EE4011: RF IC Design

Introduction to Noise

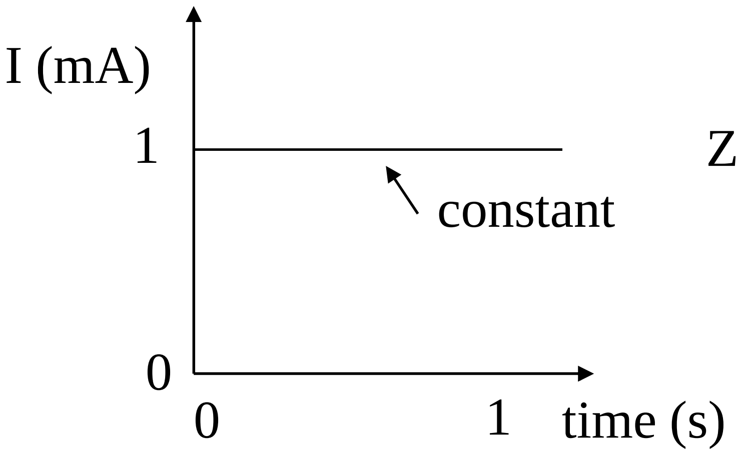
Noise

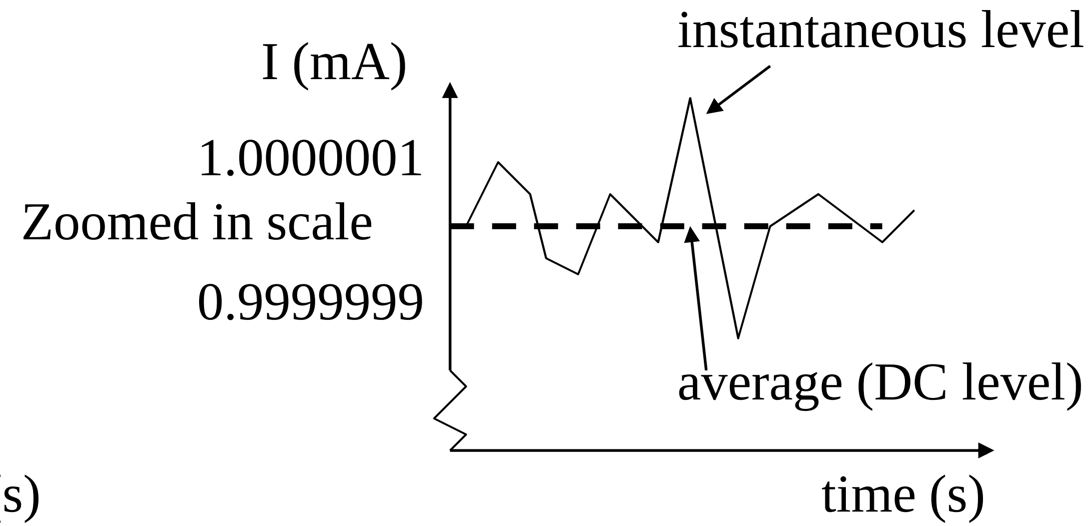
In general conversation the term “noise” tends to be used to refer to any unwanted signal which is corrupting the desired signal. Such “noise” might therefore be interference signals from other users, unwanted harmonic distortion and intermodulation signals caused by amplifier non-linearities and unwanted signals picked up from other electrical devices such as motors and generators. All of these sources of “noise” are deterministic i.e. the causes can be identified and coutermeasures can be taken to reduce this “noise” such as high-linearity amplifiers, good shielding, restriction of the frequency ranges for different applications and users, etc.

Even when all the deterministic sources of “noise” have been eliminated there is still a residual unwanted noise in all electronic circuits which arises due to the random thermal fluctuations in the electronic components of the system – this gives rise to a non-zero output even when the external input signals are removed. This internally generated noise limits the ability of the system to properly handle weak (low amplitude) input signals and is thus studied in RF (and analogue) design using terms such as noise figure, noise factor, noise temperature, equivalent input noise voltage, equivalent input noise current etc.

Visualizing Noise

Regardless of the source of noise it can be visualized as a fluctuation of the current in a device around its average (mean) value e.g. a device with 1mA average current:



