

第十一章 失真和失调

刘鸣

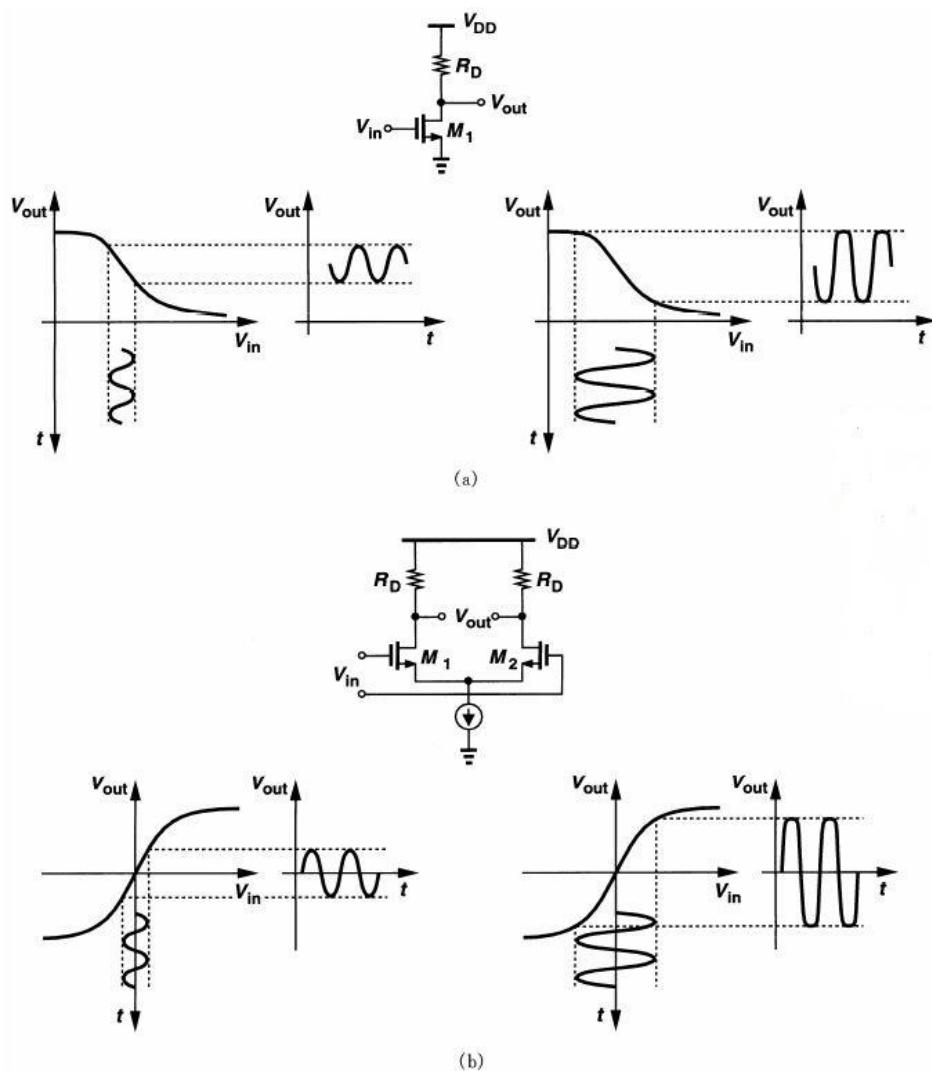
中国科学院半导体研究所

liuming@semi.ac.cn

第一部分：失真

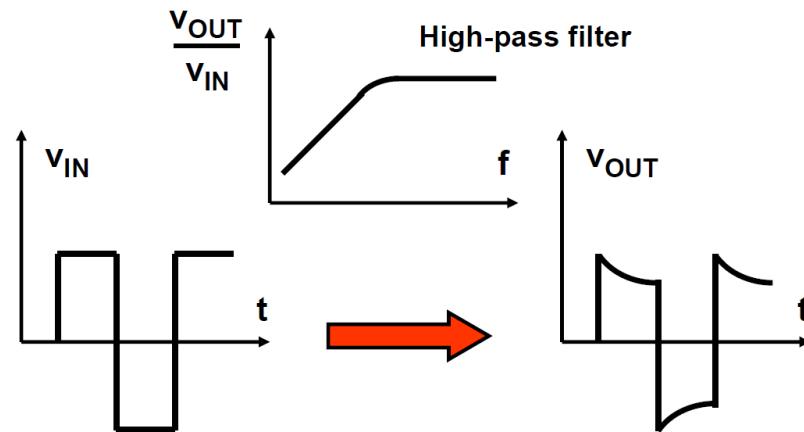
- 基本概念
- MOS失真
- 反馈与失真
- 线性化技术

失真的定义

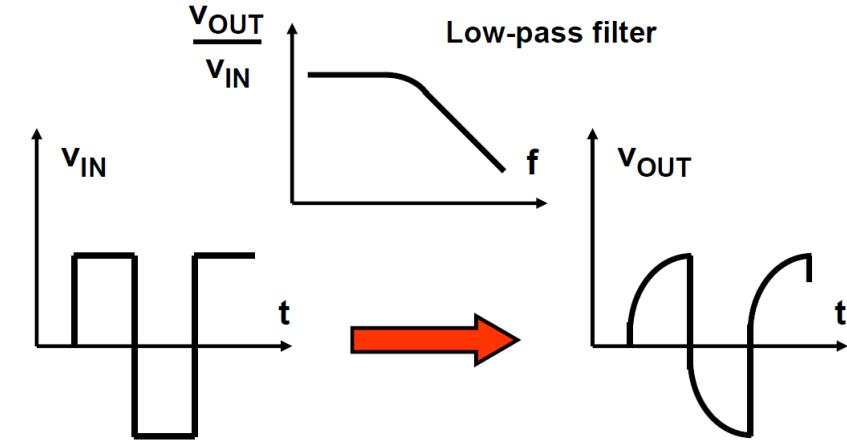


失真又称“畸变”，指信号在传输过程中与原有信号或标准相比所发生的偏差。在理想的放大器中，输出波形除放大外，应与输入波形完全相同，但实际上，不能做到输出与输入的波形完全一样，这种现象叫失真。

线性失真



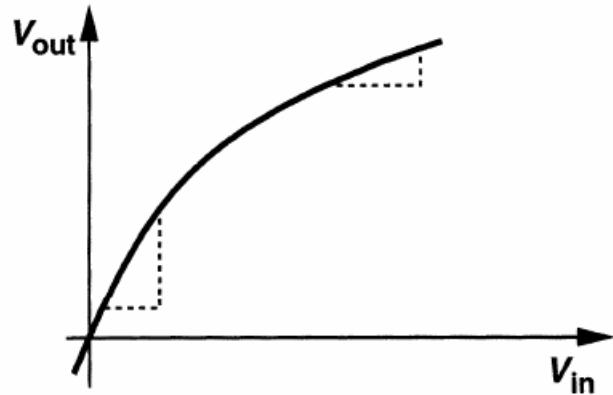
高通滤波引起的线性失真



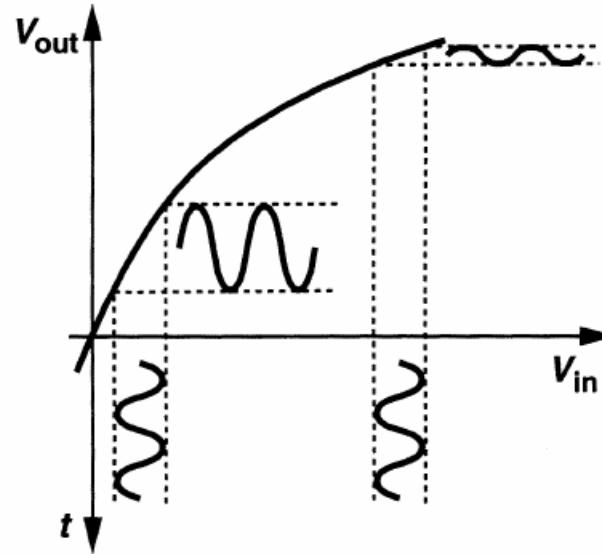
低通滤波引起的线性失真

线性失真是滤波作用的结果，由于滤波的作用，信号的波形发生变化。

非线性失真



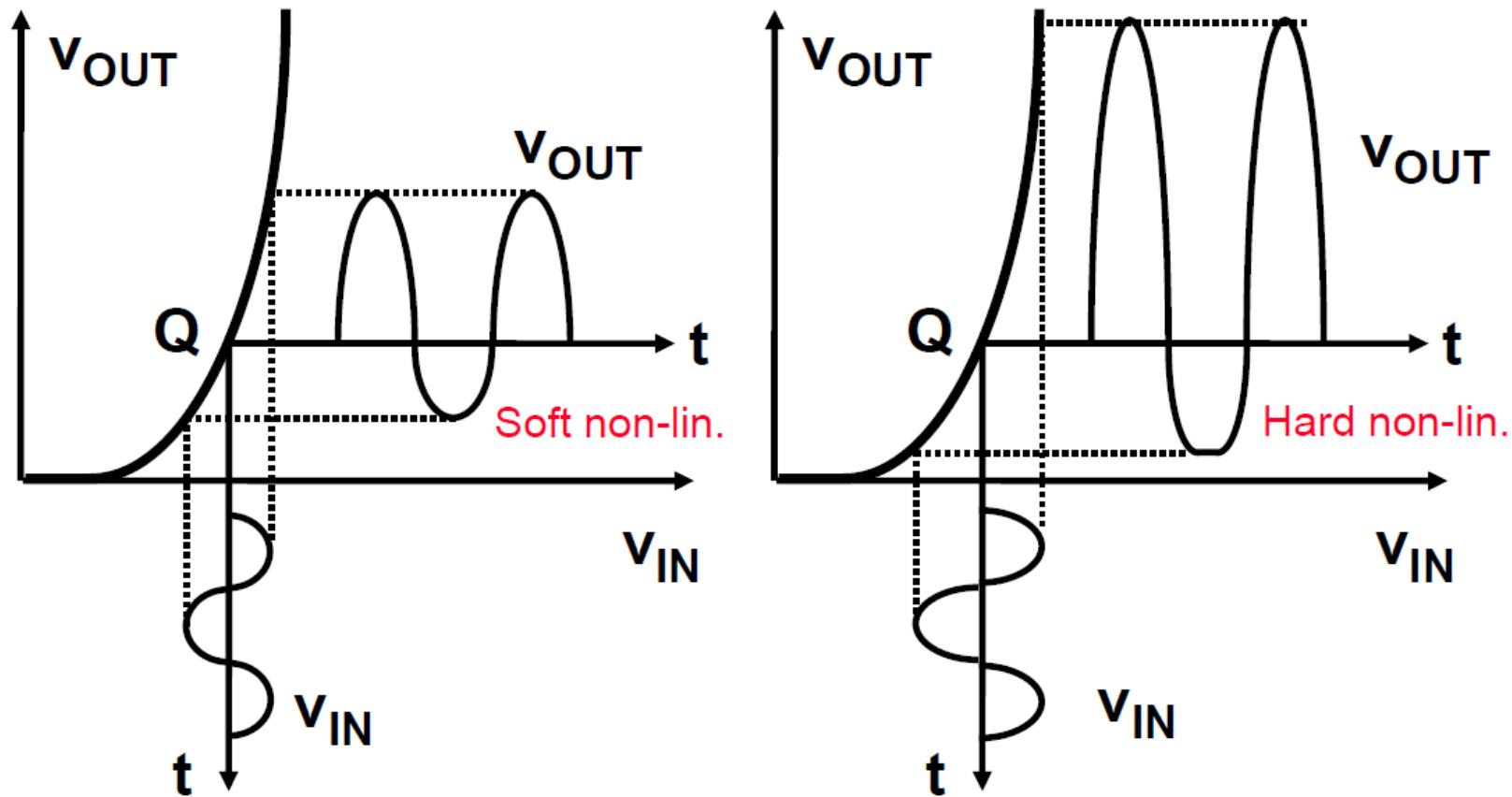
(a)



(b)

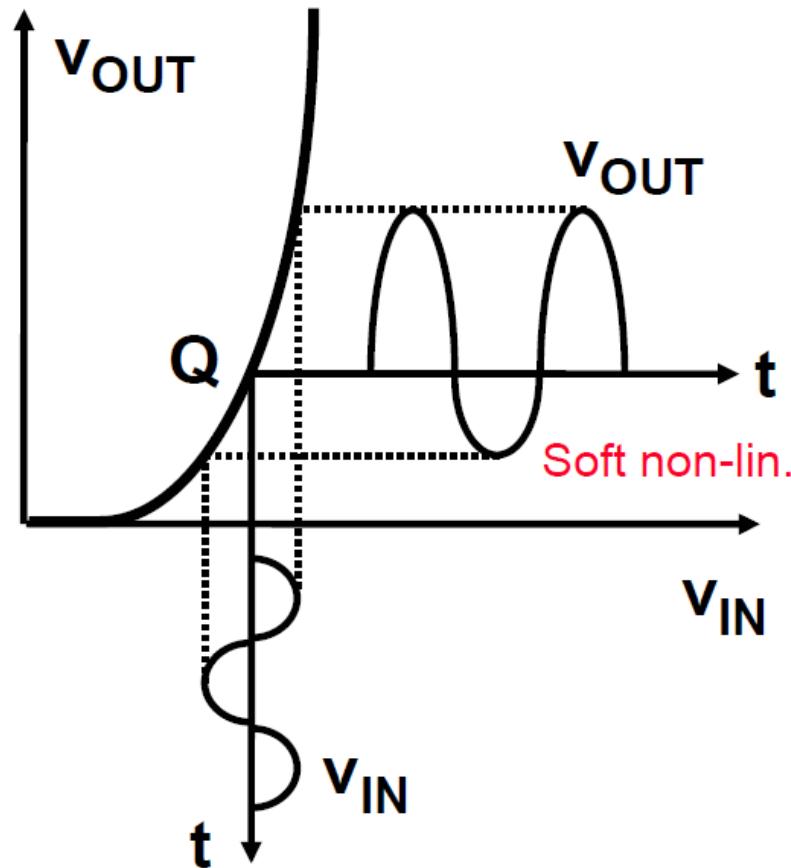
非线性失真是由于传输函数的非线性导致输出特性的斜率或者小信号增益随输入电平的变化，分为硬性非线性和软性非线性。

硬性非线性和软性非线性



本课主要关注软性非线性!

非线性失真的公式



$$v_{IN}(t) \iff v_{OUT}(t)$$

$$\begin{aligned} v_{OUT} = & a_0 + \\ & a_1 v_{IN} + a_2 v_{IN}^2 + a_3 v_{IN}^3 + \dots \end{aligned}$$

传输曲线的非线性，可以以幂级数展开来描述

幂级数中系数的计算

$$y = a_0 + a_1 u + a_2 u^2 + a_3 u^3 + \dots$$

$$a_0 = y \Big|_{u=0}$$

$$a_1 = \frac{dy}{du} \Big|_{u=0}$$

$$a_2 = \frac{1}{2} \left. \frac{d^2y}{du^2} \right|_{u=0}$$

$$a_3 = \frac{1}{6} \left. \frac{d^3y}{du^3} \right|_{u=0}$$

谐波失真(Harmonic Distortion, HD)的定义

$$y = a_0 + a_1 u + a_2 u^2 + a_3 u^3 + \dots$$

With $u = U \cos \omega t$

$$\cos^2 x = 1/2 (1 + \cos 2x)$$

$$\cos^3 x = 1/4 (3 \cos x + \cos 3x)$$

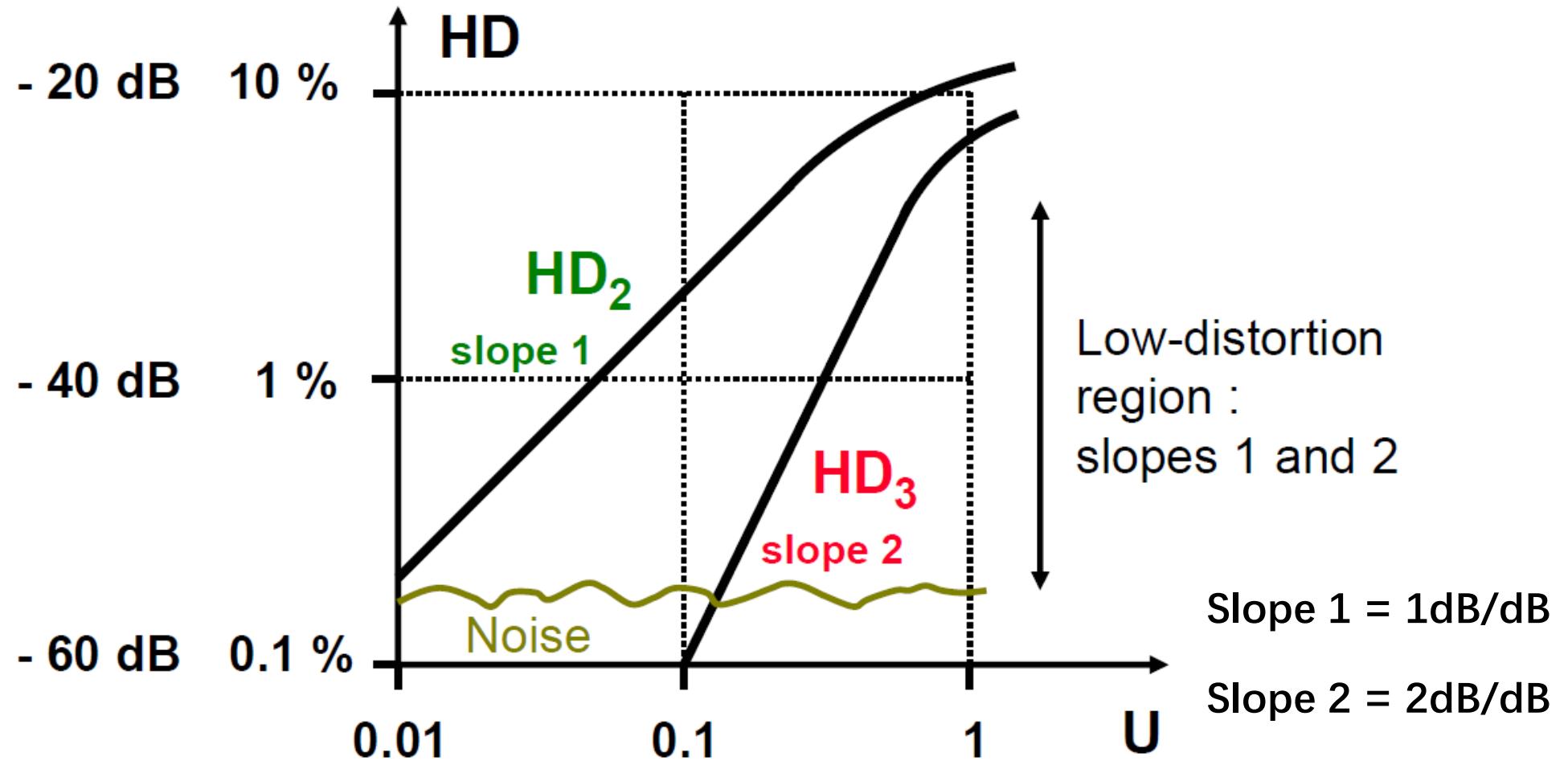
$$y = a_0 + a_1 u + a_2 u^2 + a_3 u^3 + \dots = a_0 +$$

$$(a_1 + \frac{3}{4} a_3 U^2) U \cos \omega t + \frac{a_2}{2} U^2 \cos 2\omega t + \frac{a_3}{4} U^3 \cos 3\omega t$$

