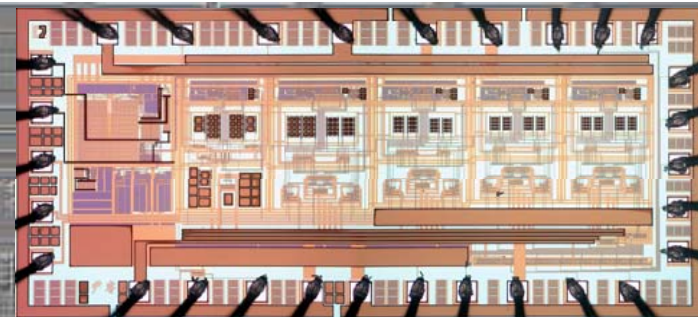




高级模拟集成电路设计 (Analog Design Essentials)

2011年12月19日

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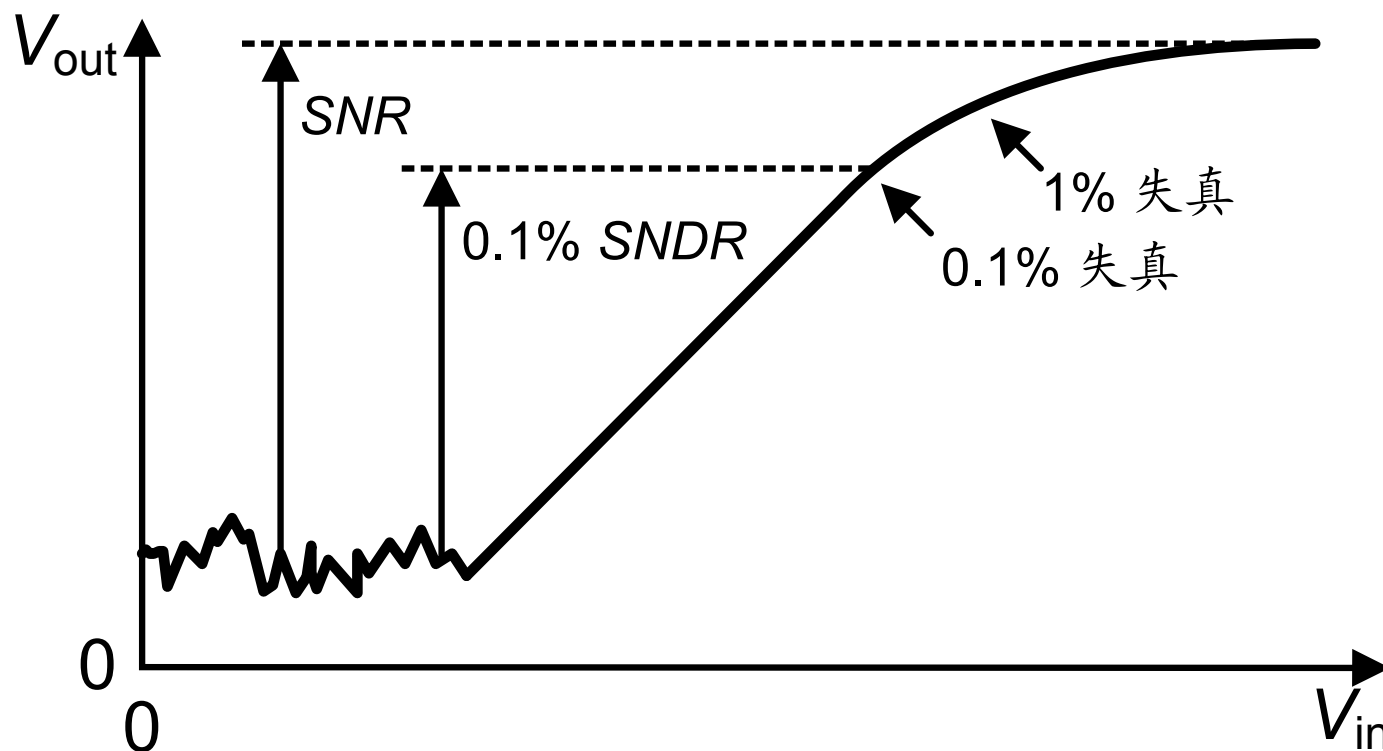
<http://rfic.fudan.edu.cn/Courses.htm>

复旦大学/微电子学系/射频集成电路设计研究小组

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基本晶体管级的噪声性能

信号噪声比和信号噪声失真比



信号噪声比: Signal-to-Noise Ratio

信号噪声失真比: Signal-to-Noise-and-Distortion Ratio

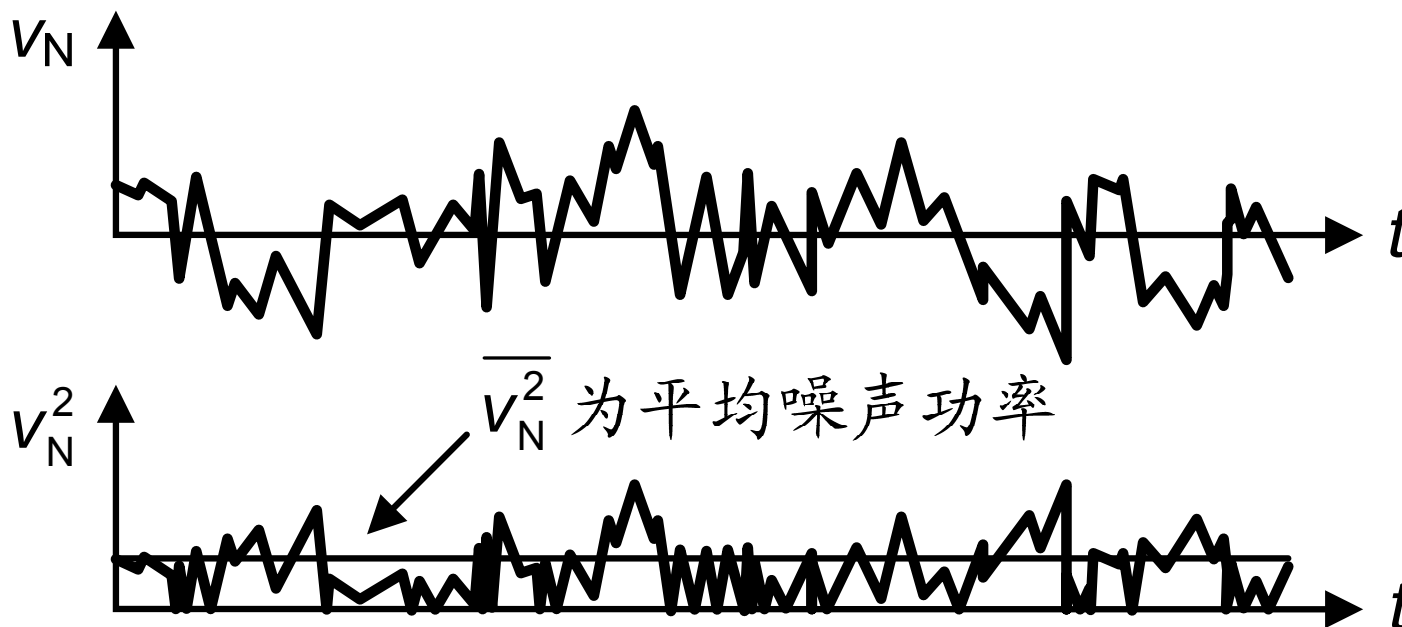
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- 电压/电流检测器的噪声对比

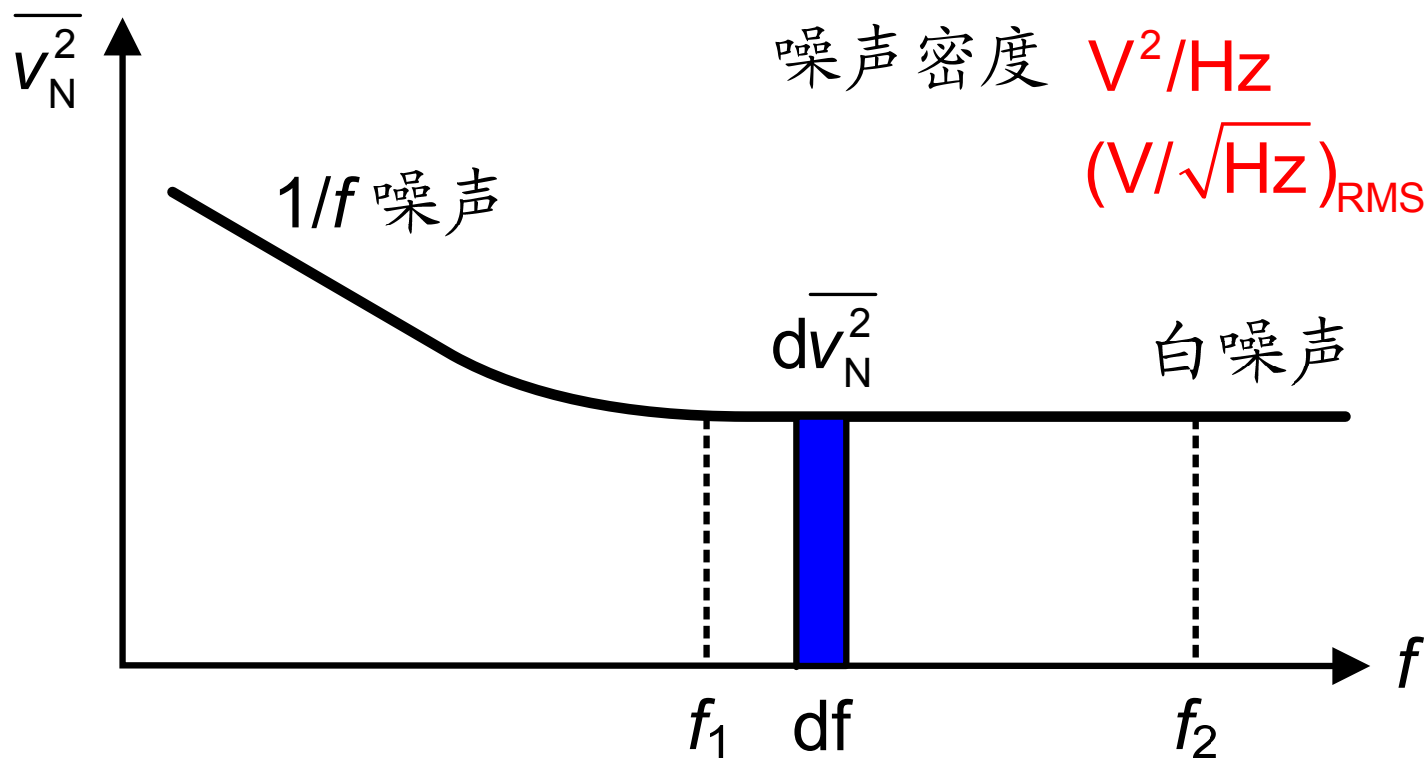
Ref.: W. Sansen : Analog Design Essentials, Springer 2006

噪声和时间的关系



Ref.: Van der Ziel (Prentice Hall 1954, Wiley 1986), Ott (Wiley 1988)

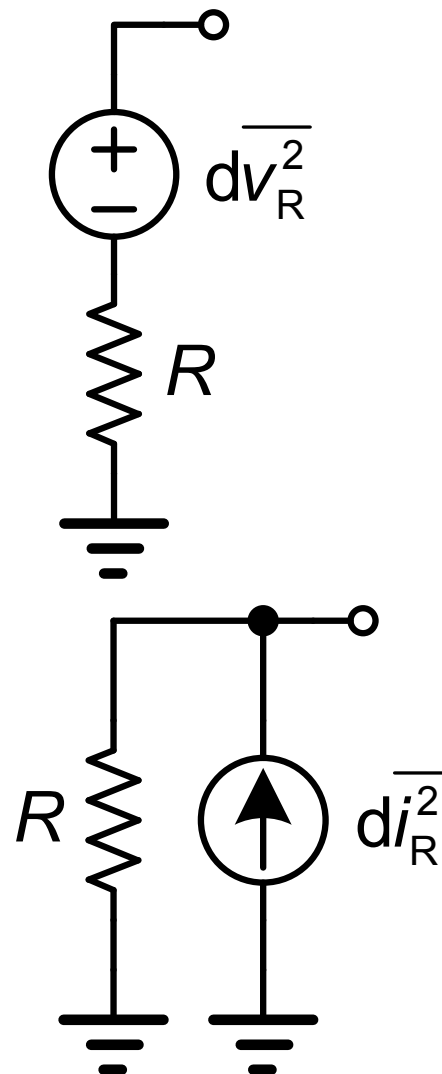
噪声和频率的关系



积分噪声 V_{RMS}

$$\overline{V_{12}} = \sqrt{\overline{V_N^2}} = \sqrt{\int_{f_1}^{f_2} d\overline{V_N^2} df} = \sqrt{(f_2 - f_1) d\overline{V_N^2}}$$

电阻的噪声为热噪声



$$\overline{dv_R^2} = 4kTRdf$$

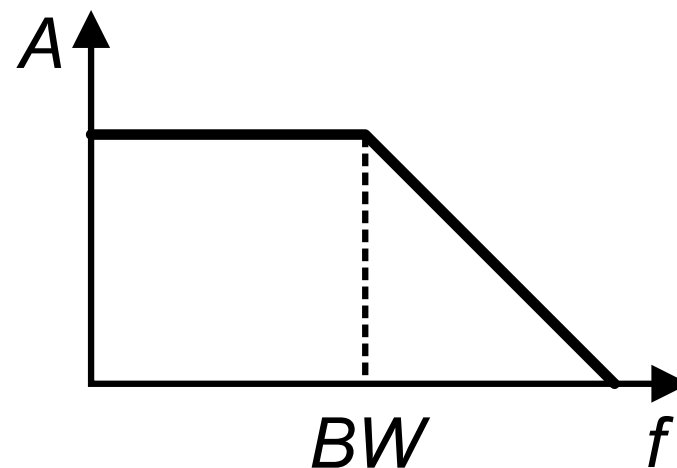
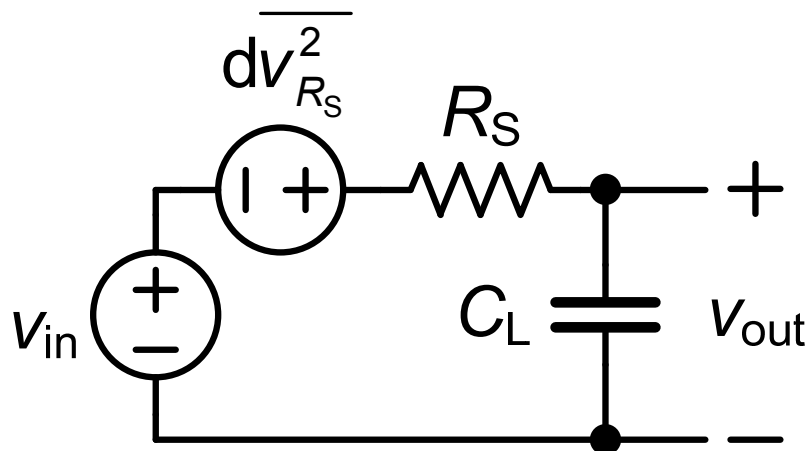
为白噪声，值由 T 决定，与 I_R 无关

当 $R=1\text{ k}\Omega$ ， $T=300\text{ K}(27\text{ C}^\circ)$ 时

$$\sqrt{\overline{dv_R^2}} = 4\text{ n(V}/\sqrt{\text{Hz}})_{\text{RMS}}$$

$$\overline{di_R^2} = \frac{\overline{dv_R^2}}{R^2} = \frac{4kT}{R}df \quad \text{为白噪声}$$

电阻的积分噪声—1

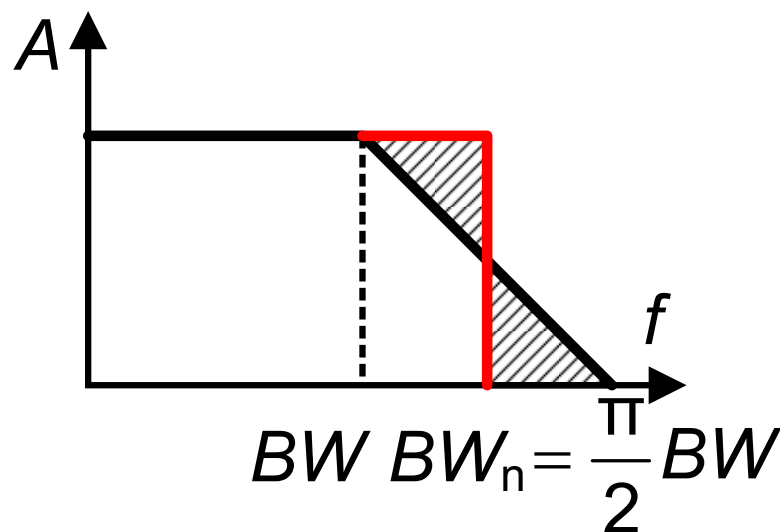


$$\overline{dv_{R_S}^2} = 4kTR_S df$$

$$\overline{v_{R_S}^2} = \int_0^{\infty} \frac{\overline{dv_{R_S}^2}}{1 + (f/BW)^2}$$

$$BW = \frac{1}{2\pi R_S C_L}$$

电阻的积分噪声—2



$$\overline{V_{R_S}^2} = \int_0^{\infty} \frac{dv_{R_S}^2}{1 + (f/BW)^2}$$

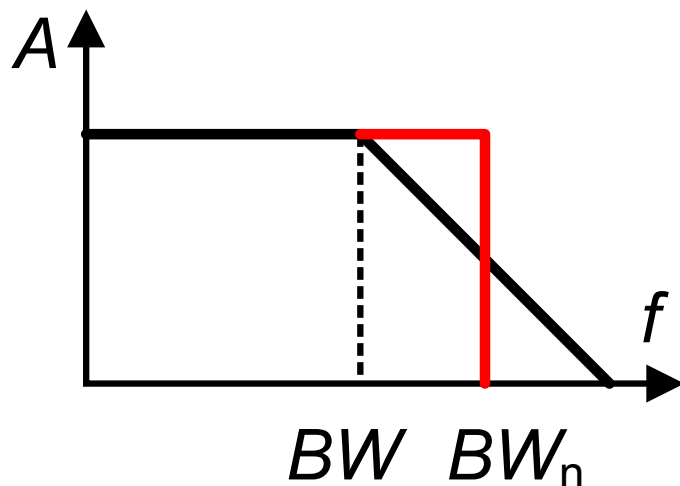
$$\int_0^{\infty} \frac{dx}{1 + x^2} = \frac{\pi}{2}$$

$$\overline{V_{R_S}^2} = 4kTR_S BW \frac{\pi}{2}$$

$$\overline{V_{R_S}^2} = \frac{kT}{C_L}$$

$$C_L = 1 \text{ pF} \quad v_{R_S} = 64.5 \text{ } \mu\text{V}_{\text{RMS}}$$

噪声密度与积分噪声



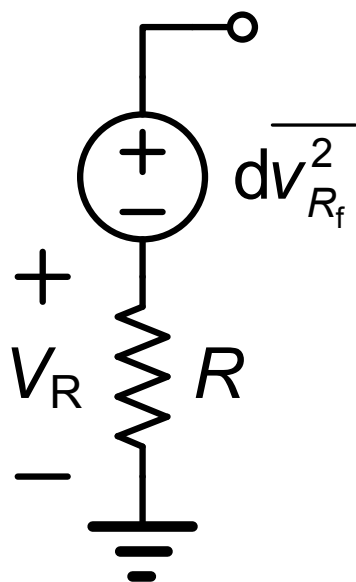
$$d\overline{v_{R_S}^2} = 4kTR_S df$$

$$\overline{v_{R_S}^2} = \int_0^\infty \frac{d\overline{v_{R_S}^2}}{1 + (f/BW)^2} = \frac{kT}{C_L}$$

噪声密度 (V^2/Hz) $\sim R_S$ (或 $1/g_m$)

积分噪声 $V_{\text{RMS}} \sim 1/C_L$

电阻也有1/f 噪声



$$\overline{dv_{R_f}^2} = V_R^2 \frac{KF_R R_{\square}}{A_R} \frac{df}{f} \quad 1/f \text{ 噪声}$$

$$KF_{RSi} \approx 2 \times 10^{-21} \text{ Scm}^2$$

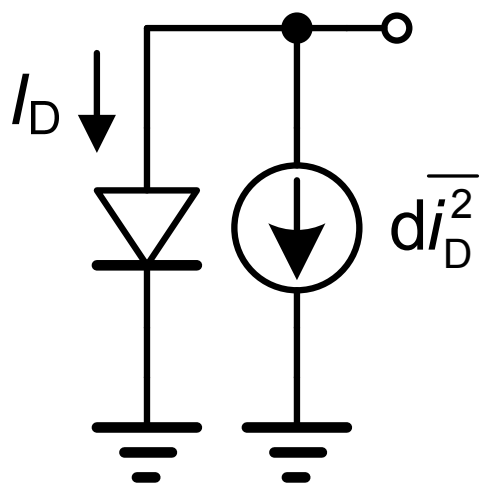
$$KF_{Rpoly} \approx 10KF_{RSi}$$

例如：20个方块，每个 $50 \Omega/\square$ ，构成 $R=1 \text{ k}\Omega$ ，宽为 $1 \mu\text{m}$ ，
 $V_R=0.1 \text{ V}$ ，在 1 Hz 时

$$\sqrt{\overline{dv_{R_f}^2}} = 16 \text{ n(V}/\sqrt{\text{Hz}})_{\text{RMS}}$$

Ref.: Vandamme, ESSDERC '04

二极管的噪声为散射噪声

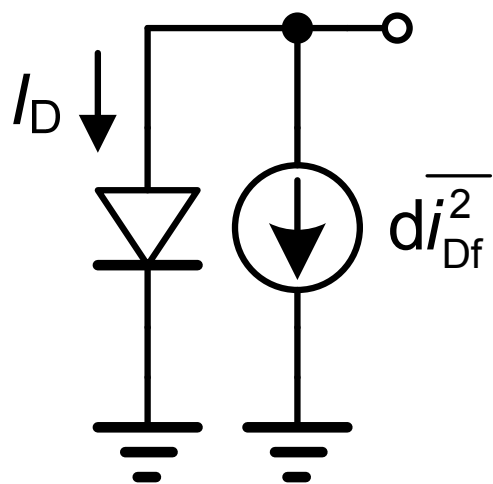


$$\overline{di_D^2} = 2qI_D df \quad q = 1.6 \times 10^{-19} \text{ C}$$

为白噪声，值由 I_D 决定，与 T 无关

$$I_D = 50 \text{ } \mu\text{A} \text{ 时 } \sqrt{\overline{di_D^2}} = 4 \text{ p(A}/\sqrt{\text{Hz}})_{\text{RMS}}$$