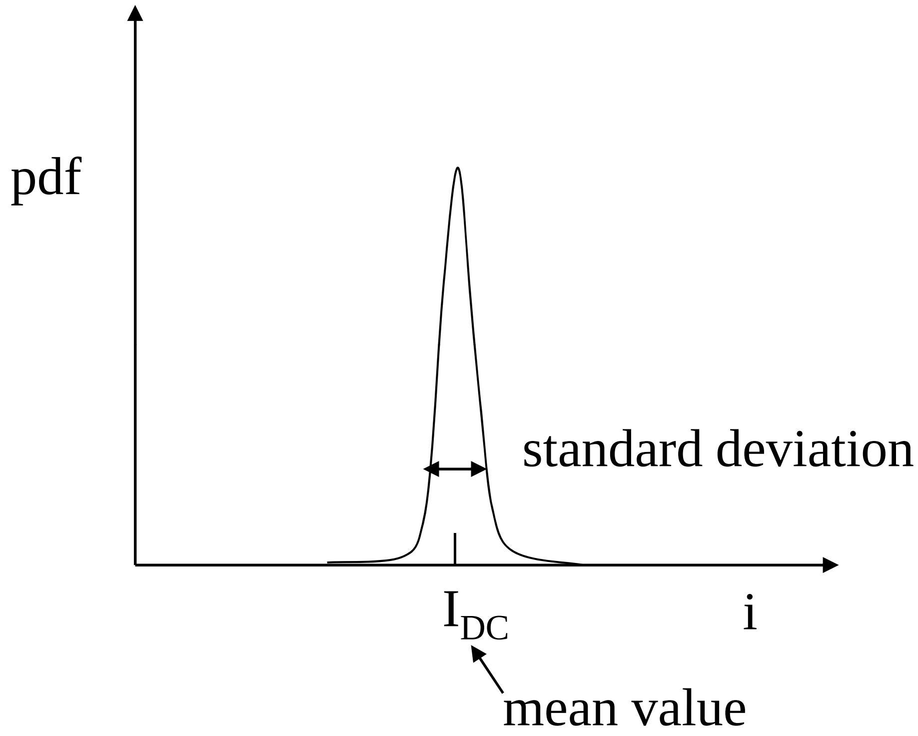


No noise: No variation in current

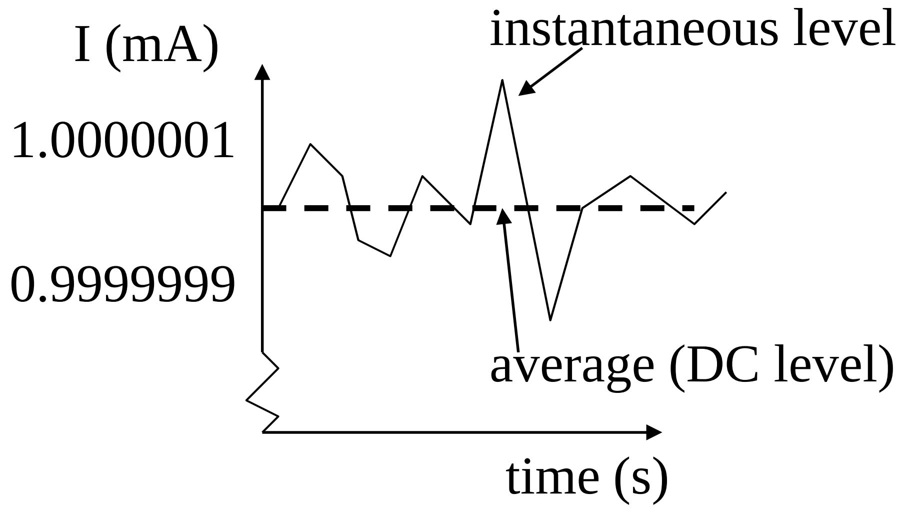
Real device with noise: The current varies “randomly” about its mean value.

Noise as a Statistical Quantity

In the presence of noise, the current can be considered to be governed by statistics which indicate the mean value (the average DC current) and the standard deviation or variance. Thus, current follows a probability density function (pdf):



Specifying Noise – rms Noise Current



Labelling the instantaneous current as i, the DC level as I_{DC} and the instantaneous variation from the DC level as i_n gives:

$$i = I_{DC} + i_n$$

The average value of the noise current i_n is zero so a more useful indication of the power associated with the noise signal is the mean square current. This is also the variance of the instantaneous current i.e.

$$\mathrm{var}(i) = \mathrm{var}(I_{DC} + i_n) = \mathrm{var}(I_{DC}) + \mathrm{var}(i_n) = \overline{i_n^2}$$

Main Noise Types

1. Thermal noise
   This occurs due to the random thermal motion of carriers in a resistive material. It is present whether there is a DC current flowing in the material or not. It depends strongly on resistance and temperature and has a constant power density up to several hundred GHz ("white noise").

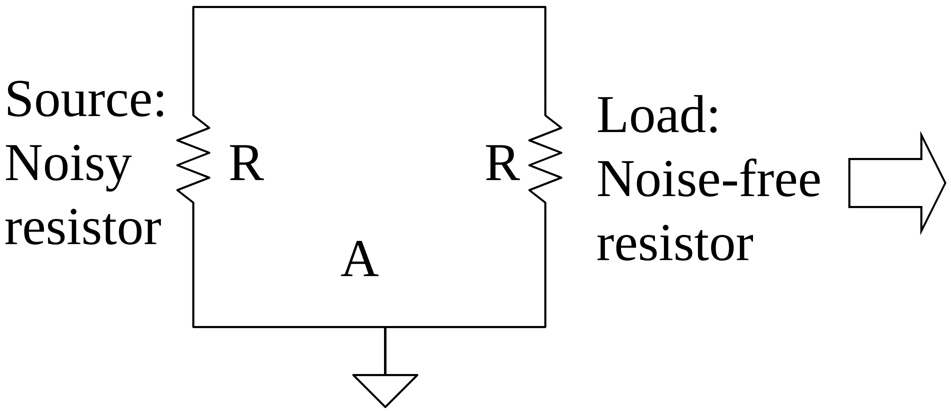
2. Shot noise
   This is associated with current flow through a barrier such as a pn junction or an ultra-thin oxide. It only occurs where there is a net DC current flow across the barrier and is directly proportional to this current flow. It also has a constant spectral density ("white noise").