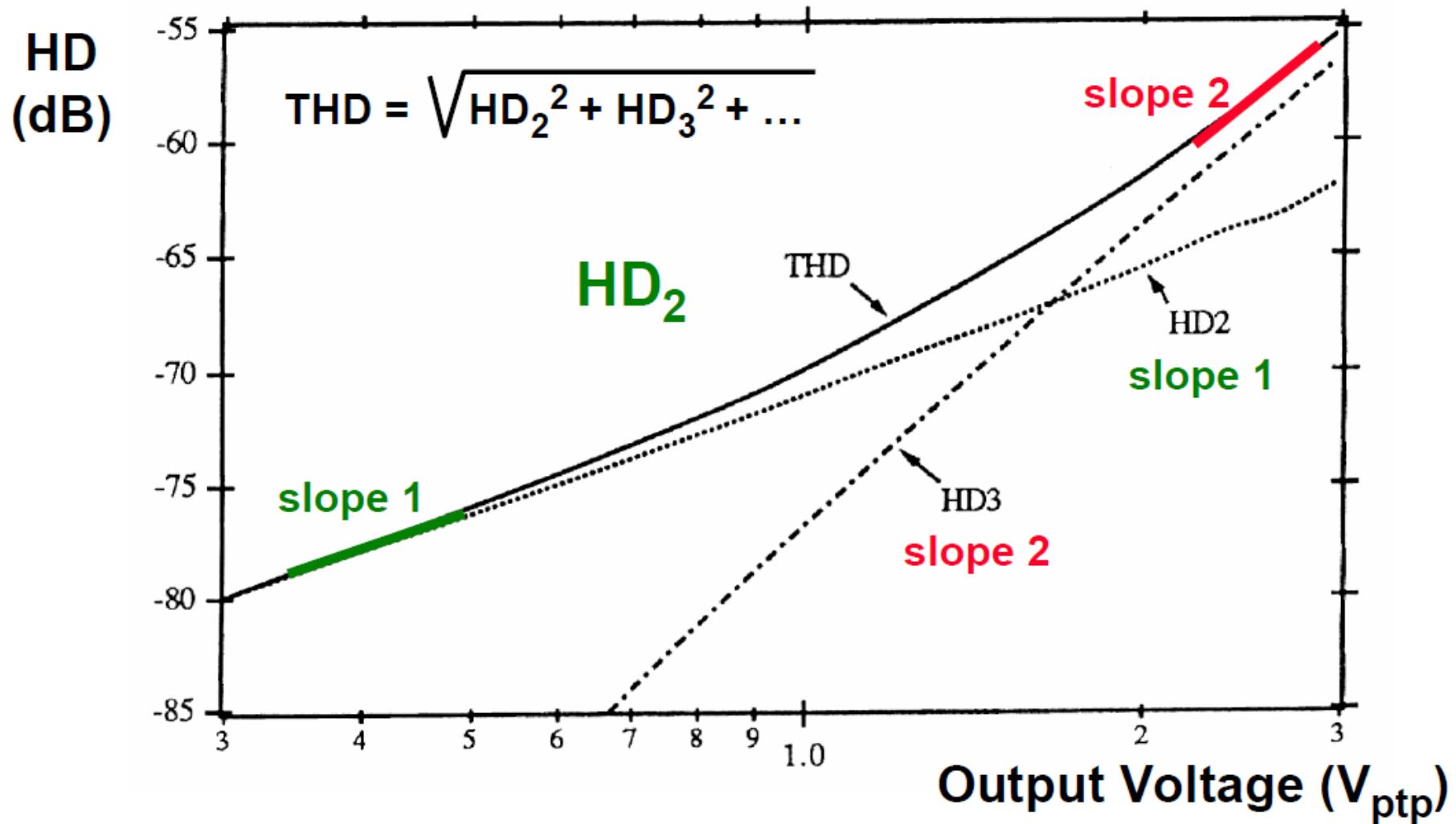
$$HD_2 = \frac{1}{2} \frac{a_2}{a_1} U$$

$$HD_3 = \frac{1}{4} \frac{a_3}{a_1} U^2$$

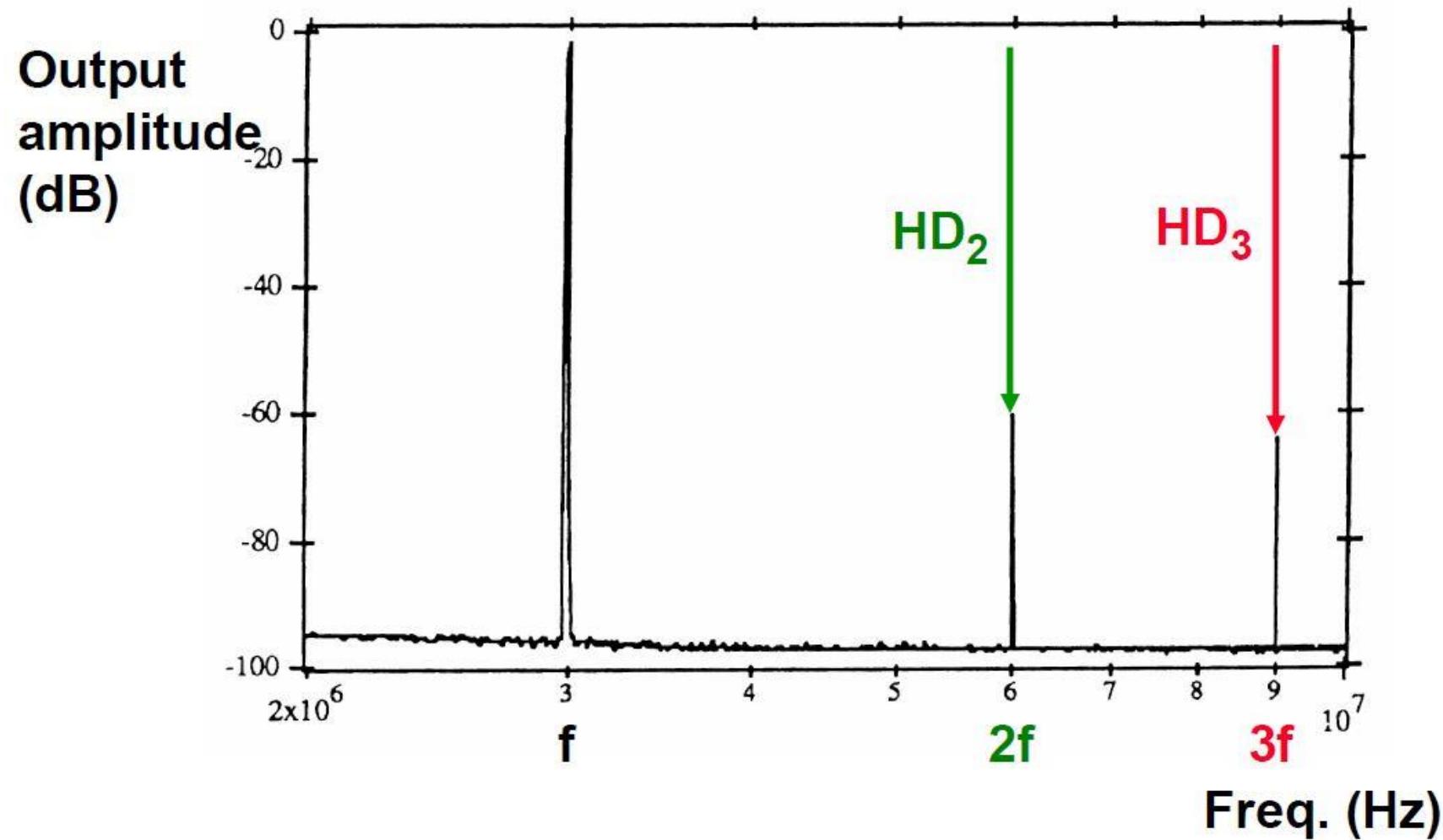
HD的幅度与输入信号的关系



一个电阻的谐波失真



输出频谱分析



互调失真 (Intermodulation Distortion, IM) 的定义

$$y = a_0 + a_1 u + a_2 u^2 + a_3 u^3 + \dots$$

with $u = U (\cos \omega_1 t + \cos \omega_2 t)$

$$y = a_0 + \dots$$

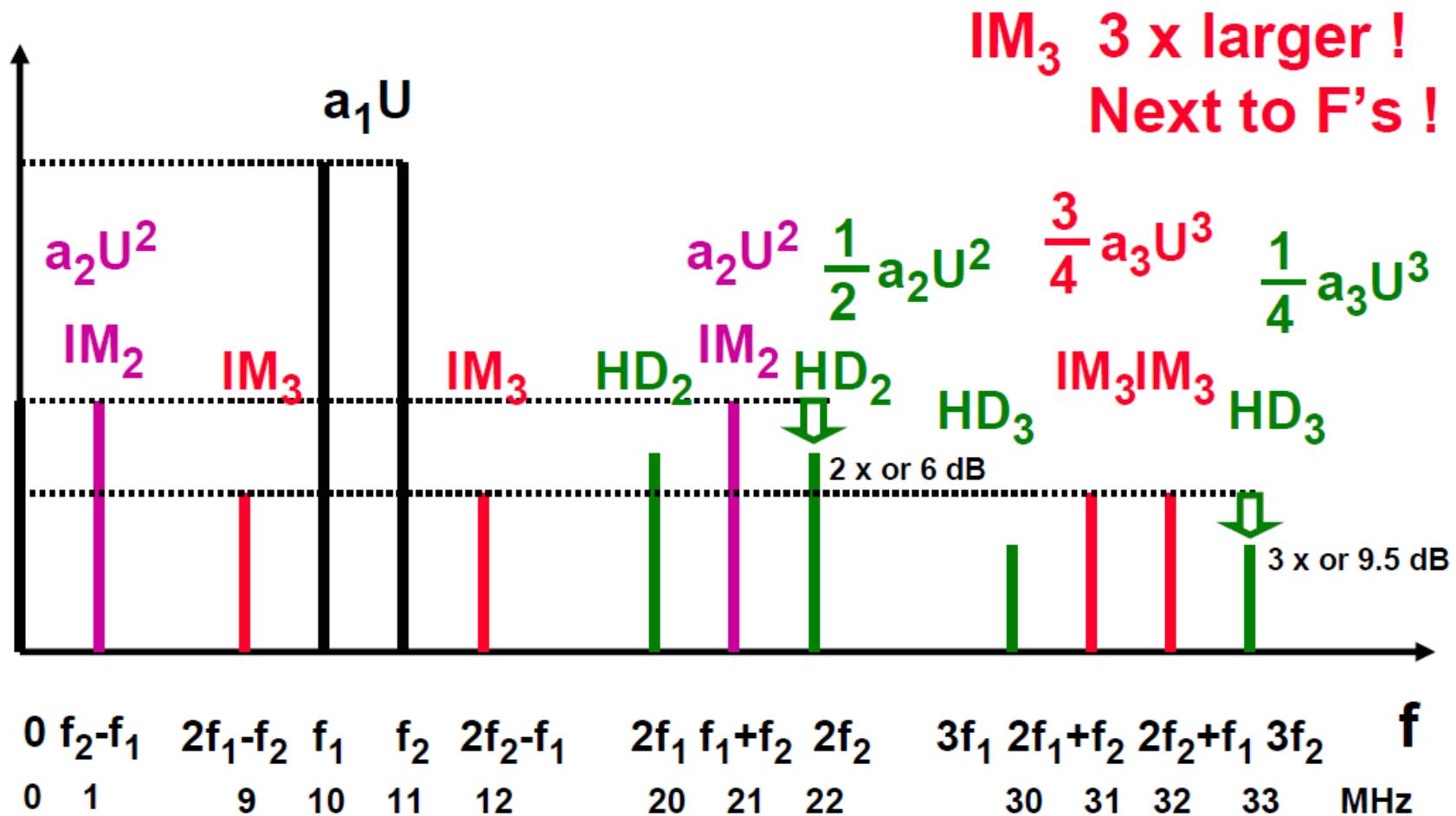
IM₂ at $\omega_1 \pm \omega_2$

IM₃ at $2\omega_1 \pm \omega_2$ and $\omega_1 \pm 2\omega_2$

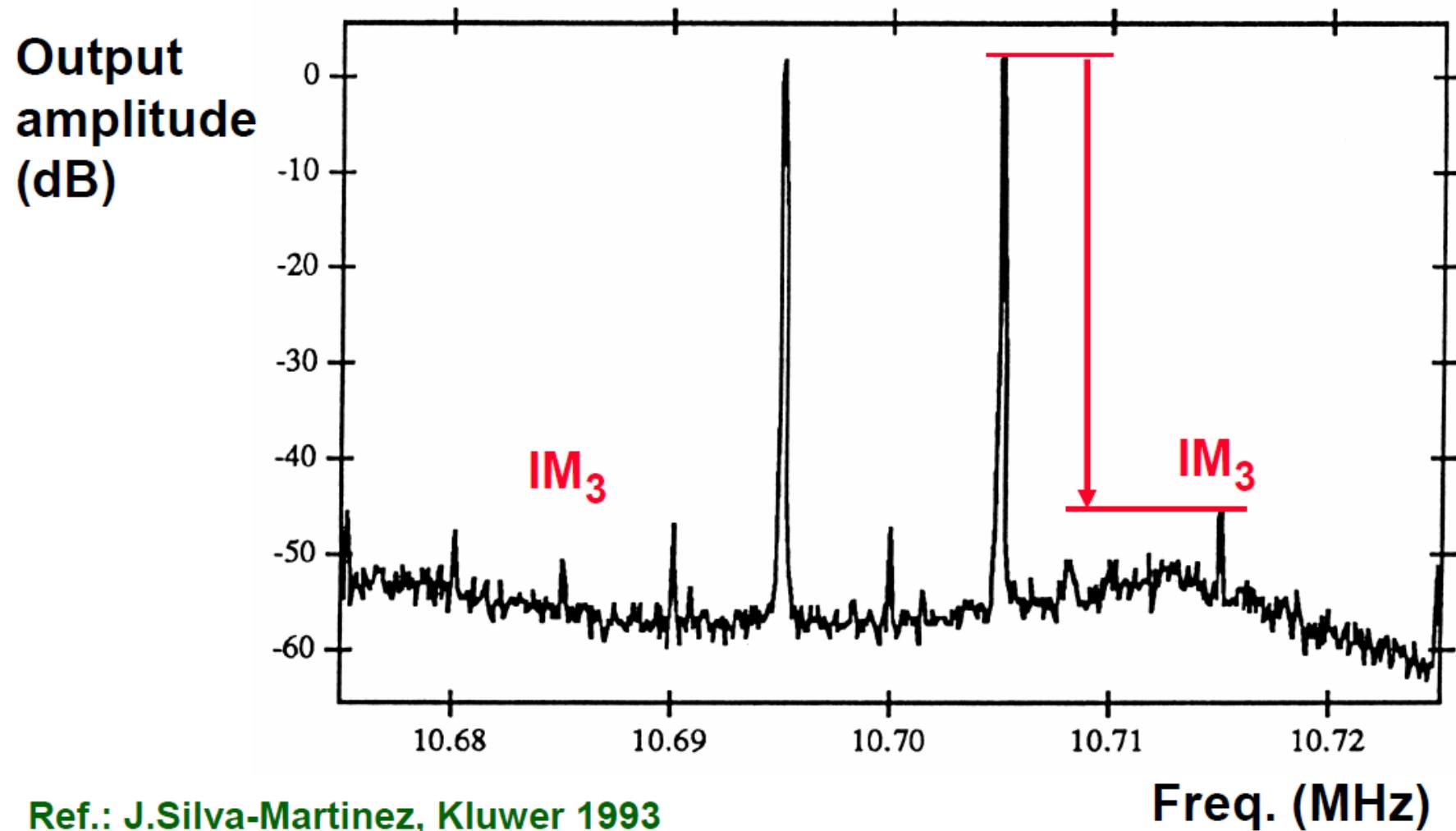
$$\boxed{IM_2 = 2 HD_2 = \frac{a_2}{a_1} U}$$

$$\boxed{IM_3 = 3 HD_3 = \frac{3}{4} \frac{a_3}{a_1} U^2}$$

IM的分布图 (一个实例)



运放的输出频谱（实例）



第一部分：失真

- 基本概念
- **MOS失真**
 - 单端放大器
 - 差分放大器
- 反馈与失真
- 线性化技术

单管放大器的非线性

$$I_{DS} = K (V_{GS} - V_T)^2$$

$$I_{DS} + i_{ds} = K (V_{GS} + v_{gs} - V_T)^2$$

$$i_{ds} = K(V_{GS} + v_{gs} - V_T)^2 - K(V_{GS} - V_T)^2$$

$$i_{ds} = 2K(V_{GS} - V_T)v_{gs} + Kv_{gs}^2$$

单管放大器只有**2**阶失真！

a1, a2, a3的计算

$$a_1 = 2K(V_{GS} - V_T)$$

$$a_2 = K$$

$$a_3 = 0$$

$$HD_2 = \frac{1}{2} \frac{a_2}{a_1} V_{gs} = \frac{v_{gs}}{4(V_{GS} - V_T)} \quad HD_3 = 0$$

归一化的电流摆幅

$$i_{ds} = 2K(V_{GS} - V_T)v_{gs} + Kv_{gs}^2$$

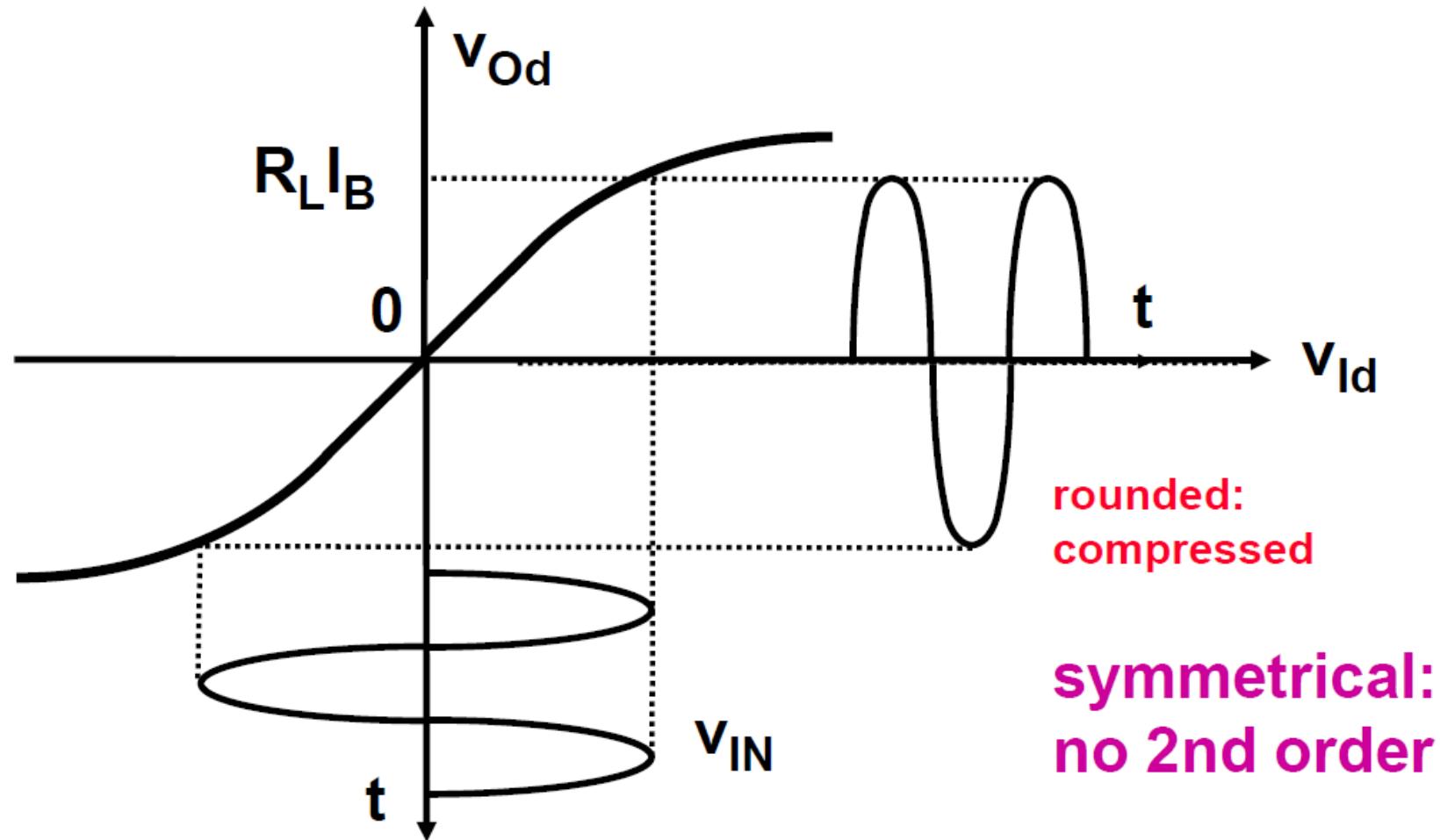
$$I_{DS} = K (V_{GS} - V_T)^2$$

$$y = \frac{i_{ds}}{I_{DS}} = \frac{2v_{gs}}{V_{GS} - V_T} + \frac{1}{4} \left(\frac{2v_{gs}}{V_{GS} - V_T} \right)^2$$

$$y = U + \frac{1}{4} U^2 \qquad U = \frac{2v_{gs}}{V_{GS} - V_T}$$

y 是相对电流摆幅

差分电路的非线性



单端电路的非线性

$$|A_v| \approx g_m R_D = \mu C_{ox} \frac{W}{L} (V_{GS} - V_T) R_D$$

$$\begin{aligned} I_{D0} &= \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH} + V_m \cos \omega t)^2 \\ &= \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})^2 + \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH}) V_m \cos \omega t \\ &\quad + \frac{1}{2} \mu_n C_{ox} \frac{W}{L} V_m^2 \cos^2 \omega t \\ &= I + \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH}) V_m \cos \omega t + \frac{1}{4} \mu_n C_{ox} \frac{W}{L} V_m^2 [1 + \cos(2\omega t)] \end{aligned}$$

$$HD_2 = \frac{V_m}{4(V_{GS} - V_{TH})}$$

差分电路的非线性 (1)

$$\begin{aligned} I_{D1} - I_{D2} &= \frac{1}{2} \mu_n C_{ox} \frac{W}{L} V_{in} \sqrt{\frac{4I_{SS}}{\mu_n C_{ox} \frac{W}{L}} - V_{in}^2} \\ &= \mu_n C_{ox} \frac{W}{L} V_{in} (V_{GS} - V_{TH}) \sqrt{1 - \frac{V_{in}^2}{4(V_{GS} - V_{TH})^2}} \\ &\approx \mu_n C_{ox} \frac{W}{L} V_{in} (V_{GS} - V_{TH}) [1 - \frac{V_{in}^2}{8(V_{GS} - V_{TH})^2}] \\ &= \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH}) [V_m \cos \omega t - \frac{V_m^3 \cos^3 \omega t}{8(V_{GS} - V_{TH})^2}] \end{aligned}$$