二极管也有1/f 噪声



$$\overline{di_{Df}^2} = I_D \frac{KF_D}{A_D} \frac{df}{f}$$

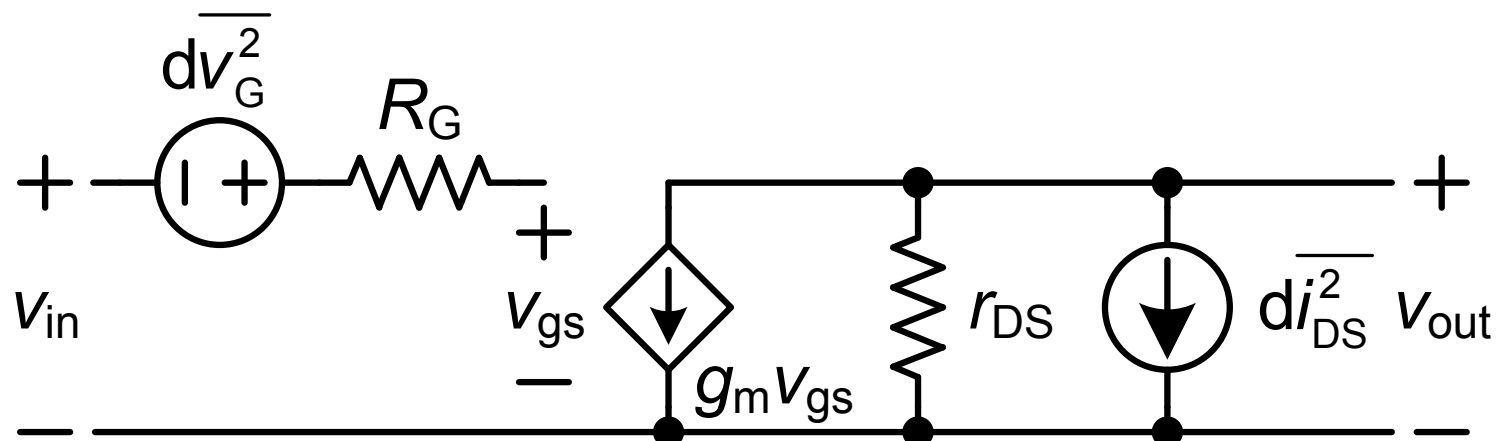
为1/f 噪声

$$KF_D \approx 10^{-21} \text{ Acm}^2$$

例如：二极管 $A_D = 5 \mu\text{m} \times 2 \mu\text{m} = 10 \mu\text{m}^2$, $I_D = 0.1 \text{ mA}$
在1 kHz时

$$\sqrt{\overline{di_{Df}^2}} = 1 \text{ n(A}/\sqrt{\text{Hz}})_{\text{RMS}}$$

MOST的噪声

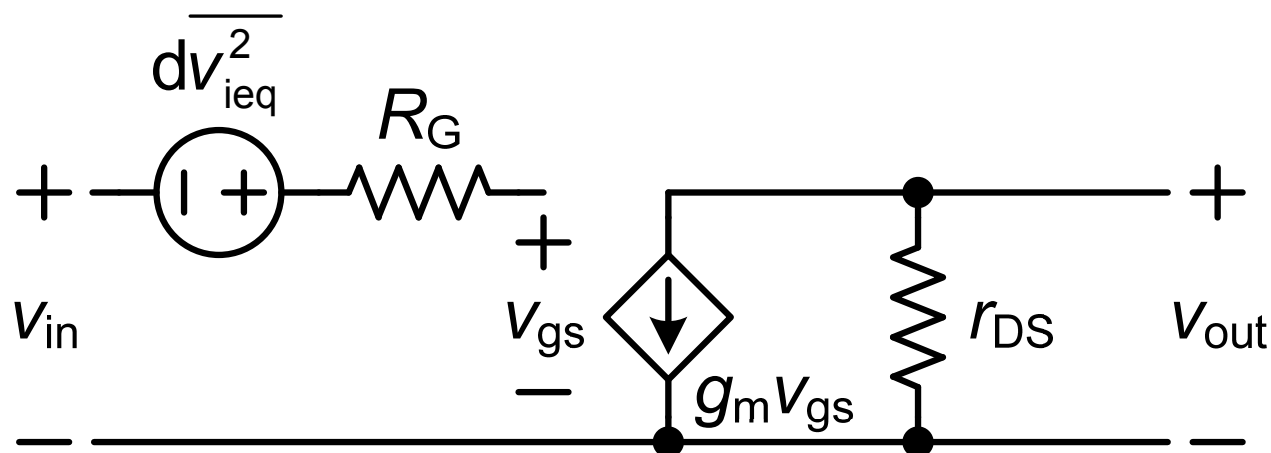


$$\overline{dv_G^2} = 4kTR_G df$$

$$\overline{di_{DS}^2} = \frac{4kT}{R_{CH}} df = 4kT \frac{2}{3} g_m df$$

Ref.: Van der Ziel, Prentice Hall 1954, Wiley 1986.

MOST: 等效输入噪声—白噪声

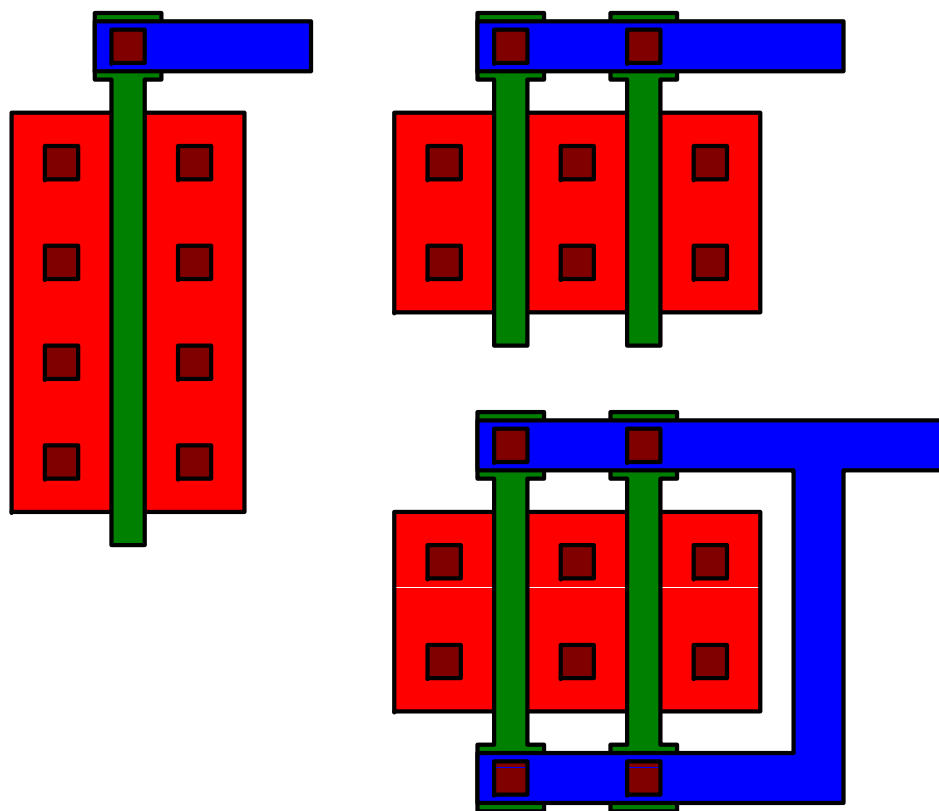


$$\overline{dv_{ieq}^2} = 4kT(R_{eff})df \quad R_{eff} = \frac{2/3}{g_m} + R_G$$

$$\text{高频时: } \overline{di_{ieq}^2} = (C_{GS}\omega)^2 \overline{dv_{ieq}^2} \quad \text{与 } \overline{dv_{ieq}^2} \text{ 相关}$$

MOST的栅极串联电阻 R_G

双端连接的多插指结构减小串联电阻



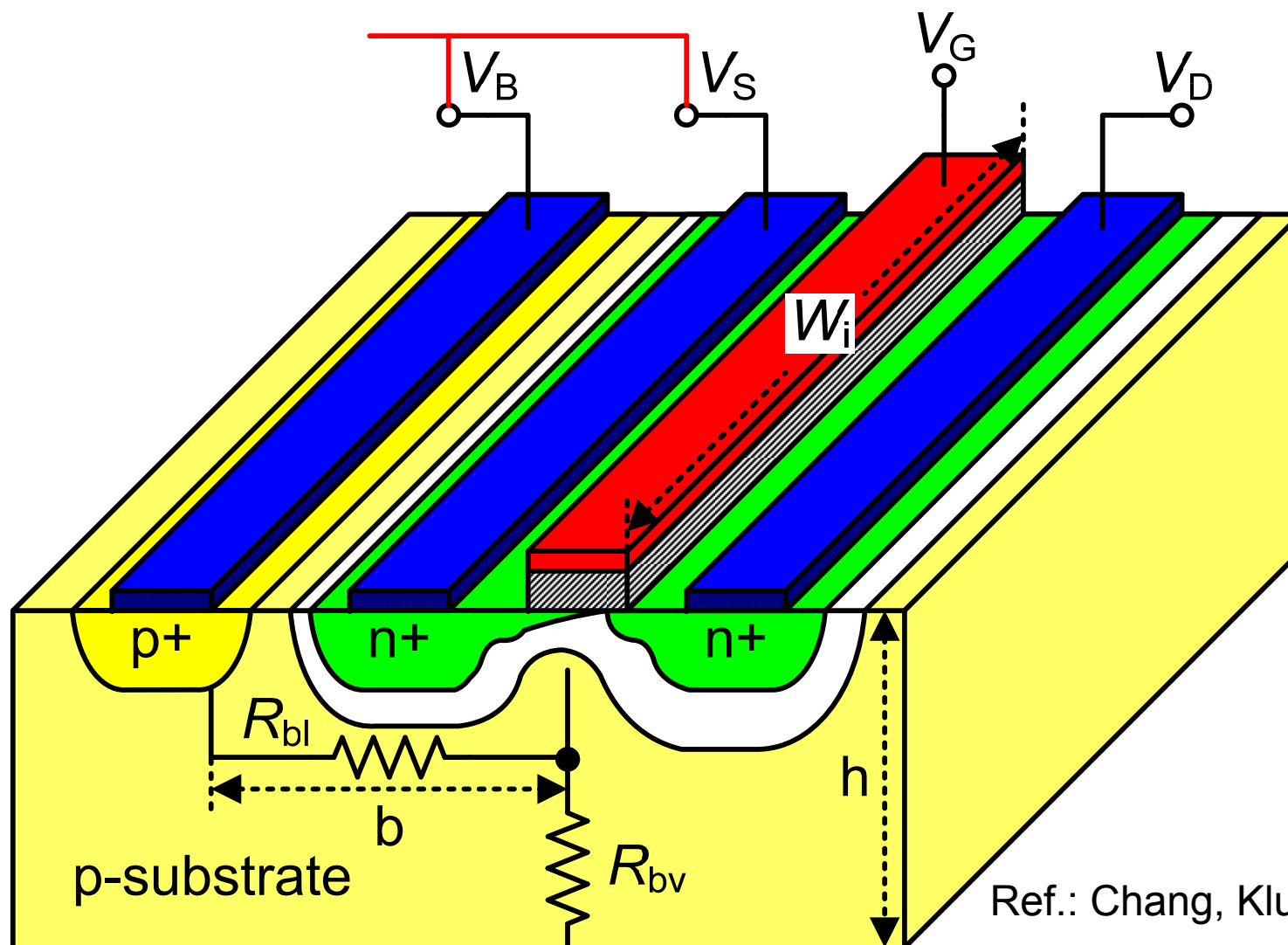
单端连接

$$R_G = \frac{1}{3n^2} \frac{R_{sq} W}{L}$$

两端连接

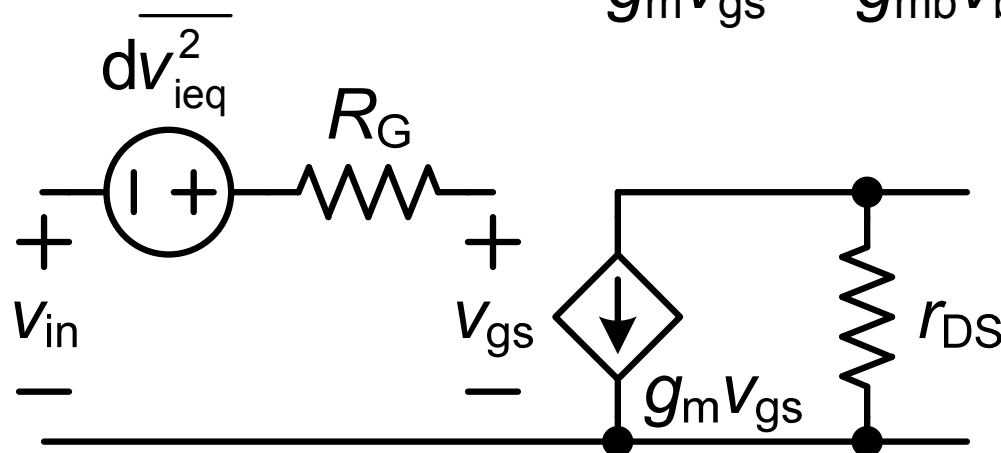
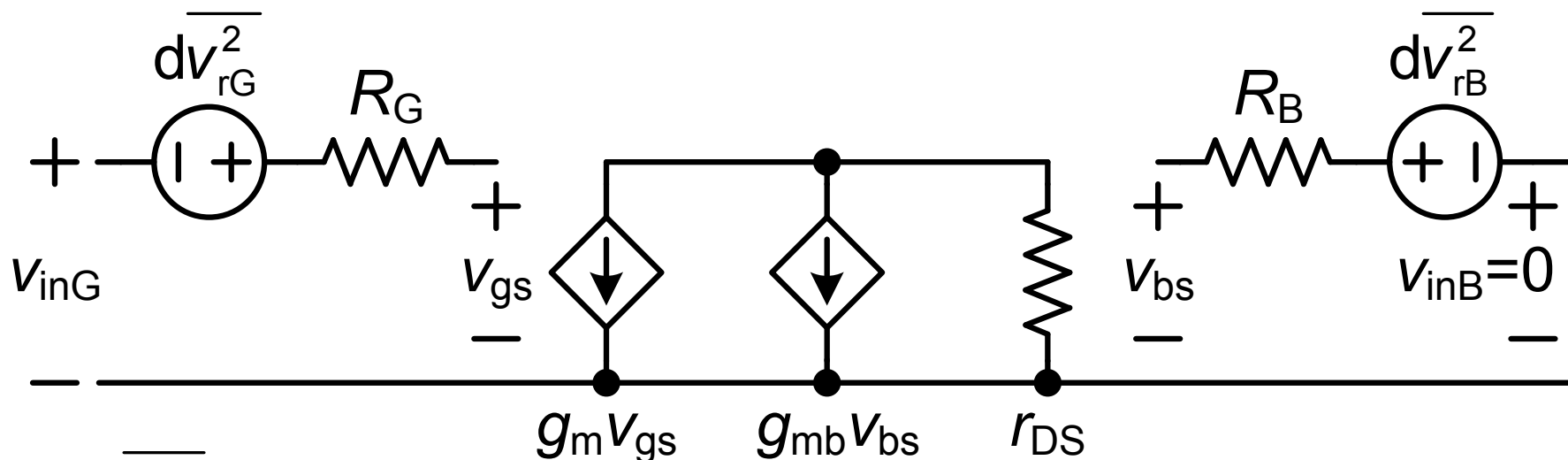
$$R_G = \frac{1}{12n^2} \frac{R_{sq} W}{L}$$

MOST的衬底电阻 R_B



Ref.: Chang, Kluwer 1991

衬底电阻产生的噪声

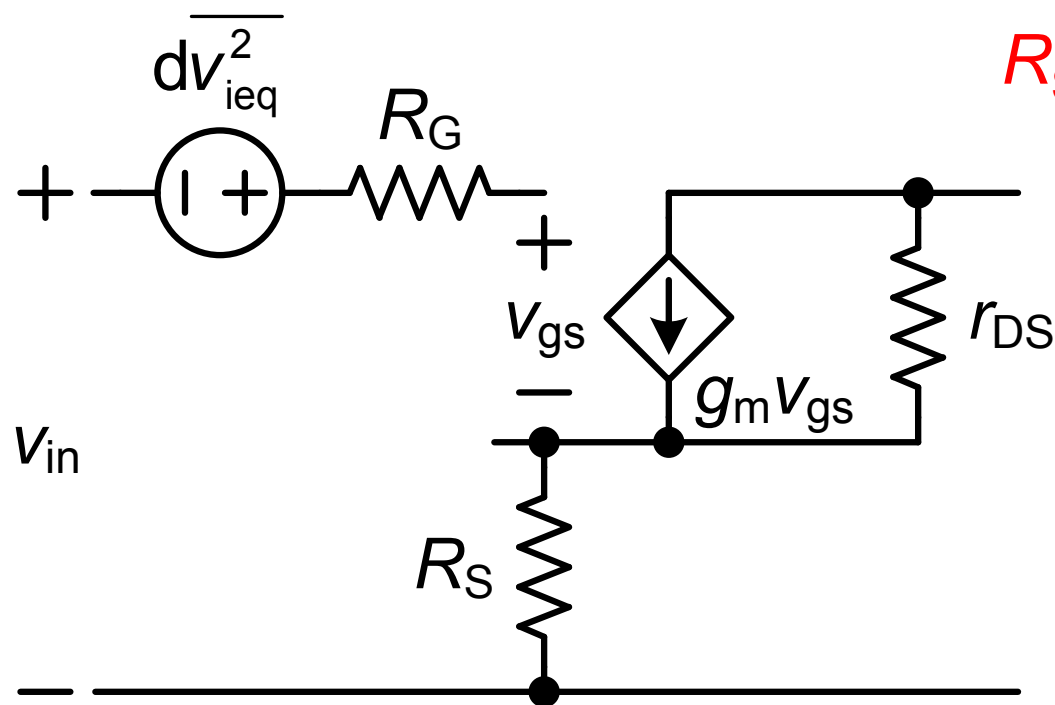


$$\overline{dv_{ieq}^2} = 4kT(R_{eff})df$$

$$R_{eff} = \frac{2/3}{g_m} + R_G + R_B(n-1)^2$$

$$n-1 = C_D/C_{ox} = g_{mb}/g_m$$

源极电阻产生的噪声

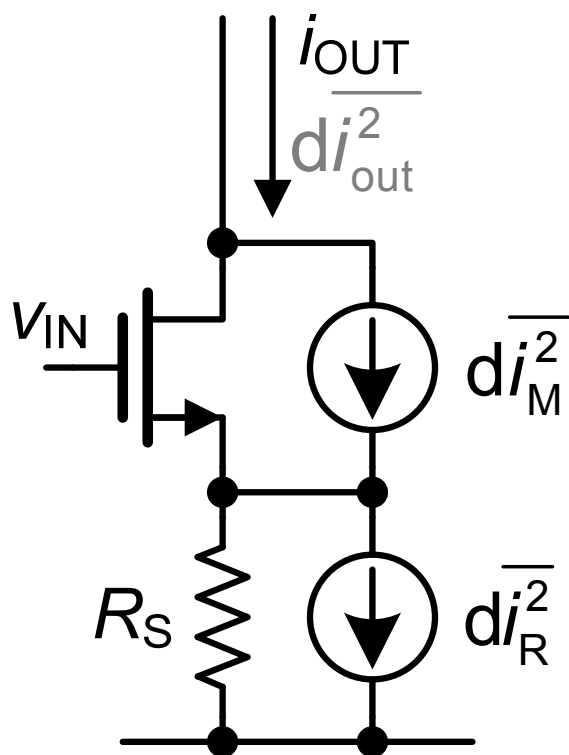


R_S 的噪声 $\Leftrightarrow R_G$ 的噪声

$$\overline{dv_{ieq}^2} = 4kT(R_{eff})df$$

$$R_{eff} = \frac{2/3}{g_m} + R_S + R_G + R_B(n-1)^2$$

源极电阻 R_S 产生的噪声



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

$$\overline{di_M^2} = 4kT \frac{2}{3} g_m df \quad \overline{di_{outM}^2} = \frac{\overline{di_M^2}}{(1 + g_m R_S)^2}$$

