



高级模拟集成电路设计 (Analog Design Essentials)

2014年12月25日

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

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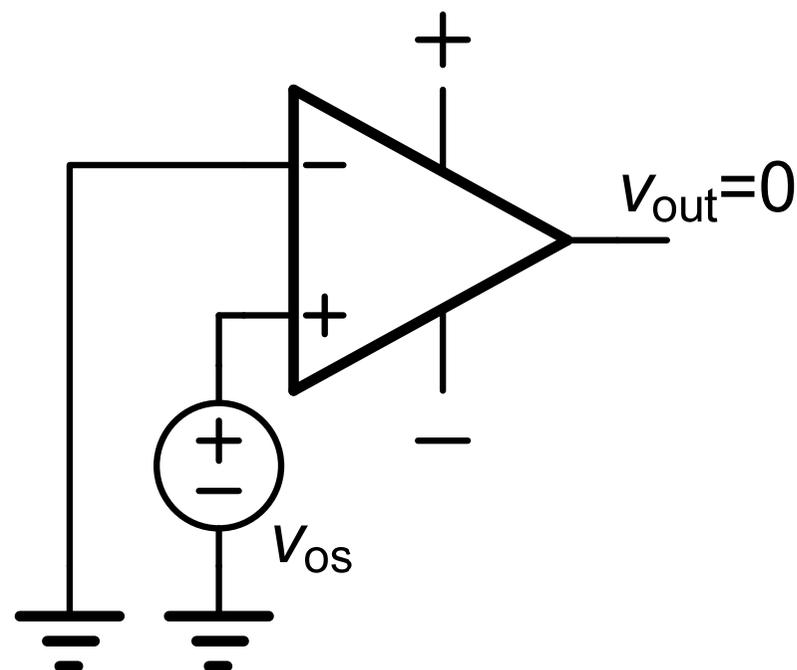
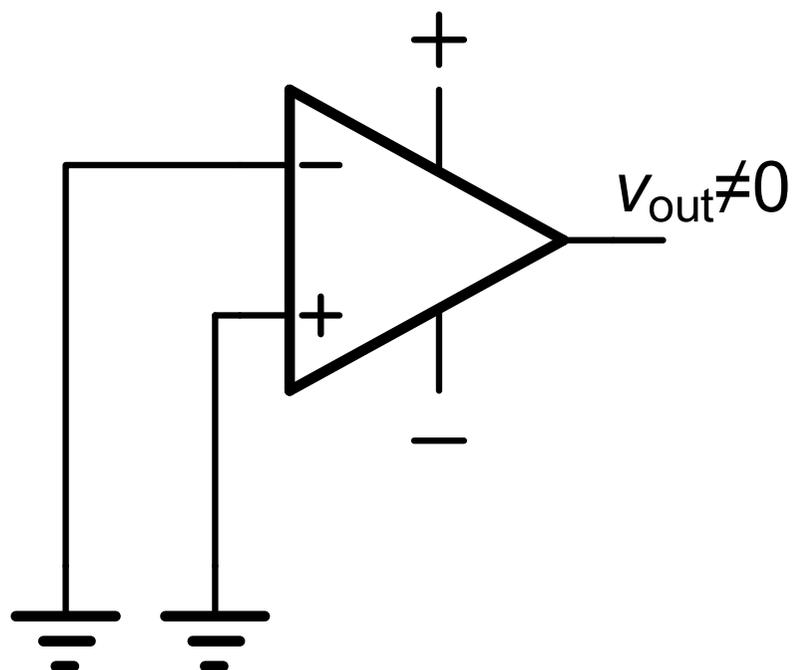
失调和 **CMRR**: 随机因素和系统因素

目录

- 随机失调和 $CMRR_r$
- 系统失调和 $CMRR_s$
- $CMRR$ 与频率的关系
- 设计规则
- MOST与双极型晶体管的比较

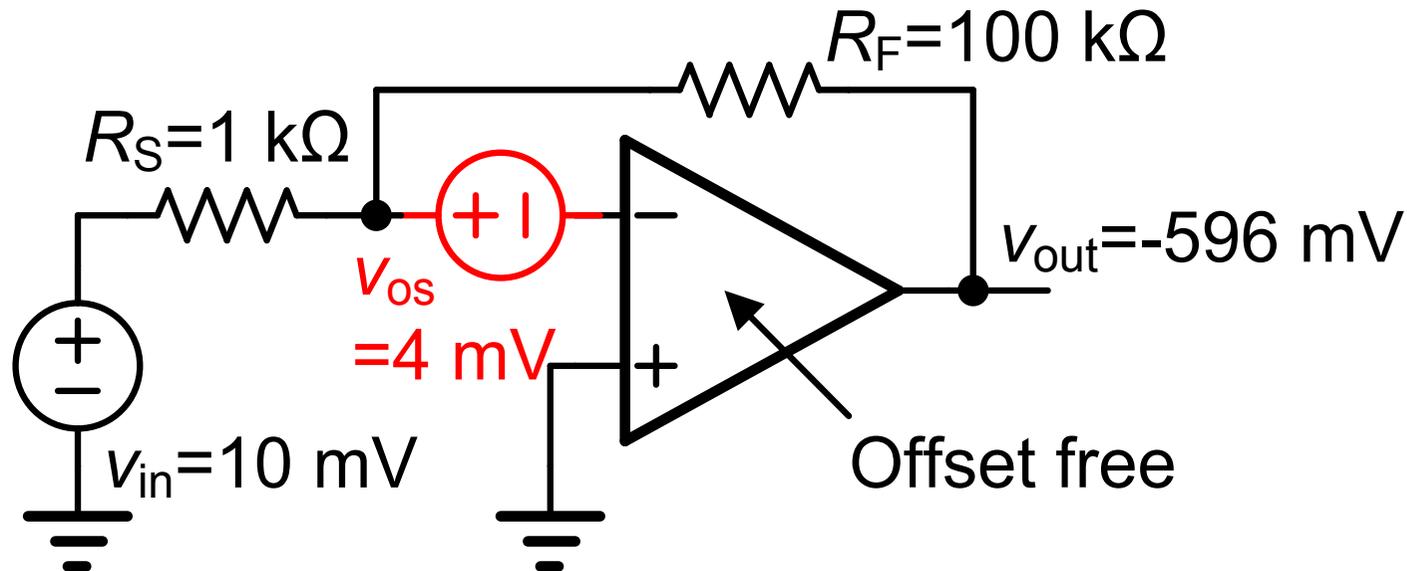
Ref.: W. Sansen : Analog Design Essentials, Springer 2006
Pelgrom, JSSC Oct.1989, 1433-1439
Croon, JSSC Aug.02, 1056-1064
Croon, Springer, 2005

失调的定义



失调电压 V_{os}

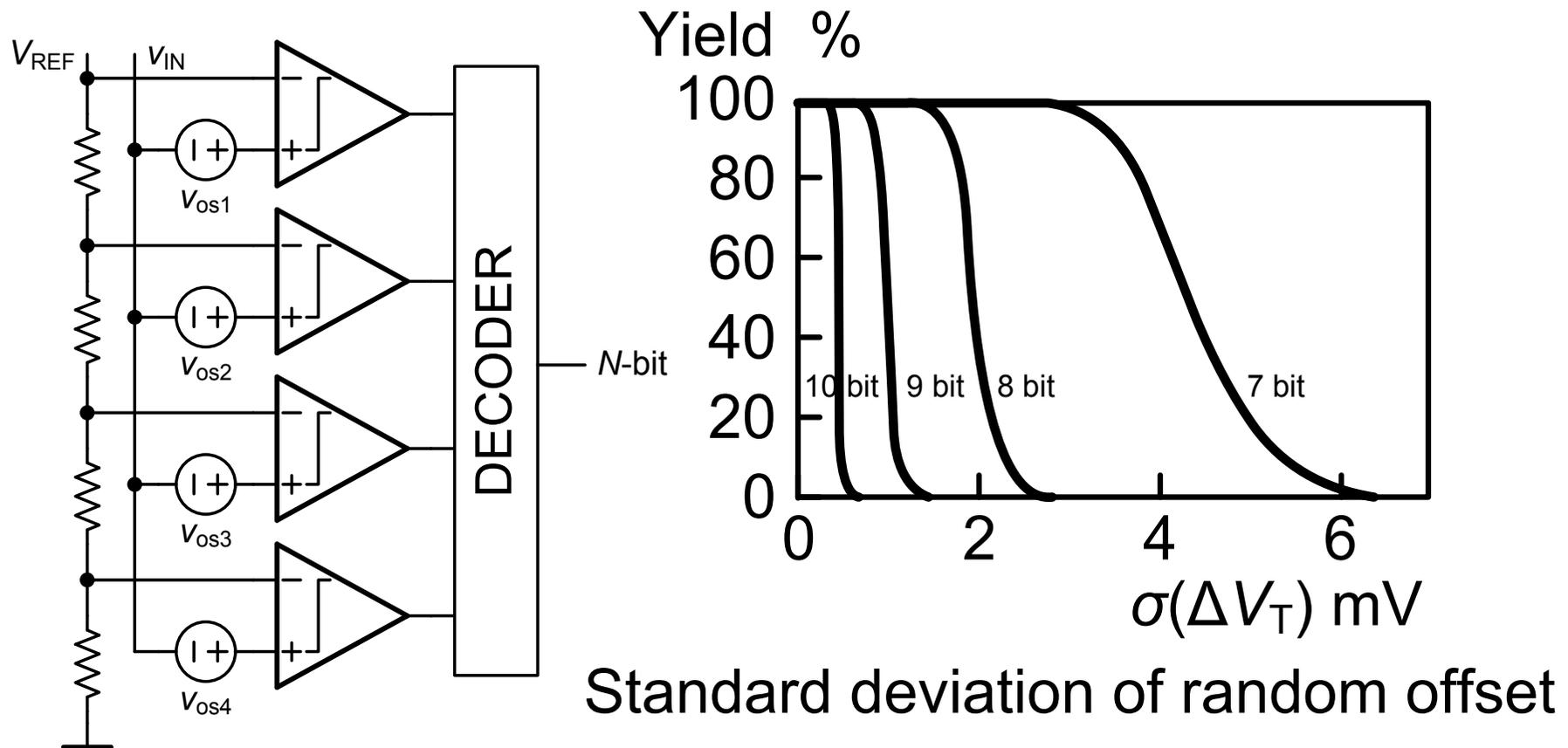
由失调引起的增益误差



$$\frac{V_{in} - V_{os}}{R_S} = \frac{V_{os} - V_{out}}{R_F}$$

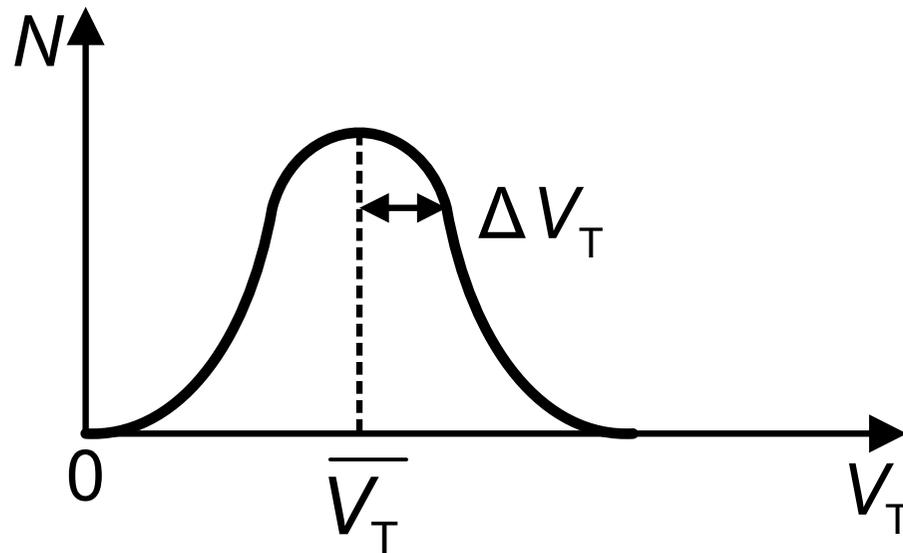
增益由100倍变为59倍。

由失调引起的flash-ADC良率下降



Ref.: Pelgrom, IEDM 1998, pp.789.

