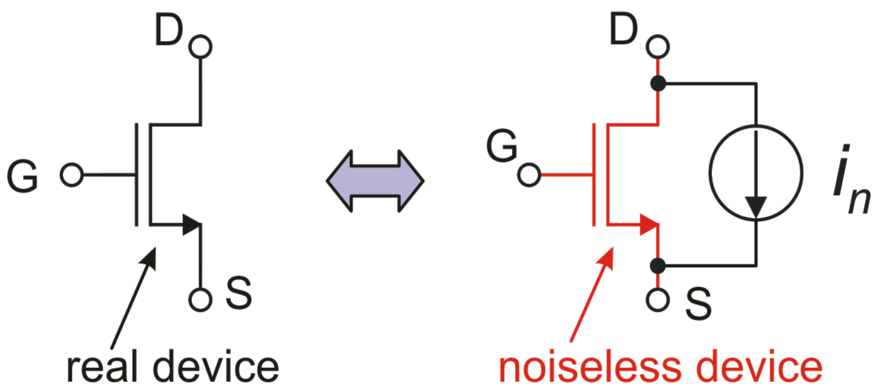
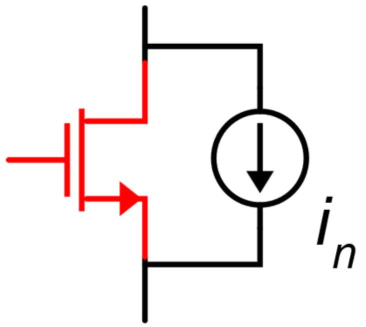
Noise in active devices

MOSFETs



This noise schematization is valid up to a frequency that depends on the process and device length.
Generally, for integrated MOSFETs, it is possible to use this single-source model up to frequencies of several hundred MHz

Mosfet Thermal noise



Being frequency independent, thermal noise is the origin of the **broad-band** noise in MOSFETs

$$S_{In-T}(f)=\frac{8}{3}kTg_m\cdot m$$

$$m=1+\frac{g_{mB}}{g_m}$$

Typically:

$$1<m<1.5$$

A more general expression that resembles thermal noise in resistors:

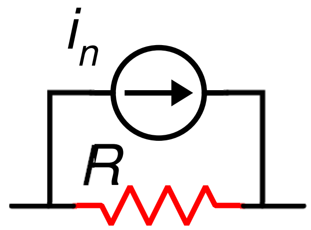
$$S_{In-T}(f)=\gamma_n 4kTg_m$$

$$\gamma_n=\frac{2}{3}m\approx 1$$

For simplicity, we will use:

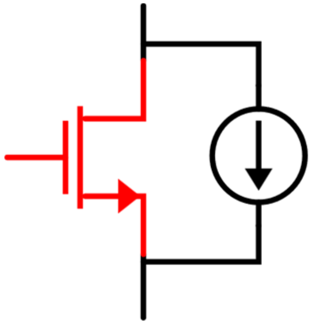
$$S_{In-T}(f)=\frac{8}{3}kTg_m$$

Thermal noise of a resistor: Equivalent noise current.



$$S_{In-R}=4kT\frac{1}{R}=4kTG$$

Mosfet flicker noise



"design friendly expression"

$$S_{In-F}(f) = \frac{N_f}{WL}\frac{1}{f}g_m^2$$

Frequently used by designers of analog integrated circuits

N_f is a parameter that depends on the process

N-MOS: $\boldsymbol{N_{fn}}$

P-MOS: $\boldsymbol{N_{fp}}$

Dimensions of N_f are: $\mathrm{V}^2 \cdot (\mu\mathrm{m})^2$

General expression:

$$S_{In-F}(f) = \frac{k_{fi} I^{\alpha}}{C_{OX} L_{eff}^2}\frac{1}{f^{\gamma}}$$

This_expression of the flicker PSD can be used in traditional SPICE noise models

Relationship between the two noise expressions

Simplified expression:

$$S_{In-F}(f) = \frac{N_f}{WL}\frac{1}{f} g_m^2$$

Strong inversion:

$$g_m = \sqrt{2\beta I_D} \qquad \beta = \mu C_{OX}\frac{W}{L}$$

$$S_{In-F}(f) = \frac{N_f}{WL}\frac{1}{f} 2\mu C_{OX}\frac{W}{L} I_D = \frac{N_f 2\mu C_{OX} I}{L^2}\cdot\frac{1}{f}$$