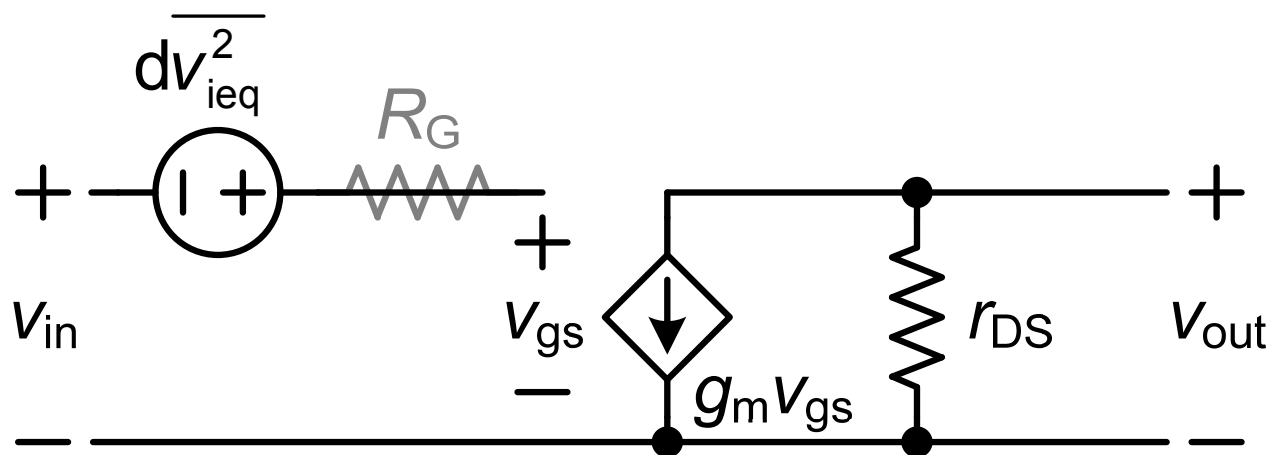
$$\overline{di_R^2} = \frac{4kT}{R} df \quad \overline{di_{outR}^2} = \left(\frac{g_m R_S}{1 + g_m R_S} \right)^2 \overline{di_R^2}$$

$$\overline{di_{out}^2} = G_m^2 4kT R_S \left(\frac{2/3}{g_m R_S} + 1 \right) df$$

$$\overline{dv_{ieq}^2} = 4kT R_S \left(\frac{2/3}{g_m R_S} + 1 \right) df$$

$$R_{eff} = \frac{2/3}{g_m} + R_S$$

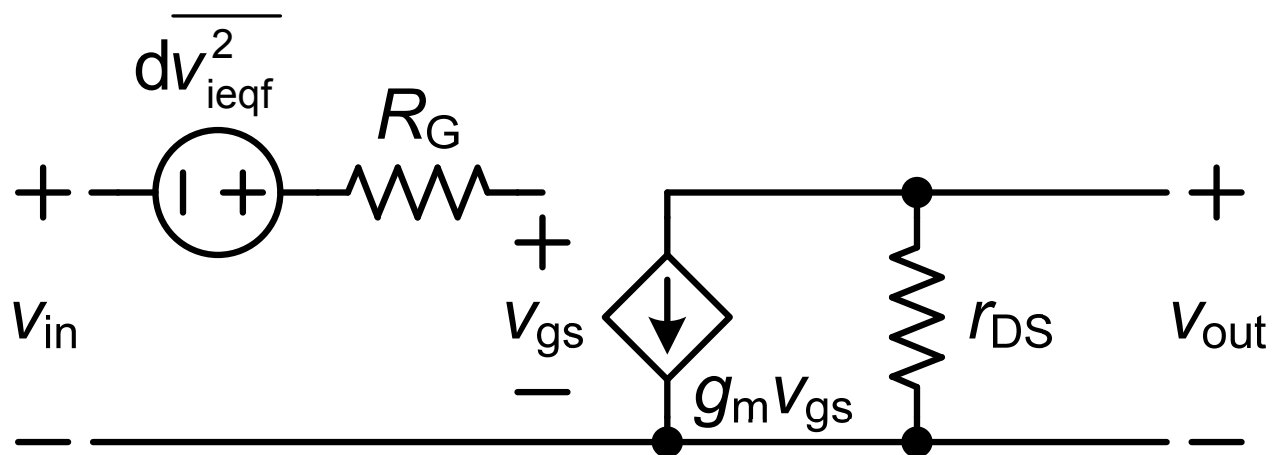
MOST: 等效输入噪声—练习



$$\overline{dV_{ieq}^2} \approx 4kT \left(\frac{2/3}{g_m} \right) df$$

当 $V_{GS} - V_T = 0.2 \text{ V}$, $I_{DS} = 65 \text{ } \mu\text{A}$ 时, 求 $\overline{dV_{ieq}^2}$

MOST: 等效输入噪声— $1/f$ 噪声



$$\overline{dv_{ieqf}^2} = \frac{KF_F}{WLC_{ox}^2} \frac{df}{f}$$

$$\text{pMOST } KF_F \approx 10^{-32} \text{ C}^2/\text{cm}^2$$

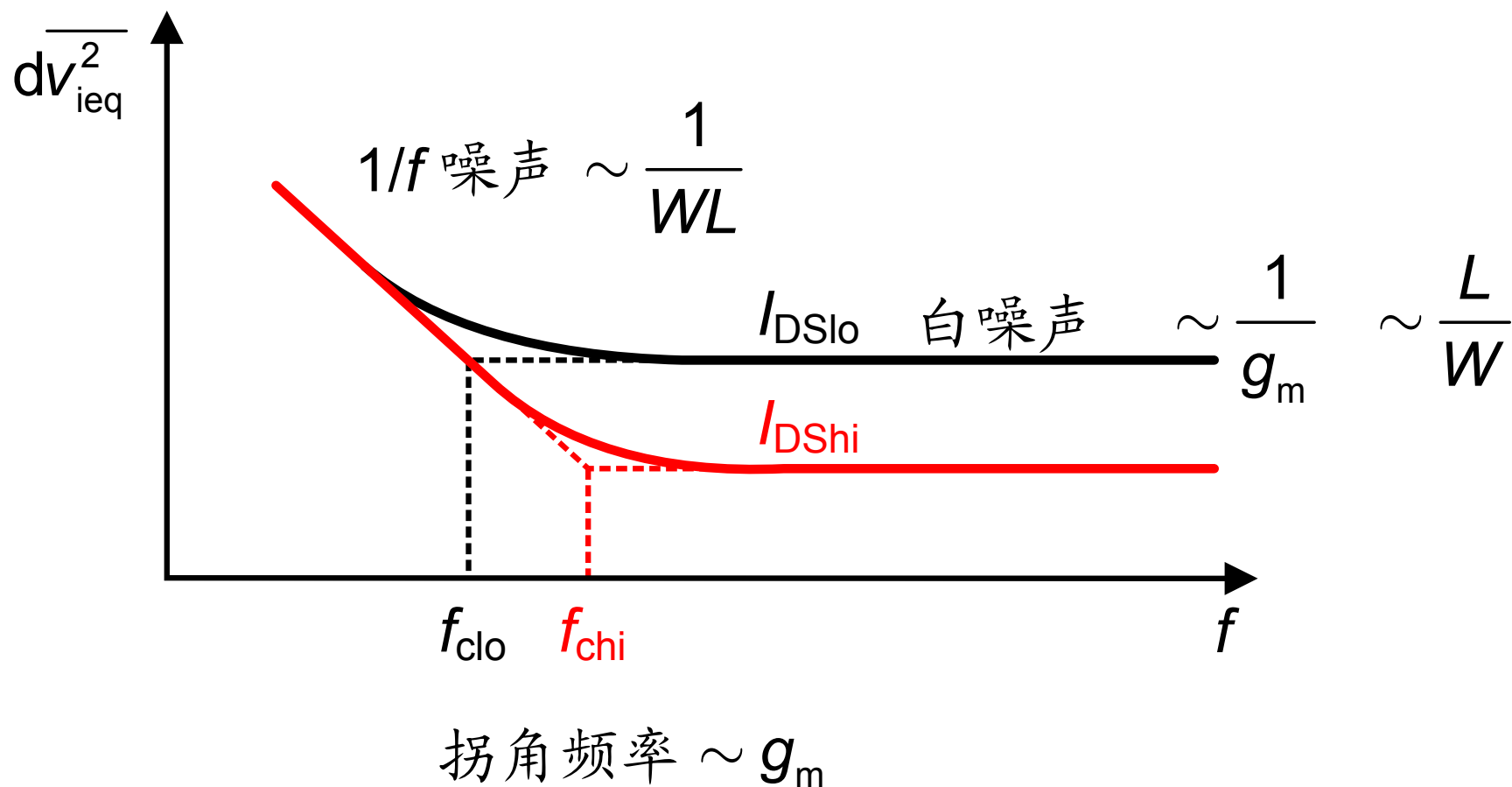
$$\text{nMOST } KF_F \approx 4 \times 10^{-31} \text{ C}^2/\text{cm}^2$$

$$\text{pJFET } KF_F \approx 10^{-33} \text{ C}^2/\text{cm}^2$$

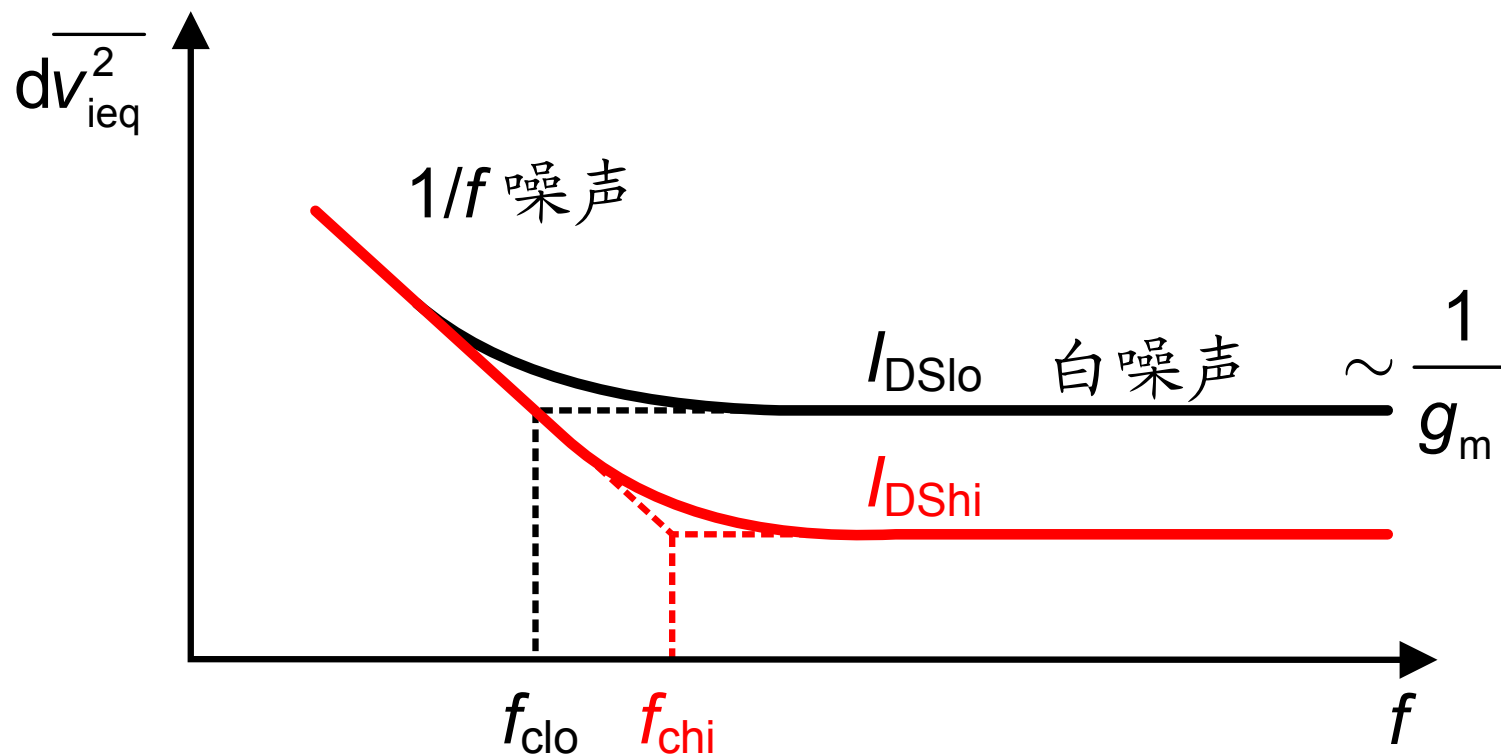
W 和 L 的单位为cm，

C_{ox} 的单位为F/cm²

电流与噪声：拐角频率

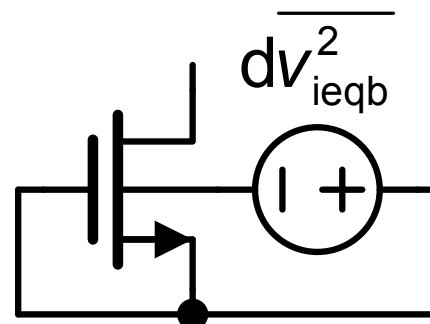
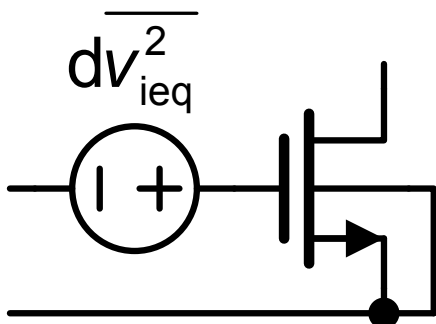


电流与噪声：练习，求 f_c



练习：当 $I_{DS} = 65 \mu A$ 、 $K'_n = 60 \mu A/V^2$ 、 $L = 1 \mu m$ (0.35 μm 工艺) 时，求 f_c ？

从衬底看到的噪声



$$n - 1 = C_D / C_{ox} = g_{mb} / g_m$$

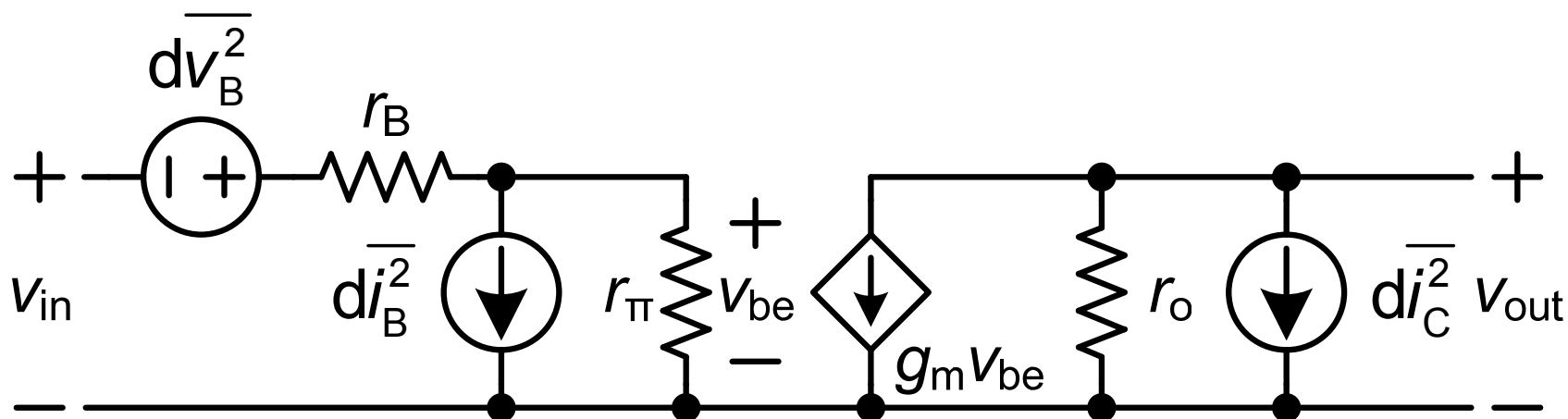
$$\overline{dv_{ieq}^2} = 4kT \frac{2/3}{g_m} df$$

$$\overline{dv_{ieqb}^2} = 4kT \frac{2g_m}{3g_{mb}^2} df$$

$$\overline{dv_{ieqf}^2} = \frac{KF_F}{WLC_{ox}^2} \frac{df}{f}$$

$$\overline{dv_{ieqfb}^2} = \frac{KF_F}{WLC_{ox}^2} \frac{g_m^2}{g_{mb}^2} \frac{df}{f}$$

三极管的噪声



$$\overline{dv_B^2} = 4kTr_B df$$

$$\overline{di_B^2} = 2qI_B df$$

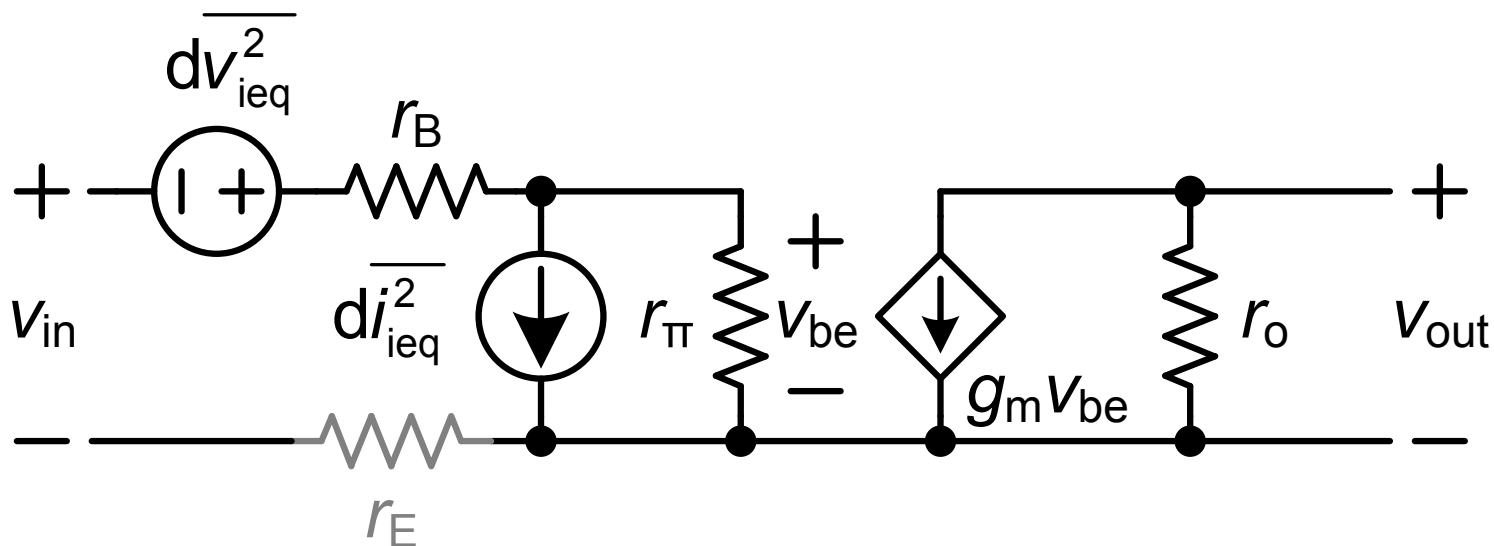
$$\overline{di_C^2} = 2qI_C df$$

$$\overline{dv_{Bf}^2} = \frac{KF_B I_B}{A_{EB}} \frac{df}{f}$$

$$KF_B \approx 10^{-21} \text{ Acm}^2$$

Ref.: Van der Ziel (Prentice Hall 1954)

三极管：等效输入噪声



$$\overline{dv_{ieq}^2} = 4kT(R_{eff})df \quad R_{eff} = \frac{1/2}{g_m} + r_B + r_E$$

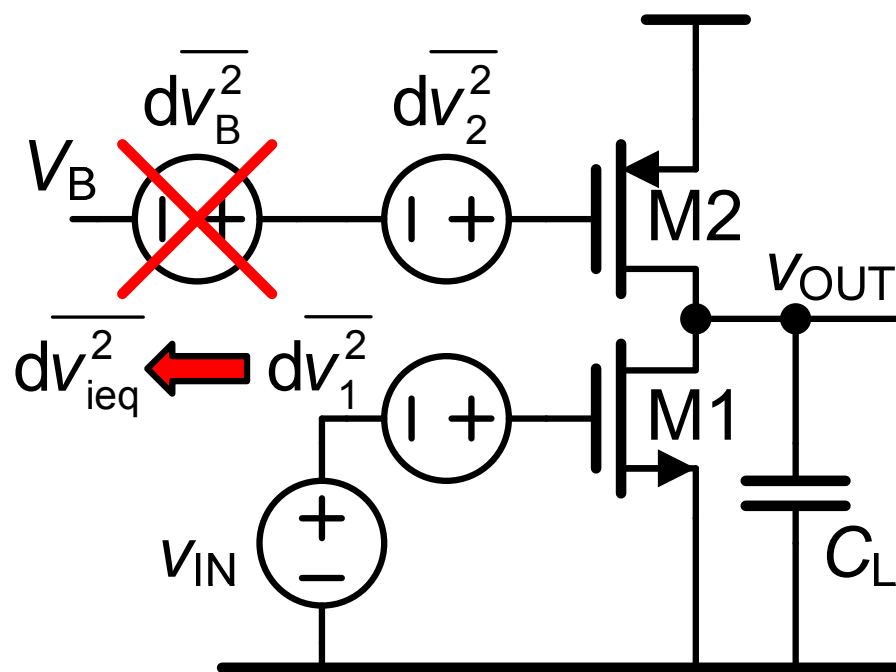
$$\overline{di_{ieq}^2} = \overline{di_B^2} = 2qI_B df$$

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

接有源负载的放大器的噪声



如果忽略 $\overline{dv_B^2}$

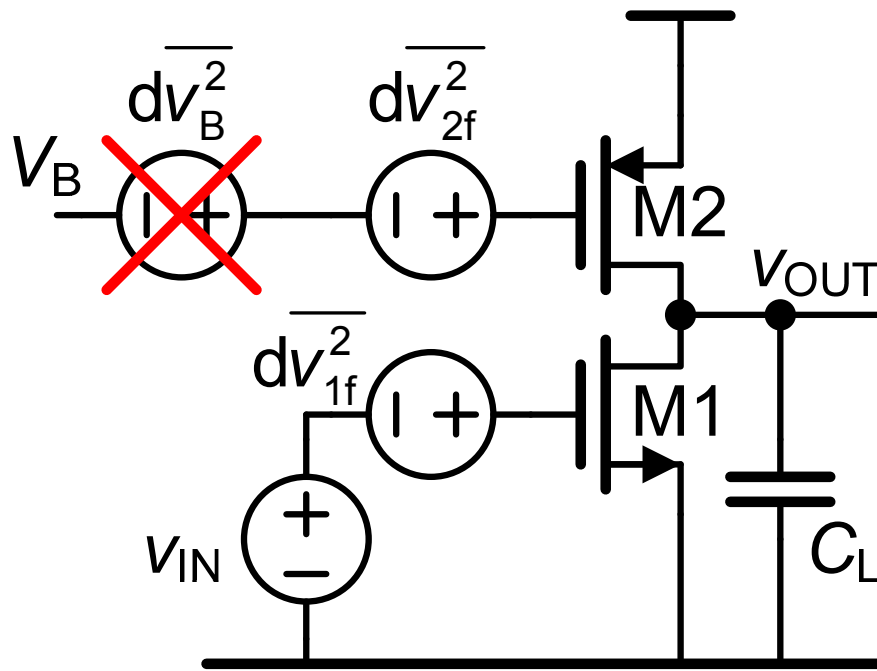
$$\overline{di_{out}^2} = g_{m1}^2 \overline{dv_1^2} + g_{m2}^2 \overline{dv_2^2}$$

$$\overline{dv_{ieq}^2} = \overline{dv_1^2} + \overline{dv_2^2} \left(\frac{g_{m2}}{g_{m1}} \right)^2$$

$$\overline{dv_{ieq}^2} = \overline{dv_1^2} \left(1 + \frac{g_{m2}}{g_{m1}} \right)$$