随机失调：失配



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

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

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

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

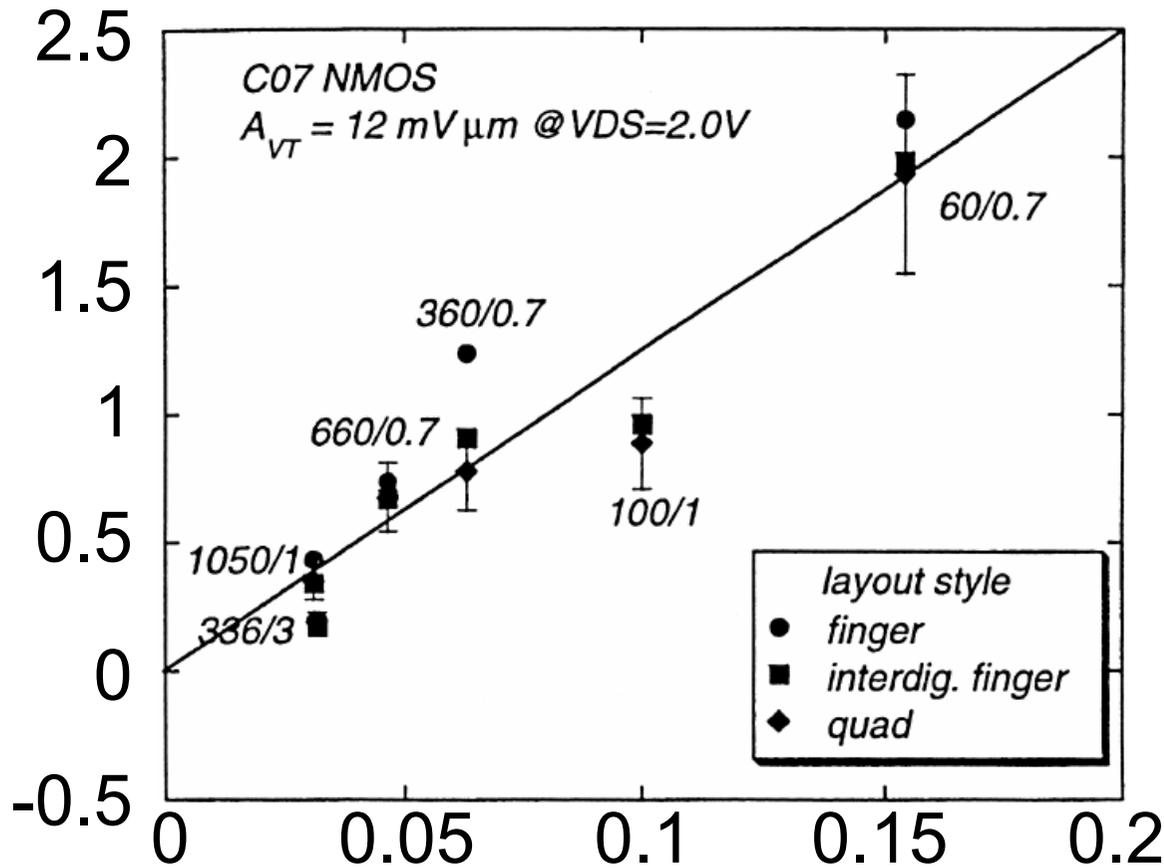
对于0.25 μm的nMOST

$$A_{VT} \approx 5 \text{ mV}\mu\text{m}$$

pMOST将+50%

阈值电压的标准方差

$\sigma(\Delta V_T)$ mV



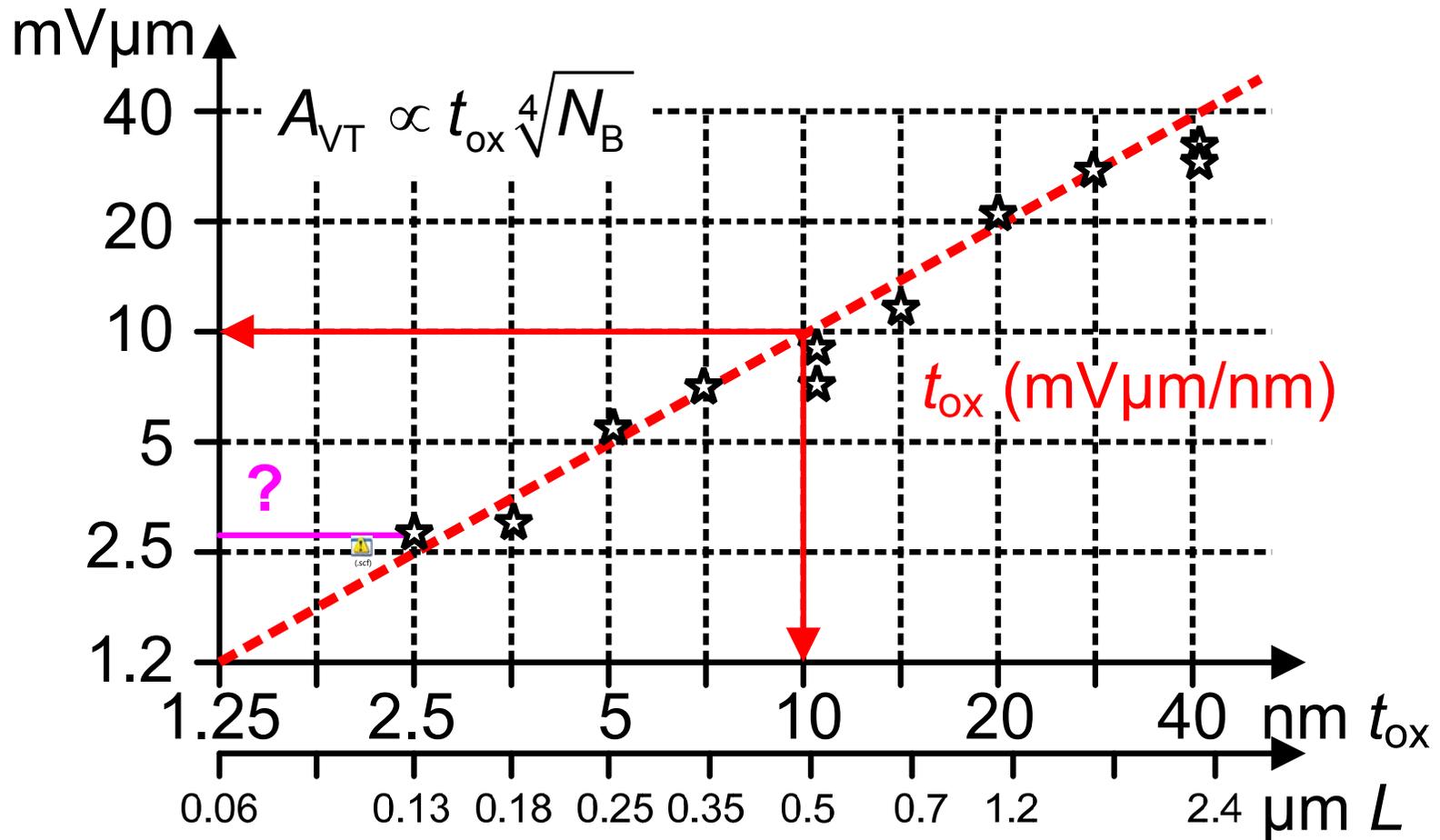
$$\sigma_{\Delta V_T} = \frac{A_{VT}}{\sqrt{WL}}$$

0.7 μm 的CMOS
 $W/L=60/0.7 \mu\text{m}$

$\sigma(\Delta V_T) \approx 2 \text{ mV}$

$1/\sqrt{WL}$
 $1/\mu\text{m}$

阈值电压的失配系数 A_{VT}



随机失调：失配

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

$$A_{K'} \approx 0.0056 \mu\text{m} \quad \text{pMOST将+50\%}$$

$$\frac{\Delta W/L}{W/L} = A_{WL} \sqrt{\frac{1}{W^2} + \frac{1}{L^2}}$$

$$A_{WL} = 0.02 \mu\text{m} \quad \text{pMOST将+50\%}$$

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

$$A_{\gamma} = 0.016 \mu\text{m} \quad \text{pMOST将-25\%}$$

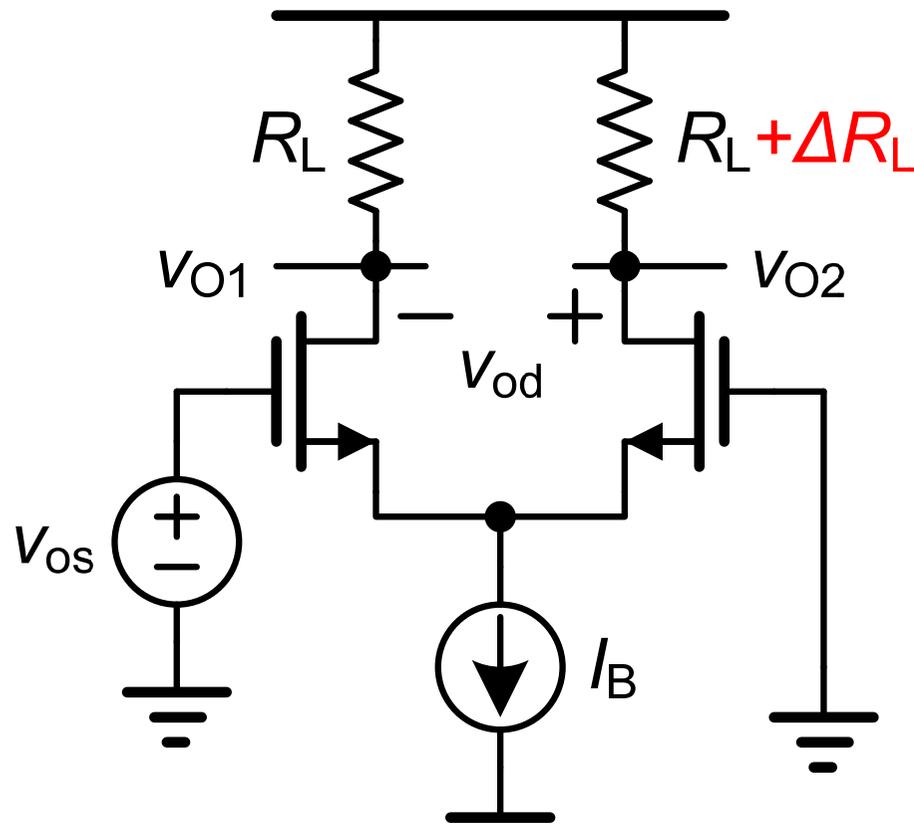
↑
如果 $V_B = V_S$ ，忽略

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

nMOST的失配系数

工艺 L	(μm)	2.5	1.2	0.7	0.5	0.35	0.25
t_{ox}	(nm)	50	25	15	11	8	6
A_{VT}	(mV μm)	30	21	13	7.1	6	$\Rightarrow 0$
A_{WL}	(% μm)	2.5	1.8	2.5	1.3	2	$\Rightarrow 1.8$
S_{VT}	(mV/mm)	0.3	0.3	0.4	0.2		
S_{WL}	(%/mm)	0.3		0.2	0.2		

差分对的随机失调

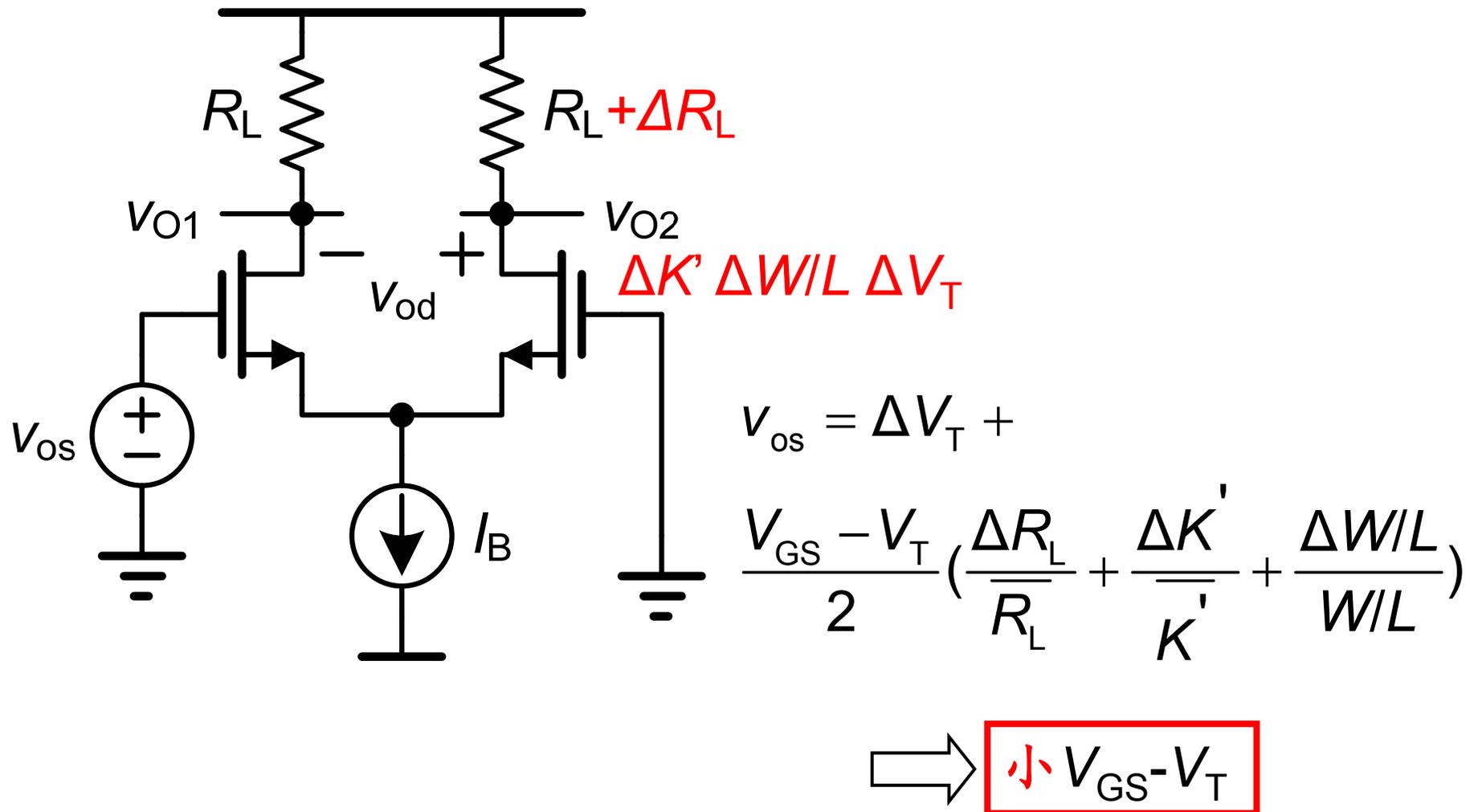


$$V_{od} = \Delta R_L \frac{I_B}{2}$$

$$\begin{aligned} V_{os} &= \frac{V_{od}}{g_m R_L} \\ &= \frac{\Delta R_L}{R_L} \frac{I_B}{2g_m} \\ &= \frac{\Delta R_L}{R_L} \frac{V_{GS} - V_T}{2} \end{aligned}$$

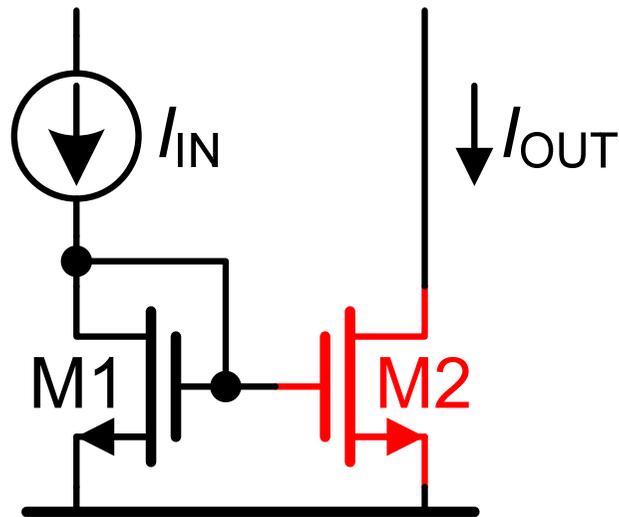
Ref.: Laker, Sansen : Design of analog ..., MacGrawHill 1994

差分对的随机失调



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

电流镜的随机失调



$\Delta K' \Delta W/L \Delta V_T$

$$\Delta I_{OUT} = g_m \Delta V_T + \left(\frac{\Delta K'}{K'} + \frac{\Delta W/L}{W/L} \right) I_{OUT}$$

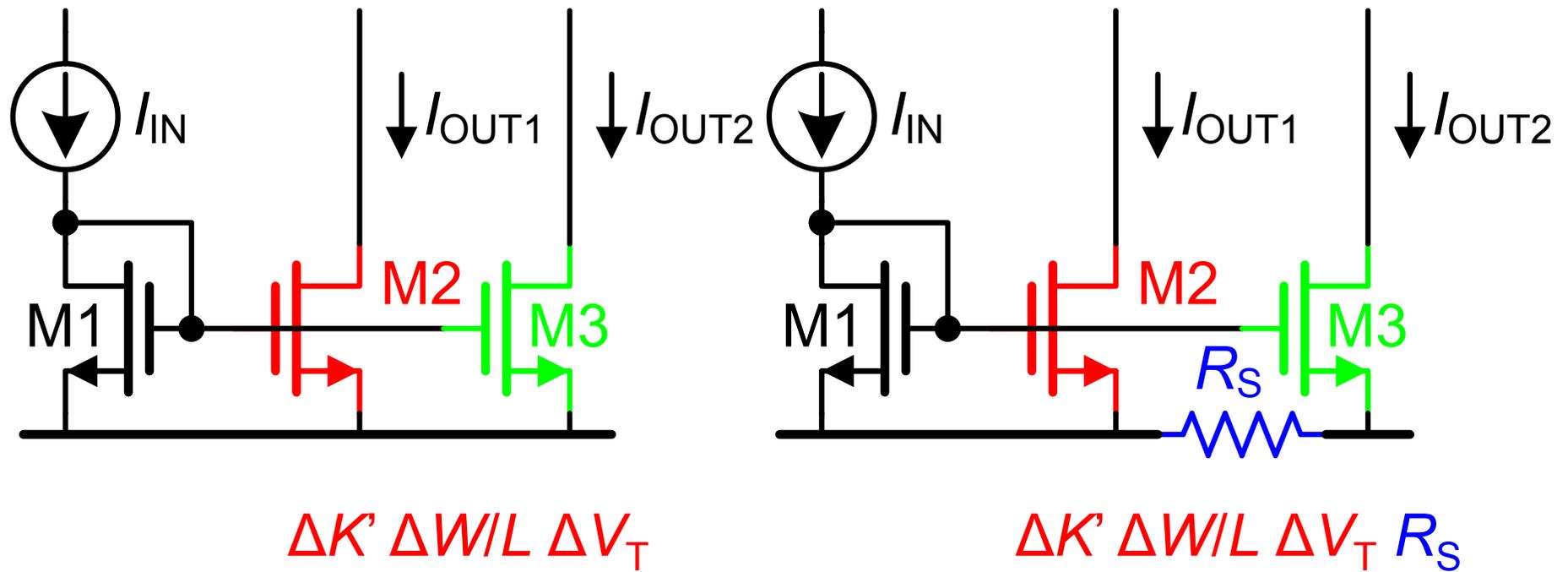
$$\frac{\Delta I_{OUT}}{I_{OUT}} =$$

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

⇒ 大 $V_{GS} - V_T$

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

电流镜的其他失调



电流的失配

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

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

$$\sigma^2 \left(\frac{\Delta I_{DS}}{I_{DS}} \right) = \sigma^2 \left(\frac{\Delta \beta}{\beta} \right) + \sigma^2 (\Delta V_T) \underbrace{\frac{4}{(V_{GS} - V_T)^2}}_1 \underbrace{\frac{1}{(nkT/q)^2}}_{\left(\frac{g_m}{I_{DS}} \right)^2}$$

