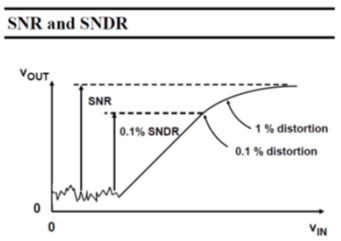
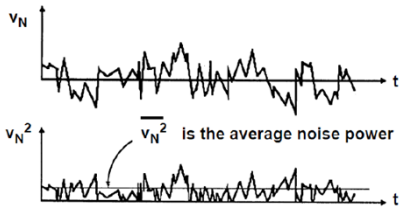
Noise

physical



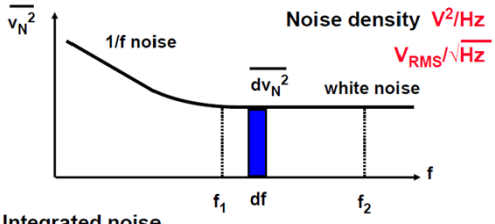
Transistor inherent characteristics
–Affecting the circuit accuracy: errors

Noise definition



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

Noise versus frequency

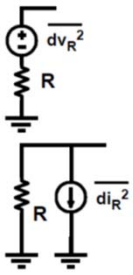


Integrated noise

V_{RMS}

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

Noise of a resistor is thermal noise



$\overline{dv_R^2} = 4kT\,R\,df$ is white

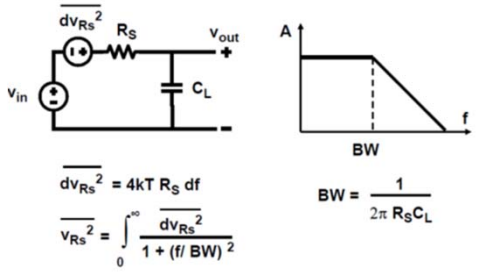
depends on T, not on I_R

for R = 1 kΩ $\sqrt{\overline{dv_R^2}} = 4\ nV_{RMS}/\sqrt{Hz}$

at T = 300 K or 27°C

$$\overline{di_R^2} = \frac{\overline{dv_R^2}}{R^2} = \frac{4kT}{R}\,df \quad \text{is white}$$

Integrated Noise of Resistor -1

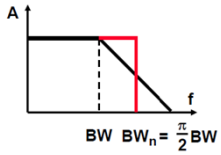


$$\overline{dv_{Rs}^2} = 4kT\,R_S\,df$$

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

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

Integrated Noise of Resistor -2



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

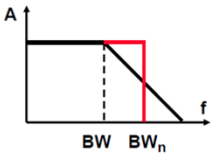
$$\int_0^\infty \frac{dx}{1+x^2} = \frac{\pi}{2}$$

$$\overline{v_{Rs}^2} = 4kT\,R_S BW\,\frac{\pi}{2}\,df$$

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

C_L = 1pF v_{Rs} = 65 μV_{RMS}

Noise density vs integrated noise



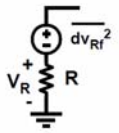
$$\overline{dv_{Rs}^2} = 4kT\,R_S\,df$$

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

Noise density (V^2/Hz) ~ R_S (or $1/g_m$)

Integrated noise (V_{RMS}) ~ $1/C_L$

A resistor also has 1/f noise



$$\overline{dv_{Rf}^2} = V_R^2\,\frac{KF_R R}{A_R}\,\frac{df}{f}$$ is 1/f

$KF_{RSi} \approx 2\,10^{-21}$ Scm²

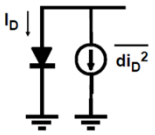
$KF_{Rpoly} \approx 10\,KF_{RSi}$

for R = 1 kΩ with 20 □'s of 50 Ω/□ and 1 μm wide and V_R = 0.1 V

$\sqrt{\overline{dv_{Rf}^2}}$ = 16 $nV_{RMS}/\sqrt{Hz}$ at 1 Hz

Ref. Vandamme, ESSDERC '04

Noise of a diode is shot noise



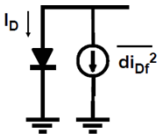
$$\overline{di_D^2} = 2q\,I_D\,df$$ is white

