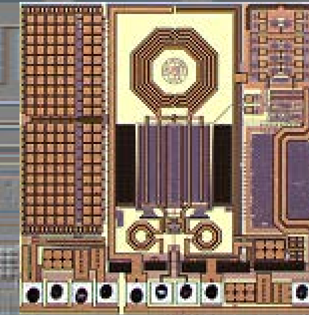

模拟集成电路设计原理
(Principle of Analog Integrated Circuit Design, INF0130025.02)

2014年12月18日

唐长文 教授

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

复旦大学/微电子学院/射频集成电路设计研究小组

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基本晶体管级的噪声性能

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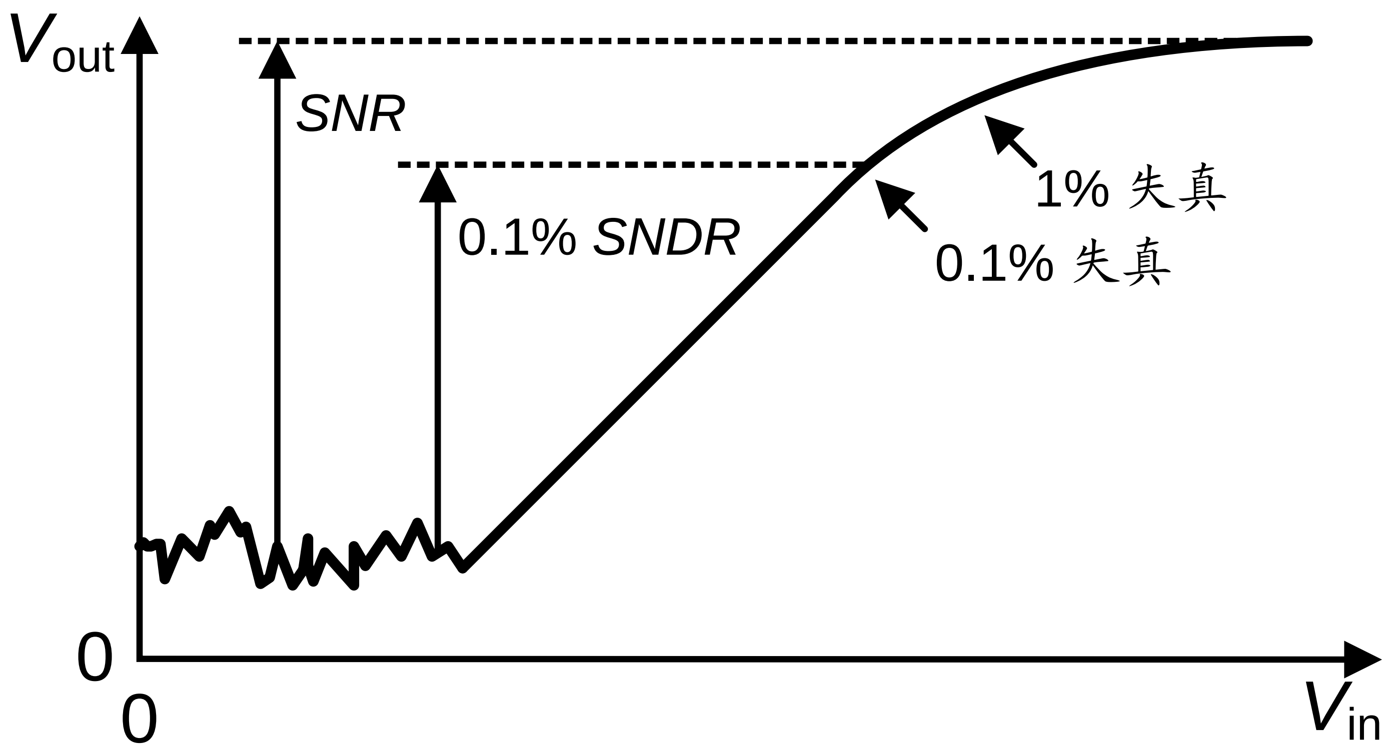
信号噪声比和信号噪声失真比



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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- 共源放大器的噪声
- 源极跟随器的噪声
- 共栅放大器的噪声
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- 差分对的噪声
- 密勒CMOS OTA的噪声
- 容性噪声匹配
- 电压/电流检测器的噪声对比

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

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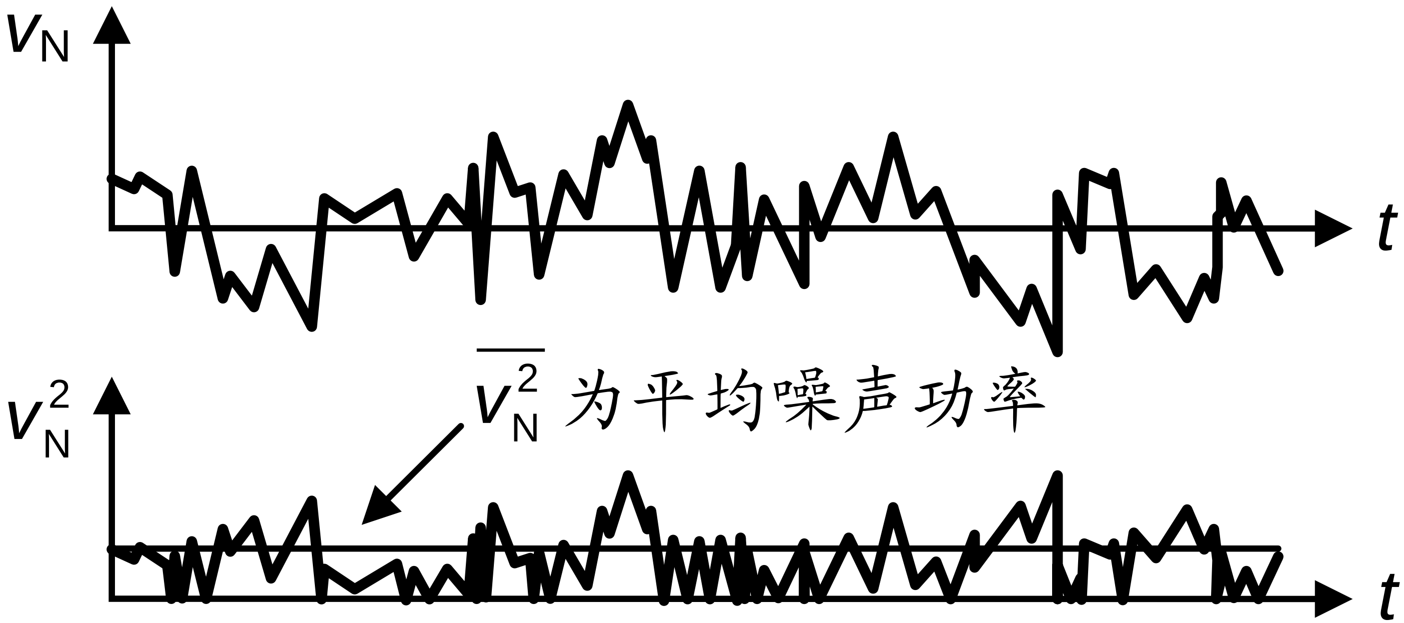
噪声和时间的关系



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

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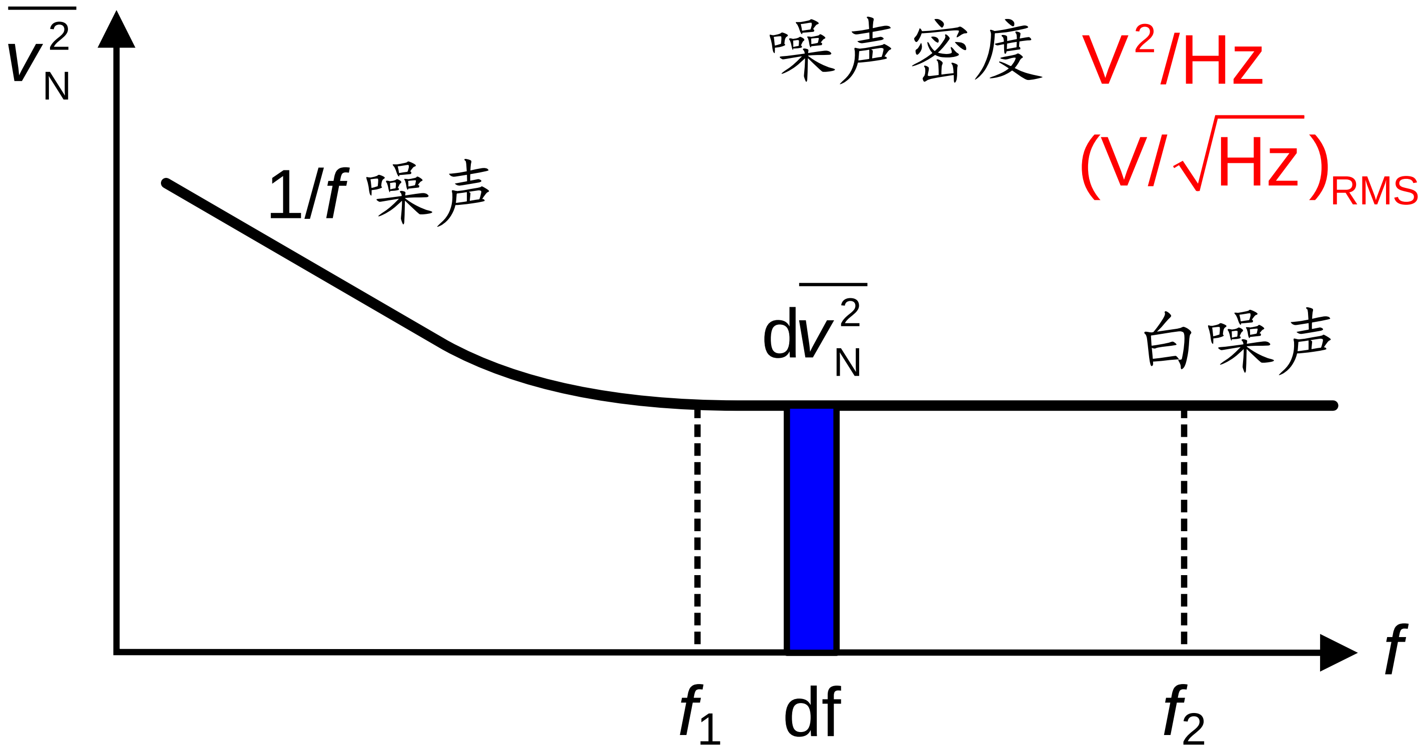
噪声和频率的关系



积分噪声 V_{RMS}

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

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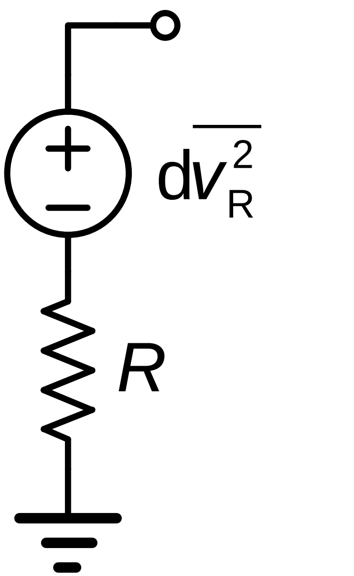
电阻的噪声为热噪声

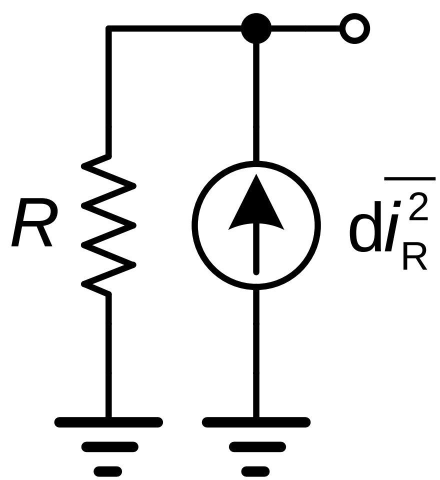


$$d\overline{v_R^2} = 4kTR\,df$$

为白噪声，值由T决定，与I_R无关

当R=1 kΩ，T=300 K(27 C°) 时

$$\sqrt{d\overline{v_R^2}} = 4\ \mathrm{n}(\mathrm{V}/\sqrt{\mathrm{Hz}})_{\mathrm{RMS}}$$



$$d\overline{i_R^2} = \frac{d\overline{v_R^2}}{R^2} = \frac{4kT}{R}df$$ 为白噪声

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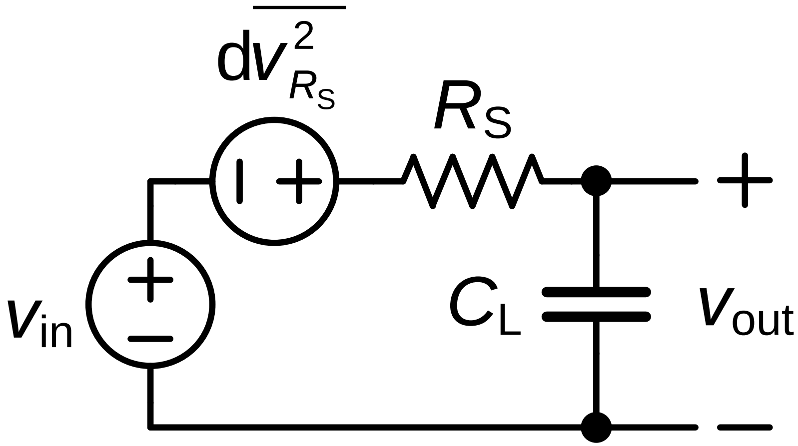
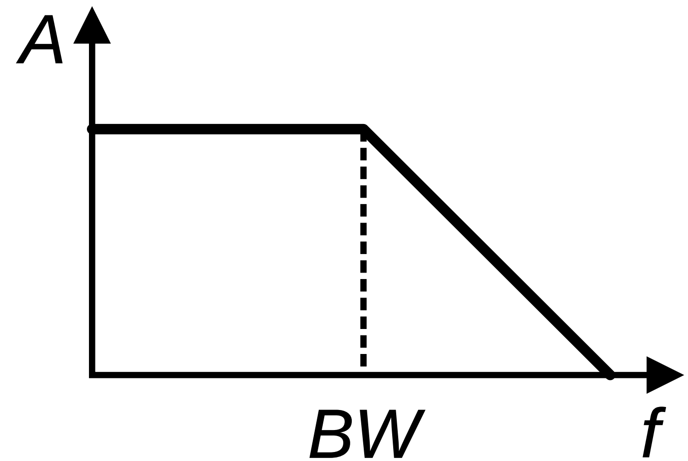
电阻的积分噪声—1





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

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

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

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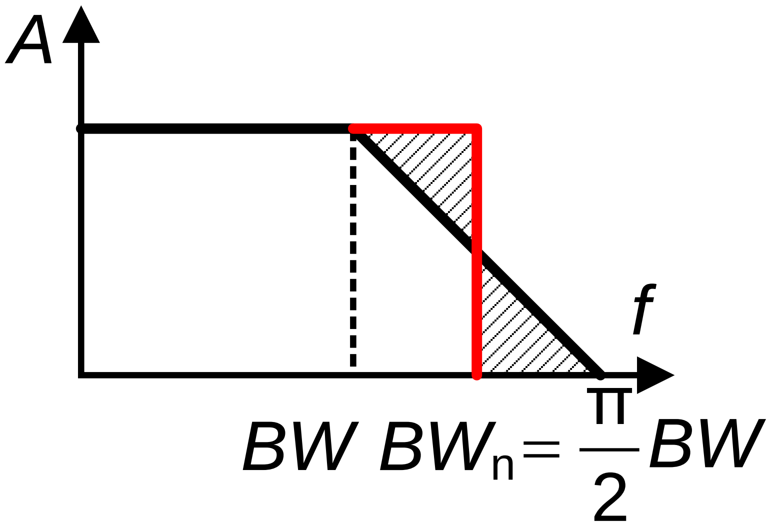
电阻的积分噪声—2



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

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

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

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

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

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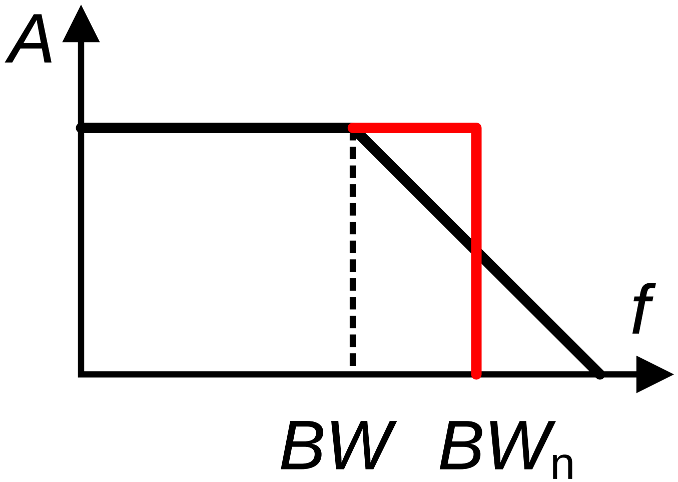
噪声密度与积分噪声



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

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

噪声密度 $(V^2/Hz) \sim R_S$ (或$1/g_m$)

积分噪声 $V_{RMS} \sim 1/C_L$

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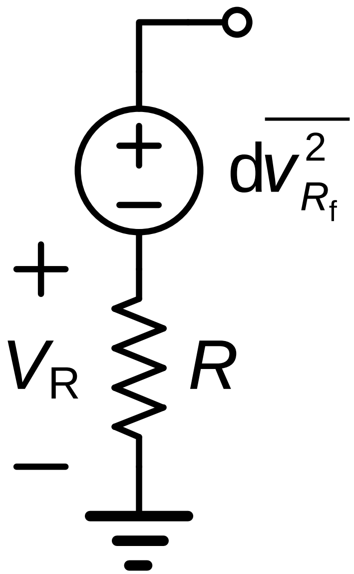
电阻也有1/f 噪声



$$\overline{dv^2_{R_f}} = v^2_R \frac{KF_R R_\square}{A_R} \frac{df}{f} \quad 1/f\text{ 噪声}$$

$$KF_{RSi} \approx 2\times10^{-21}\ \text{Scm}^2$$

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

例如：20个方块，每个50 Ω/□，构成R=1 kΩ，宽为1 μm，V_R=0.1 V，在1 Hz时

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

Ref.: Vandamme, ESSDERC ‘04

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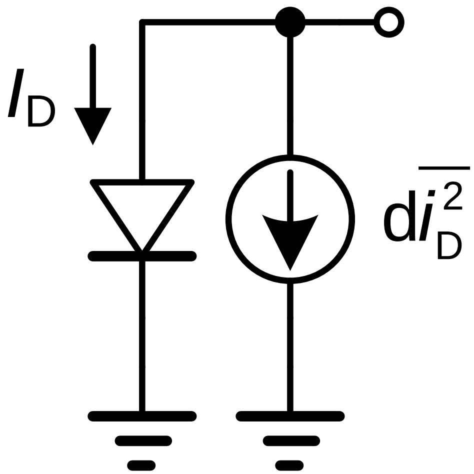
二极管的噪声为散射噪声



$$d\overline{i_D^2} = 2qI_D df \qquad q = 1.6\times10^{-19}\ \mathrm{C}$$

为白噪声，值由I_D决定，与T无关

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

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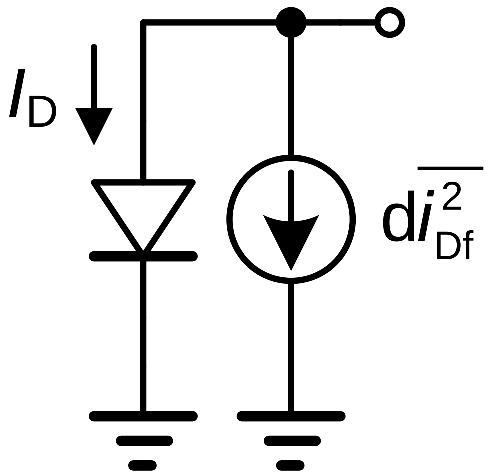
二极管也有1/f 噪声