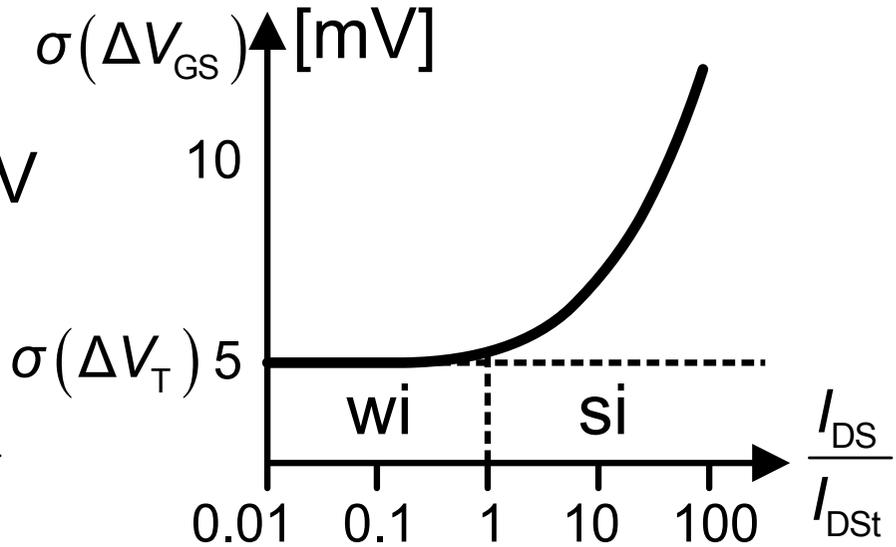
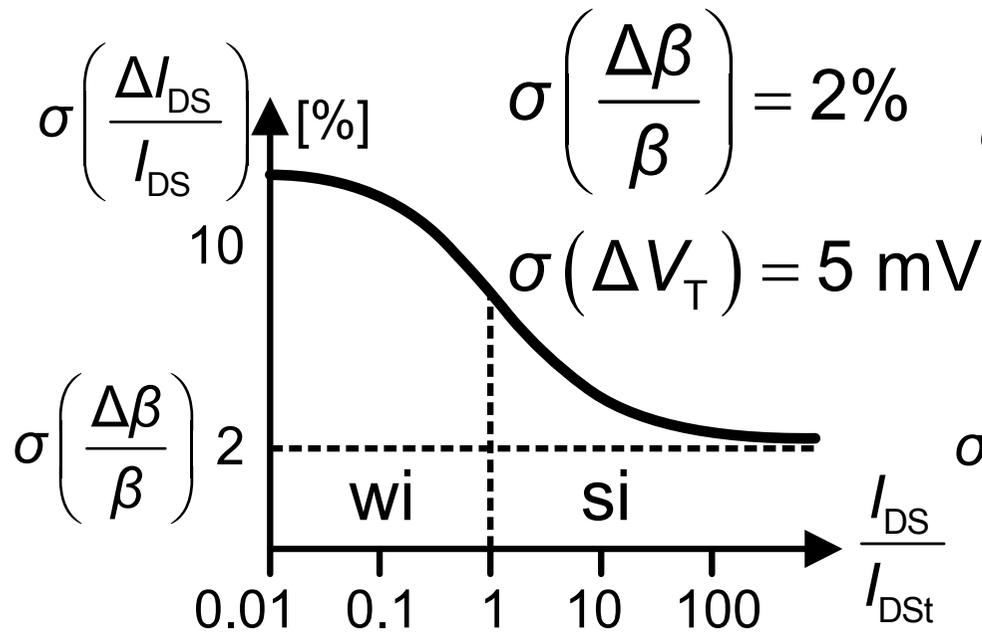
工作于弱反型区

常规

工作于强反型区

弱反型和强反型漏电流失配

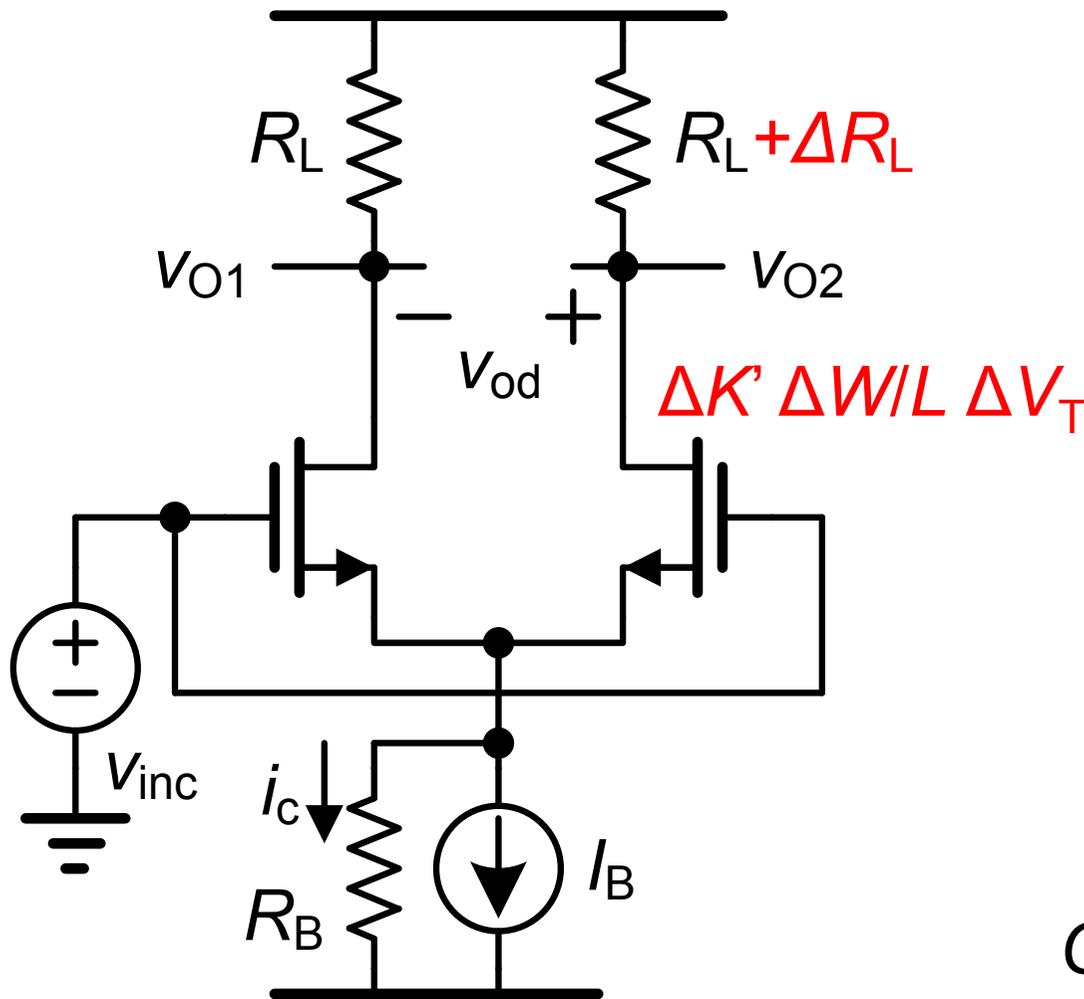
$$\sigma^2\left(\frac{\Delta I_{DS}}{I_{DS}}\right) = \sigma^2\left(\frac{\Delta\beta}{\beta}\right) + \sigma^2(\Delta V_T) \underbrace{\frac{4}{(V_{GS} - V_T)^2}}_{\text{强反型}} \quad \text{或} \quad \underbrace{\frac{1}{(nkT/q)^2}}_{\text{弱反型}}$$



$$I_{DSt} = \frac{\beta}{2} \left(2n \frac{kT}{q} \right)^2$$

$$\beta = \frac{K' W}{n L}$$

差分对的随机CMRR-1



$$V_{od} = A_{dd} v_{id} + A_{dc} v_{ic}$$

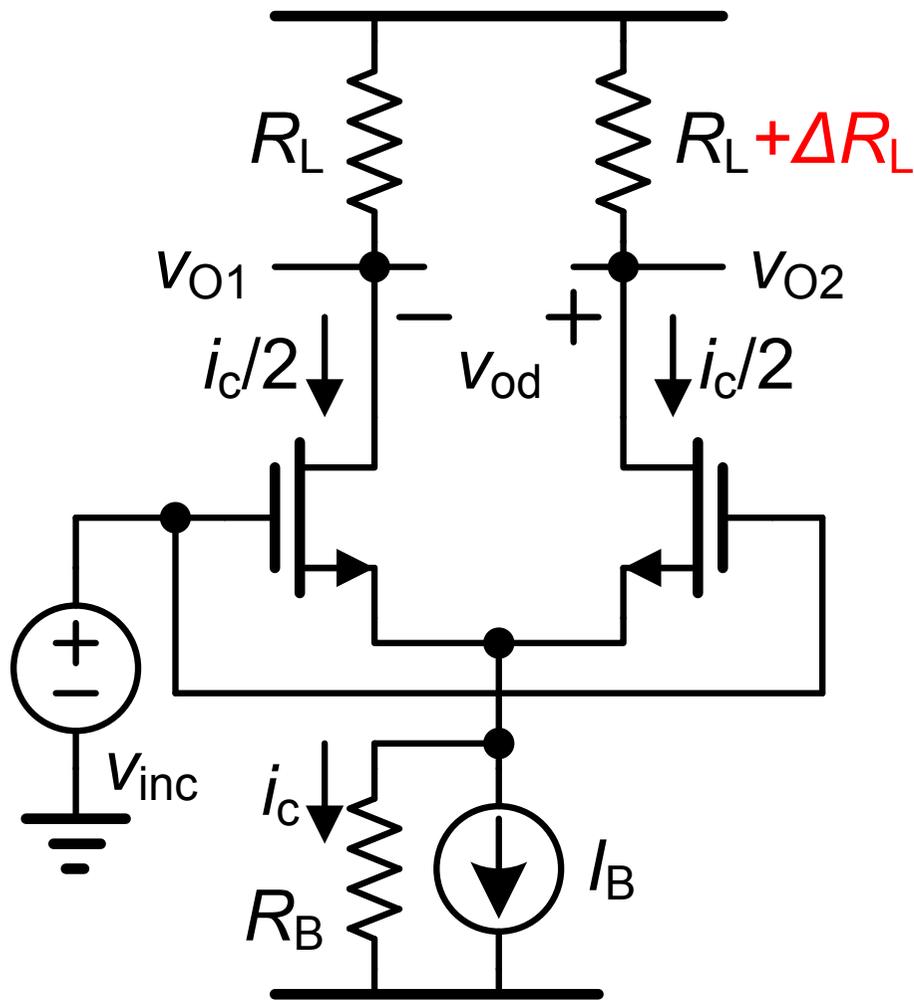
$$V_{oc} = A_{cd} v_{id} + A_{cc} v_{ic}$$

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

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

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

差分对的随机CMRR-2



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

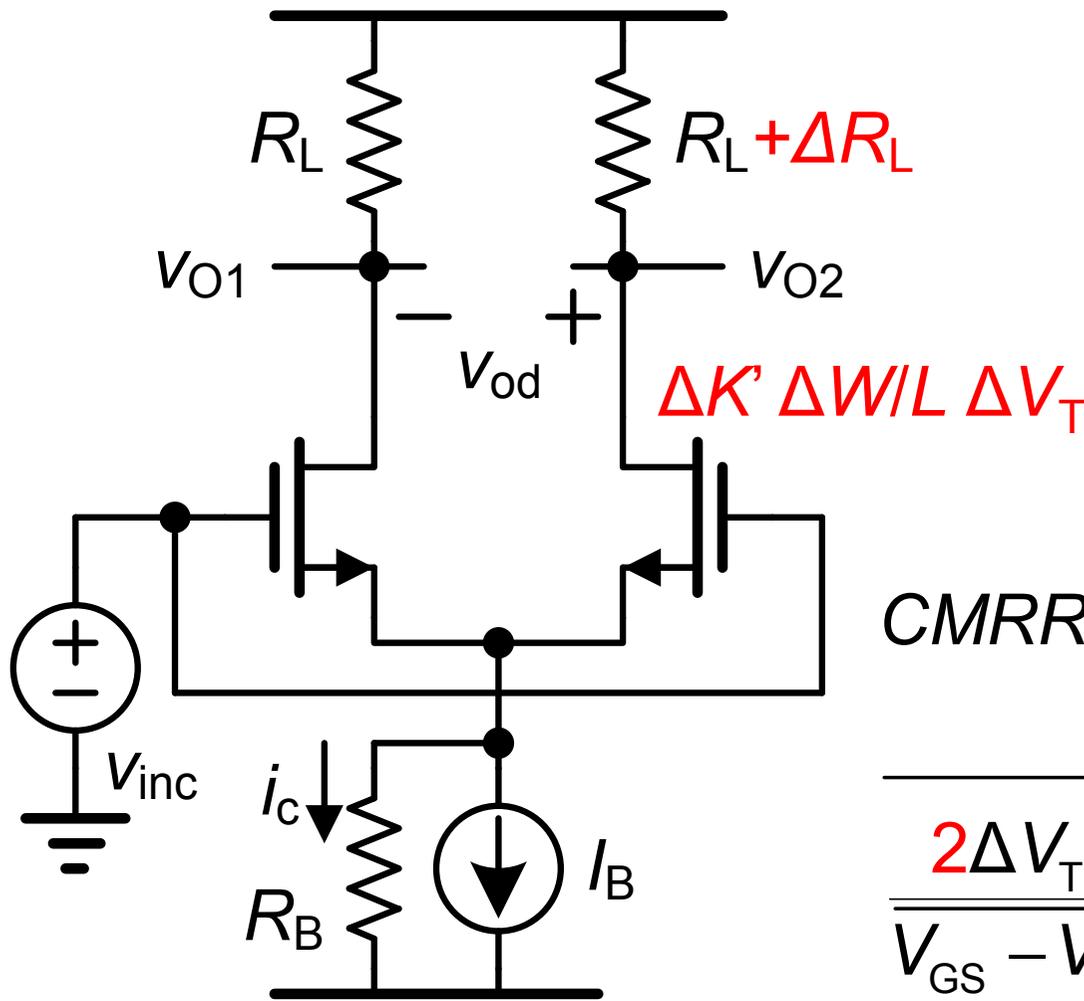
$$V_{ic} = V_{inc} \Rightarrow i_c = \frac{V_{inc}}{R_B}$$