小 g_{m2} : $(W/L)_2 \downarrow$
 $(V_{GS} - V_T)_2 \uparrow$

接有源负载的放大器的 $1/f$ 噪声



如果忽略 $\overline{dv_B^2}$

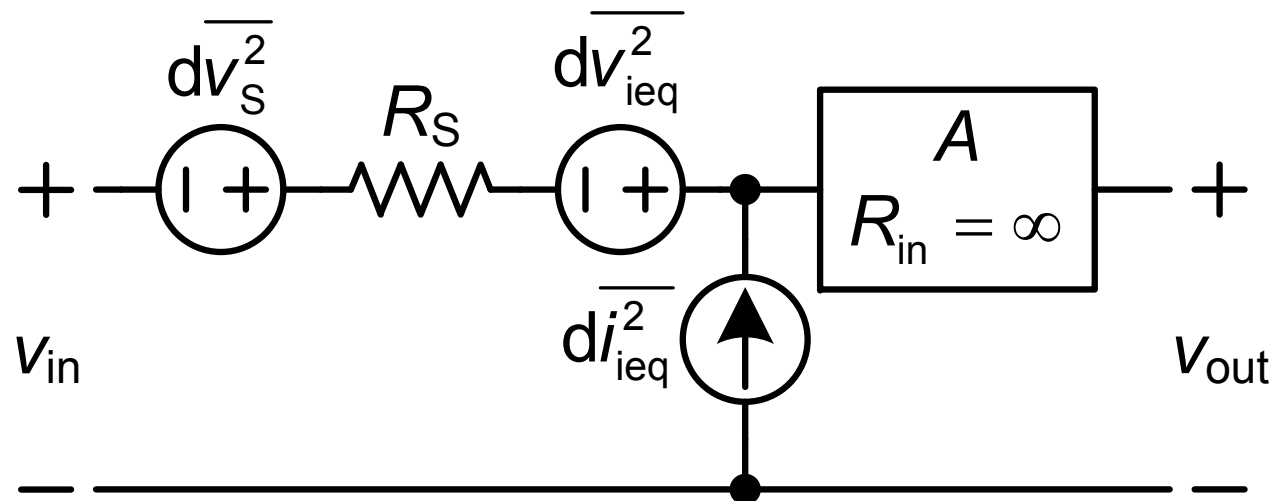
$$\overline{dv_{if}^2} = \overline{dv_{1f}^2} + \overline{dv_{2f}^2} \left(\frac{g_{m2}}{g_{m1}} \right)^2$$

$$\overline{dv_{if}^2} = \overline{dv_{1f}^2} \left[1 + \left(\frac{g_{m2}}{g_{m1}} \right)^2 \left(\frac{\overline{dv_{2f}}}{\overline{dv_{1f}}} \right)^2 \right]$$

$$\overline{dv_{if}^2} = \overline{dv_{1f}^2} \left[1 + \frac{KF_2}{KF_1} \frac{K_2'}{K_1'} \left(\frac{L_1}{L_2} \right)^2 \right]$$

$\overline{dv_{if}^2}$ 最小: $L_{1opt} = L_2 \sqrt{\frac{KF_1}{KF_2} \frac{K_1'}{K_2'}} \approx 10L_2$ 那么 $\overline{dv_{if}^2} = 2\overline{dv_{1f}^2}$

放大器的噪声系数



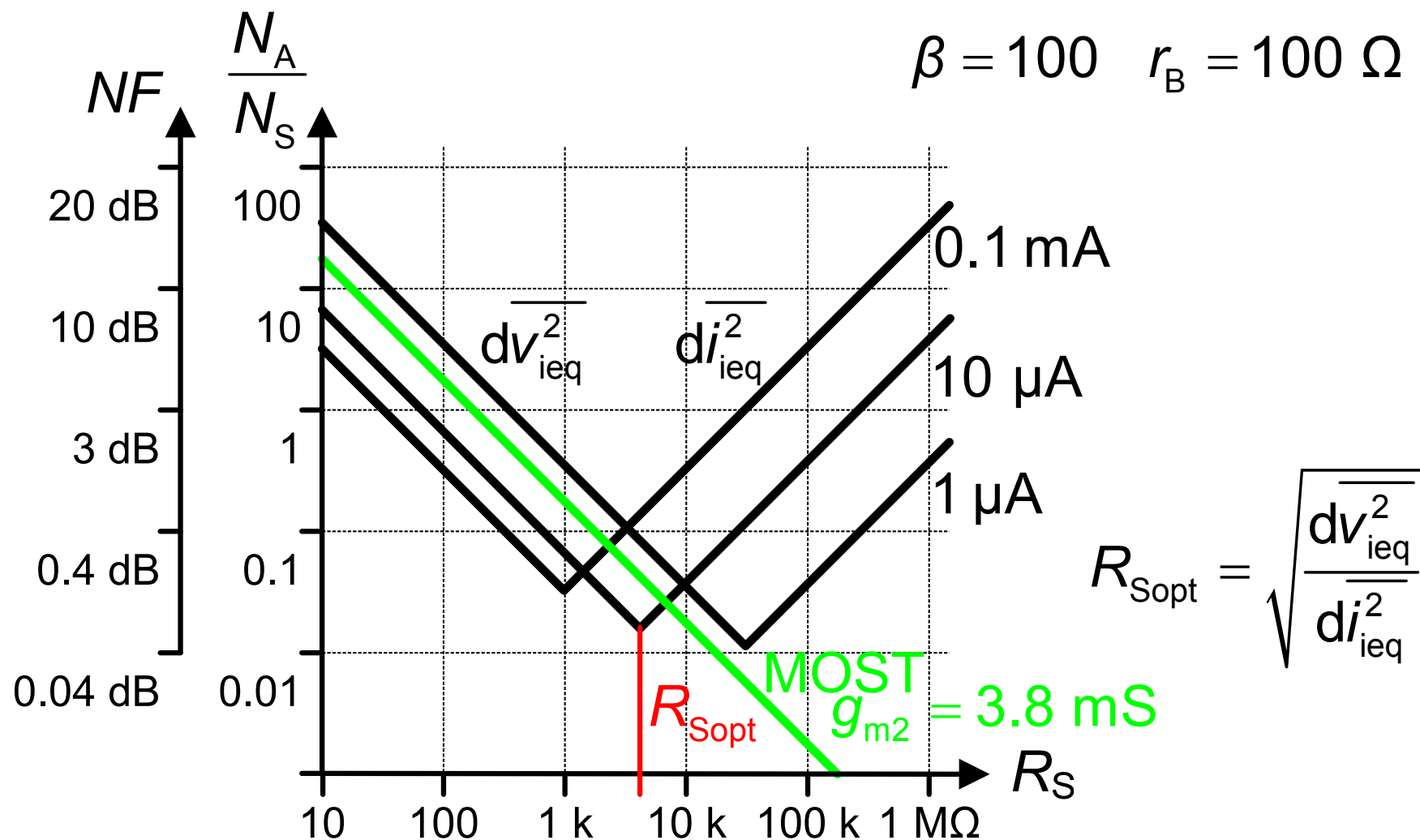
$$NF = \frac{N_S + N_A}{N_S} = 1 + \frac{N_A}{N_S}$$

$$NF = 1 + \frac{\overline{dv_{ieq}^2} + R_S^2 \overline{di_{ieq}^2}}{4kTR_S df}$$

电压驱动 $NF \sim \frac{1}{R_S}$

电流驱动 $NF \sim R_S$

电阻噪声匹配

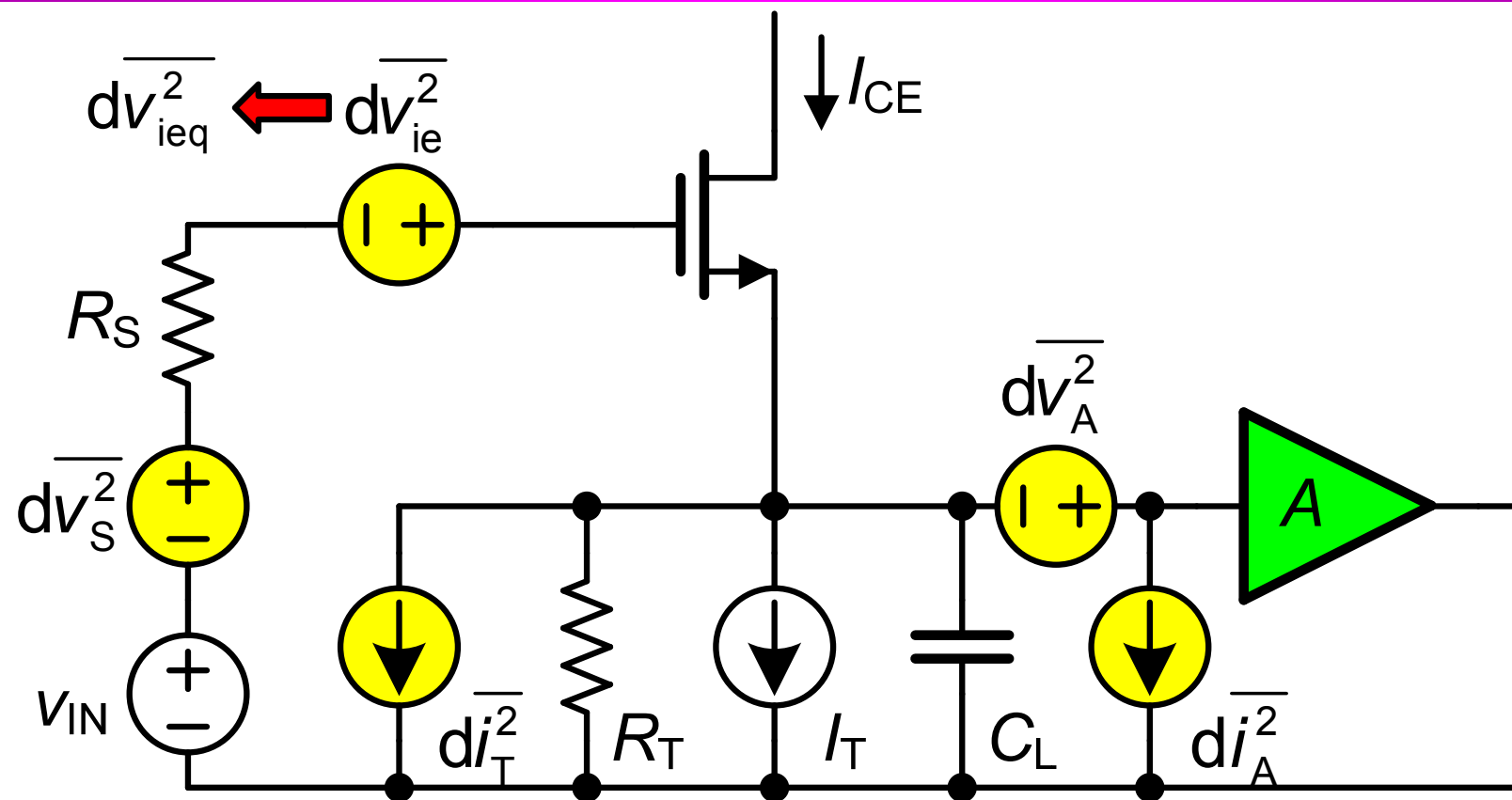


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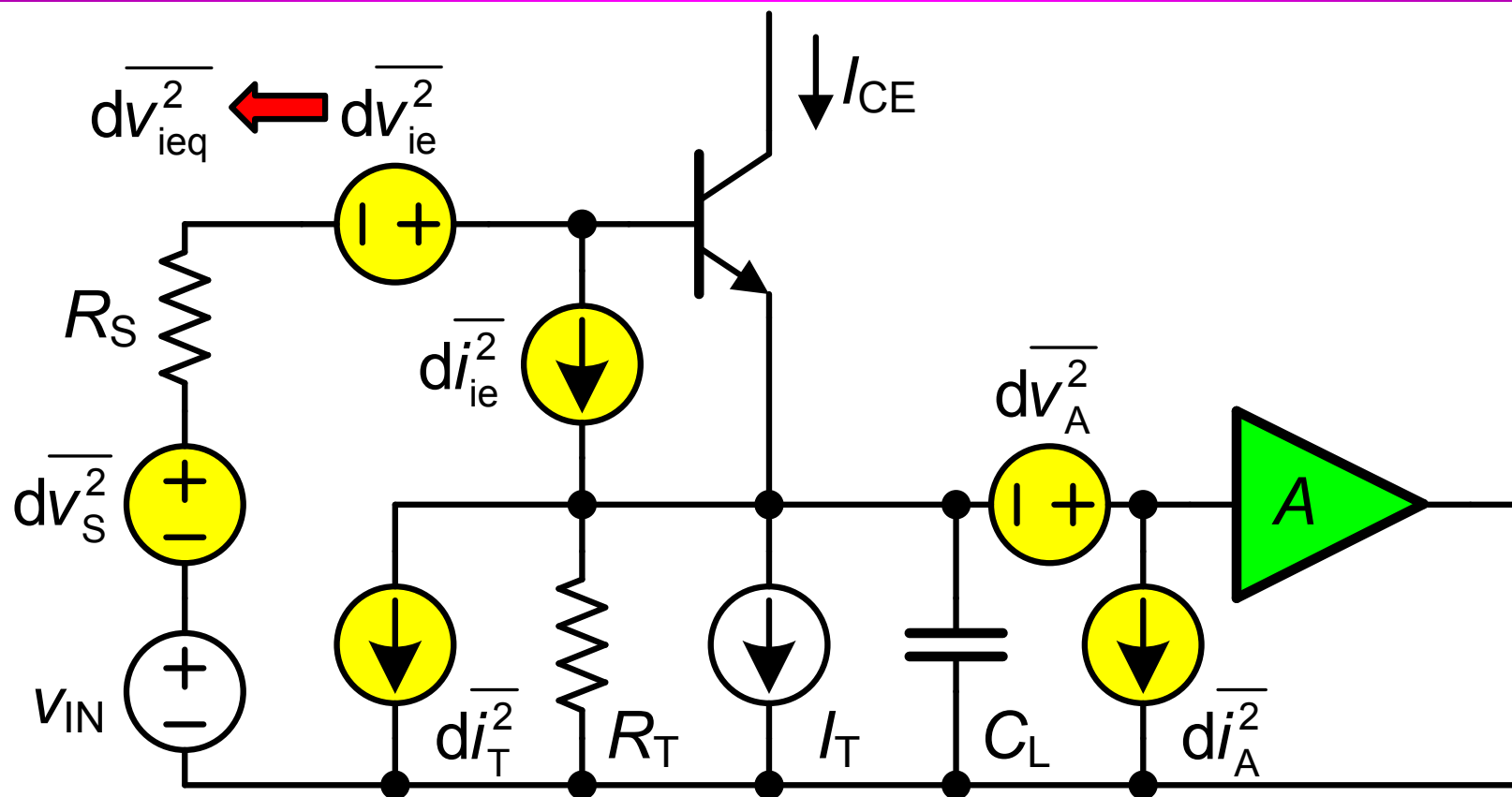
Ref.: W. Sansen : Analog Design Essentials, Springer 2006

源极跟随器的噪声



$$\overline{dv_{ieq}^2} = \overline{dv_{ie}^2} + \overline{dv_A^2} + \left(\overline{di_T^2} + \overline{di_A^2} \right) \left(\frac{R_T}{1 + g_m R_T} \right)^2$$

射极跟随器的噪声



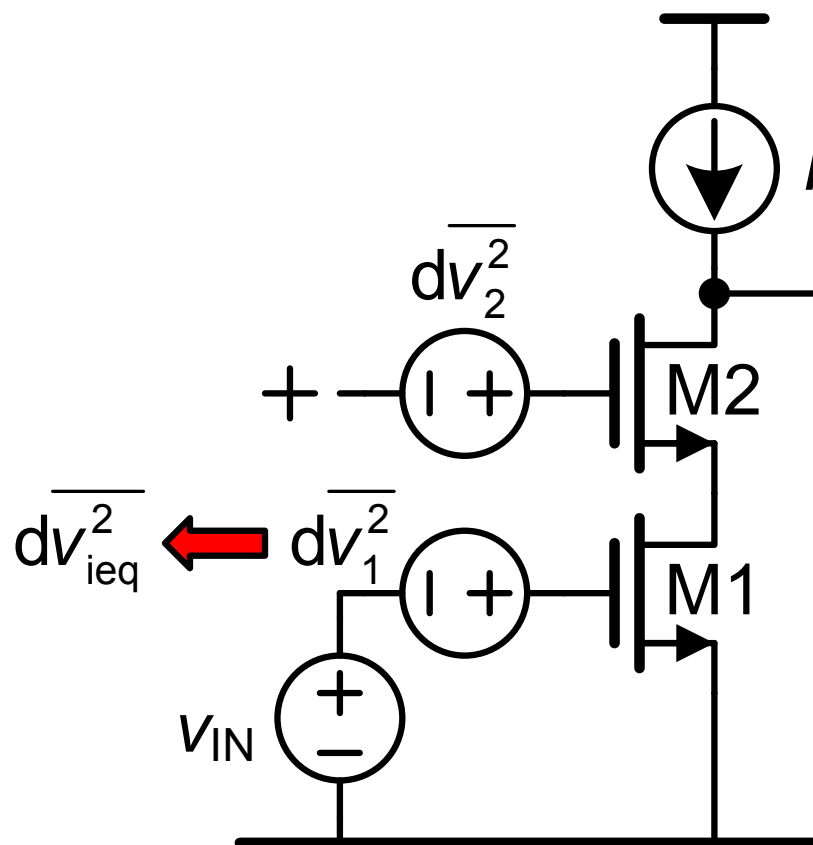
$$\overline{dv_{ieq}^2} = \overline{dv_{ie}^2} + \overline{dv_A^2} + \left(R_S - \frac{1}{g_m}\right)^2 \overline{di_{ie}^2} + \left(\overline{di_T^2} + \overline{di_A^2}\right) \left(\frac{R_T}{1 + g_m R_T}\right)^2$$

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共栅放大器的噪声

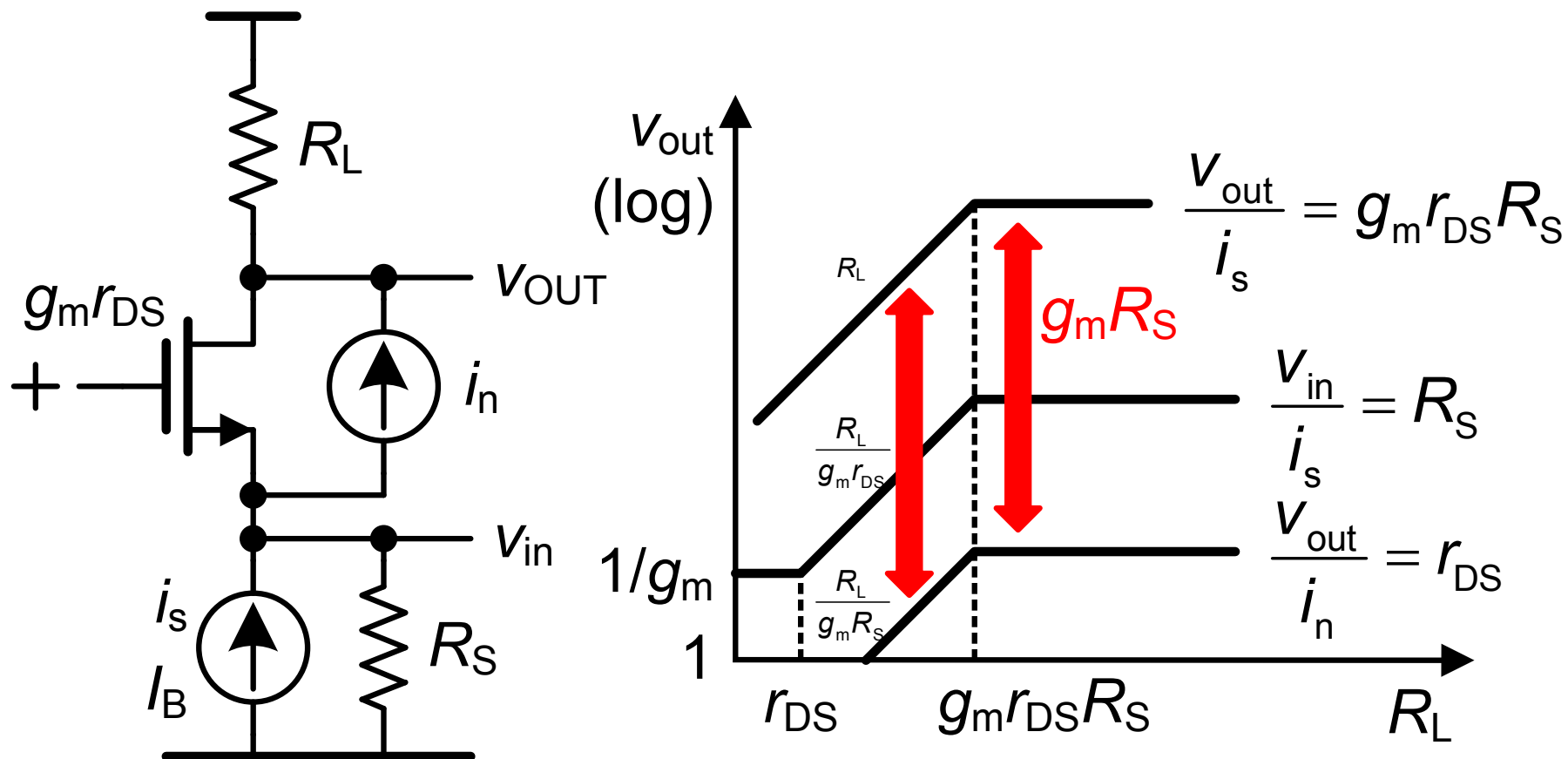


$$g_{m2}r_{DS1} \gg 1$$

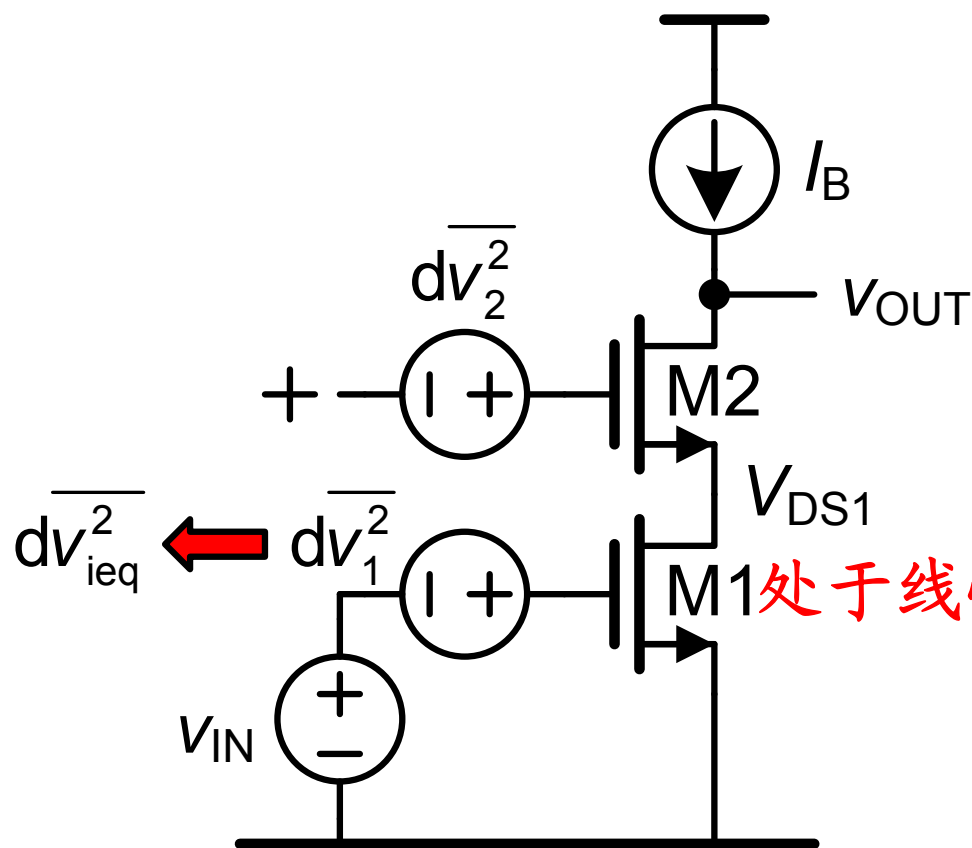
$$\begin{aligned} \overline{dv_{ieq,M2}^2} &= \overline{dv_2^2} \left(\frac{g_{m2}}{1 + g_{m2}r_{DS1}} \right)^2 \frac{1}{g_{m1}^2} \\ &\approx \overline{dv_2^2} \frac{1}{(g_{m1}r_{DS1})^2} \end{aligned}$$

$$\overline{dv_{ieq}^2} = \overline{dv_1^2} + \overline{dv_2^2} \frac{1}{(g_{m1}r_{DS1})^2} \approx \overline{dv_1^2}$$