差分电路的非线性 (2)

因为 $\cos^3 \omega t = [3 \cos \omega t + \cos(3\omega t)]/4$

$$I_{D1} - I_{D2} = g_m \left[V_m - \frac{3V_m^3}{32(V_{GS} - V_{TH})} \right] \cos \omega t - g_m \frac{V_m^3}{32(V_{GS} - V_{TH})^2} \cos 3\omega t$$

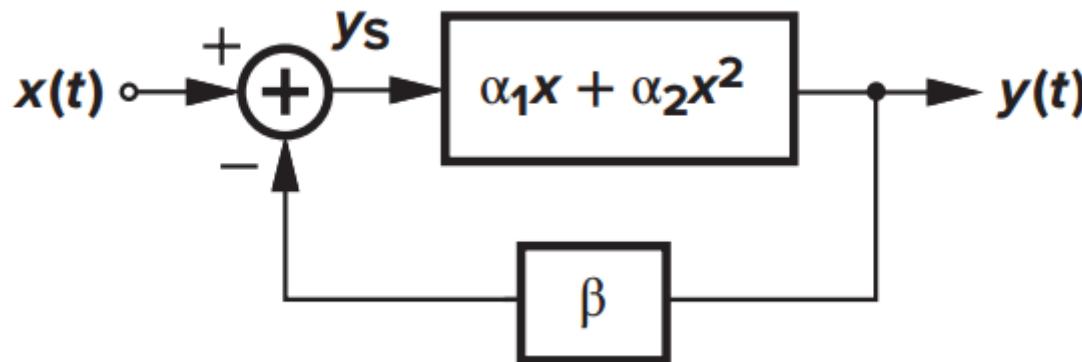
$$HD_3 \approx \frac{V_m^2}{32(V_{GS} - V_{TH})^2}$$

因为 $V_{GS} - V_{TH} \gg V_m$, 所以 HD_3 比 HD_2 小很多, 所以差分电路的非线性要比单端共源电路小很多

第一部分：失真

- 基本概念
- MOS失真
 - 单端放大器
 - 差分放大器
- 反馈与失真
- 线性化技术

负反馈对非线性的影响



$$y_s = x(t) - \beta y(t)$$

$$= V_m \cos \omega t - \beta(a \cos \omega t + b \cos 2\omega t)$$

$$= (V_m - \beta a) \cos \omega t - \beta b \cos 2\omega t$$

负反馈对非线性的影响

$$\begin{aligned}y(t) &= \alpha_1[(V_m - \beta) \cos \omega t - \beta b \cos 2\omega t] \\&\quad + \alpha_2[(V_m - \beta a) \cos \omega t - \beta b \cos 2\omega t]^2 \\&= [\alpha_1(V_m - \beta a) - \alpha_2(V_m - \beta a)\beta b] \cos \omega t \\&\quad + \left[-\alpha_1\beta b + \frac{\alpha_2(V_m - \beta a)^2}{2} \right] \cos 2\omega t + \dots\end{aligned}$$

$$a = \frac{\alpha_1}{1 + \beta\alpha_1} V_m$$

$$\begin{aligned}a &= (\alpha_1 - \alpha_2\beta b)(V_m - \beta a) \\b &= -\alpha_1\beta b + \frac{\alpha_2(V_m - \beta a)^2}{2}\end{aligned}\Rightarrow\begin{aligned}b &= \frac{\alpha_2 V_m^2}{2} \frac{1}{(1 + \beta\alpha_1)^3}\end{aligned}\Rightarrow$$

牺牲了增益，获得了较低的非线性！

$$\frac{b}{a} = \frac{\alpha_2 V_m}{2} \frac{1}{\alpha_1} \frac{1}{(1 + \beta\alpha_1)^2}$$

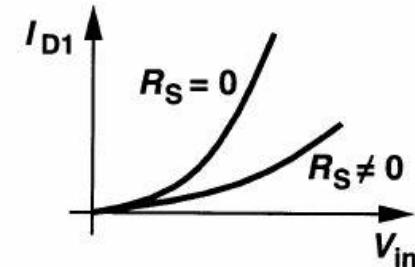
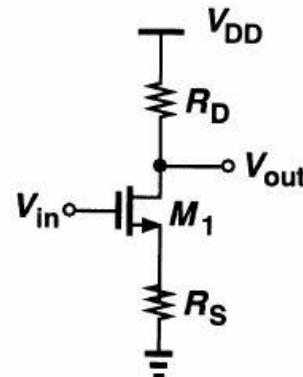
第一部分：失真

- 基本概念
- MOS失真
 - 单端放大器
 - 差分放大器
- 反馈与失真
- 线性化技术

线性化技术

- 原理

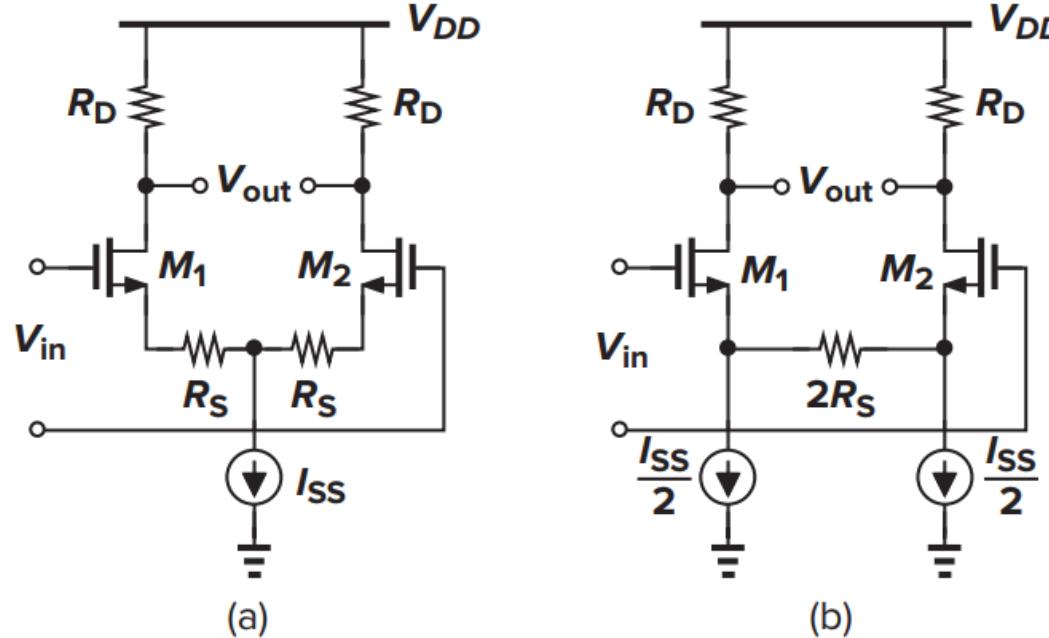
$$G_m = \frac{g_m}{1 + g_m R_s}$$



当 $g_m R_s$ 远大于 1 时， G_m 与输入无关，使得 $G_m R_D$ 也与输入无关。

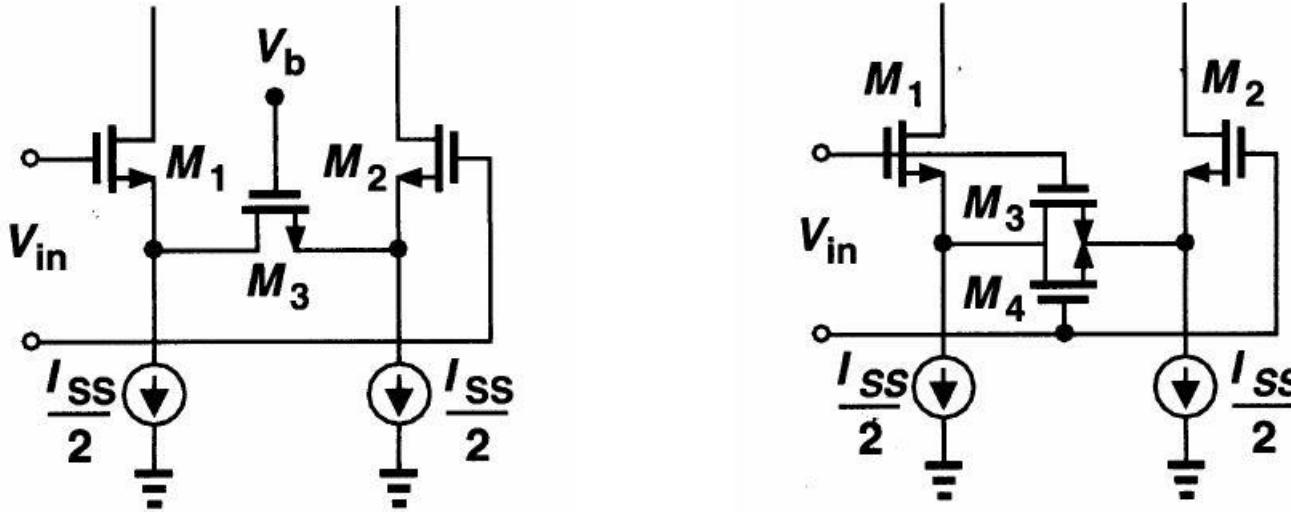
线性化的基本原理：减小电路的增益对输入电平的依赖。这通常转换为使增益相对独立于晶体管的偏置电流。

差动电路的线性化技术



两个电路均可提高线性。但(a)中，消耗了 $I_{SS}R_S/2$ 的电压余度；(b) 具有较高的噪声（以及失调电压），因为两个尾电流源引入了一些差分误差。

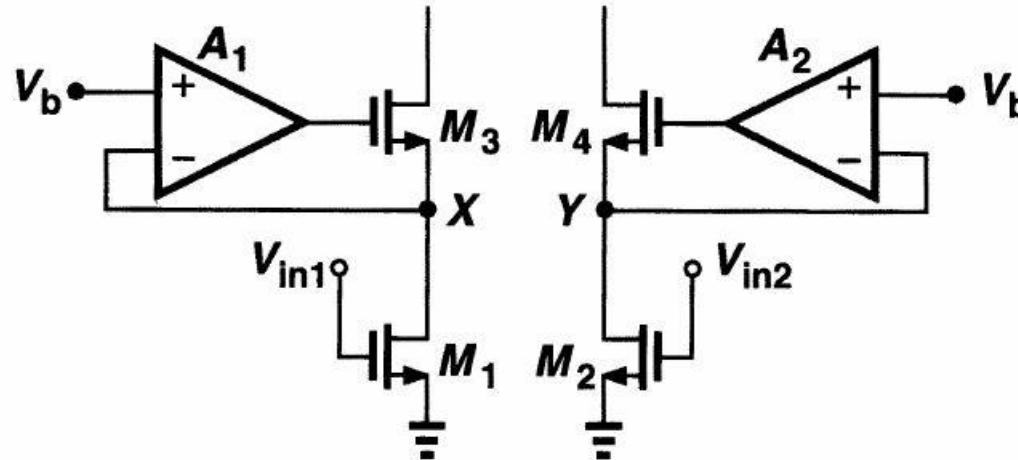
MOSFET实现负反馈电阻



负反馈中的电阻通常用工作于深线性区的MOSFET来替代。

左图的 V_b 必须跟踪输入共模电平，才能精确地确定 R_{on3} ，改进的右图中， $V_{in} > 0$ 时，由于 $V_{D3} = V_{G3} - V_{GS1}$ ， M_3 保持线性区，即使 M_4 进入饱和区，电路仍能保持相对线性。

避免使用电阻的另一种线性方法



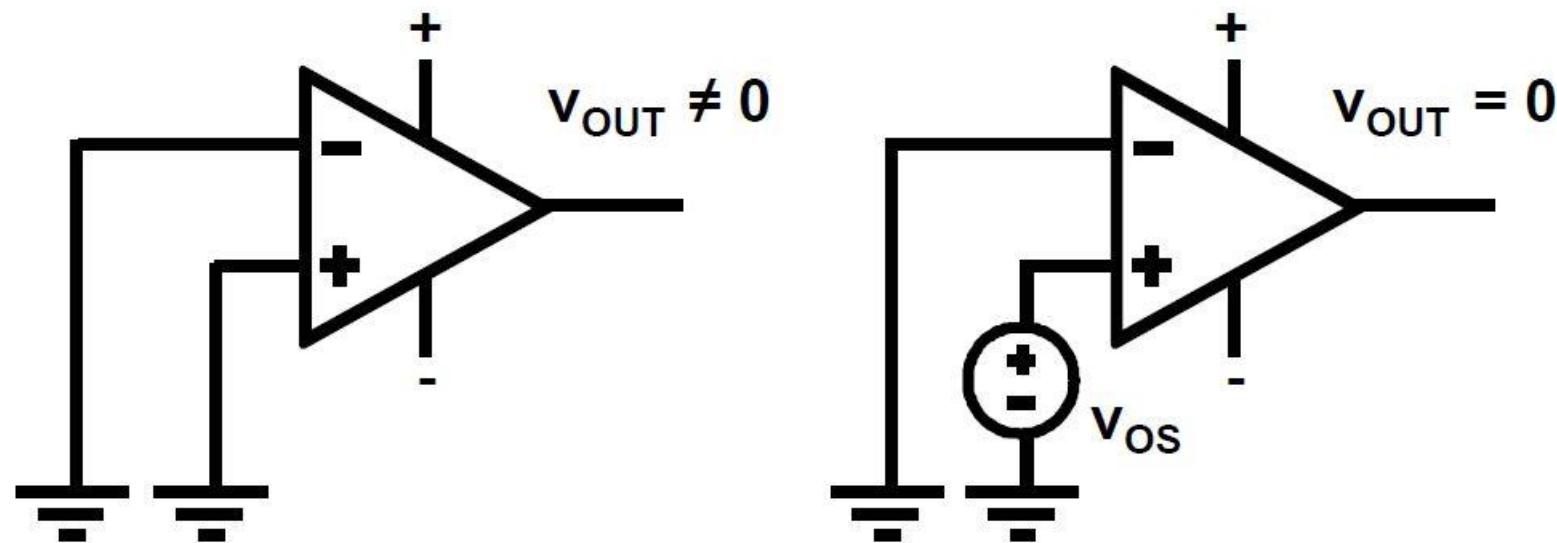
工作在线性区的MOSFET，如果其漏源电压保持恒定，就可提供一个线性的 I_D/V_{GS} 特性。

缺点： V_{DS} 必须足够低，因此 M_1 与 M_2 的跨导较小；输入共模电平必须被严格控制并跟踪 V_b ； M_3 、 M_4 与两个辅助放大器在输出端会产生很大的噪声。

第二部分：失调

- 随机性失调
- 系统性失调
- 失调消除技术

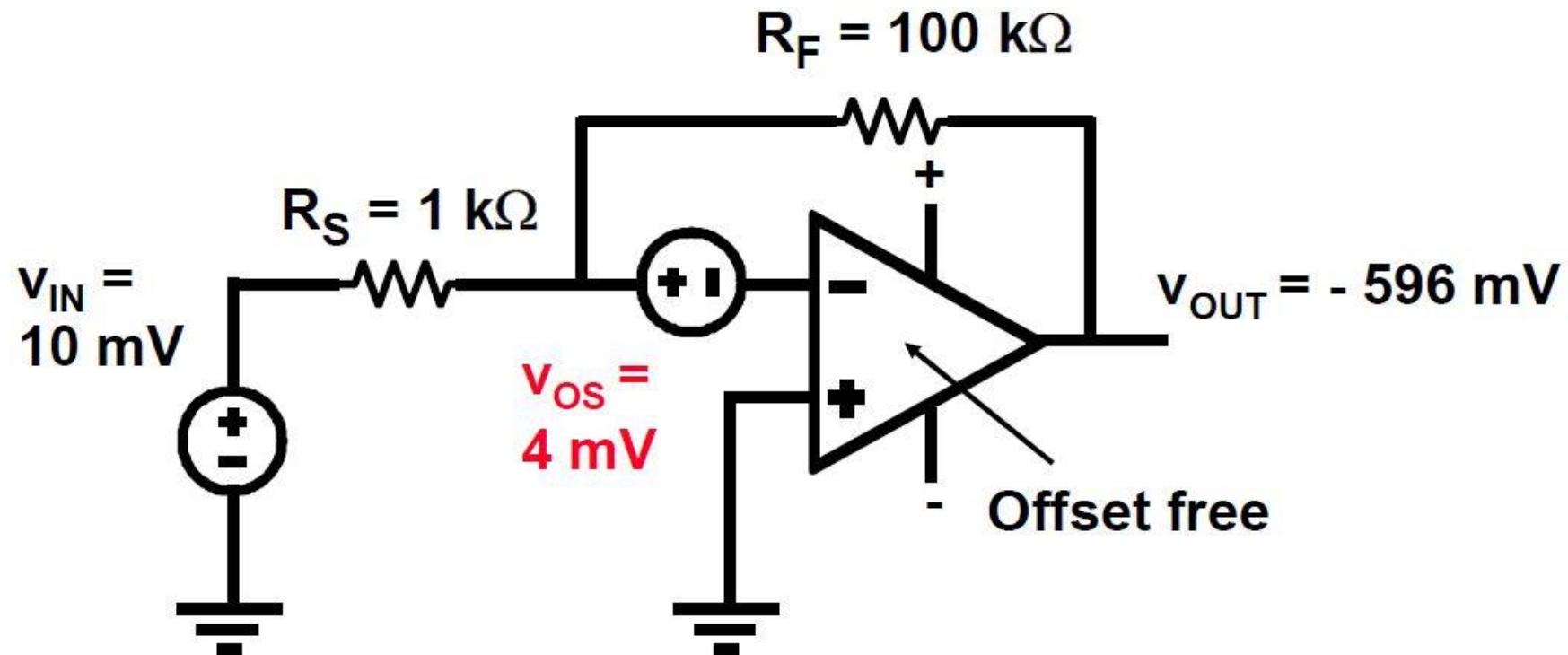
失调的定义



Offset voltage v_{os}

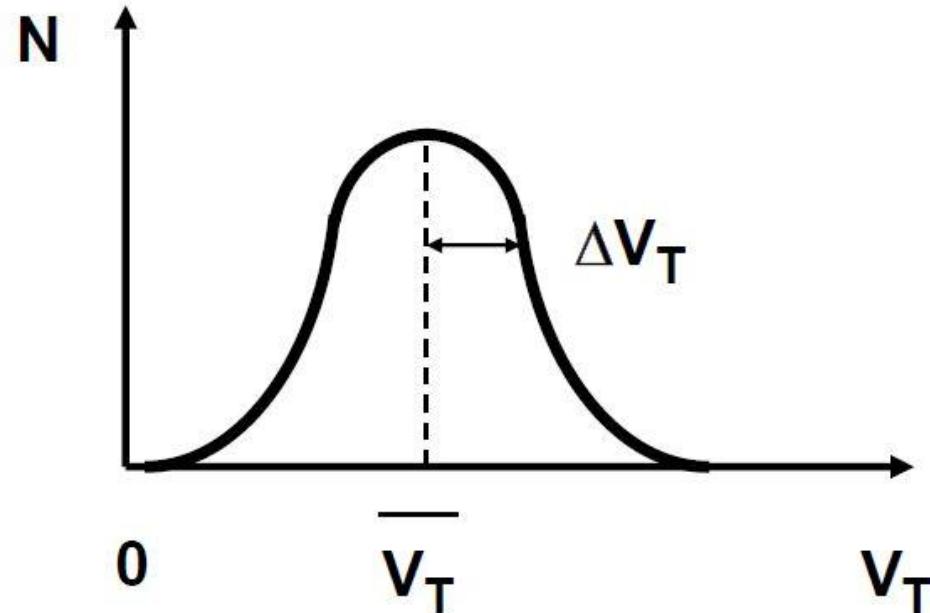
V_{os} 就是失调电压
@ $V_{out}=0$

带失调的运放



The gain is 59 instead of 100 !