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

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

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

差分对的随机CMRR-3



CMRR =

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

随机失调和 $CMRR$ 的关系

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

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

I_B 由单晶体管电流源提供

$$V_{osr} CMRR = \frac{V_{GS} - V_T}{2} 2g_m R_B = I_B R_B = V_E L_B = 5 \dots 15 \text{ V}$$

$$V_{osr} CMRR = \quad \quad \quad = 10 \text{ V}$$

随机失调和 **CMRR** 的关系

$$V_{\text{osr}} \text{CMRR}_r \approx V_E L_B \approx 10 \text{ V} \quad (\sim L_B)$$

10 mV 60 dB \approx 10 V MOSTs

1 mV 80 dB \approx 10 V 双极型晶体管

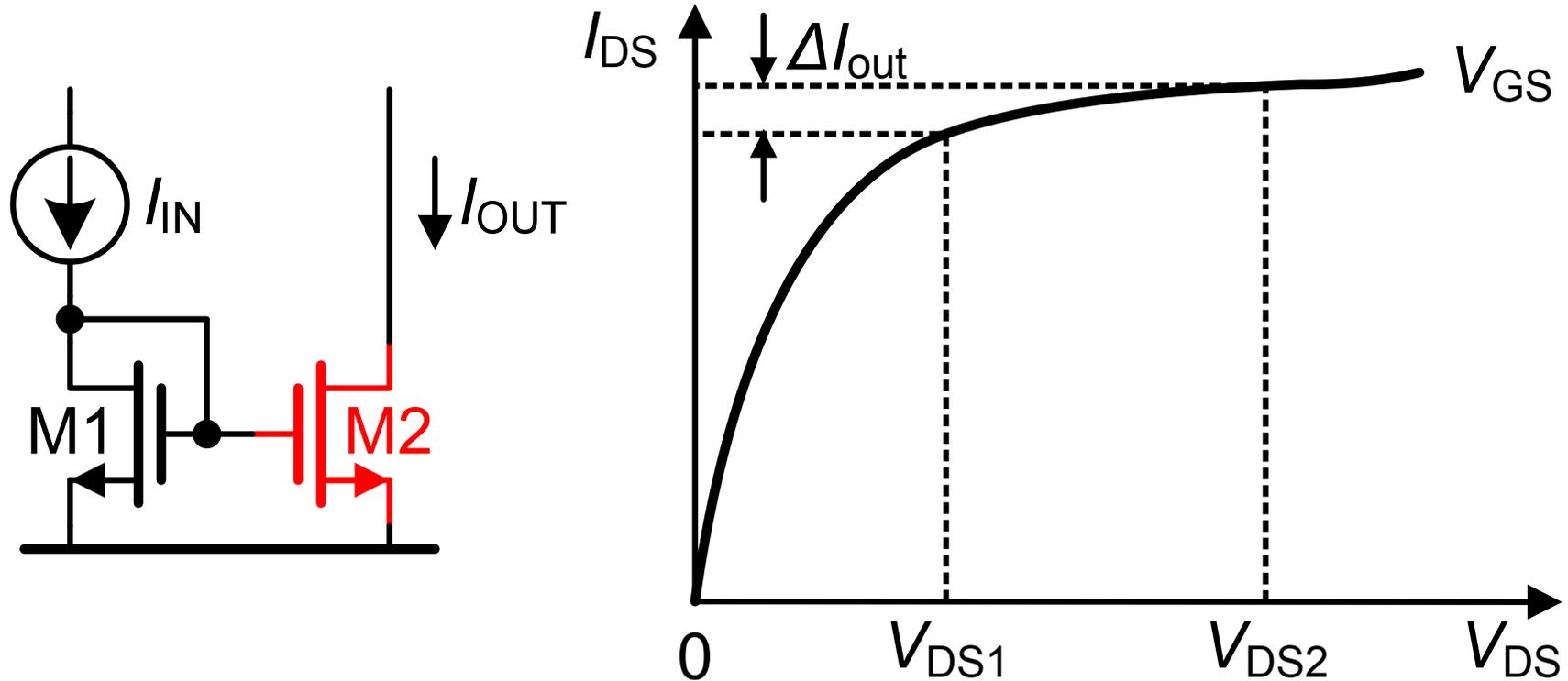
10 μ V 120 dB \approx 10 V 修正：使用激光修正
使用熔丝修正

Low offset = High **CMRR**

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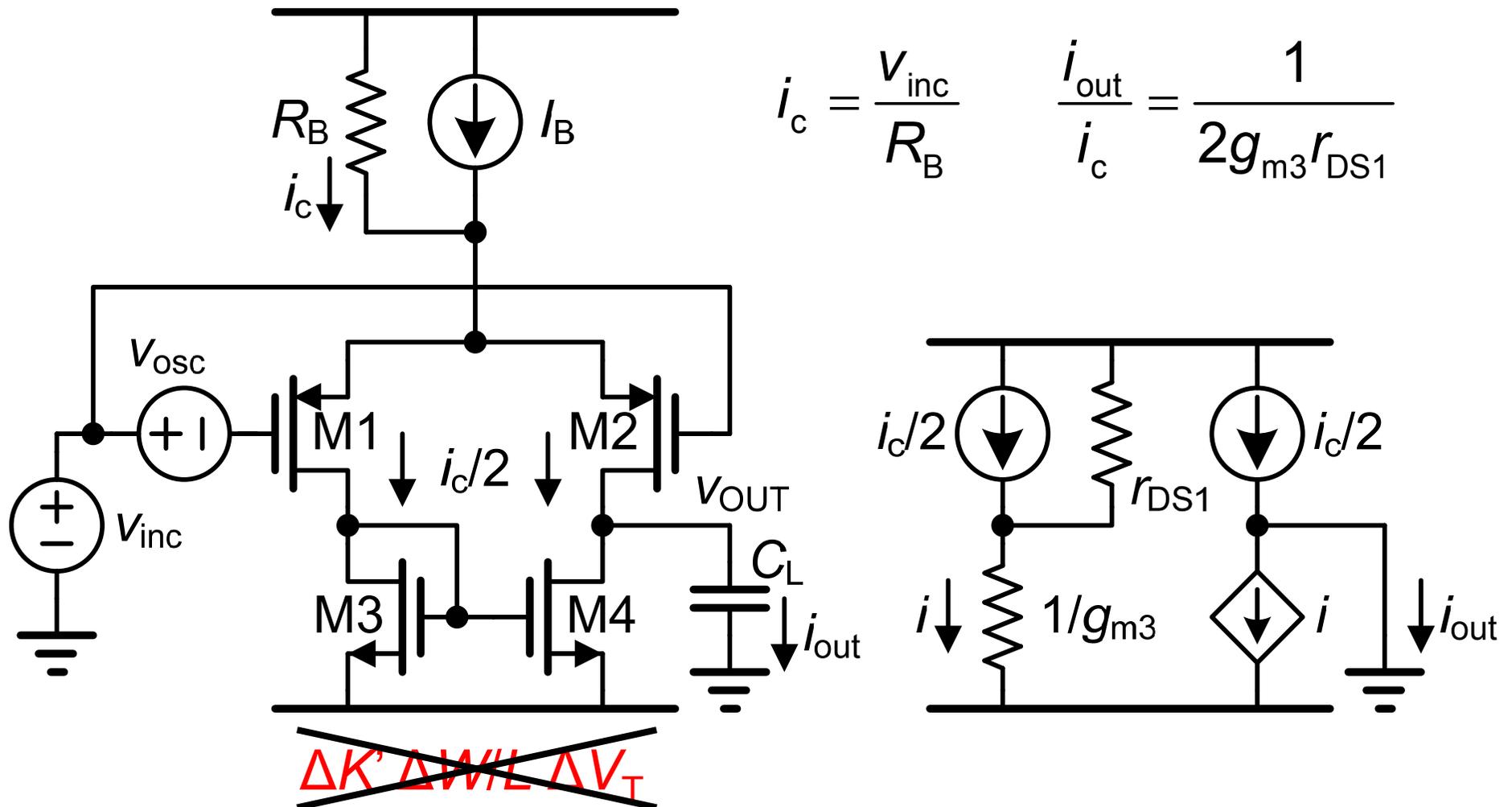
电流镜的系统失调



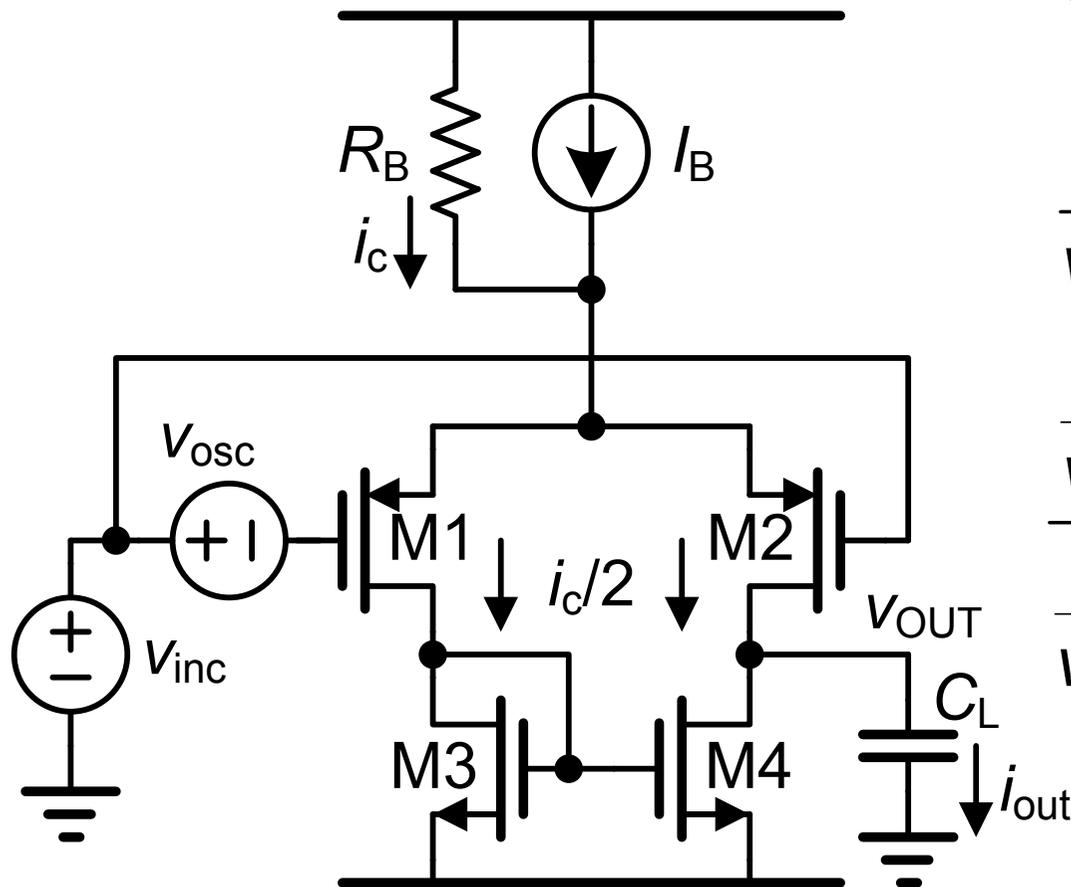
~~$\Delta K' \Delta W/L \Delta V_T$~~

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

差分对的系统 $CMRR-1$



差分对的系统 $CMRR-2$



$$\frac{i_{out}}{V_{inc}} = \frac{1}{R_B} \frac{1}{2g_{m3}r_{DS1}}$$

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

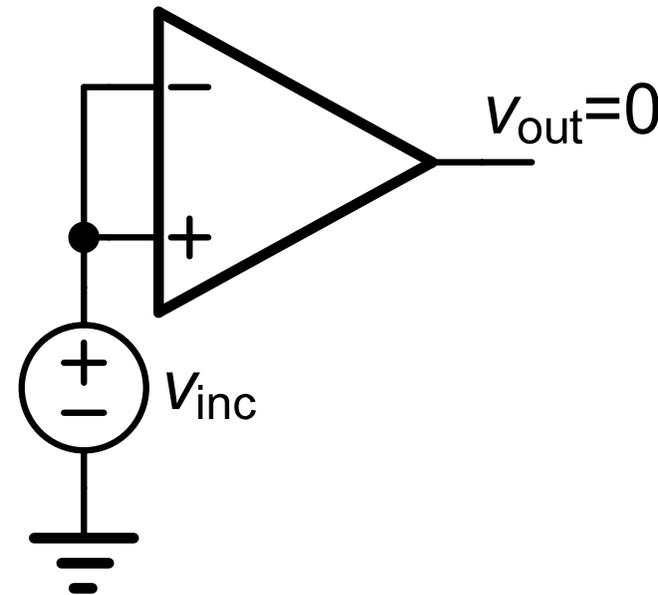
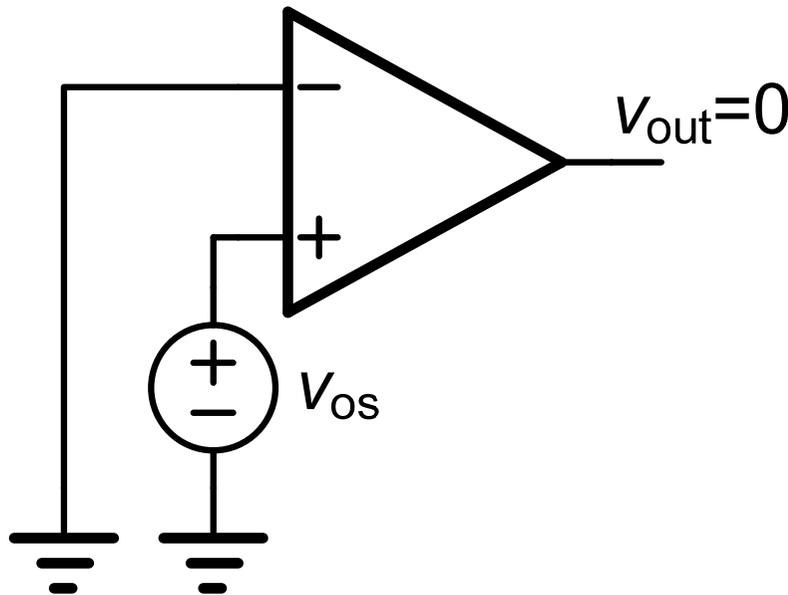
$$\frac{i_{out}}{V_{inc}} = \frac{V_{osc}}{V_{inc}} = \frac{A_{dc}}{A_{dd}} = \frac{1}{CMRR_s}$$

