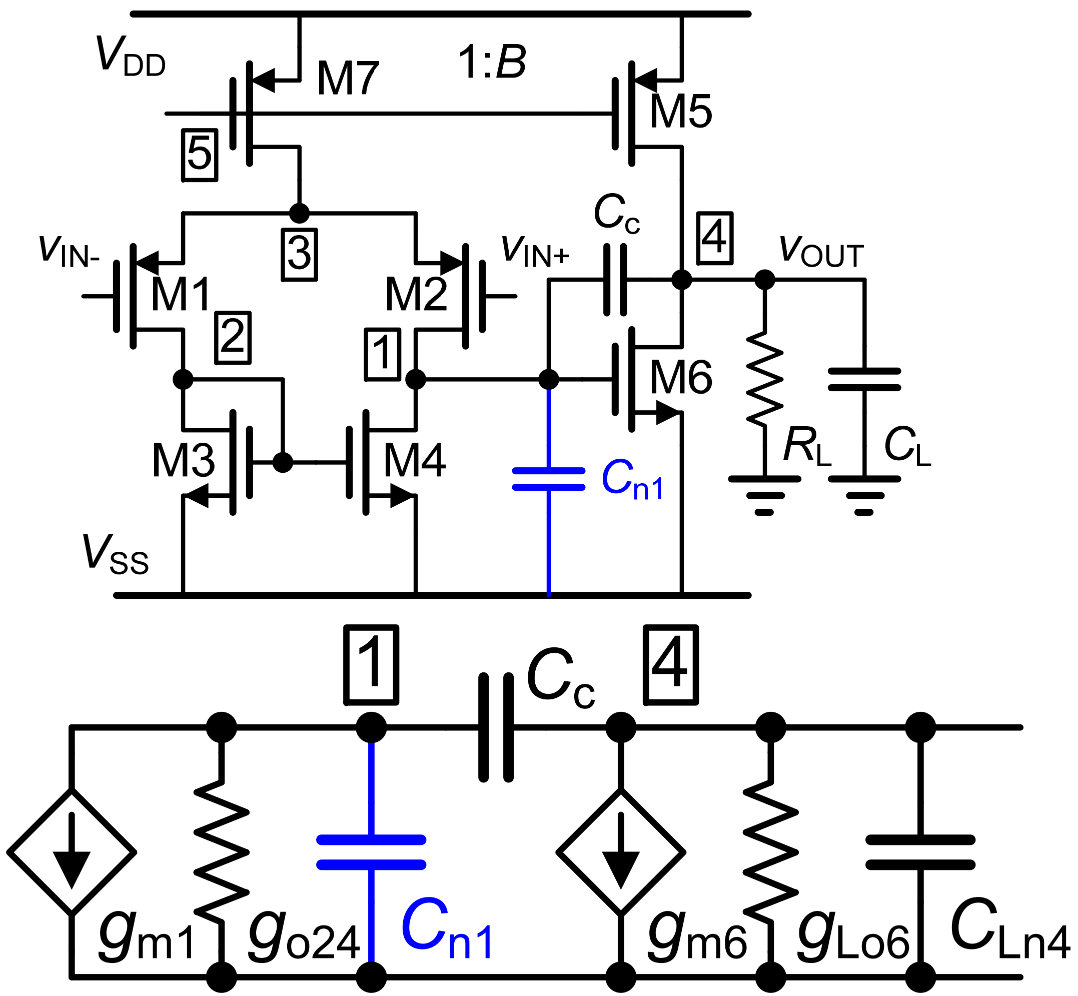
1 4

具有高阻抗

产生两个极点

用C_c进行分离

CMOS密勒OTA：小信号

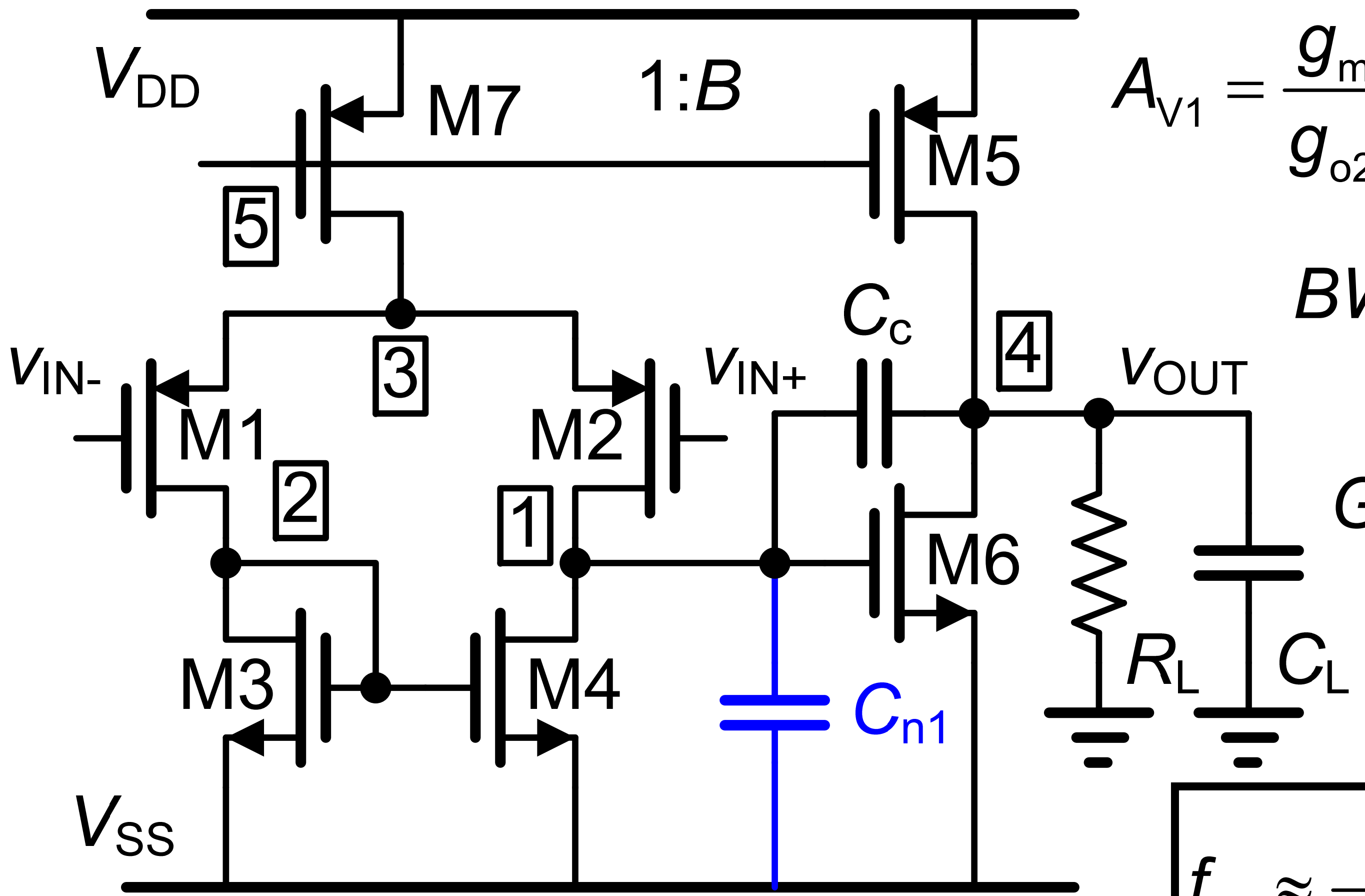


$I_{DS1} = 1.1\ \mu A$ $\quad I_{DS6} = 25\ \mu A$

$$GBW = 1\ \text{MHz}$$
$$C_L = 10\ \text{pF}$$
$$R_L = 10\ \text{k}\Omega$$

$$g_{m1} = 7.5\ \mu S$$
$$g_{o24} = 0.03\ \mu S$$
$$C_{n1} = 0.37\ \text{pF}$$
$$C_c = 1\ \text{pF}$$
$$g_{m6} = 246\ \mu S$$
$$g_{Lo6} = 20\ \mu S$$
$$C_{Ln4} = 10.2\ \text{pF}$$

CMOS密勒OTA：*GBW*



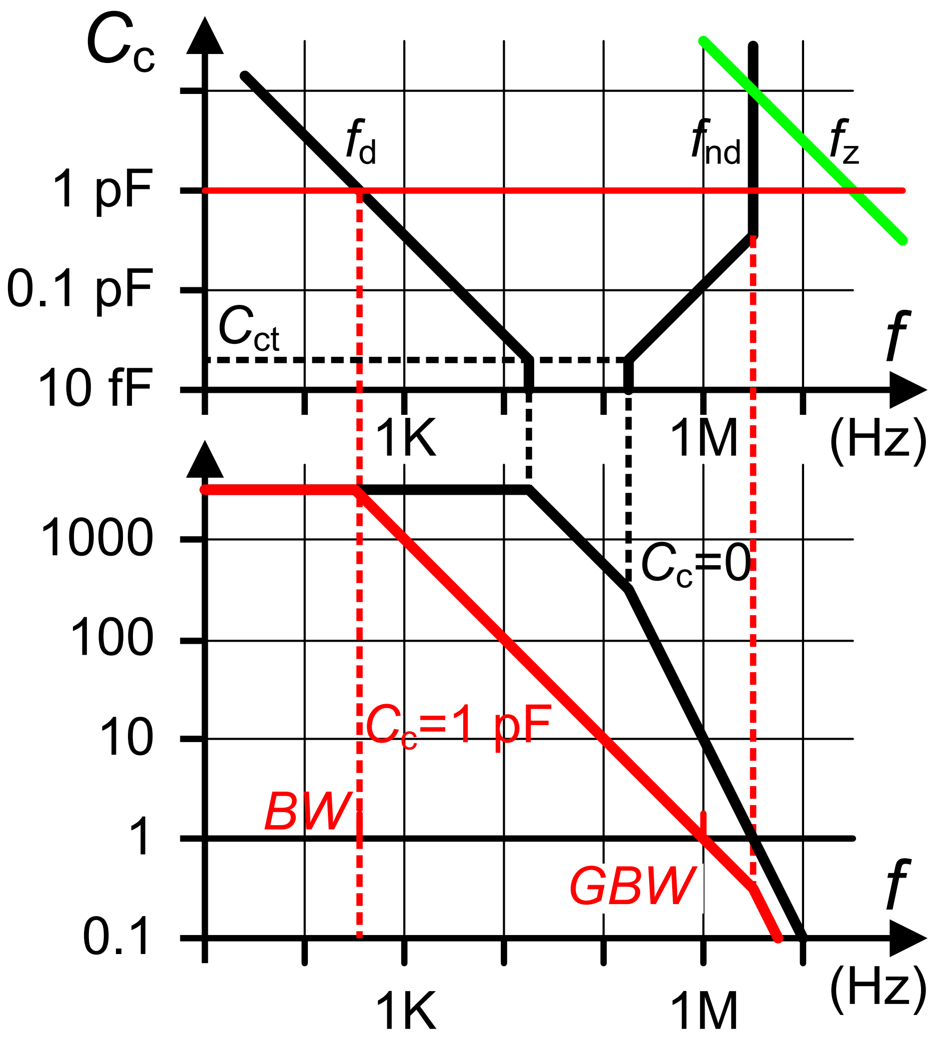
$$A_{V1}=\frac{g_{m1}}{g_{o24}}\quad A_{V2}=\frac{g_{m6}}{g_{Lo6}}$$

$$BW=\frac{g_{o24}}{2\pi A_{V2}C_c}$$

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

$$\boxed{f_{nd}\approx\frac{g_{m6}}{2\pi C_{Ln4}}\frac{1}{1+\frac{C_{n1}}{C_c}}}$$

CMOS密勒OTA：极点和零点



极点分离

从 $C_c \approx \dfrac{C_{n1}}{A_{V2}} \approx 20$ fF 开始

$C_c = 1$ pF足够

$$f_z = \frac{g_{m2}}{2\pi C_c}$$

目录

CMOS密勒OTA：设计规划

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

$$f_{nd} \approx \frac{g_{m6}}{2\pi C_{Ln4}} \frac{1}{1+\frac{C_{n1}}{C_c}}$$

$GBW = 100\ \mathrm{MHz}$ $C_L = 2\ \mathrm{pF}$

两个方程，

三个变量g_{m1}、g_{m6}、C_c？

求解：选择g_{m1}或g_{m6}或C_c？

选择 C_c=1 pF 有问题吗?

CMOS密勒OTA设计：参变量C_c 1

选择 $C_c \approx 3C_{n1}$ 得 $GBW = \dfrac{g_{m1}}{2\pi C_c}$ 和 $3GBW \approx \dfrac{g_{m1}}{2\pi C_{Ln4}} \dfrac{1}{1.3}$

$$\boxed{\frac{g_{m6}}{g_{m1}} \approx 4\frac{C_L}{C_c}}$$

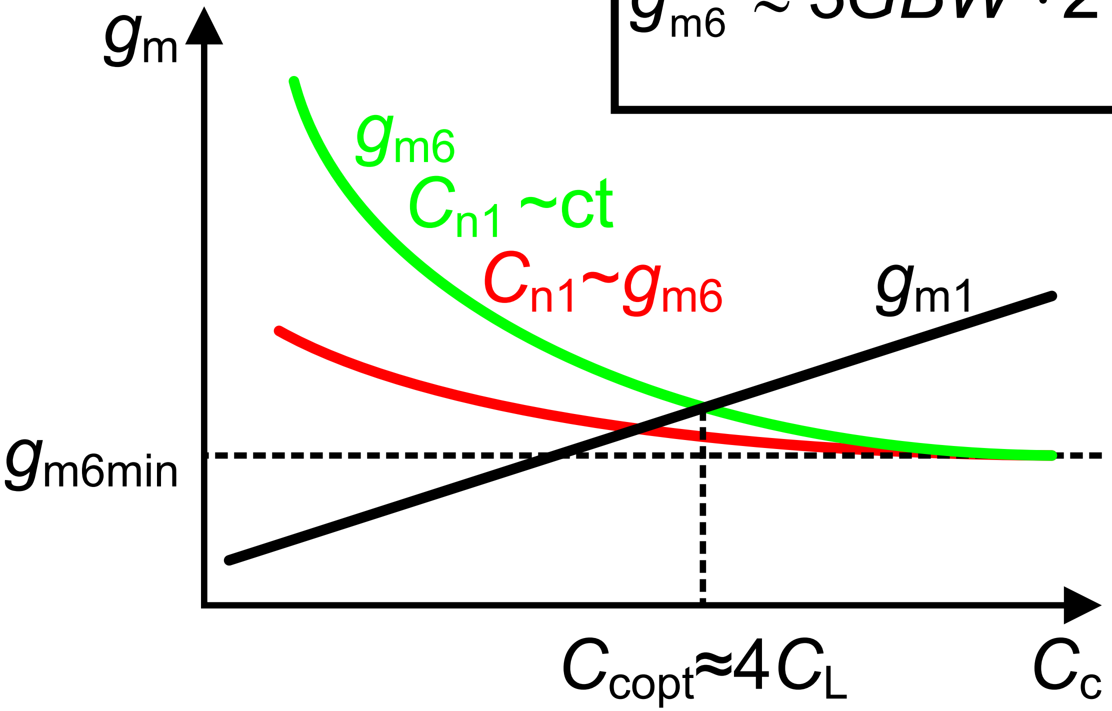
$GBW = 100\ \text{MHz} \quad C_L = 2\ \text{pF}$

选择 $C_{n1} < C_c < C_L$

选择 $C_c = 1\ \text{pF}$ 得 $g_{m1} = 0.63\ \text{mS}$ 和 $g_{m6} = 5.0\ \text{mS}$

CMOS密勒OTA设计：参变量C_c 2

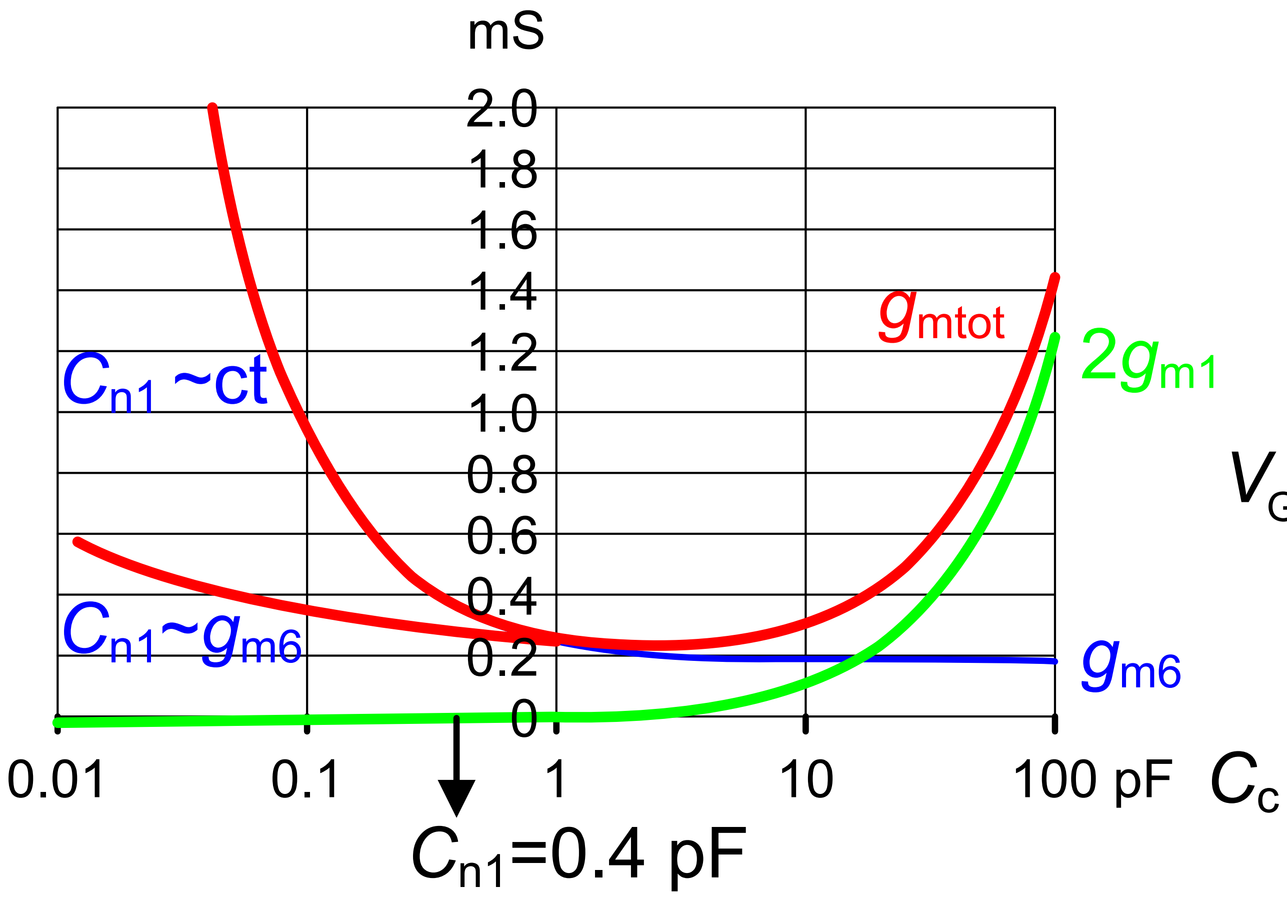
$$g_{m6} \approx 3GBW \cdot 2\pi C_{Ln4} \cdot \left(1 + \frac{C_{n1}}{C_c}\right)$$



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

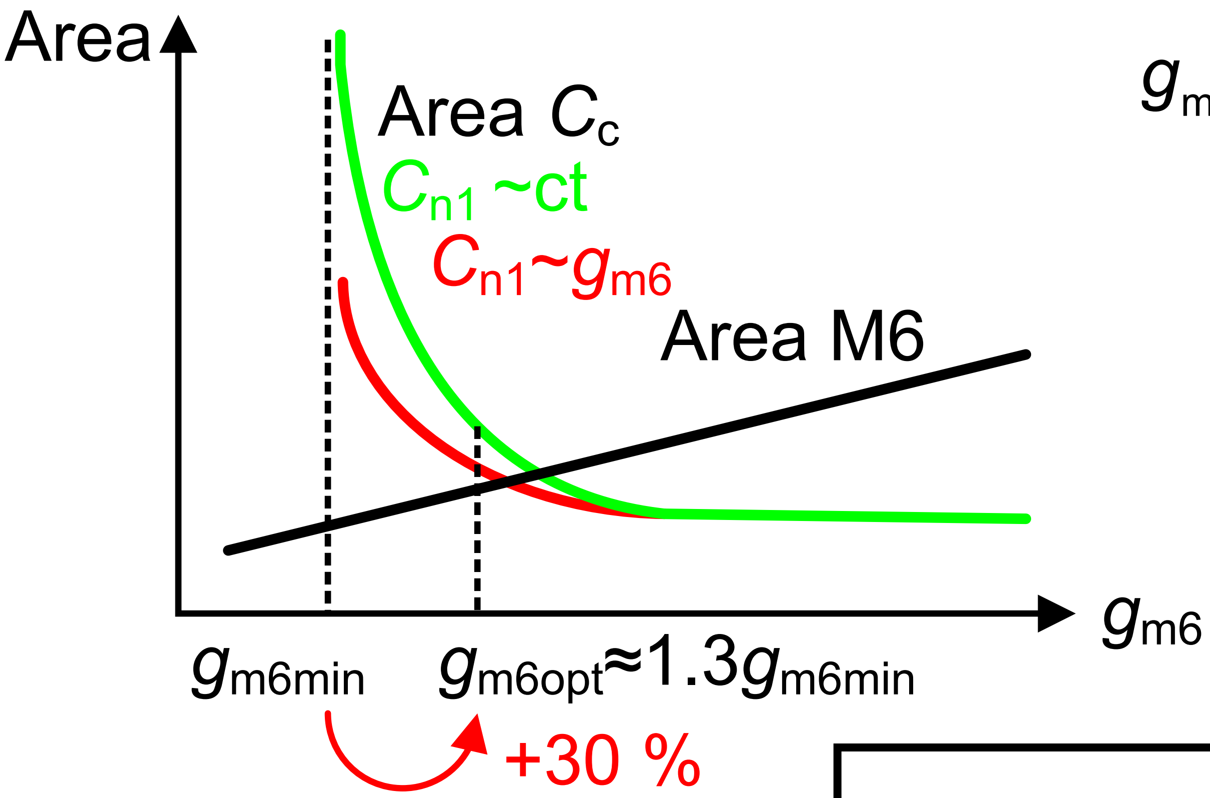
$$g_{m6min} = 3GBW(2\pi C_L)$$

1 MHz CMOS密勒OTA：参变量C_c



$$GBW = 1\ \text{MHz}$$
$$C_L = 10\ \text{pF}$$
$$C_{n1} = 0.4\ \text{pF}$$
$$K' = 20\ \mu\text{A/V}^2$$
$$V_{GS} - V_T = 0.2\ \text{V}$$
$$L = 10\ \mu\text{m}$$