尺寸失配引起阈值起伏



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

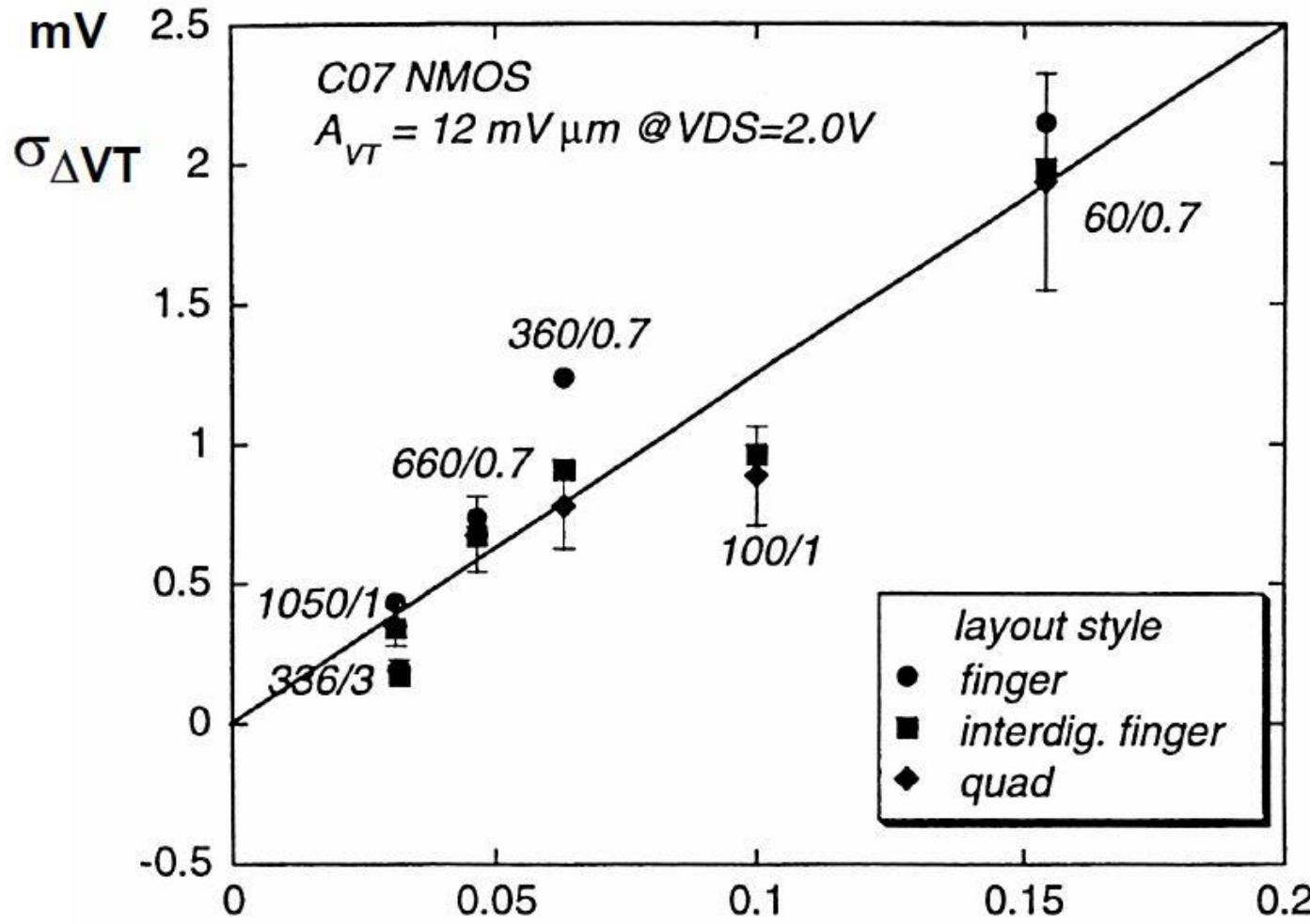
$$\sigma_{\Delta VT} = \frac{A_{VT}}{\sqrt{WL}}$$

$$A_{VT} \sim t_{ox} \sqrt[4]{N_B}$$

Ref: Keyes, JSSC Aug. 1975, 245-247
Shyu, JSSC Dec 1984, 948-955
Lakshmikumar, JSSC Dec 1986, 1057-1066
Pelgrom, JSSC Oct. 1989, 1433-1439
Croon, JSSC Aug. 2002, 1056-1064

$A_{VT} \approx 5 \text{ mV}\mu\text{m}$
for 0.25 μm nMOST
+50 % for pMOST

阈值起伏方差 $\sigma_{\Delta VT}$

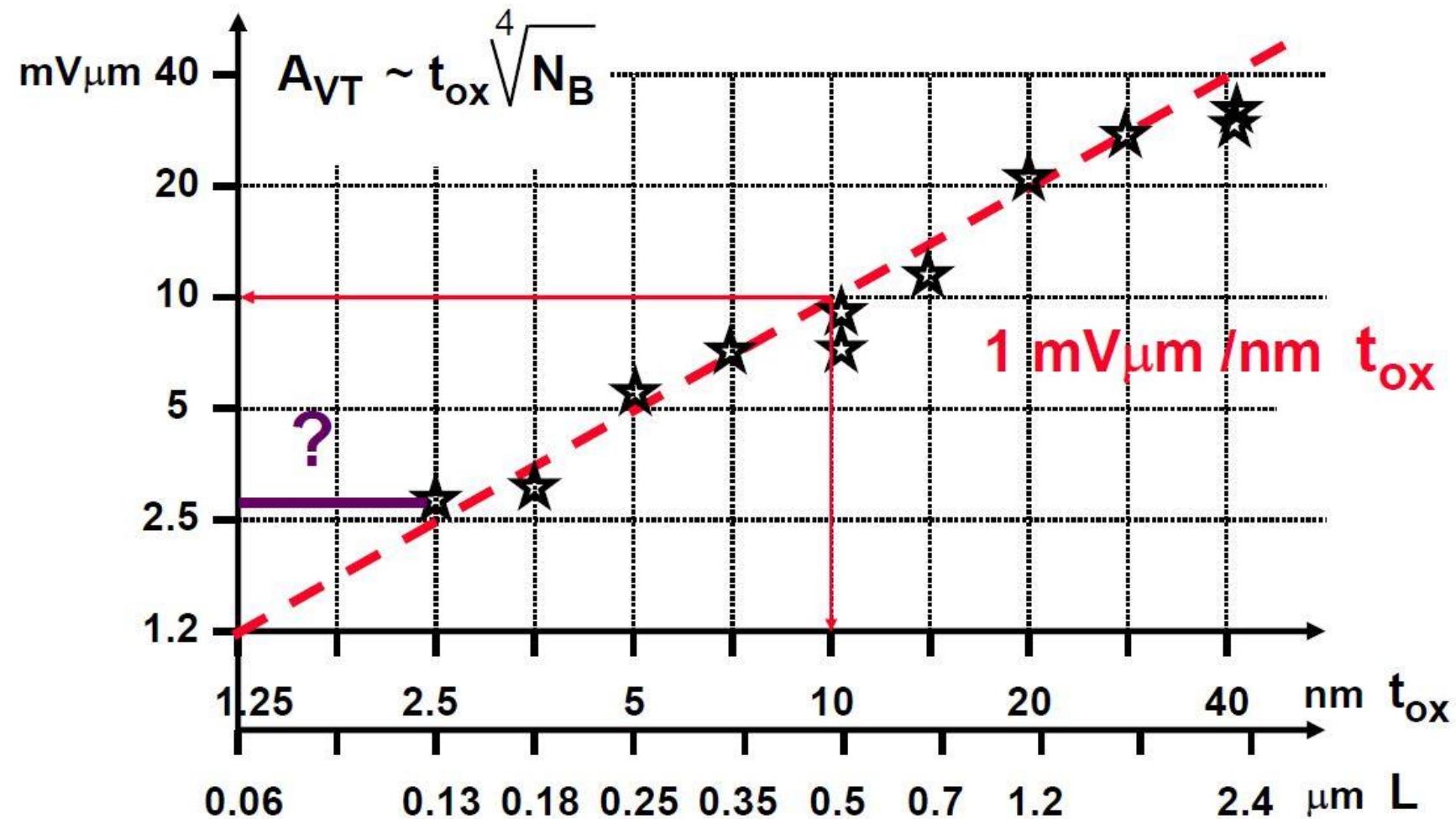


$$\sigma_{\Delta VT} = \frac{A_{VT}}{\sqrt{WL}}$$

$\sigma(\Delta V_T) \approx 2 \text{ mV}$
 $W/L = 60/0.7 \mu\text{m}$
in $0.7 \mu\text{m}$ CMOS

$$1/\sqrt{WL}$$

阈值失配 A_{VT}



MOS管的随机误差

$$\frac{\Delta K'}{K'} = \frac{A_{K'}}{\sqrt{WL}}$$

$A_{K'} \approx 0.0056 \mu\text{m}$ +50 % for pMOS

$$\frac{\Delta W/L}{W/L} = A_{WL} \sqrt{\frac{1}{W^2} + \frac{1}{L^2}} \quad A_{WL} \approx 0.02 \mu\text{m}$$

+50 % for pMOS

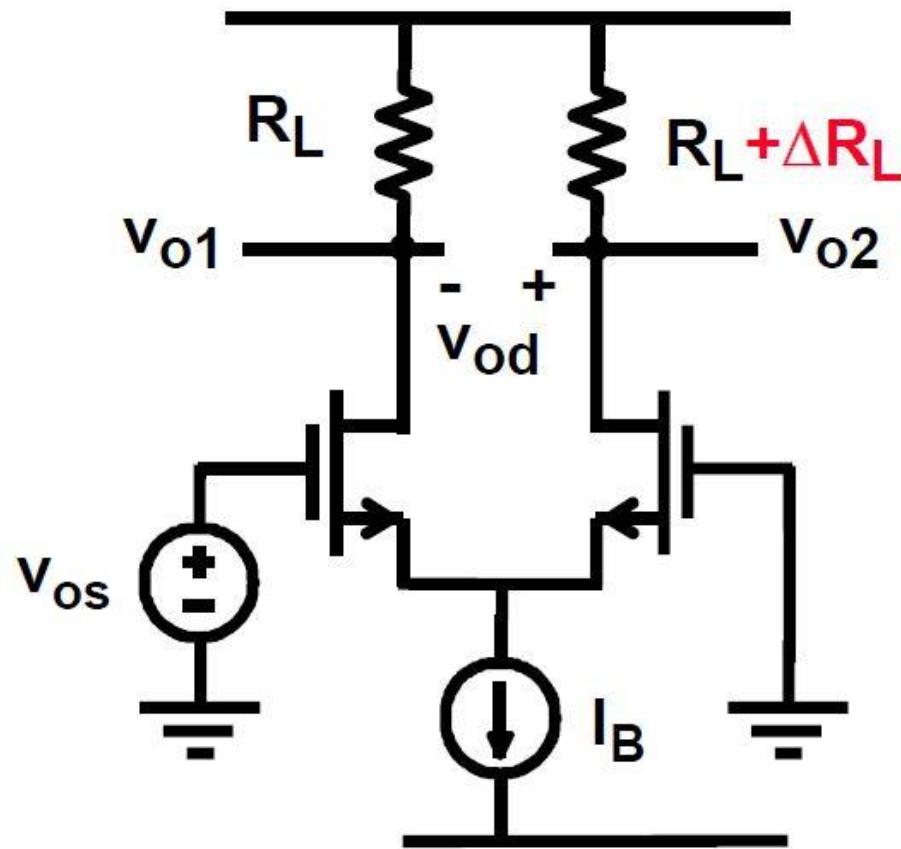
$$\frac{\Delta \gamma}{\gamma} = \frac{A_\gamma}{\sqrt{WL}}$$

$A_\gamma \approx 0.016 \mu\text{m}$ -25 % for pMOS

Negligible if $B = S$

Ref.: Pelgrom : JSSC Oct.1989, pp.1430-1440

差分对的随机失调电压



$$v_{od} = \Delta R_L \frac{I_B}{2}$$

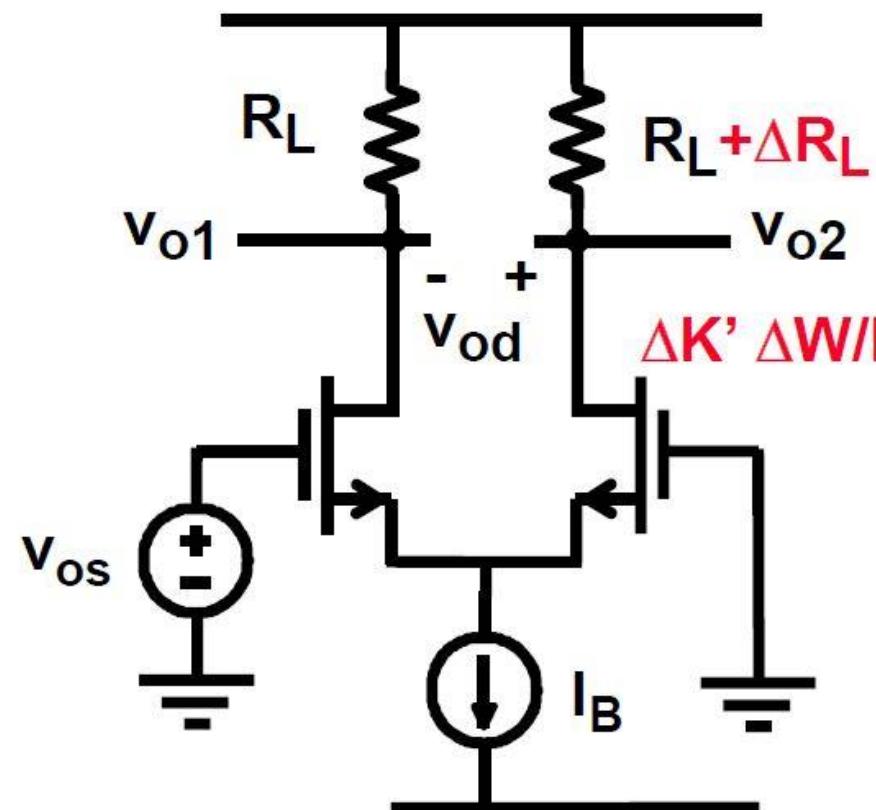
$$v_{os} = \frac{v_{od}}{g_m R_L}$$

$$v_{os} = \frac{\Delta R_L}{R_L} \frac{I_B}{2g_m}$$

$$v_{os} = \frac{\Delta R_L}{R_L} \frac{V_{GS} - V_T}{2}$$

Ref.: Laker, Sansen : Design of analog ..., MacGrawHill 1994

差分对的随机失调电压



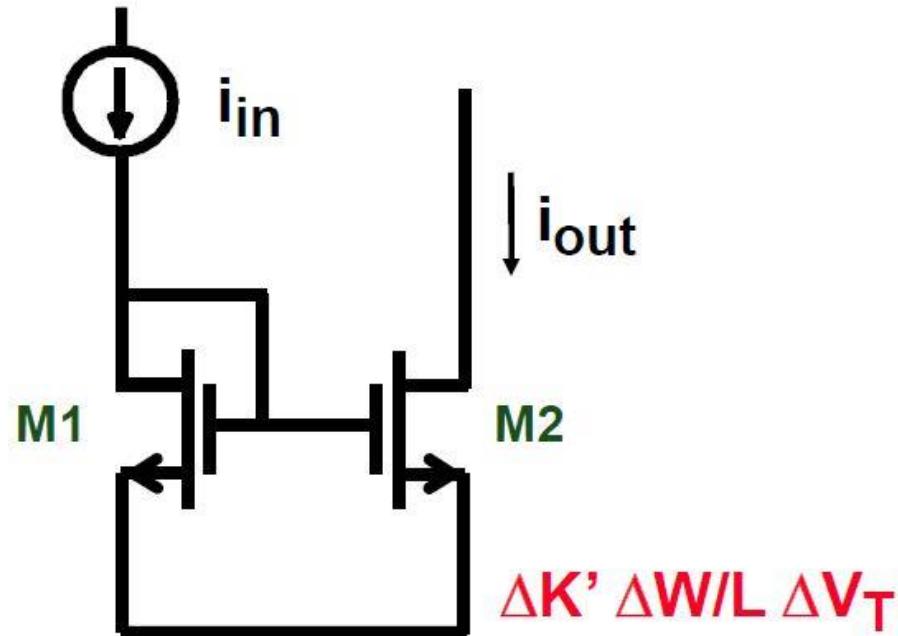
$$v_{os} = \Delta V_T + \frac{V_{GS} - V_T}{2} ($$

$$\frac{\Delta R_L}{R_L} + \frac{\Delta K'}{K'} + \frac{\Delta W/L}{W/L})$$

→ small $V_{GS} - V_T$

Ref.: Laker, Sansen : Design of analog ..., MacGrawHill 1994

电流镜的失调

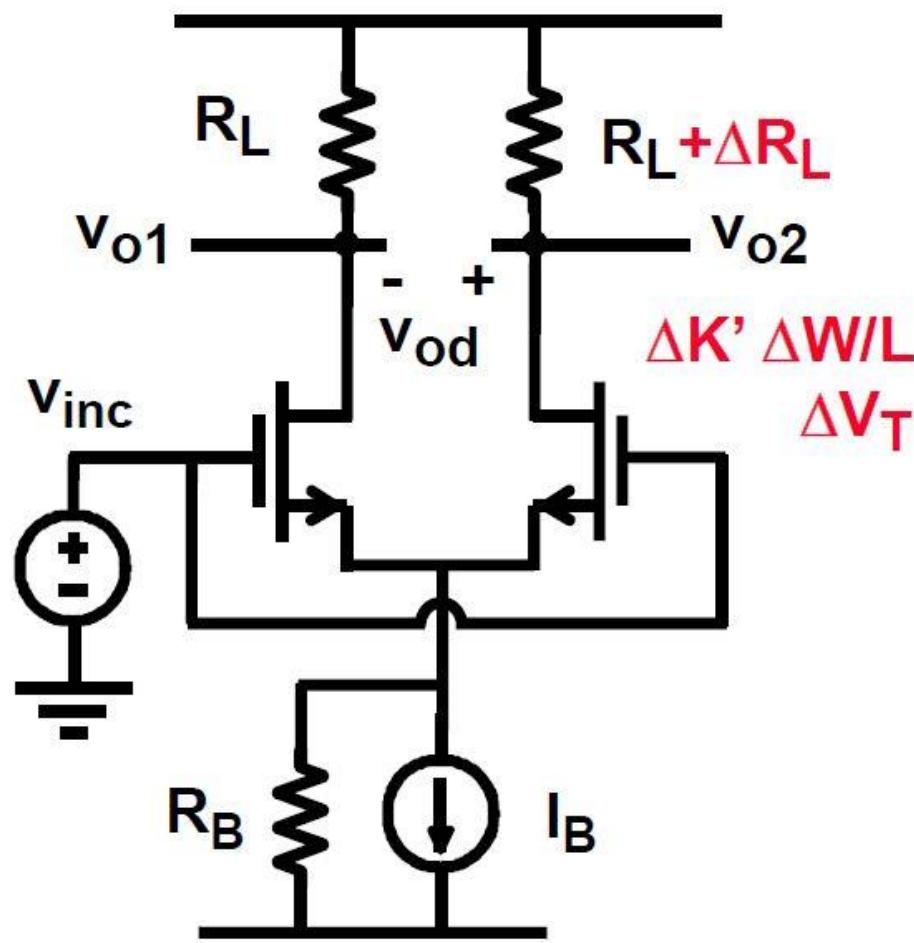


$$\frac{\Delta I_{out}}{I_{out}} = \frac{\Delta V_T}{(V_{GS} - V_T)/2} + \frac{\Delta K'}{K'} + \frac{\Delta W/L}{W/L}$$