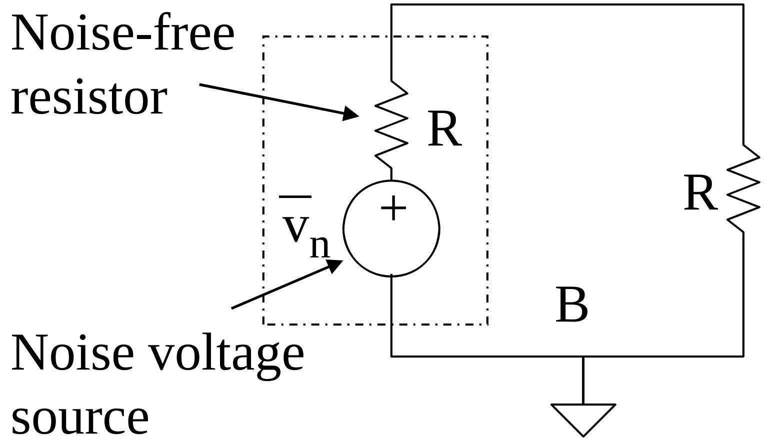
3. 1/f noise
   Many semiconductor devices have imperfections or interfaces where "traps" can capture and subsequently release electrons. When many of these traps are present, the overall effect is to give a noise component whose power spectral density drops with increasing frequency – hence the name 1/f noise.

Resistor Thermal Noise - 1

The available noise power from a resistor at temperature T is $kT\Delta f$ where k=Boltzmanns constant, T=temperature in Kelvin, Δf = noise bandwidth of system.

The noisy resistor can be represented by a noise-free resistor in series with a noise voltage source. Imagine a noisy resistor connected to a "noise free" resistor with the same value:



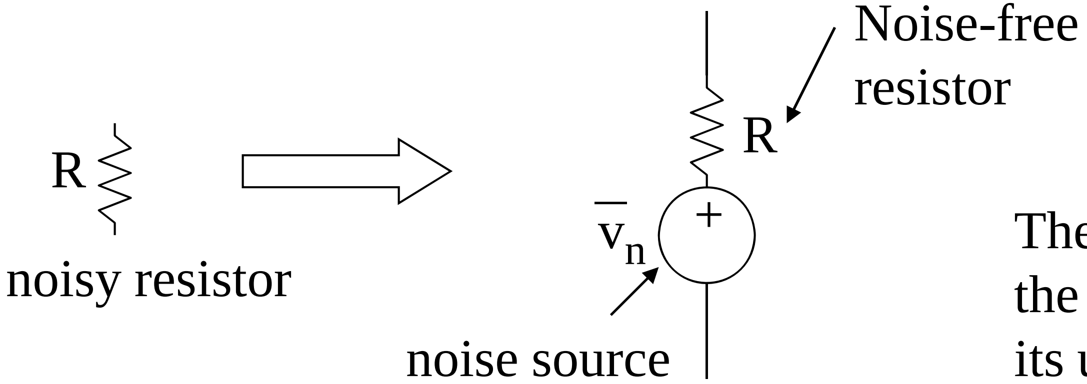


In circuit A the power delivered to the load is $kT\Delta F$
In circuit B the power delivered to the load is $v_n^2/4R$
To give the same power in the load:

$$\frac{v_n^2}{4R} = kT\Delta f \Rightarrow v_n^2 = 4kTR\Delta f$$

Resistor Thermal Noise - 2

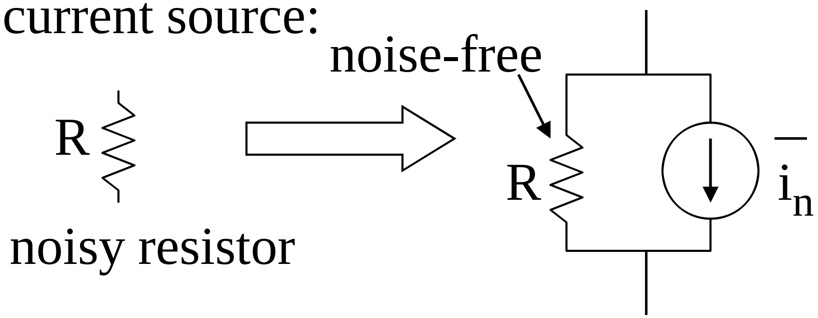
Representing a noisy resistor by a noise-free resistor in series with a noise voltage source is the Thevenin equivalent circuit:



$$\overline{v_n^2} = 4kTR\Delta f$$

The bar means that the voltage is the mean square voltage reflecting its underlying statistical nature.