共栅放大器的输入参考噪声



接线性MOST的共栅放大器的噪声



$$\alpha_1 = \frac{V_{DS1}}{V_{GS1} - V_T} \quad \alpha_1 < 0.5$$

$$I_{DS1} = \beta_1 V_{DS1} (V_{GS1} - V_T)$$

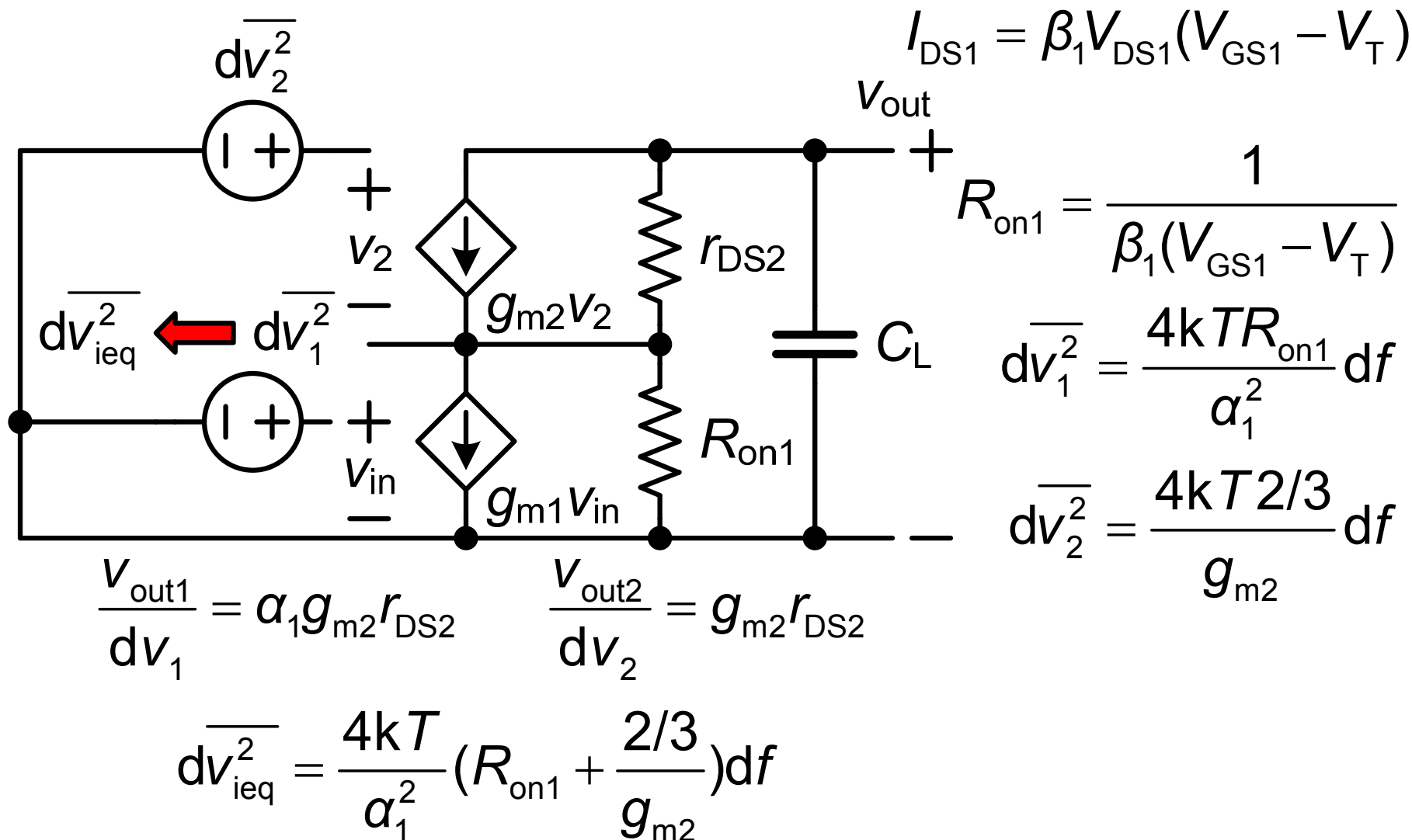
$$R_{on1} = \frac{1}{\beta_1 (V_{GS1} - V_T)}$$

$$A_V = \alpha_1 g_{m2} r_{DS2}$$

$$\overline{dv_{ieq}^2} = \frac{4kT}{\alpha_1^2} \left(R_{on1} + \frac{2/3}{g_{m2}} \right) df$$

处于线性区

共栅放大器的小信号模型

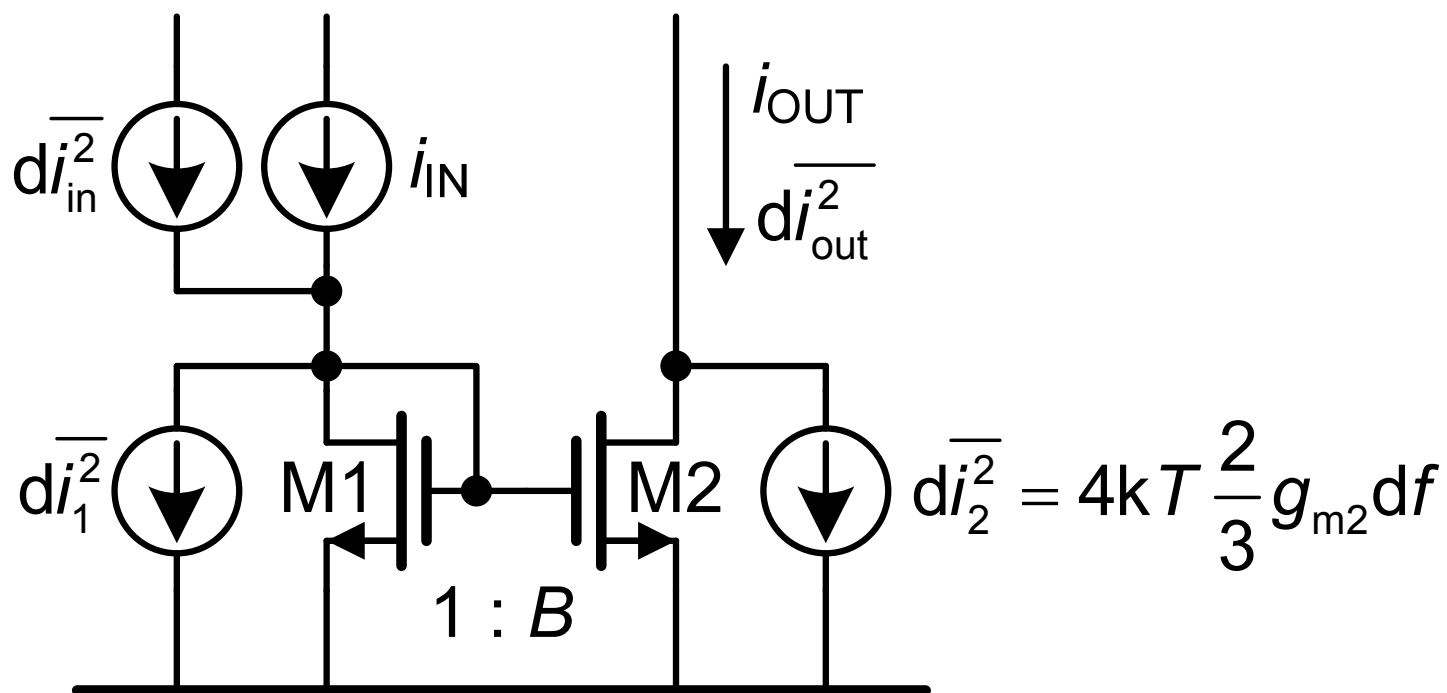


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Ref.: W. Sansen : Analog Design Essentials, Springer 2006

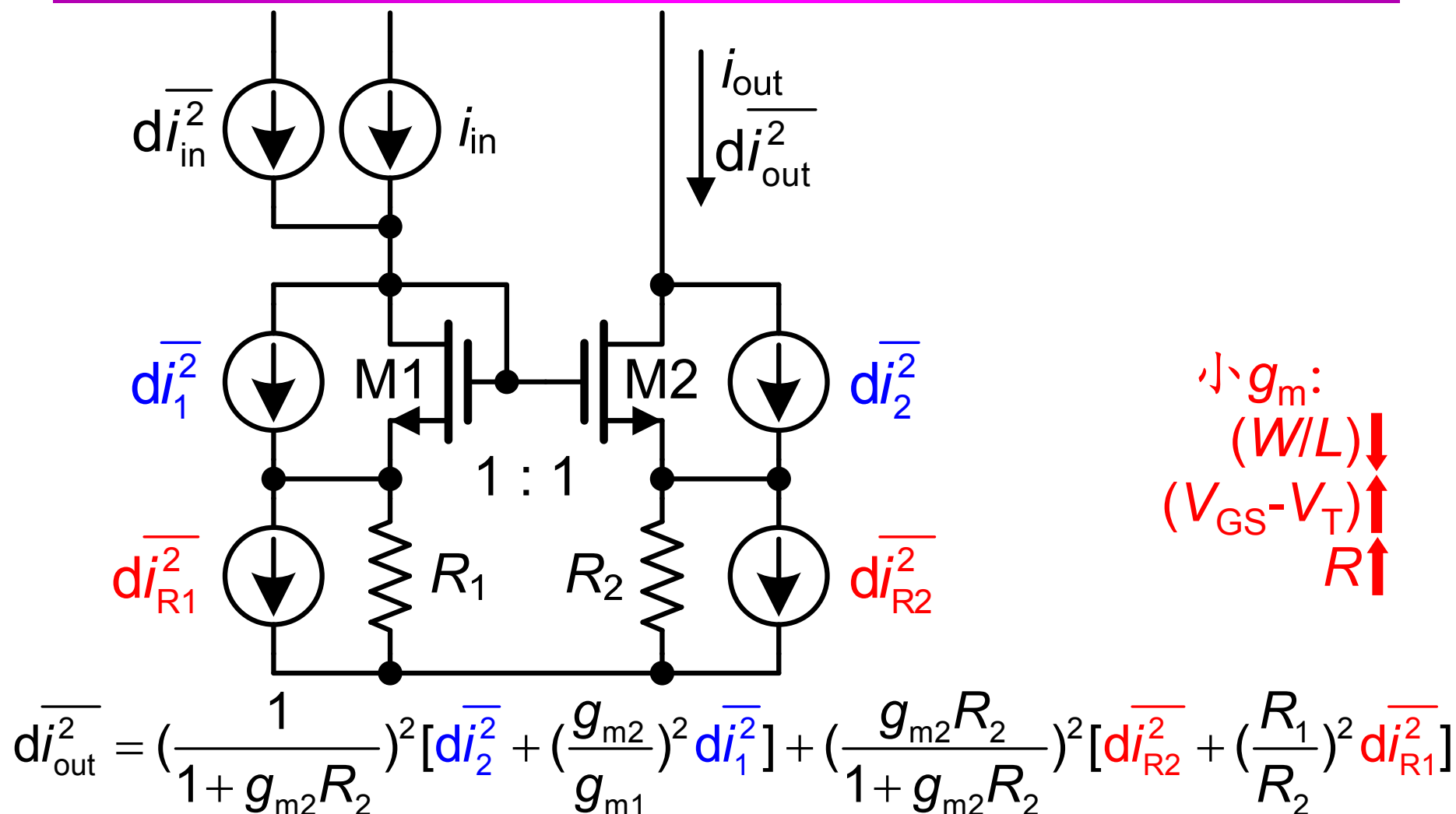
电流镜的噪声



$$di_{out}^2 = di_2^2 + B^2(di_{in}^2 + di_1^2)$$

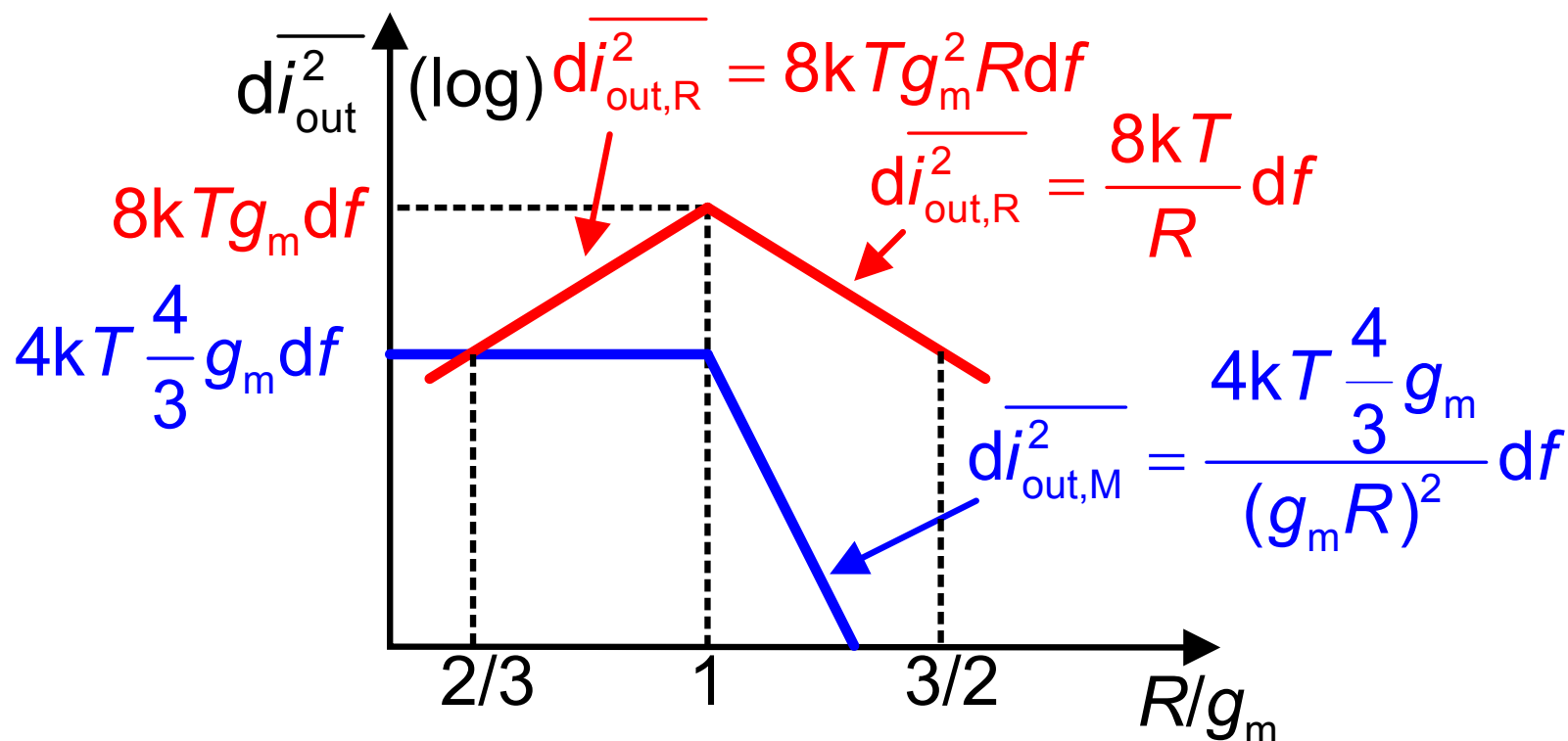
小 g_m :
 $(W/L) \downarrow$
 $(V_{GS} - V_T) \uparrow$

源极接串联电阻的电流镜的噪声—1



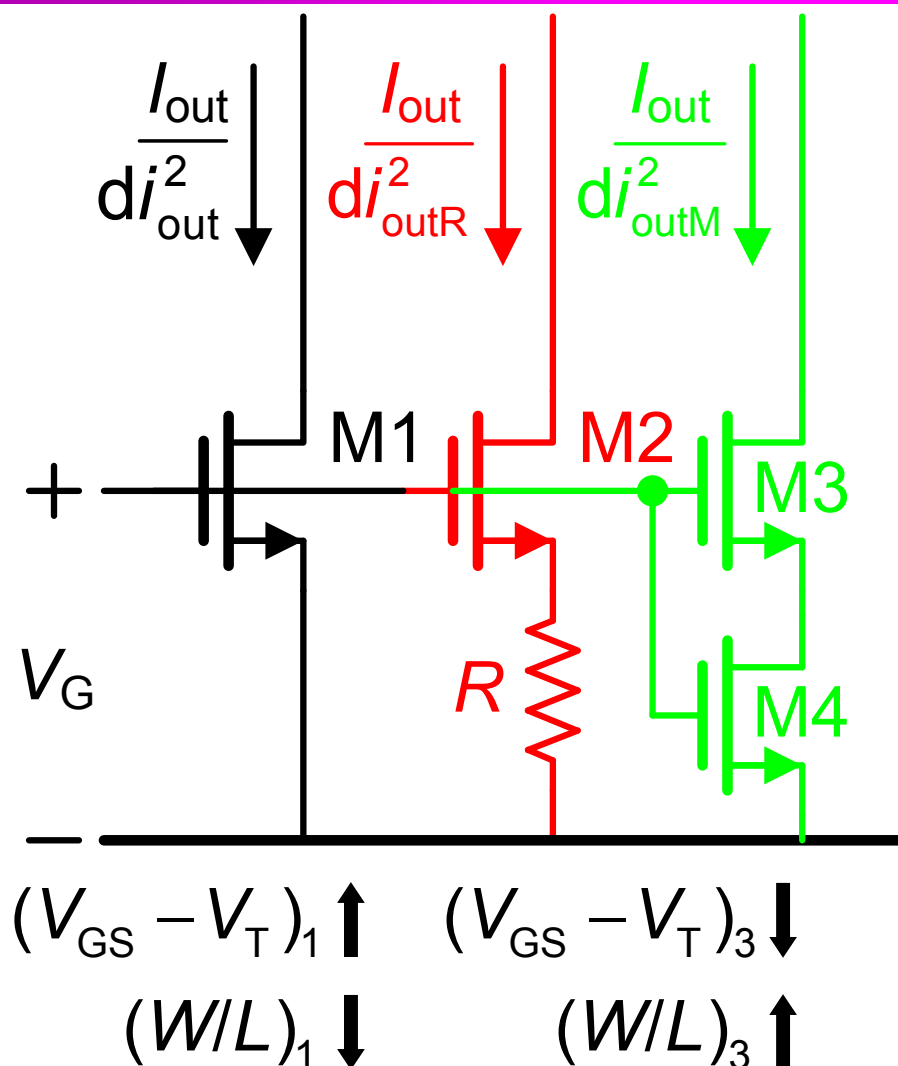
源极接串联电阻的电流镜的噪声—2

$$\left. \begin{array}{l} g_{m1} = g_{m2} = g_m \\ R_1 = R_2 = R \end{array} \right\} \Rightarrow \overline{di_{out}^2} = 2\left(\frac{1}{1 + g_m R}\right)^2 \overline{di^2} + 2\left(\frac{g_m R}{1 + g_m R}\right)^2 \overline{di_R^2}$$



Ref.: Bilotti, JSSC Dec 75, 516-524

源极接串联电阻的电流镜



相同的 I_{out} 和相同的 V_G :

$$\overline{di_{outR}^2} = \overline{di_{out}^2}$$

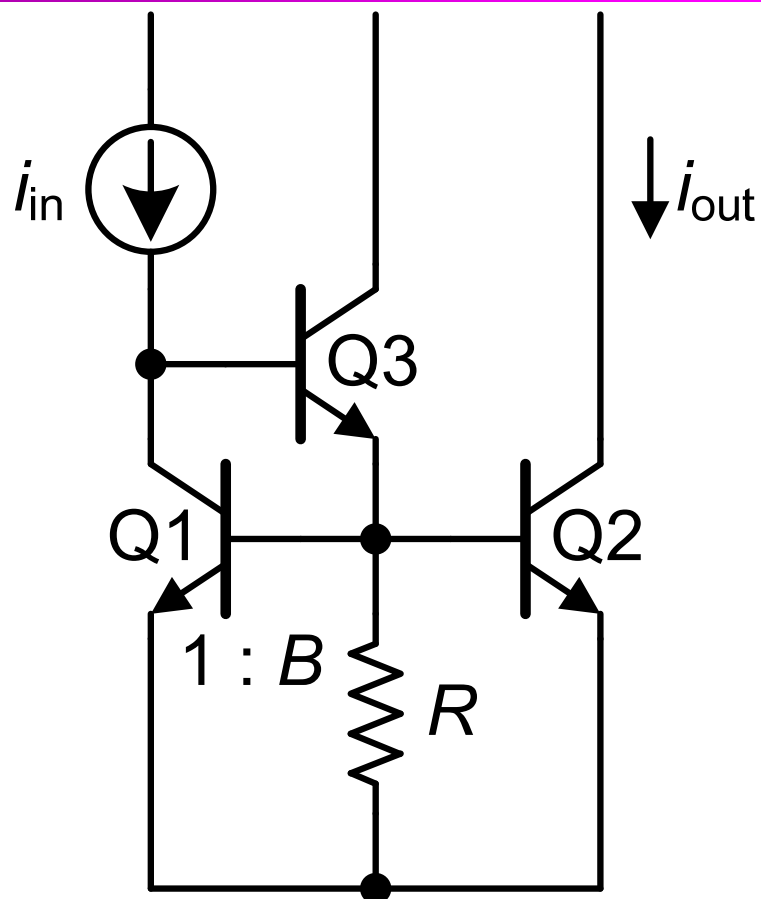
小 g_m :