→ large $V_{GS} - V_T$

Ref.: Laker, Sansen : Design of analog ..., MacGrawHill 1994

差分对的共模抑制比-1



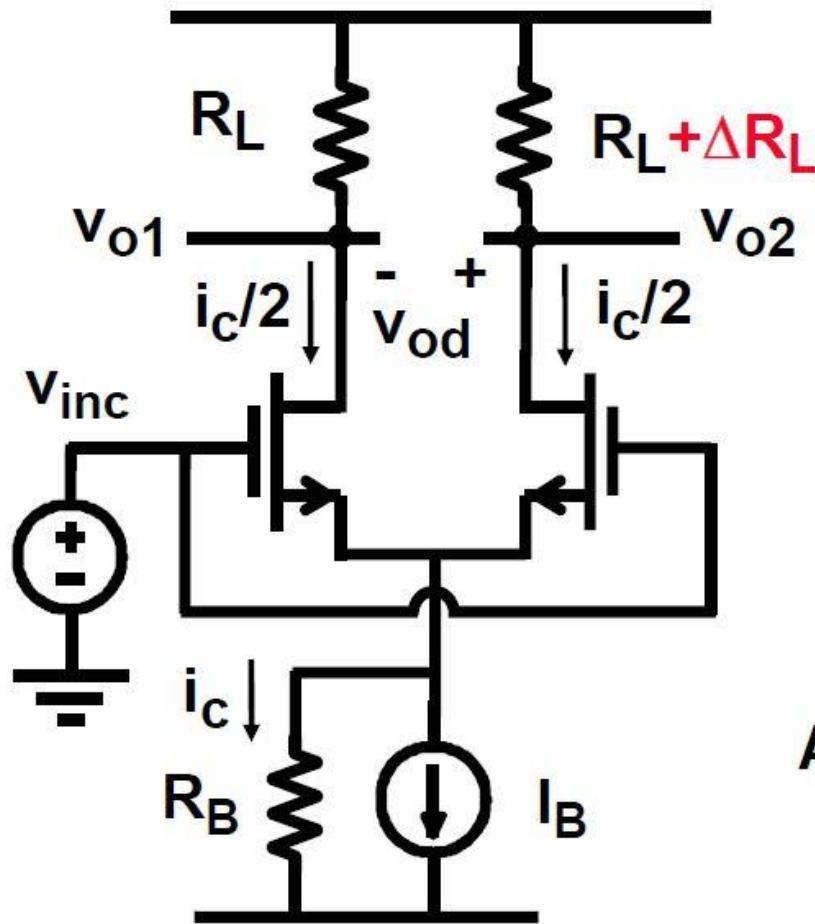
$$v_{od} = A_{dd} v_{id} + A_{dc} v_{ic}$$
$$v_{oc} = A_{cd} v_{id} + A_{cc} v_{ic}$$

$$A_{dd} = \left. \frac{v_{od}}{v_{id}} \right|_{v_{ic}=0} = g_m R_L$$

$$A_{dc} = \left. \frac{v_{od}}{v_{ic}} \right|_{v_{id}=0} \approx 0$$

$$CMRR = \frac{A_{dd}}{A_{dc}} \approx \infty$$

差分对的共模抑制比-2



$$A_{dc} = \left. \frac{v_{od}}{v_{ic}} \right|_{v_{id}=0} \neq 0$$

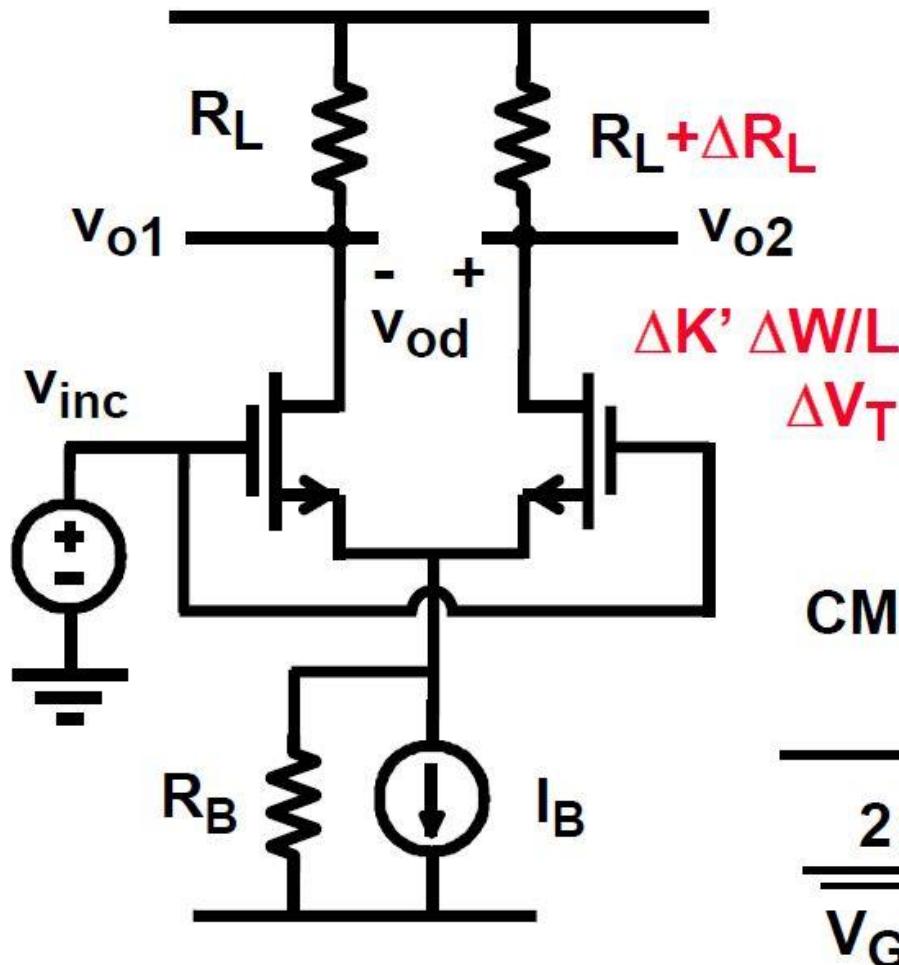
$$v_{ic} = v_{inc} \implies i_c = \frac{v_{inc}}{R_B}$$

$$v_{od} = \Delta R_L i_c / 2$$

$$A_{dc} = \frac{\Delta R_L}{2 R_B}$$

$$\boxed{CMRR = \frac{2 g_m R_B}{\Delta R_L / R_L}}$$

差分对的共模抑制比-3



CMRR =

$$\frac{2 g_m R_B}{\frac{2 \Delta V_T}{V_{GS} - V_T} + \frac{\Delta R_L}{R_L} + \frac{\Delta K'}{K'} + \frac{\Delta W/L}{W/L}}$$

失调与共模抑制比的关系

$$v_{OSr} = \Delta V_T + \frac{V_{GS} - V_T}{2} \left(\frac{\Delta R_L}{R_L} + \frac{\Delta K'}{K'} + \frac{\Delta W/L}{W/L} \right)$$

$$CMRR_r = \frac{2 g_m R_B}{\frac{2 \Delta V_T}{V_{GS} - V_T} + \frac{\Delta R_L}{R_L} + \frac{\Delta K'}{K'} + \frac{\Delta W/L}{W/L}}$$

$$v_{OSr} CMRR_r = \frac{V_{GS} - V_T}{2} 2 g_m R_B = I_B R_B = V_E L_B = 5 \dots 15 V$$

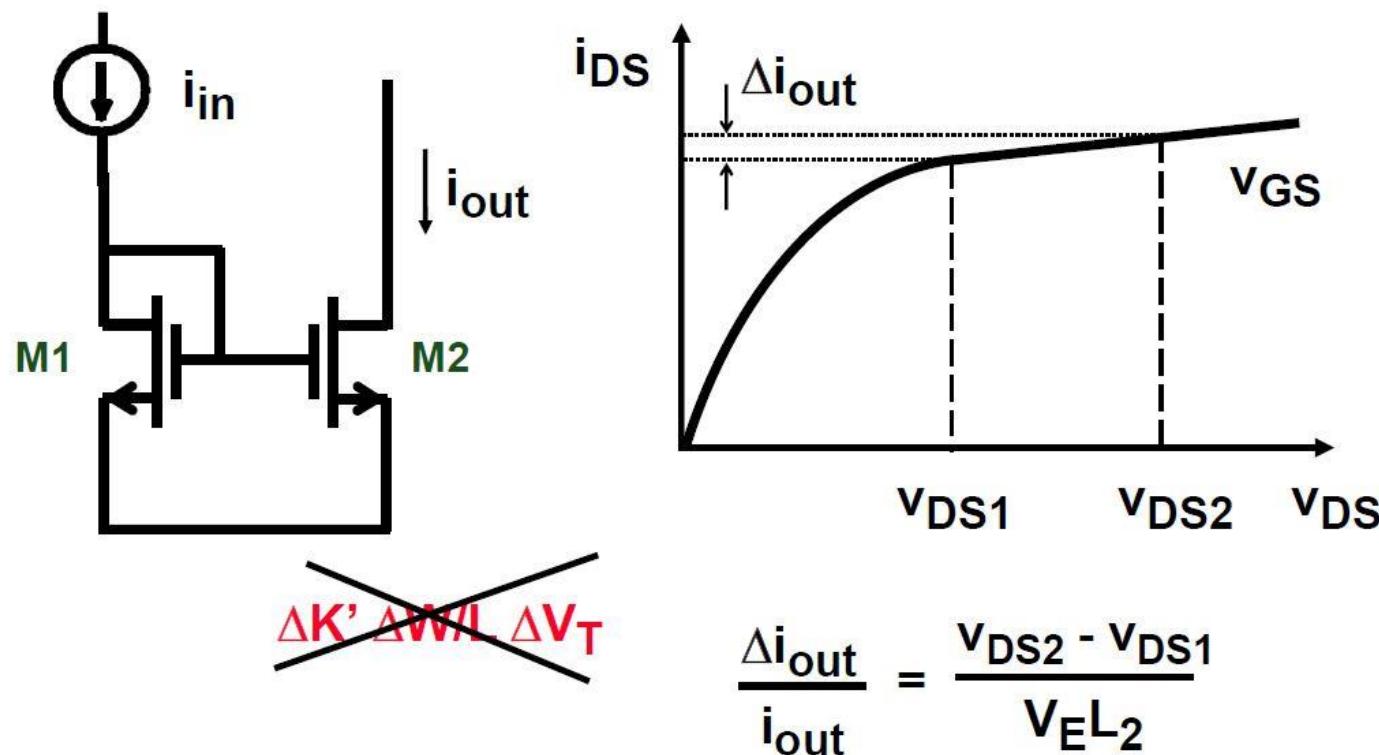
$$v_{OSr} CMRR_r = 10 V$$

第二部分：失调

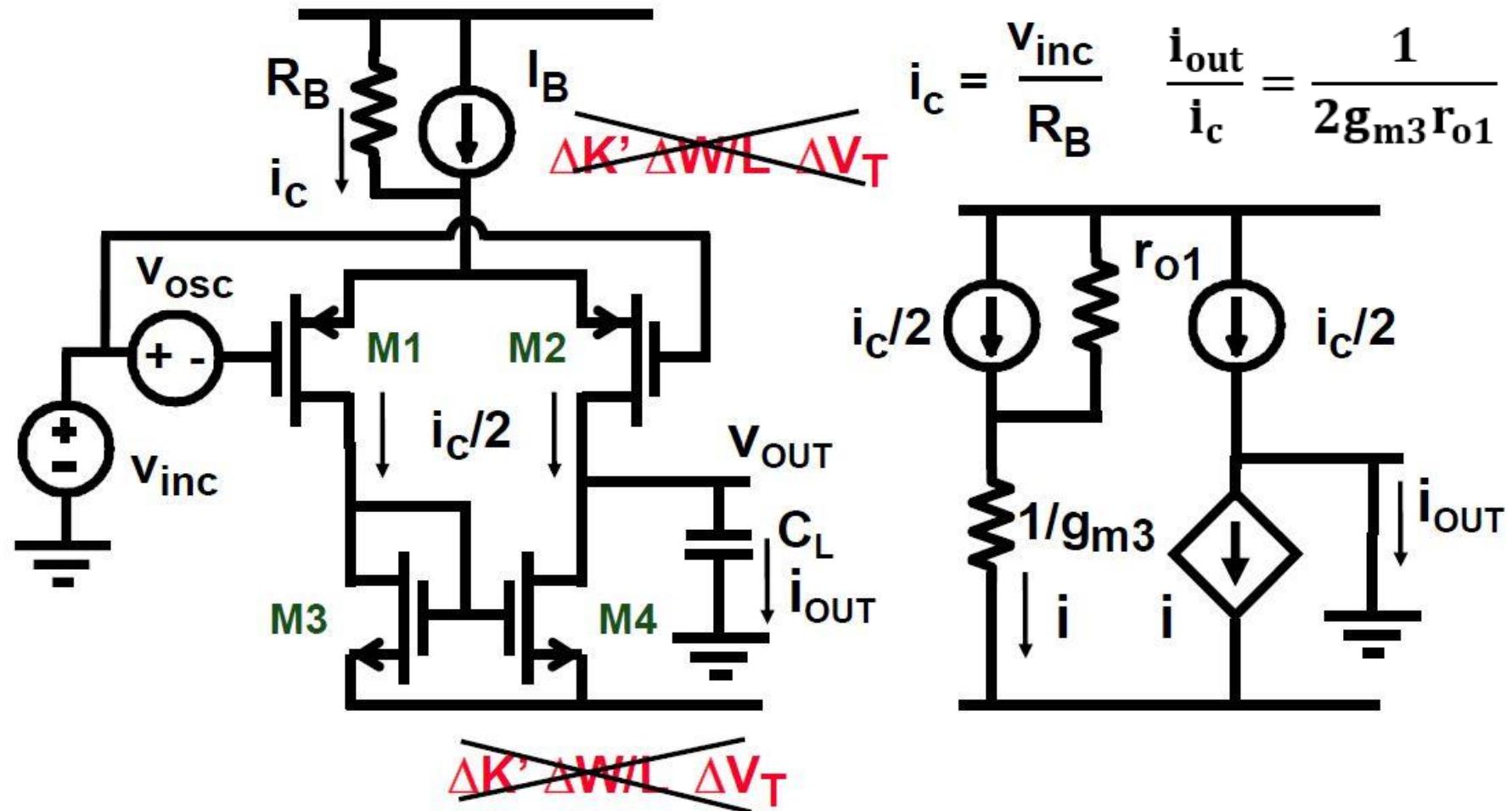
- 随机性失调
- 系统性失调
- 失调消除技术

系统随机失调

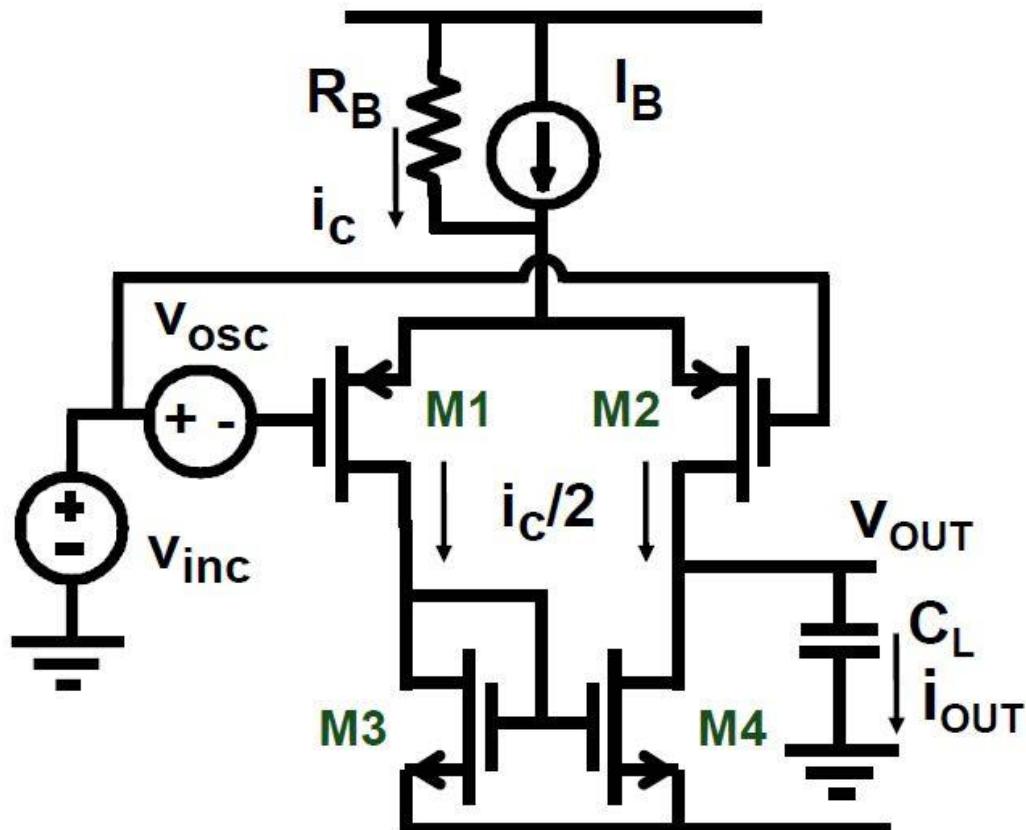
- 电流镜中的系统失调



差分对共模抑制比的系统误差-1



差分对共模抑制比的系统误差-2



$$\frac{i_{out}}{v_{inc}} = \frac{1}{R_B} \frac{1}{2g_{m3}r_{o1}}$$

$$\frac{i_{out}}{v_{osc}} = g_{m1}$$

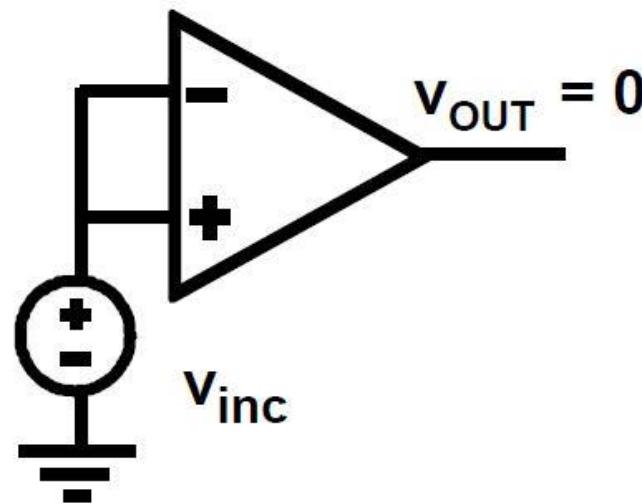
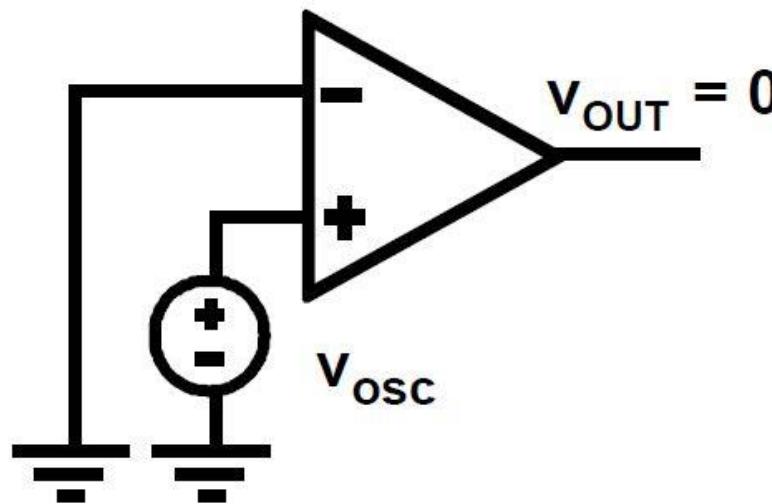
$$\frac{\frac{i_{out}}{v_{inc}}}{\frac{i_{out}}{v_{osc}}} = \frac{A_{dc}}{A_{dd}} = \frac{1}{CMRR_s}$$

差分对共模抑制比的系统误差-3

$$\frac{\frac{v_{out}}{v_{osc}}}{\frac{v_{out}}{v_{inc}}} = \frac{v_{osc}}{v_{inc}} = \frac{A_{dc}}{A_{dd}} = \frac{1}{CMRR_s}$$

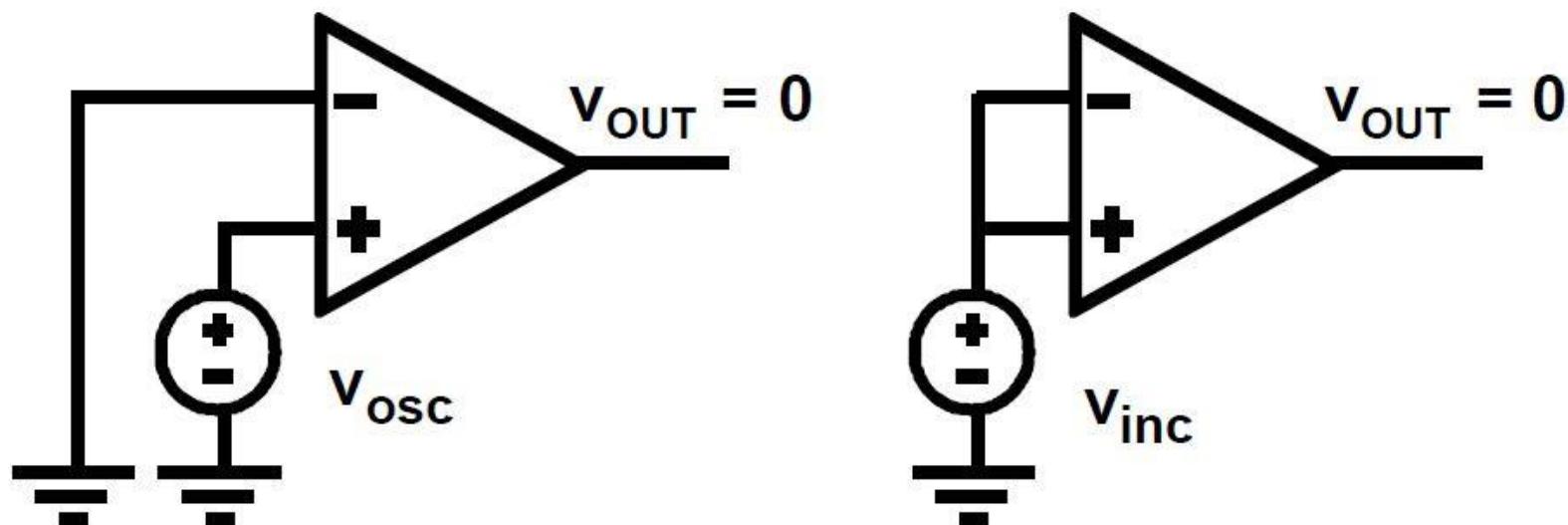
$$CMRR_s = \frac{1}{2} g_{m1} R_B g_{m3} r_{o1}$$