Alternatively, thermal noise can be represented by a Norton equivalent circuit with a current source:



$$\overline{i_n^2} = \frac{\overline{v_n^2}}{R^2} = \frac{4kTR\Delta f}{R^2} = \frac{4kT\Delta f}{R}$$

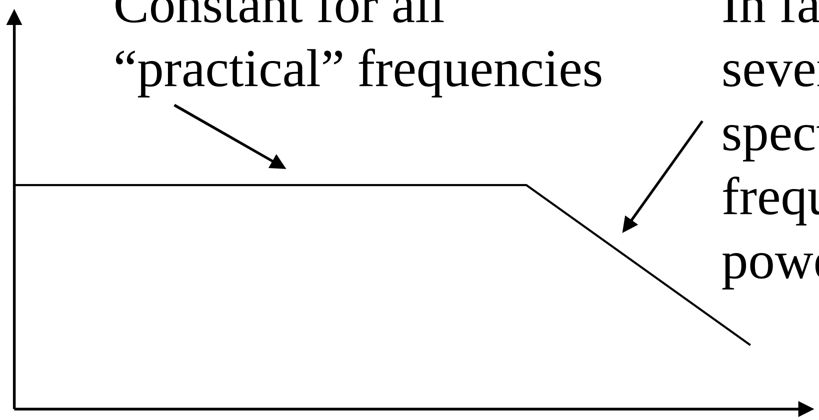
Because of its statistical nature the instantaneous value (or direction) of the noise voltage or current is not known – therefore the sign (or arrow) on the noise sources are not significant (except in the case of correlated noise sources).

Spectral Density of Thermal Noise

$$\overline{v_n^2} = 4kTR\Delta f \Rightarrow \frac{\overline{v_n^2}}{\Delta f} = 4kTR \quad \text{If } \Delta F = 1 \text{ then } \overline{v_n^2} = 4kTR \quad V^2 / Hz$$

$$\frac{\overline{v_n^2}}{\Delta f} = 4kTR$$

This gives the power of the noise signal per unit bandwidth. For thermal noise this does not vary with frequency i.e. the spectral density is constant for all frequencies. Thus, thermal noise is called *white noise* which is analogous to white light.



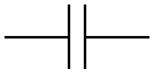
In fact, for frequencies above several hundred GHz, thermal noise spectral density rolls off with frequency giving a finite total noise power.

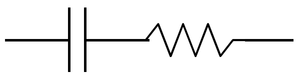
Sources of Thermal Noise - 1

Any resistive element of a circuit will have an associated thermal noise. Additionally, any resistive part of an electronic component will have thermal noise provided that the resistance corresponds to a **physical** part of the device. Resistances which have been *derived* for the convenience of small-signal models do not have thermal noise – the noise associated with the mechanisms giving rise to these derived resistances are modelled directly.

Pure reactive elements have no thermal noise. However, real reactive elements have parasitic resistances which give rise to thermal noise.

Resistor:  has thermal noise

Ideal capacitor:  no thermal noise

Real capacitor:  has thermal noise from parasitic resistor

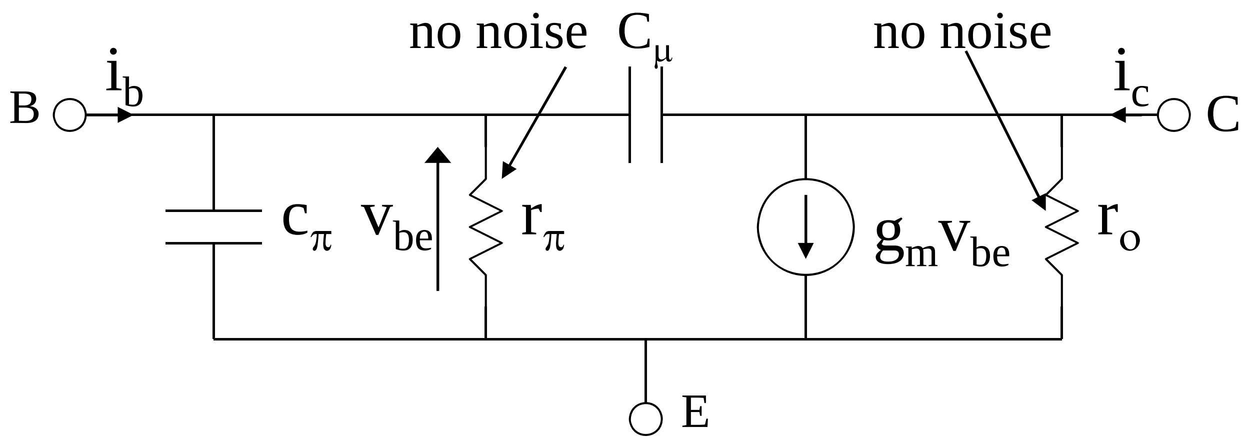
Ideal inductor:  no thermal noise

Real inductor:  has thermal noise from parasitic resistor

For a capacitor or inductor the thermal noise in the parasitic resistance will cause current flow in the capacitance or inductance and thus a voltage drop across them.