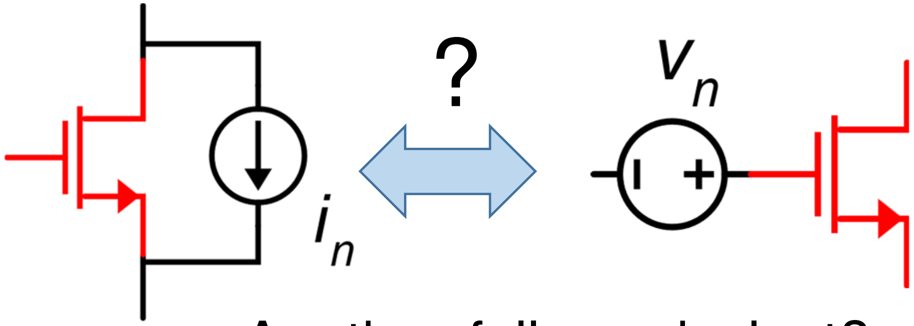
General expression:

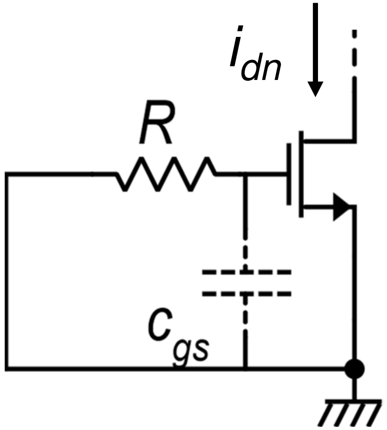
$$S_{In-F}(f) = \frac{k_{fi} I^{\alpha}}{C_{OX} L_{eff}^2}\frac{1}{f^{\gamma}}$$

$$\begin{cases} \gamma = 1 \\ \alpha = 1 \end{cases} \qquad N_f = \frac{k_{fi}}{2\mu C_{OX}^2}$$

with this choice, the general expression is equivalent to the design-friendly one

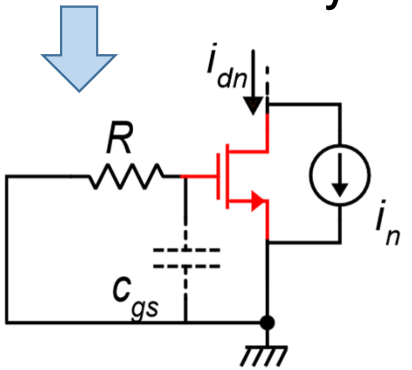
Equivalent gate noise

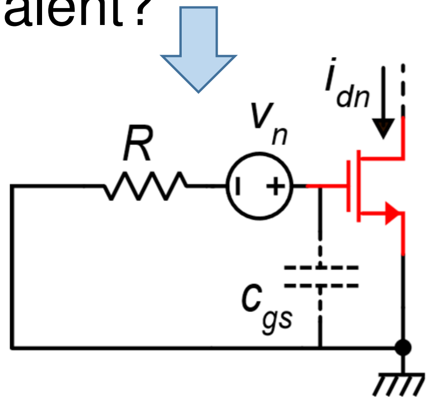




Let us consider a resistive input termination and let us focus on the noise added to the drain current ...

Are they fully equivalent?