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

depends on I_D, not on T

for I_D = 50 μA $\sqrt{\overline{di_D^2}}$ = 4 $pA_{RMS}/\sqrt{Hz}$

A diode also has 1/f noise



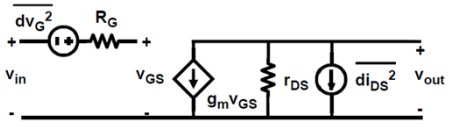
$$\overline{di_{Df}^2} = I_D\,\frac{KF_D}{A_D}\,\frac{df}{f}$$ is 1/f

$KF_D \approx 10^{-21}$ Acm²

For a diode of A_D = 5 x 2 μm = 10 μm^2 and I_D = 0.1 mA

$\sqrt{\overline{di_{Df}^2}}$ = 1 $nA_{RMS}/\sqrt{Hz}$ at 1 Hz

Noise of a MOST

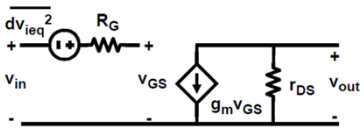


$$\overline{dv_G^2} = 4kT\,R_G\,df$$

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

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

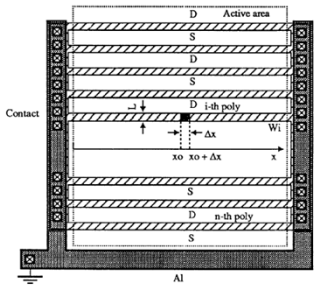
MOST: equivalent input noise: white



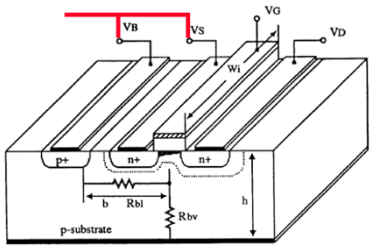
$\overline{dv_{ieq}^2} = 4kT\,(R_{eff})\,df \qquad R_{eff} = \frac{2/3}{g_m} + R_G$

Hi Freq.: $\overline{di_{ieq}^2} = (C_{GS}\,\omega)^2\,\overline{dv_{ieq}^2}$ is correlated