$(W/L) \downarrow$

$(V_{GS} - V_T) \uparrow$

$V_G \uparrow$

双极型晶体管电流镜的噪声



Q_3 引入的噪声:

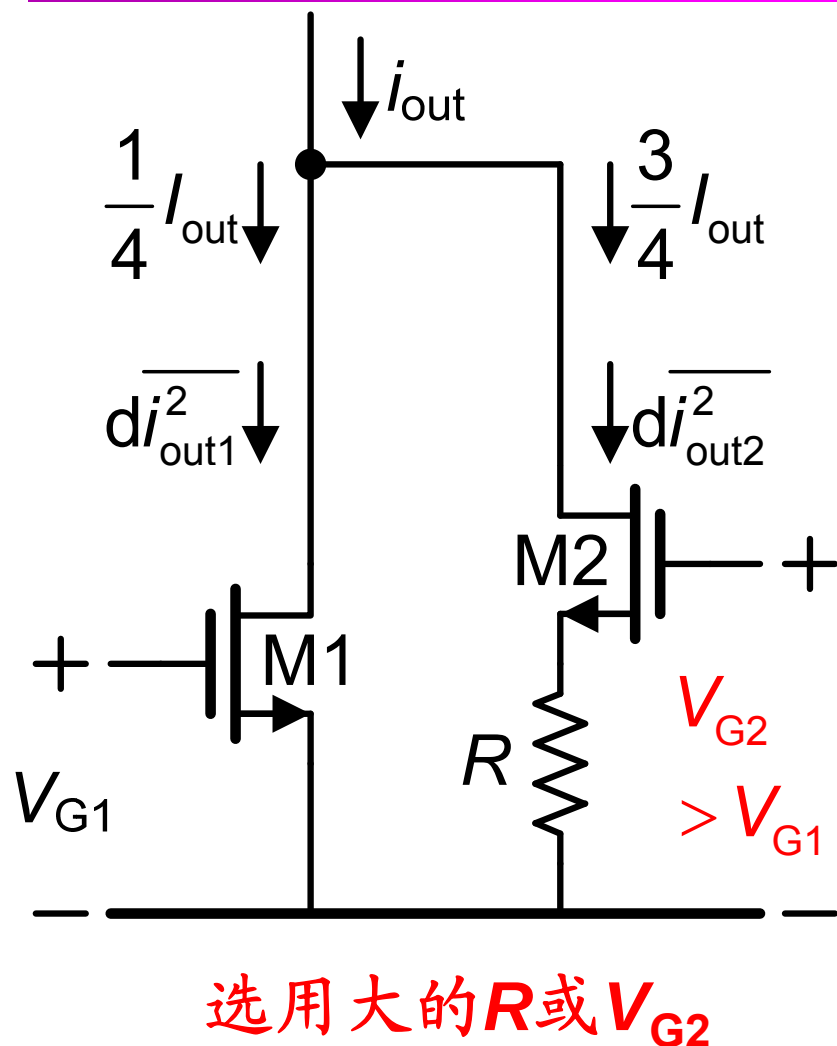
$$\overline{di_{outQ3}^2} = 2qI_{C3}df$$

R 引入的噪声:

$$\overline{di_{outR}^2} = 4kT/Rdf$$

二者均需除以 β_3^2 后加到输出，
因此，均可或忽略！

接串联电阻的低噪声电流镜



相同的 I_{out} 和不同的 V_G :

1个MOST:

$$\overline{di_{out}^2} = \frac{8kT}{3} \frac{2I_{out} df}{V_{GS} - V_T}$$

2个MOST: $V_{G2} > V_{G1}$

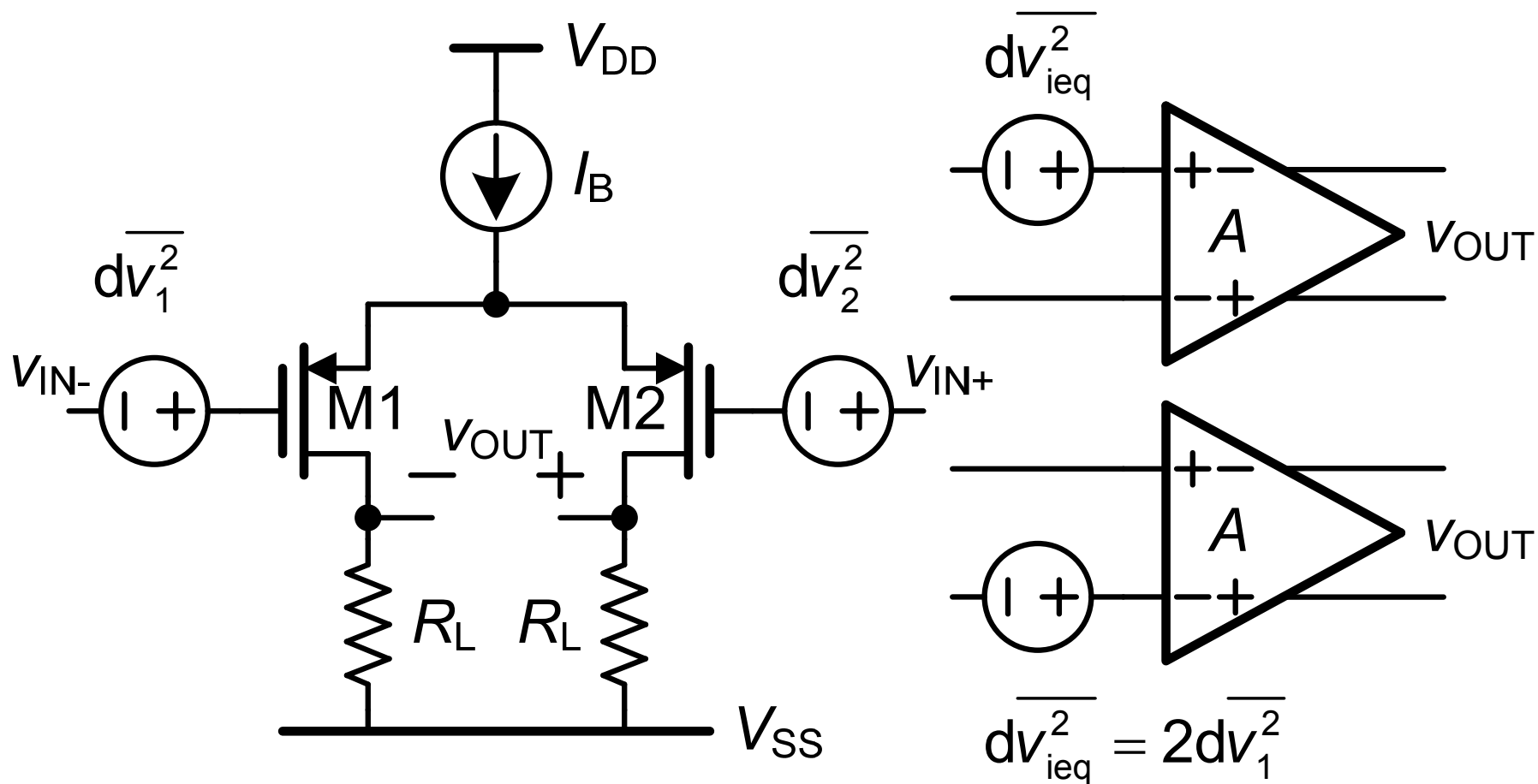
$$\overline{di_{out}^2} = \overline{di_{out1}^2} + \overline{di_{out2}^2} = \frac{8kT}{3} \frac{2I_{out} df}{V_{G1} - V_T} \left(\frac{1}{4} + \frac{9}{16} \frac{V_{G1} - V_T}{V_{G2} - V_{G1}} \right)$$

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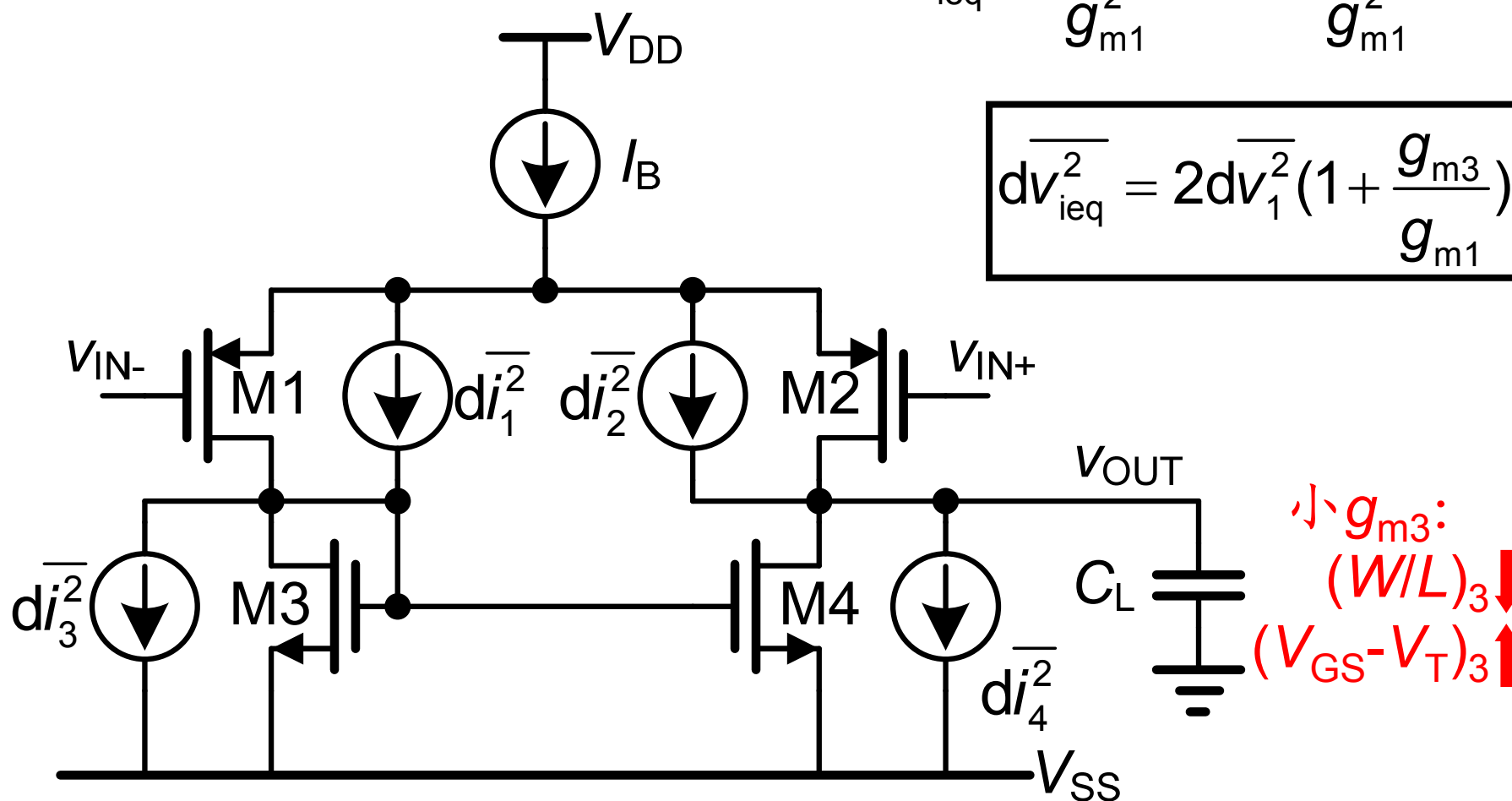
差分对的噪声



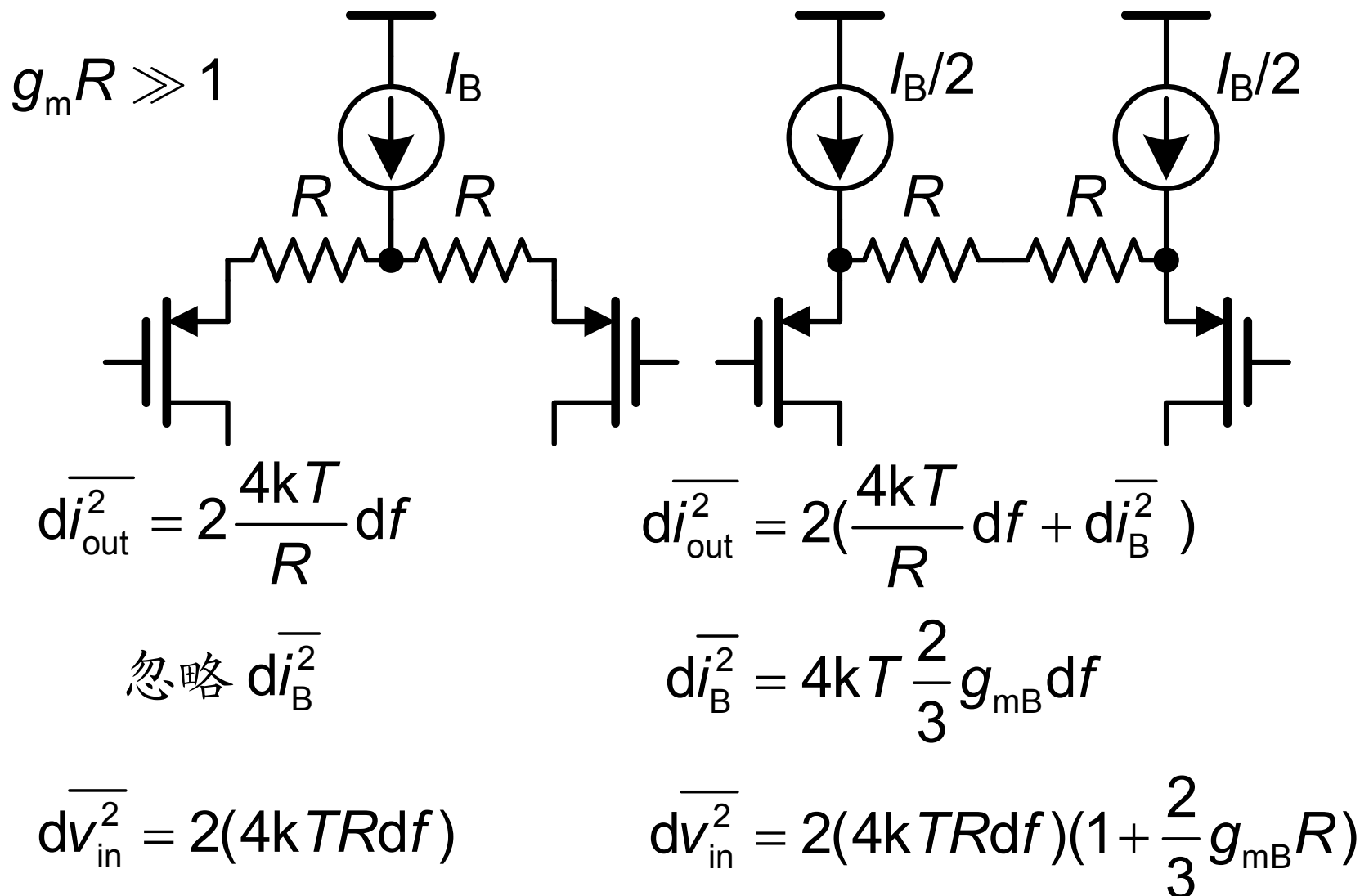
接有源负载差分对的噪声

$$\overline{dv_{ieq}^2} = \frac{\overline{di_{out}^2}}{g_{m1}^2} = \frac{2\overline{di_1^2} + 2\overline{di_3^2}}{g_{m1}^2}$$

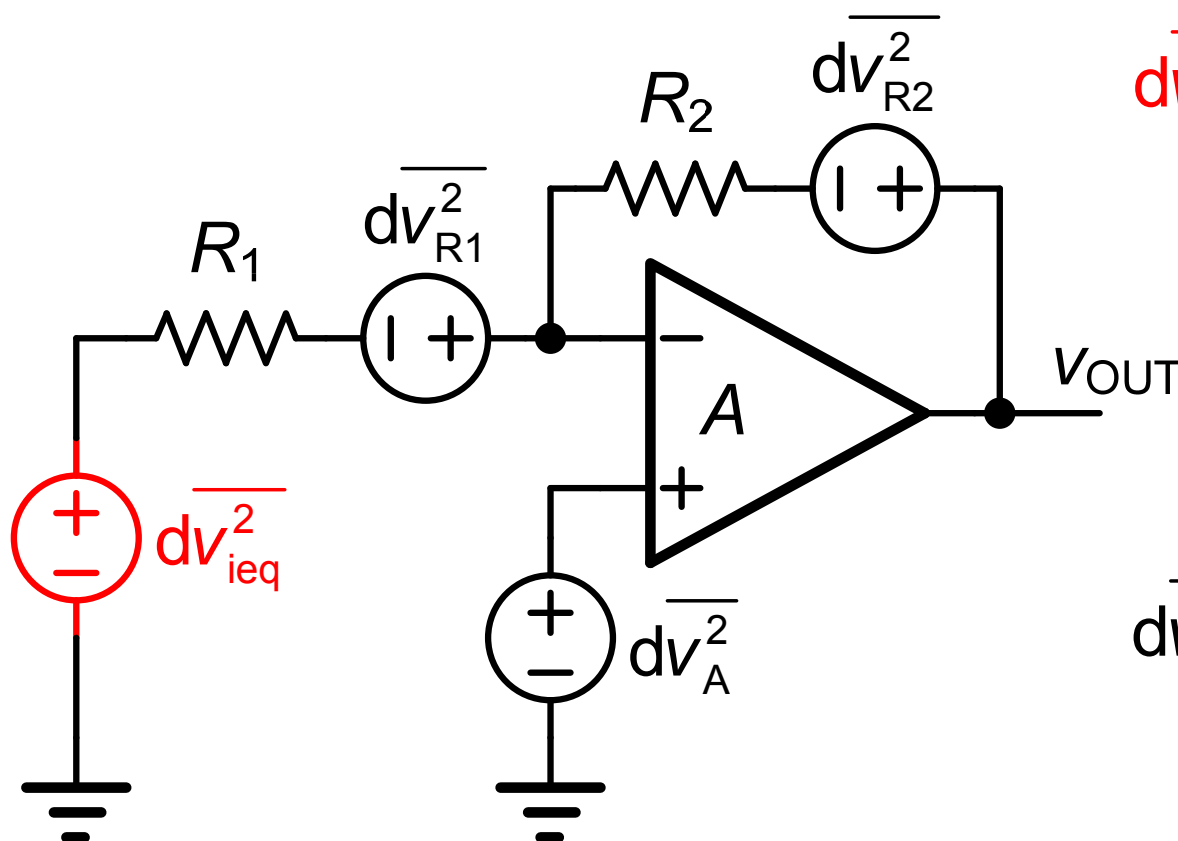
$$\overline{dv_{ieq}^2} = 2\overline{dv_1^2} \left(1 + \frac{g_{m3}}{g_{m1}}\right)$$



接源电阻的差分对



放大器的噪声



$$dv_{ieq}^2 = \sum dv_{out}^2 \left(\frac{R_1}{R_2} \right)^2$$

$$dv_{outR1}^2 = dv_{R1}^2 \left(\frac{R_2}{R_1} \right)^2$$

$$dv_{outR2}^2 = dv_{R2}^2$$

$$dv_{outA}^2 = dv_A^2 \left(1 + \frac{R_2}{R_1} \right)^2$$

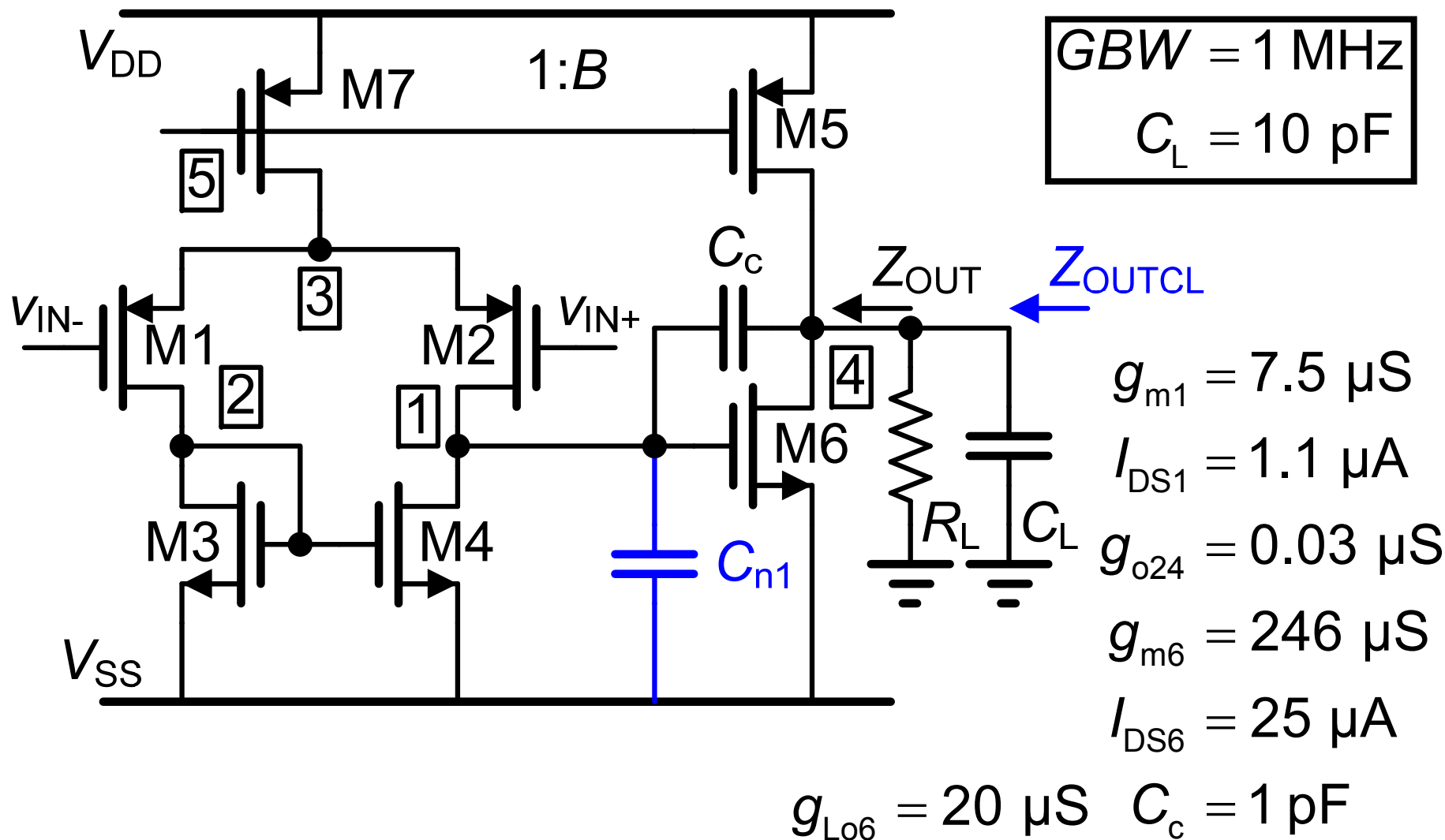
$$dv_{ieq}^2 = dv_{R1}^2 + dv_{R2}^2 \left(\frac{R_1}{R_2} \right)^2 + dv_A^2 \left(1 + \frac{R_1}{R_2} \right)^2 \approx dv_{R1}^2 + dv_A^2$$