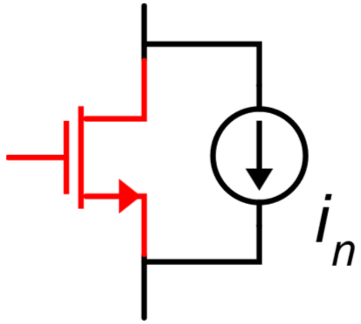


$$i_{dn} = i_n$$

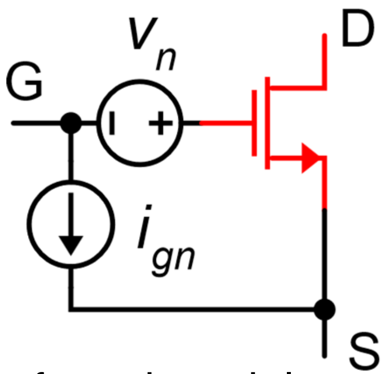
$$i_{dn} = g_m v_{gs} = g_m v_n \frac{1}{1 + j\omega R c_{gs}}$$

Substituting $\boldsymbol{i_n}$ with a single voltage source in series with the gate gives a contribution that depends on the resistance (R) seen by the gate.

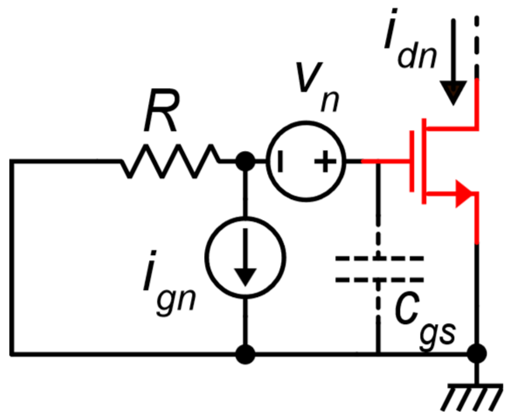
Equivalence between the output referred and input referred noise models



output referred model



input referred model



$$i_{dn} = g_m \left(v_n \frac{1}{1 + j\omega R c_{gs}} - i_{gn} \frac{1}{1/R + j\omega c_{gs}} \right) = g_m \left(\frac{v_n - i_{gn} R}{1 + j\omega R c_{gs}} \right)$$

By setting:

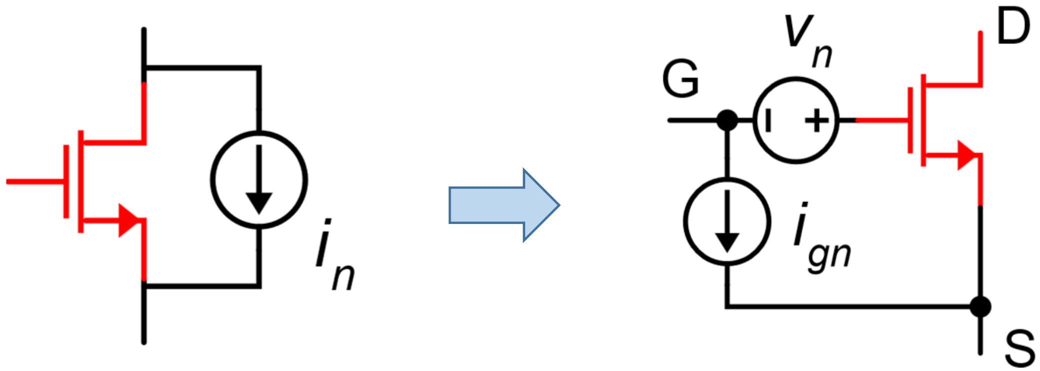
$$i_{gn} = -j\omega c_{gs} v_n$$

$$i_{dn} = v_n g_m$$

Independent of R, as required for the equivalence with the output referred model.