$$CMRR_s v_{osc} = v_{inc}$$

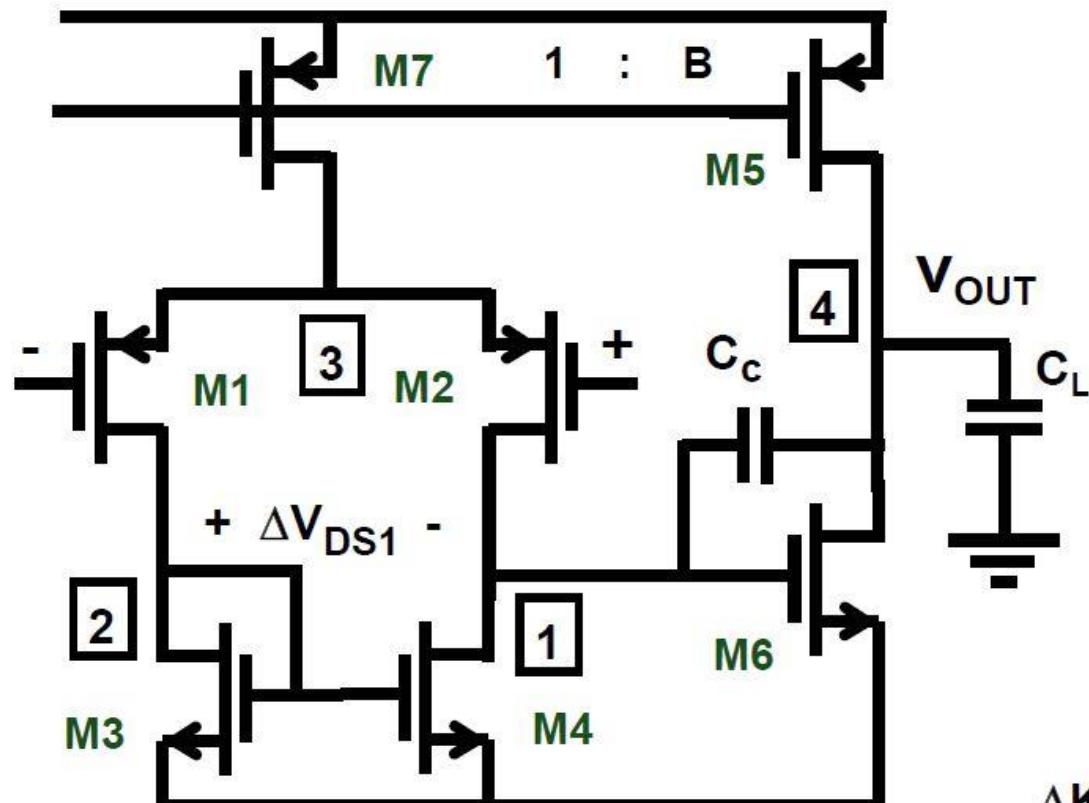


总失调

$$\frac{1}{CMRR} = \frac{1}{CMRR_r} + \frac{1}{CMRR_s}$$



带米勒电容的放大器失调(例1)



$$A_{v1} = g_{m1} r_{o2} // r_{o4}$$

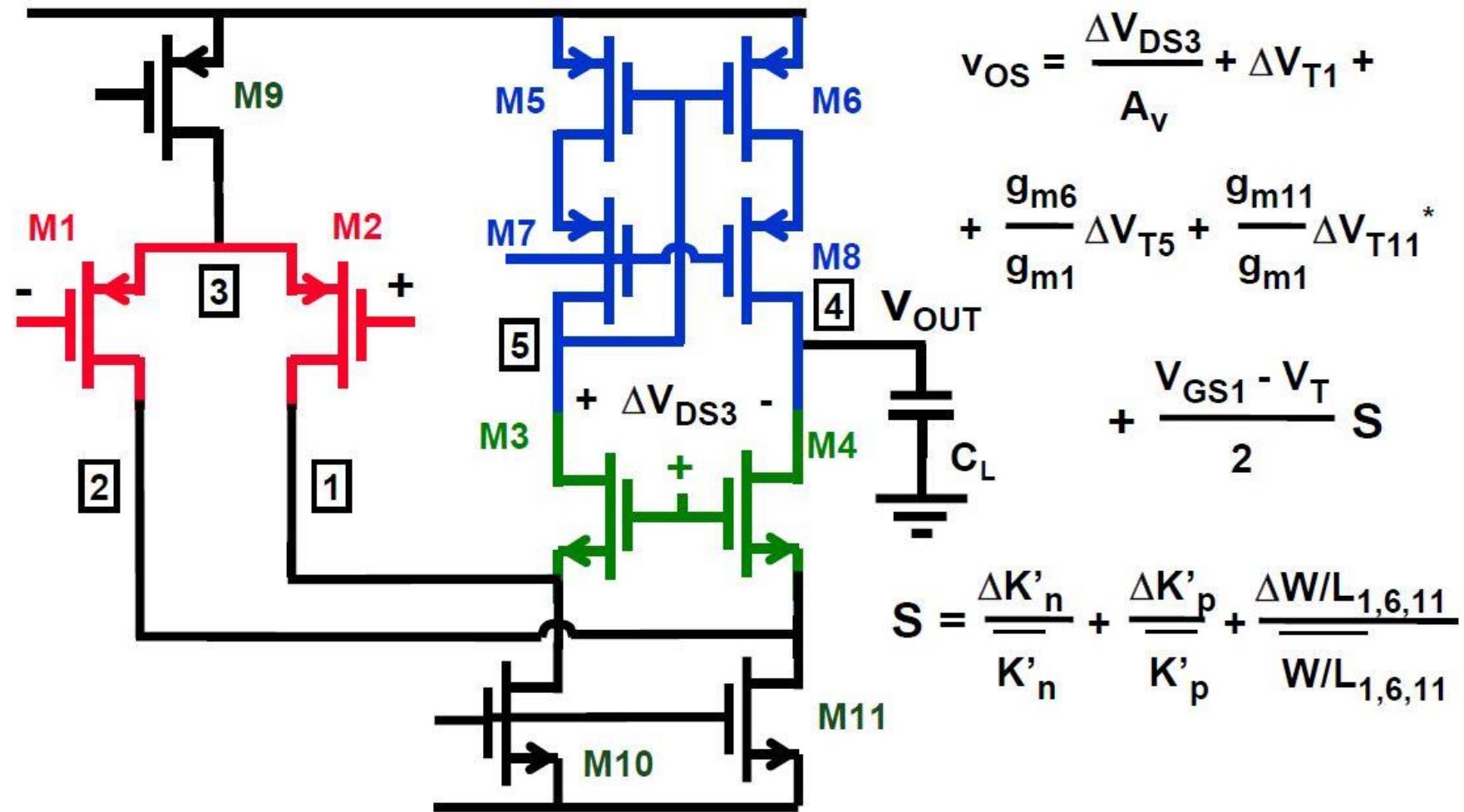
$$v_{OS} = \frac{\Delta V_{DS1}}{A_{v1}} +$$

$$\Delta V_{T1} + \frac{g_{m3}}{g_{m1}} \Delta V_{T3}^* +$$

$$+ \frac{V_{GS1} - V_T}{2} S$$

$$S = \frac{\Delta K'_n}{K'_n} + \frac{\Delta K'_p}{K'_p} + \frac{\Delta W/L_1}{W/L_1} + \frac{\Delta W/L_3}{W/L_3}$$

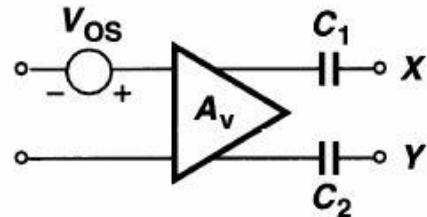
折叠共源共栅放大器的失调(例2)



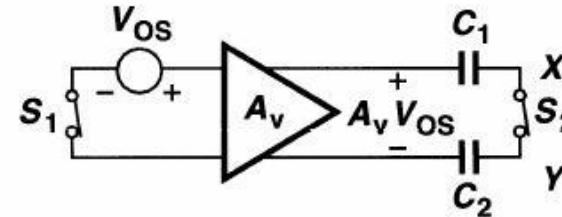
第二部分：失调

- 随机性失调
- 系统性失调
- 失调消除技术
 - 电路消除技术
 - 版图消除技术

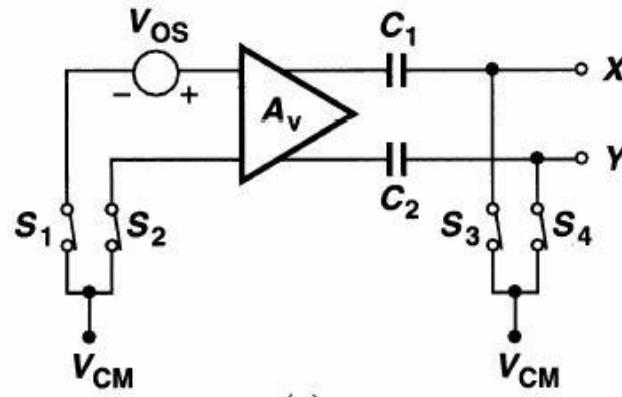
输出失调消除技术(1)



(a)



(b)



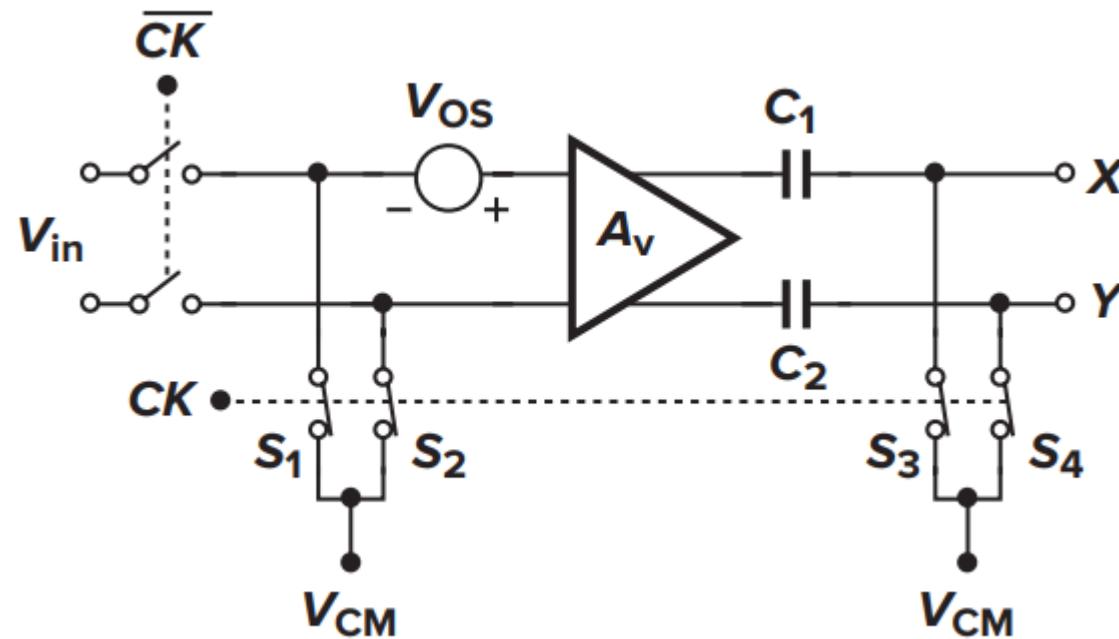
(c)

(a)简单放大器的输出端接两个耦合电容；

(b)输入与输出均短接的(a)电路；

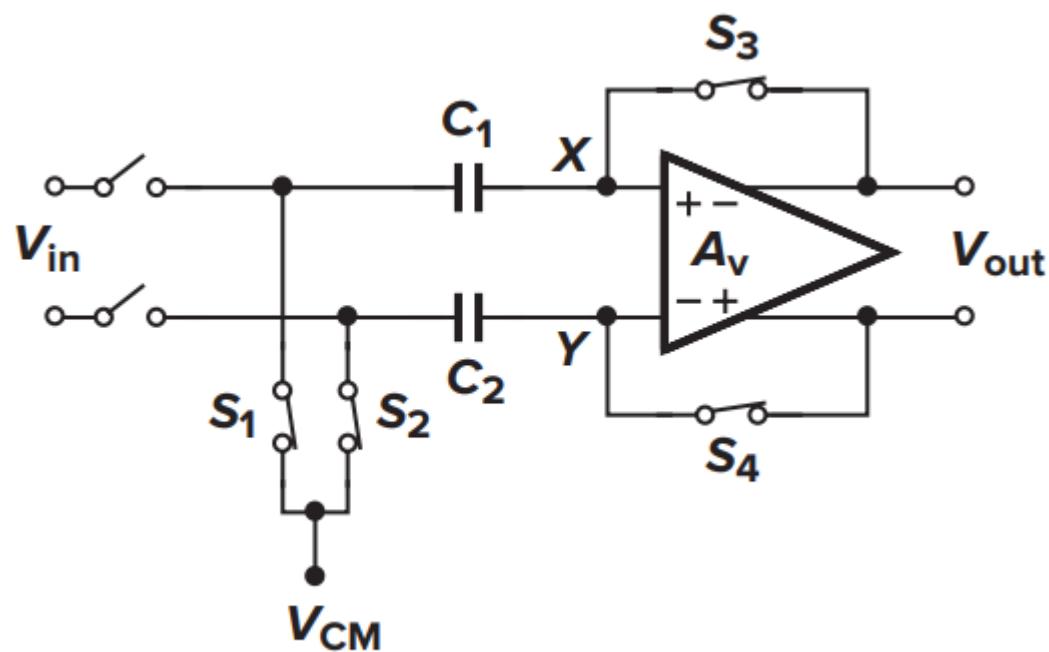
(c)在失调消除时设置合适的共模电平；

输出失调消除技术(2)



$A_v V_{OS}$ 可能会使放大器输出“饱和”。由于这个原因，通常选择 A_v 的值小于 10

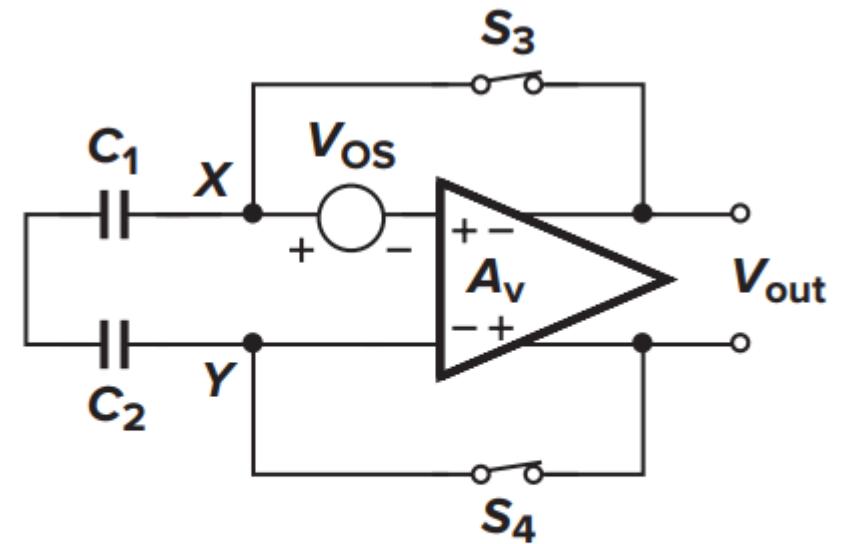
输入失调消除技术(1)



(a)

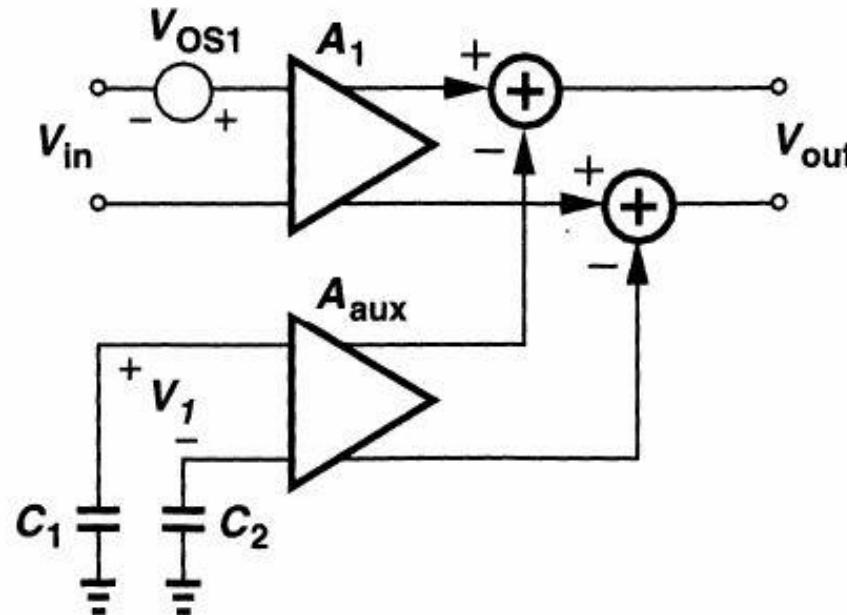
$$V_{out} = \frac{A_v}{1 + A_v} V_{OS}$$

$$\approx V_{OS}$$



(b)

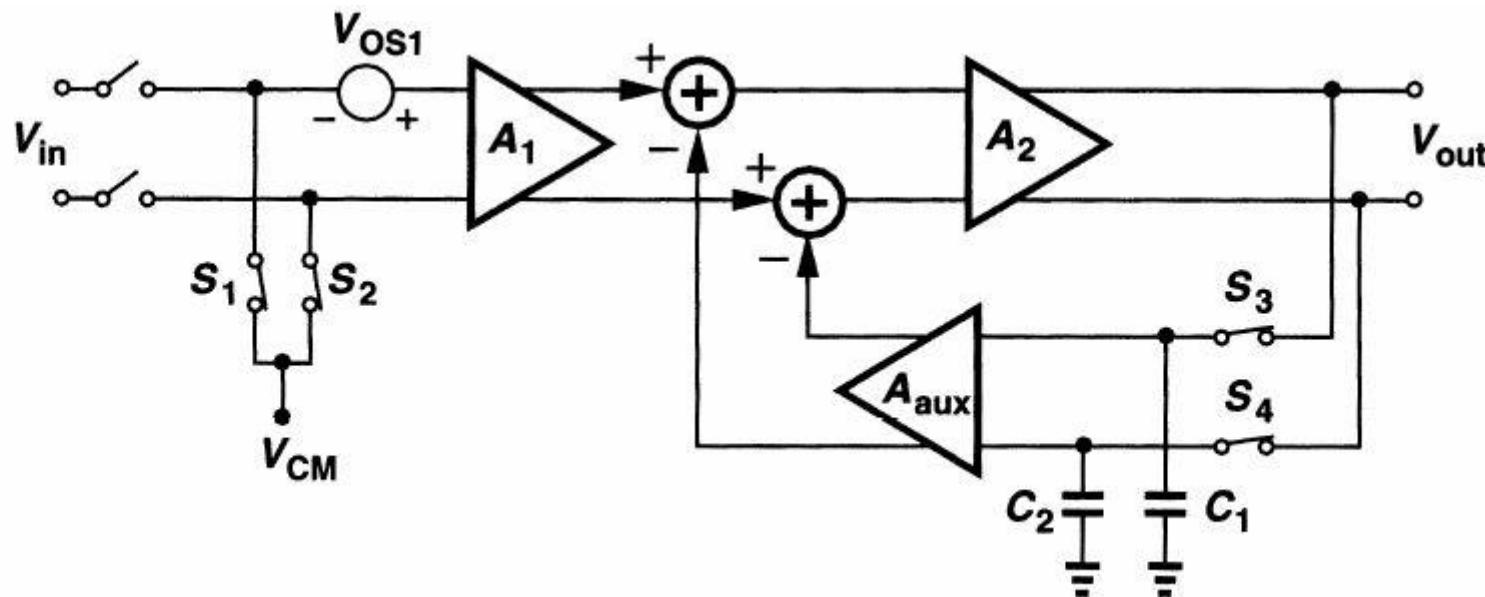
信号通路与失调存储电容的隔离



- 输入与输出的存储技术，其缺点是在信号通路上引入了电容，会减小电路中极点的值，从而降低相位裕度。
- 使用一个“辅助”放大器来隔离信号通路与失调存储电容，而且满足以下条件

$$V_{OS1}A_1 = V_1 A_{aux}$$

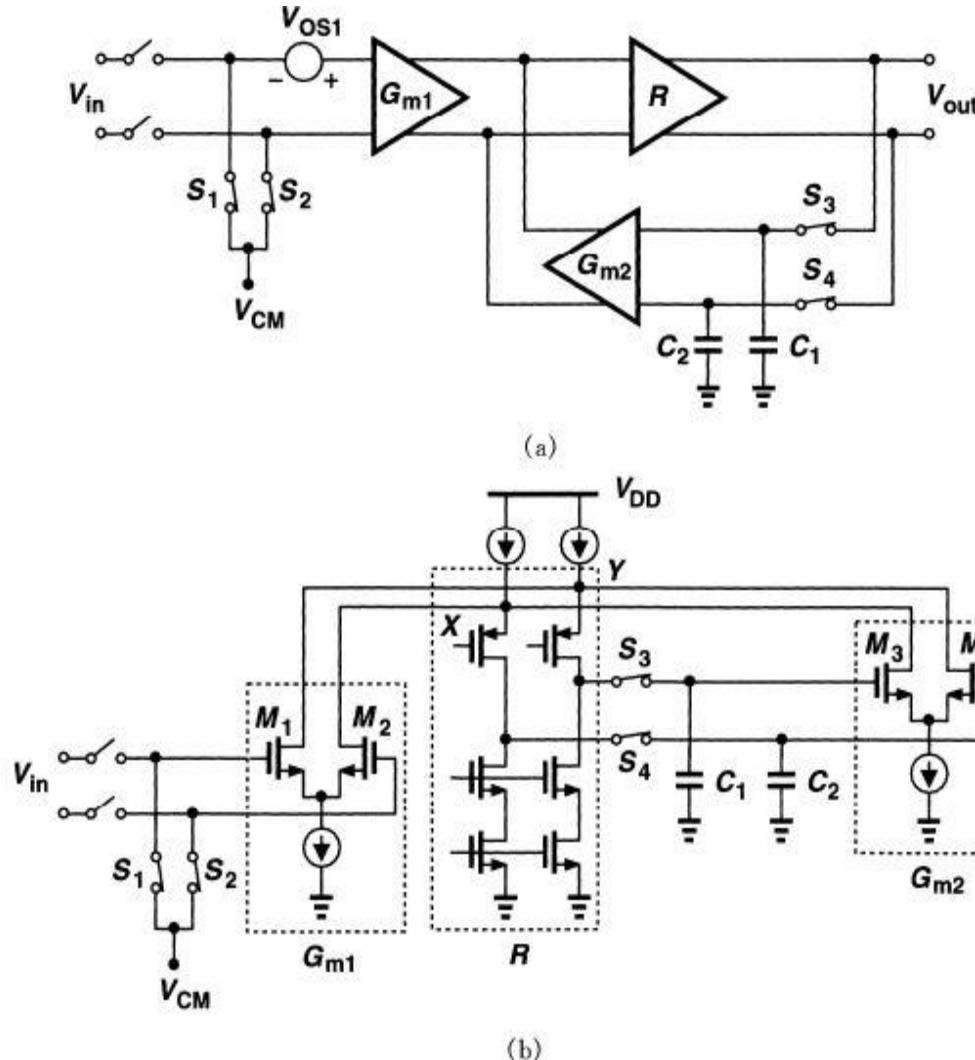
隔离的实现原理



$$[G_{m1}V_{OS1} - G_{m2}(V_{out} - V_{OS2})]R = V_{out}$$

$$V_{out} = \frac{G_{m1}RV_{OS1} + G_{m2}RV_{OS2}}{1 + G_{m2}R}$$

隔离的实现电路



$$\begin{aligned}
 V_{OS,tot} &= \frac{V_{out}}{G_{m1}R} \\
 &= \frac{V_{OS1}}{1 + G_{m2}R} + \frac{G_{m2}}{G_{m1}} \frac{V_{OS2}}{1 + G_{m2}R} \\
 &\approx \frac{V_{OS1}}{G_{m2}R} + \frac{V_{OS2}}{G_{m1}R}
 \end{aligned}$$