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

为1/*f* 噪声

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

例如：二极管 $A_D = 5\ \mu m \times 2\ \mu m = 10\ \mu m^2$，$I_D = 0.1\ mA$

在1 kHz时

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

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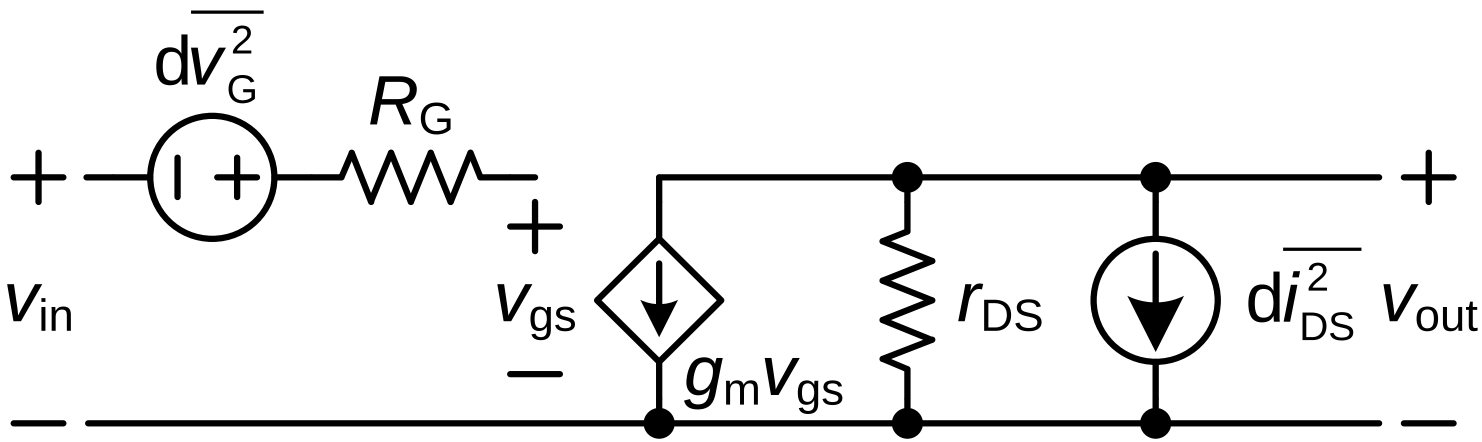
MOST的噪声



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

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

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

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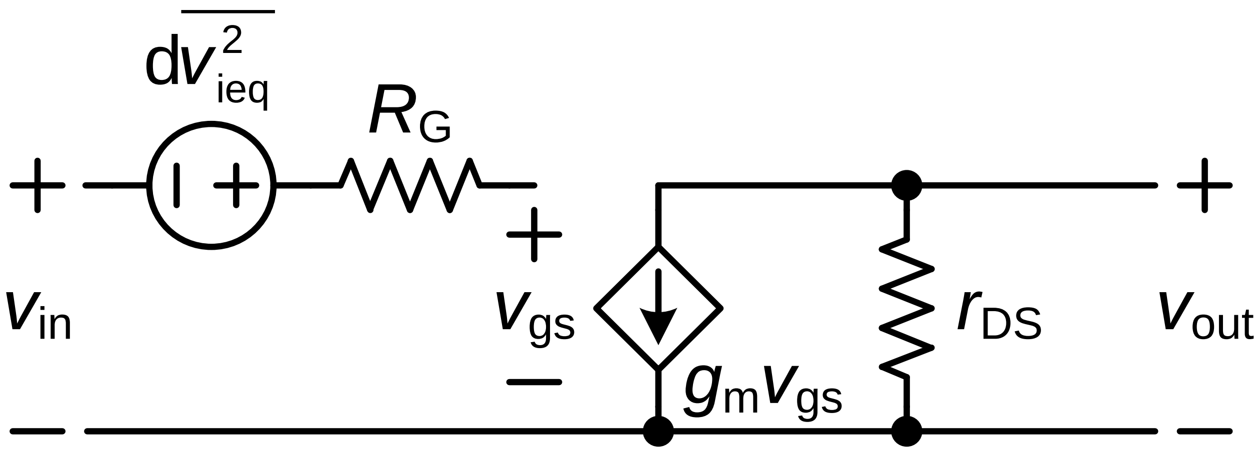
MOST：等效输入噪声—白噪声



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

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

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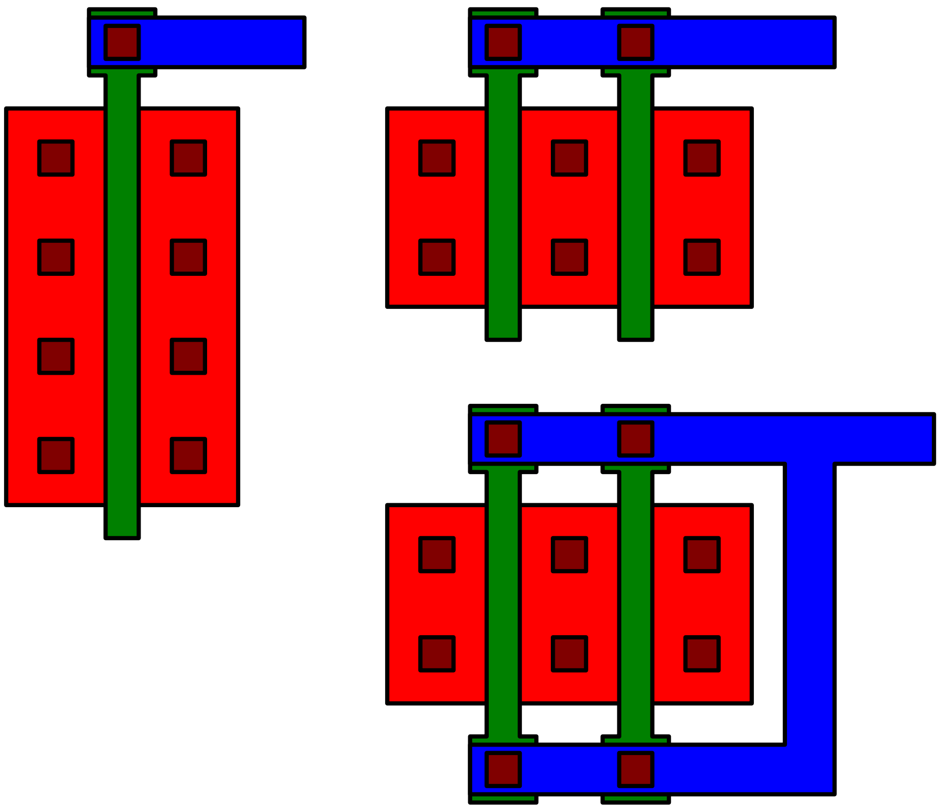
MOST的栅极串联电阻R_G

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

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

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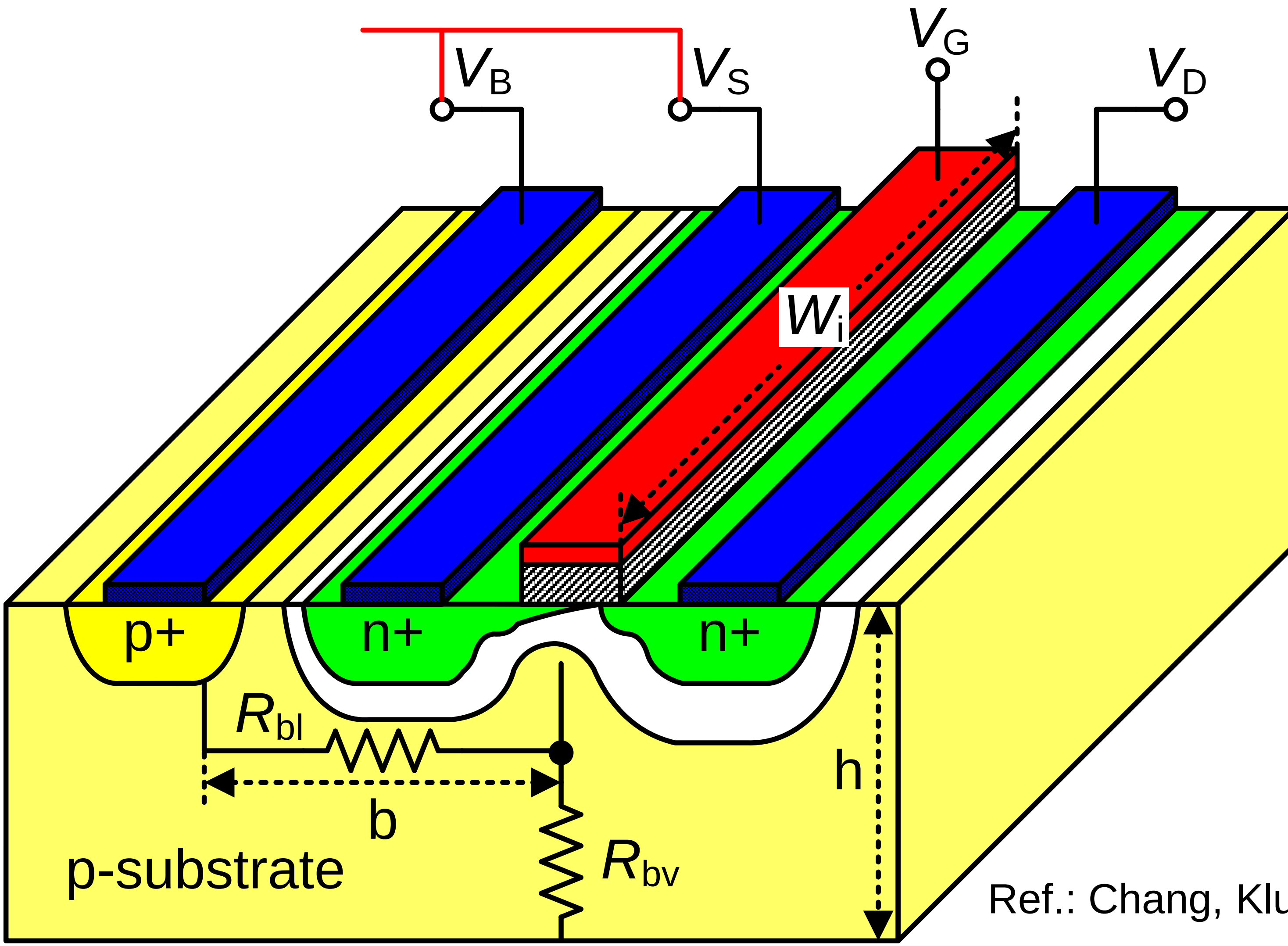
MOST的衬底电阻R_B



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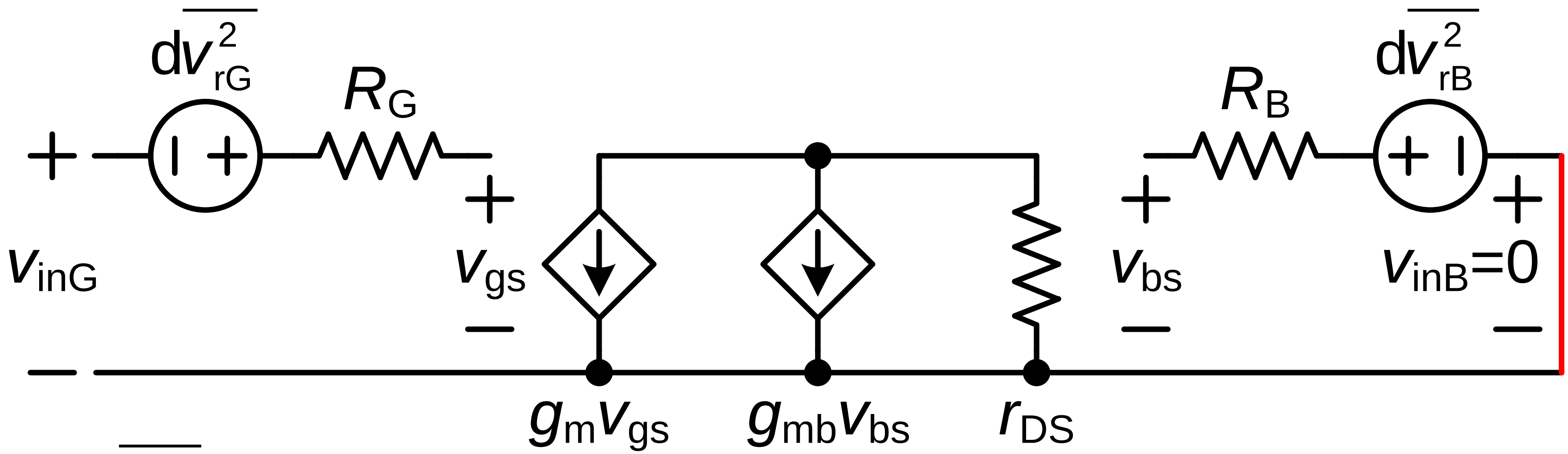
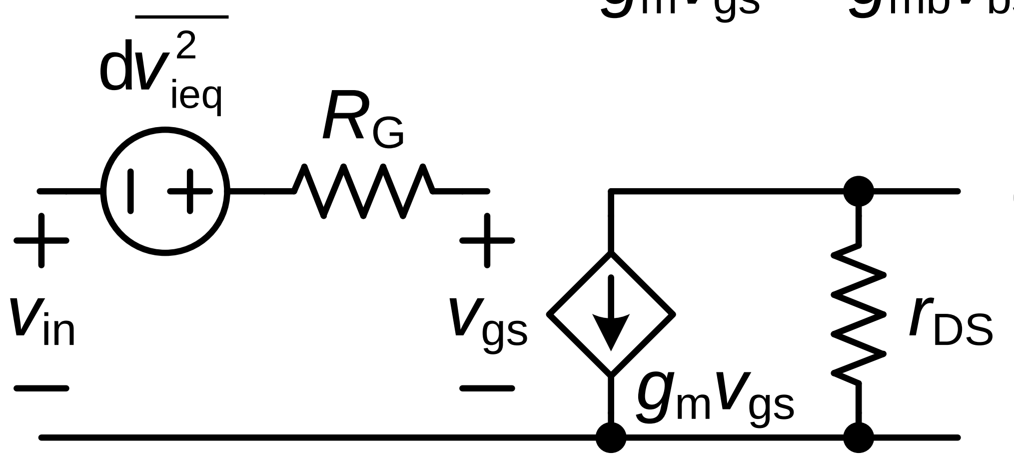
衬底电阻产生的噪声





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

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

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

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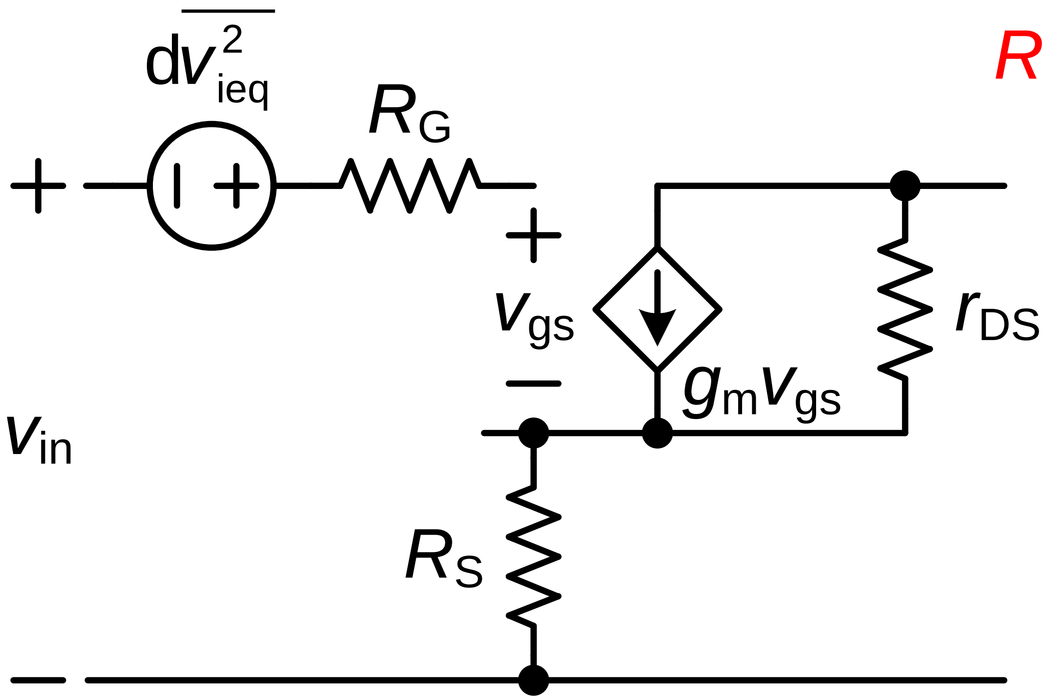
源极电阻产生的噪声



R_S的噪声<=> R_G的噪声

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

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

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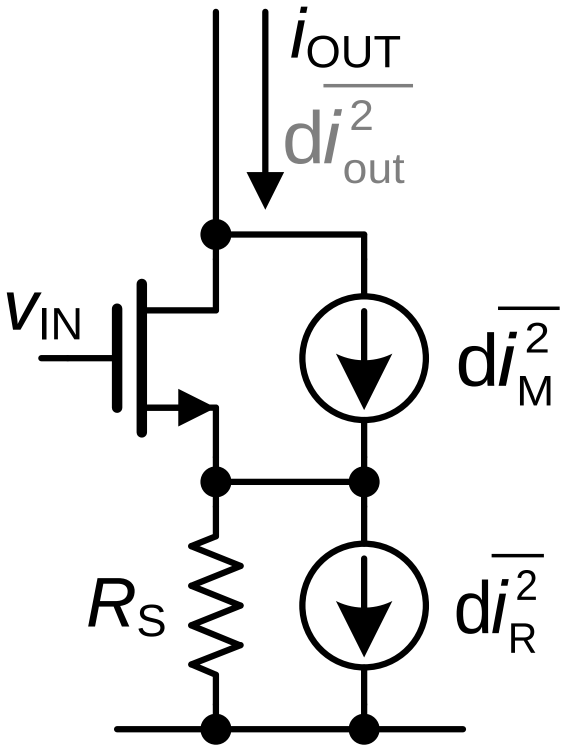
源极电阻R_S产生的噪声



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

$$\overline{di^2_M} = 4kT\frac{2}{3}g_m df \qquad \overline{di^2_{outM}} = \frac{\overline{di^2_M}}{(1+g_m R_S)^2}$$

$$\overline{di^2_R} = \frac{4kT}{R}df \qquad \overline{di^2_{outR}} = \left(\frac{g_m R_S}{1+g_m R_S}\right)^2 \overline{di^2_R}$$

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

$$\overline{dv^2_{ieq}} = 4kTR_S\left(\frac{2/3}{g_m R_S}+1\right)df \qquad R_{eff} = \frac{2/3}{g_m}+R_S$$

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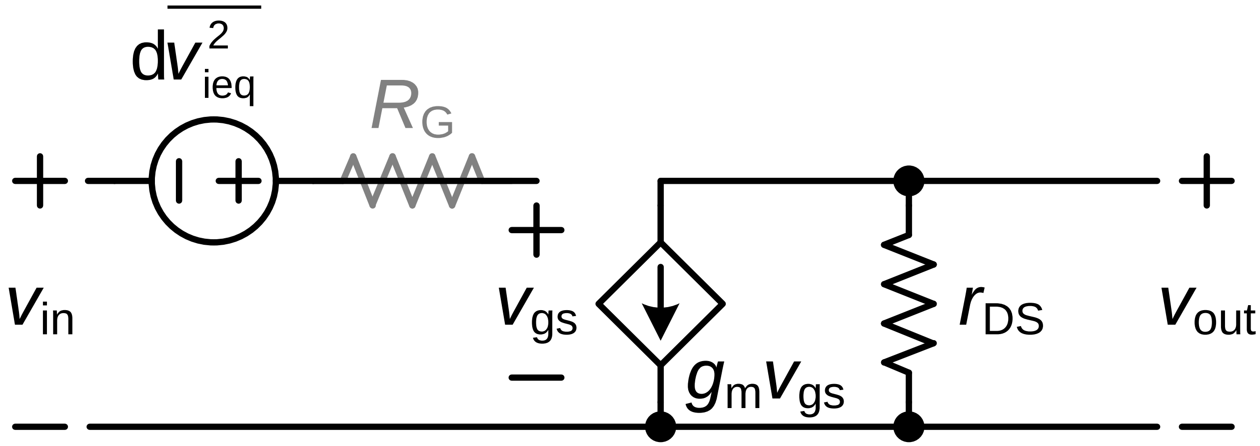
MOST：等效输入噪声—练习