差分对的系统 $CMRR$ -3

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

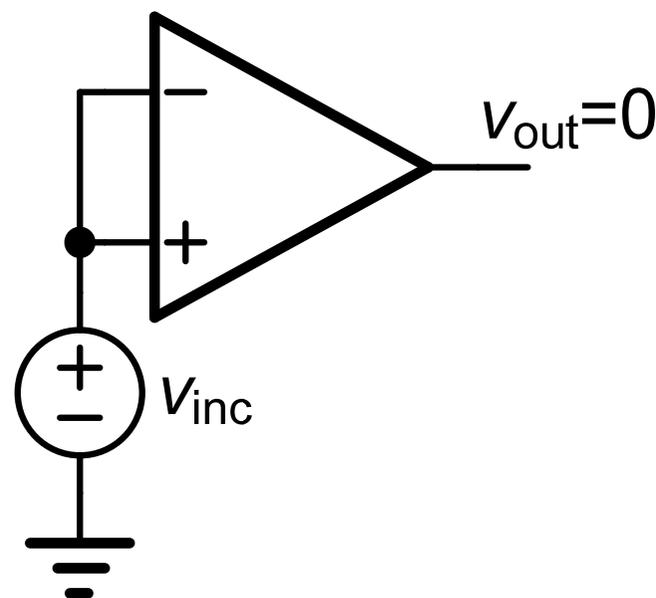
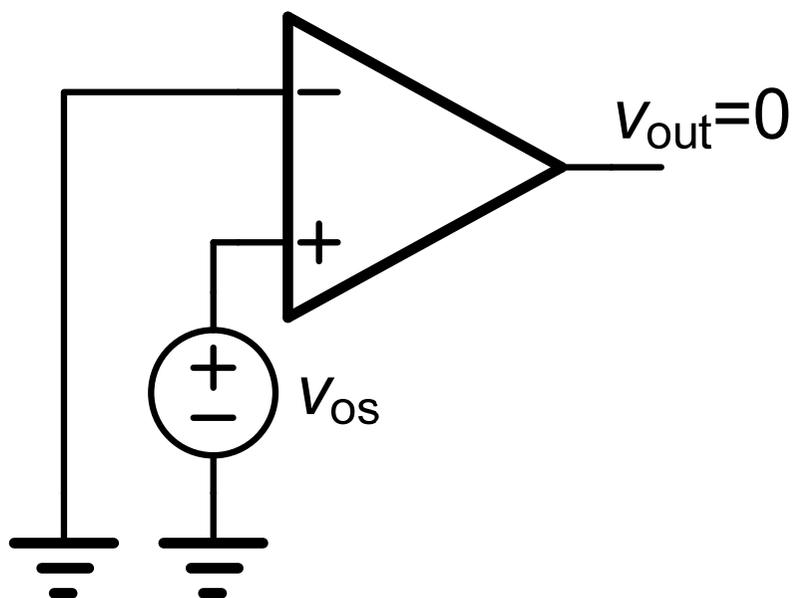
$$CMRR_s = 2g_{m1} R_B g_{m3} r_{DS1}$$

$$CMRR_s V_{osc} = V_{inc}$$

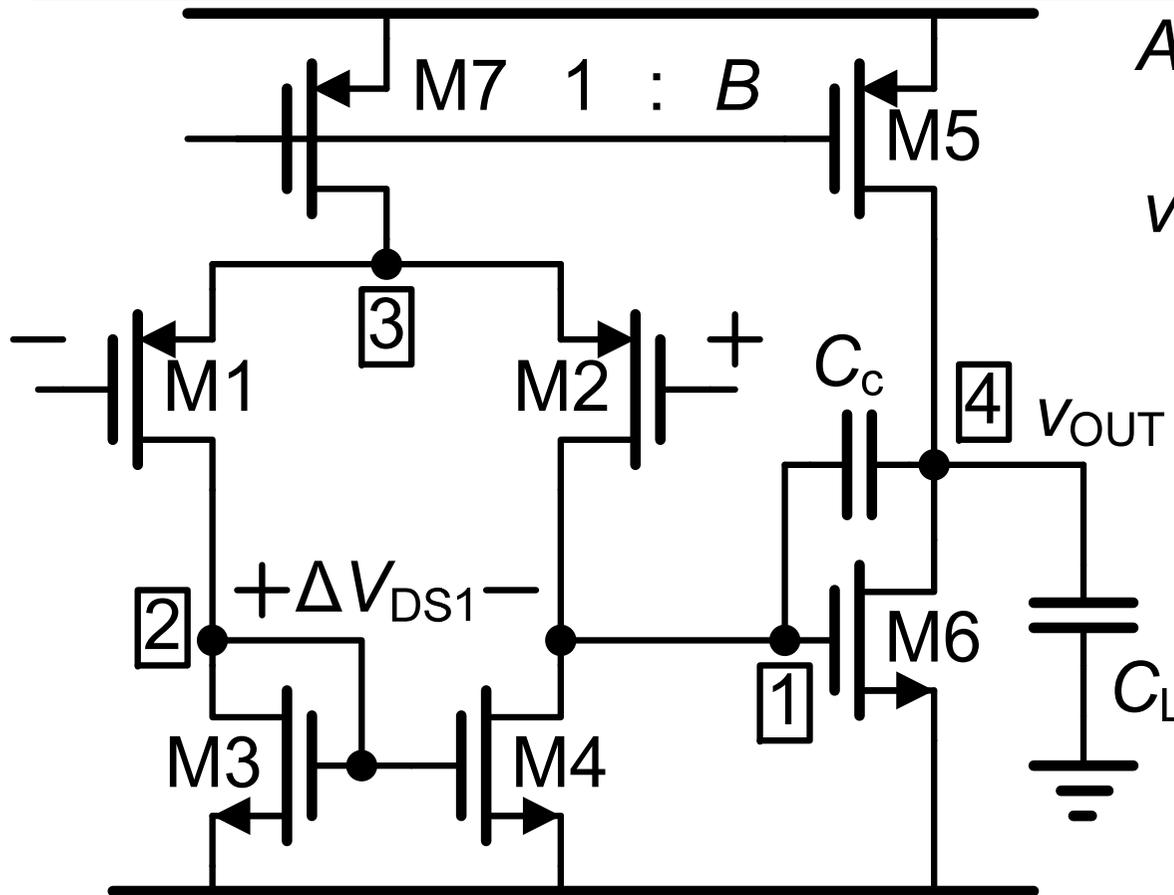


总 $CMRR$

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



密勒CMOS OTA的失调



$$A_{V1} = g_{m1} (r_{DS2} // r_{DS4})$$

$$V_{os} = \frac{\Delta V_{DS1}}{A_{V1}} + \Delta V_{T1}$$

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

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

$$+ \frac{g_{m3}}{g_{m1}} \frac{V_{GS3} - V_T}{2} S_{T3}^*$$

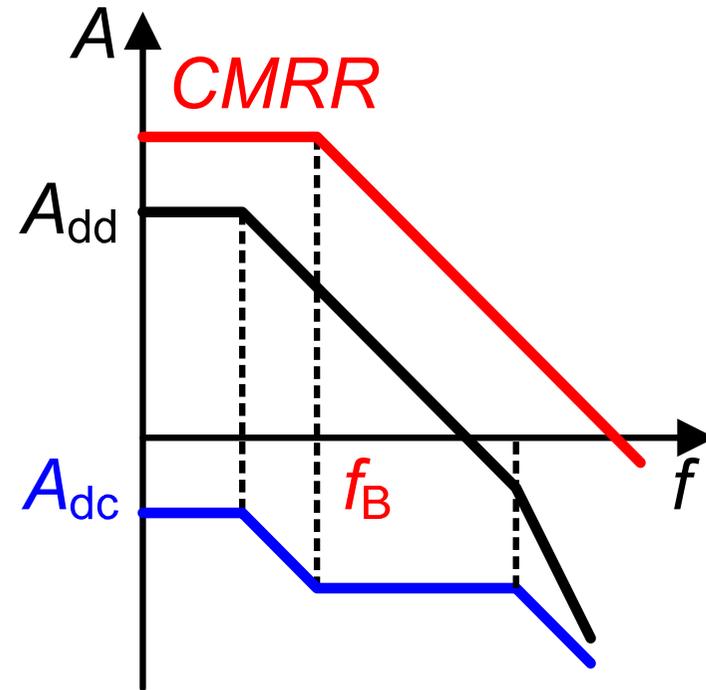
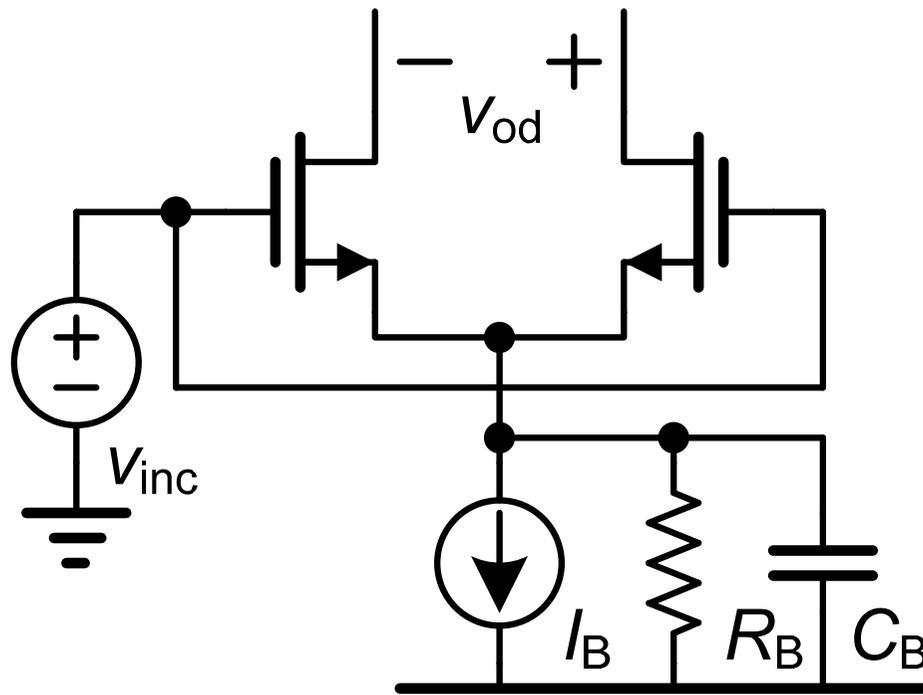
$$S = \frac{\Delta K'_n}{K'_n} + \frac{\Delta W/L_1}{W/L_1}, \quad S_{T3}^* = \frac{\Delta K'_p}{K'_p} + \frac{\Delta W/L_3}{W/L_3}$$

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

CMRR与频率的关系



$C_B \approx C_{GS}$ $R_B \approx 100/g_m \gg f_B \approx f_T/100$
 但 C_B 中包含 $C_{well,bulk}$!!!

$$f_B = \frac{1}{2\pi R_B C_B}$$

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低失调的版图规则

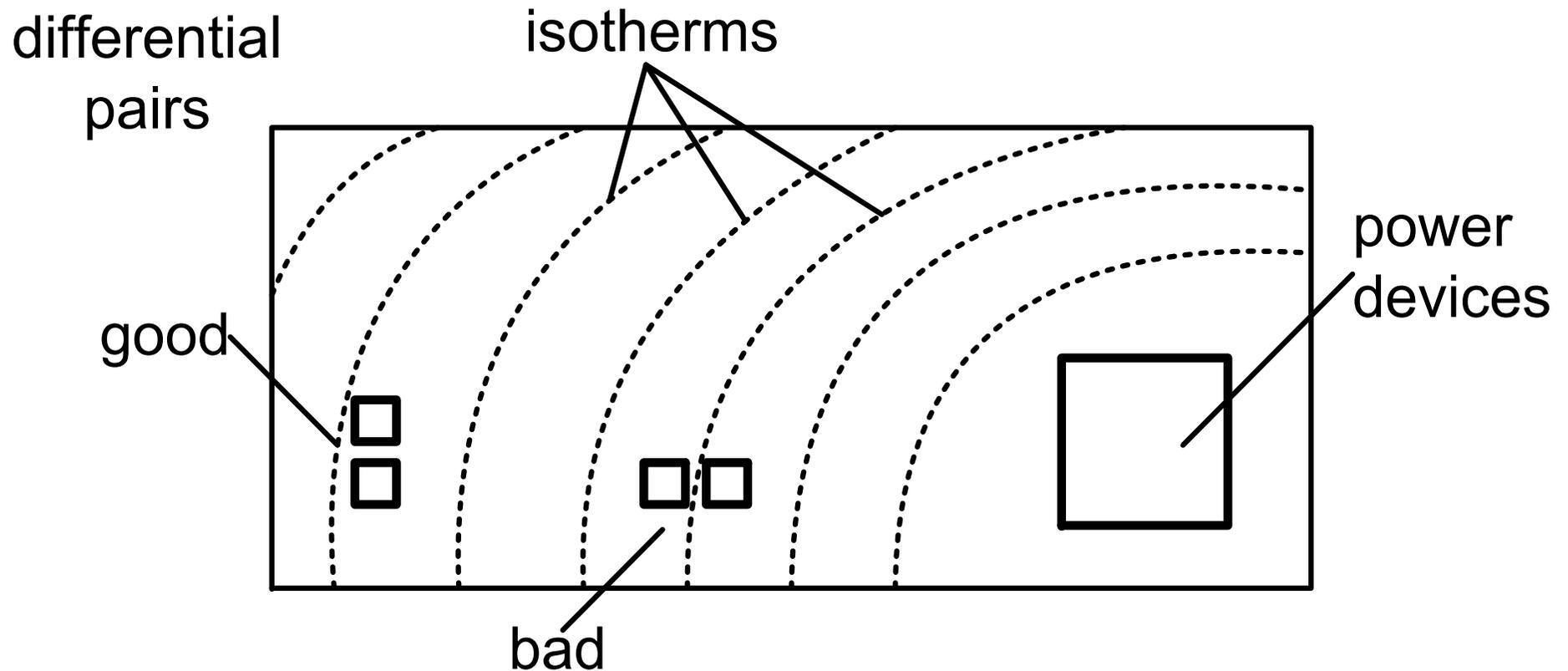
1. 属性相同
2. 等温
3. 增加尺寸
4. 减小距离
5. 方向相同
6. 相同的面积/周长比
7. 圆形
8. 中心对称布局
9. 末端加哑元
10. 通常三极管匹配性更好

Ref.: Hastings, "The Art of Analog Layout" Prentice Hall 2001
R. Soin, .. "A-D Asics, .. "Peregrinus, 1991