Sources of Thermal Noise - 2

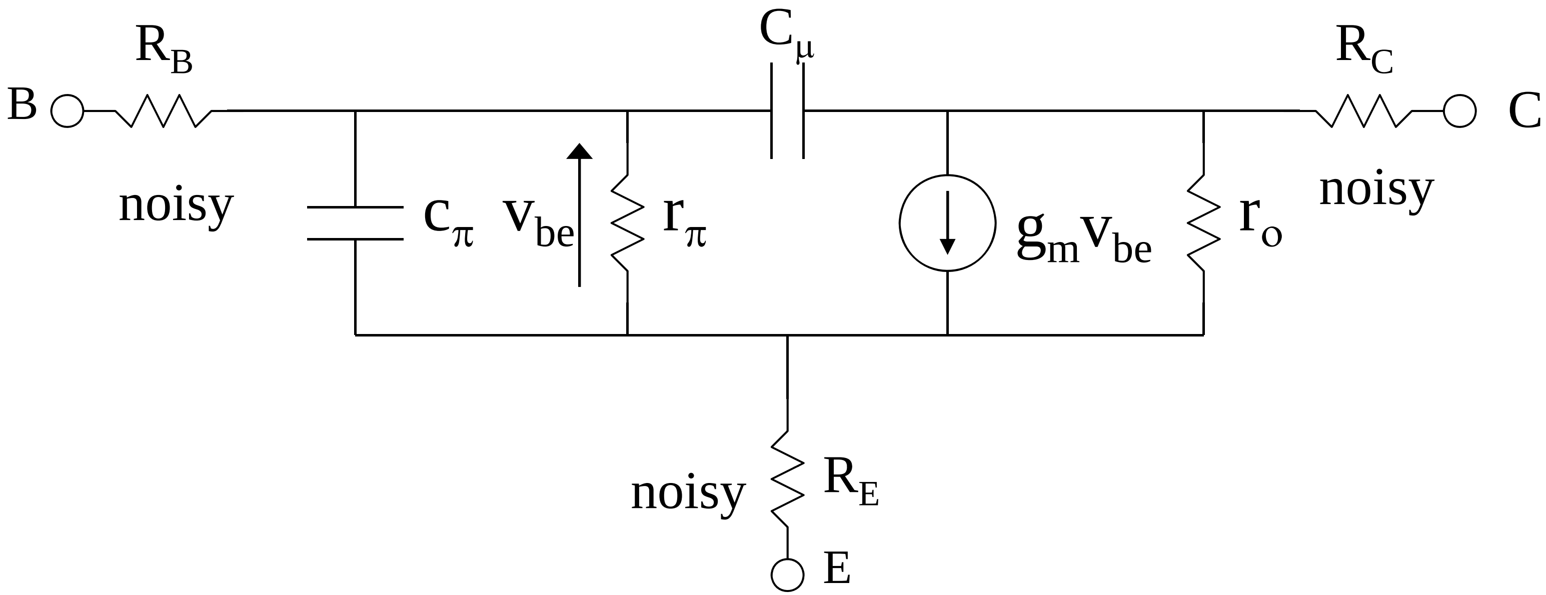
Recall the simple equivalent circuit for a BJT:



r_π and r_o are equivalent resistances which were derived to allow easy calculation of the small-signal input currents and output currents respectively. They do not correspond to physical resistors in the device structure and so do not have thermal noise.