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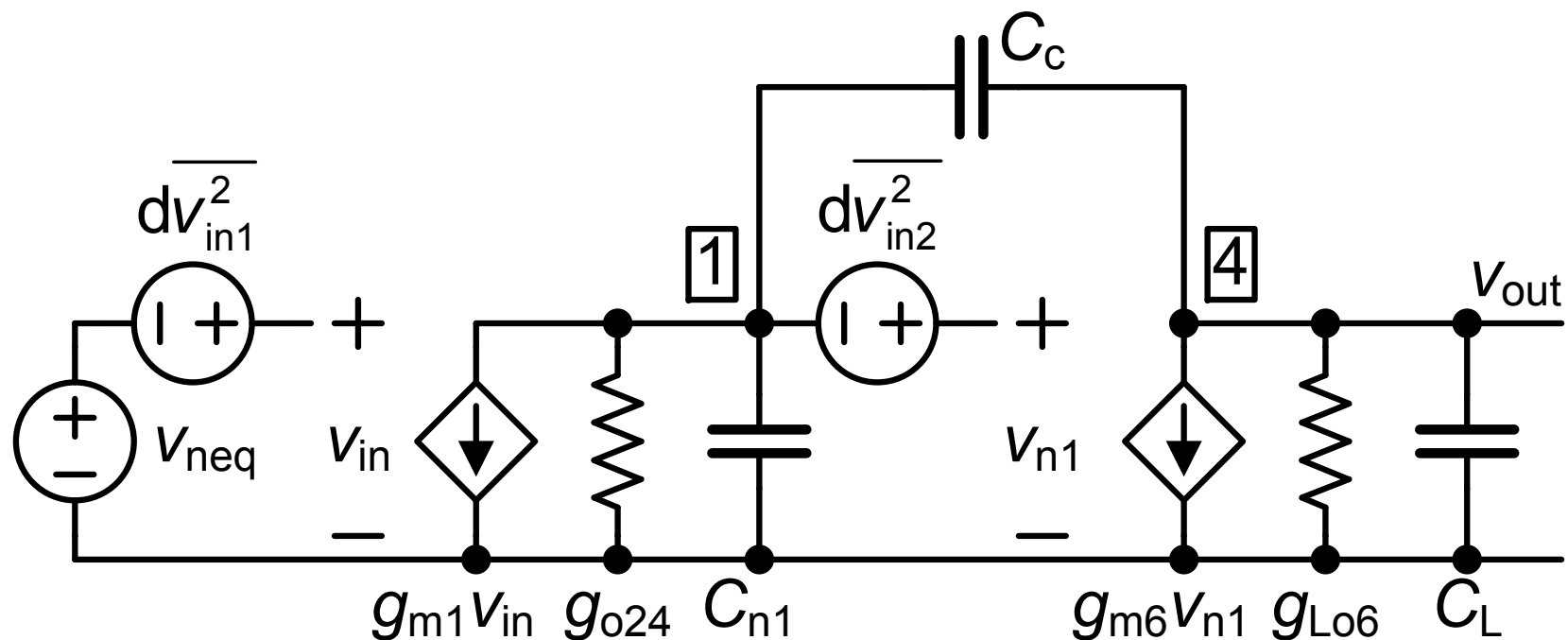
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密勒CMOS OTA



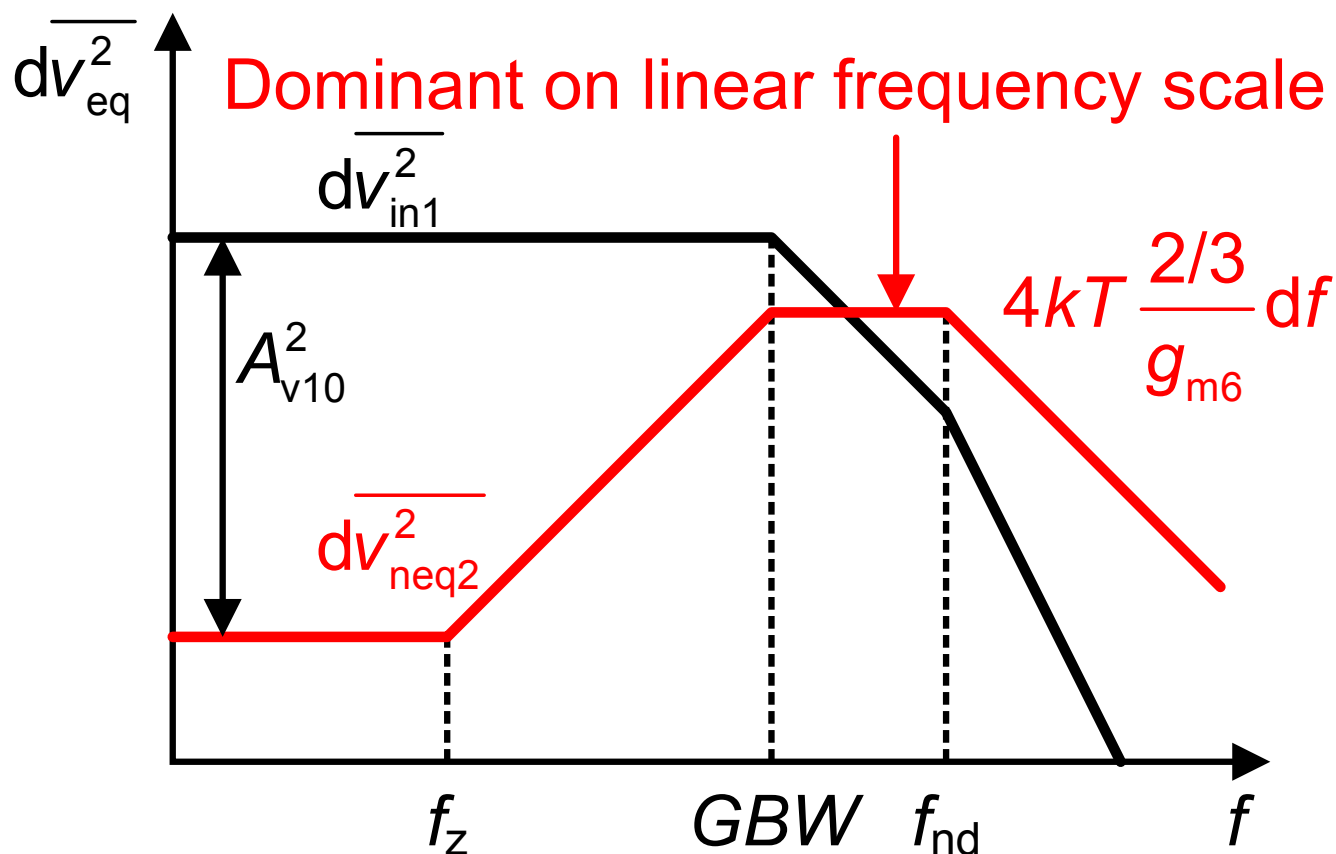
密勒CMOS OTA：噪声密度 1



$$\overline{dv_{in1}^2} = 4kT \frac{4/3}{g_{m1}} df$$

$$\overline{dv_{in2}^2} = 4kT \frac{2/3}{g_{m6}} df$$

密勒CMOS OTA: 噪声密度 2

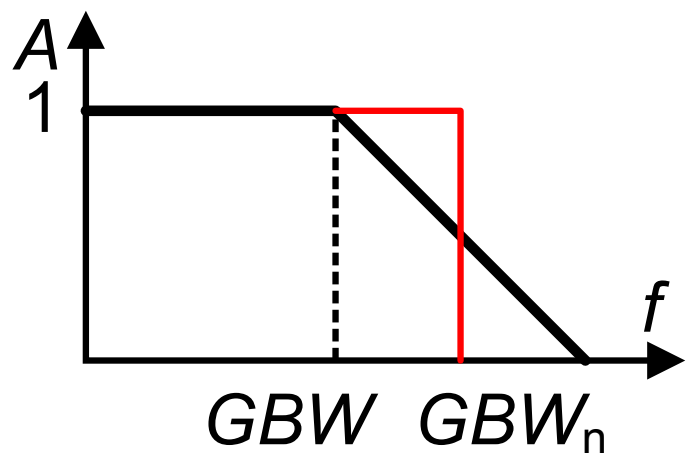


$$\overline{dv_{neq2}^2} = \frac{\overline{dv_{in2}^2}}{|A_{v1}|^2}$$

$$A_{v10} = \frac{g_{m1}}{g_{o24}}$$

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

密勒CMOS OTA: 积分噪声



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

$$\overline{v_{nieq}^2} = \int_0^{\infty} \frac{dv_{nieq}^2}{1 + (f/GBW)^2}$$

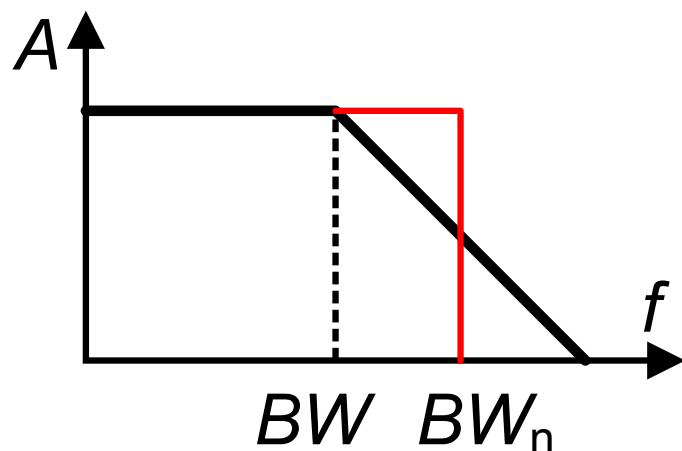
$$\int_0^{\infty} \frac{dx}{1 + x^2} = \frac{\pi}{2}$$

$$\overline{v_{nieq}^2} = 4kT \frac{4/3}{g_{m1}} GBW \frac{\pi}{2}$$

$$C_c = 1 \text{ pF} \quad v_{Rs} = 74.5 \text{ } \mu\text{V}_{\text{RMS}}$$

$$\overline{v_{nieq}^2} = \frac{4kT}{3C_c}$$

噪声密度与积分噪声



$$d\overline{v_{in}^2} = 4kT \frac{4/3}{g_{m1}} df$$

$$\overline{v_{ni}^2} = \int_0^\infty \frac{d\overline{v_{ni}^2}}{1 + (f/GBW)^2} = \frac{4kT}{3C_c}$$

噪声密度(V^2/Hz) $\sim 1/g_m$ (或 R_S)

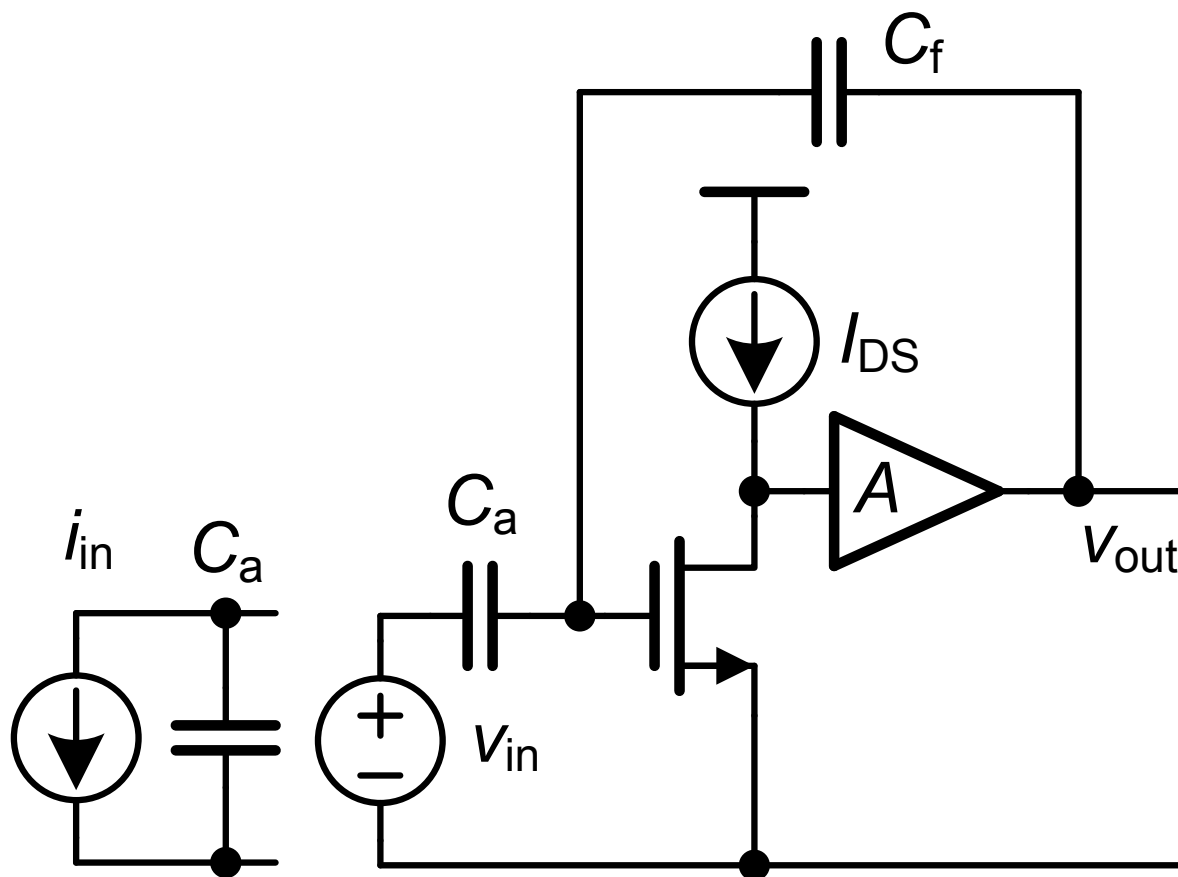
积分噪声(V_{REM}) $\sim 1/C_c$

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容性源放大器



$$A_V = \frac{C_a}{C_f}$$

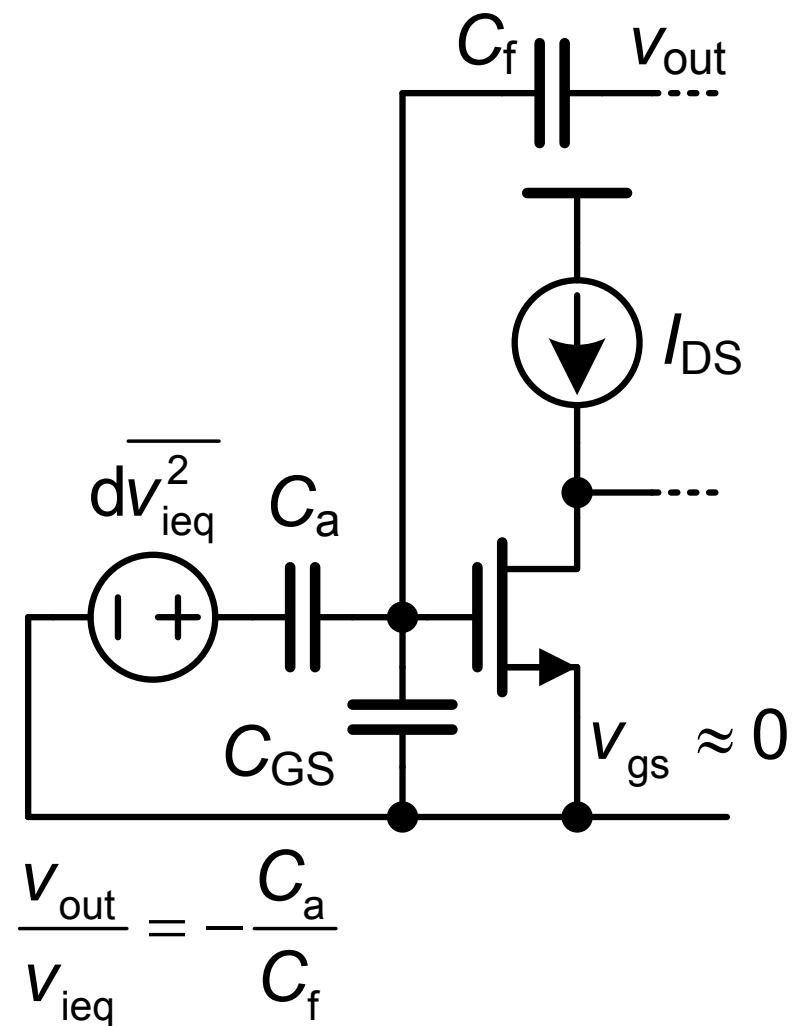
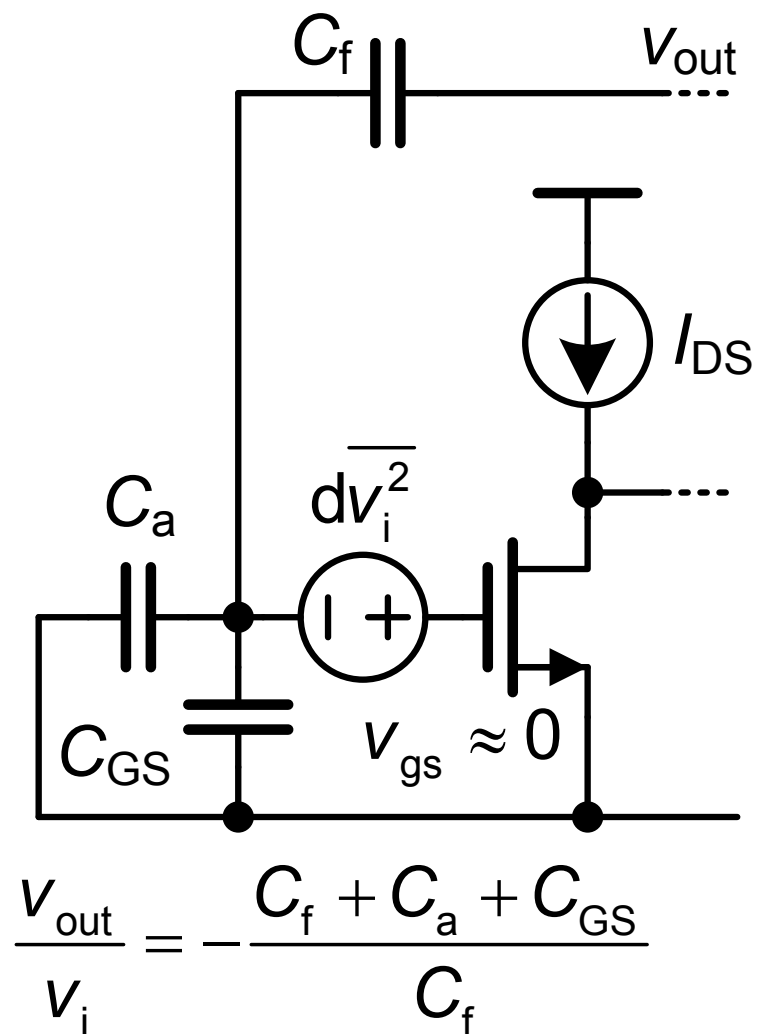
$$C_a = 5 \text{ pF}$$

$$C_f = 1 \text{ pF}$$

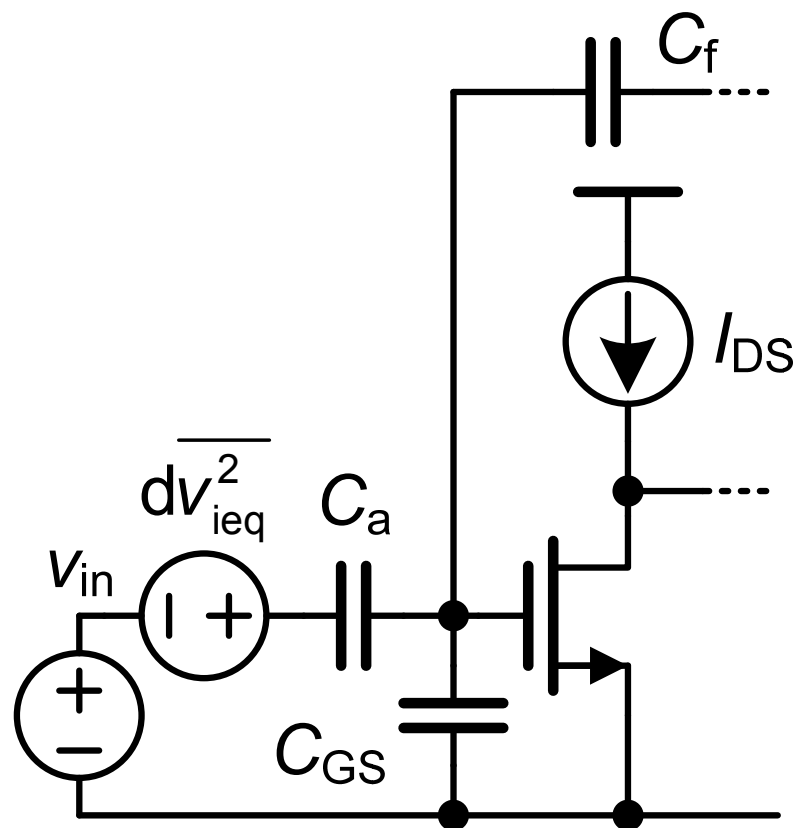
$$C_{GS} = kW \quad k \approx 2 \text{ fF}/\mu\text{m}$$

W_{opt} ? I_{DSopt} ? 如果 $V_{\text{in}} = 10 \text{ mV}_{\text{RMS}}$, $(S/N)_{\text{opt}}$?