原理图的缺点：两个电压增益级；输出电压的相加/减。

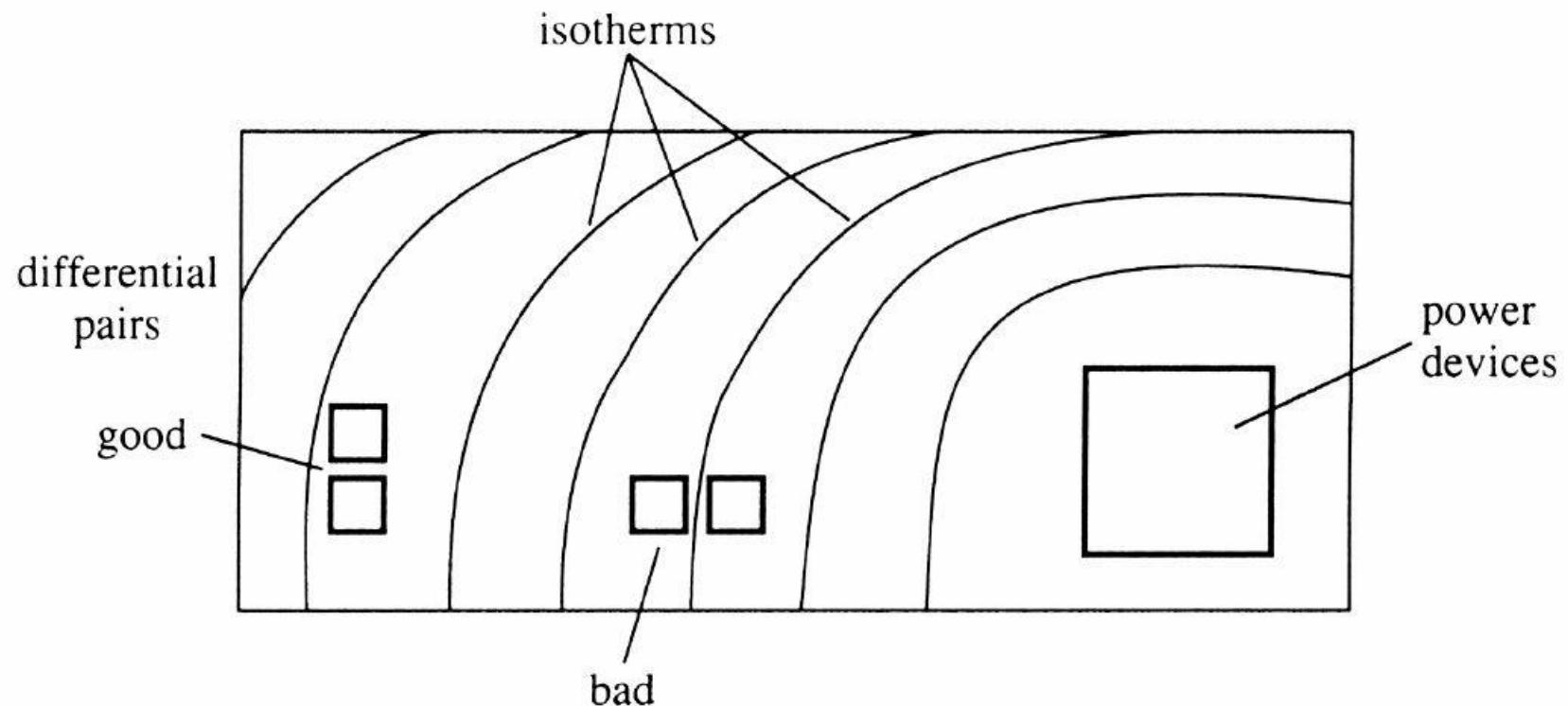
第二部分：失调

- 随机性失调
- 系统性失调
- 失调消除技术
 - 电路消除技术
 - 版图消除技术

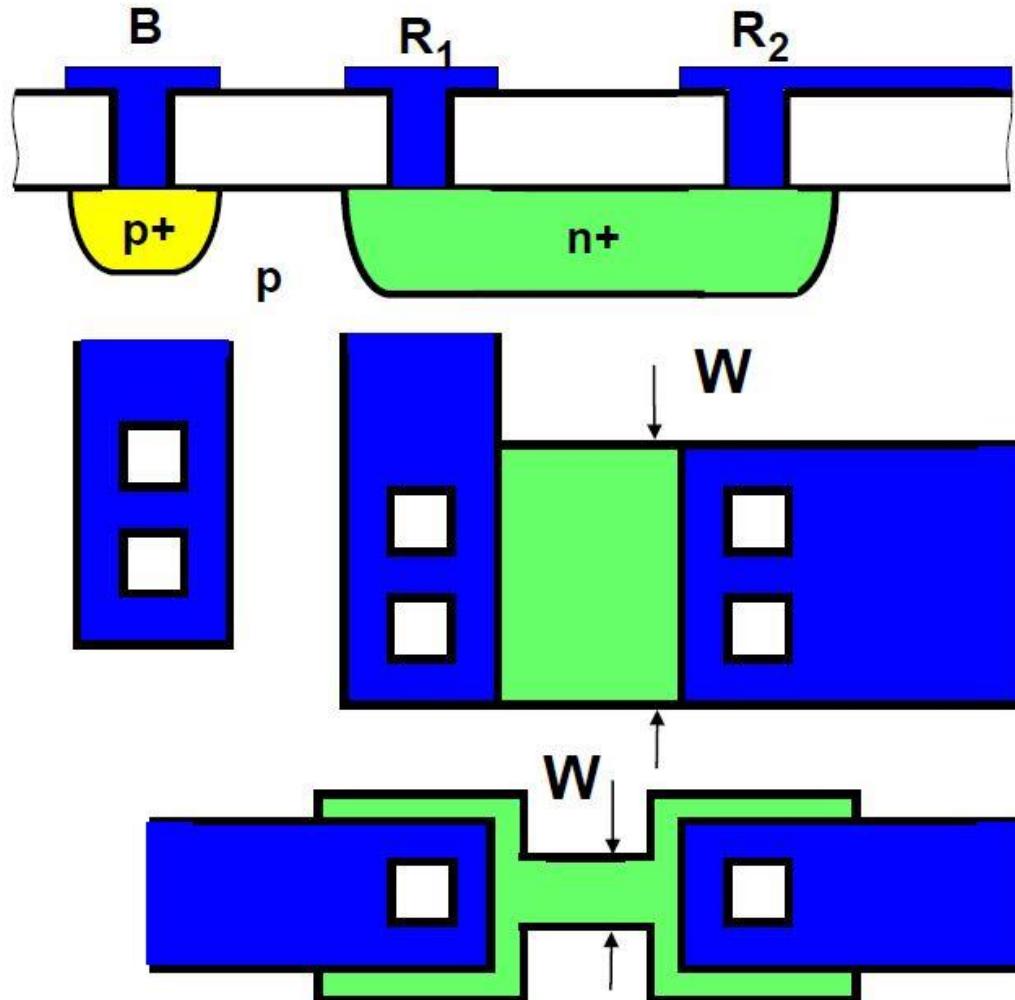
版图消除技术

- 对称
- 等温
- 增大尺寸
- 最小间距
- 相同的方向
- 等面积/周长
- 圆角
- 中心化版图
- 末端伪单元

等温



增大尺寸

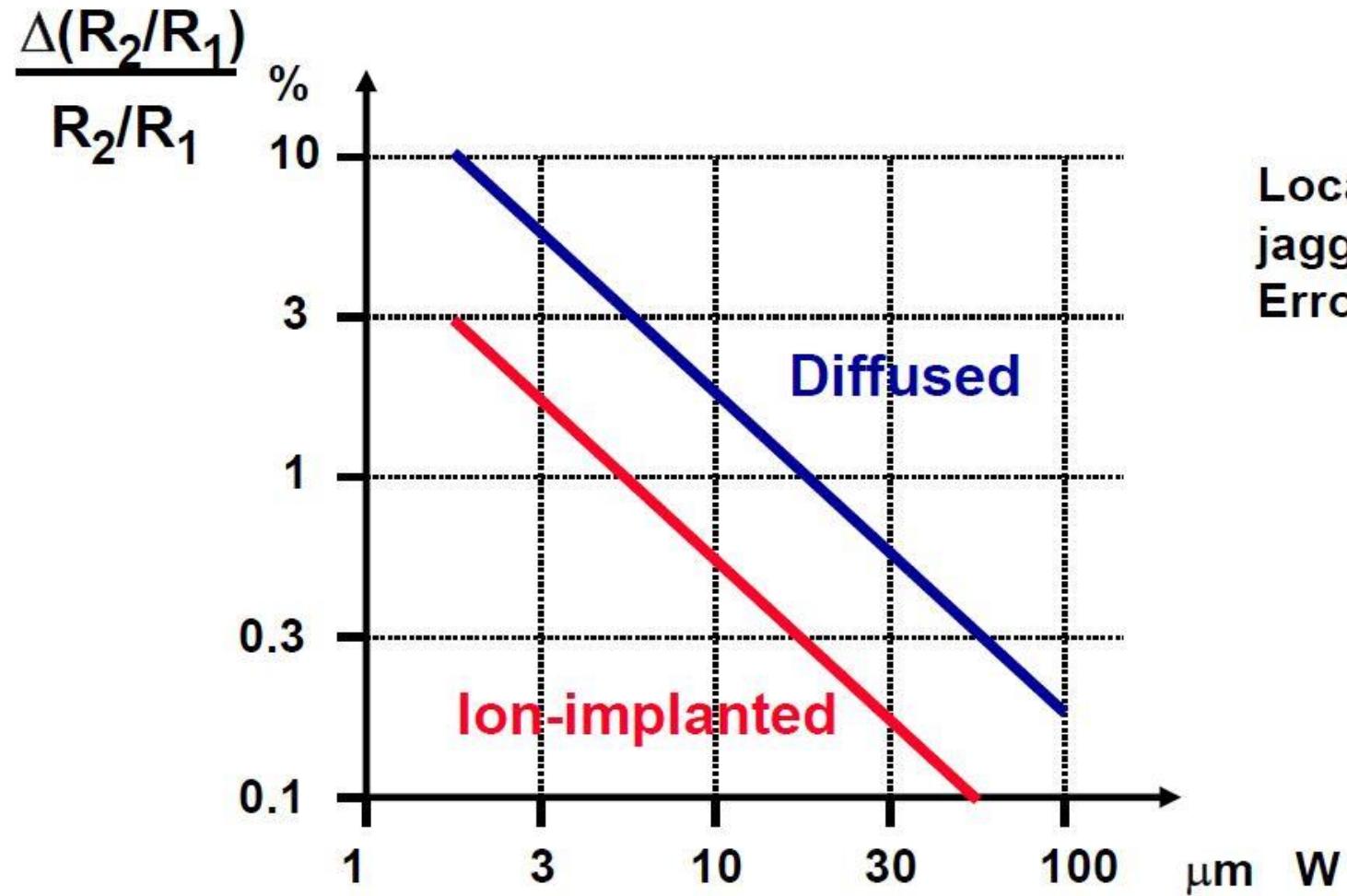


CMOS中的
源、漏电阻

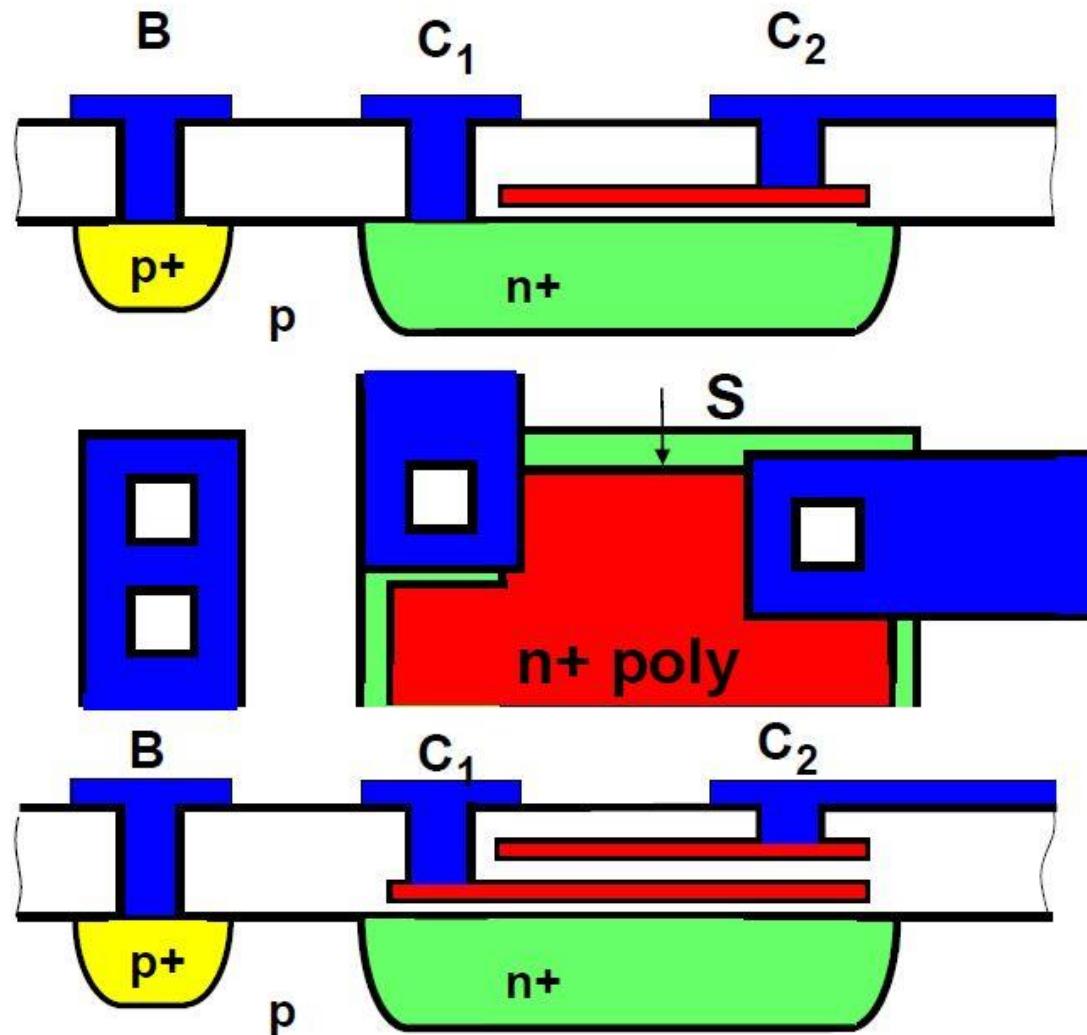
电阻精度

Process	Type	$\rho \square$ Ω/\square	absolute accuracy percent	temperature coefficient percent/ $^{\circ}\text{C}$	voltage coefficient percent/V	breakdown voltage V
Bipolar	base diffusion	150	10	0.12	2	50
	emitter diffusion	10	20	0.02	0.5	7
	pinch resistance	5 k	40	0.33	5	7
	epi layer	1 k	10	0.3	1	60
	aluminum	50 m	20	0.01	0.02	90
	ion-implantation	2 k	1	0.02	0.2	20
	ion-implantation	200	0.3	0.02	0.05	20
CMOS	S/D diffusion	20-50	20	0.2	0.5	20
	well	2.5 k	10	0.3	1	20
	poly gate	50	20	0.2	0.05	40
	poly resistance	1.5 k	1	0.05	0.02	20
	aluminum	50 m	20	0.01	0.02	90
Thin film	NiCr(Ta)	200	1	0.005	0.005	90
	aluminum	50 m	20	0.01	0.02	90

电阻尺寸与失配的关系



电容版图



Poly to S/D capacitor

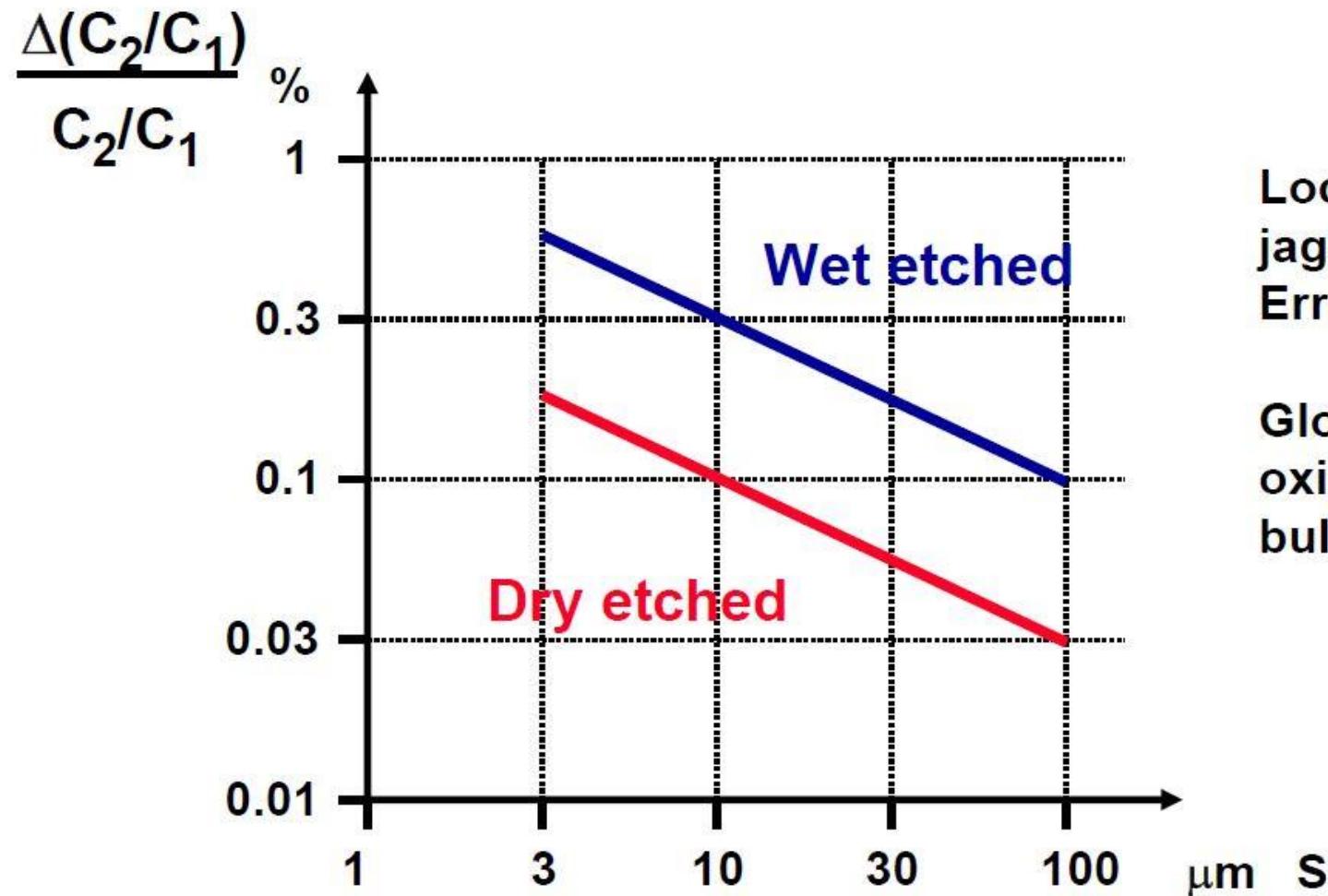
Poly to poly capacitor

$$C_{\text{par}} \approx \frac{1}{6 \dots 15} C_{\text{pp}}$$

电容精度

Process	Type	C nF/cm ²	absolute accuracy percent	temperature coefficient percent/°C	voltage coefficient percent V	breakdown voltage V
Bipolar	C_{CB}	16	10	0.02	2	50
	C_{EB}	50	10	0.02	1	7
	C_{CS}	8	20	0.01	0.5	60
CMOS	C_{ox} (50 nm)	70	5	0.002	0.005	40
	$C_{m,poly}$	12	10	0.002	0.005	40
	$C_{poly,poly}$	56	2	0.002	0.005	40
	$C_{poly,substrate}$	6.5	10	0.01	0.05	20
	$C_{m,substrate}$	5.2	10	0.01	0.05	20
	$C_{poly,substrate}$	6.5	10	0.01	0.05	20

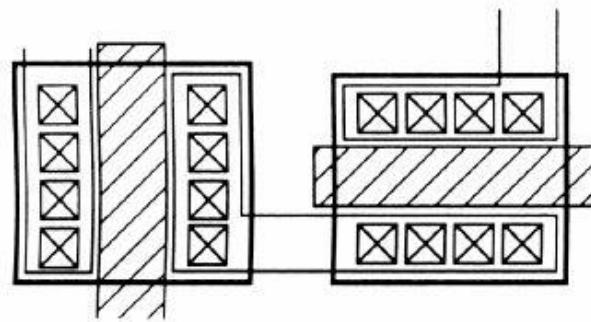
湿法和干法刻蚀的精度对比



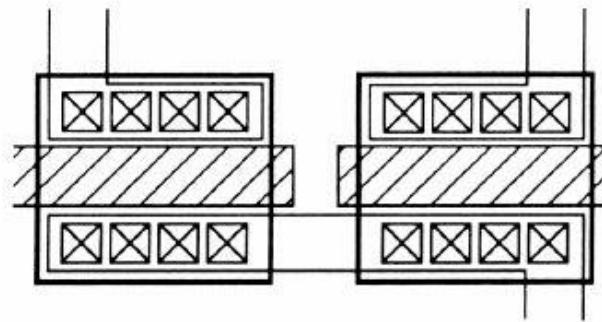
Local errors :
jagged edges, ..
Error $\sim 1/\text{size}$

Global errors :
oxide thickness,
bulk doping, ..