Sources of Thermal Noise - 3

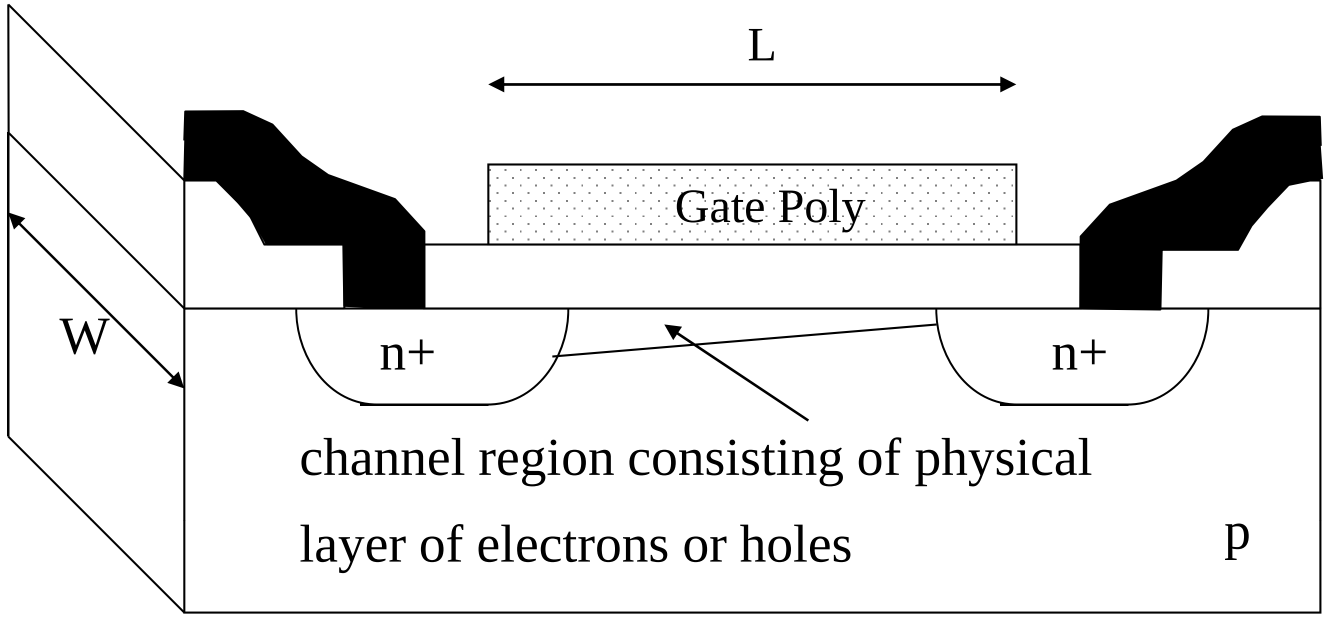
A real bipolar has parasitic emitter, base and collector resistances:



The parasitic resistances correspond to physical layers and therefore have thermal noise. This is one of the main reasons why parasitic resistances must be reduced as much as possible in low-noise devices.

Sources of Thermal Noise - 4

The channel region of a MOSFET:



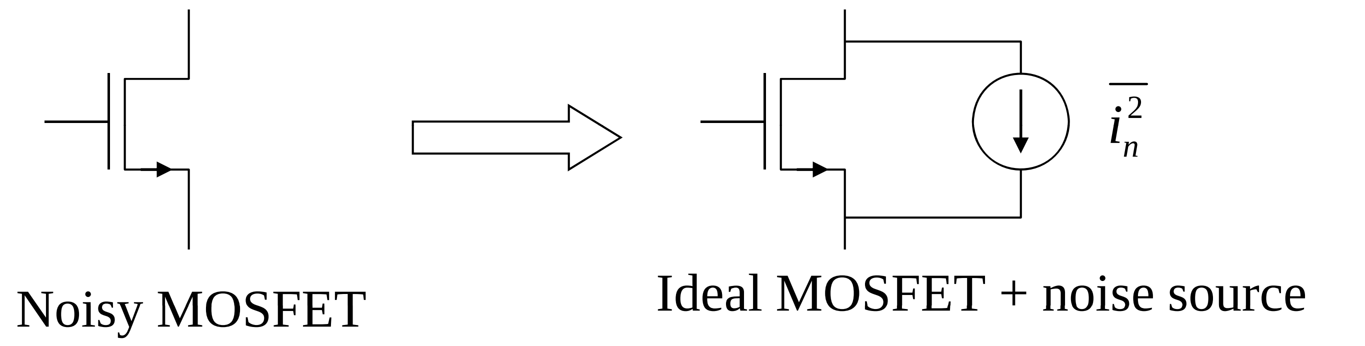
The channel region of a MOSFET corresponds to a physical layer where there is a high density of electrons or holes – this layer is resistive and thus has thermal noise. Similarly, the channel region of a JFET or a MESFET has thermal noise.