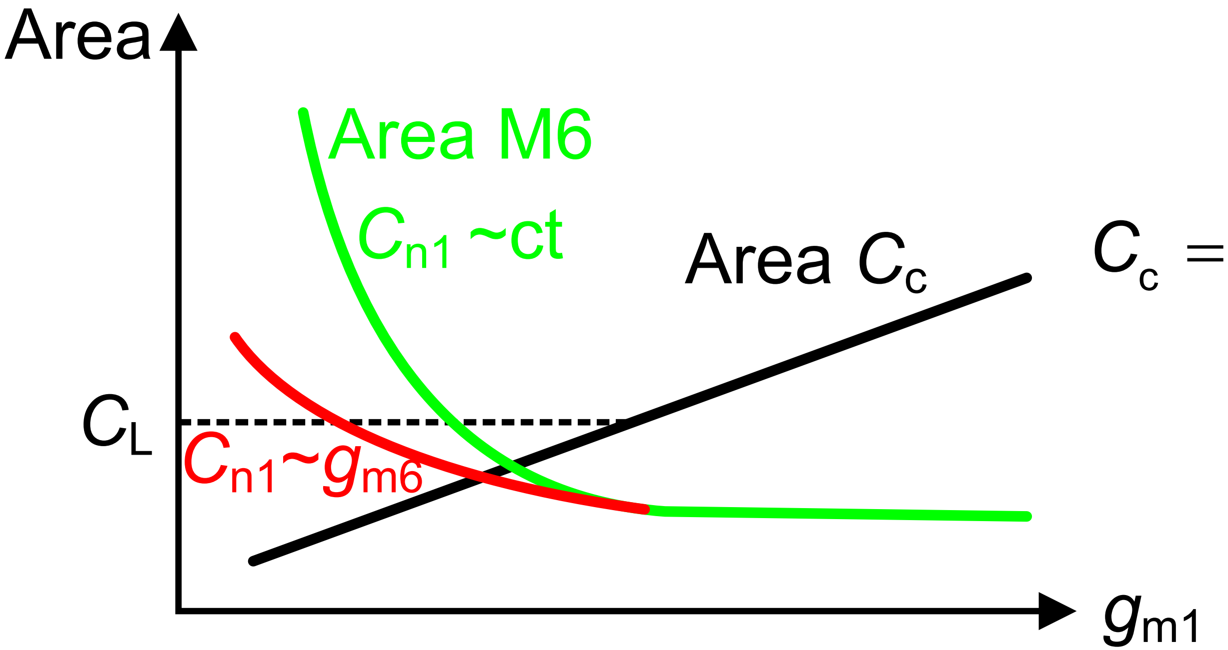
CMOS密勒OTA设计：参变量g_{m6}



$$g_{m6min} = 3GBW(2\pi C_L)$$

$$\boxed{g_{m6} \approx 3GBW \cdot 2\pi C_{Ln4} \cdot (1 + \frac{C_{n1}}{C_c})}$$

CMOS密勒OTA设计：参变量g_{m1}



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

$$\boxed{g_{m6} \approx 3GBW \cdot 2\pi C_{Ln4} \cdot (1 + \frac{C_{n1}}{g_{m1}} 2\pi GBW)}$$

高速密勒OTA的优化设计 1

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

$$f_{nd} = \frac{g_{m6}}{2\pi C_L}\frac{1}{1+C_{n1}/C_c}$$

$$C_L = \alpha C_c \qquad \alpha \approx 2$$

$$C_c = \beta C_{n1} = \beta C_{GS6} \qquad \beta \approx 3$$

$$f_{nd} = \gamma GBW \qquad \gamma \approx 2$$

$$C_{GS} = kW \qquad k = 2\ \mathrm{fF}/\mu\mathrm{m}$$

$$GBW = \frac{f_{nd}}{\gamma} = \frac{g_{m6}}{2\pi C_L}\frac{1}{\gamma(1+1/\beta)} = \frac{f_{T6}}{\alpha\beta\gamma(1+1/\beta)}$$

$$C_L = \alpha C_c = \alpha\beta C_{n1} = \alpha\beta C_{GS6} = \alpha\beta k W_6$$

如果$C_L \uparrow$ 则$W_6 \uparrow$

高速密勒OTA的优化设计 2

代入f_{T6}得

$$f_{T6} = \frac{g_{m6}}{2\pi C_{GS6}}$$

$$f_{T6} = \frac{1}{L_{6\min}} \frac{13.5}{1 + 2.8L_{6\min}/V_{GST6}}$$

L的单位为μm
f_T的单位为GHz

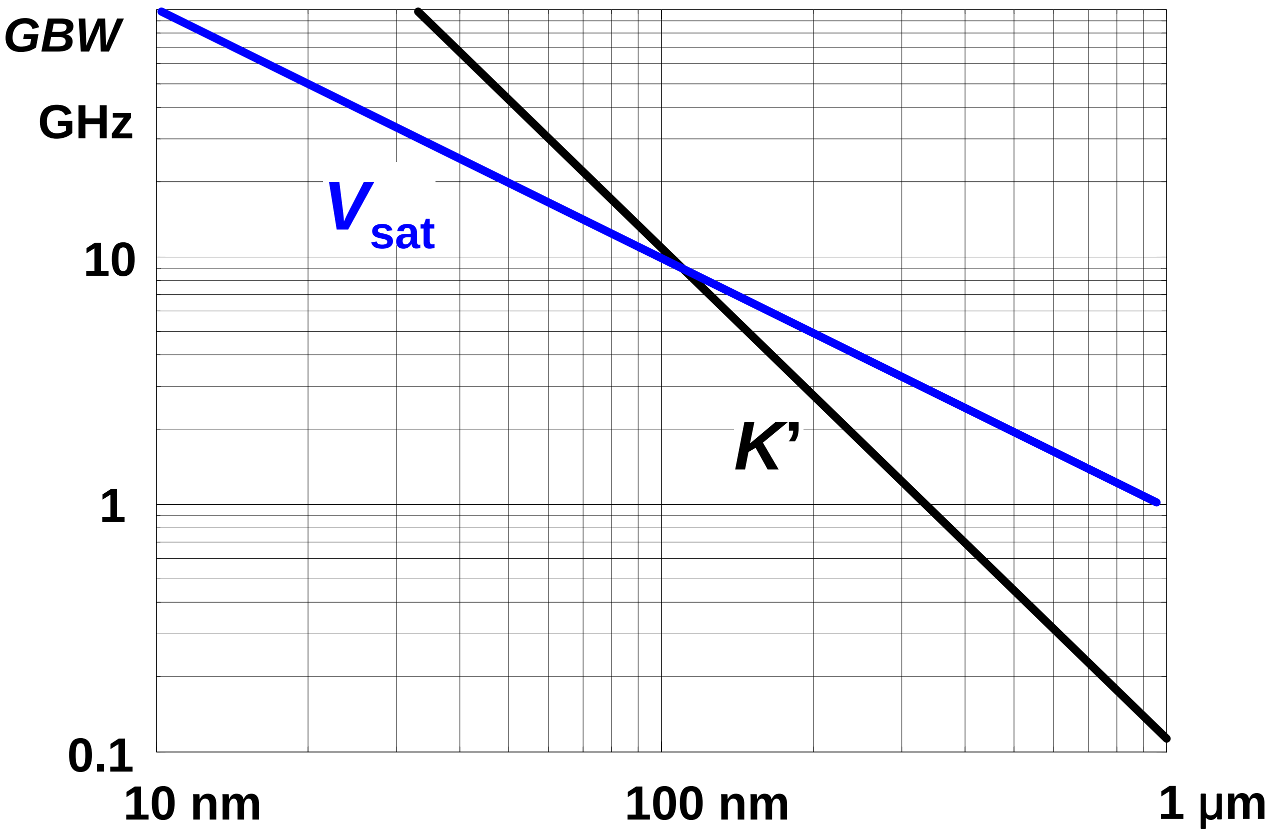
$$\boxed{GBW = \frac{f_{T6}}{\alpha\beta\gamma(1+1/\beta)}}$$

GBW不是由C_L决定，只由f_T决定！
f_T由L(和V_{GST})决定!!!

当V_{GST}=0.2 V，L_{min}<65 nm;

或V_{GST}=0.5 V，L_{min}<0.18 μm 时，晶体管进入速度饱和区

最大GBW与沟道长度L_{min}



$$V_{GS} - V_T = 0.2\ \text{V}$$

$$\alpha \approx 2$$

$$\beta \approx 3$$

$$\gamma \approx 2$$

$$16x$$

$$GBW \approx \frac{f_{T6}}{16}$$

高速密勒OTA的设计优化

- 选择$\alpha\,\beta\,\gamma$
- 由给定的*GBW*得到最小的f_{T6}
- 由选定的$(V_{GS6}-V_T)$
  选择最大沟道长度L_6(最大化增益)
- 由C_L计算W_6，
  确定I_{DS6}
- 由α以及C_L计算C_c
- 由C_c计算g_{m1}和I_{DS1}
- 由g_{m1}或C_c确定噪声

设计练习：*GBW* = 0.4 GHz & C_L = 5 pF

- 选择$\alpha\,\beta\,\gamma$ — 2 3 2
- 由给定的*GBW*得到最小的f_{T6} — $f_{T6} = 6.4$ GHz
- 由选定的$(V_{GS6} - V_T)$，
  选择最大沟道长度L_6 (最大化增益) — $L_6 = 0.5$ μm
- L_6取最小沟道长度L_{min}
- 由C_L计算W_6， — $W_6 = 417$ μm
  确定I_{DS6} ($K_n' = 70$ μA/V^2) — $I_{DS6} = 2.3$ mA
  确定C_{n1} ($k = 2$ fF/μm) — $C_{n1} = 0.83$ pF
- 由α以及C_L计算C_c — $C_c = 2.5$ pF
- 由C_c计算g_{m1}和I_{DS1} — $I_{DS1} = 0.63$ mA

低速密勒OTA的优化设计 1

$$\boxed{GBW = \frac{f_{T6}}{\alpha\beta\gamma(1+1/\beta)}}$$

$$\frac{f_T}{f_{TH}} = \sqrt{i}\left(1 - e^{-\sqrt{i}}\right) \approx \sqrt{i}\left(1 - 1 + \sqrt{i}\right) \approx i \quad \text{当} i \text{较小时}$$

$$f_{TH} = \frac{3}{2}\frac{2\mu kT/q}{2\pi L^2}$$

GBW不是由C_L决定，只由f_T决定！

f_T由L和i 决定!!!

低速密勒OTA的优化设计 2

- 选择$\alpha\beta\gamma$
- 由给定的GBW得到最小的f_{T6}
- 由给定的f_{TH6}
  选择最大沟道长度L_6 (最大增益)
- 计算i_6
- 由C_{L}计算W_6，
  确定I_{DST6}和I_{DS6}
- 由α以及C_{L}计算C_{c}
- 由C_{c}计算g_{m1}和I_{DS1}
- 由g_{m1}或C_{c}确定噪声

设计练习：*GBW* = 1 MHz & C_L= 5 pF

● 选择$\alpha\,\beta\,\gamma$	2 3 2
● 由*GBW*=1 MHz得到最小的f_{T6}	$f_{T6}=16$ MHz
● 由给定的f_{TH6}	$f_{TH6}=2$ GHz
选择最大沟道长度L_6(最大增益)	$L_6=0.5$ μm
● 反型系数i	$i=0.008$
● 由C_L计算W_6，	$W_6=417$ μm
确定I_{DST6} ($K_n^{'}=70$ μA/V^2)	$I_{DST6}=0.33$ mA
确定I_{DS6}	$I_{DS6}=2.7$ μA
确定C_{n1}($k=2$ fF/μm)	$C_{n1}=0.83$ pF
● 由α以及C_L计算C_c	$C_c=2.5$ pF
● 由C_c计算g_{m1}和I_{DS1}	$I_{DS1}=1.6$ μA

目录

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- GBW和相位裕度的设计
- 其他指标：输入范围、输出范围、*SR*…

CMOS密勒OTA：规范 1

1. Introductory analysis

1.1 DC currents and voltages on all nodes

1.2 Small-signal parameters of all transistors

2. DC analysis

2.1 Common-mode input voltage range vs supply Voltage

2.2 Output voltage range vs supply Voltage

2.3 Maximum output current (sink and source)

CMOS密勒OTA：规范 2

3. AC and transient analysis

3.1 AC resistance and capacitance on all nodes

3.2 Gain versus frequency : *GBW*, …

3.3 Gainbandwidth versus biasing current

3.4 Slew rate versus load capacitance

3.5 Output voltage range versus frequency

3.6 Settling time

3.7 Input impedance vs frequency (open & closed loop)

3.8 Output impedance vs frequency (open & closed loop)

CMOS密勒OTA：规范 3

4. Specifications related to offset and noise

4.1 Offset voltage versus common-mode input Voltage

4.2 *CMRR* versus frequency

4.3 Input bias current and offset

4.4 Equivalent input noise voltage versus frequency

4.5 Equivalent input noise current versus frequency

4.6 Noise optimization for capacitive/inductive sources

4.7 *PSRR* versus frequency

4.8 Distortion

CMOS密勒OTA：规范 4

5. Other second-order effects

5.1 Stability for inductive loads

5.2 Switching the biasing transistors

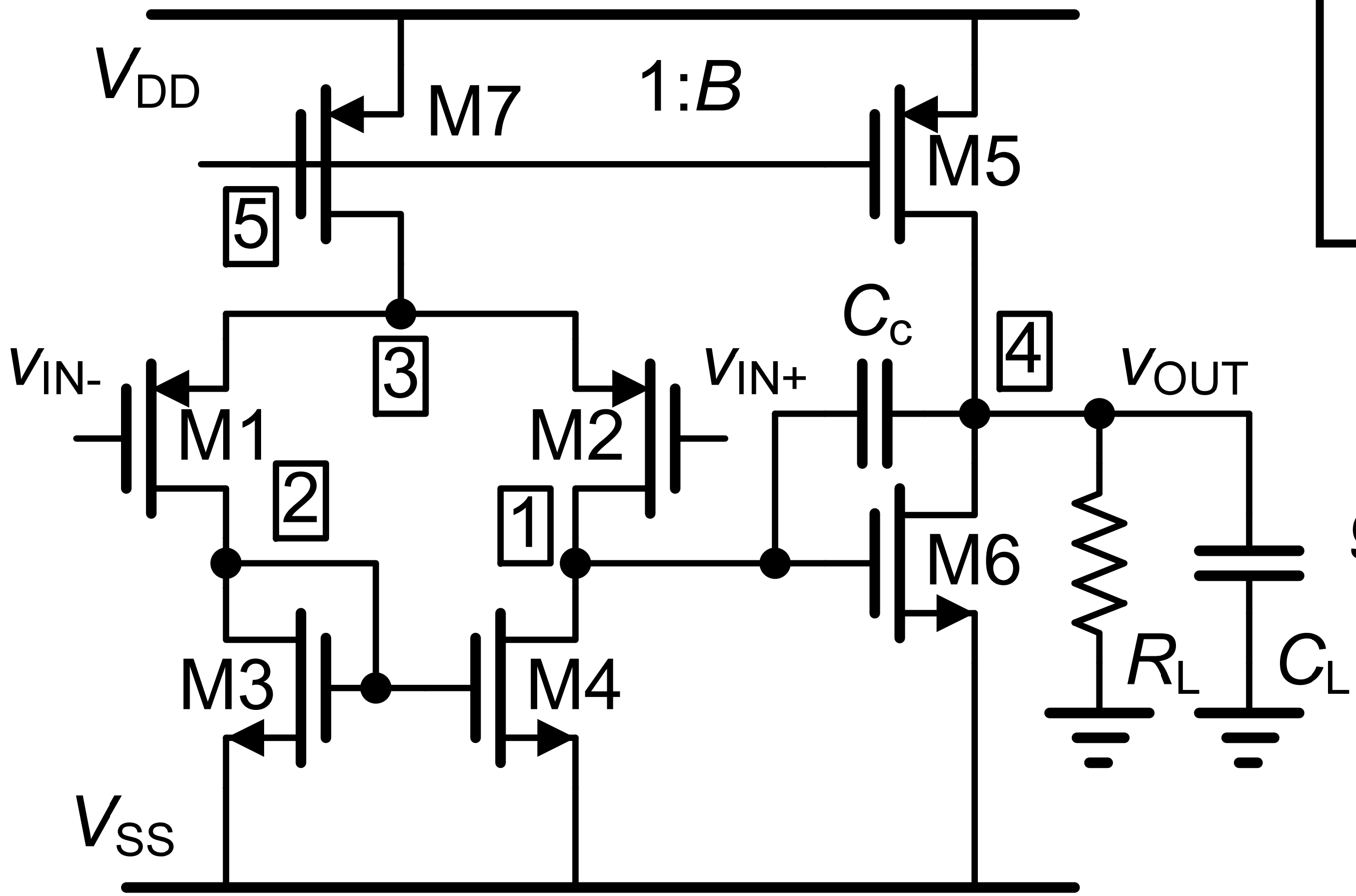
5.3 Switching or ramping the supply voltages

5.4 Different supply voltages, temperatures, ...

MCO：其他规范

- Common-mode input voltage range
- Output voltage range
- Slew Rate
- Output impedance
- Noise

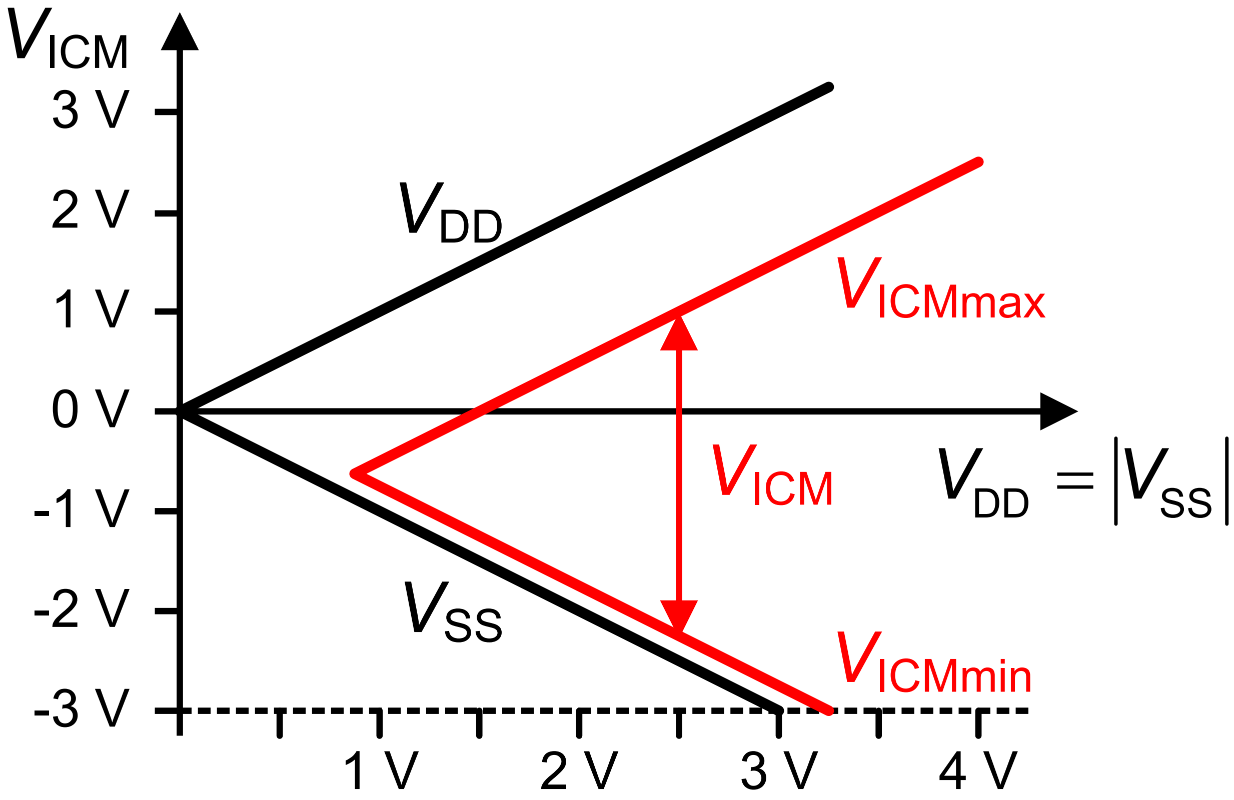
CMOS密勒OTA



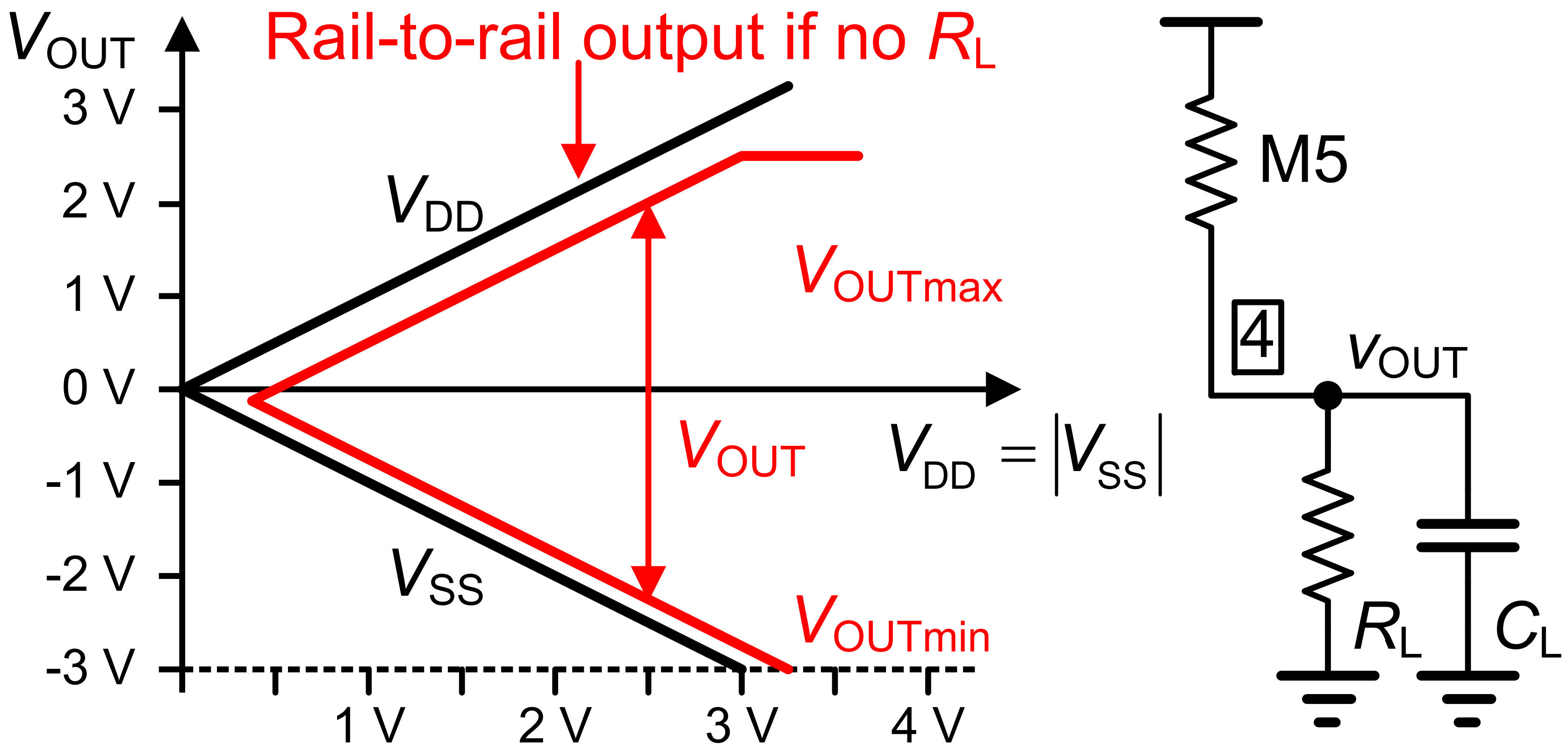
$$GBW = 1\ \text{MHz}$$
$$C_L = 10\ \text{pF}$$
$$R_L = 10\ \text{k}\Omega$$

$$g_{m1} = 7.5\ \mu\text{S}$$
$$I_{DS1} = 1.1\ \mu\text{A}$$
$$g_{o24} = 0.03\ \mu\text{S}$$
$$g_{m6} = 246\ \mu\text{S}$$
$$I_{DS6} = 25\ \mu\text{A}$$
$$C_c = 1\ \text{pF}$$
$$g_{Lo6} = 20\ \mu\text{S}$$