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

当 V_{GS}-V_T=0.2 V，I_{DS}=65 μA时，求$\overline{dv_{ieq}^2}$

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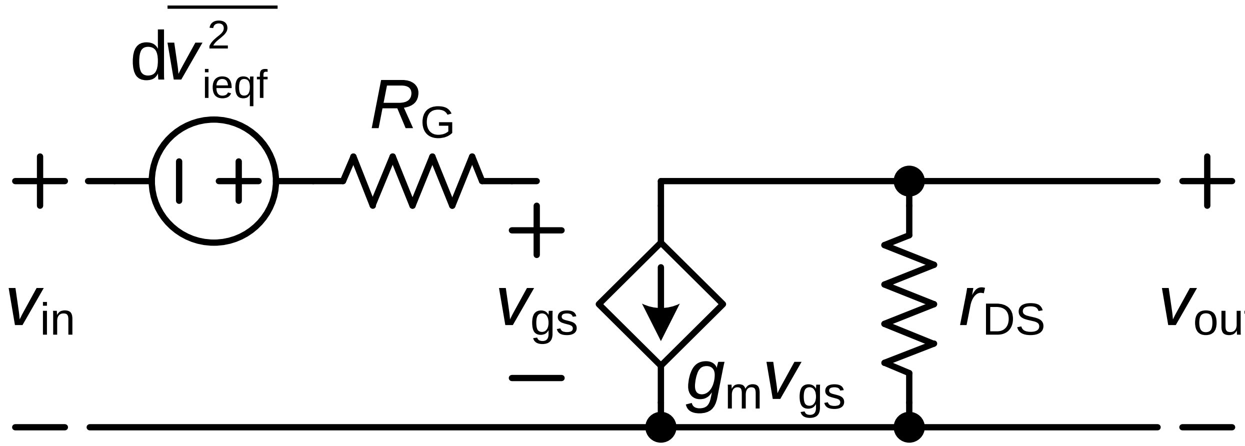
MOST：等效输入噪声—1/*f* 噪声



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

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

W和L的单位为cm，　nMOST $KF_F \approx 4\times10^{-31}\ \mathrm{C^2/cm^2}$

C_{ox}的单位为F/cm²　pJFET $KF_F \approx 10^{-33}\ \mathrm{C^2/cm^2}$

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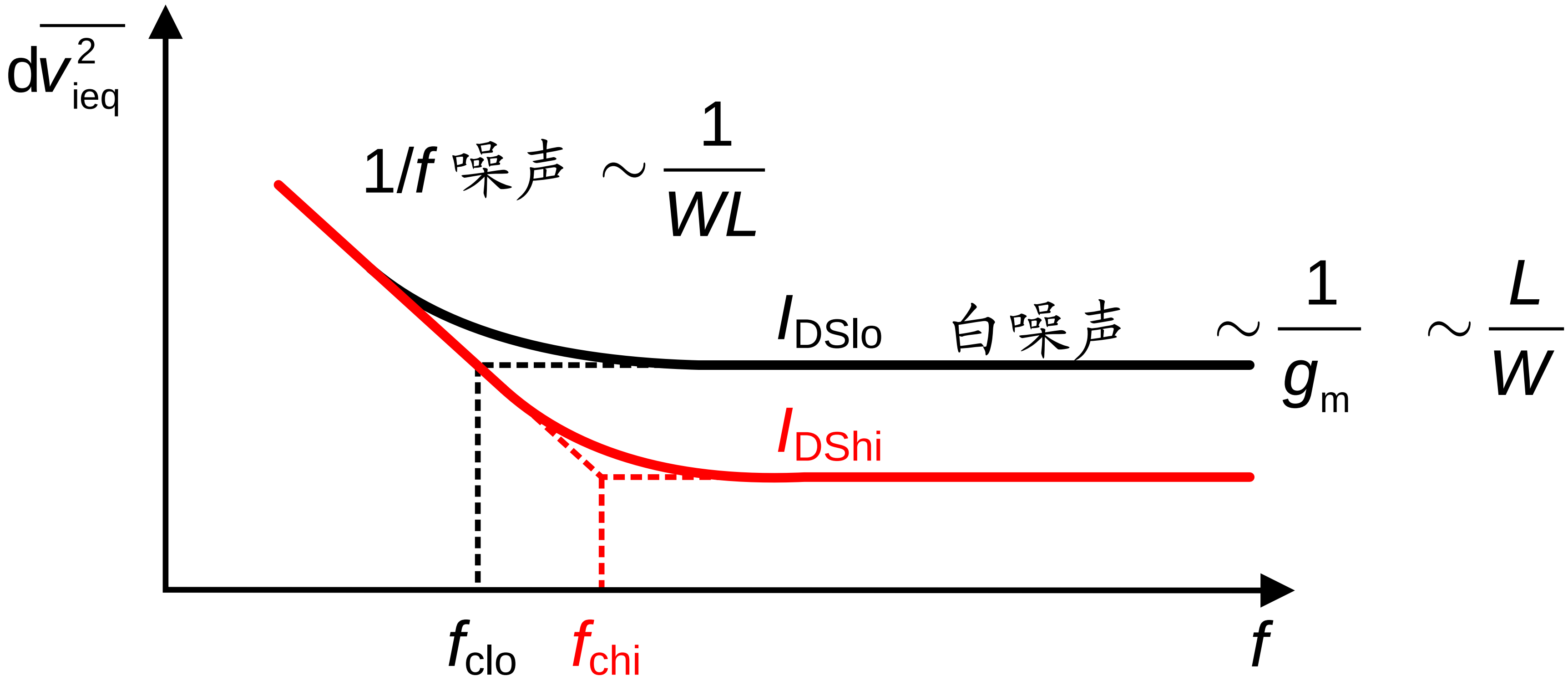
电流与噪声：拐角频率



拐角频率 $\sim g_m$

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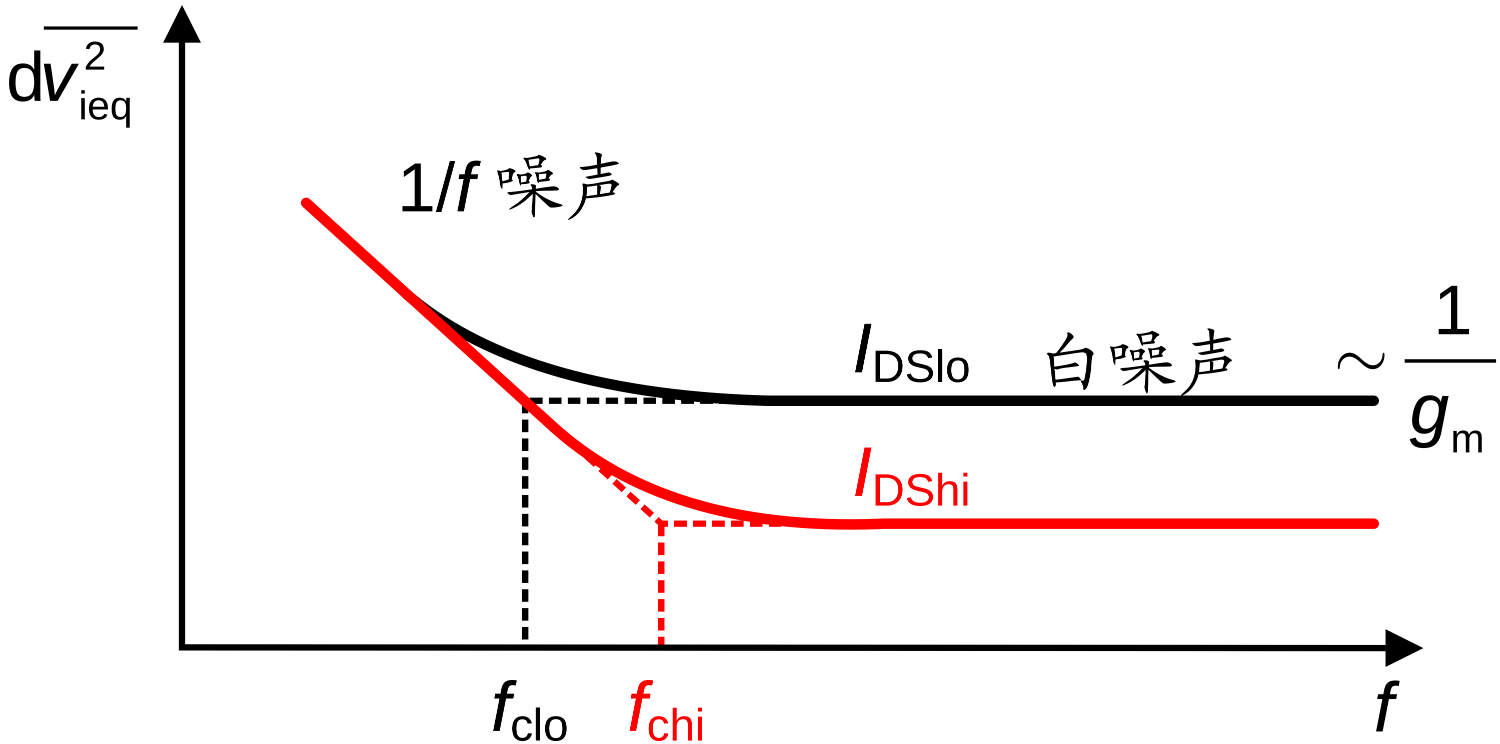
电流与噪声：练习，求f_c



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？

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从衬底看到的噪声

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

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

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

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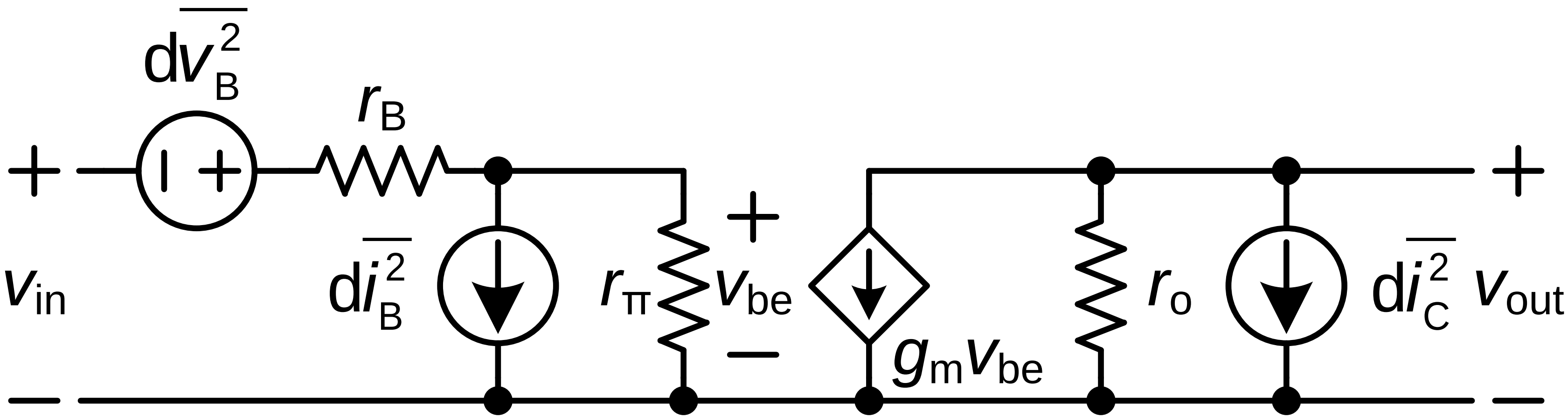
三极管的噪声



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

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

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

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

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

Ref.: Van der Ziel (Prentice Hall 1954)

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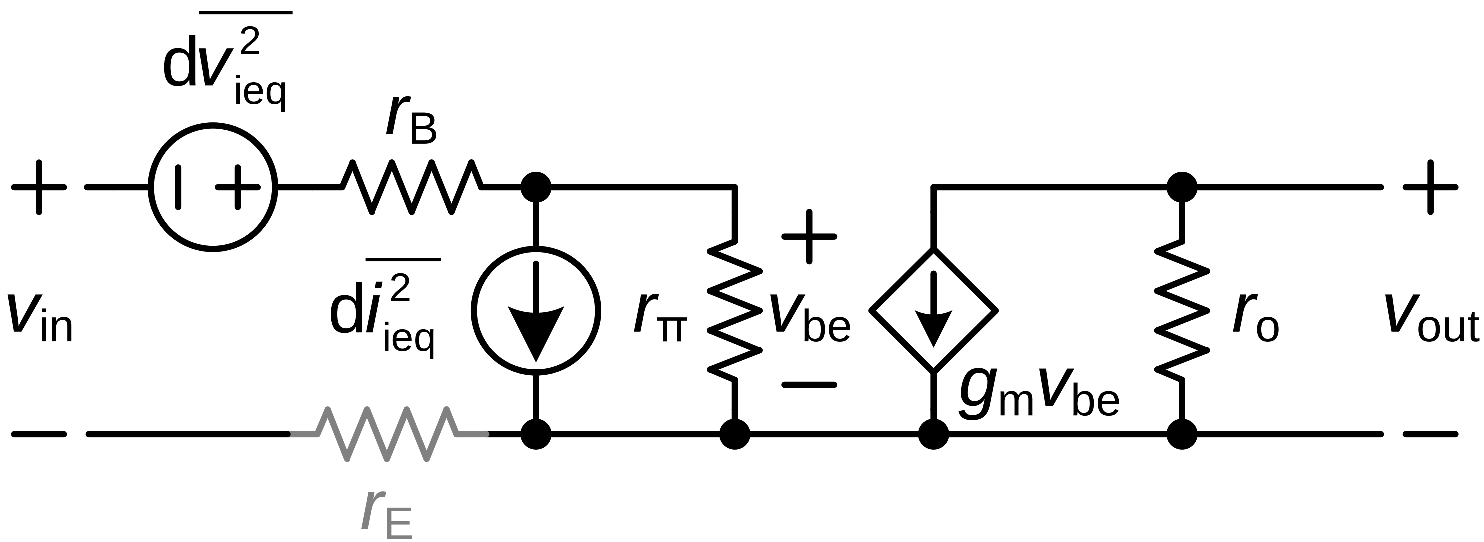
三极管：等效输入噪声



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

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

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

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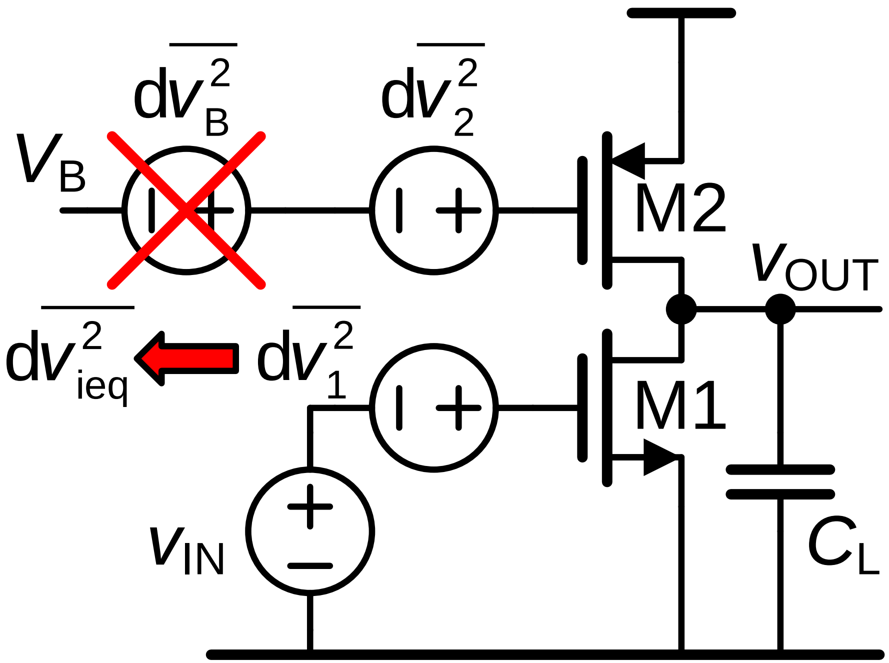
接有源负载的放大器的噪声



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}: $(W/L)_2$ ↓

$(V_{GS}-V_T)_2$ ↑

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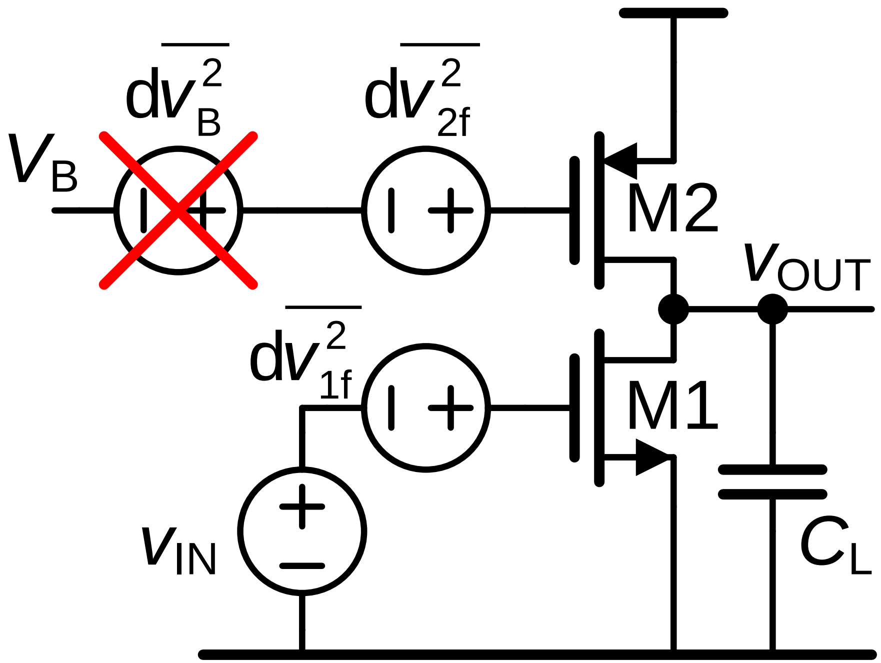
接有源负载的放大器的1/f 噪声



如果忽略 $\overline{dv_B^2}$

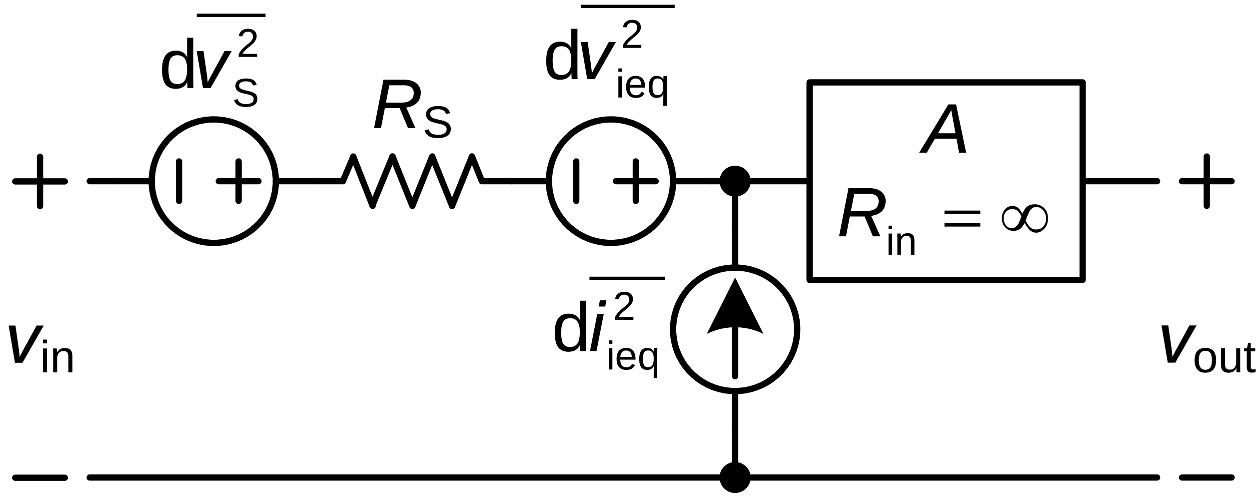
$$\overline{dv_{if}^2}=\overline{dv_{1f}^2}+\overline{dv_{2f}^2}\left(\frac{g_{m2}}{g_{m1}}\right)^2$$

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

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

$\overline{dv_{if}^2}$ 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 $NF\sim R_S$