Simple MOSFET Thermal Noise Model

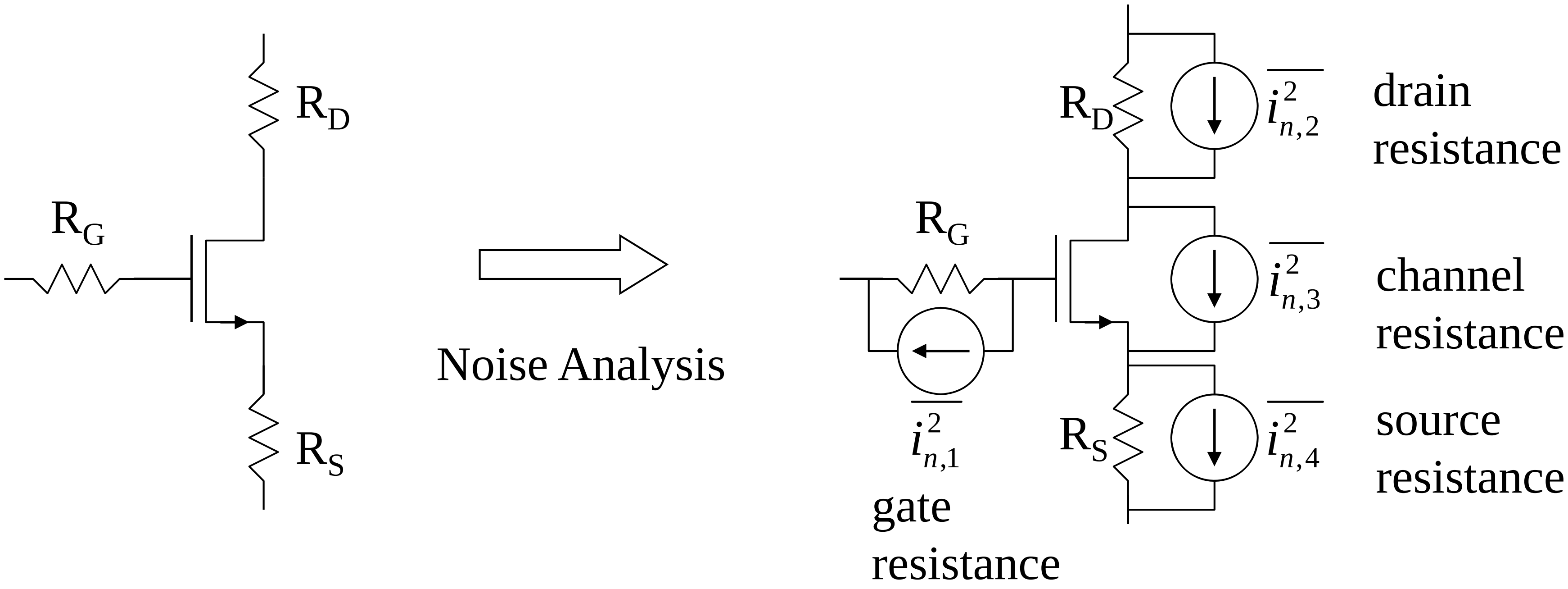
A simple model for the thermal noise due to the channel resistance of a MOSFET is:

$$\overline{i_n^2} = 4kT\frac{2}{3}g_m\Delta F$$

For circuit analysis this is placed in parallel with the ideal noise-free MOSFET:

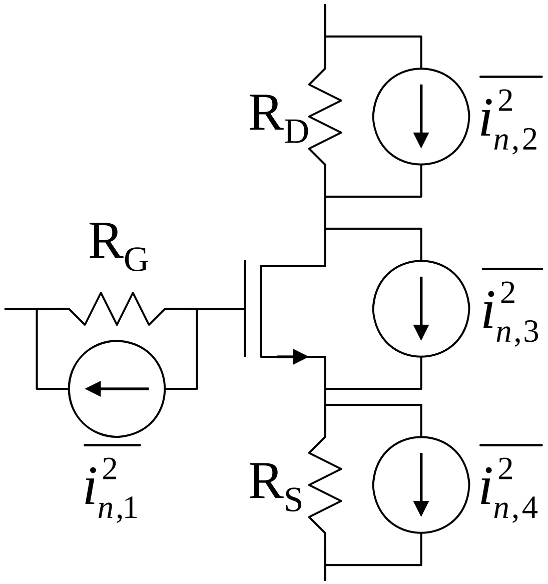


Thermal Noise in MOSFETs



In a real circuit consisting of many transistors the number of sources of noise can be very large. Most noise sources are independent and their effect on the circuit output must be calculated individually as a mean square voltage (or current) at the output. Some noise sources are correlated so they need to be treated together in a noise analysis. The individual results are then added to give the total mean-square output noise voltage or current.

Noise Simulations – ac Analysis



The noise voltages or currents can be treated as ac sources. Therefore most circuit noise analysis uses the small-signal models and is performed with a small-signal simulation where the noise sources are considered to be the signal inputs. Even through there are many noise sources, this analysis is usually fast because small-signal simulations are linear. The small-signal approach works well for circuits which are predominantly linear such as amplifiers and filters. It doesn’t provide all the information needed when circuits have a strong non-linearity such as oscillators and frequency synthesizers. In these cases a non-linear noise analysis is necessary which is available in most modern RF CAD packages.