Finally, setting: $v_n = \dfrac{i_n}{g_m}$ $\Rightarrow$ $i_{dn} = i_n$

Equivalence between the output referred and input referred noise models



$$i_n \longrightarrow \begin{cases} v_n = \dfrac{i_n}{g_m} \\ i_{gn} = -j\omega c_{gs} v_n \end{cases}$$

$$(i_n = v_n g_m)$$

Note that i_{gn} is dependent on v_n (they are correlated stochastic processes)

Transformations between drain noise current and gate noise voltage

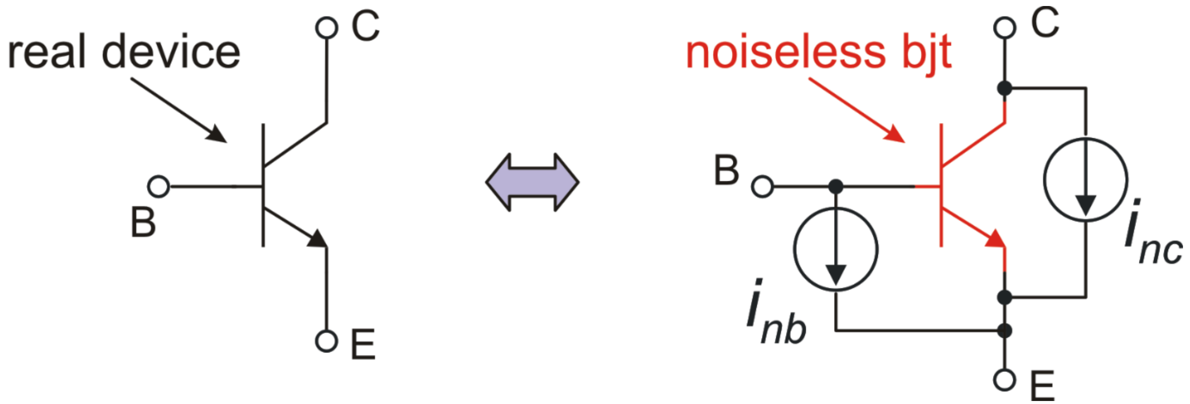
$$v_n = \frac{i_n}{g_m} \qquad i_n = v_n g_m$$

$$S_{Vn}(f) = \frac{S_{In}(f)}{g_m^2} \qquad S_{In}(f) = g_m^2 S_{Vn}(f)$$

Thermal noise: $S_{In-T}(f) = \frac{8}{3} kT g_m \cdot m \Rightarrow S_{Vn-T}(f) = \frac{8}{3} kTm \frac{1}{g_m}$

Flicker noise: $S_{In-F}(f) = \frac{N_f}{WL} \frac{1}{f} g_m^2 \Rightarrow S_{Vn-F}(f) = \frac{N_f}{WL} \frac{1}{f}$

Noise in BJTs



Simplified BJT noise model

Since the BJT has a non negligible base current, it is necessary to use **<u>two distinct current noise</u>** sources for the base and the collector

Collector noise current PSD:

$$S_{InC} = 2qI_C$$

Only shot noise (broad-band)

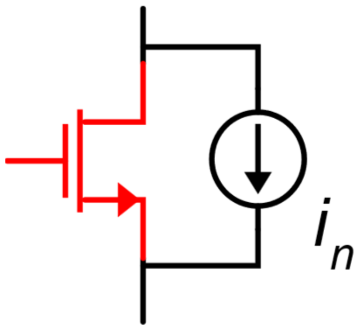
Base noise current PSD:

$$S_{InB} = 2qI_B + k_{fB} \frac{I_B^{\alpha}}{f}$$

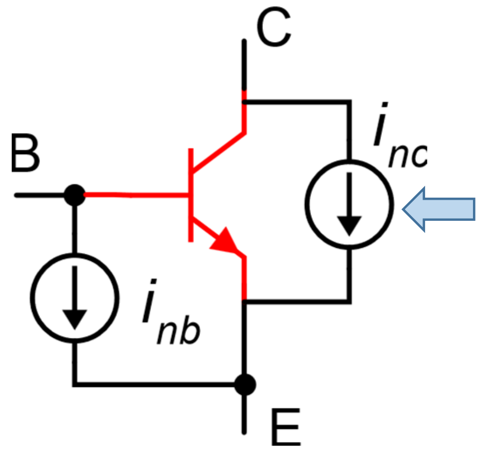
Base flicker noise

Base shot noise (broad-band)