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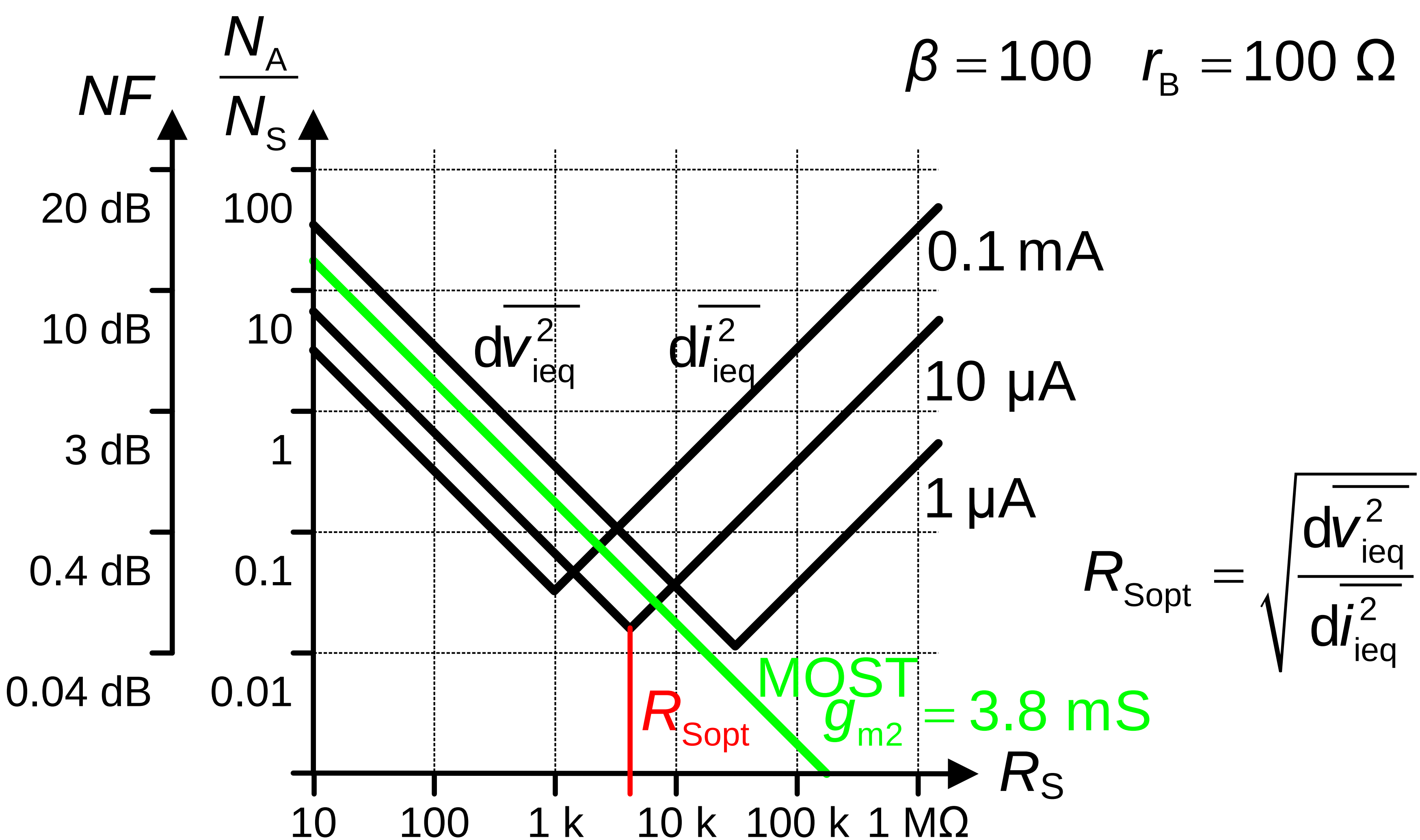
电阻噪声匹配



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

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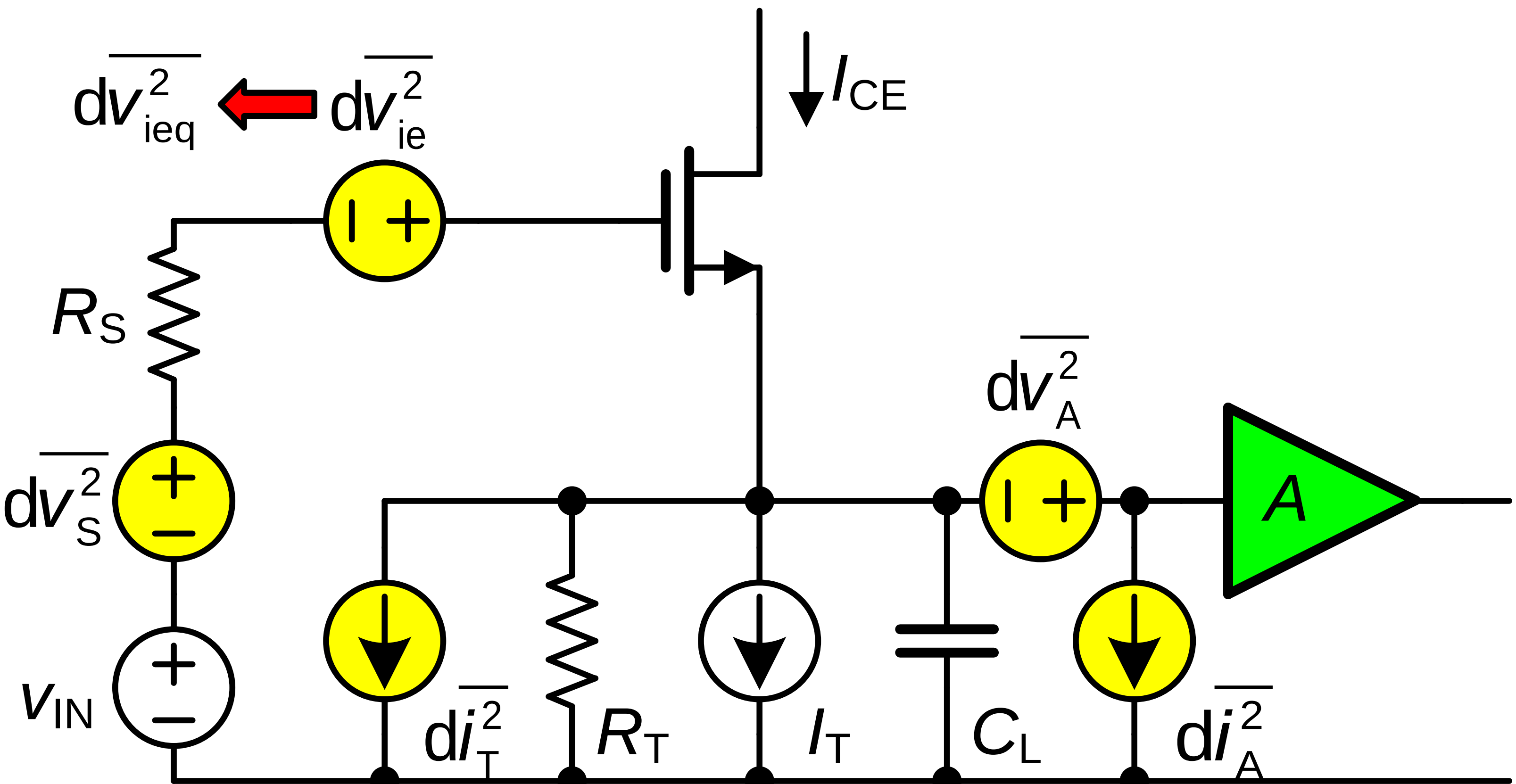
源极跟随器的噪声



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

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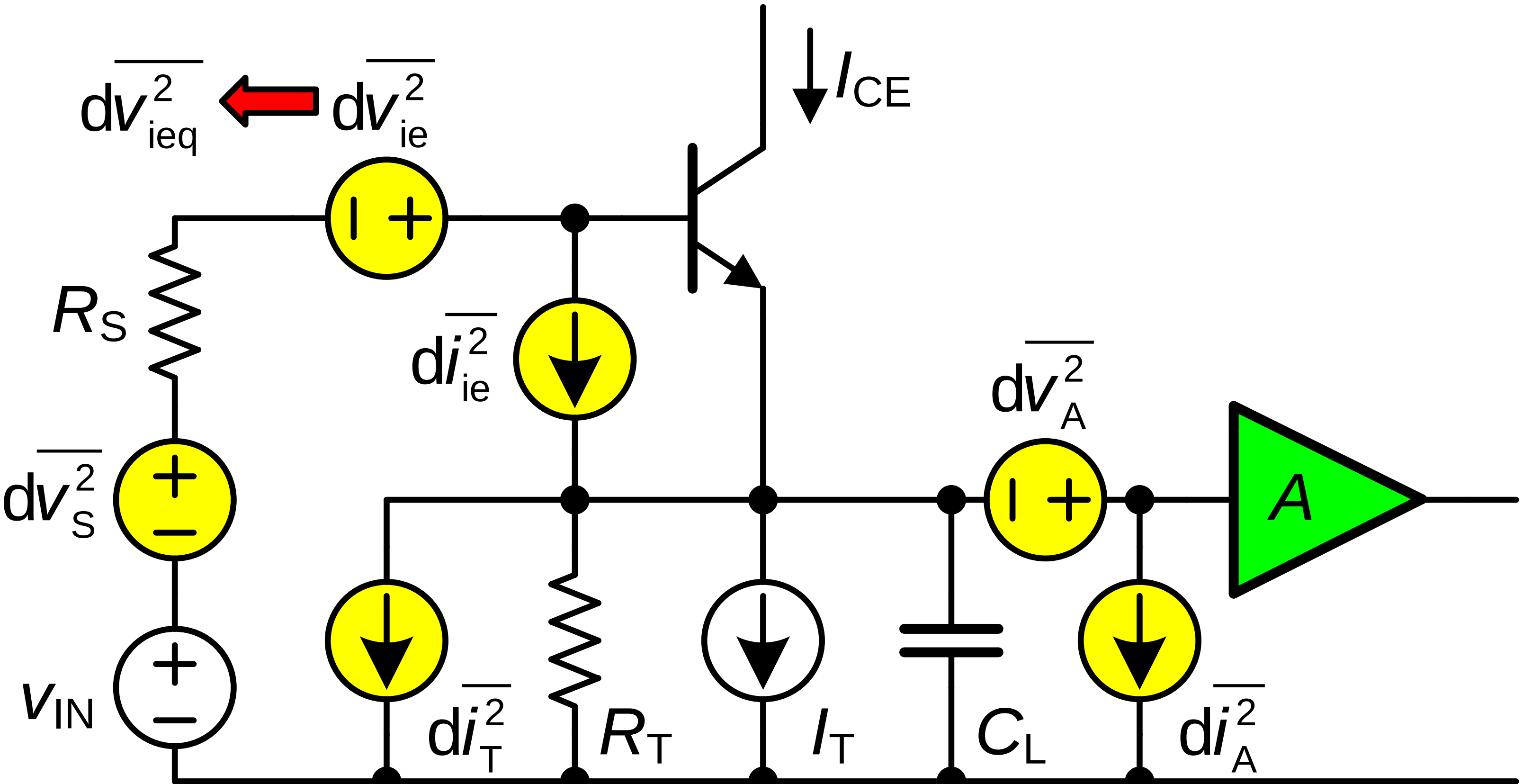
射极跟随器的噪声



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

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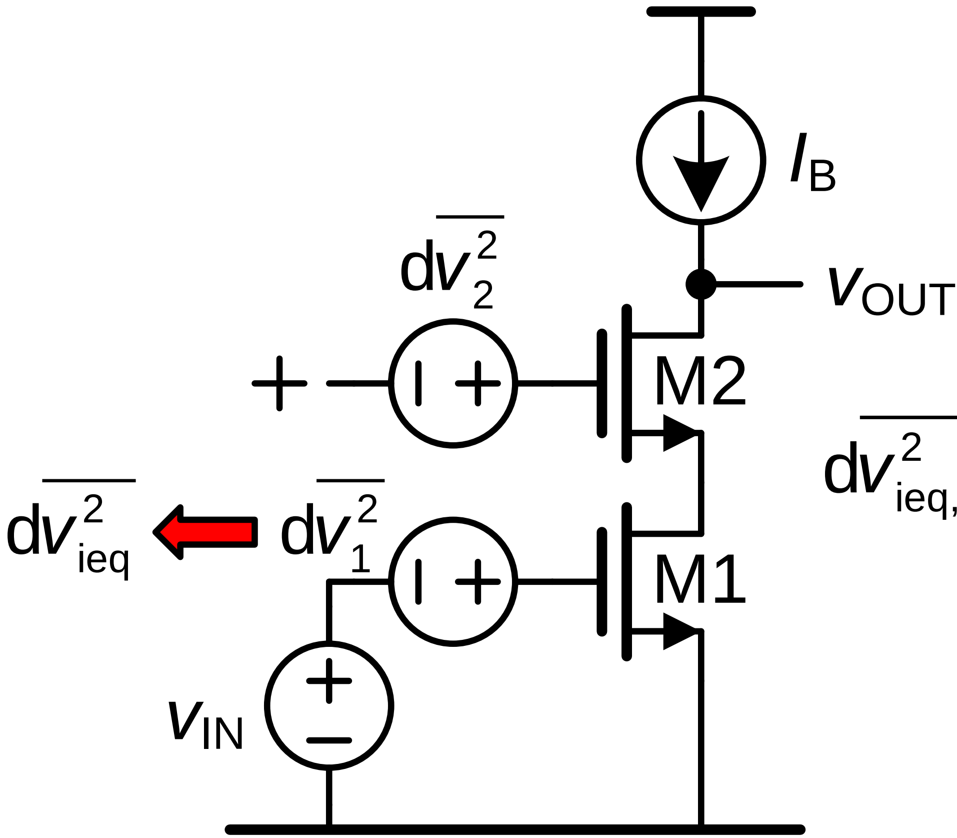
Ref.: W. Sansen : Analog Design Essentials, Springer 2006

共栅放大器的噪声



$$g_{m2} r_{DS1} >> 1$$

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

$$\approx \overline{dv_2^2}\frac{1}{(g_{m1}r_{DS1})^2}$$

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

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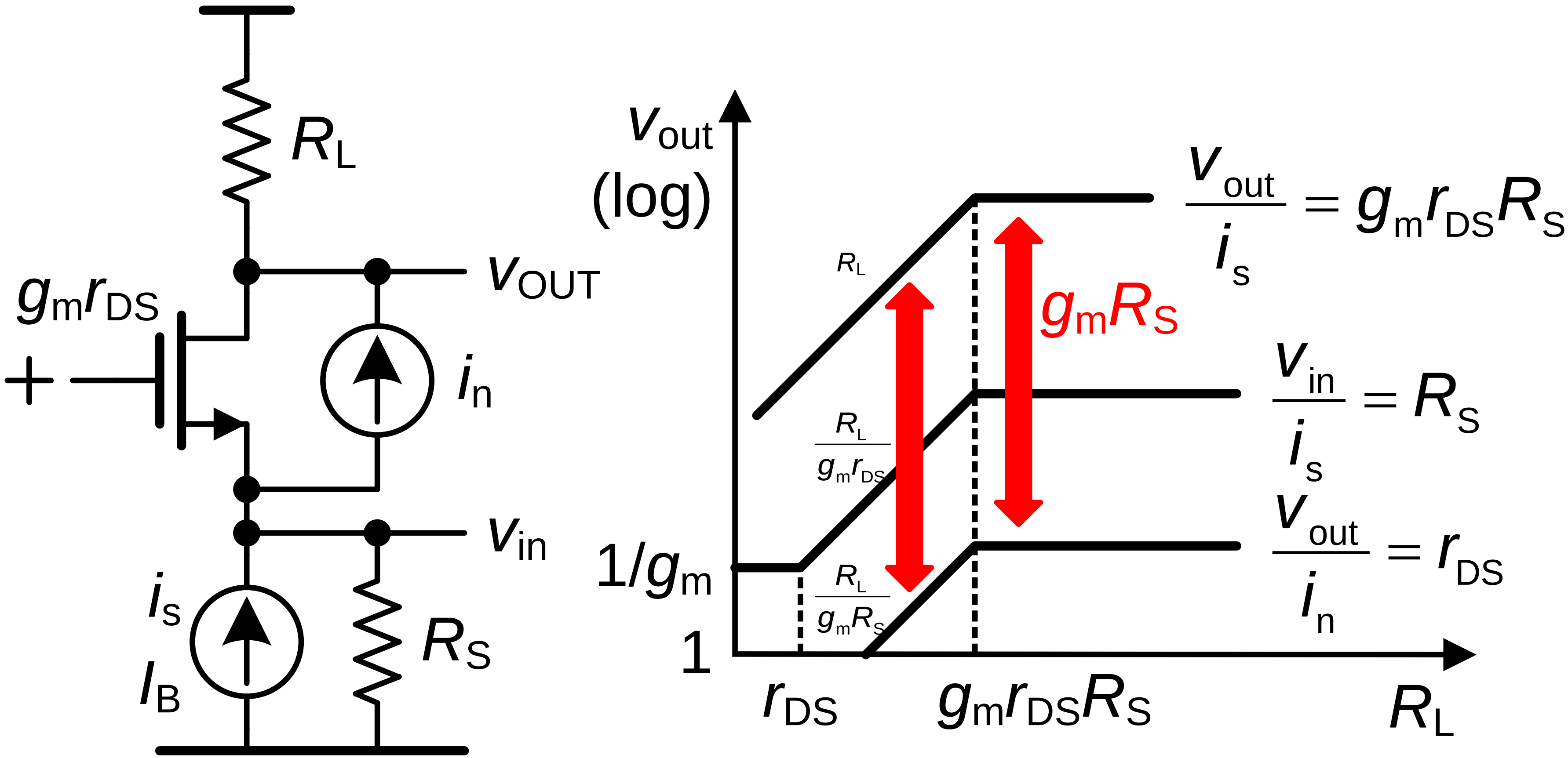
共栅放大器的输入参考噪声



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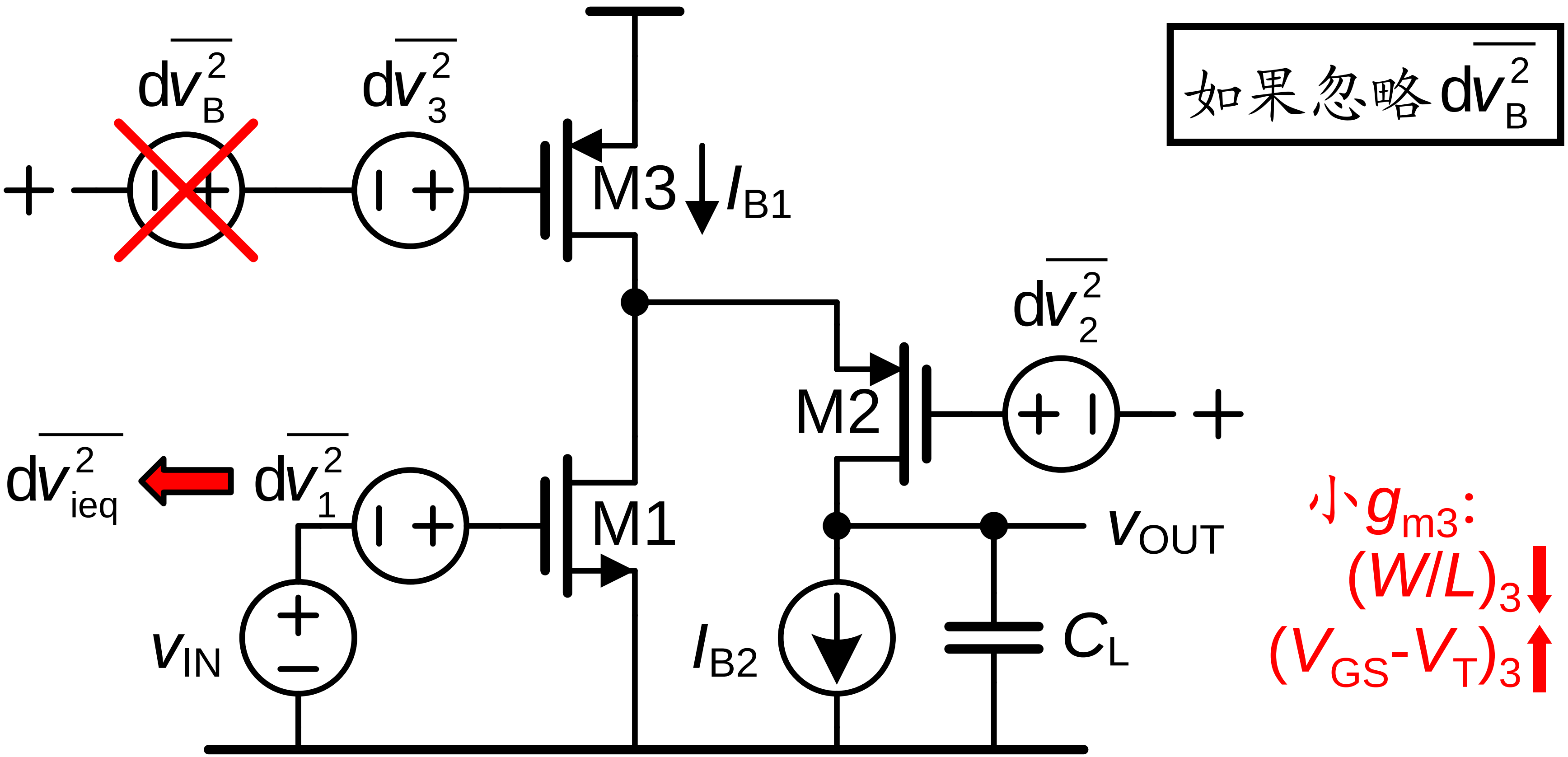
折叠共栅放大器的噪声



$$\overline{dv_{ieq}^2} = \overline{dv_1^2} + \overline{dv_2^2}\frac{1}{[g_{m1}(r_{DS1}//r_{DS3})]^2} + \overline{dv_3^2}\frac{g_{m3}^2}{g_{m1}^2}$$