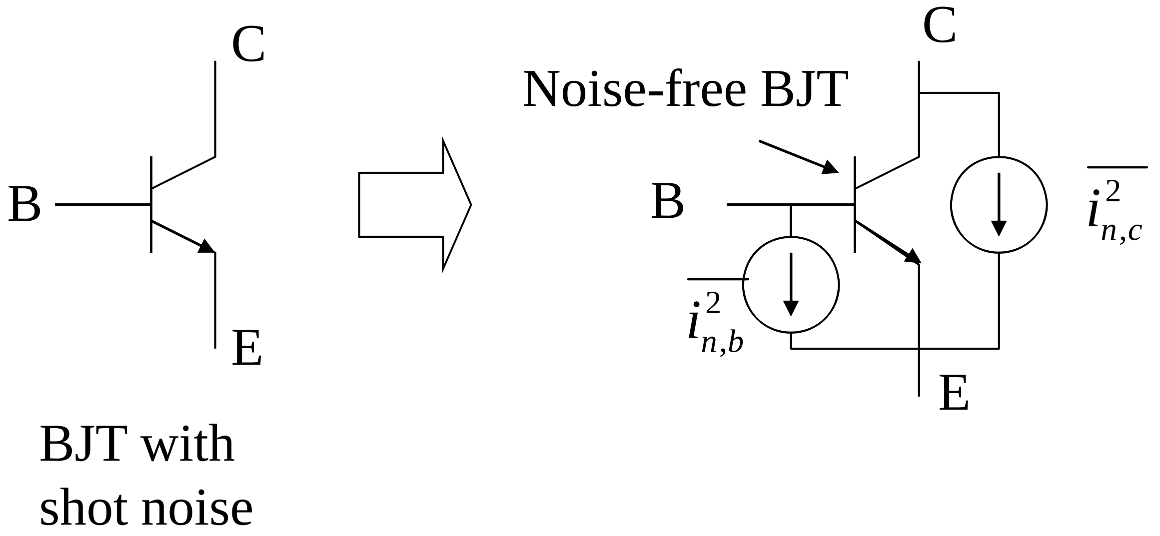
Shot Noise

This noise is associated with the flow of carriers across a potential barrier such as a pn junction or a Schottky junction. Therefore it occurs in diodes, bipolar devices, Schottky diodes, etc. It occurs because the instants in time at which the carriers cross the barrier are randomly distributed. It is usually represented by a noise current source in parallel with the junction:

$$\overline{i_n^2} = 2qI_{DC}\Delta f$$

Like thermal noise the shot noise power spectral density is constant up to very high frequencies so it is *white noise*. However, shot noise depends on the DC current flow in the device – if there is no DC current flow there is no shot noise.
In a BJT, both the base current and the collector current flow through pn junctions - therefore there are shot noise components associated with both base and collector currents.
Subthreshold current is a MOSFET is also associated with current flow through a pn junction and so in subthreshold, MOSFETs exhibit shot noise.

Shot Noise Components in BJT



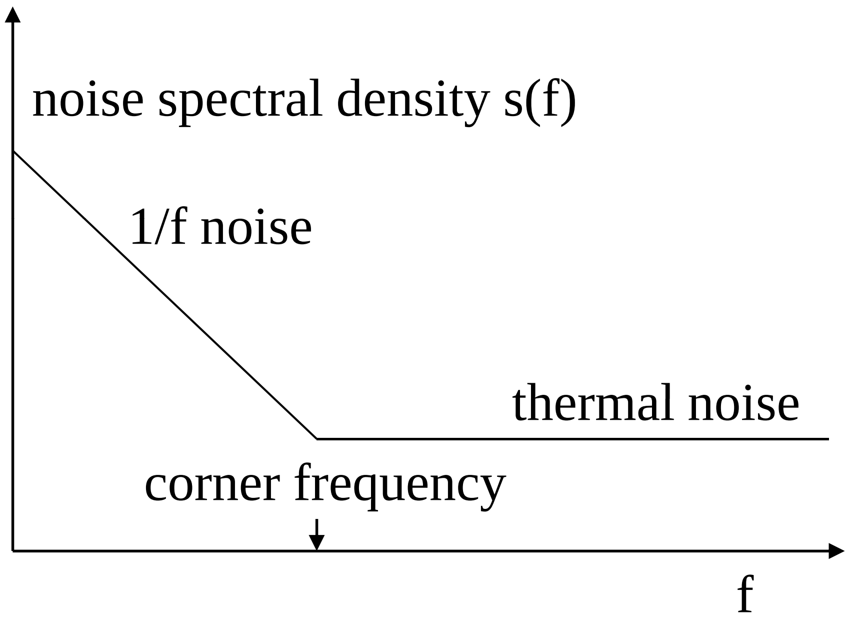
$$\overline{i_{n,b}^2} = 2qI_B\Delta f$$

$$\overline{i_{n,c}^2} = 2qI_C\Delta f$$

Flicker (1/f) Noise

Many electronic components (especially MOSFETs) exhibit a noise signal whose spectral density decreases with increasing frequency – this is known as flicker or 1/f noise. At low frequencies this is the dominant noise mechanism in MOSFETs and is represented *either* by a noise current source between drain and source *or* by a noise voltage source at the gate:

$$\overline{i_n^2} = \frac{K}{f}\frac{g_m^2}{WLC_{OX}^{'}}\Delta f \qquad \text{or} \qquad \overline{v_n^2} = \frac{K}{f}\frac{1}{WLC_{OX}^{'}}\Delta f$$



K is a constant depending on the process. 1/f noise decreases with increasing device area so large area devices are often used for low noise. The 1/f corner frequency is the frequency at which the 1/f noise drops to the level of the device thermal noise. Devices with low corner frequencies have better (lower) noise at any given frequency.