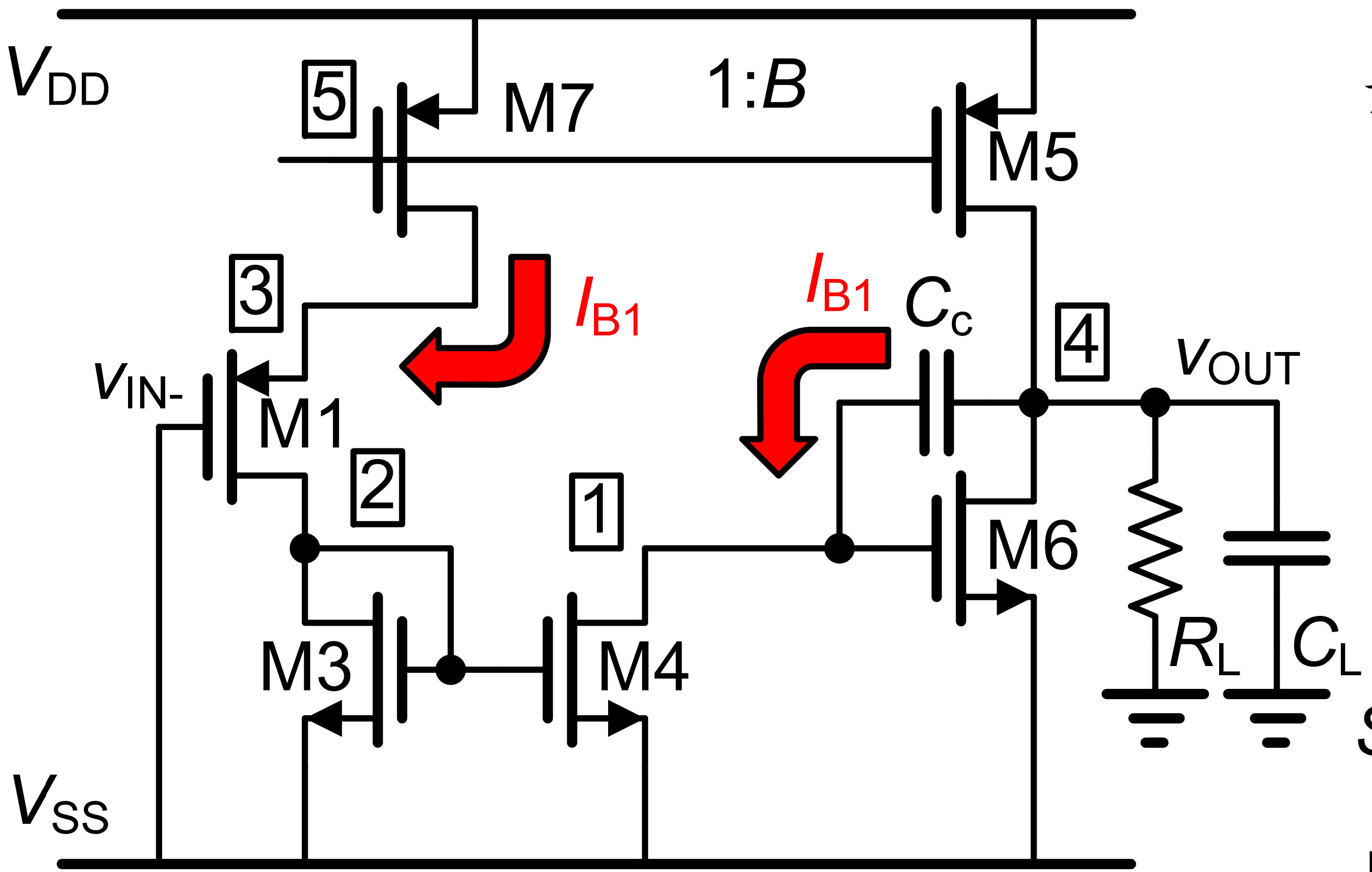
CMOS密勒OTA：共模输入电压范围



CMOS密勒OTA：输出电压范围



CMOS密勒OTA：压摆率 1



开关输入：

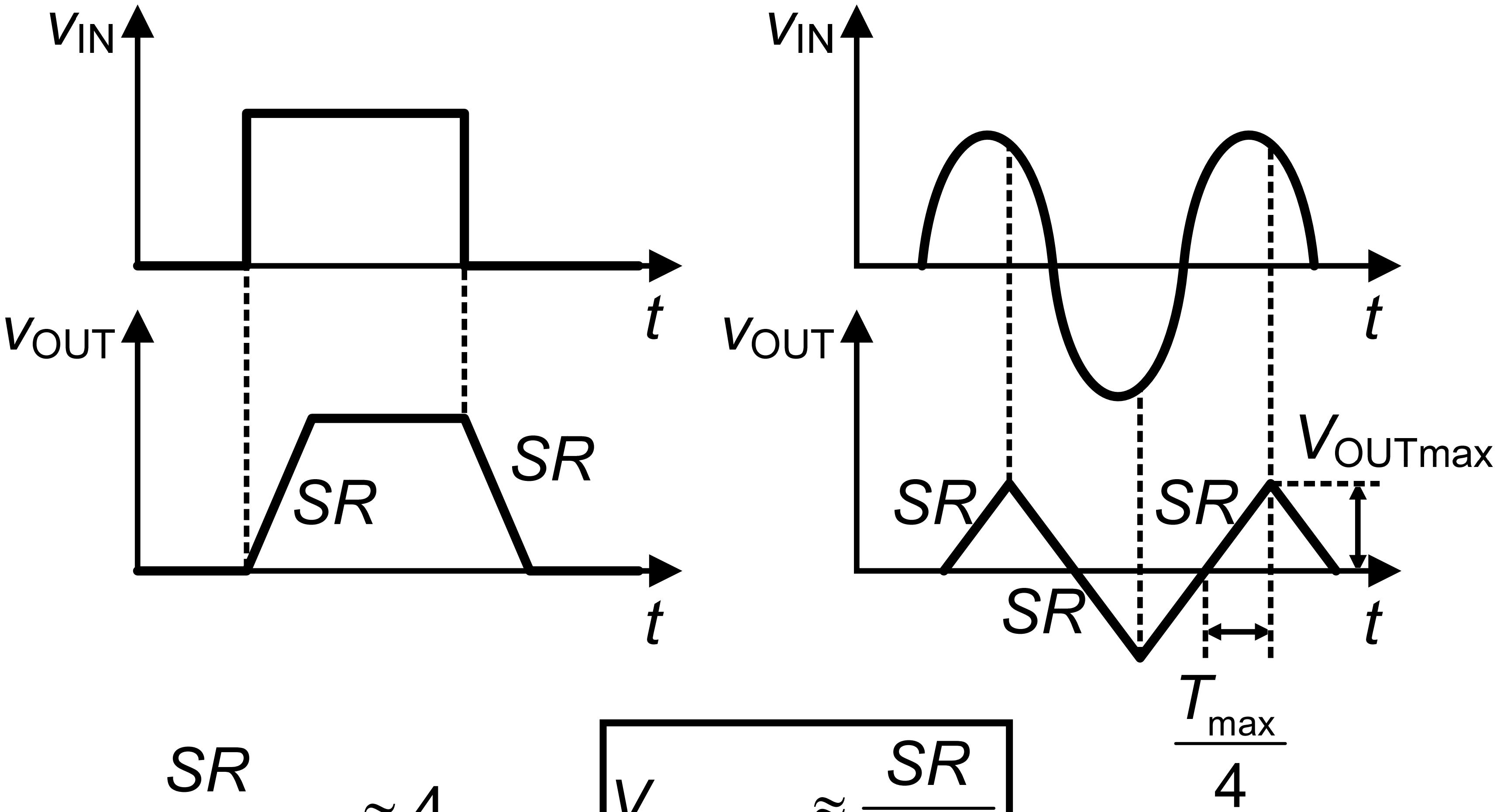
$v_{IN+} > 1$

$v_{IN\_} > 0$

$$SR = \frac{\Delta V_{OUT}}{\Delta t}$$

$$\boxed{SR = \frac{I_{B1}}{C_C}}$$

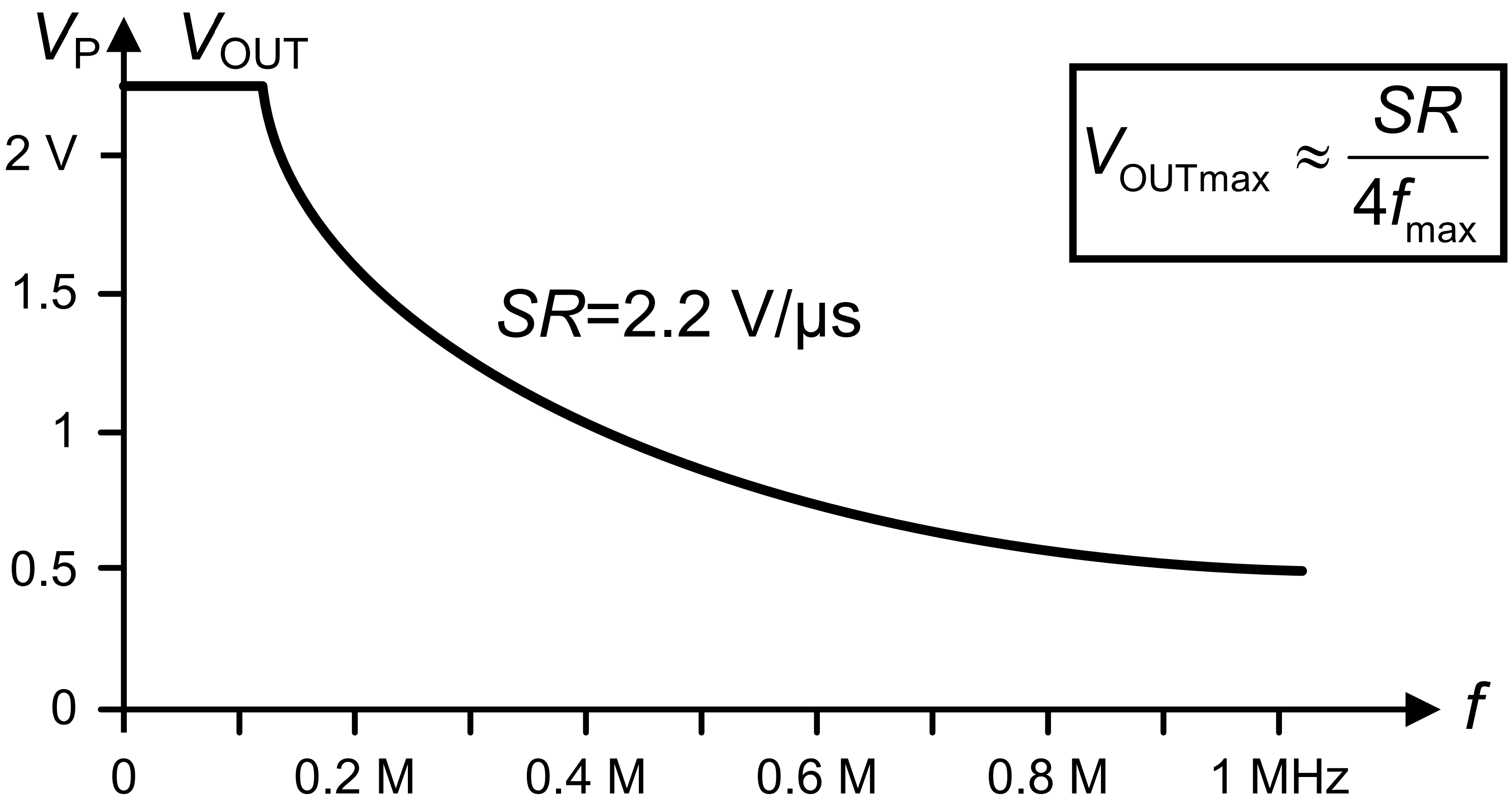
CMOS密勒OTA：压摆率 2



$$\frac{SR}{V_{OUTmax} f_{max}} \approx 4$$

$$\boxed{V_{OUTmax} \approx \frac{SR}{4 f_{max}}}$$

CMOS密勒OTA：压摆率 3



GBW与SR的关系

$$\boxed{\frac{SR}{GBW} = 4\pi\frac{I_{DS1}}{g_{m1}}}$$

x 10

$$\frac{I_{DS1}}{g_{m1}} = \frac{V_{GS1} - V_T}{2} \approx 0.1 \;...\; 0.3\ \mathrm{V} \quad \text{MOST(si)}$$

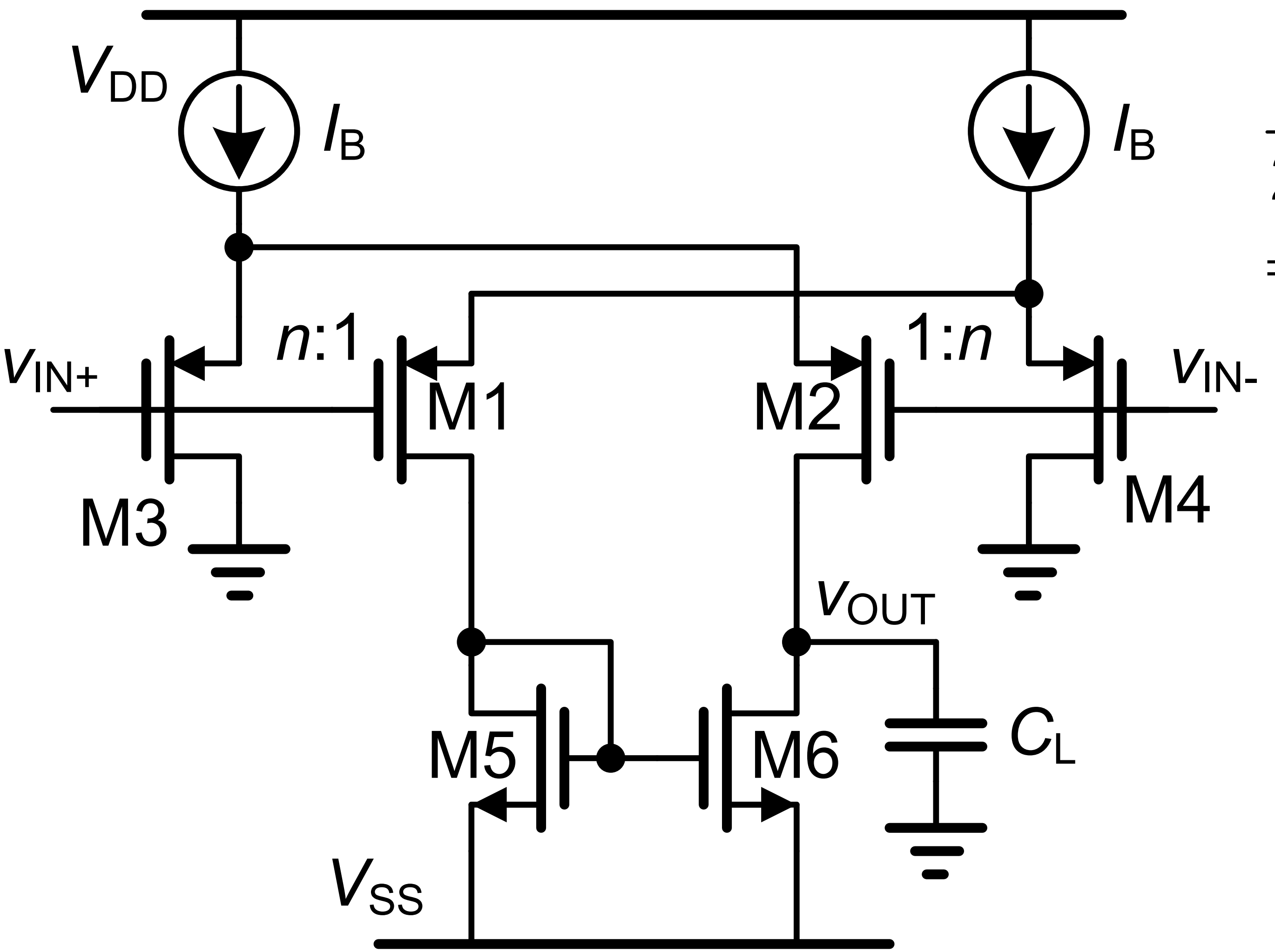
$$\frac{I_{DS1}}{g_{m1}} = \frac{nkT}{q} \approx 30 \;...\; 50\ \mathrm{mV} \quad \text{MOST(wi)}$$

$$\frac{I_{CE1}}{g_{m1}} = \frac{kT}{q} \approx 26\ \mathrm{mV} \quad \text{Bipolar trans.}$$

$$\frac{I_{CE1}}{g_{m1}} = (1 + g_{m1}R_E)\frac{kT}{q} \approx 0.5\ \mathrm{V} \quad 接R_E$$

Ref.: Solomon, JSSC Dec 74, 314-332

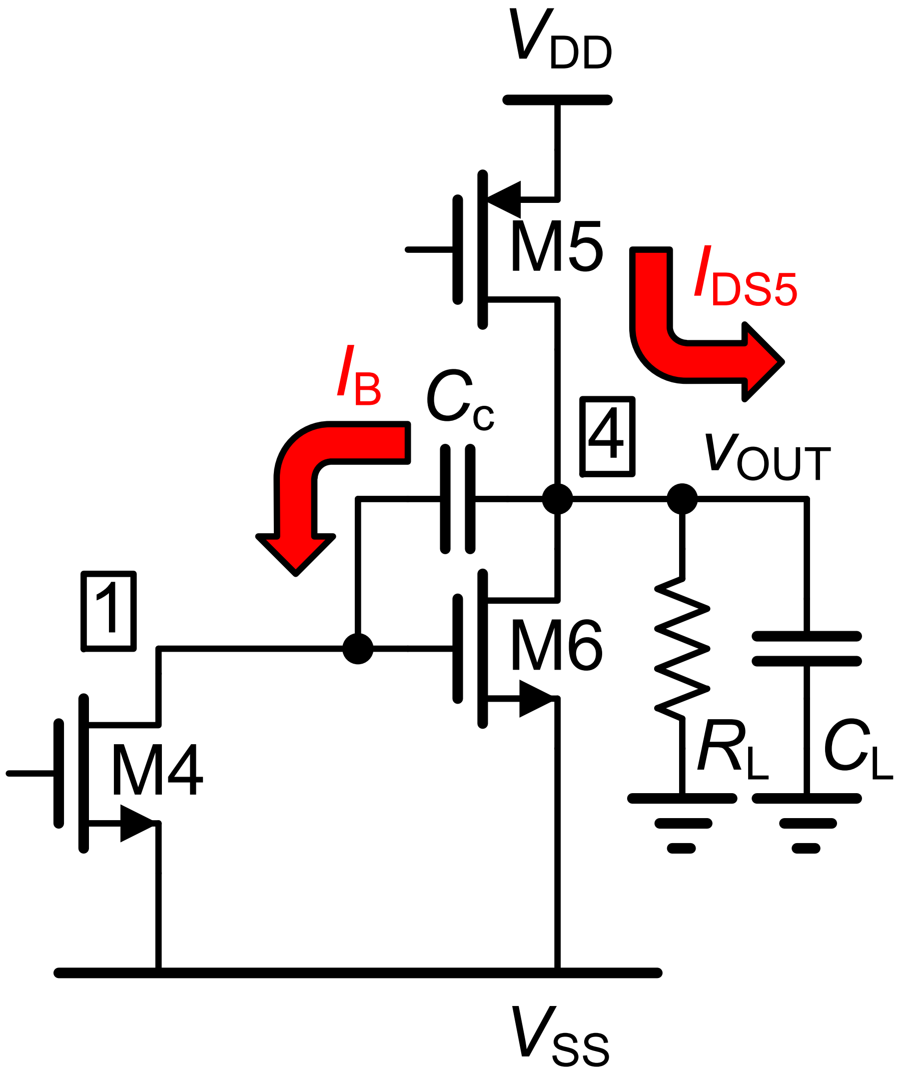
提高压摆率的方法



$$\frac{SR}{2\pi GBW} = x(n+1)$$

Ref.: Schmoock, JSSC Dec.75, 407-411

内部和外部压摆率



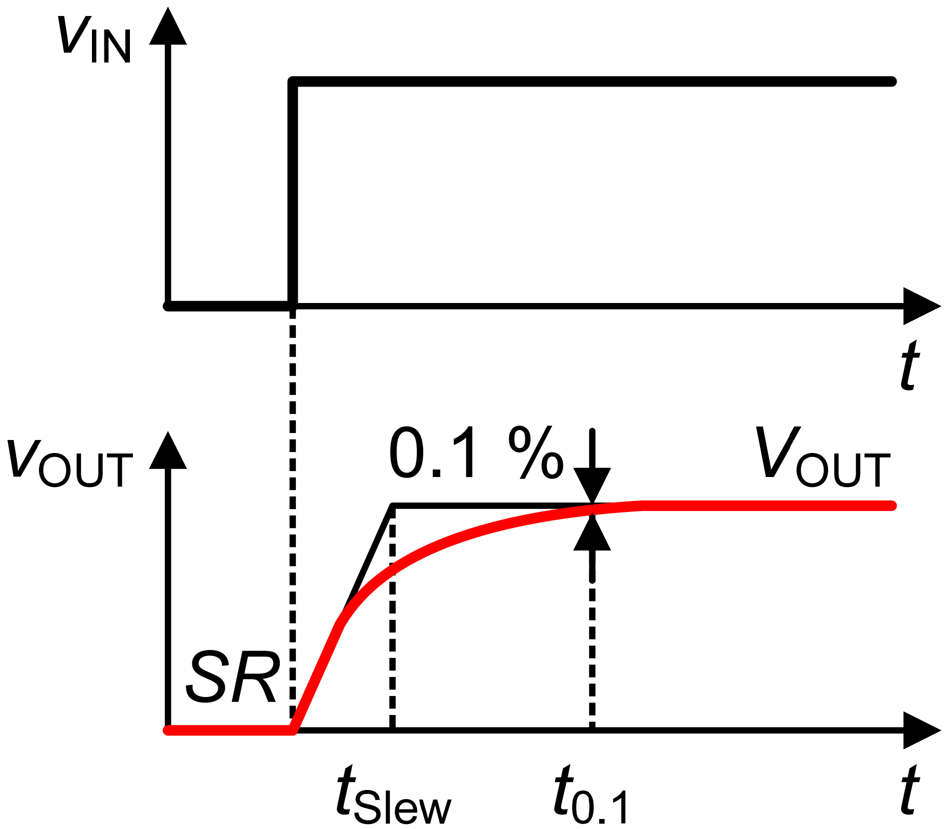
$$SR_{int} = \frac{I_B}{C_c}$$

$$SR_{ext} = \frac{I_{DS5}}{C_L}$$ 比较大！

$$\frac{g_{m6}}{g_{m1}} = 4\frac{C_L}{C_c} = \frac{I_{DS5}}{I_{DS1}}$$

$$\frac{I_{DS5}}{C_L} \approx 2\frac{2I_{DS1}}{C_c}$$

压摆率和建立时间



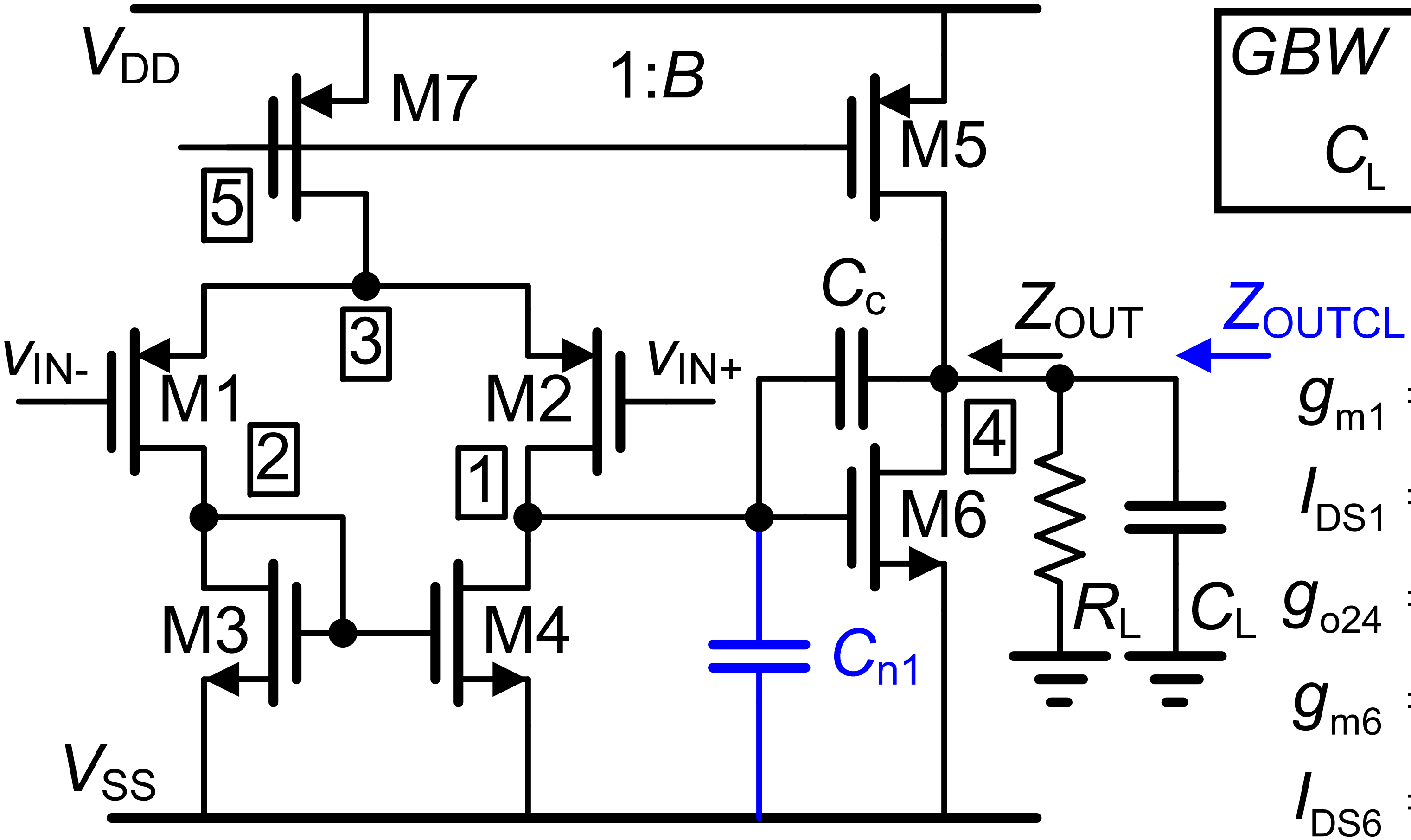
$$t_{\text{TOT}} = t_{\text{Slew}} + t_{0.1}$$