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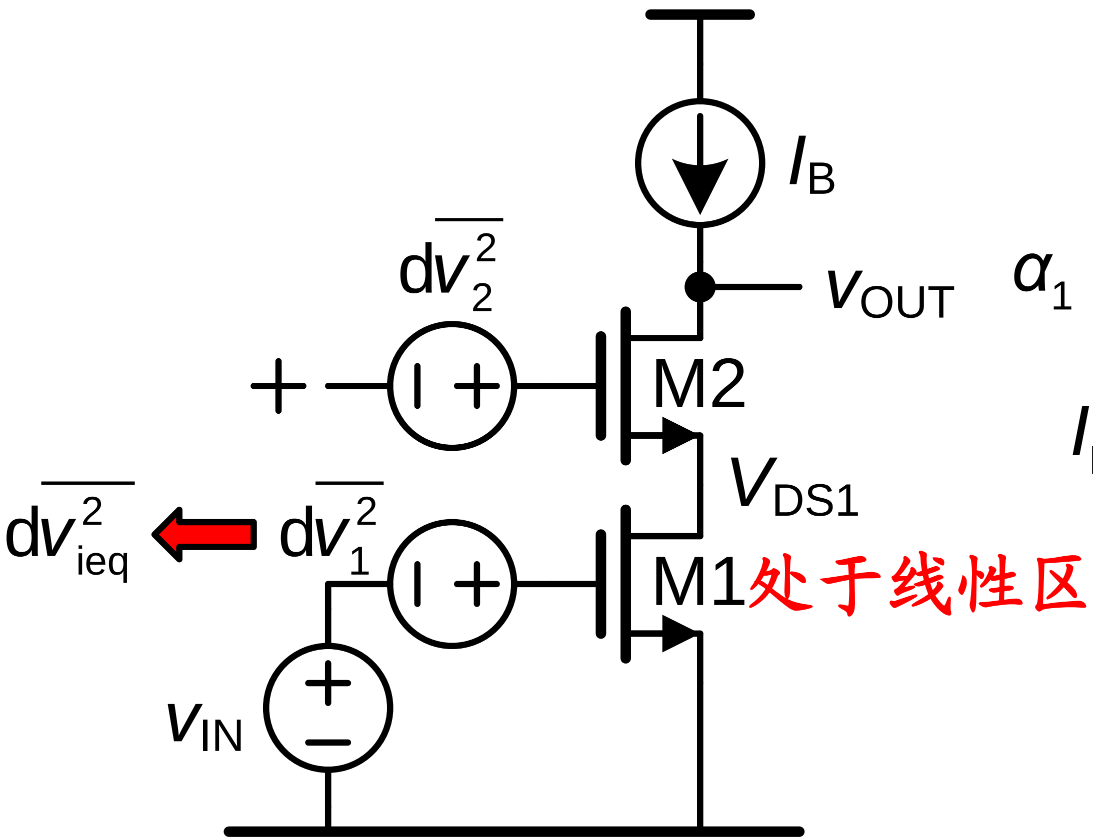
接线性MOST的共栅放大器的噪声



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

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

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

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

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

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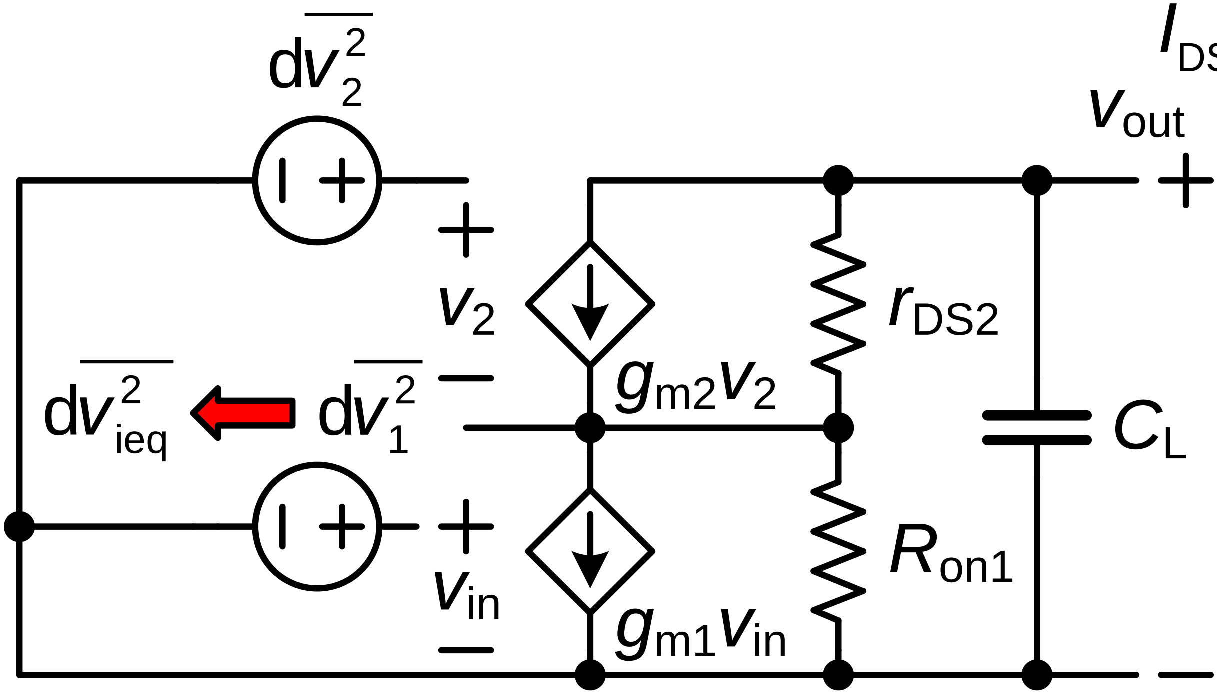
共栅放大器的小信号模型

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



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

$$\overline{dv_1^2} = \frac{4kTR_{on1}}{\alpha_1^2}df$$

$$\overline{dv_2^2} = \frac{4kT\,2/3}{g_{m2}}df$$

$$\frac{v_{out1}}{dv_1} = \alpha_1 g_{m2} r_{DS2} \qquad \frac{v_{out2}}{dv_2} = g_{m2} r_{DS2}$$

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

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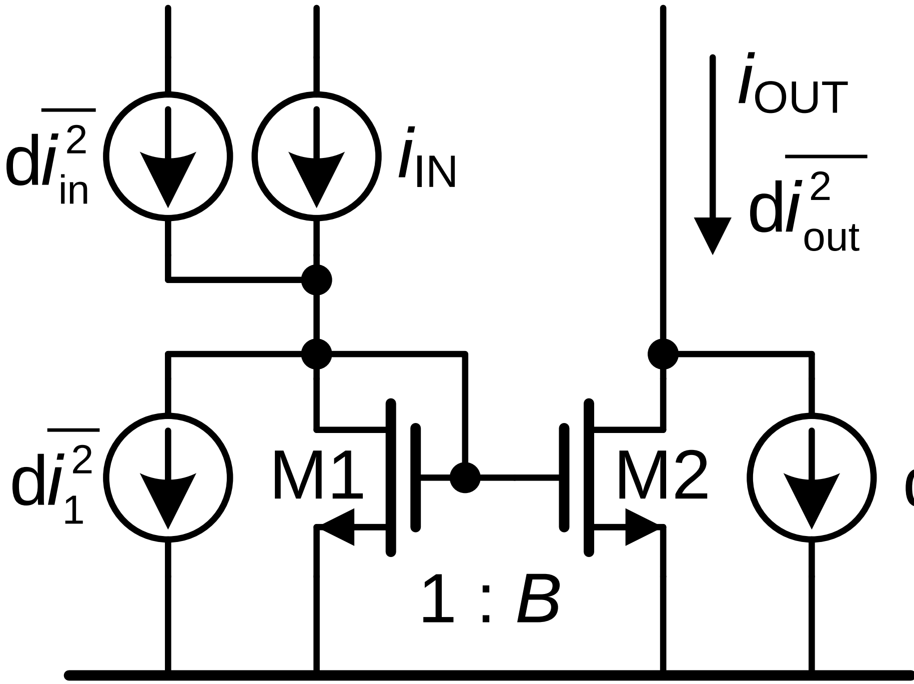
电流镜的噪声



$$\overline{di_2^2} = 4kT\frac{2}{3}g_{m2}df$$

小g_m:
(W/L)↓
$(V_{GS}-V_T)$↑

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

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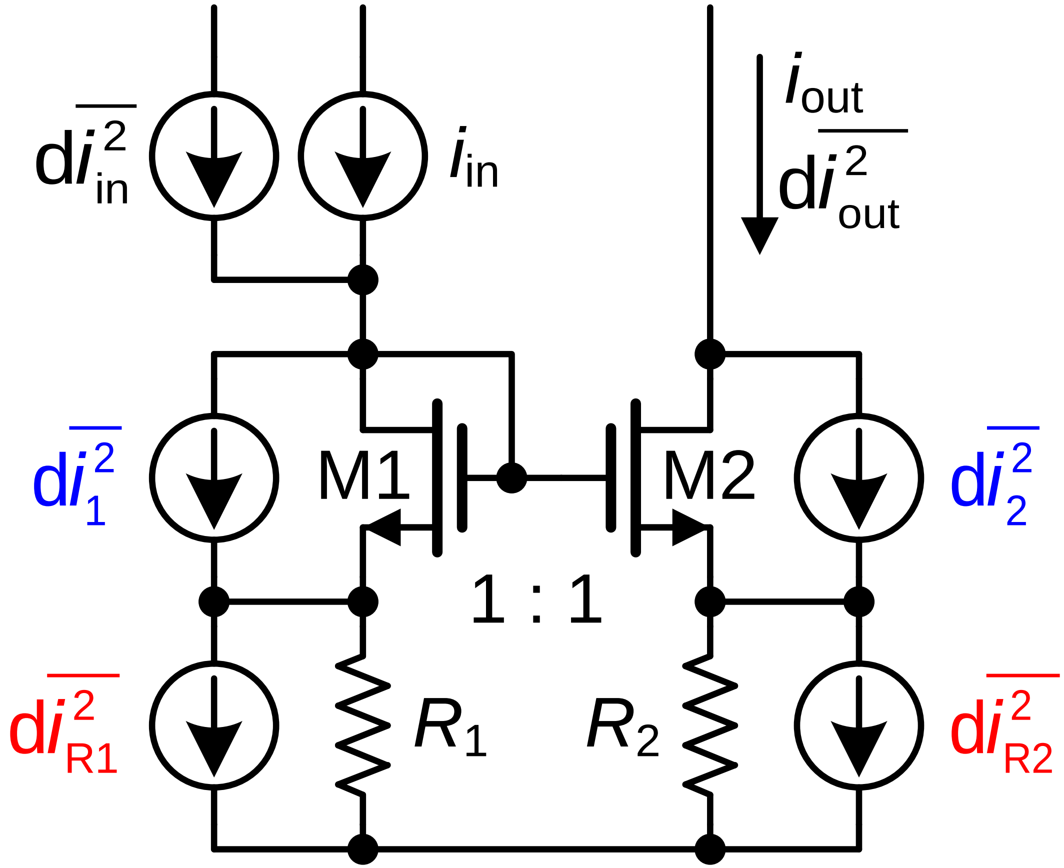
源极接串联电阻的电流镜的噪声—1



小 g_m:

(W/L) ↓

$(V_{GS}-V_T)$ ↑

R ↑

$$\overline{di_{out}^2} = \left(\frac{1}{1+g_{m2}R_2}\right)^2\left[\overline{di_2^2} + \left(\frac{g_{m2}}{g_{m1}}\right)^2\overline{di_1^2}\right] + \left(\frac{g_{m2}R_2}{1+g_{m2}R_2}\right)^2\left[\overline{di_{R2}^2} + \left(\frac{R_1}{R_2}\right)^2\overline{di_{R1}^2}\right]$$

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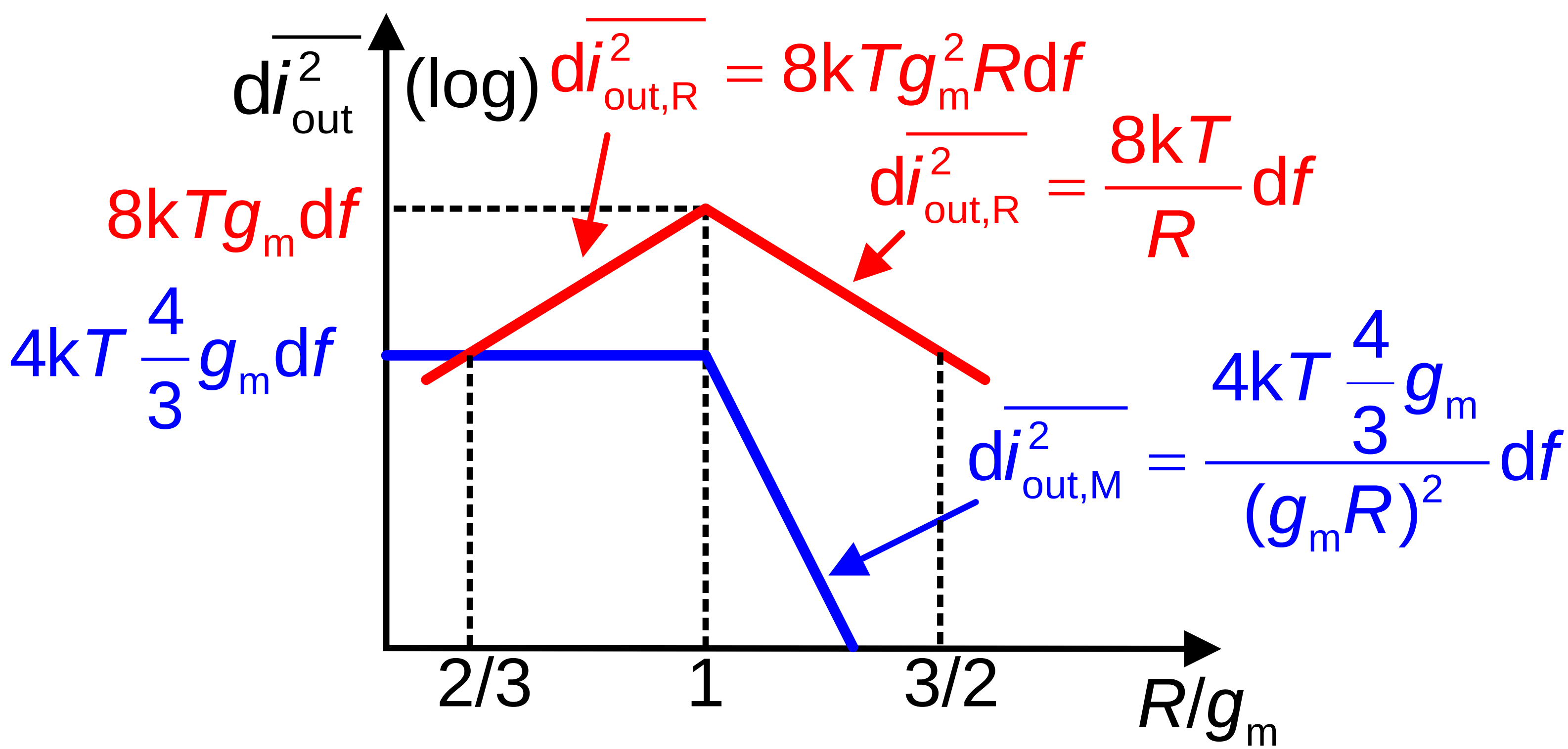
源极接串联电阻的电流镜的噪声—2

$$\left.\begin{array}{l} g_{m1}=g_{m2}=g_m \\ R_1=R_2=R \end{array}\right\} \Rightarrow \mathrm{d}\overline{i_{out}^2}=2\left(\frac{1}{1+g_mR}\right)^2\mathrm{d}\overline{i^2}+2\left(\frac{g_mR}{1+g_mR}\right)^2\mathrm{d}\overline{i_R^2}$$



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

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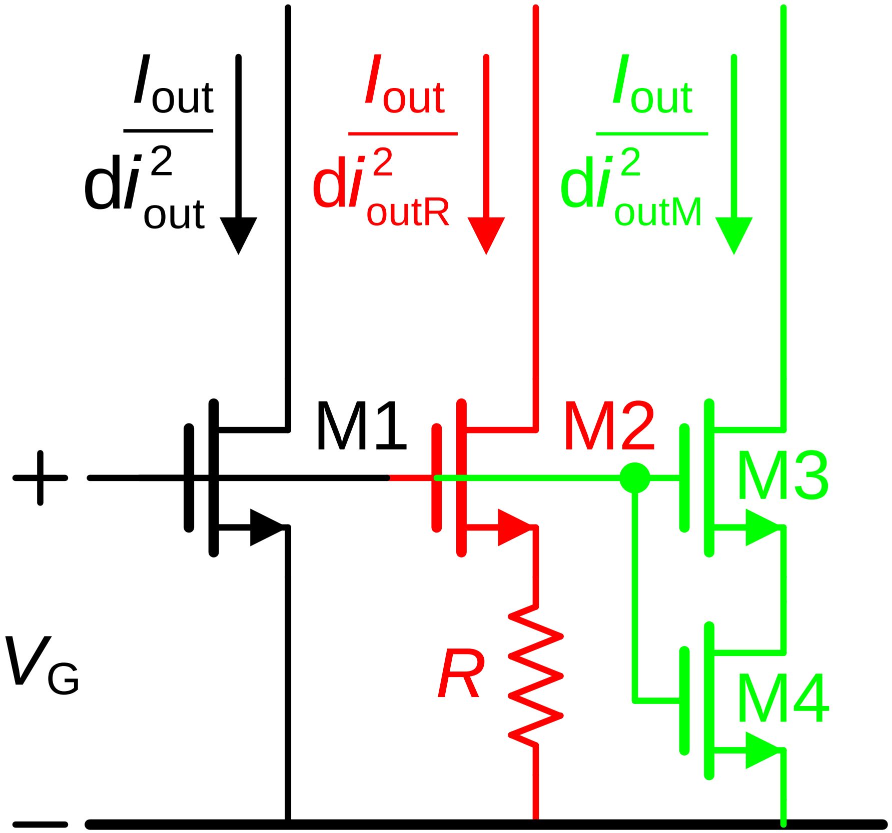
源极接串联电阻的电流镜



相同的 I_{out} 和相同的 V_G：

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

$(V_{GS} - V_T)_1 \uparrow$ $(V_{GS} - V_T)_3 \downarrow$

$(W/L)_1 \downarrow$ $(W/L)_3 \uparrow$

小 g_m：

$(W/L) \downarrow$

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

$V_G \uparrow$

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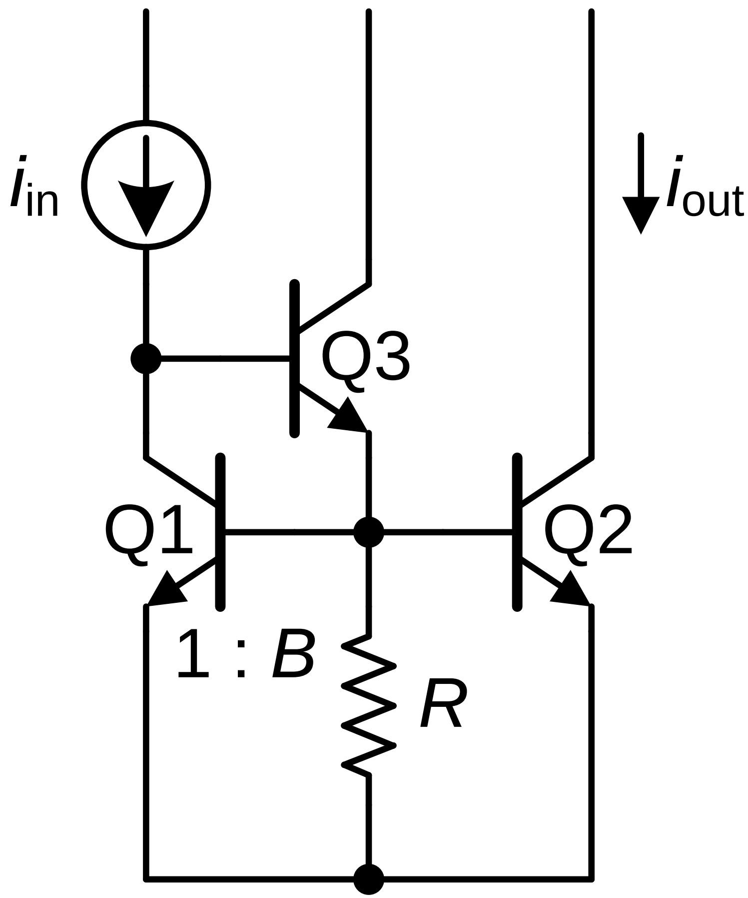
双极型晶体管电流镜的噪声



