Semiconductor Technology from A to Z

Analog & Mixed-Signal Design

Noise in Semiconductor Devices

Thermal Noise

Thermal noise, also called Johnson-Nyquist noise, arises from the random thermal motion of charge carriers in any resistor and is present even in thermal equilibrium, independent of any flowing current. The spectral noise voltage density of a resistor R at absolute temperature T is $v_n^2/\Delta f = 4kTR$, where k is the Boltzmann constant; for a 1 kΩ resistor at room temperature (300 K), this works out to a noise voltage density of about 4 nV/√Hz. The noise is constant over a wide frequency range (white noise) and can only be reduced by lowering the temperature or the resistance value.

In MOS transistors, thermal noise mainly occurs in the conducting channel and is often modeled as an equivalent noise current at the drain terminal, whose magnitude depends on the transistor transconductance and, in typical analog amplifier stages, is a major contributor to an operational amplifier input-referred noise voltage of a few nV/√Hz.

Shot Noise

Shot noise arises because an electrical current does not flow continuously but as a sequence of discrete, statistically independent arriving charge carriers, for example when crossing a potential barrier such as the p-n junction of a diode. The spectral noise current density is likewise frequency-independent (white) and equals $i_n^2/\Delta f = 2qI$, where q is the elementary charge and I the average direct current through the barrier; for a diode current of 1 mA, this gives a noise current density of about 18 pA/√Hz.

Unlike thermal noise, which exists even without any current flow, shot noise only occurs when current actually flows across a potential barrier and is therefore particularly significant in bipolar transistors and diodes, while it plays a minor role in the channel of a MOSFET, which has no true potential barrier.

1/f Noise (Flicker Noise)

1/f noise, also called flicker noise, has a spectral power density that rises inversely with frequency and therefore dominates at low frequencies. In MOS transistors it is generally attributed to charge carriers being temporarily trapped and released at traps near the interface between silicon and gate oxide, causing the channel charge and therefore the drain current to fluctuate; PMOS transistors often show markedly lower 1/f noise, sometimes by an order of magnitude, than comparable NMOS transistors, owing to hole conduction occurring further from the gate oxide in a buried channel.

The frequency at which the spectral power density of 1/f noise equals that of white thermal noise is called the corner frequency and lies in the range of a few kilohertz to a few megahertz for typical CMOS processes. Because 1/f noise particularly limits the precision of low-frequency and near-DC measurements, low-noise amplifiers use techniques such as chopper stabilization, in which the signal of interest is modulated, typically to a range of a few tens of kilohertz to a few megahertz, before amplification and then demodulated back afterward, so that it is processed outside the dominant 1/f noise region.