低失调的版图规则

1. 属性相同
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10. 通常三极管匹配性更好

放置在相同的等温线上

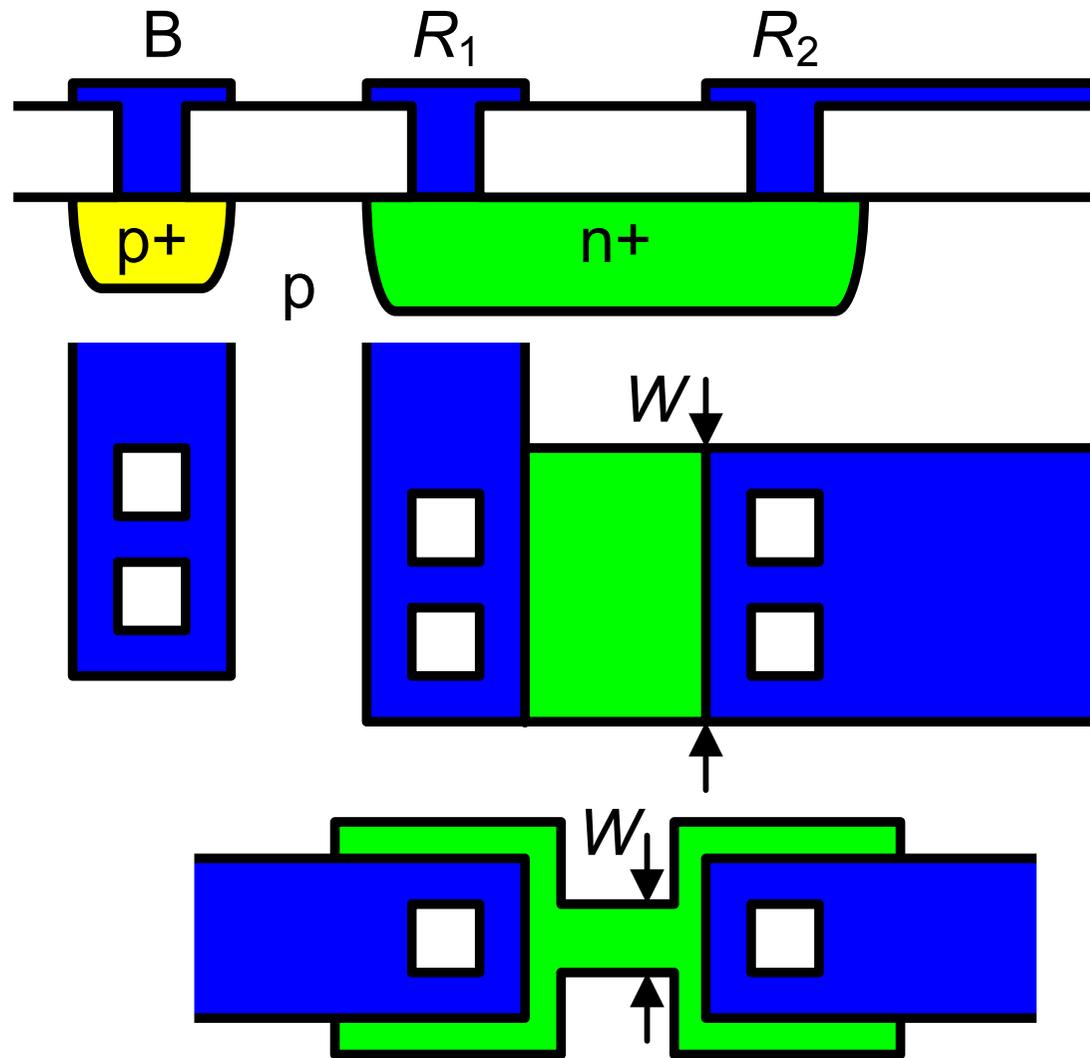


Ref.: Solomon, JSSC Dec 74, 314-332

低失调的版图规则

1. 属性相同
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10. 通常三极管匹配性更好

电阻版图



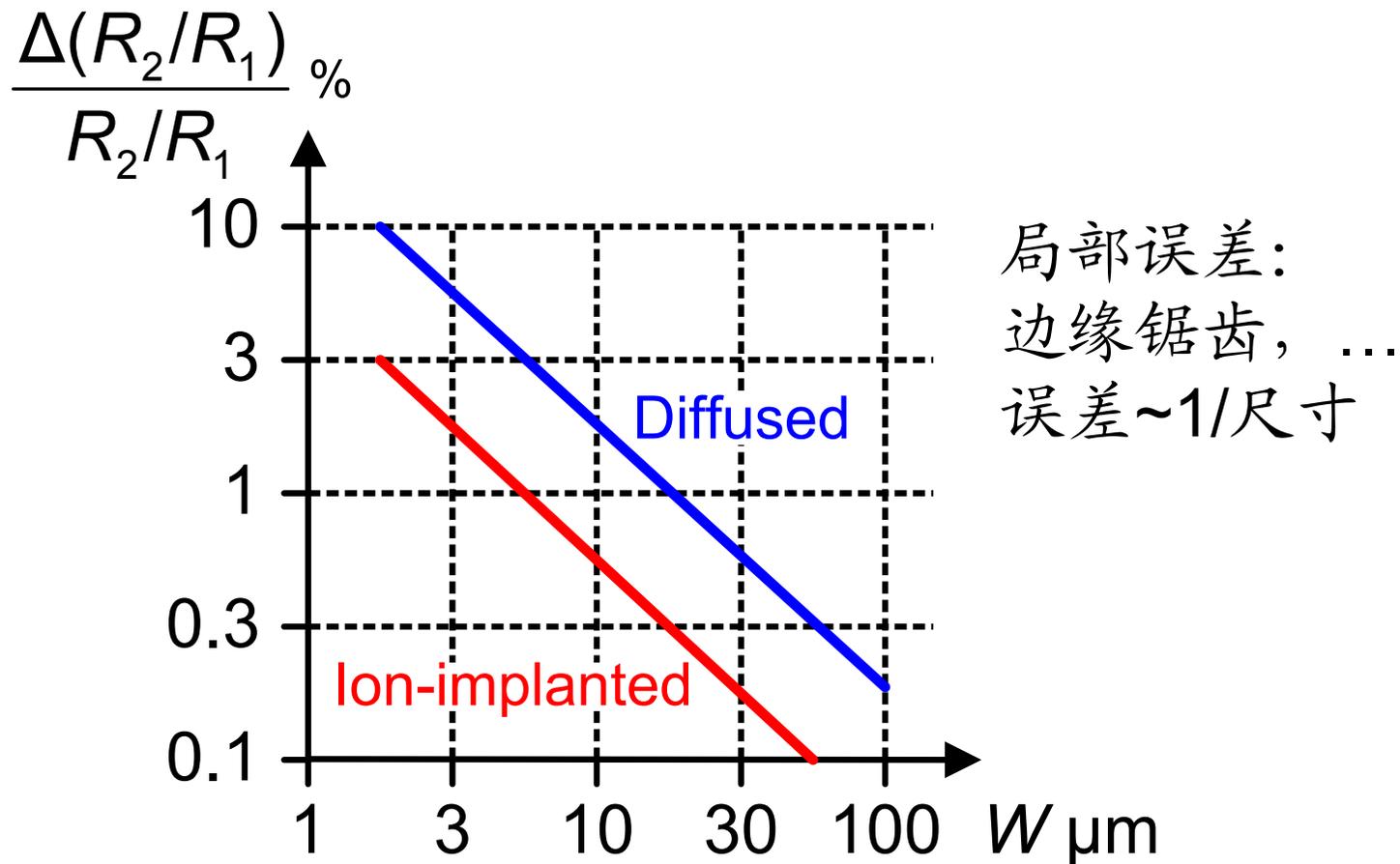
CMOS工艺的
源/漏扩散电阻

Ref.: Laker, Sansen :
Design of analog ...,
MacGrawHill 1994
Table 2-6

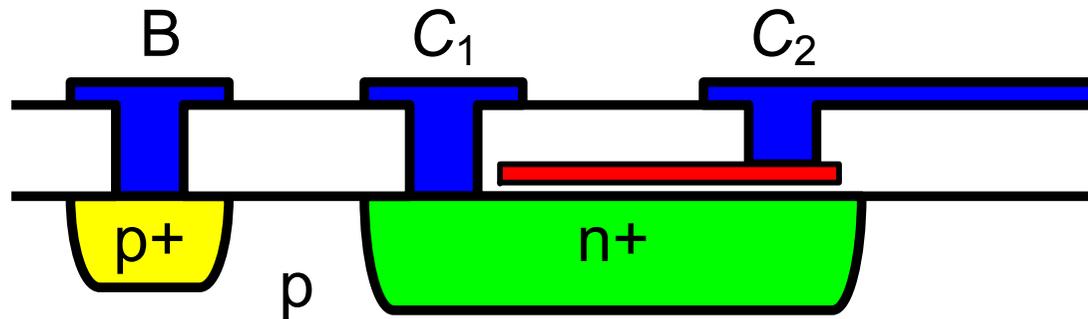
电阻

Process	Type	ρ 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	0.01	0.01	90
	aluminum	50 m	20	0.01	0.02	90

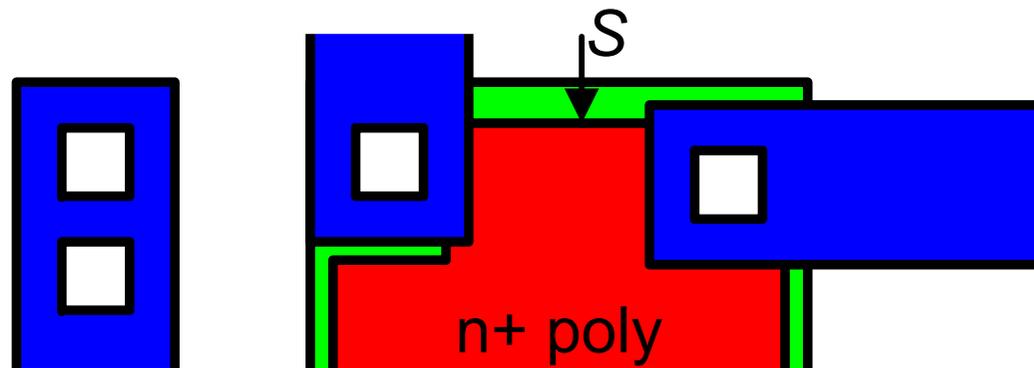
电阻的失配与尺寸的关系



电容版图



多晶硅到源/漏
的电容



多晶硅到多晶硅
的电容

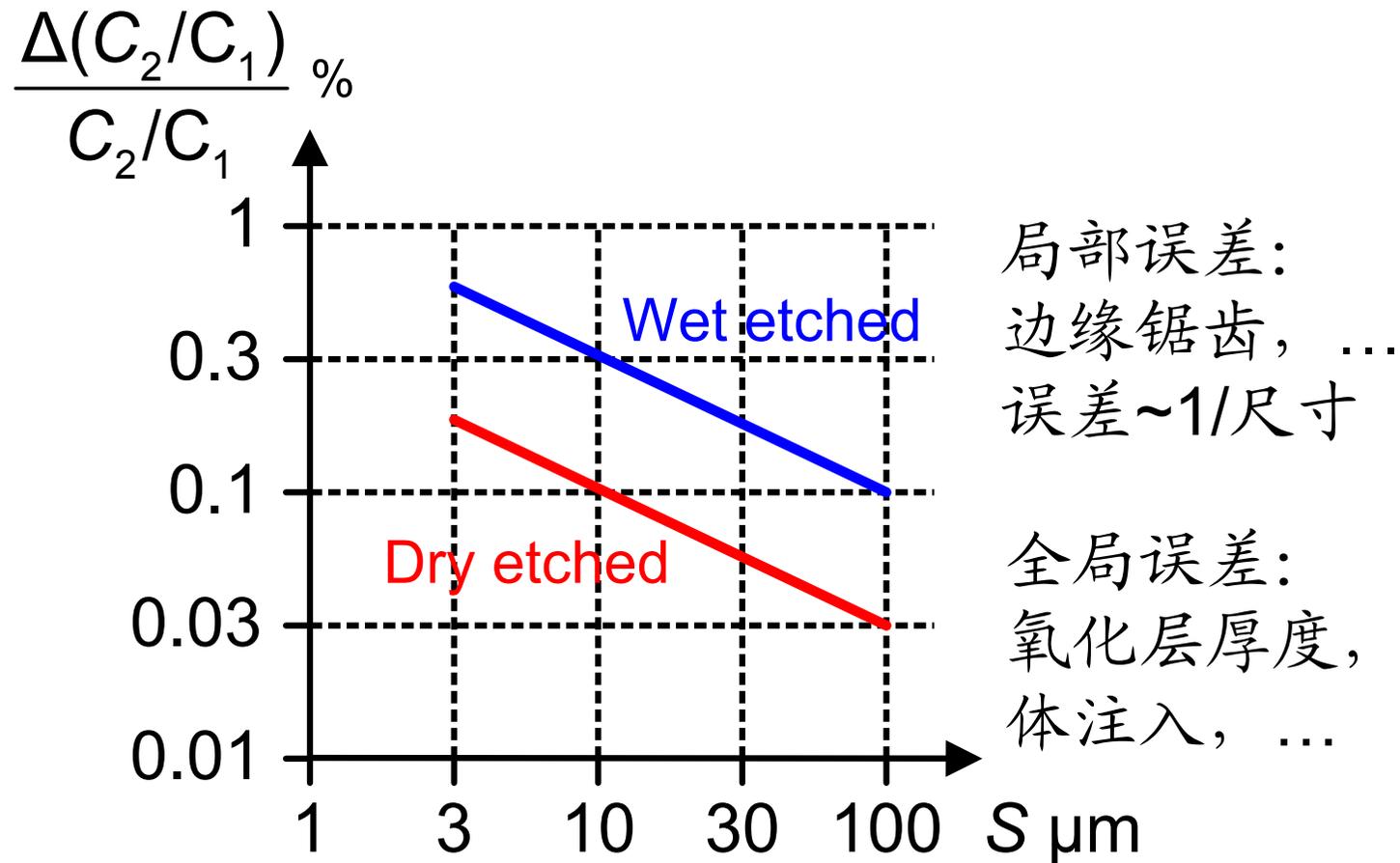
$$C_{\text{par}} = \frac{1}{6 \dots 15} C_{\text{pp}}$$

电容

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	$C_{CS}(50\text{ nm})$	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	0.005	0.05	20

Ref.: Laker, Sansen :Design of analog ...,MacGrawHill 1994 Table 2-7

电容的失配与尺寸的关系



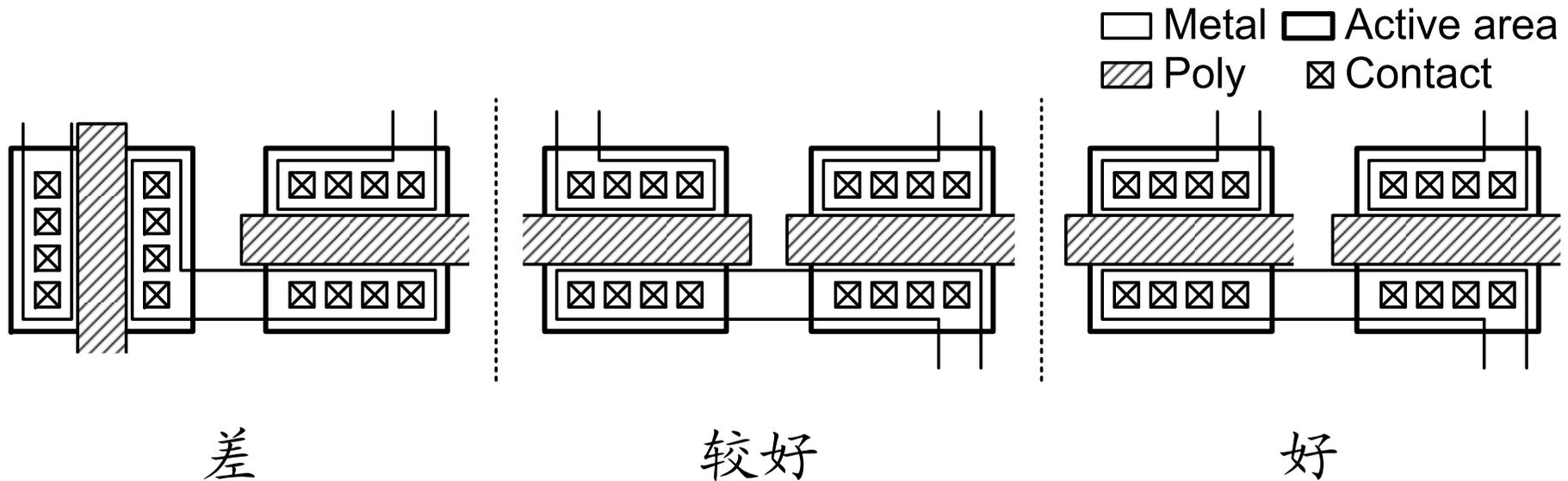
低失调的版图规则

1. 属性相同
2. 等温
3. 增加尺寸
4. 减小距离
5. 方向相同
6. 相同的面积/周长比
7. 圆形
8. 中心对称布局
9. 末端加哑元
10. 通常三极管匹配性更好