MOSFET vs BJT: Broadband noise



Let us consider only the drain (i_n) and collector (i_{nc}) noise sources.



$$S_{In-T}(f) = \gamma_{n-MOS}\, 4kTg_m$$

$$\gamma_{n-MOS} = \frac{2}{3} m \approx 1$$

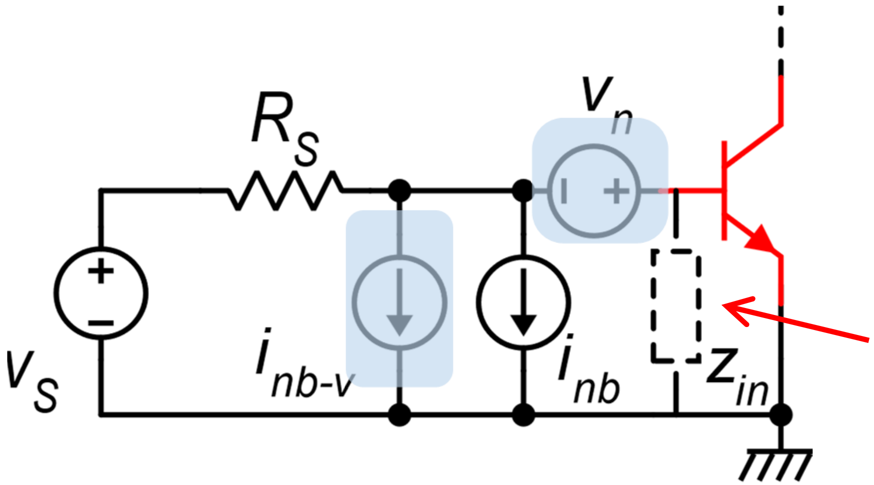
$$S_{InC} = 2qI_C$$

$$g_m = \frac{I_C}{V_T} \Rightarrow I_C = g_m V_T = g_m \frac{kT}{q}$$

$$S_{InC} = 2qg_m \frac{kT}{q} = 2kTg_m$$

$$S_{InC}(f) = \gamma_{n-BJT}\, 4kTg_m \qquad \gamma_{n-BJT} = \frac{1}{2}$$

BJT input referred noise voltage



$$v_n = \frac{i_{nC}}{g_m}$$

$$\frac{1}{z_{in}} \cong \frac{1}{r_{be}} + j\omega c_{be}$$

$$i_{bn-v} = -\frac{v_n}{z_{in}}$$

$$\text{if } |z_{in}| >> R_S \qquad v_{be} \cong v_S + v_n$$

BJT: $$S_{Vn} = 2kT\frac{1}{g_m} = 2kT\left(\frac{V_T}{I_C}\right)$$

In this case, the noise voltage source v_n is the only significant contribution to the input referred noise

MOSFET: $$S_{Vn-th} \cong 4kT\frac{1}{g_m} = 4kT\frac{V_{TE}}{I_D}$$

Much more noise for the same static current consumption!

The Noise Efficiency Factor (NEF)

Since the single-BJT amplifier offers an excellent trade-off between noise and power consumption, in 1987 M. Steyaert (KU Leuven University) proposed a FOM (figure of merit) called NEF to characterize all voltage amplifiers in terms of noise efficiency

$$NEF = \frac{V_{rms-rti}}{\sqrt{4kT\left(\frac{V_T}{I_{\text{supply}}}\right)B\frac{\pi}{2}}}$$

Total *rms* noise of the amplifier under consideration

Effective noise bandwidth and total current consumption of the amplifier under consideration

Denominator = $\sqrt{2} \cdot V_{rms-bjt}$

Input *rms* voltage of a BJT with same current and BW of the amplifier