$$t_{\text{Slew}} = \frac{V_{\text{OUT}}}{SR}$$

$$t_{0.1} = \frac{7}{2\pi BW}$$

$$\ln(1000) \approx 7$$

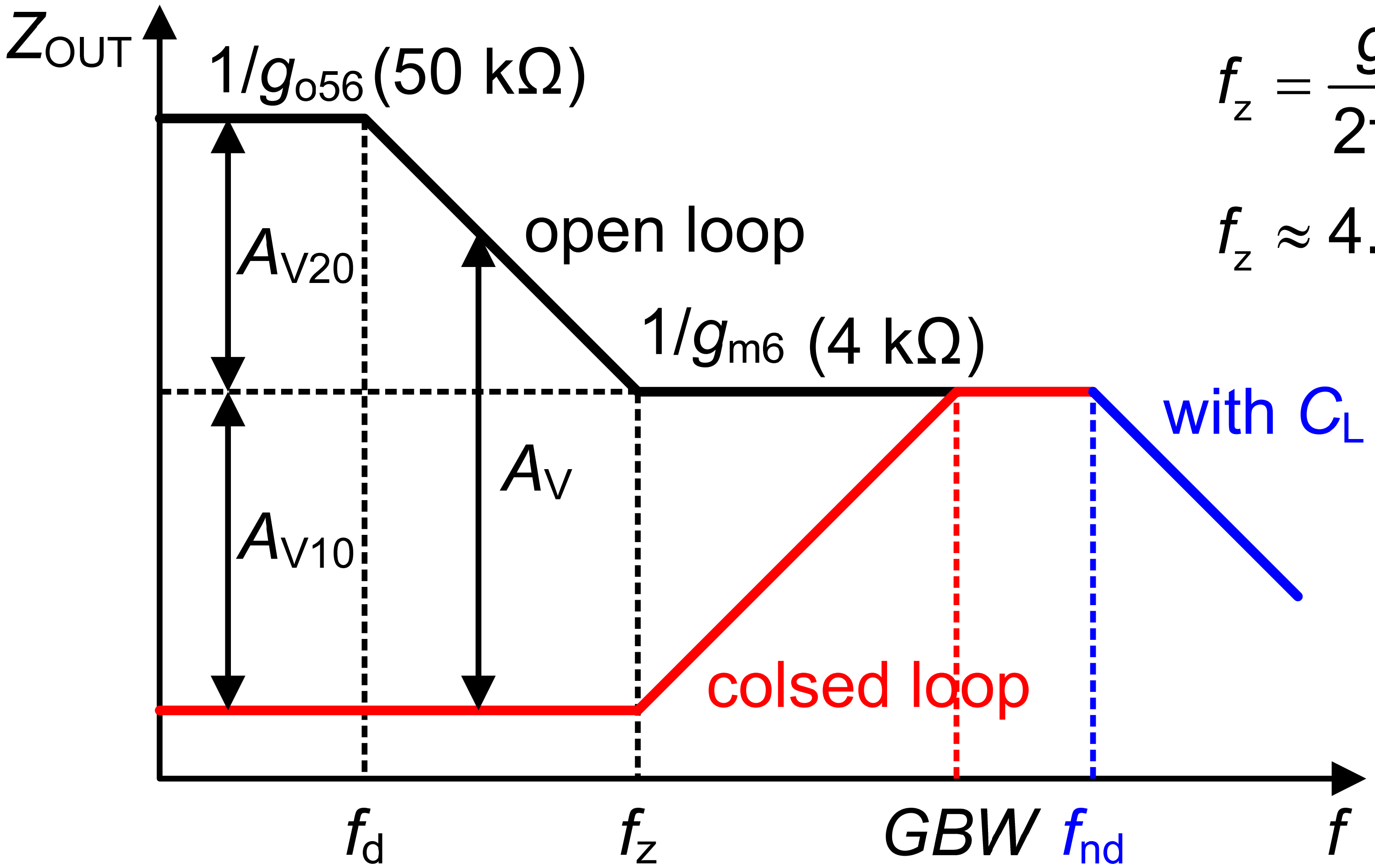
CMOS密勒OTA输出阻抗



$$GBW = 1\ \mathrm{MHz}$$
$$C_L = 10\ \mathrm{pF}$$

$$g_{m1} = 7.5\ \mu\mathrm{S}$$
$$I_{DS1} = 1.1\ \mu\mathrm{A}$$
$$g_{o24} = 0.03\ \mu\mathrm{S}$$
$$g_{m6} = 246\ \mu\mathrm{S}$$
$$I_{DS6} = 25\ \mu\mathrm{A}$$
$$C_c = 1\ \mathrm{pF}$$
$$g_{L6} = 20\ \mu\mathrm{S}$$

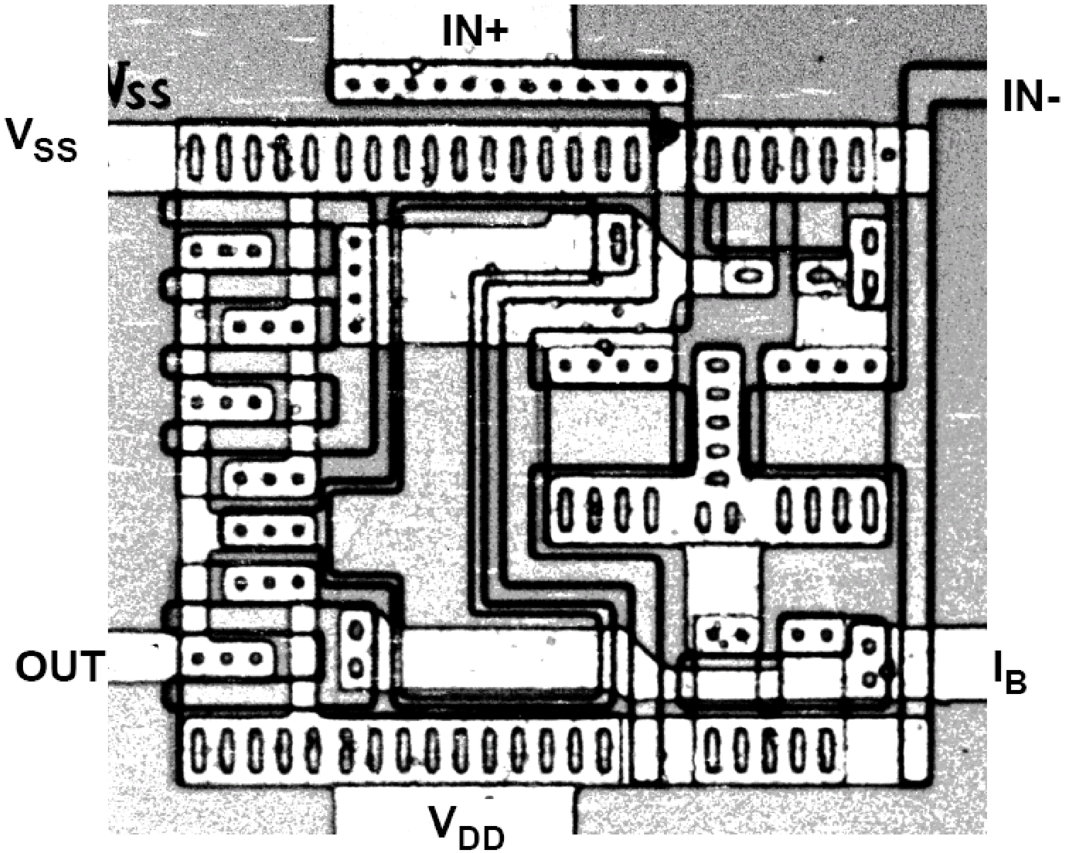
CMOS密勒OTA：输出阻抗Z_{OUT}



$$f_z = \frac{g_{o24}}{2\pi C_c}$$

$$f_z \approx 4.8\text{ kHz}$$

CMOS密勒OTA版图照片



$$GBW = 1\ \text{MHz}$$

$$C_L = 10\ \text{pF}$$

$$SR = 2.2\ \text{V/μs}$$

$$V_{DD} = 5\ \text{V}$$

$$I_{TOT} = 27\ \text{μA}$$

370 MHzpF/mA

密勒CMOS OTA：练习

已知GBW=50 MHz和C_L=2 pF：选用最小是I_{DS6}！

工艺参数

$C_L = 2\ \text{pF}$、$L_{min} = 0.5\ \mu\text{m}$、$K_n^{'} = 50\ \mu\text{A/V}^2$、$K_p^{'} = 25\ \mu\text{A/V}^2$

$C_{GS} = kW(= C_{ox}WL_{min})$ 和 $k = 2\ \text{fF}/\mu\text{m}$

$V_{GS} - V_T = 0.2\ \text{V}$

求

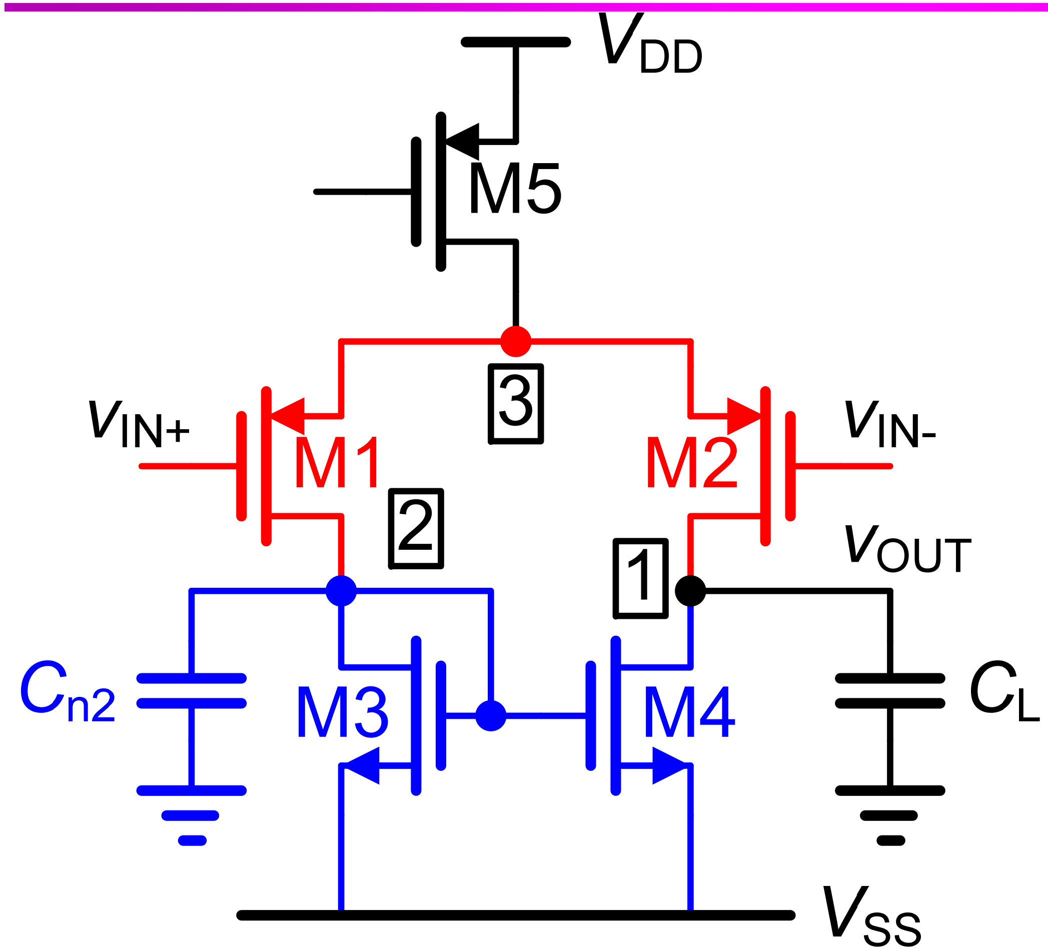
g_{m6}、I_{DS6}、W_6、$C_{n1} = C_{GS6}$、C_c、g_{m1}、I_{DS1}、$\overline{dv_{ineq}^2}$ 和 v_{inRMS}

运算放大器的重要结构

目录

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

CMOS简单OTA



差分对

电流镜

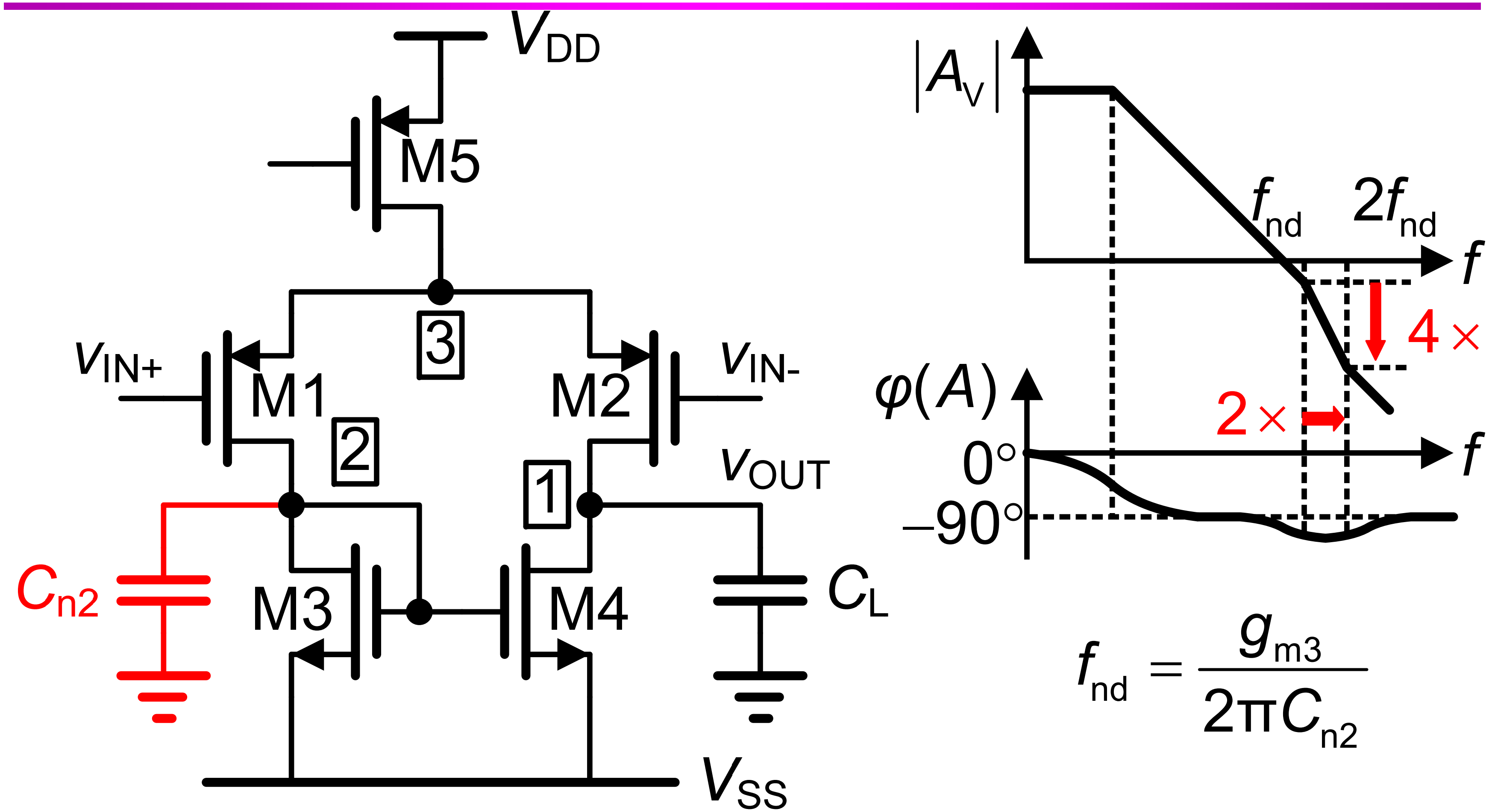
$$GBW = \frac{g_{m1}}{2\pi C_L}$$

$$f_{nd} = \frac{g_{m3}}{2\pi C_{n2}}$$

$$f_{nd} \approx \frac{f_{T3}}{4} \quad ?$$

$$C_{n2} \approx 2C_{GS3} + C_{DB3} + C_{DB1} \approx 4C_{GS3}$$

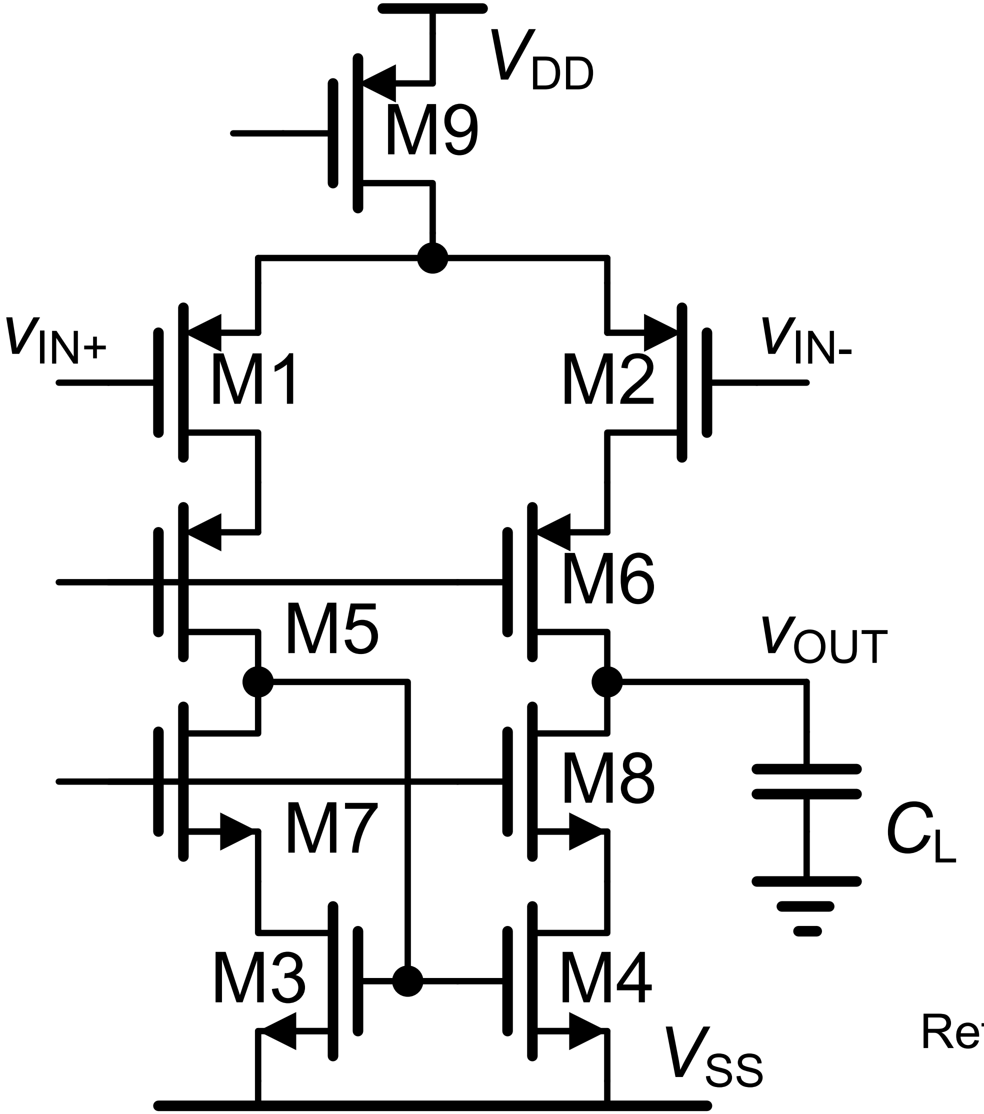
CMOS简单OTA： f_{nd} & f_z



$$f_{nd} = \frac{g_{m3}}{2\pi C_{n2}}$$

$$PM = 90° - \arctan\left(\frac{GBW}{f_{nd}}\right) + \arctan\left(\frac{GBW}{2f_{nd}}\right) \approx 85°$$