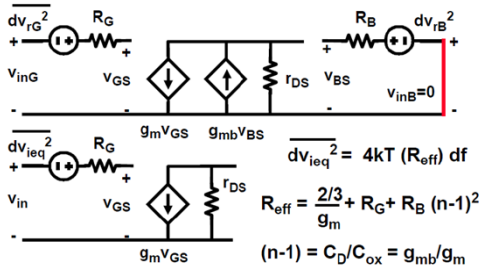
Poly Gate resistance r_G in a MOST



Substrate resistances r_B in a MOST



Noise by the Bulk resistance

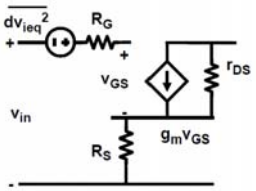


$\overline{dv_{ieq}^2} = 4kT\,(R_{eff})\,df$

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

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

Noise by the Source resistance

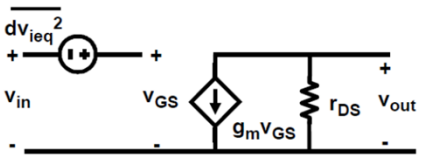


Noise of R_S = noise R_G

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

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

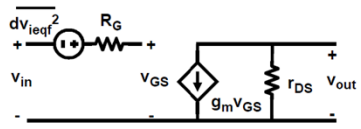
MOST: equivalent input noise: Exercise



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

$\overline{dv_{ieq}^2} \approx ?$ for $I_{DS} = 65\ \mu A$

MOST: equivalent input noise: 1/f noise



$$\overline{dv_{ieqf}^2} = \frac{KF_F}{WL\,C_{ox}^2}\frac{df}{f}$$

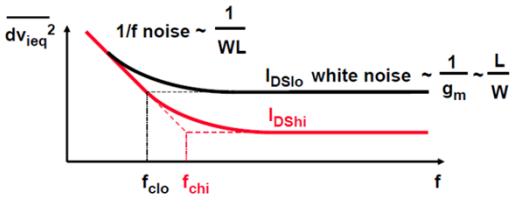
pMOST $KF_F \approx 10^{-32}$ C^2/cm^2

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

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

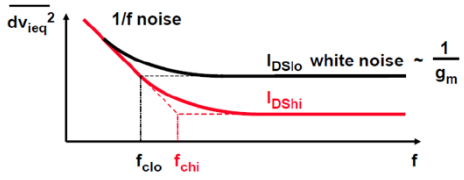
W & L in cm; C_{ox} in F/cm²

Noise vs current: corner frequency



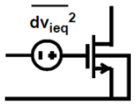
Corner frequency ~ g_m

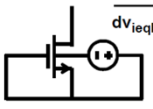
Noise vs current: exercise f_c



Ex. : f_c ? For I_{DS} = 65 µA;
K'_n = 60 µA/V² and L = 1 µm (0.35 µm process)

Noise seen at the Bulk



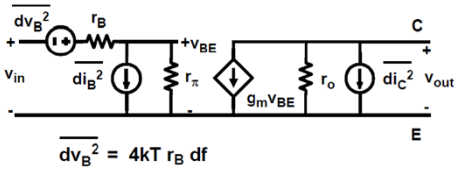


n-1 = $\frac{g_{mb}}{g_m}$

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

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

Noise of a Bipolar transistor



$$\overline{dv_B^2} = 4kT\,r_B\,df$$

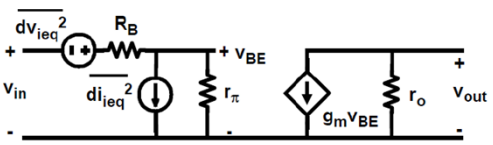
$$\overline{di_B^2} = 2q\,I_B\,df \qquad \overline{di_{Bf}^2} = \frac{KF_B\,I_B}{A_{EB}}\frac{df}{f}$$

$$\overline{di_C^2} = 2q\,I_C\,df$$

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

Ref. Van der Ziel (Prentice Hall 1954)

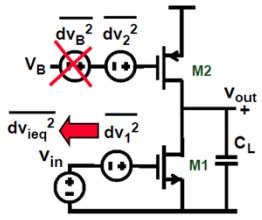
Bipolar trans.: equivalent input noise



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

$$\overline{di_{ieq}^2} = \overline{di_B^2} = 2q\,I_B\,df$$

Noise of an amplifier with active load



If $\overline{dv_B^2}$ is negligible :

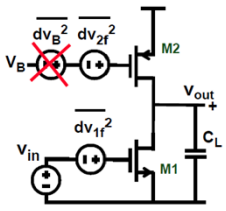
$$\overline{di_{out}^2} = g_{m1}^2 \overline{dv_1^2} + g_{m2}^2 \overline{dv_2^2}$$

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

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

Small g_{m2} : small $(W/L)_2$ or large $(V_{GS} - V_T)_2$

1/f Noise of amplifier with active load



If $\overline{dv_B^2}$ is negligible :

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

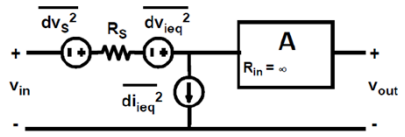
$$\overline{dv_{if}^2} = \overline{dv_{1f}^2}\left[1 + \left(\frac{g_{m2}}{g_{m1}}\right)^2 \left(\frac{\overline{dv_{2f}^2}}{\overline{dv_{1f}^2}}\right)\right]$$

$$\overline{dv_{if}^2} = \overline{dv_{1f}^2}\left[1 + \frac{KF_2}{KF_1}\frac{K'_2}{K'_1}\left(\frac{L_1}{L_2}\right)^2\right]$$