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，均可忽略！

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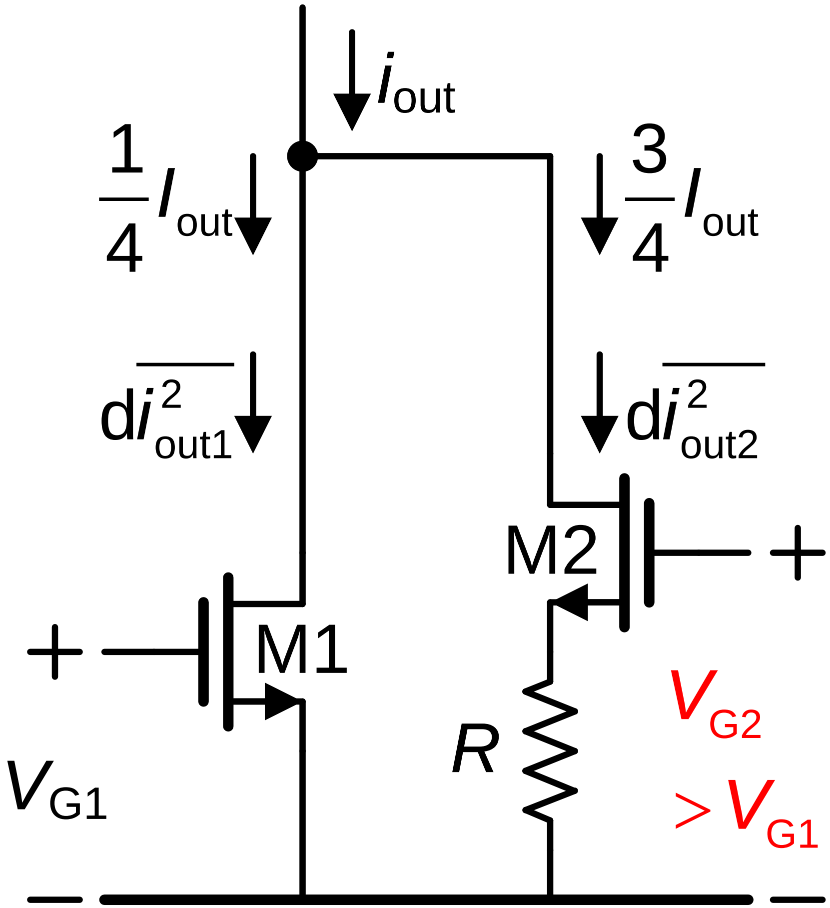
接串联电阻的低噪声电流镜



选用大的R或V_{G2}

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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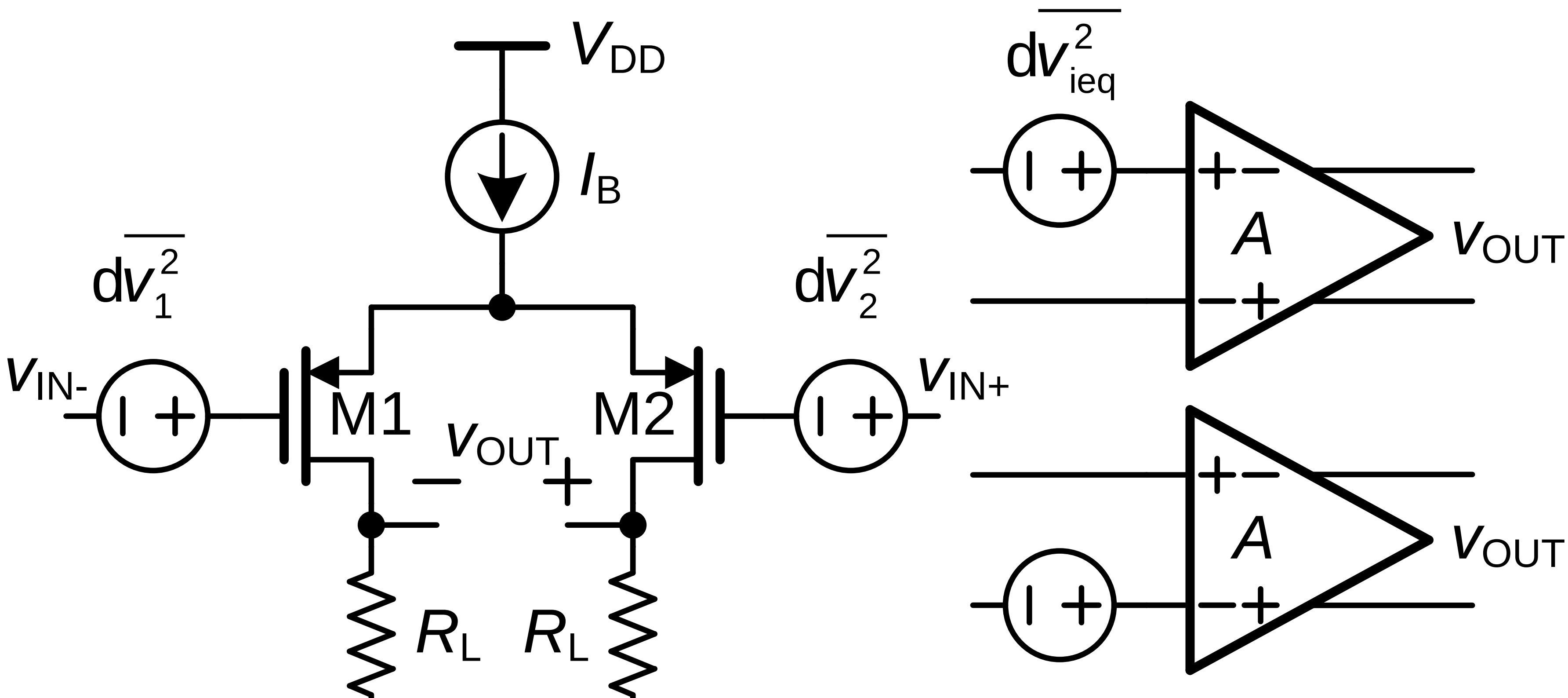
差分对的噪声



$$\overline{dv_{ieq}^2} = 2\overline{dv_1^2}$$

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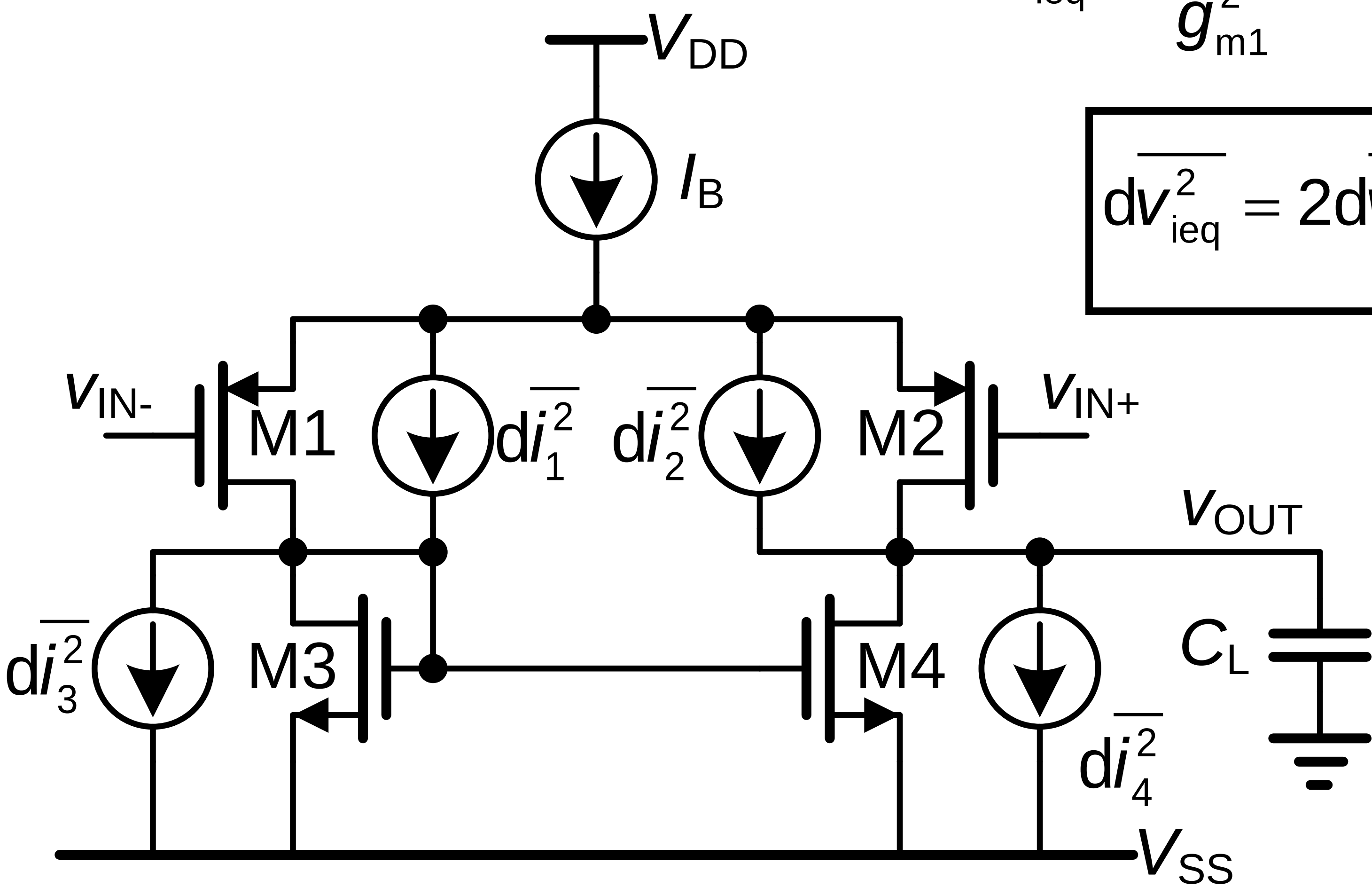
接有源负载差分对的噪声

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

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



小g_{m3}:
$(W/L)_3$↓
$(V_{GS}-V_T)_3$↑

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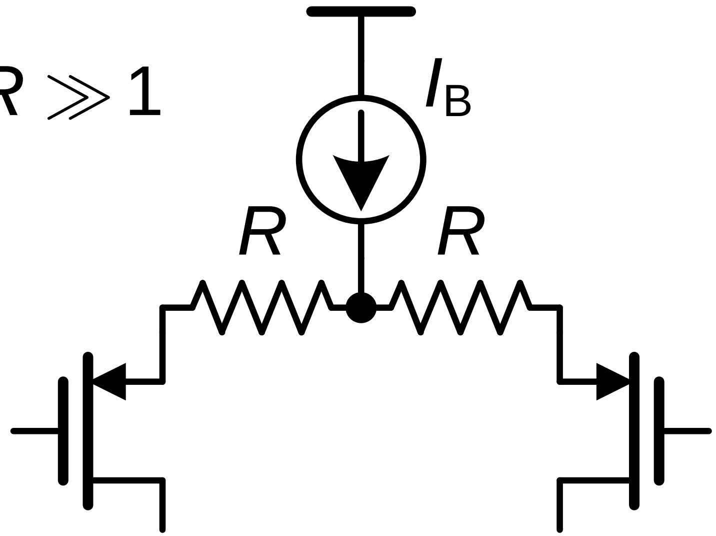
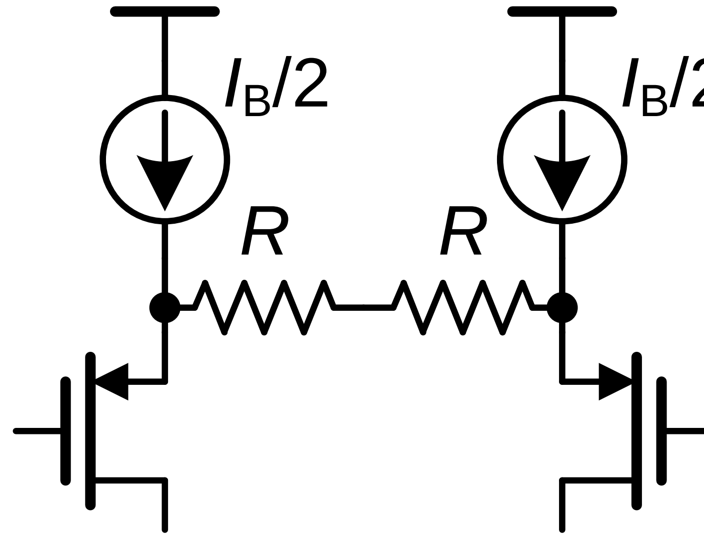
接源电阻的差分对

$g_m R \gg 1$





$$\mathrm{d}\overline{i_{out}^2} = 2\frac{4kT}{R}\mathrm{d}f$$

忽略 $\mathrm{d}\overline{i_B^2}$

$$\mathrm{d}\overline{v_{in}^2} = 2(4kTR\mathrm{d}f)$$

$$\mathrm{d}\overline{i_{out}^2} = 2\left(\frac{4kT}{R}\mathrm{d}f + \mathrm{d}\overline{i_B^2}\right)$$

$$\mathrm{d}\overline{i_B^2} = 4kT\frac{2}{3}g_{mB}\mathrm{d}f$$

$$\mathrm{d}\overline{v_{in}^2} = 2(4kTR\mathrm{d}f)\left(1+\frac{2}{3}g_{mB}R\right)$$

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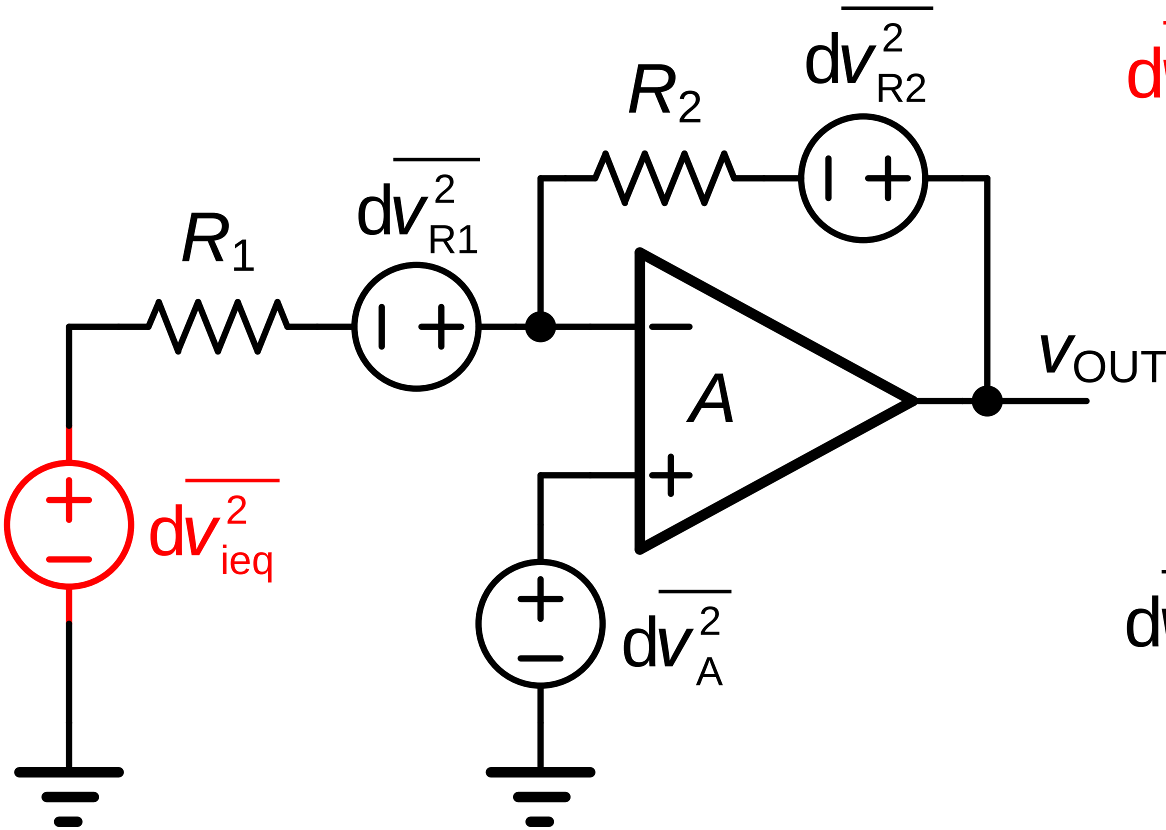
放大器的噪声



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

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

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

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

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

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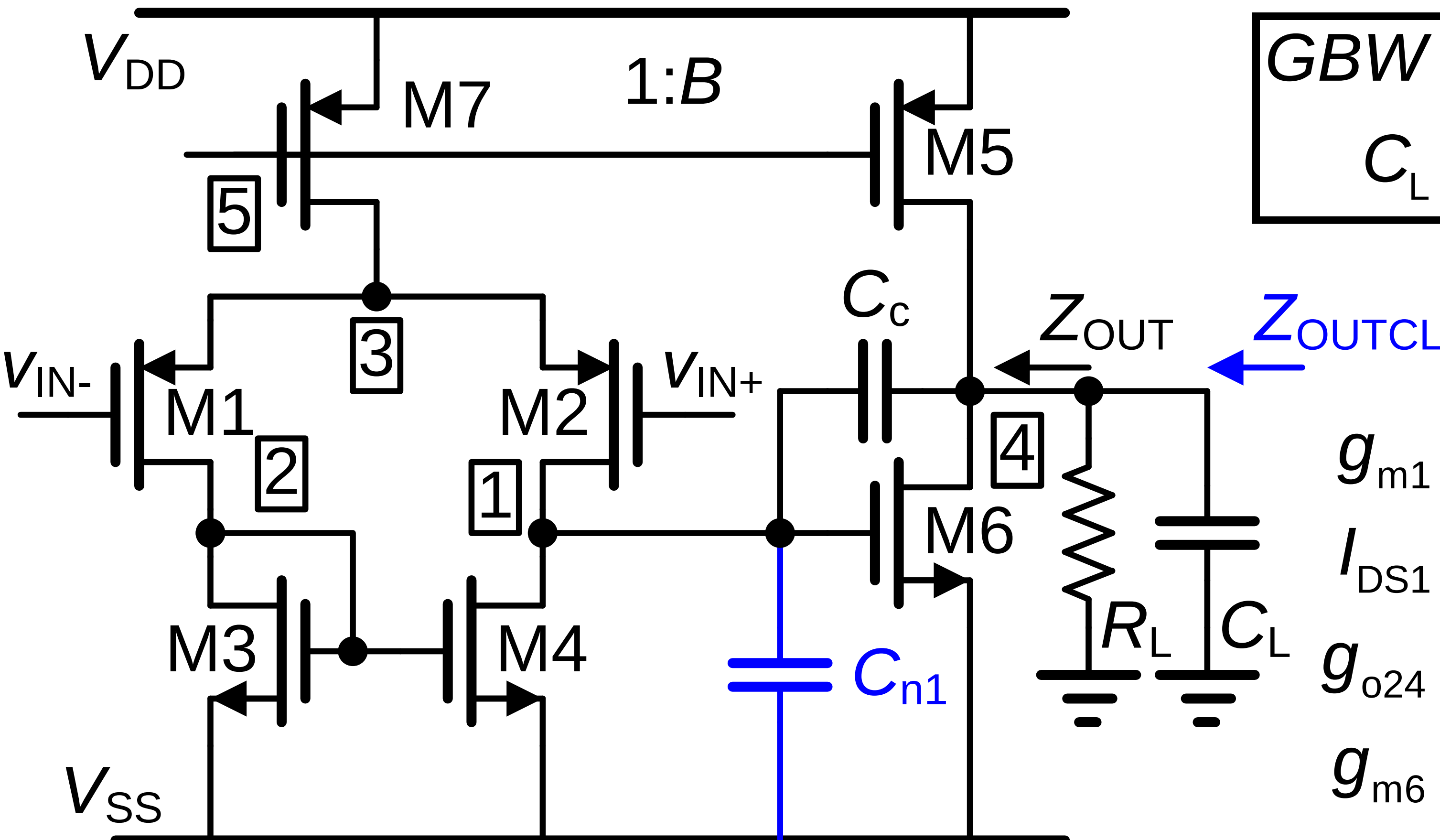
密勒CMOS OTA