CMOS套筒OTA

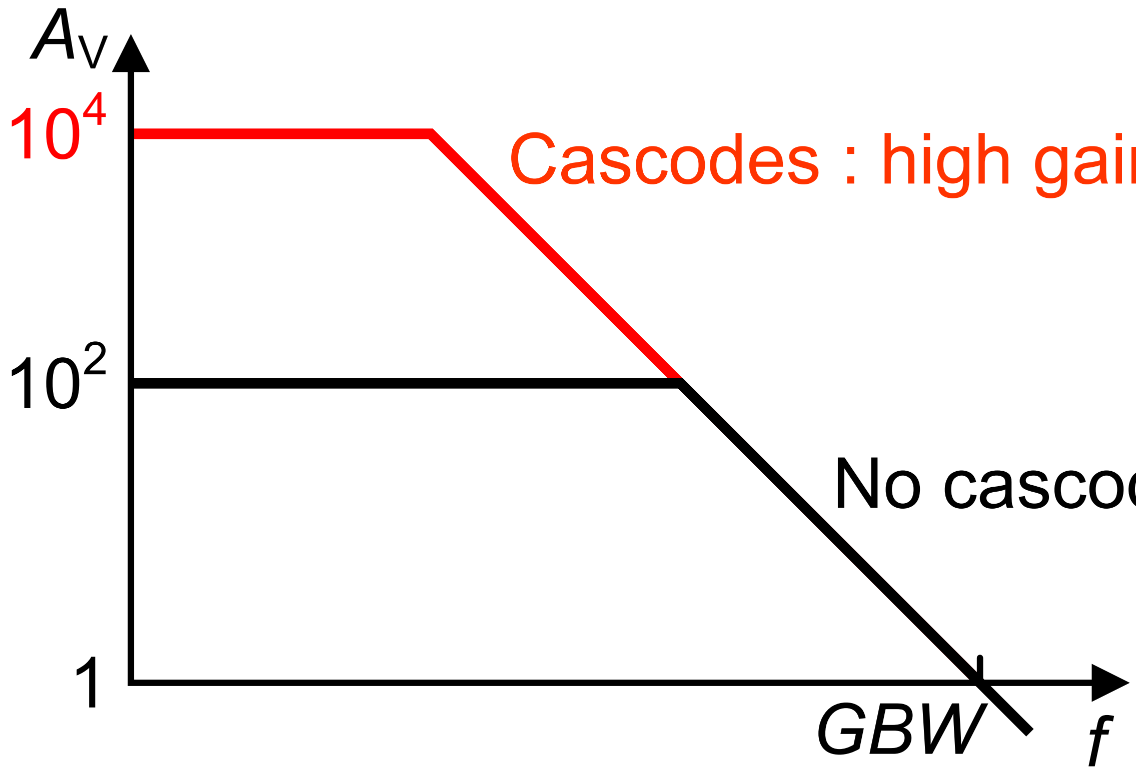


频率较低时
更大增益

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

Ref.: Gulati, JSSC Dec.98, 2010-2019

低频时共源共栅结构提升增益



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

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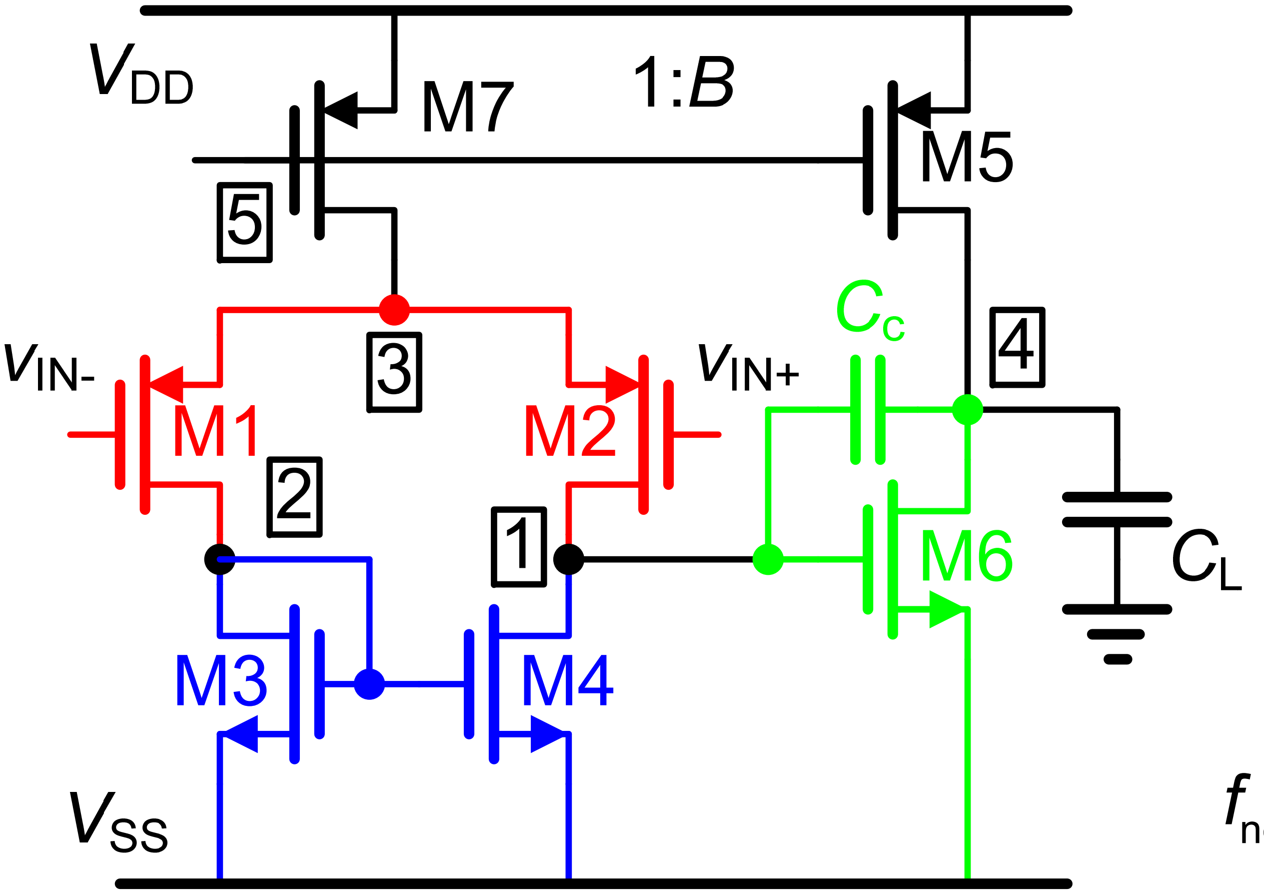
CMOS密勒OTA

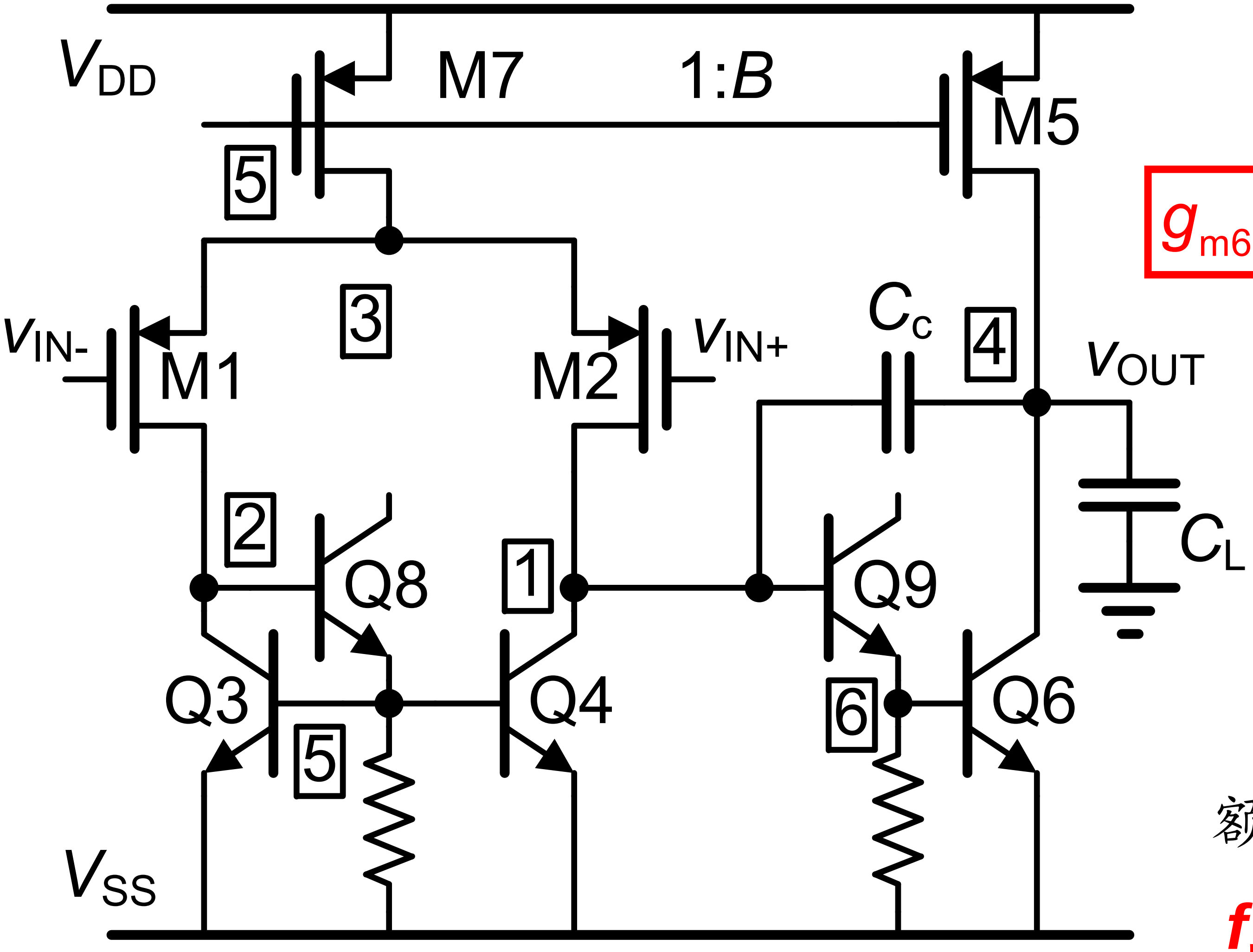


差分对
电流镜
第二级

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

$$f_{nd} = \frac{g_{m6}}{2\pi C_L} \frac{1}{1 + \frac{C_{n1}}{C_c}}$$

BiCMOS密勒OTA



$g_{m6NPN} > g_{m6NMOS}$

节点1:
高阻抗

额外节点5、6

f_{nd}?

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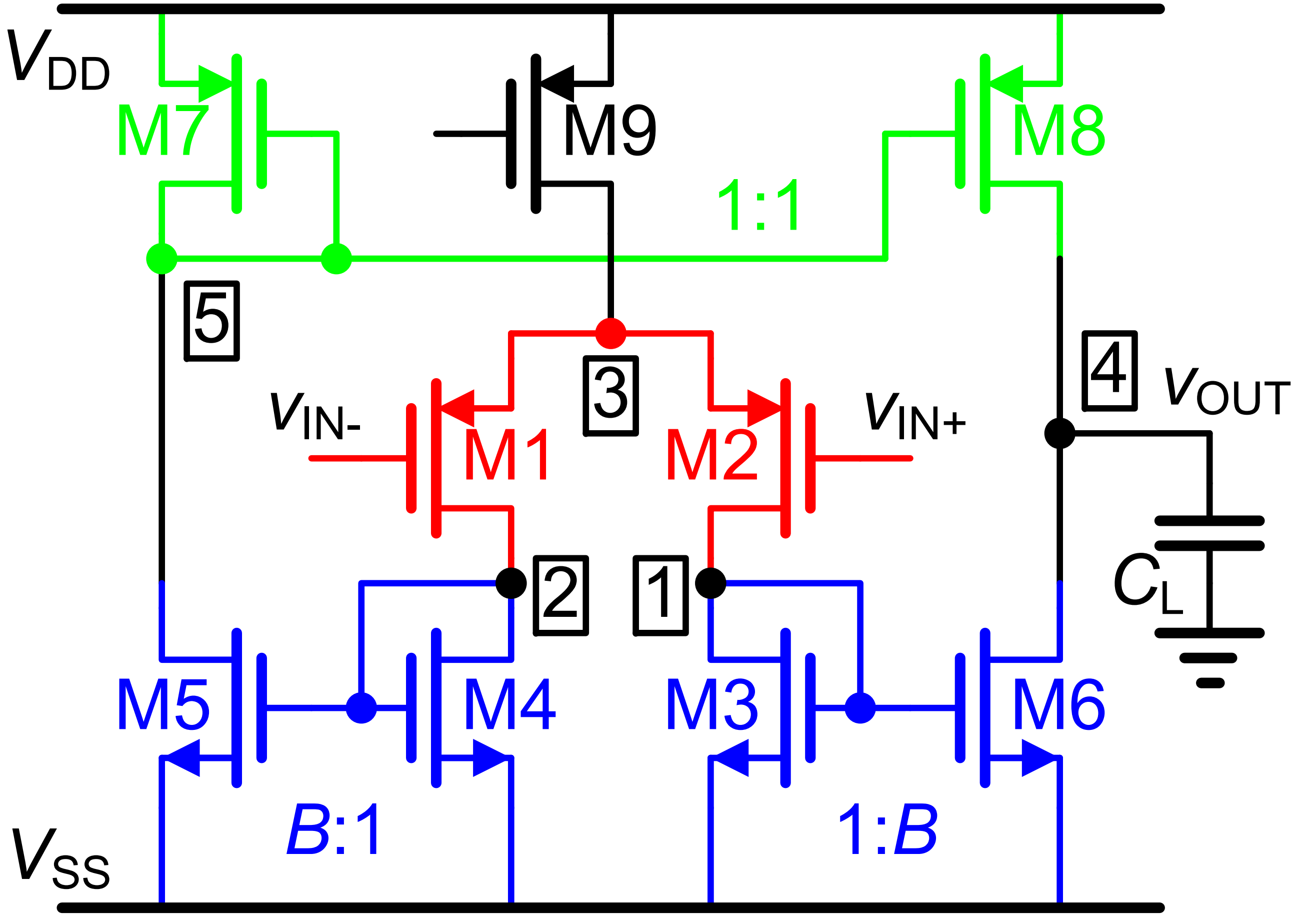
CMOS对称OTA



差分对

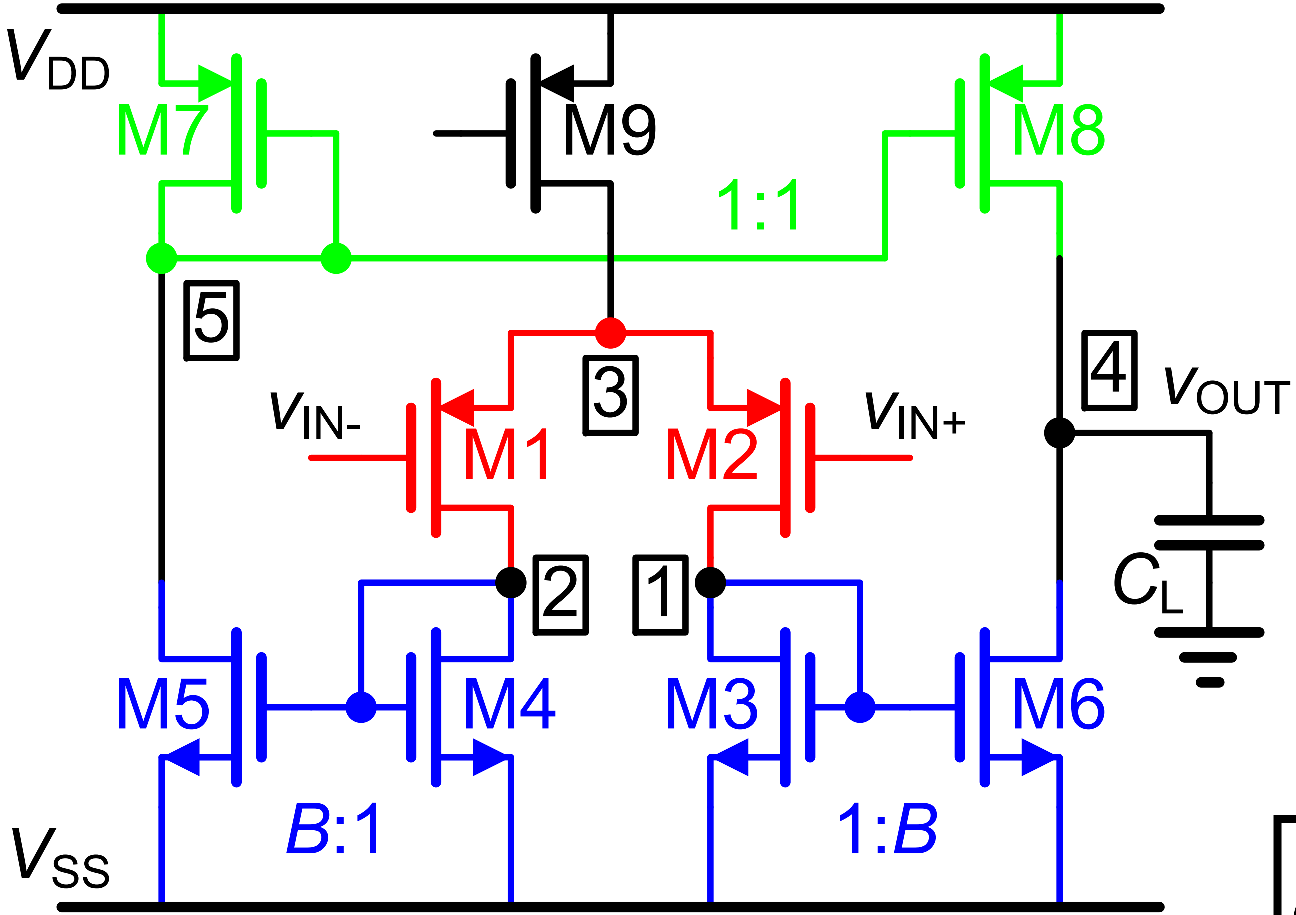
3个电流镜

对称:

节点1=节点2

轨到轨输出摆幅

CMOS对称OTA：*GBW*



$$A_V = g_{m1} B R_{n4}$$

$$= \frac{2 V_{En} L_6}{V_{GS1} - V_T}$$

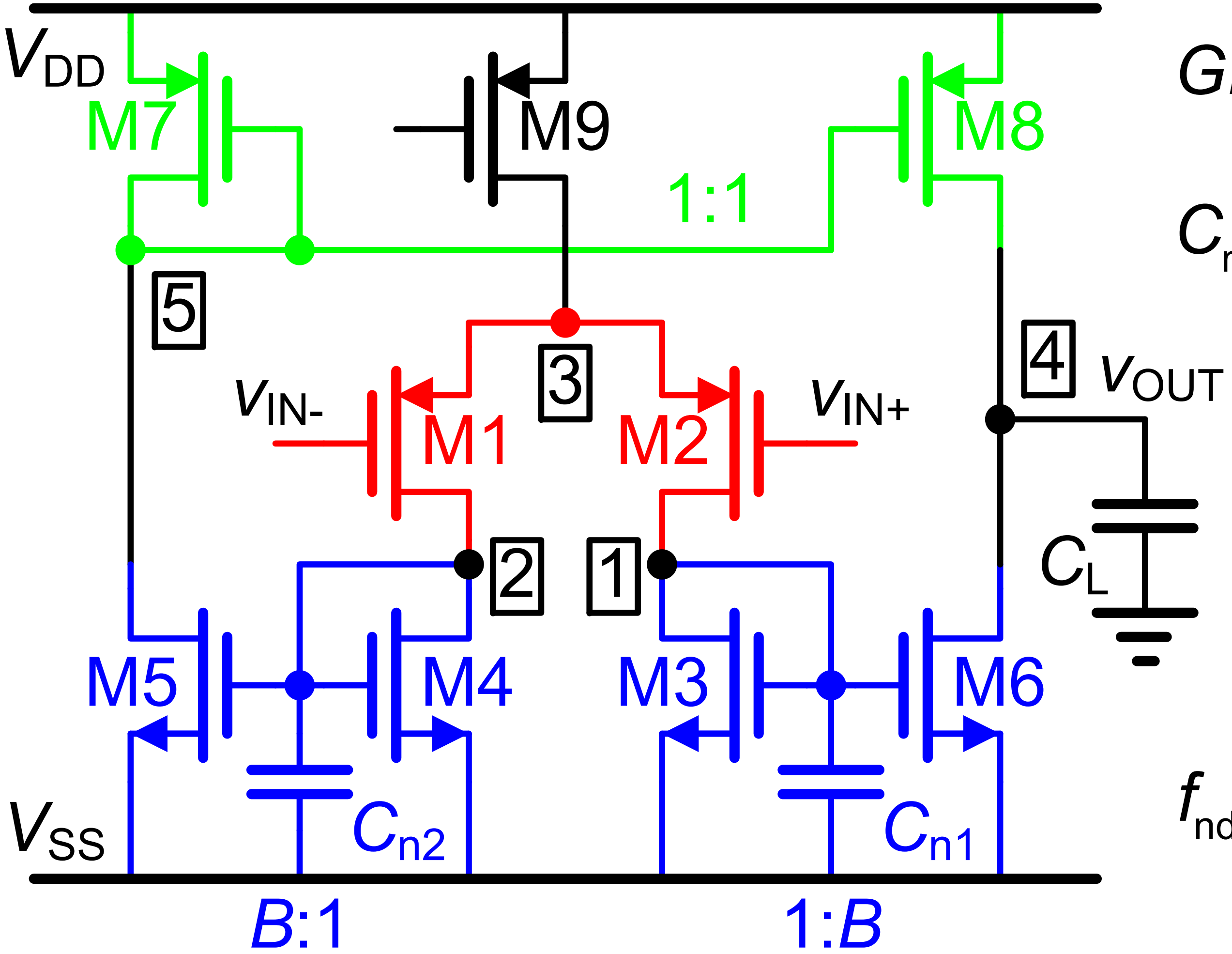
如果$L_8 > L_6$

$$BW = \frac{1}{2\pi R_{n4} C_L}$$

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

B ?

CMOS对称OTA：$f_{nd1,2}$

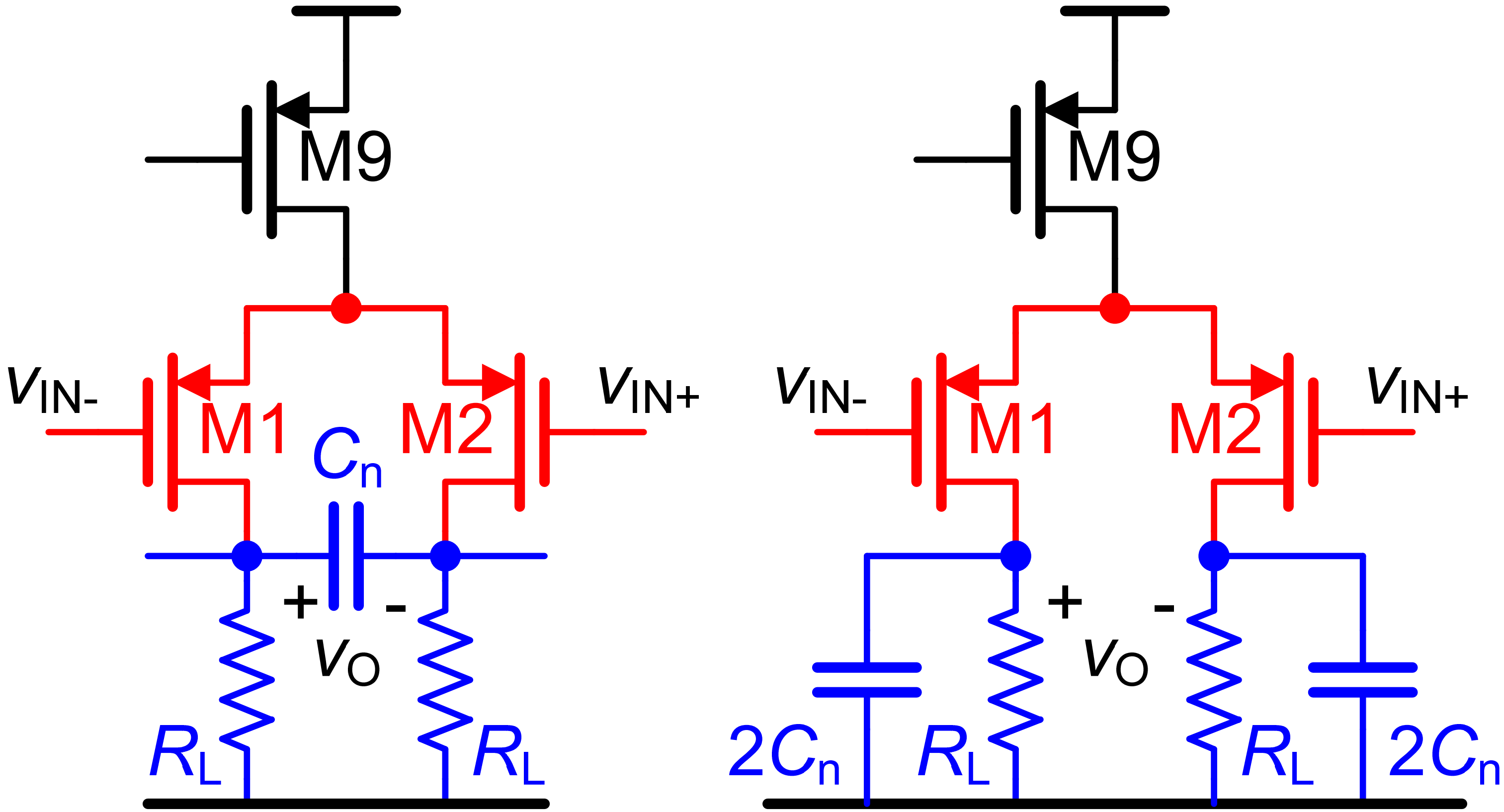


$$GBW = B\frac{g_{m1}}{2\pi C_L}$$

$$C_{n1} = (1+B)C_{GS4} + C_{DB4} + C_{DB1} \approx (3+B)C_{GS4}$$

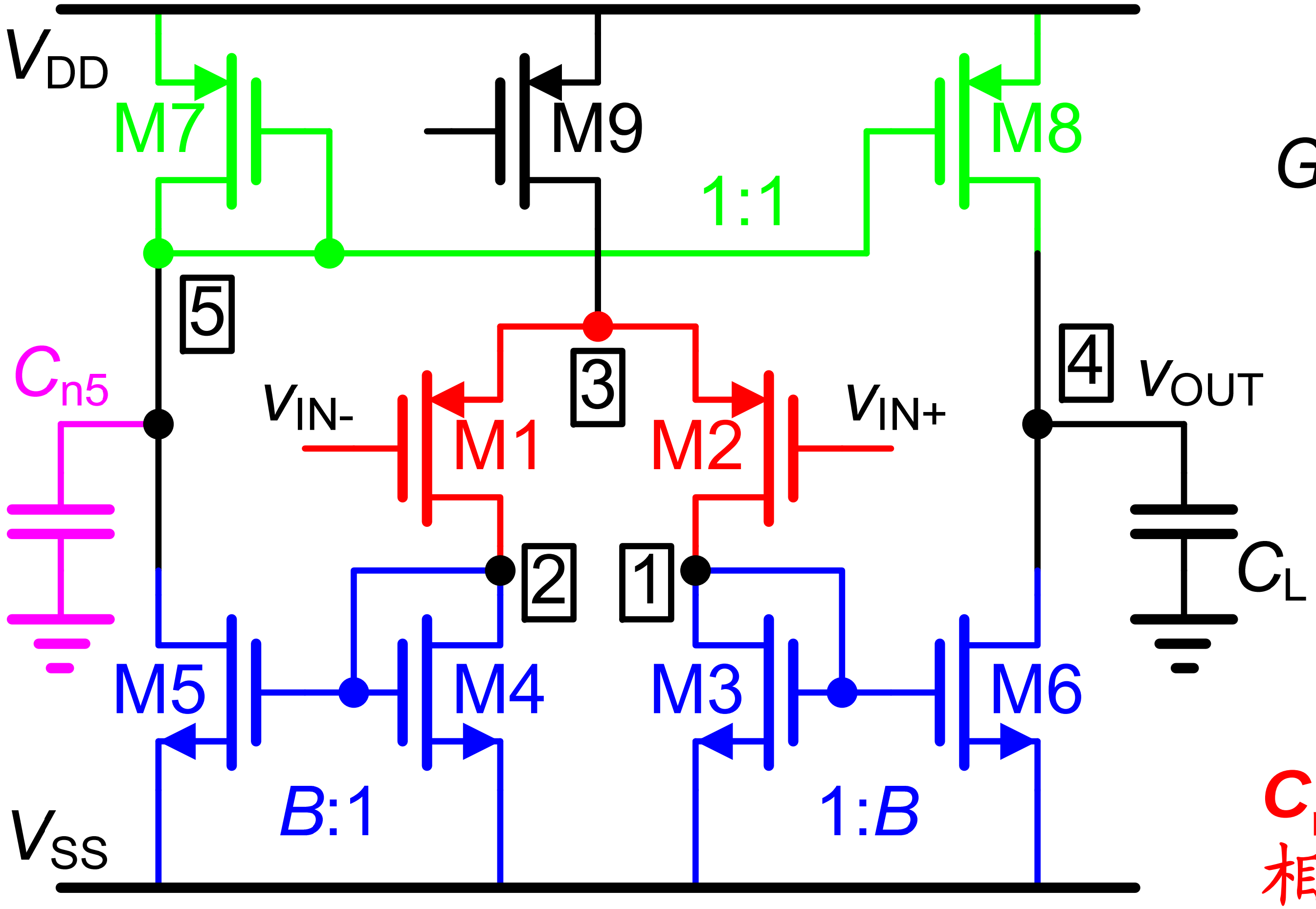
$$f_{nd} = \frac{g_{m4}}{2\pi C_{n1}} \approx \frac{f_{T4}}{3+B}$$