容性噪声匹配—1



容性噪声匹配—2



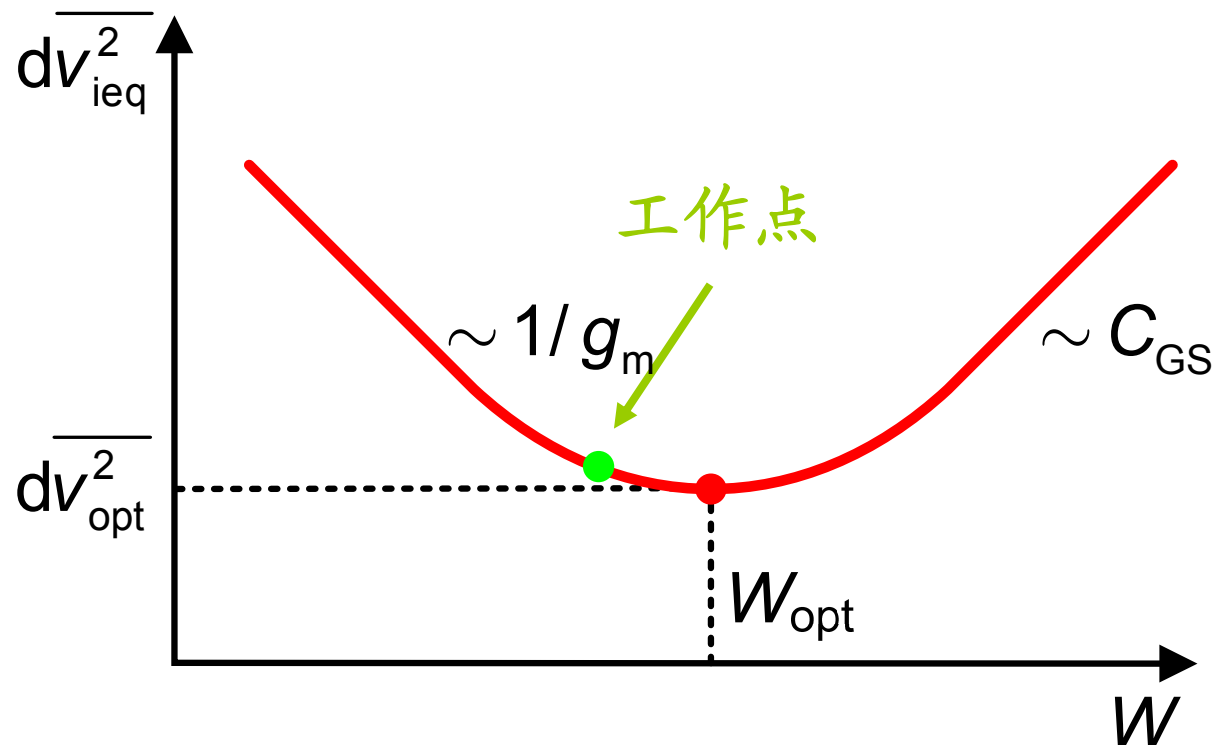
$$\overline{dv_{ieq}^2} = \frac{(C_f + C_a + C_{GS})^2}{C_a^2} \overline{dv_i^2}$$

$$\overline{dv_i^2} = \frac{8kT}{3} \frac{1}{g_m} df$$

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

$$\overline{dv_{ieq}^2} = \frac{(C_f + C_a + kW)^2}{C_a^2} \frac{L}{W} \frac{8kT}{3} \frac{1}{2K'_n (V_{GS} - V_T)}$$

容性噪声匹配—3



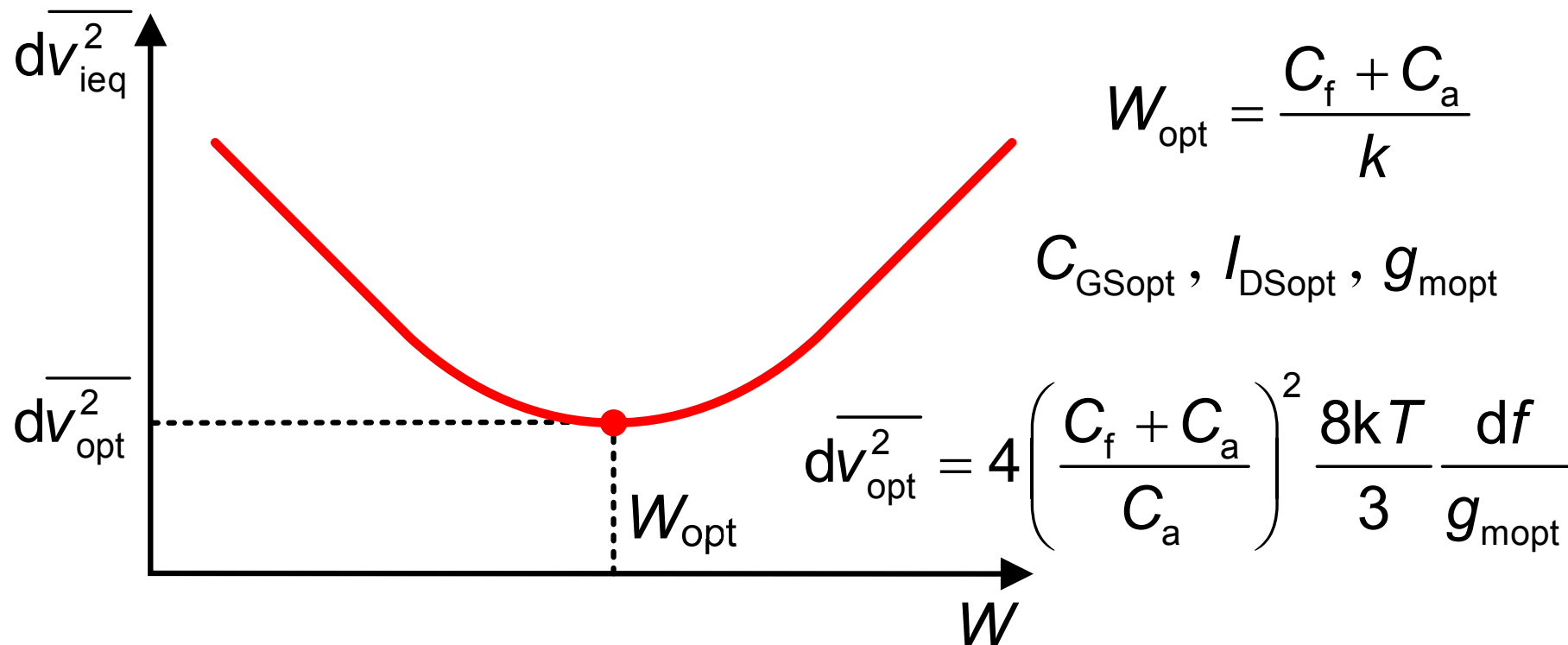
噪声匹配条件

$$C_{GS} = C_f + C_a$$

$$W_{opt} = \frac{C_f + C_a}{k}$$

$$\overline{dv_{ieq}^2} = \frac{(C_f + C_a + kW)^2}{C_a^2} \frac{L}{W} \frac{8kT}{3} \frac{1}{2K'_n(V_{GS} - V_T)}$$

容性噪声匹配—4



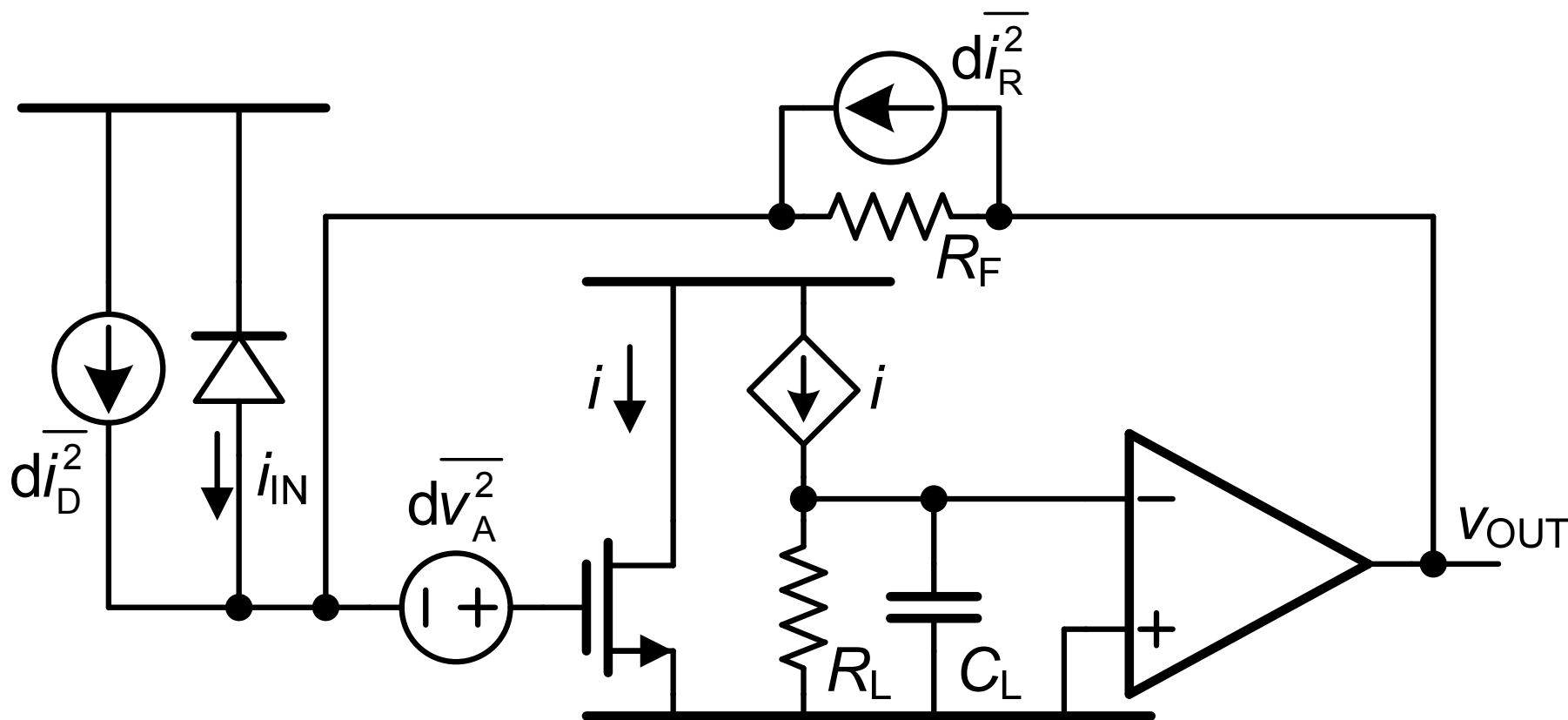
$$BW_n = \frac{\pi}{2} BW = \frac{\pi}{2} \frac{f_T}{A_V} = \frac{1}{4A_V} \frac{g_{\text{mopt}}}{C_{\text{GSopt}}} \quad \left(\frac{S}{N} \right)_{\text{opt}} = \frac{10 \text{ mV}_{\text{RMS}}}{\sqrt{\overline{dv_{\text{opt}}^2} BW_n}}$$

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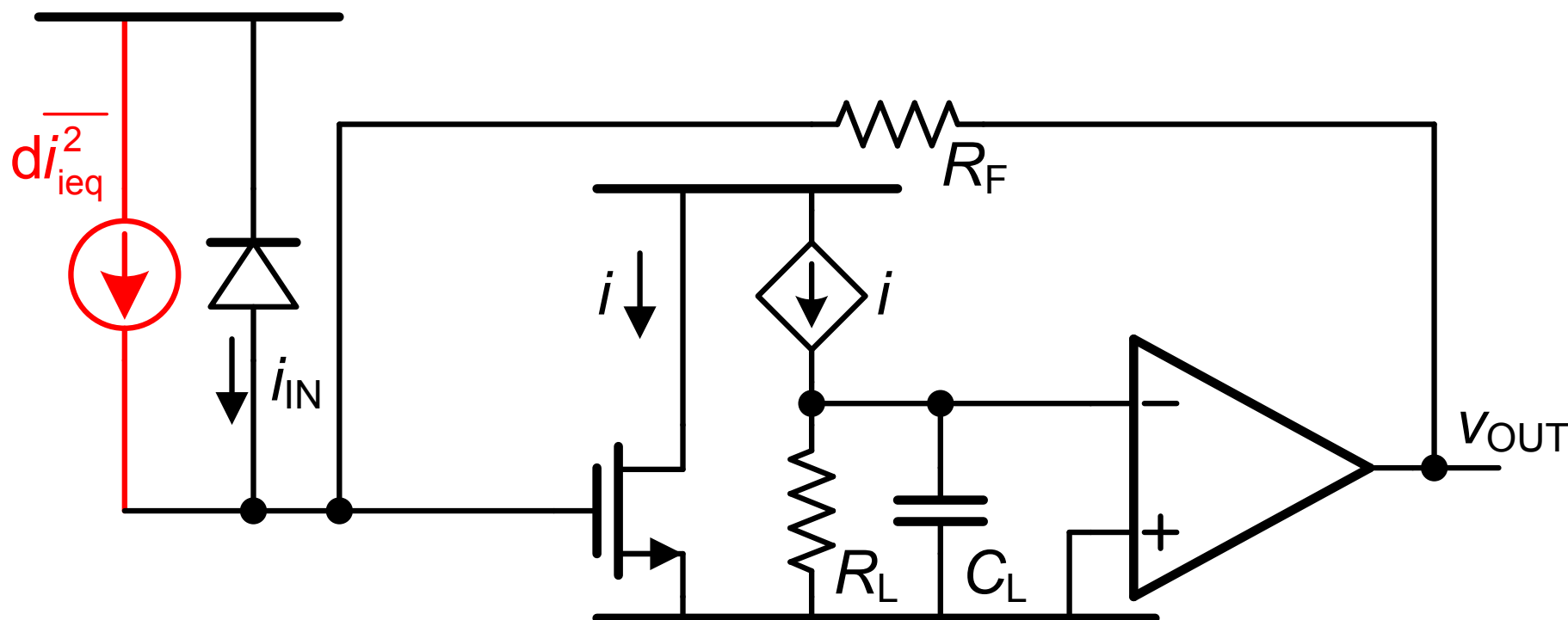
Ref.: W. Sansen : Analog Design Essentials, Springer 2006

电压检测放大器的噪声源



$$\overline{di_D^2} = 2qI_D df \quad \overline{di_R^2} = \frac{4kT}{R_F} df \quad \overline{dv_A^2} = 4kT \frac{2/3}{g_m} df$$

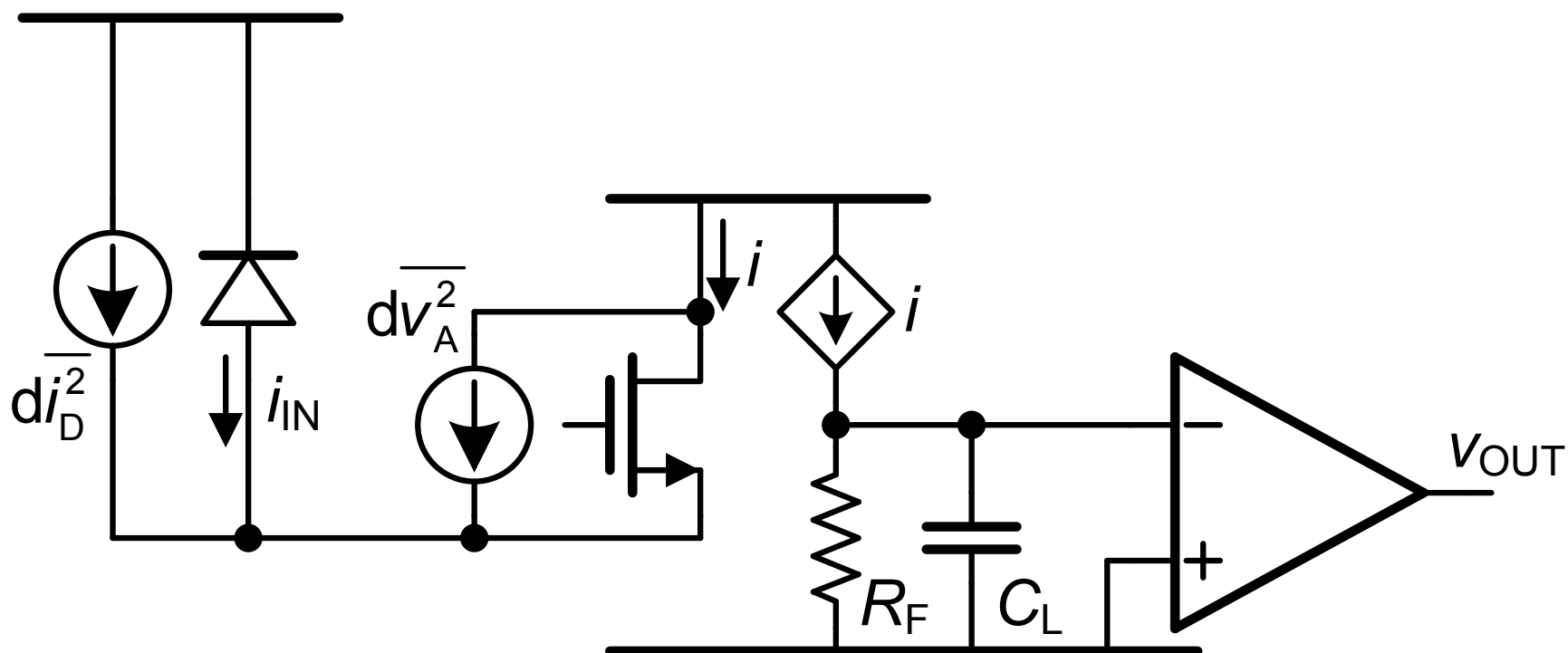
电压检测放大器的噪声密度



如果 $R_F > \frac{3/2}{g_m}$

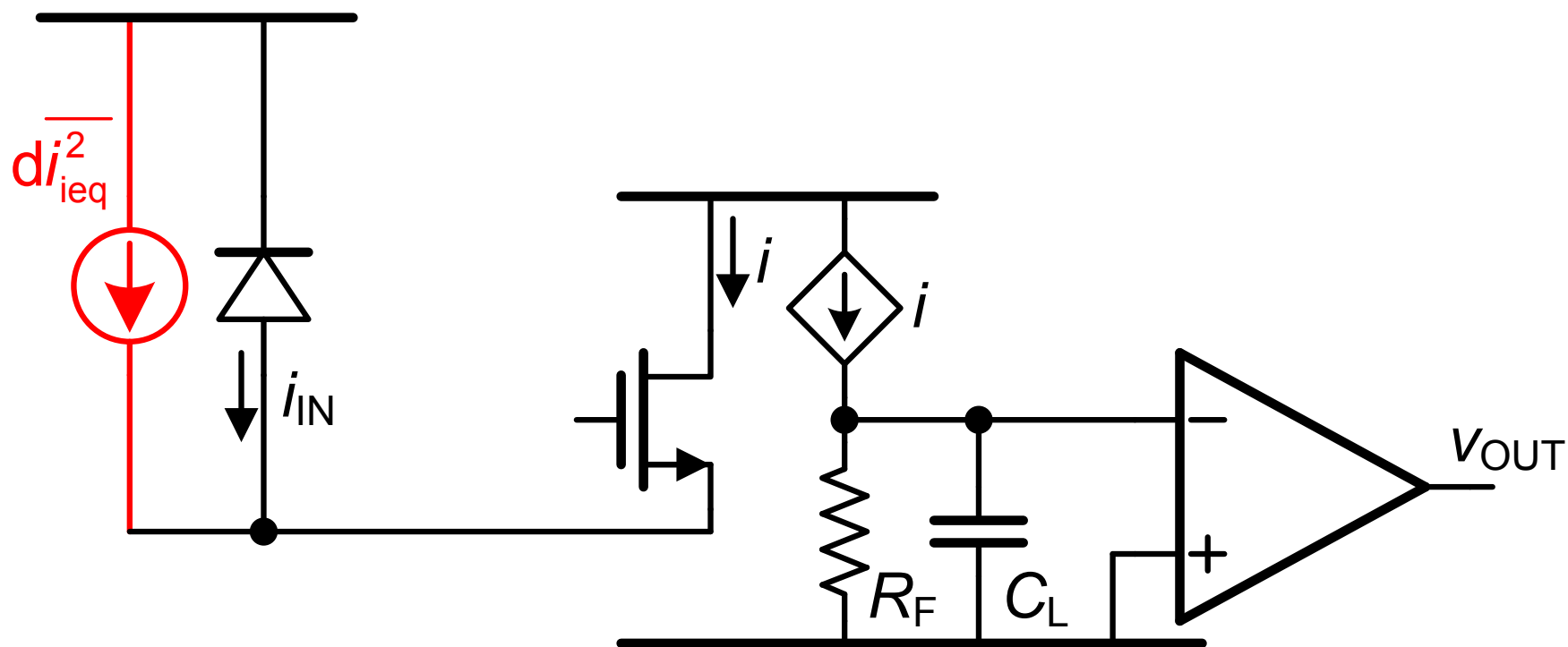
$$\overline{di_{ieq}^2} = \overline{di_D^2} + \overline{di_R^2} + \frac{\overline{dv_A^2}}{R_F^2} \approx \overline{di_D^2} + \overline{di_R^2}$$

电流检测放大器的噪声源



$$\overline{di_D^2} = 2qI_D df \quad \overline{di_A^2} = 4kT \frac{2}{3} g_m df$$

电流检测放大器的噪声密度



$$\overline{di_{ieq}^2} = \overline{di_D^2} + 4kT \frac{2}{3} g_m df$$

为晶体管噪声！

噪声密度的比较

$$\text{电压放大器: } \overline{i_{\text{IN}}^2} = d\overline{i_{\text{R}}^2} = \frac{4kT}{R_{\text{F}}} df$$

$$\text{电流放大器: } \overline{i_{\text{IN}}^2} = d\overline{i_{\text{A}}^2} = 4kT \frac{2}{3} g_{\text{m}} df$$

当 $R_{\text{F}} > \frac{3/2}{g_{\text{m}}}$ 时，电压放大器较好，噪声密度较小

积分噪声的比较

$$\text{大} I_D: \overline{i_{IN}^2} = d\overline{i_D^2} \left(BW \frac{\pi}{2} \right)$$

$$\text{电压放大器: } \overline{i_{IN}^2} = d\overline{i_R^2} \left(BW \frac{\pi}{2} \right) = \frac{kT}{R_L} \left(\frac{R_L}{R_F} \right)^2 \frac{g_m}{C_P}$$

$$\text{电流放大器: } \overline{i_{IN}^2} = d\overline{i_A^2} \left(BW \frac{\pi}{2} \right) = \frac{2}{3} \frac{kT}{R_F} \frac{g_m}{C_L}$$

当 $R_F > \frac{3}{4} R_L$ 时，电压放大器较好，积分噪声较小