低失调的版图规则

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晶体管对的失配



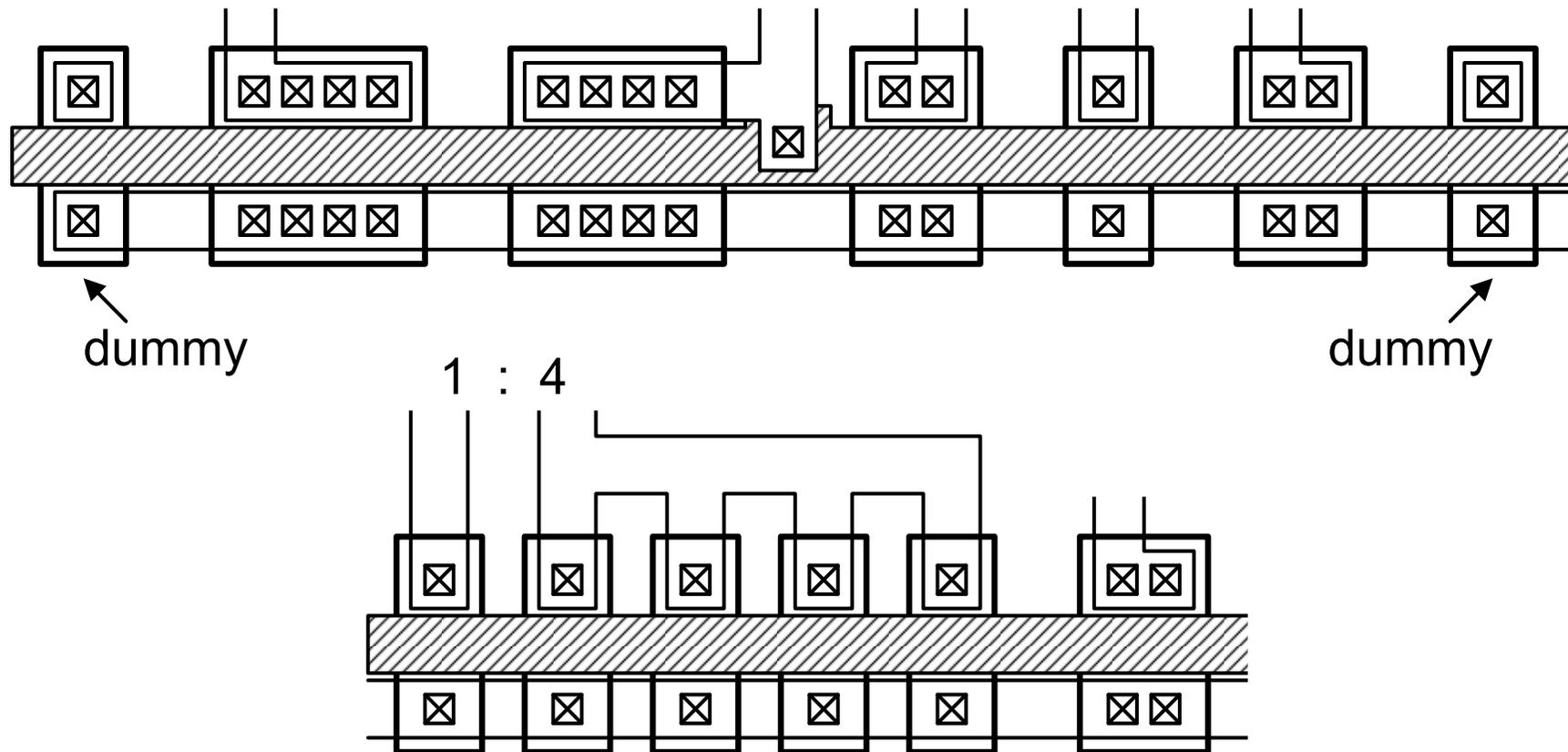
低失调的版图规则

1. 属性相同
2. 等温
3. 增加尺寸
4. 减小距离
5. 方向相同
- 6. 相同的面积/周长比**
7. 圆形
8. 中心对称布局
9. 末端加哑元
10. 通常三极管匹配性更好

电流镜的匹配

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

Metal Active area
 Poly X Contact



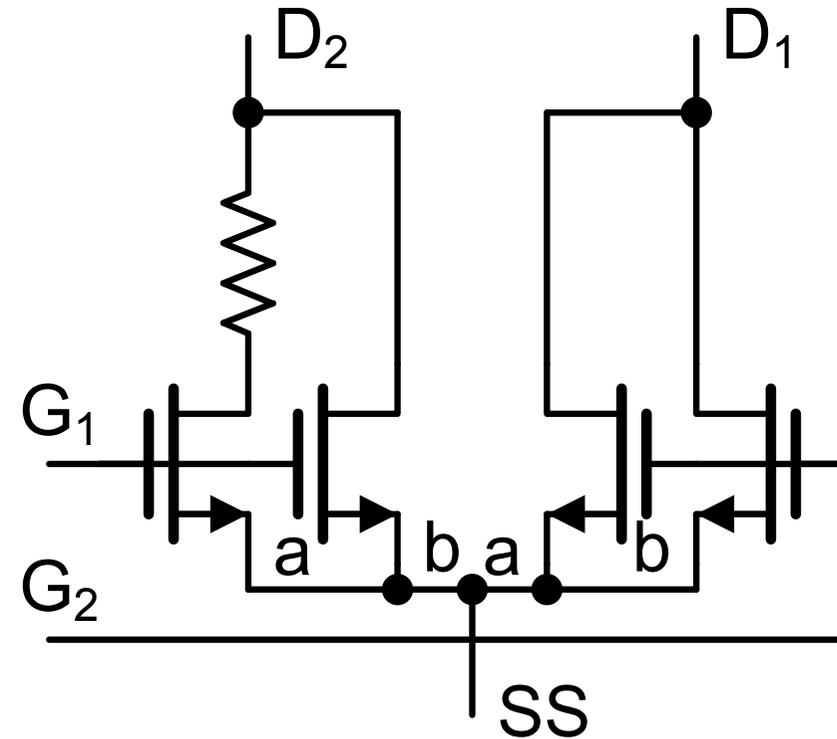
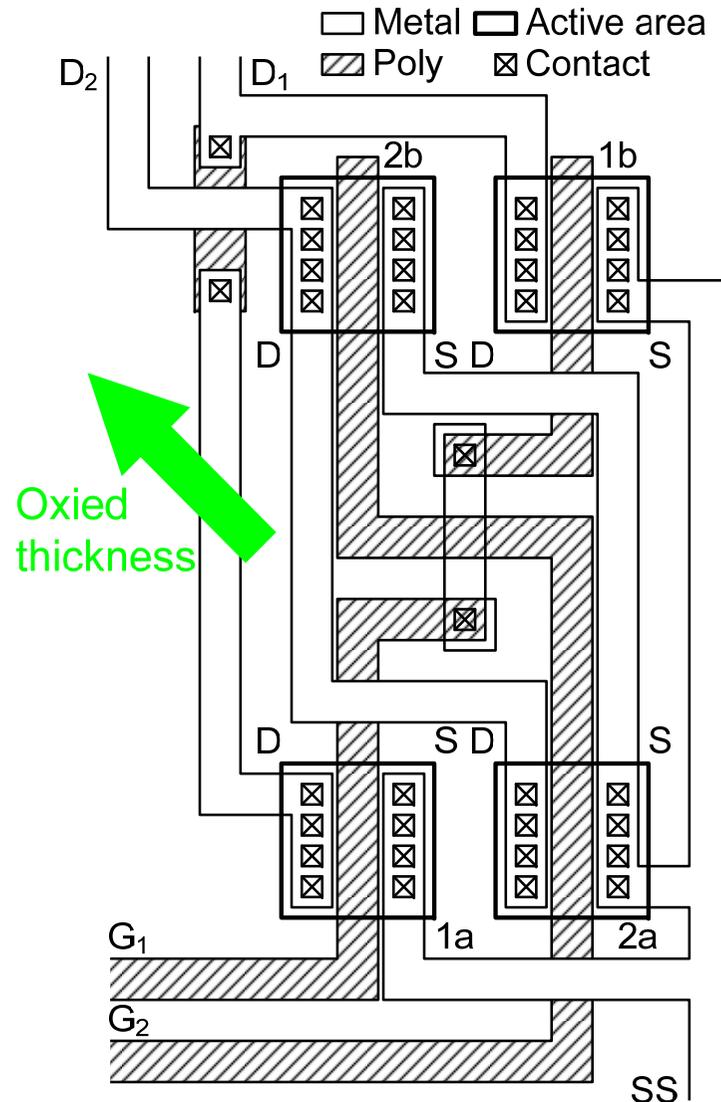
低失调的版图规则

1. 属性相同
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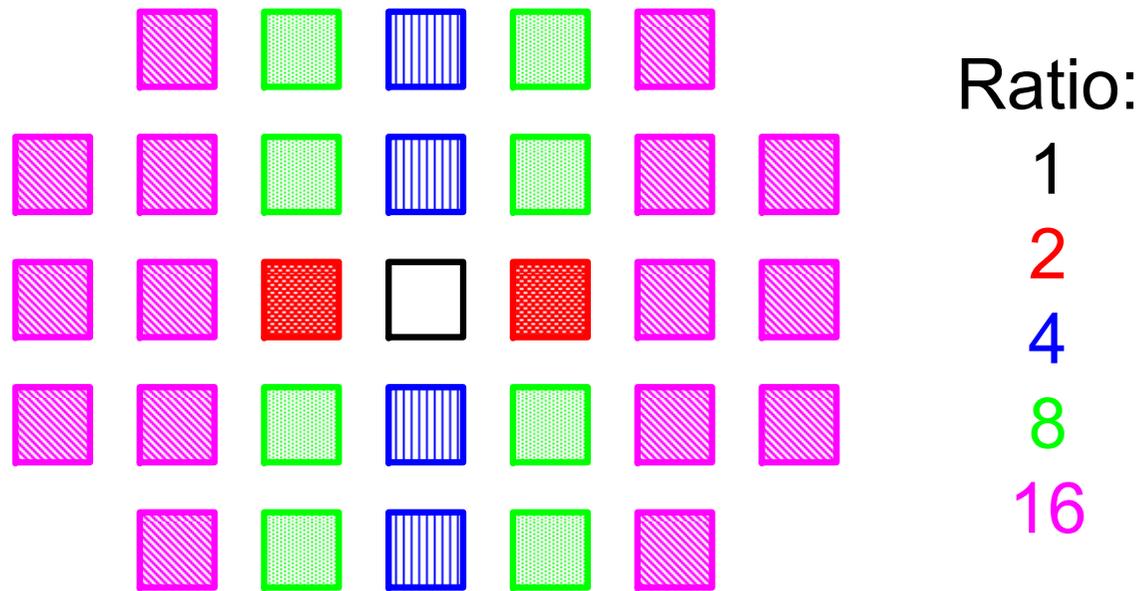
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10. 通常三极管匹配性更好

差分对的交叉耦合



对全局变化不敏感：
 氧化层厚度
 衬底掺杂浓度.....

电容的质心布局



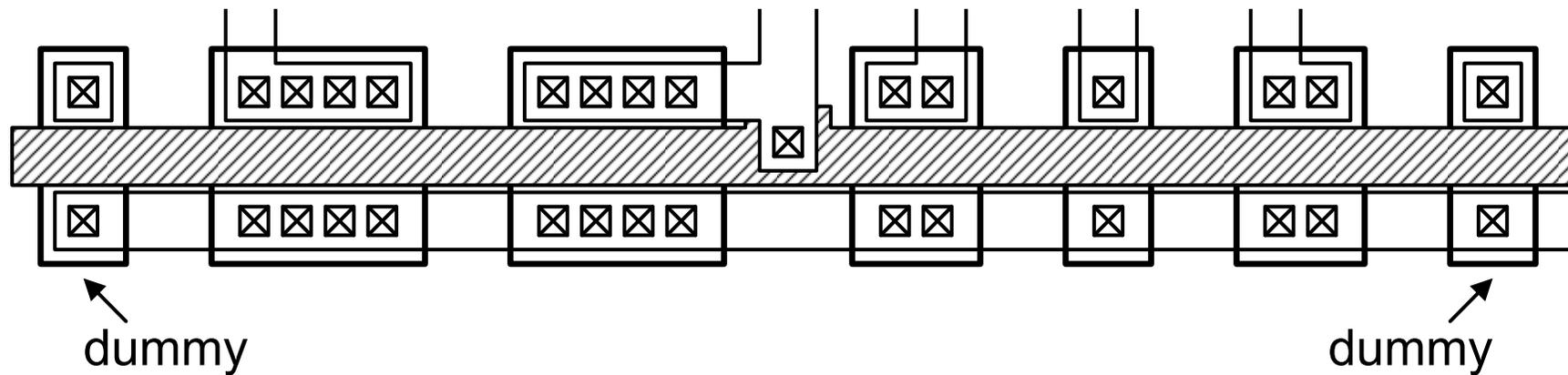
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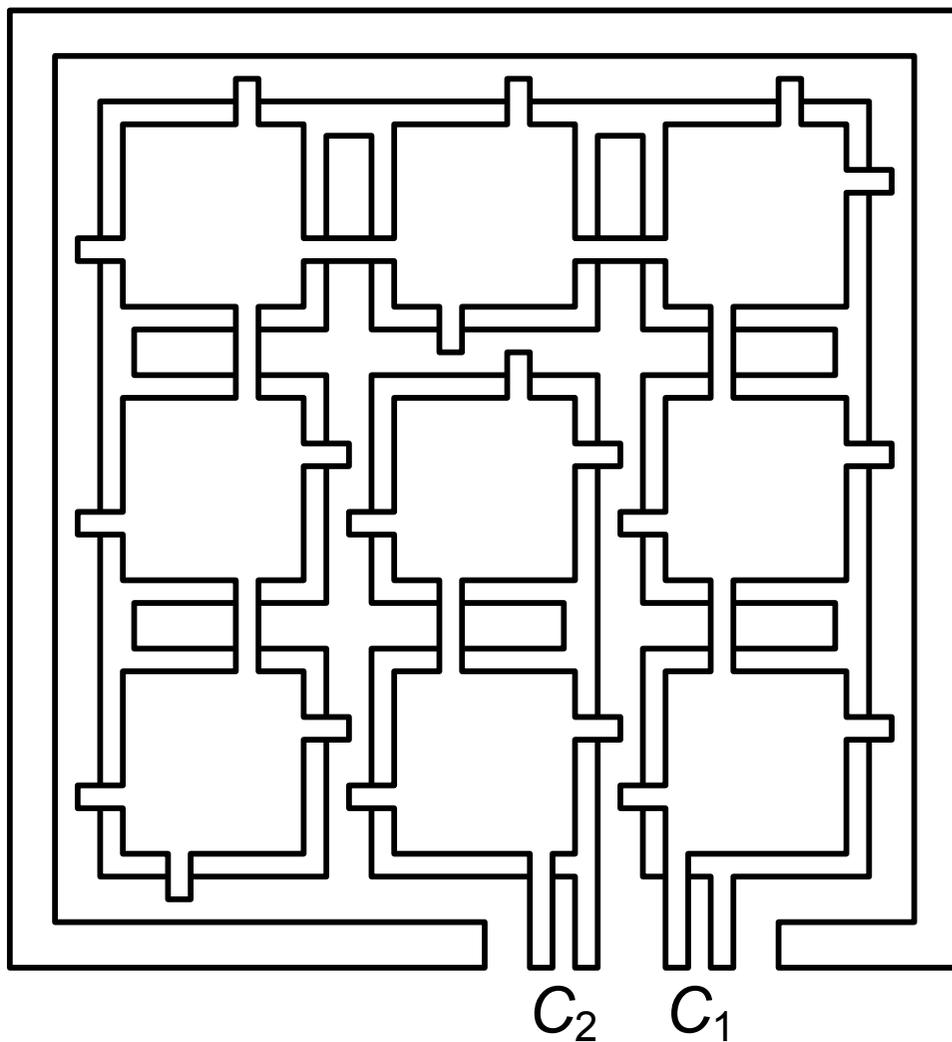
电流镜的失配