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

$$g_{m1} = 7.5\ \mu S$$
$$I_{DS1} = 1.1\ \mu A$$
$$g_{o24} = 0.03\ \mu S$$
$$g_{m6} = 246\ \mu S$$
$$I_{DS6} = 25\ \mu A$$

$$g_{Lo6} = 20\ \mu S \quad C_c = 1\text{ pF}$$

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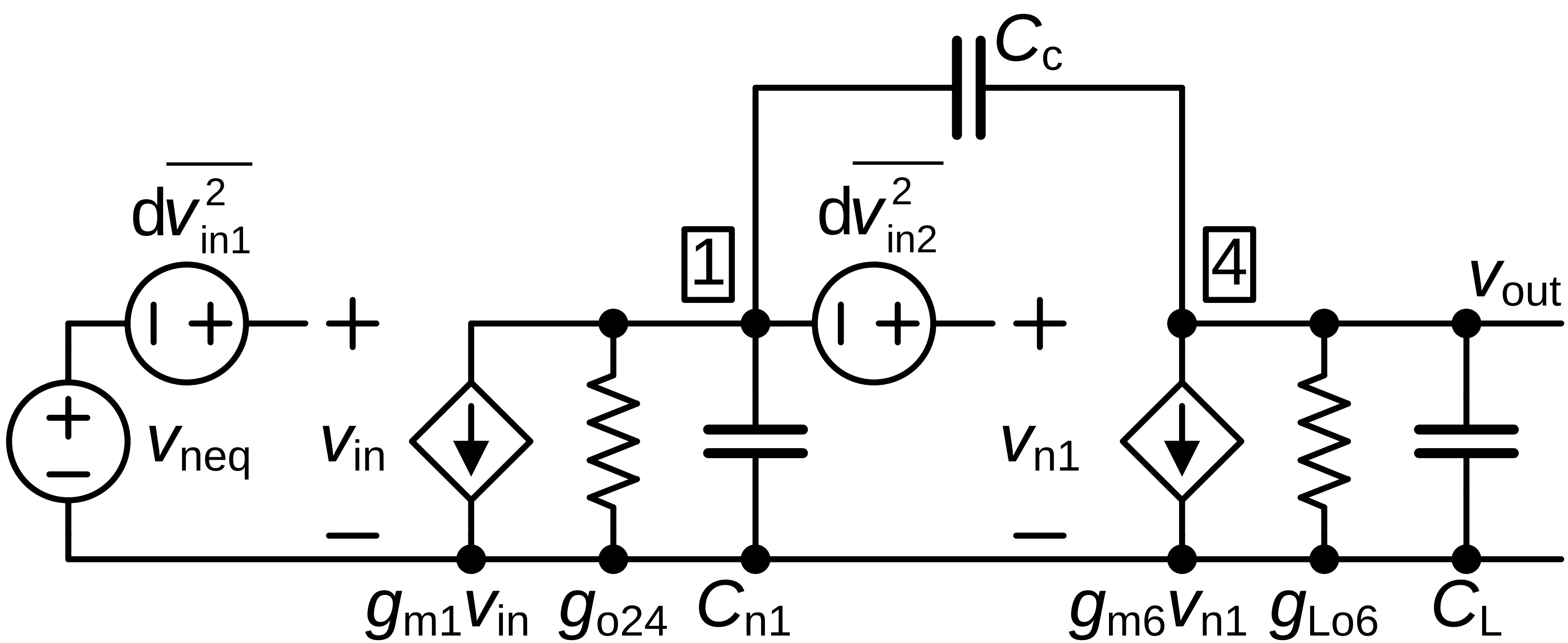
密勒CMOS OTA：噪声密度 1



$$\overline{dv_{in1}^2} = 4kT\frac{4/3}{g_{m1}}df \qquad \overline{dv_{in2}^2} = 4kT\frac{2/3}{g_{m6}}df$$

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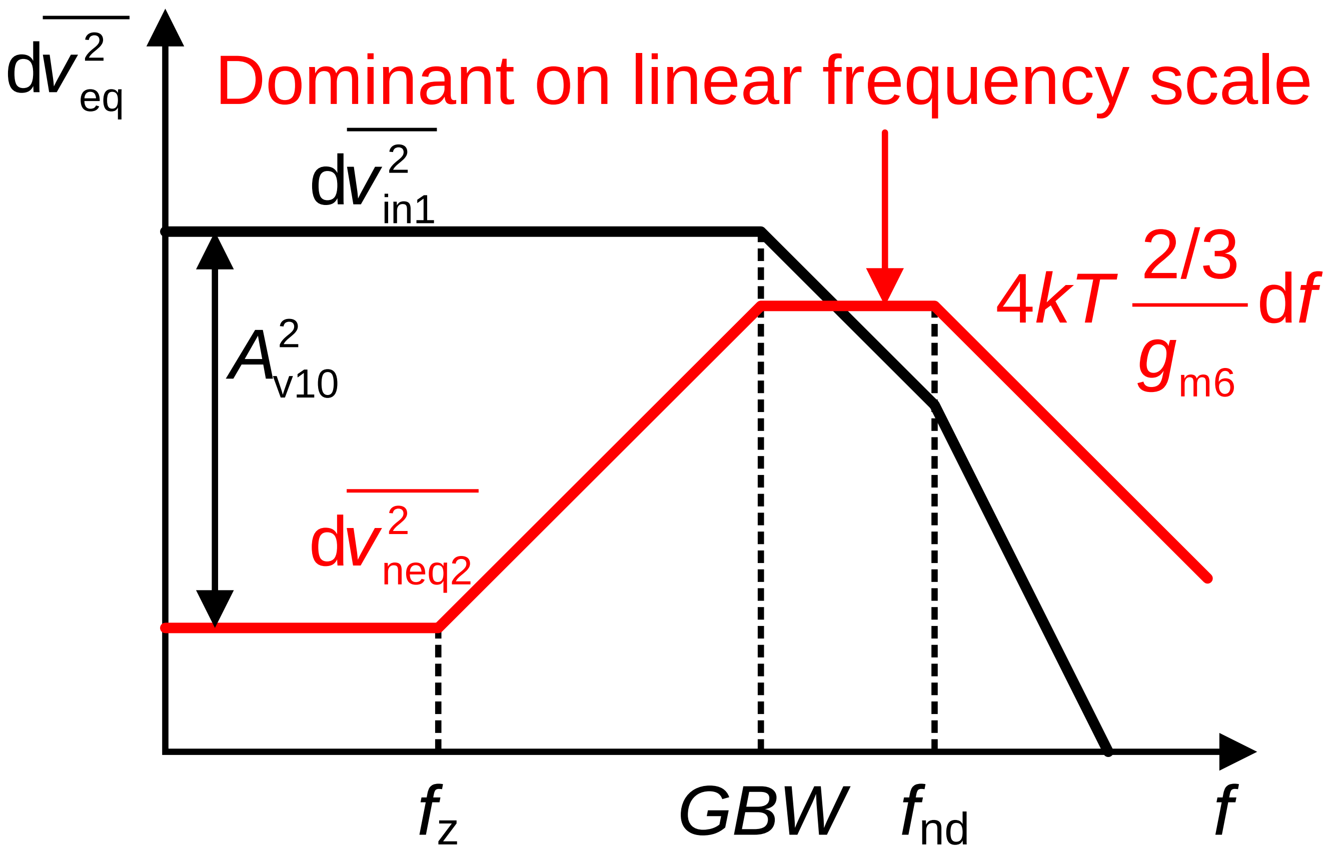
密勒CMOS OTA：噪声密度 2



$$\overline{dv_{neq2}^2} = \frac{\overline{dv_{in2}^2}}{|A_{V1}|^2}$$

$$A_{V10} = \frac{g_{m1}}{g_{o24}}$$

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

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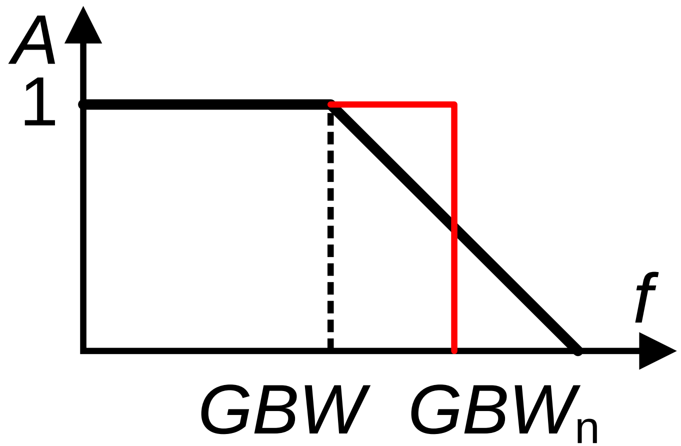
密勒CMOS OTA：积分噪声



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

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

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

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

$$C_c = 1\,\text{pF} \quad v_{Rs} = 74.5\ \mu V_{RMS}$$

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

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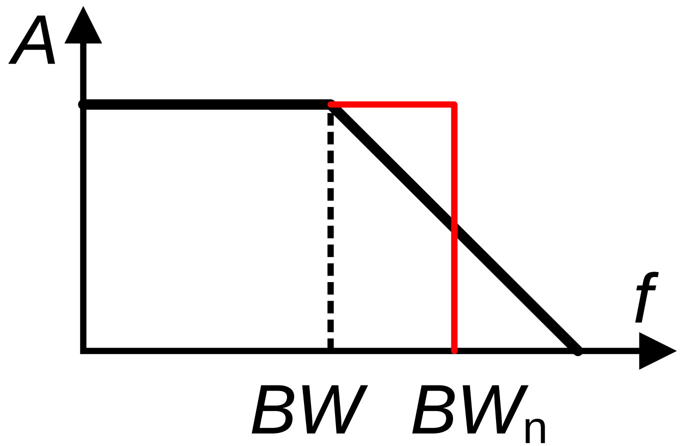
噪声密度与积分噪声



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

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

噪声密度(V^2/Hz) ~ $1/g_m$(或R_S)

积分噪声(V_{REM}) ~ $1/C_c$

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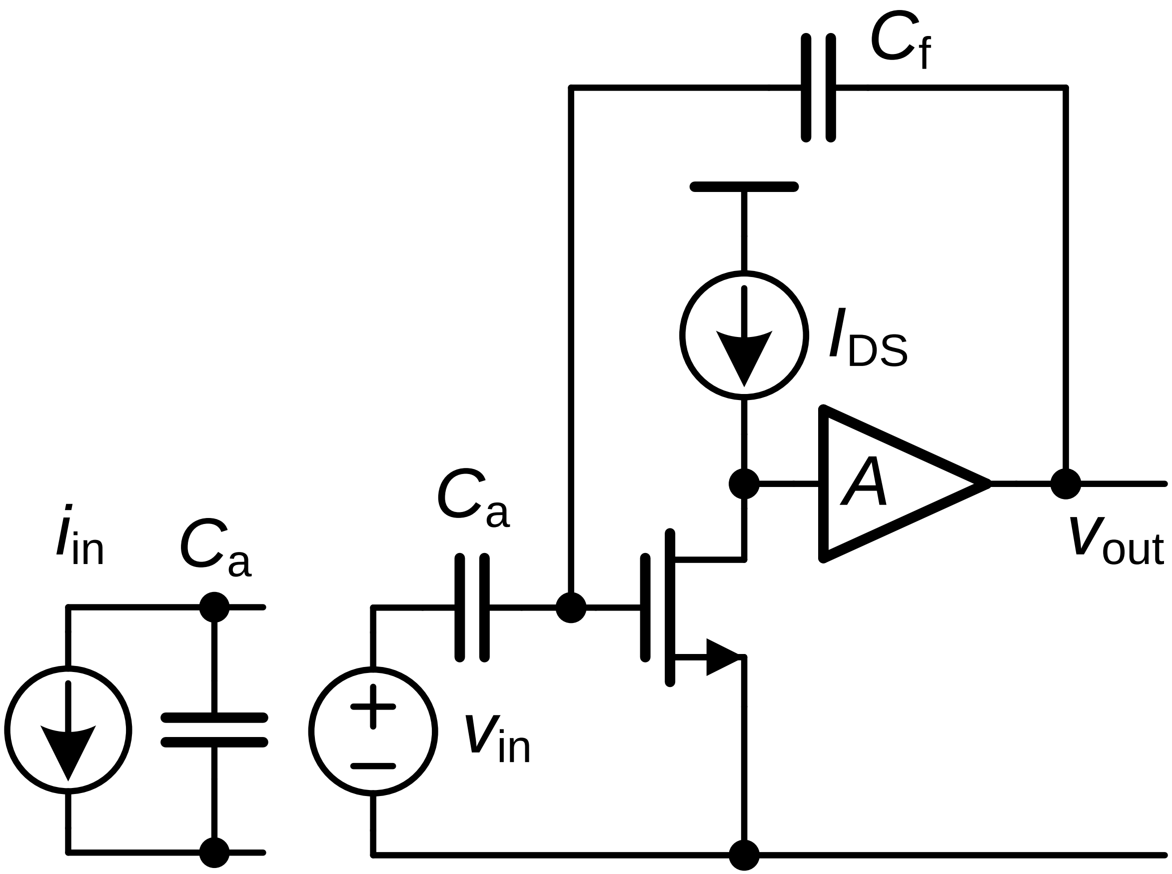
容性源放大器



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

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

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

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

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

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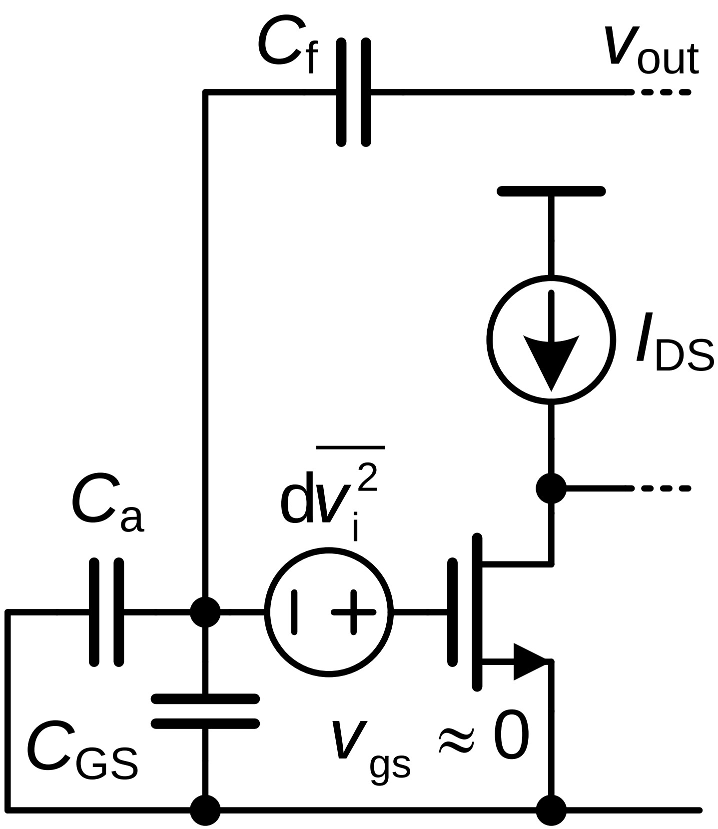
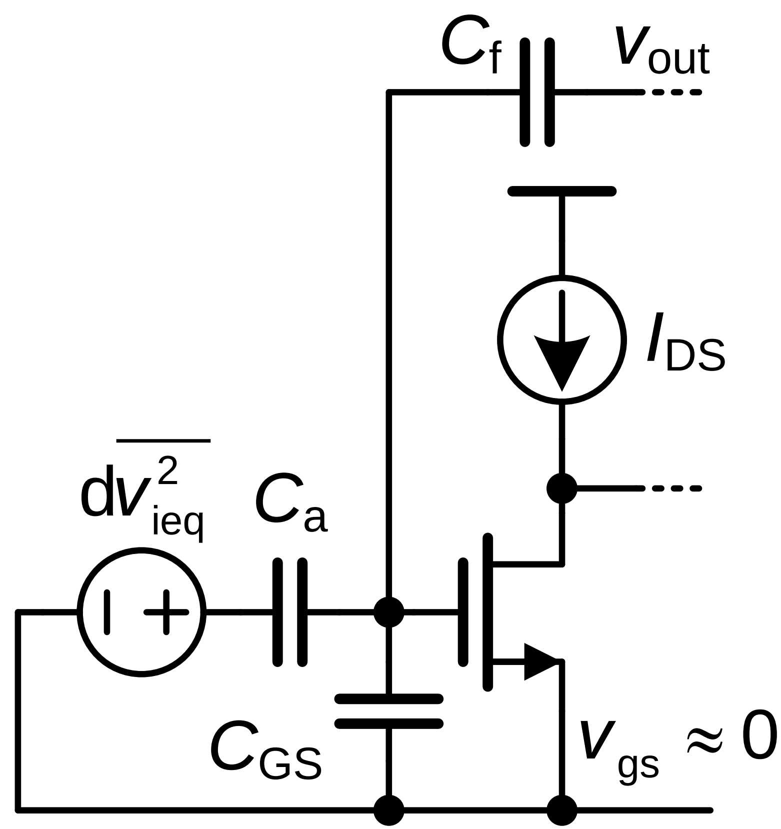
容性噪声匹配—1





$$\frac{v_{out}}{v_i} = -\frac{C_f + C_a + C_{GS}}{C_f}$$

$$\frac{v_{out}}{v_{ieq}} = -\frac{C_a}{C_f}$$

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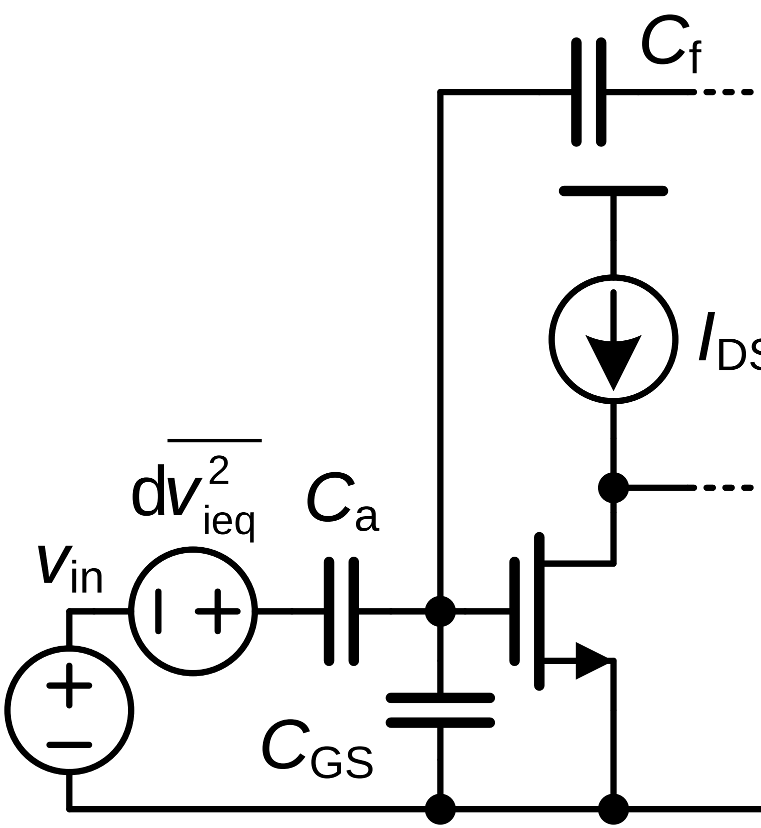
容性噪声匹配—2