差分对输出端的极点



一个单极点：$f_p = \dfrac{1}{2\pi 2R_L C_n}$

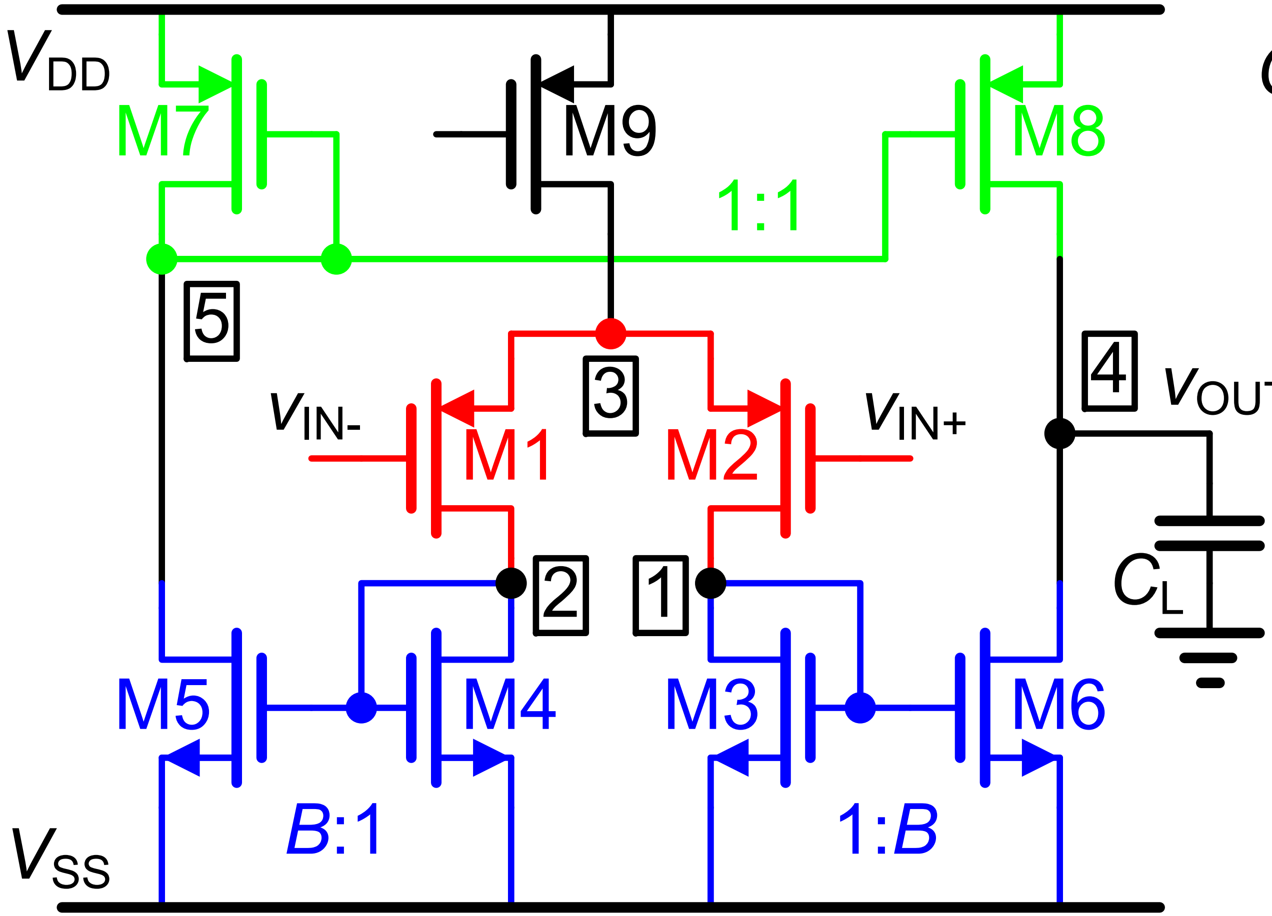
CMOS对称OTA：f_{nd5}



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

C_{n5}产生零极点对，相位恶化 3…6°

CMOS对称OTA：设计实例



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

$$f_{nd} \approx \frac{f_{T4}}{3+B}$$

$C_L = 2\ \text{pF}$

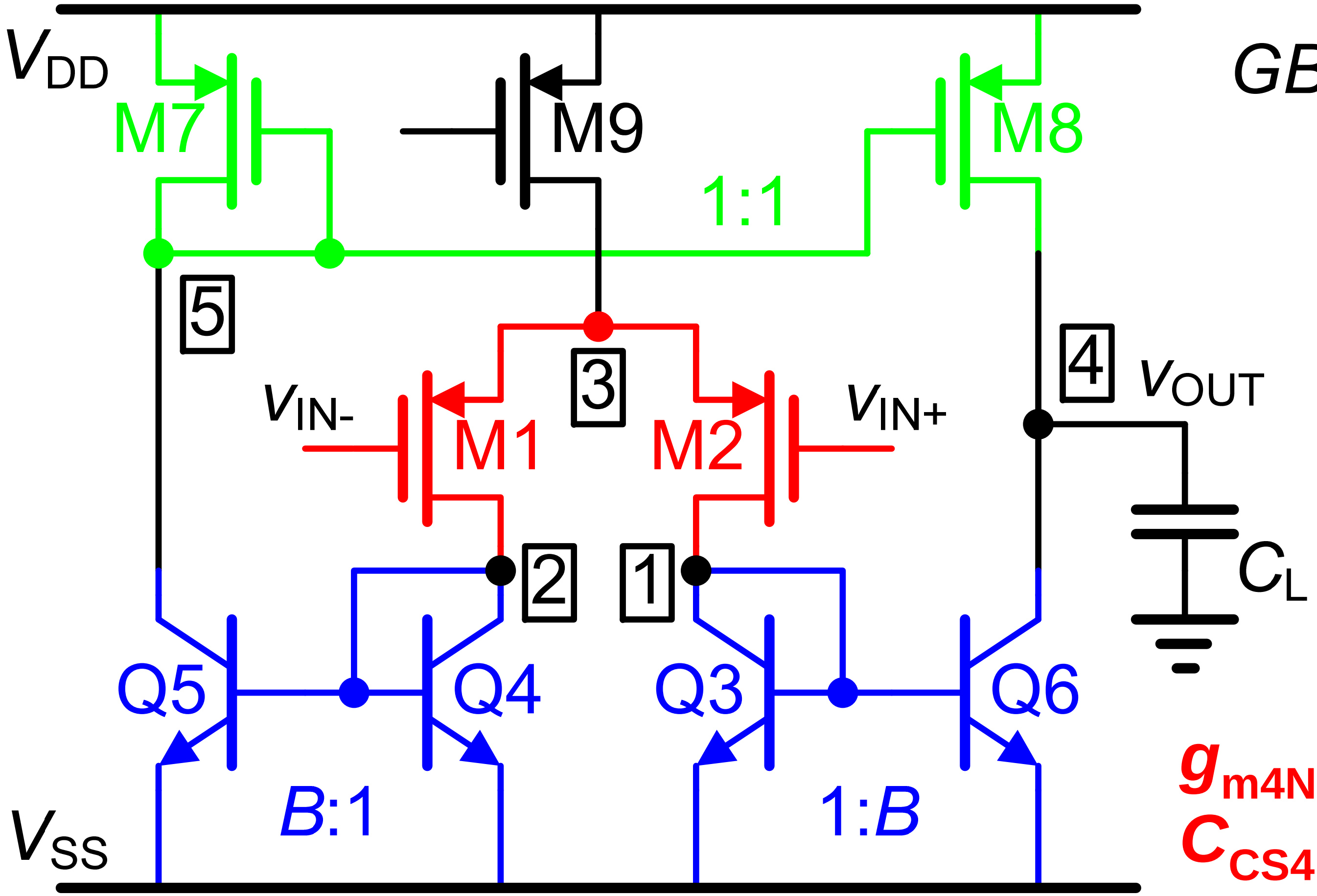
$GBW = 200\ \text{MHz}$

$V_{GS} - V_T = 0.5\ \text{V}$

$L = 1\ \mu\text{m}$

$f_{T4} = 5\ \text{GHz}$ $f_{nd} = 0.6\ \text{GHz}$ $B \approx 5$

BiCMOS对称OTA



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

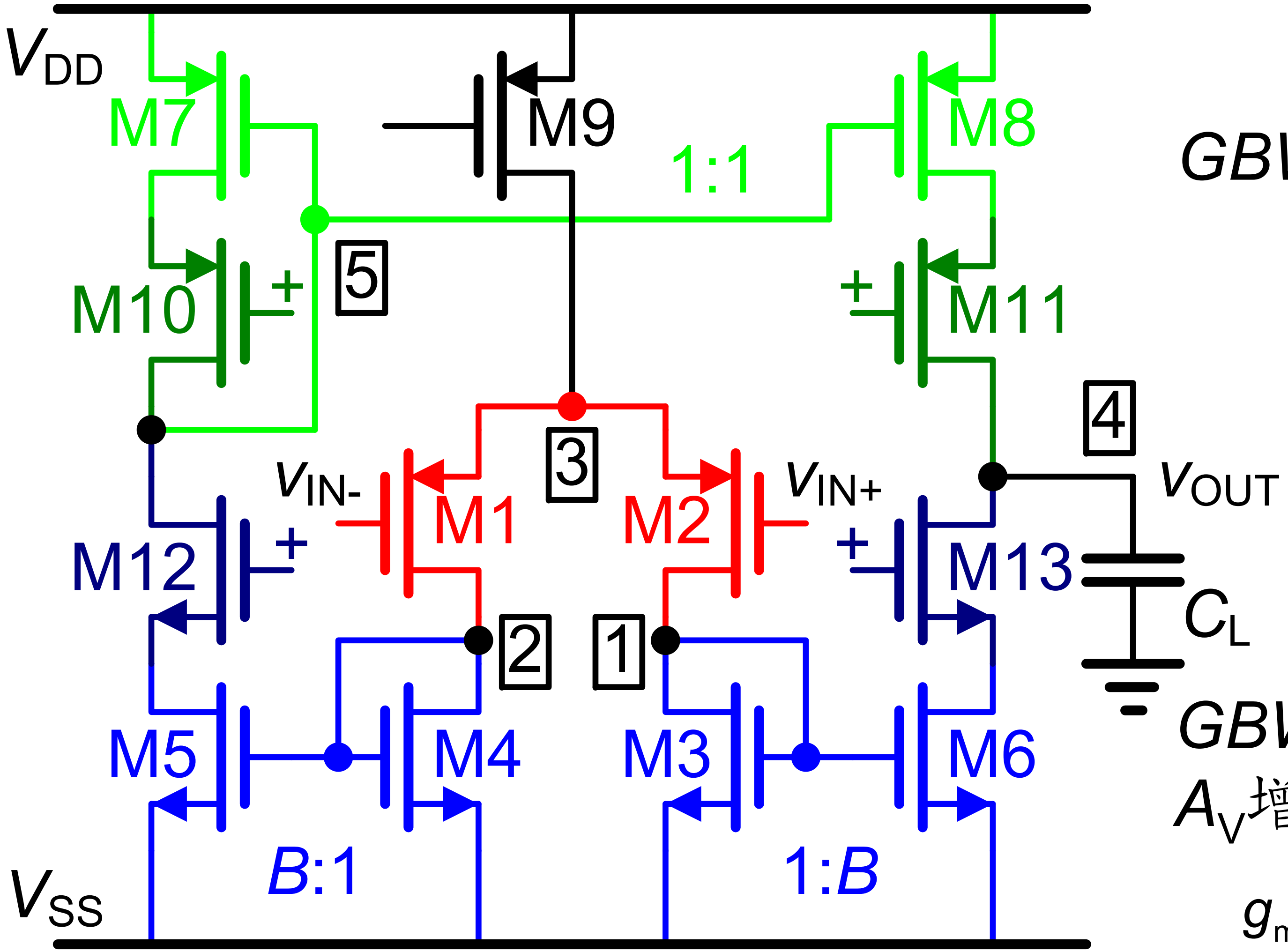
$$f_{nd} \approx \frac{f_{T4}}{3+B}$$

$g_{m4NPN} > g_{m4NMOS}$

$C_{CS4NPN} > C_{DB4NMOS}$

BiCMOS>CMOS？

接共源共栅的CMOS对称OTA



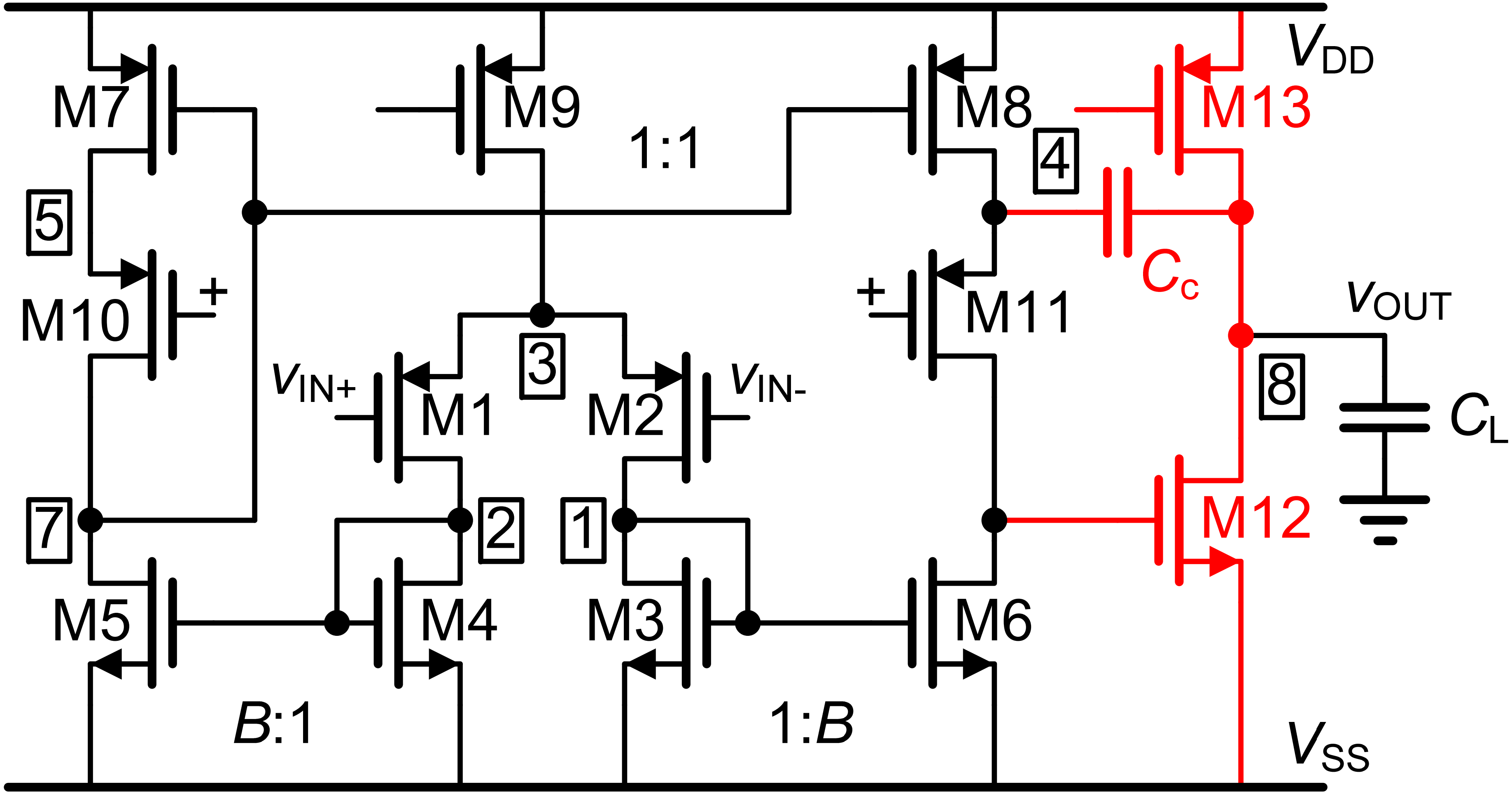
$$GBW = B\frac{g_{m1}}{2\pi C_L}$$

GBW相同，但是

A_V增加100倍!!!