$\overline{dv_{if}^2}$ has minimum at

$$L_{1opt} = L_2\sqrt{\frac{KF_1}{KF_2}\frac{K'_1}{K'_2}} \approx 10\,L_2 \quad \text{then} \quad \overline{dv_{if}^2} = 2\,\overline{dv_{1f}^2}$$

Noise figure of an amplifier



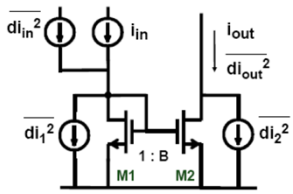
$$NF = \frac{N_S + N_A}{N_S} = 1 + \frac{N_A}{N_S}$$

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

Voltage drive $NF \sim \frac{1}{R_S}$

Current drive $NF \sim R_S$

Noise of a current mirror



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

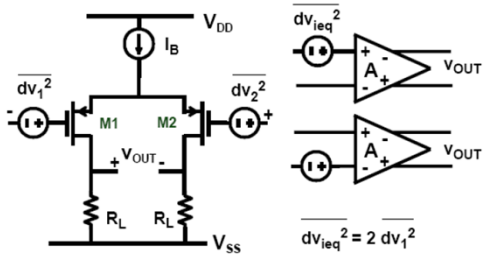
$$\overline{di_{out}^2} = \overline{di_2^2} + B^2\left(\overline{di_{in}^2} + \overline{di_1^2}\right)$$

Small g_m :

$(W/L) \downarrow$

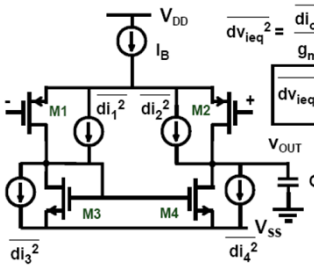
$(V_{GS}-V_T) \uparrow$

Noise of differential pair



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

Noise of differential pair with active load



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

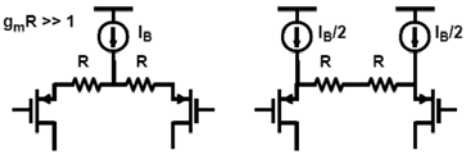
$$\overline{dv_{ieq}^2} = 2\overline{dv_1^2}\left(1 + \frac{g_{m3}}{g_{m1}}\right)$$

Small g_{m3} :

$(W/L)_3 \downarrow$

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

Differential pair with source resistors



$\overline{di_{out}^2} = 2\ \frac{4kT}{R}\ df$

$\overline{dv_{in}^2} = 2\ (4kT\ R\ df)$

$\overline{di_B^2}$ is negligible

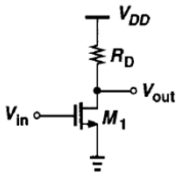
$\overline{di_{out}^2} = 2\ (\frac{4kT}{R}\ df + \overline{di_B^2}\ )$

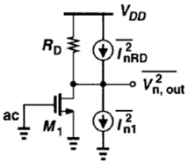
$\overline{di_B^2} = 4kT\ 2/3\ g_{mB}\ df$

$\overline{dv_{in}^2} = 2\ (4kT\ R\ df)\ (1 + 2/3\ g_{mB}R)$

Exercise

$$\overline{V_{n,out}^2} = \left(4kT\frac{2}{3}g_m + \frac{K}{C_{ox}WL}\cdot\frac{1}{f}\cdot g_m^2 + \frac{4kT}{R_D}\right)R_D^2.$$





What is the total output noise voltage? And the input-referred noise?

Recall

- Noise definition
- Noise of different components and circuits