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

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

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

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

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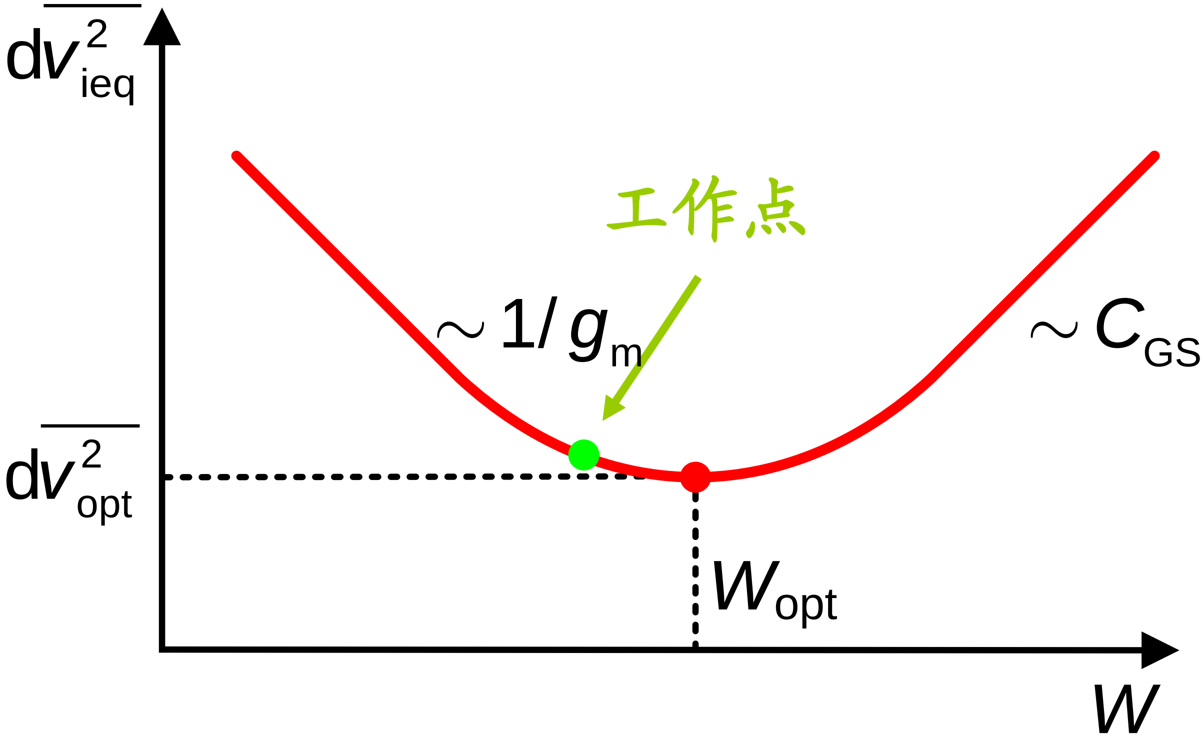
容性噪声匹配—3



噪声匹配条件

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

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

$$d\overline{v^2_{ieq}}=\frac{(C_f+C_a+kW)^2}{C_a^2}\frac{L}{W}\frac{8kT}{3}\frac{1}{2K_n'(V_{GS}-V_T)}$$

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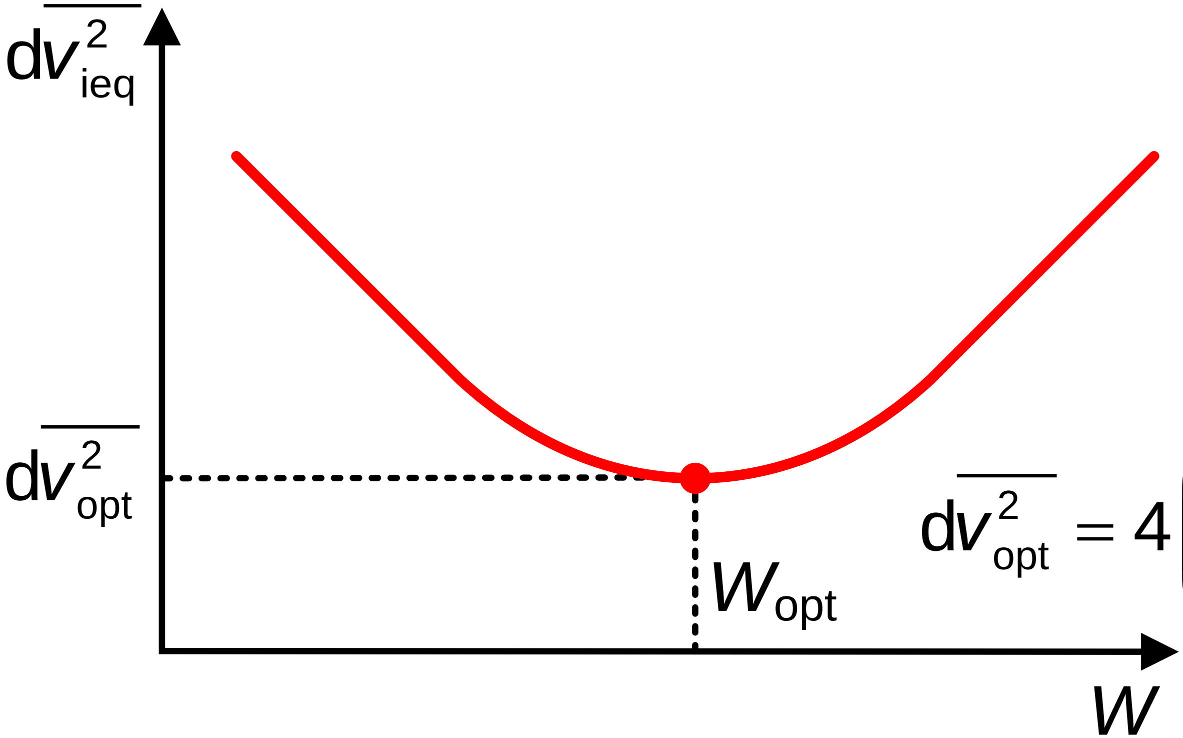
容性噪声匹配—4



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

C_{GSopt}，I_{DSopt}，g_{mopt}

$$\overline{dv^2_{opt}}=4\left(\frac{C_f+C_a}{C_a}\right)^2\frac{8kT}{3}\frac{df}{g_{mopt}}$$

$$BW_n=\frac{\pi}{2}BW=\frac{\pi}{2}\frac{f_T}{A_V}=\frac{1}{4A_V}\frac{g_{mopt}}{C_{GSopt}}$$

$$\left(\frac{S}{N}\right)_{opt}=\frac{10\ \mathrm{mV_{RMS}}}{\sqrt{\overline{dv^2_{opt}}BW_n}}$$

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

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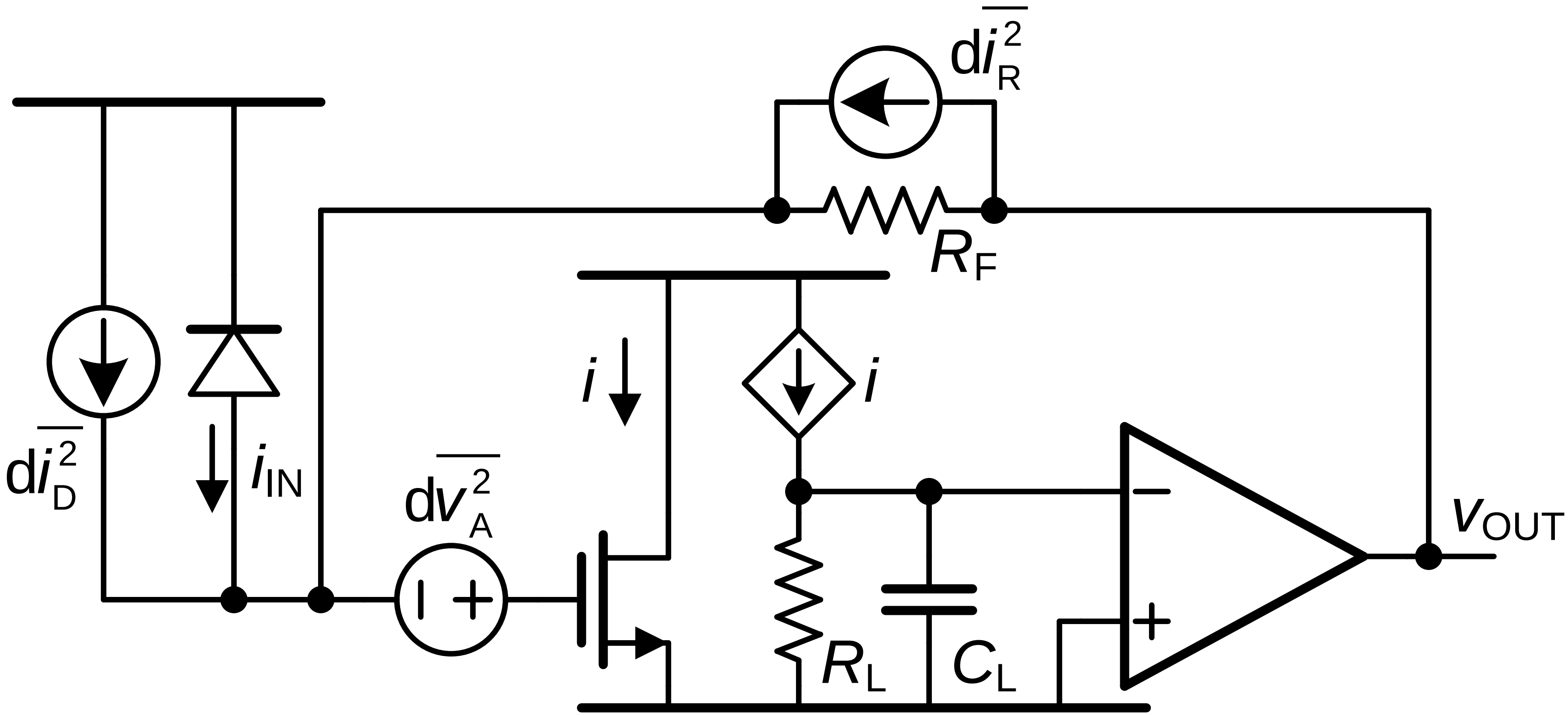
电压检测放大器的噪声源



$$d\overline{i_D^2} = 2qI_D df \qquad d\overline{i_R^2} = \frac{4kT}{R_F} df \qquad d\overline{v_A^2} = 4kT\frac{2/3}{g_m} df$$

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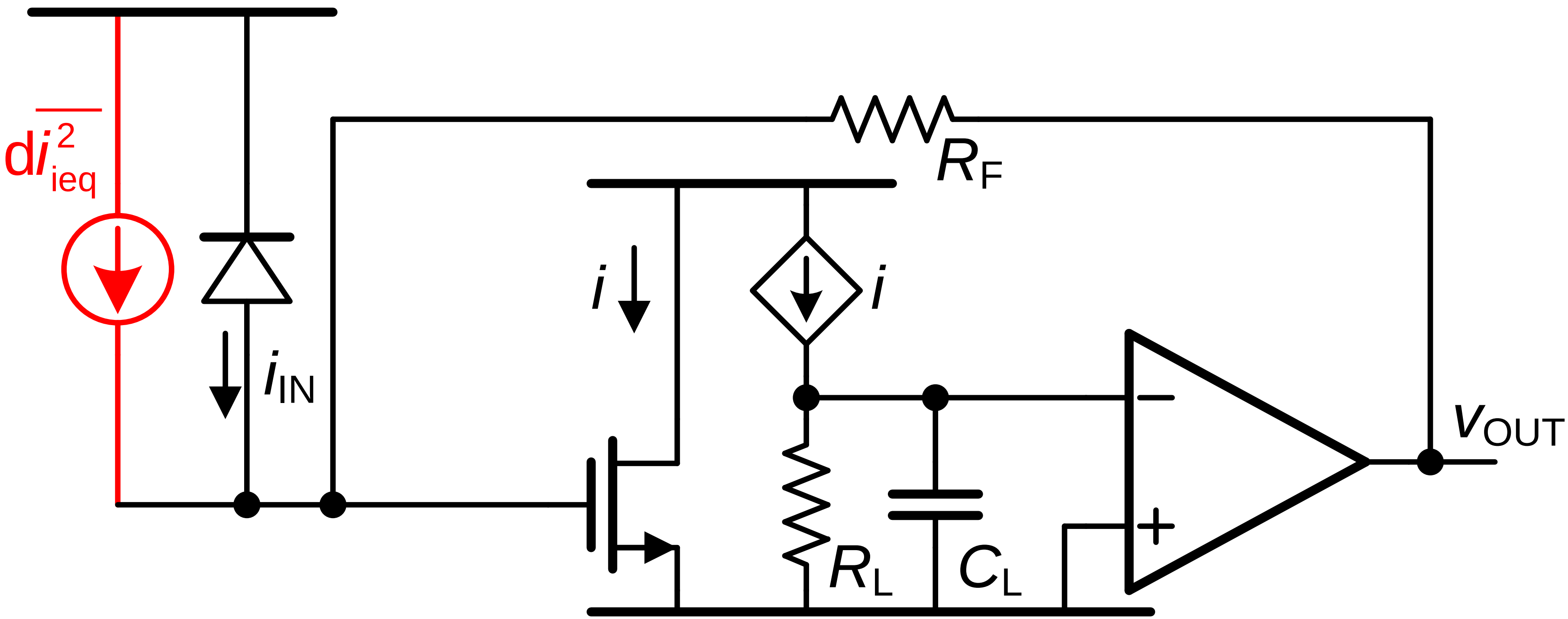
电压检测放大器的噪声密度



如果 $R_F > \dfrac{3/2}{g_m}$

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

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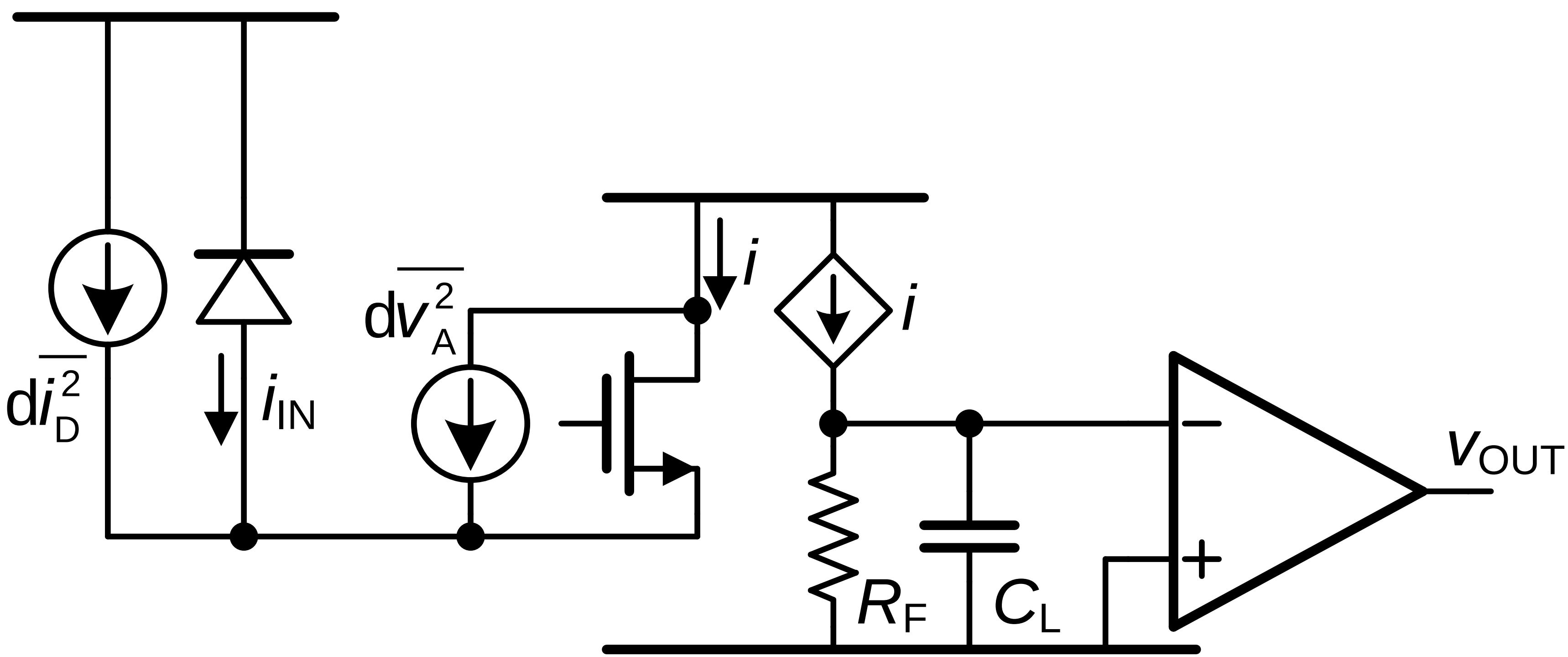
电流检测放大器的噪声源



$$d\overline{i_D^2} = 2qI_D df \qquad d\overline{i_A^2} = 4kT\frac{2}{3}g_m df$$

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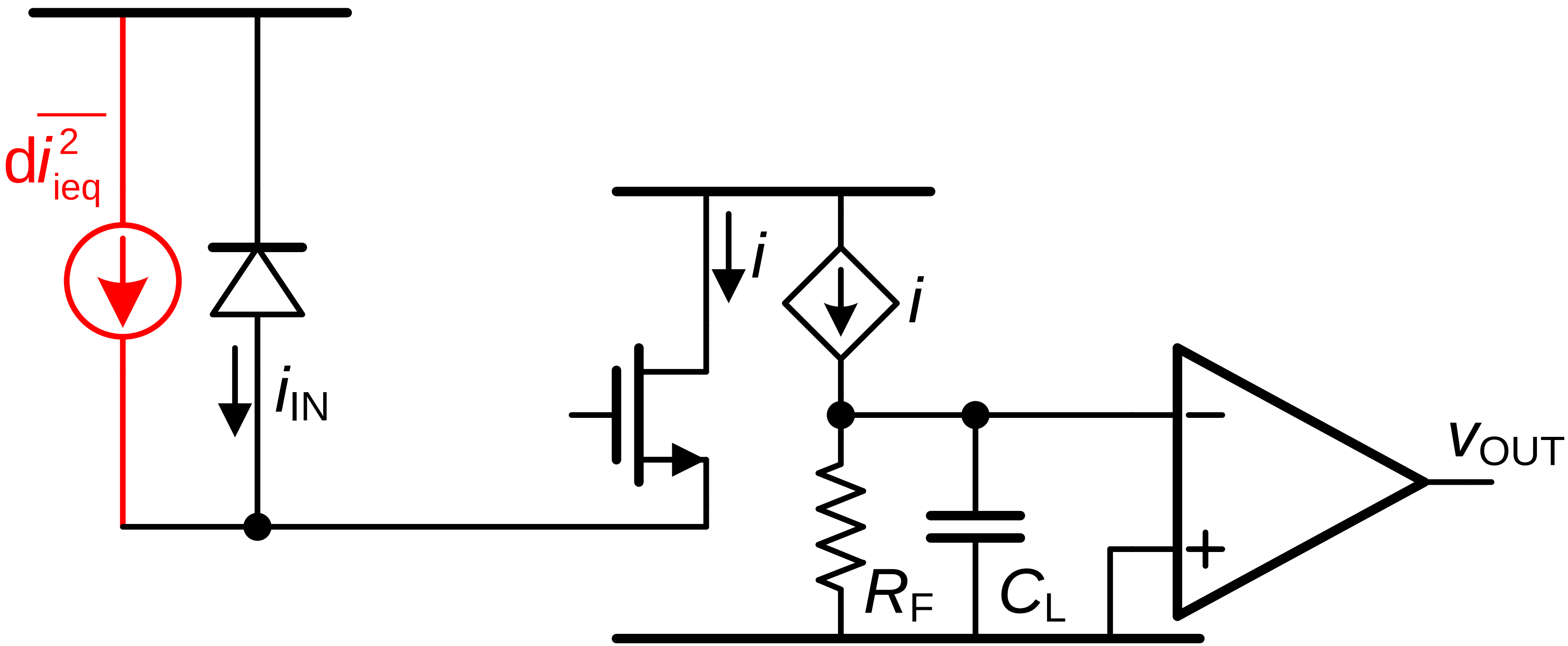
电流检测放大器的噪声密度



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

为晶体管噪声！

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噪声密度的比较

电压放大器：$\overline{i_{\mathrm{IN}}^2} = \mathrm{d}\overline{i_{\mathrm{R}}^2} = \dfrac{4\mathrm{k}T}{R_{\mathrm{F}}}\mathrm{d}f$

电流放大器：$\overline{i_{\mathrm{IN}}^2} = \mathrm{d}\overline{i_{\mathrm{A}}^2} = 4\mathrm{k}T\dfrac{2}{3}g_{\mathrm{m}}\mathrm{d}f$

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

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积分噪声的比较

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

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

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

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