$$g_m r_{DS} \approx 100$$

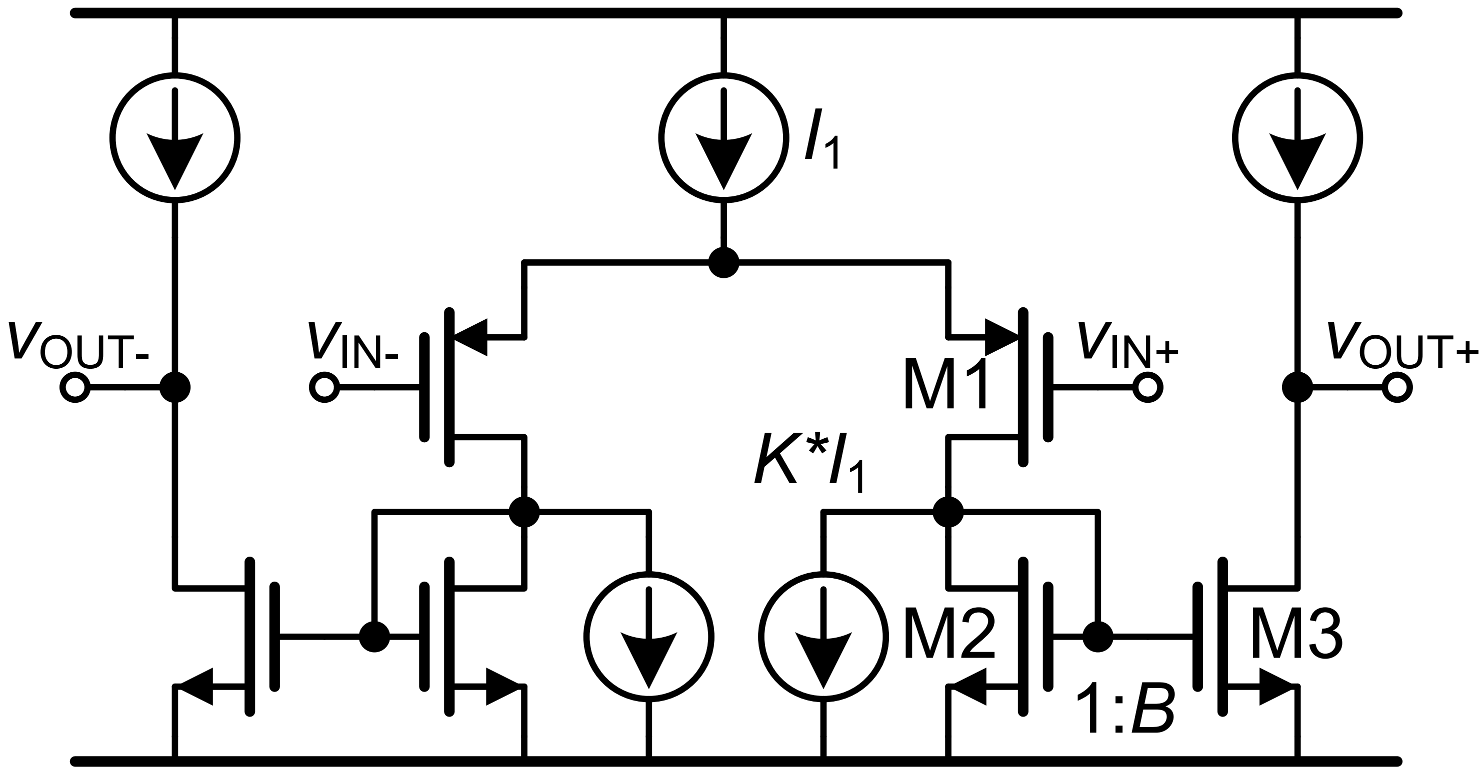
CMOS对称密勒OTA



$$GBW = B\frac{g_{m1}}{2\pi C_c}$$

没有零点！

抽取电流技术提高增益



$$A=\frac{2}{(1-k)(V_{GS}-V_T)_1\bullet\lambda_3}=\frac{A_0}{1-k}$$

Ref.: Yao, ..., JSSC Nov.04, 1809-1818

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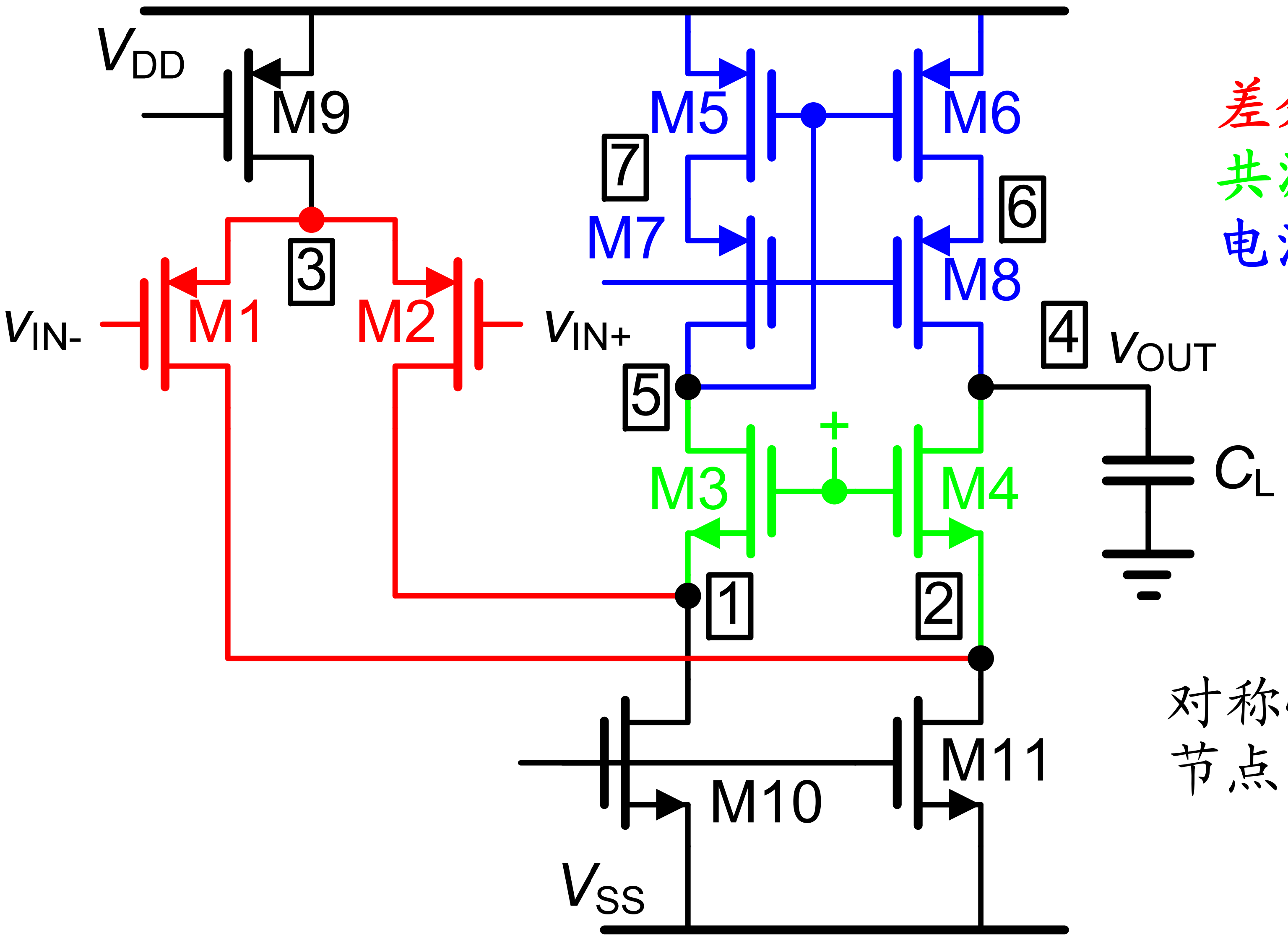
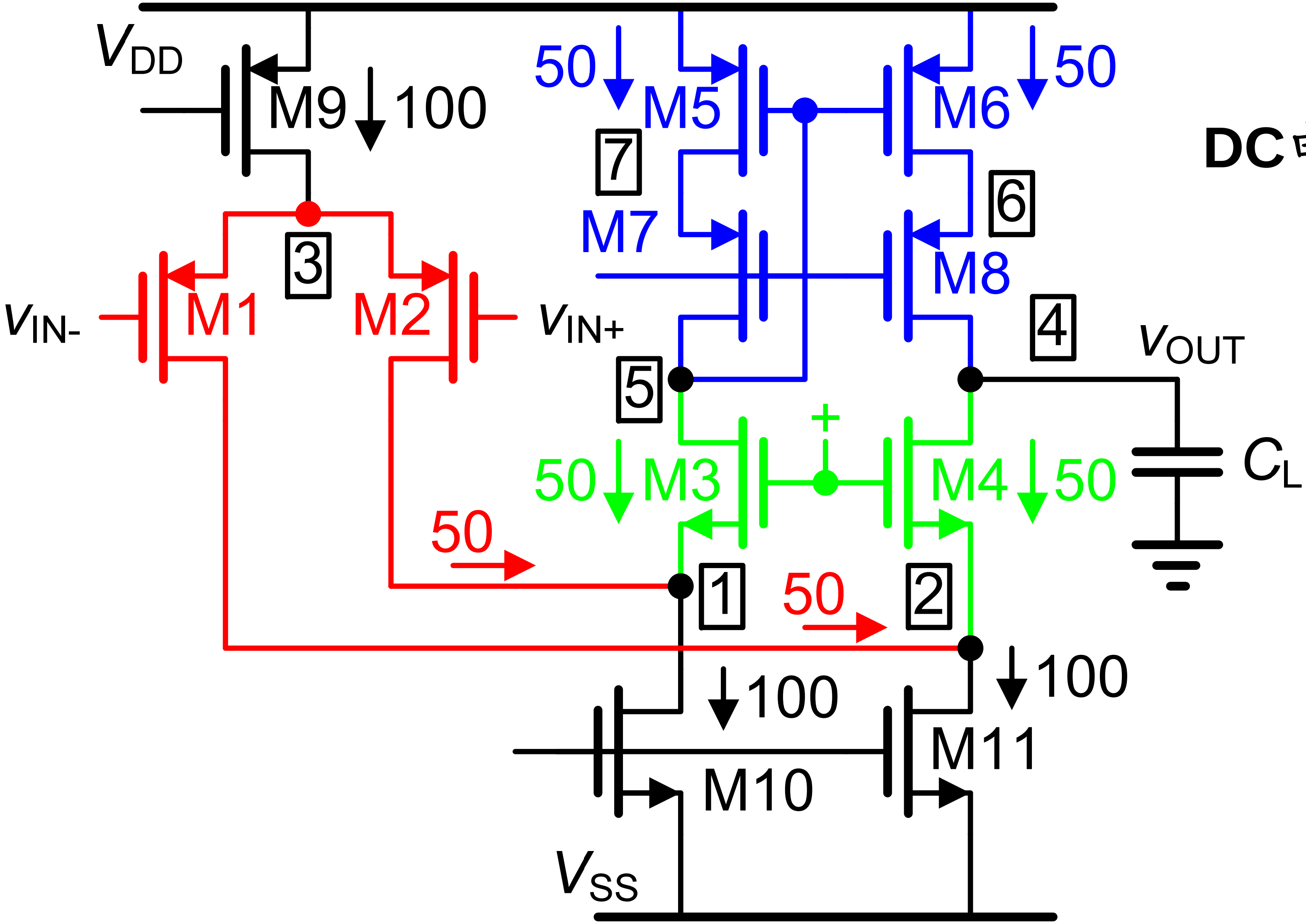
CMOS折叠共源共栅OTA