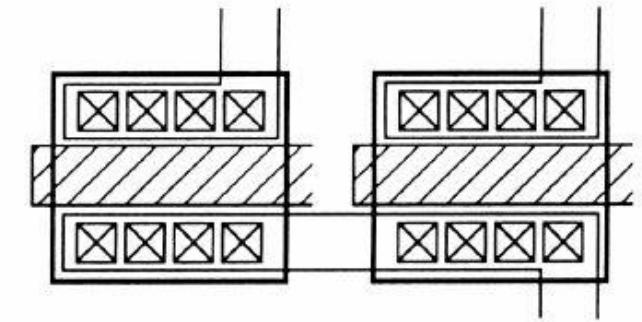
同向匹配



Bad



Better

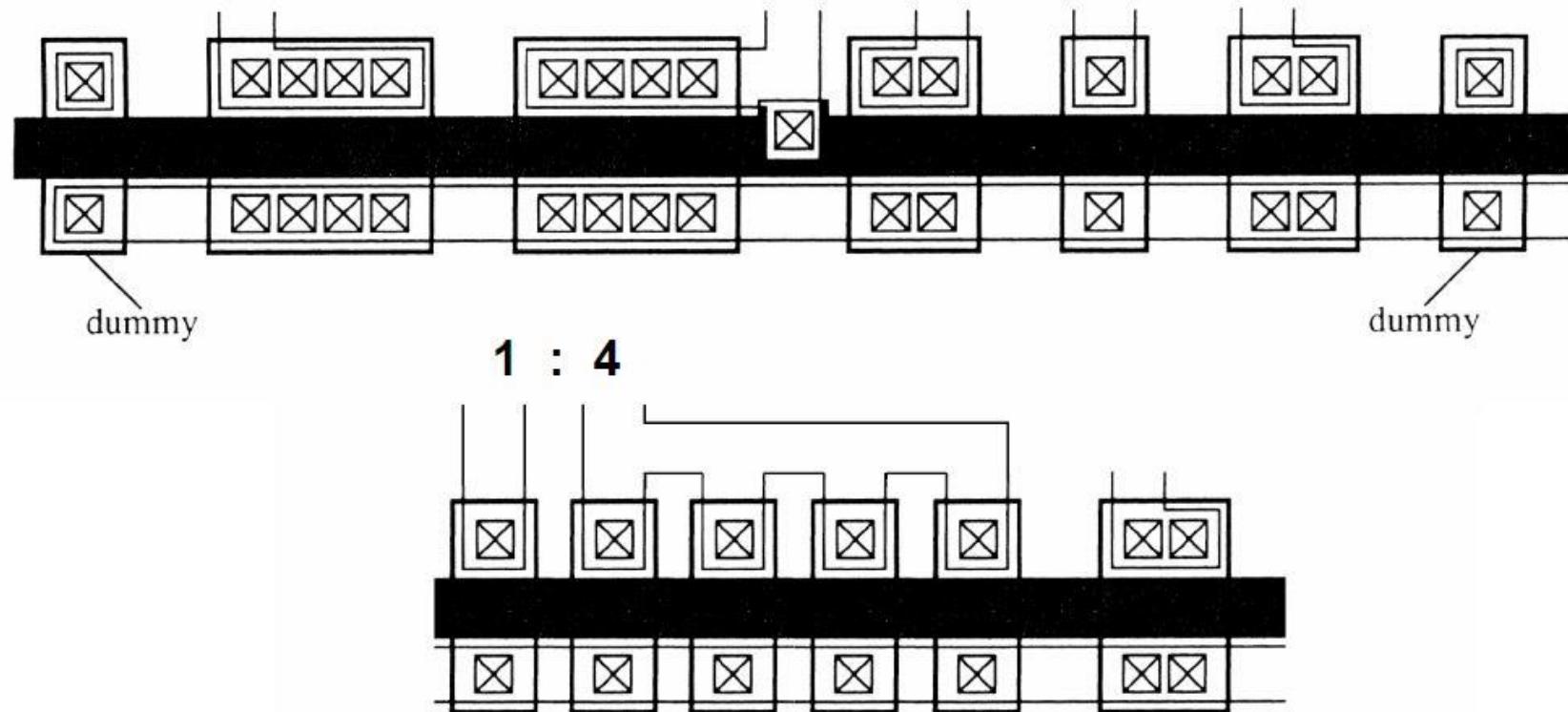


Better

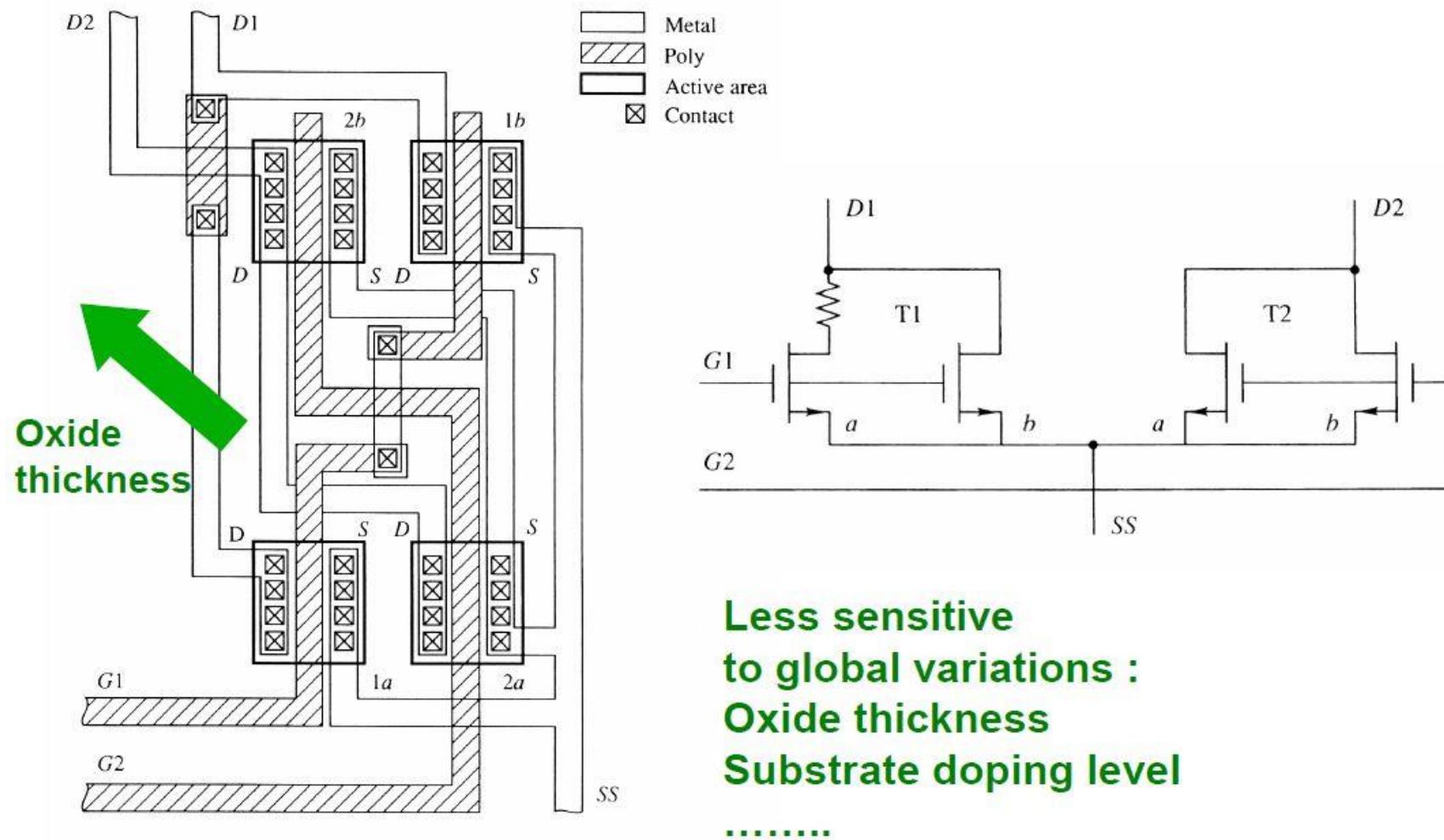
电流镜匹配的版图设计

Current mirror 4:4:2:1:2 with end dummies.

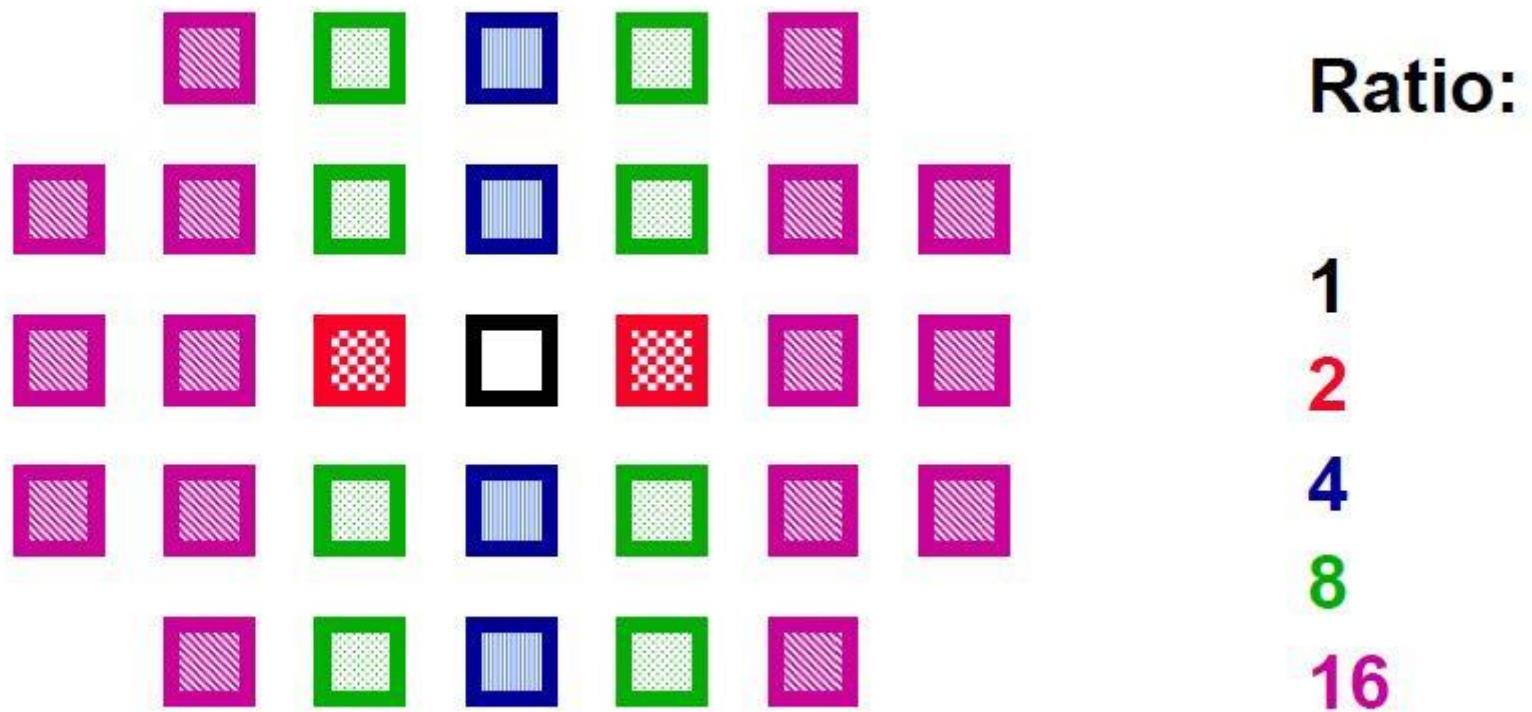
Metal Active area
Poly Contact



交叉耦合差分对

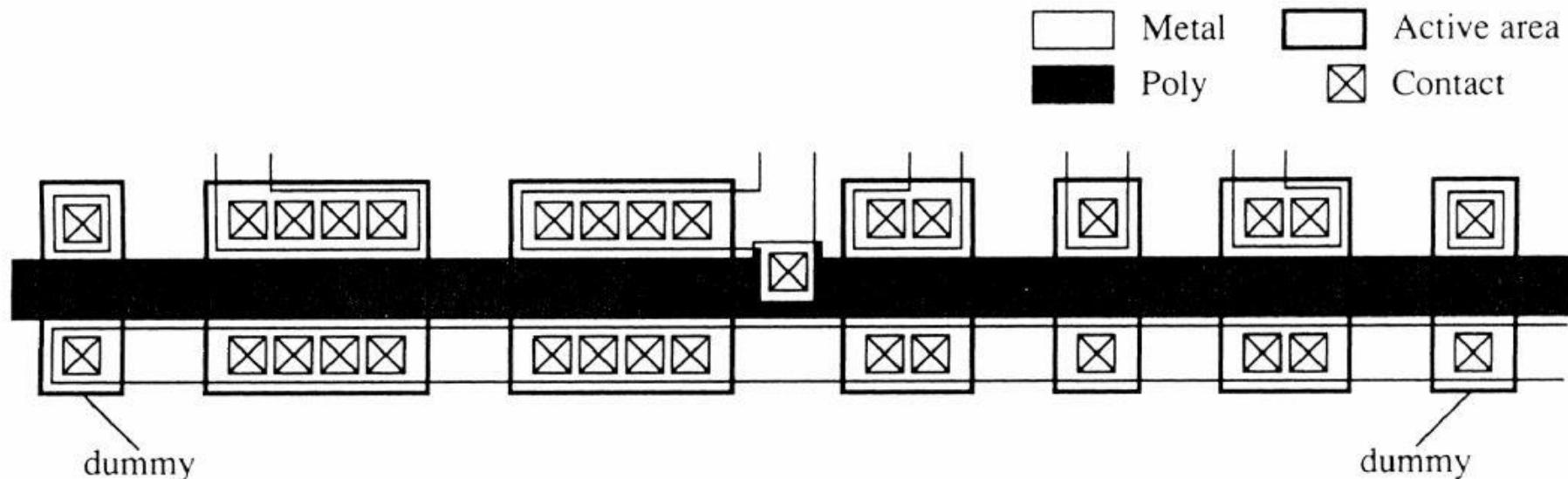


中心对称的电容设计

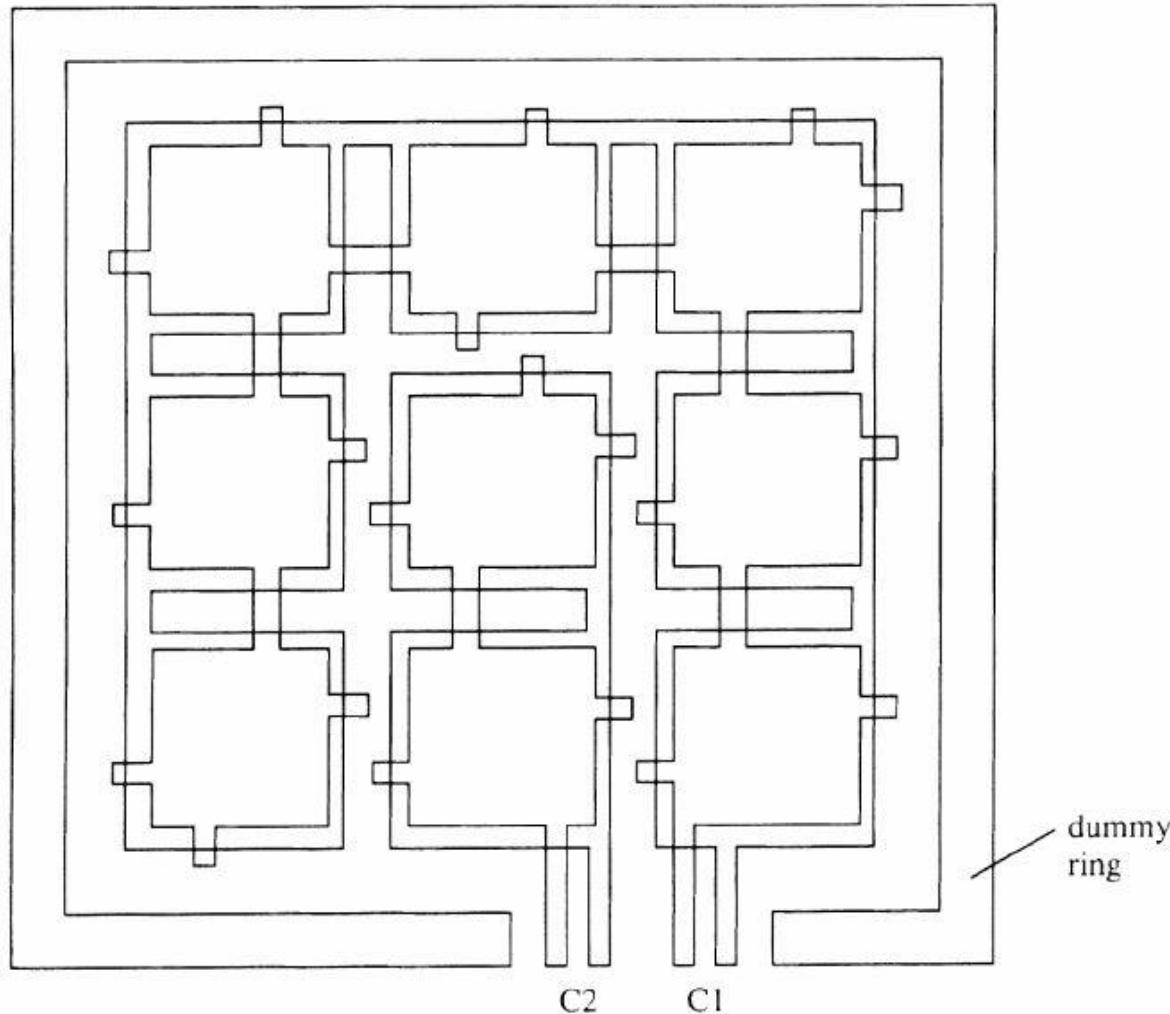


电流镜设计中的伪单元

Current mirror 4:4:2:1:2 with end dummies.



精确的电容比



Ratio 7/2 = 3.5

总结

- 掌握失真与失调的表现与原因；
- 简单定量分析失真；
- 计算简单电路的失调；
- 了解失真与失调消除的技术。

作业

- 14.2 14.5 14.11

本章结束