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

□ Metal □ Active area
▨ Poly ⊗ Contact



整数比例



比率 $7/2=3.5$

dummy
ring

Ref.: Courtesy Vittoz

低失调的版图规则

1. 属性相同
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目录

- 随机失调和 $CMRR_r$
- 系统失调和 $CMRR_s$
- $CMRR$ 与频率的关系
- 设计规则

- MOST与双极型晶体管的比较

MOST和双极型晶体管的失调

$$\text{MOST: } V_{os} = \Delta V_T + \frac{V_{GS} - V_T}{2} \left(\frac{\Delta R_L}{R_L} + \frac{\Delta K'}{K'} + \frac{\Delta W/L}{W/L} \right)$$

$$\text{Bipolar: } V_{os} = \frac{kT}{q} \left(\frac{\Delta R_L}{R_L} + \frac{\Delta I_S}{I_S} \right) \quad \text{非常小}$$

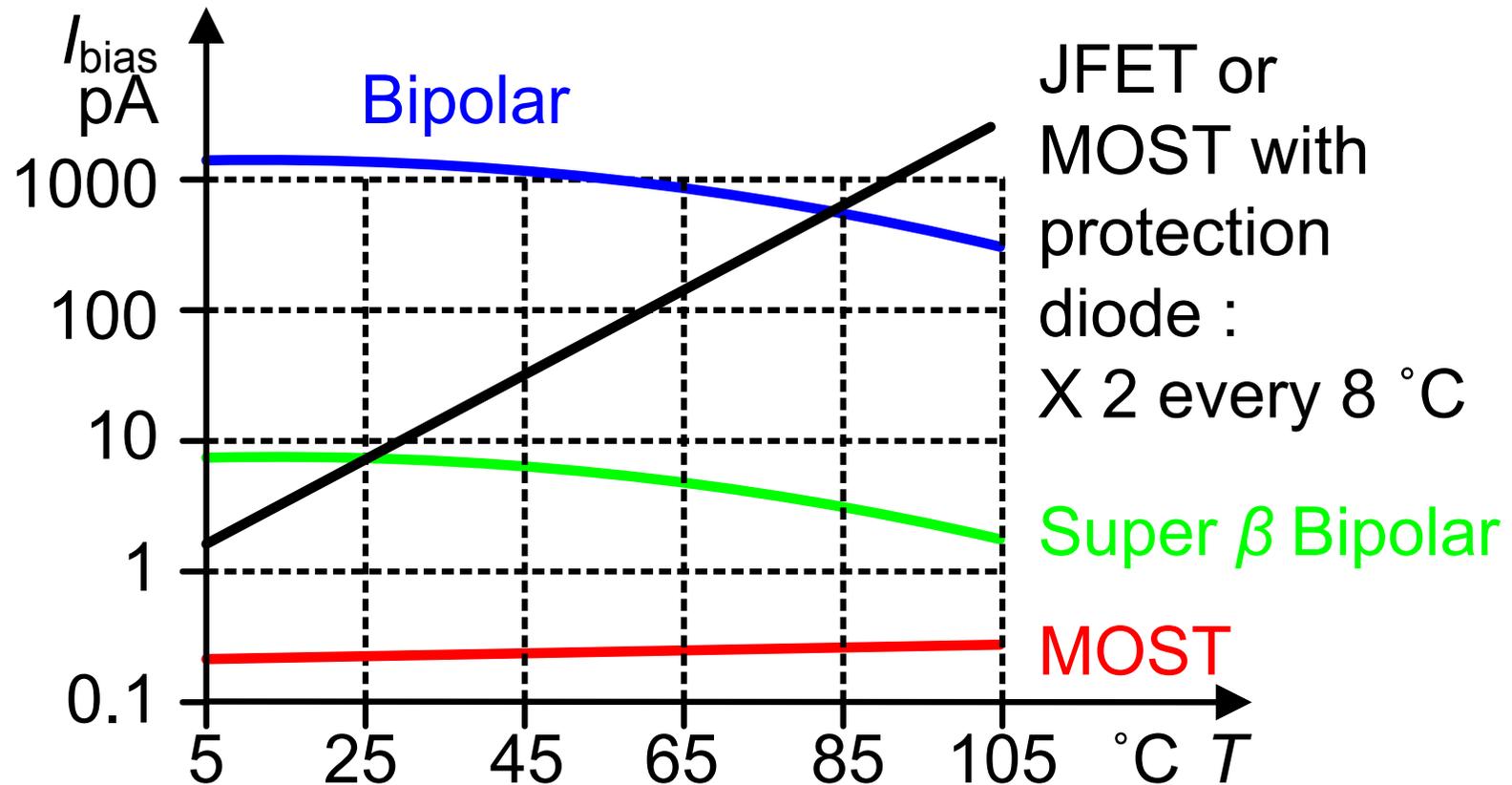
1) 没有 V_T

2) $kT/q \ll (V_{GS} - V_T)/2$

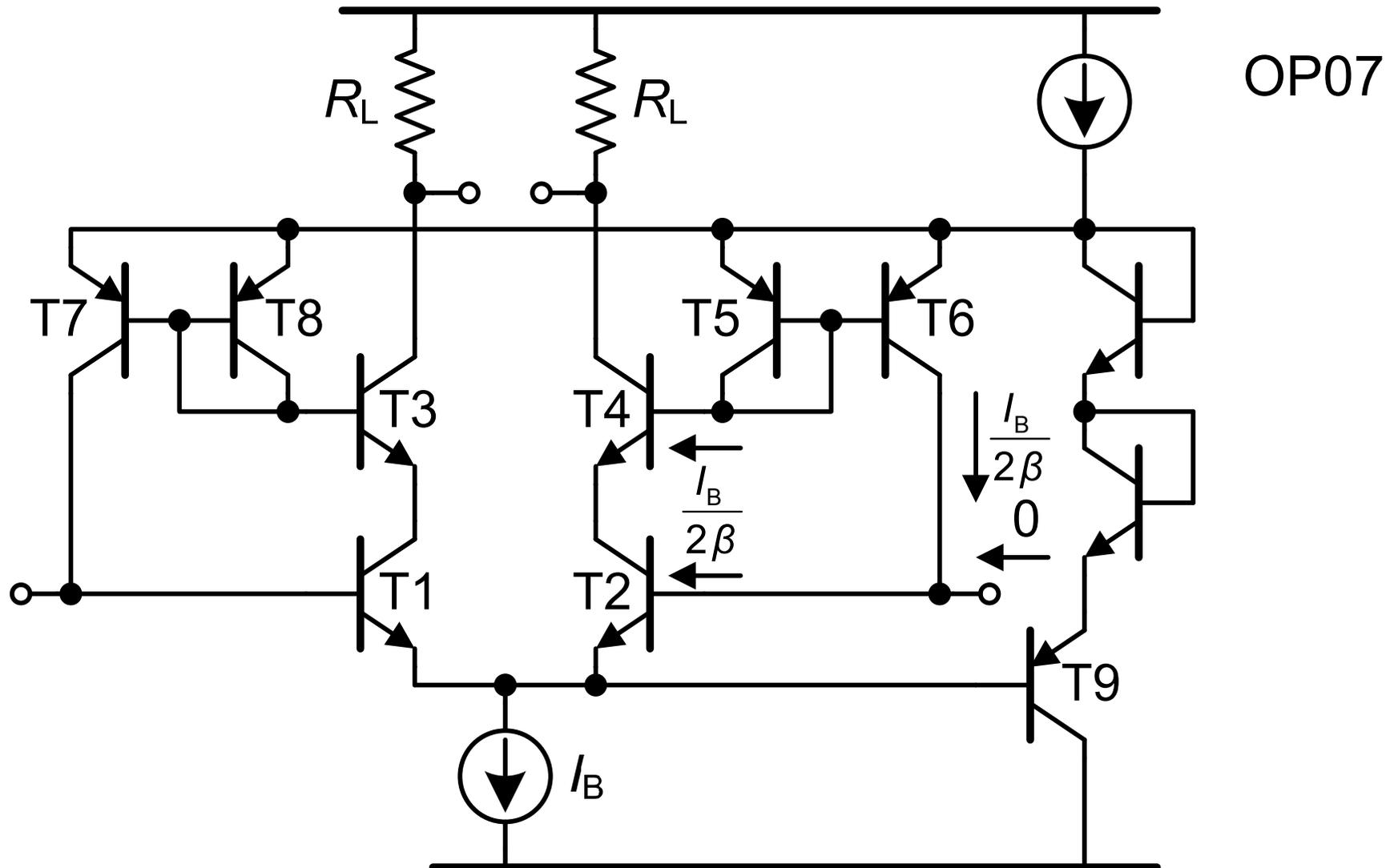
3) 可以激光修正 $\frac{\Delta V_{os}}{\Delta T} = \frac{V_{os}}{T}$

Bipolar: 存在基极电流!

偏置电流、基极电流



基极电流补偿



器件失配的性能极限

$$\frac{1}{(\text{Accuracy})^2} \approx \sigma^2 \left(\frac{\Delta I_{DS}}{I_{DS}} \right) \approx \frac{4A_{VT}^2}{WL \underbrace{(V_{GS} - V_T)^2}_{\frac{V_{DD}}{2}}}$$

$$\text{Speed} \approx f_T = \frac{2I_{DS}}{2\pi WL(2/3)C_{ox} \underbrace{(V_{GS} - V_T)}_{\frac{V_{DD}}{2}}}$$

$$\frac{\frac{2I_{DS}}{2\pi WL(2/3)C_{ox}(V_{GS} - V_T)} \cdot \frac{WL(V_{GS} - V_T)^2}{4A_{VT}^2}}{I_{DS}V_{DD}} = \frac{\frac{2I_{DS}}{2\pi WL(2/3)C_{ox}} \cdot \frac{WL \frac{V_{DD}}{2}}{4A_{VT}^2}}{I_{DS}V_{DD}} = \frac{1}{\frac{3}{16}\pi C_{ox} A_{VT}^2}$$

$$\frac{\text{Speed} \times (\text{Accuracy})^2}{\text{Power}} = \frac{1}{\frac{3}{16}\pi C_{ox} A_{VT}^2} \sim \frac{1}{t_{ox}}$$

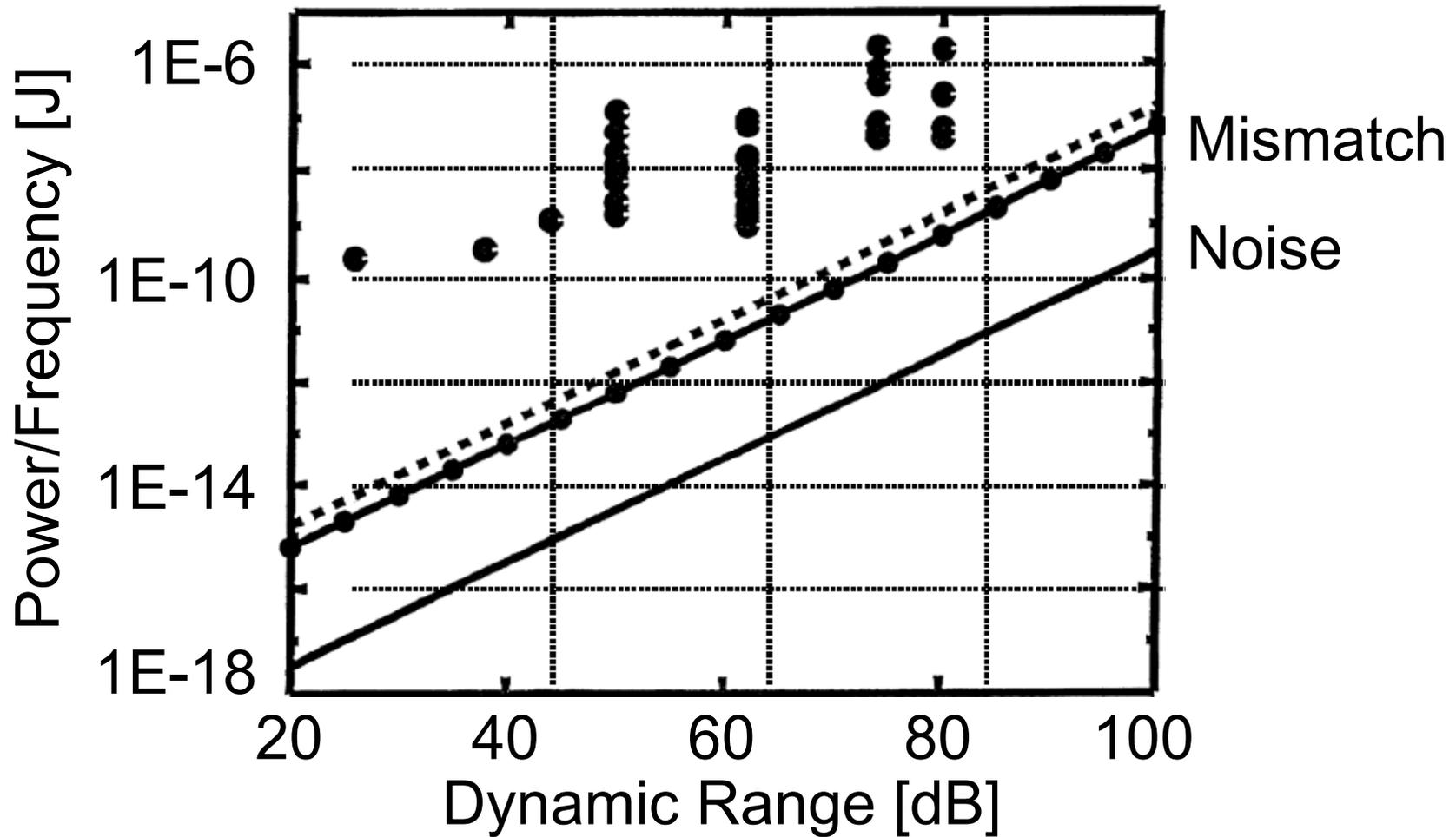
= Technological constant

器件噪声的性能极限

$$S/N = \frac{V_{pp}^2/2}{4kTR \cdot BW} \quad S/N = \frac{V_{pp}^2/8}{kT/C}$$
$$P_{\min} = \frac{V_{pp}^2}{R} \quad BW = \frac{1}{RC}$$

$$P_{\min} \approx 8kT \cdot BW(S/N)$$

高动态范围的噪声与失配



Ref.: P.Kinget, ...“Analog VLSI ..”page 67,Kluwer 1997.

深亚微米CMOS动态范围减小