差分对
共源共栅对
电流镜

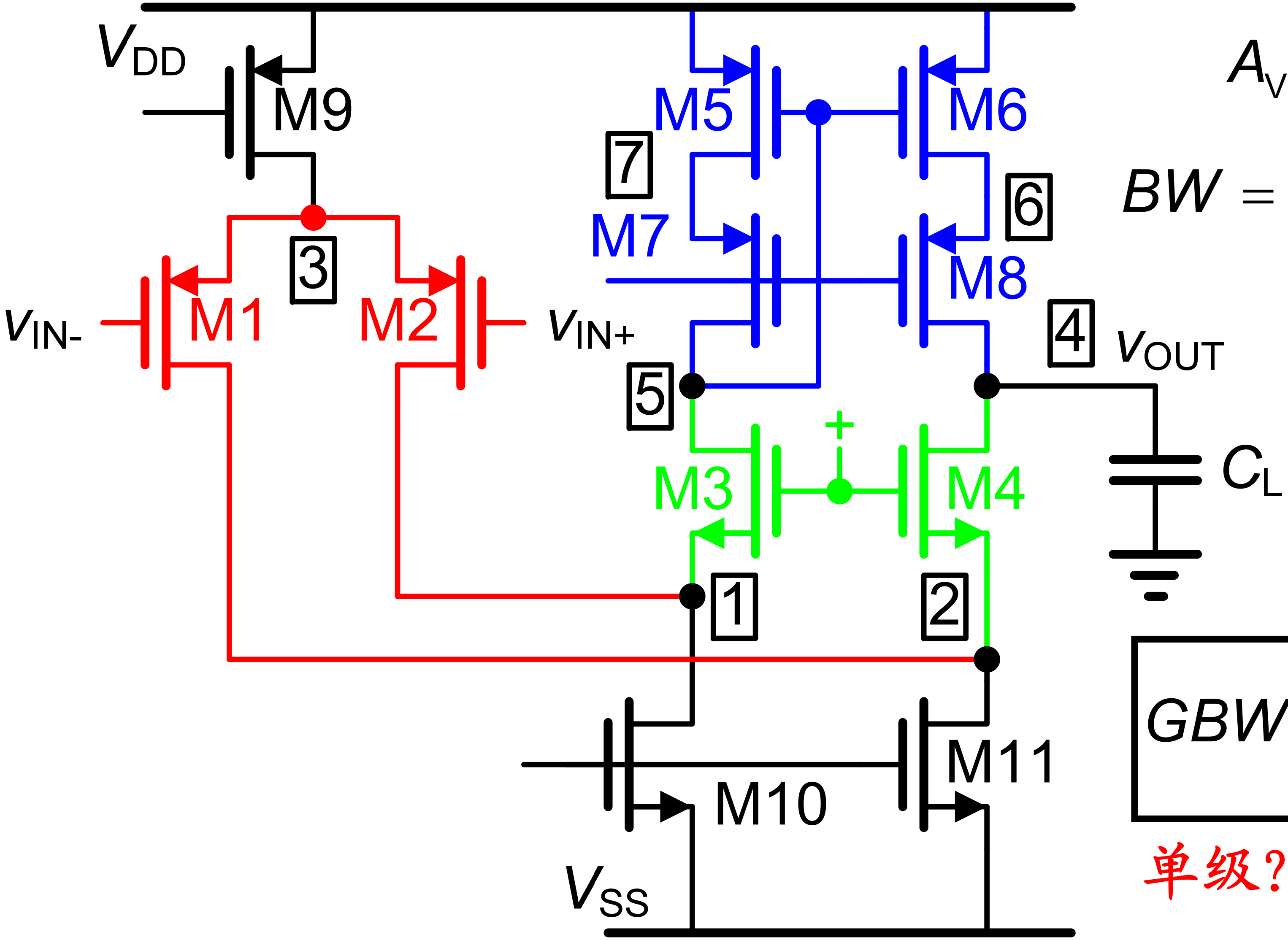
对称性：
节点1=节点2

CMOS折叠共源共栅OTA：DC



DC电流

CMOS折叠共源共栅OTA：AC



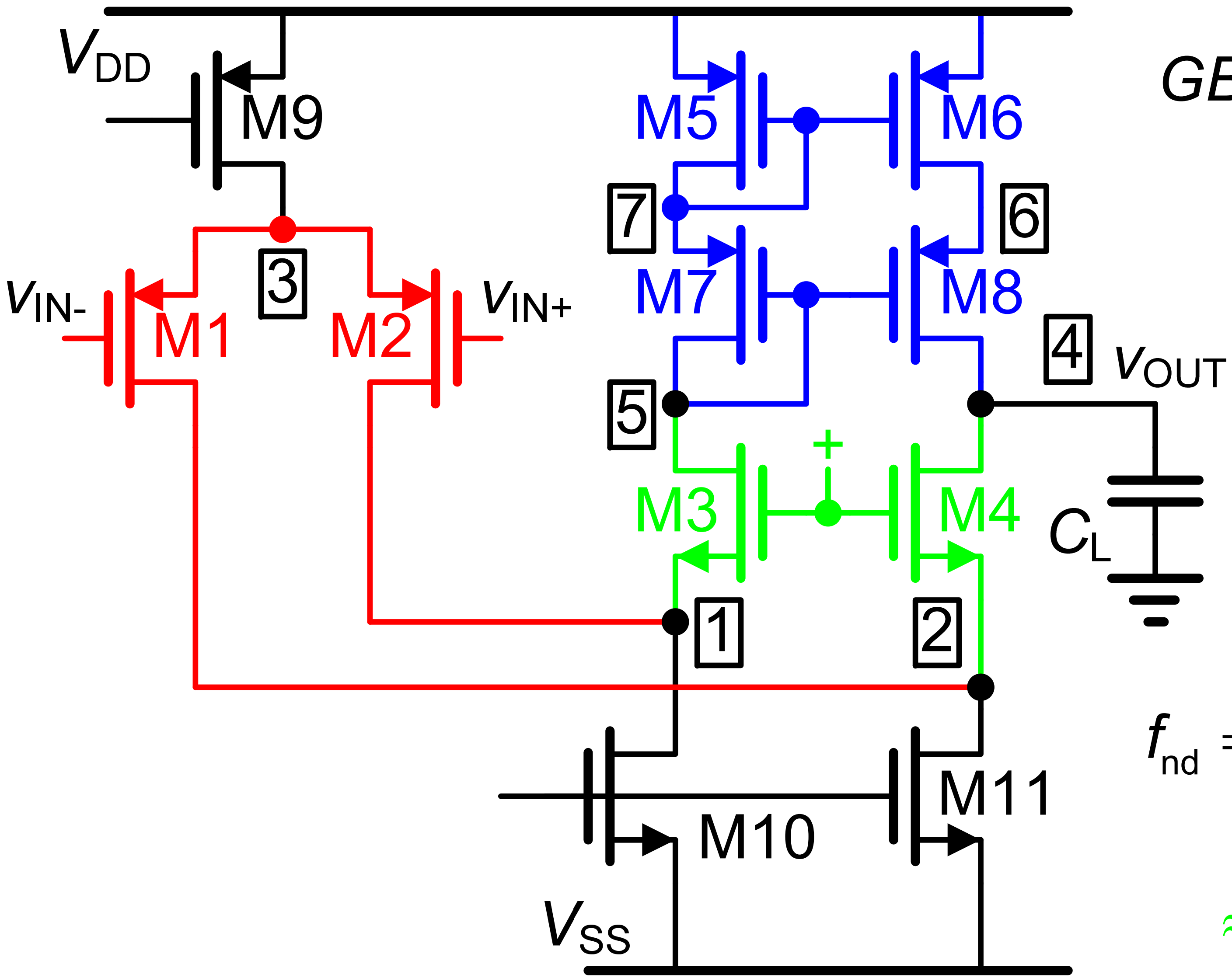
$$A_V = g_{m1}R_{n4}$$

$$BW = \frac{1}{2\pi R_{n4}C_L}$$

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

单级？单极点？

CMOS折叠共源共栅OTA：f_{nd}

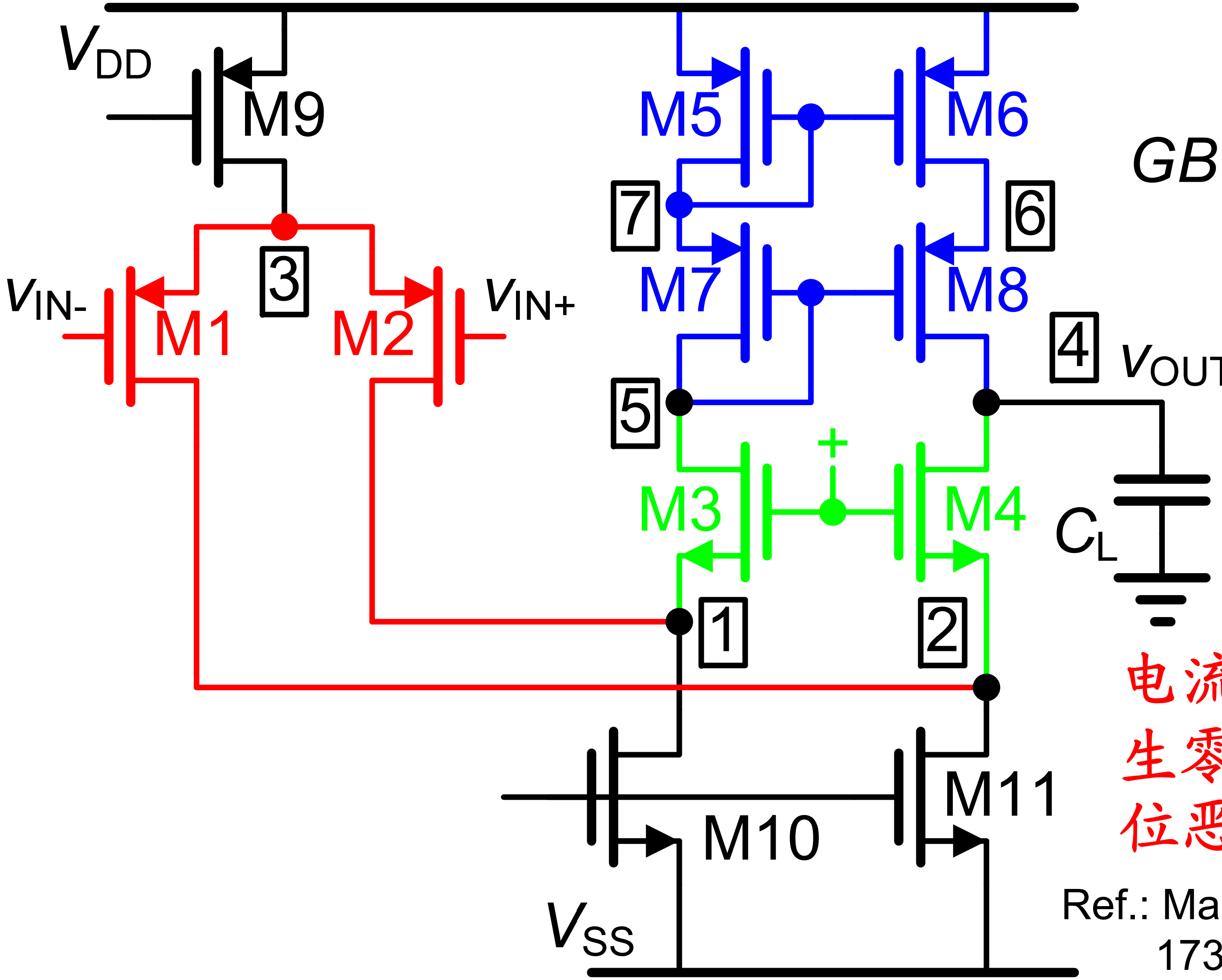


$$GBW = \frac{g_{m1}}{2\pi C_L}$$

$$C_{n1} = C_{GS3} + C_{DB2} + C_{DB10} \approx 3C_{GS3}$$

$$f_{nd} = \frac{g_{m3}}{2\pi C_{n1}} \approx \frac{f_{T3}}{3}$$ 高！

CMOS折叠共源共栅OTA: 零极点对

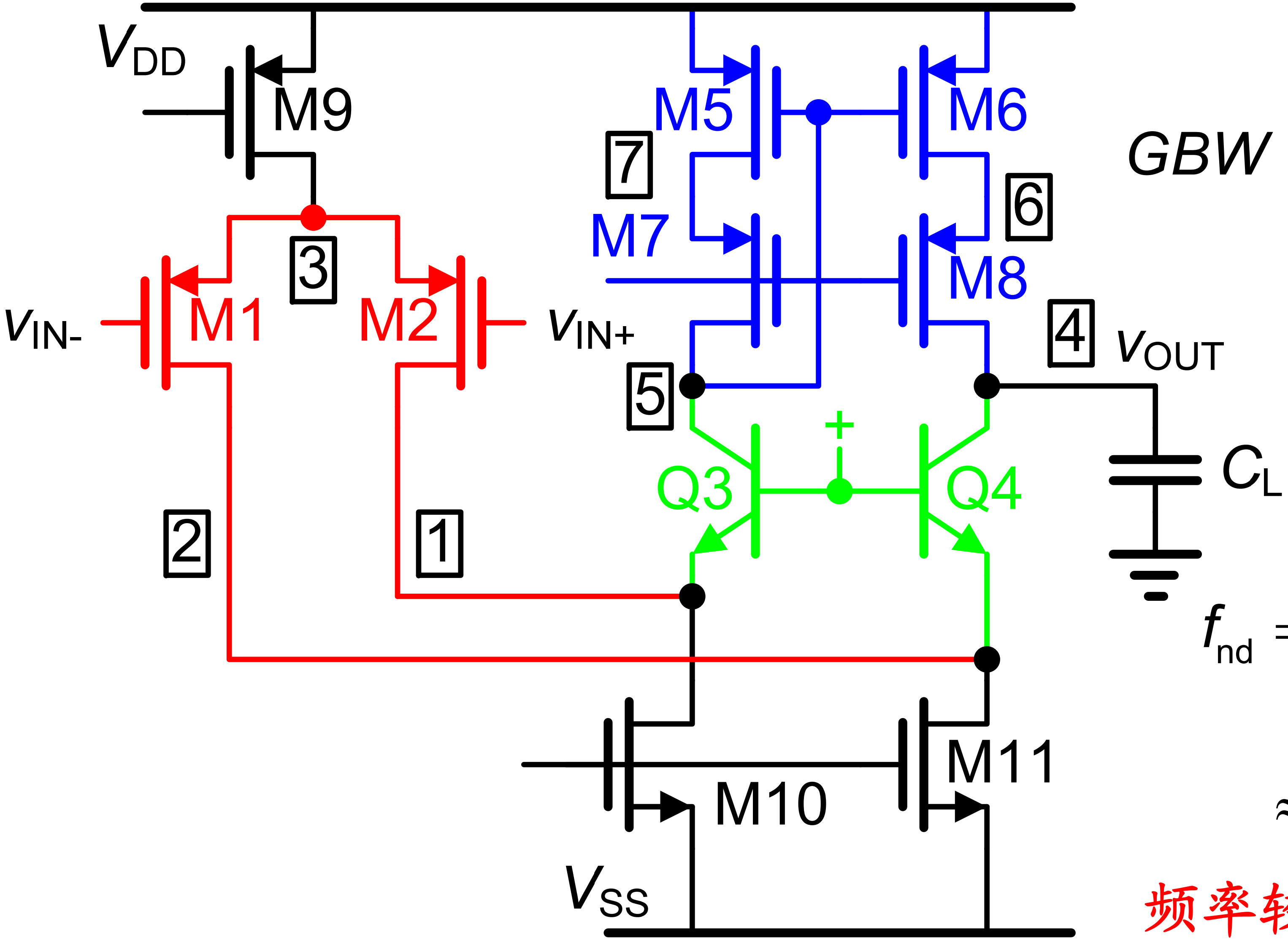


$$GBW = \frac{g_{m1}}{2\pi C_L}$$

电流镜M5-M8产生零极点对，相位恶化5…10°

Ref.: Mallya, JSSC Dec 89, 1737-1740

BiCMOS折叠共源共栅OTA

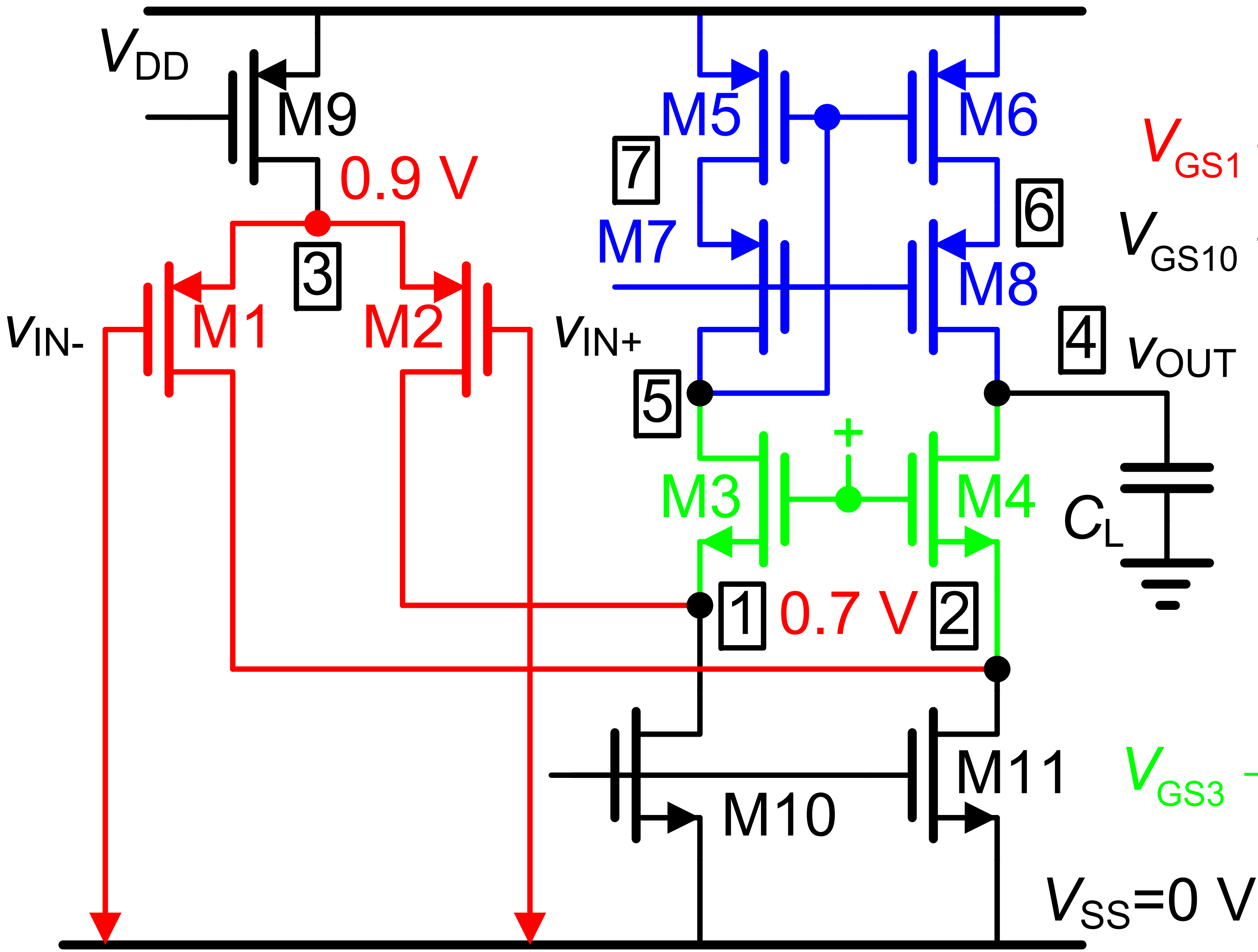


$$GBW = \frac{g_{m1}}{2\pi C_L}$$

$$f_{nd} = \frac{g_{m3}}{2\pi C_{n1}} \approx \frac{f_{T3NPN}}{3}$$

频率较高！

CMOS折叠共源共栅OTA: 输入范围



$V_T = 0.7$ V

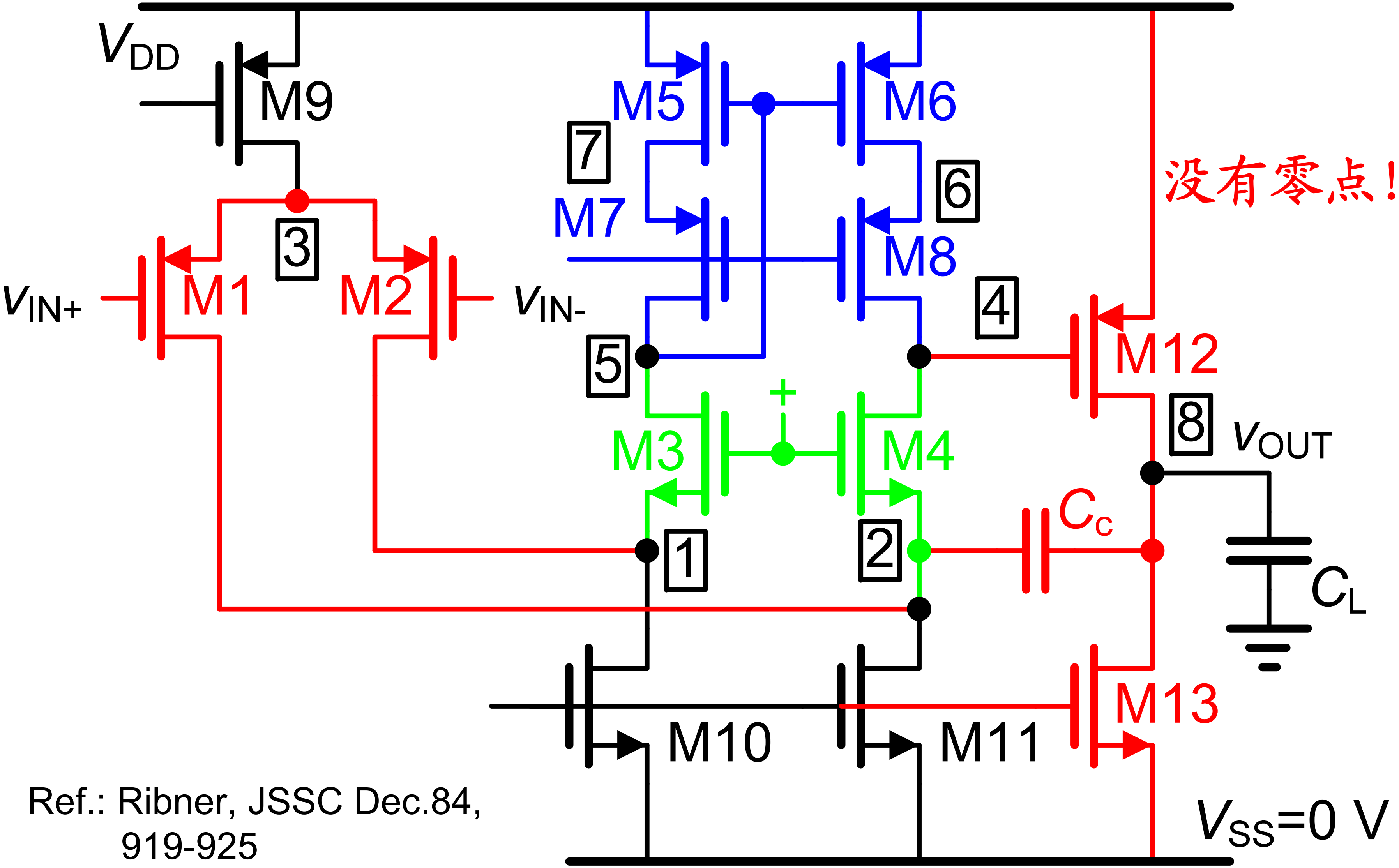
$V_{GS1} - V_T = 0.2$ V

$V_{GS10} - V_T = 0.5$ V

$V_+ = 1.4$ V

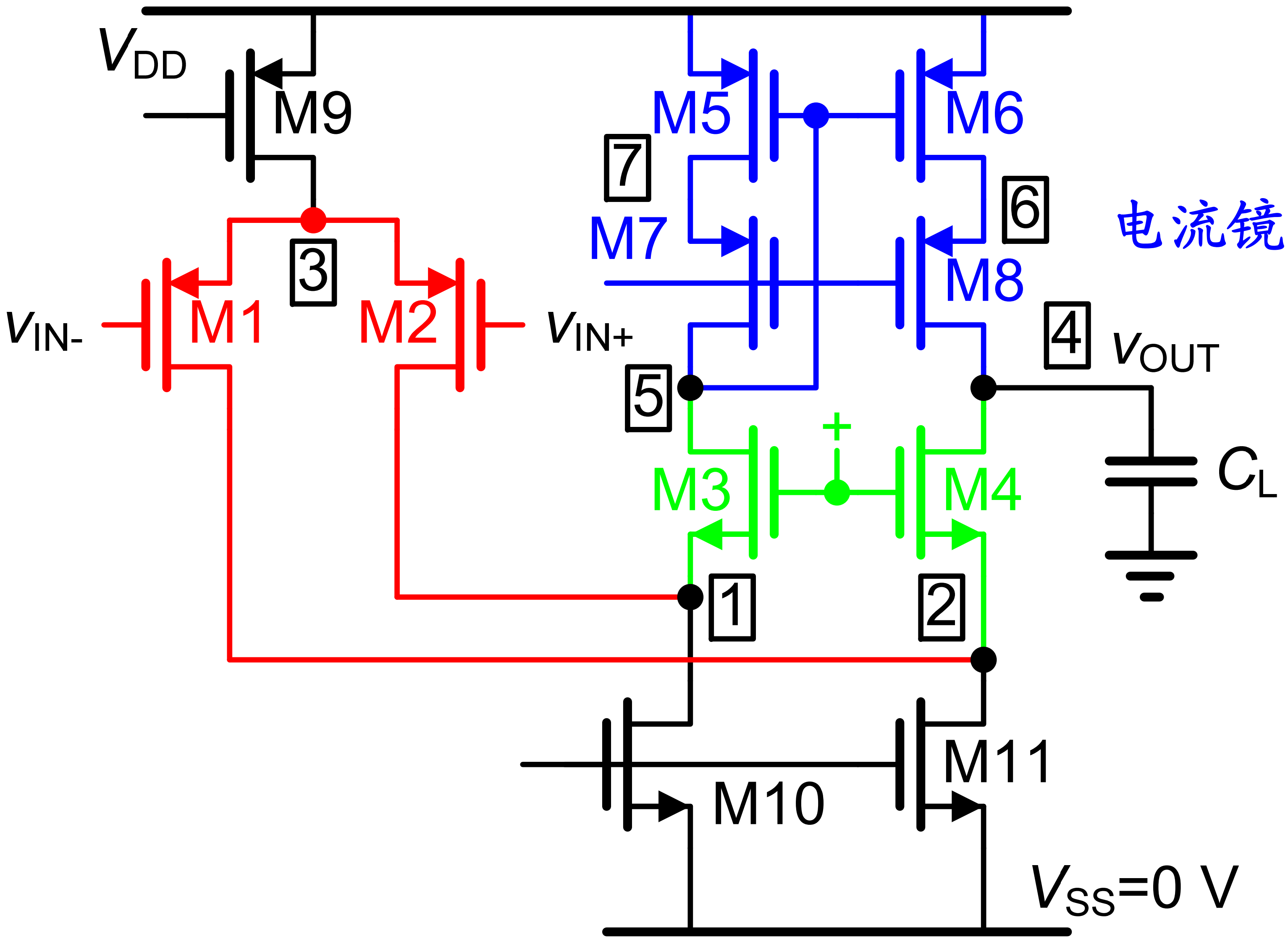
$V_{GS3} - V_T = 0.2$ V

两级折叠共源共栅OTA

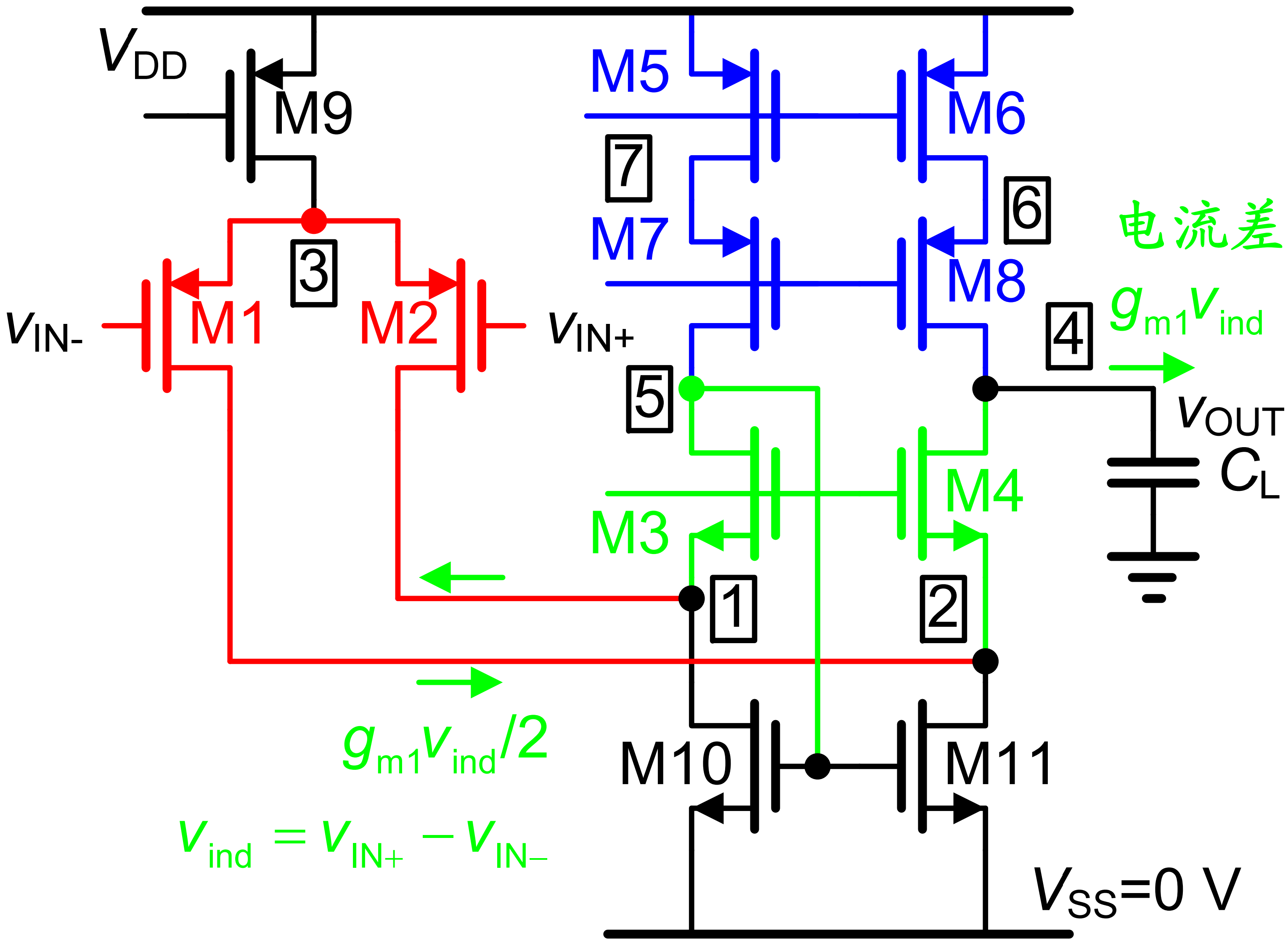


Ref.: Ribner, JSSC Dec.84,
919-925

折叠共源共栅OTA: 电流镜



折叠共源共栅OTA: 差分电流放大器



$$v_{ind} = v_{IN+} - v_{IN-}$$

OTA(放大器)的性能比较

	I_{TOT} mA	$\overline{dv^2_{in,eq}}$ $\boxed{\frac{8/3kTdf}{g_{m1}}}$	Swing
简单型 (4管)	0.25	4	avg.
对称型 (B=3)	0.33	8	max.
套筒型	0.25	4	small
折叠共源共栅	0.5	8	avg.
两级密勒 (C_L/C_c=2.5)	1.1	4	max.

GBW=100 MHz C_L= 2 pF $V_{GS}-V_T$=0.2 V 全差分结构

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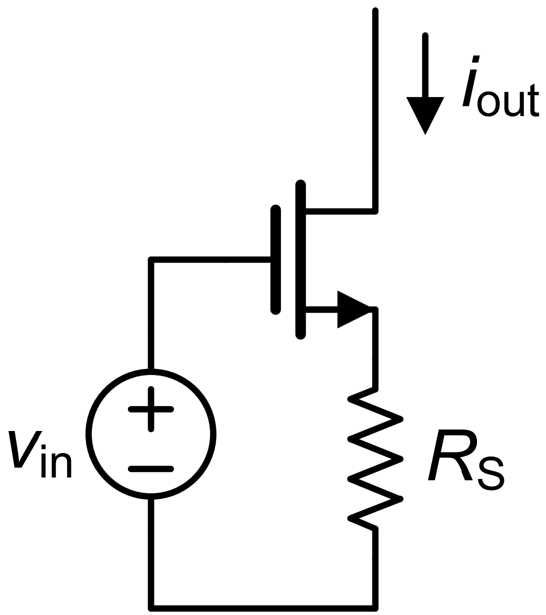
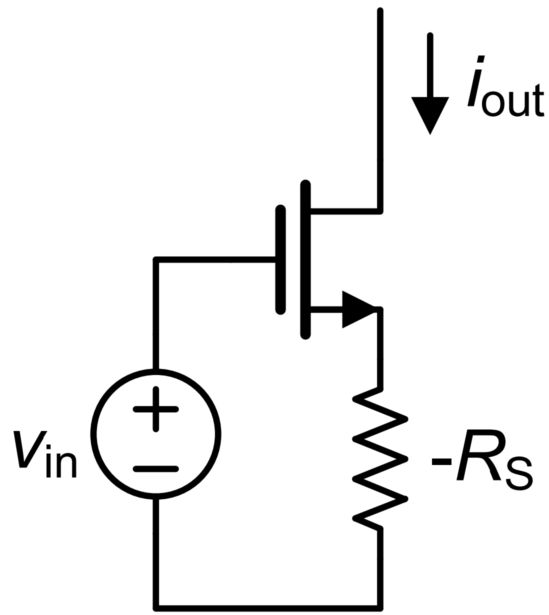
增加输入跨导 - 1

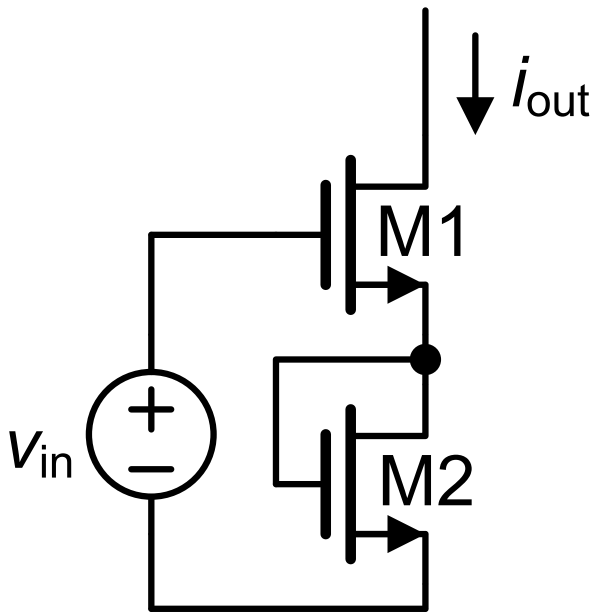


$$g_{mR}=\frac{g_m}{1+g_mR_S}$$

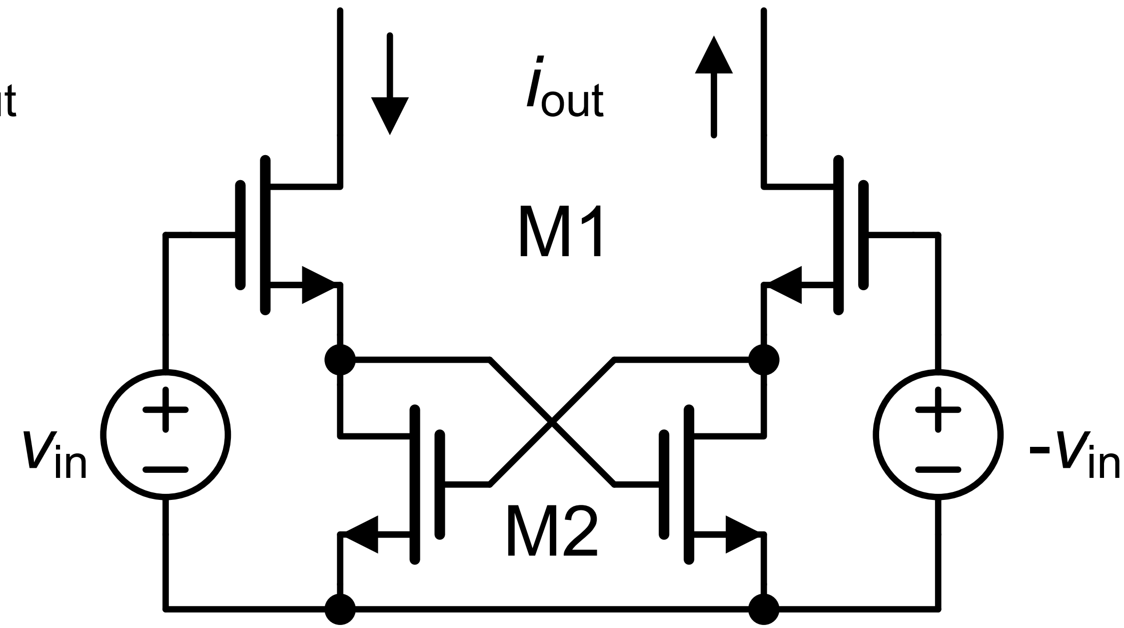


$$g_{mR}=\frac{g_m}{1-g_mR_S}$$

增加输入跨导 - 2

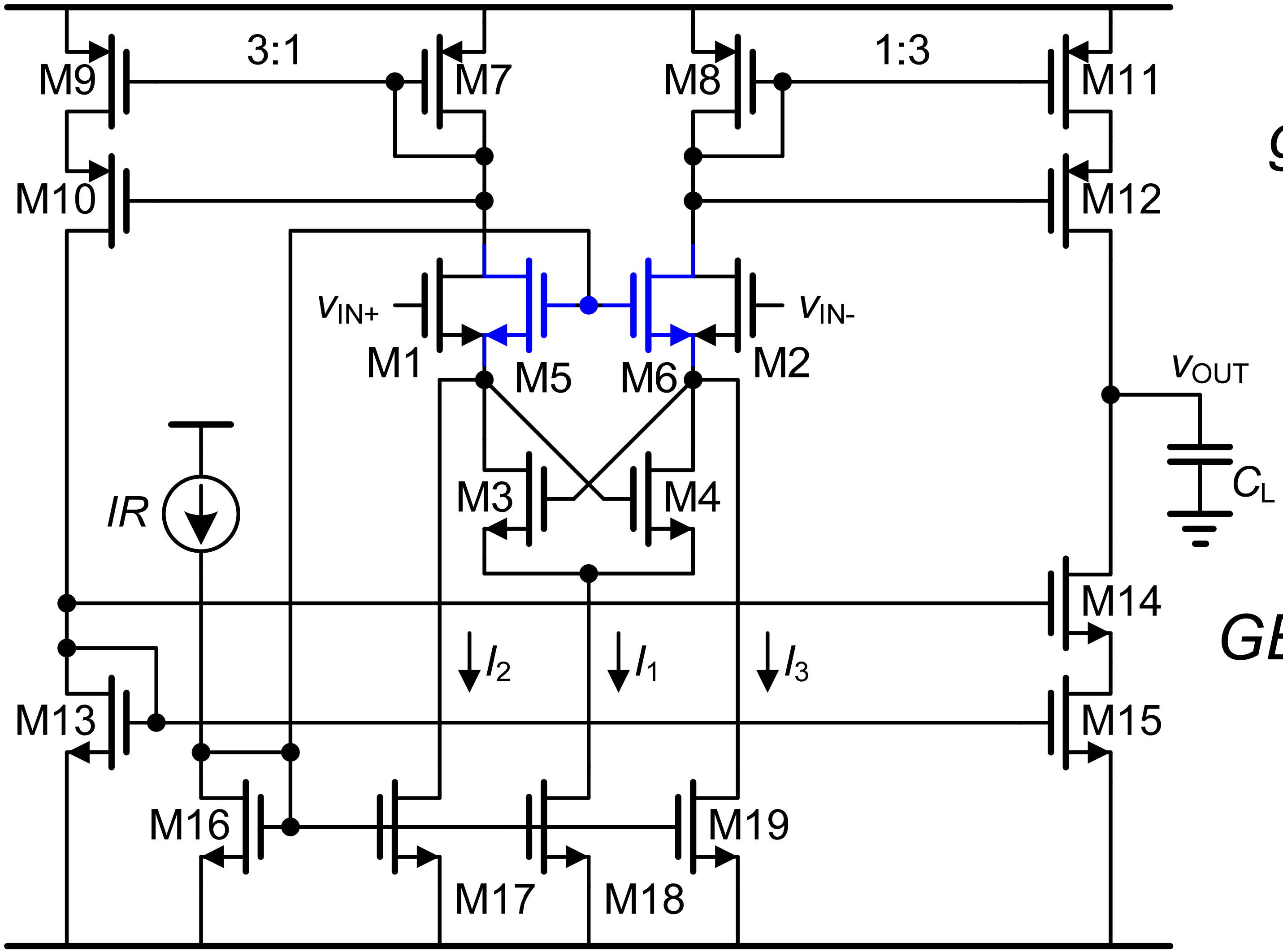


$$g_m = \frac{g_{m1}}{1+\frac{g_{m1}}{g_{m2}}}$$



$$g_m = \frac{g_{m1}}{1-\frac{g_{m1}}{g_{m2}}}$$

增加输入跨导 - 3



$$g_m = \frac{g_{m1}}{1 - \frac{g_{m1}}{g_{m3}}}$$

$$g_m \approx 3g_{m1}$$

$$GBW = \frac{3g_m}{2\pi C_L}$$

$$\approx \frac{9g_{m1}}{2\pi C_L}$$

Ref.: Castello, JSSC June 1990, pp. 669-676