Noise models for diodes and transistors

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- **pn junctions and BJTs** - shot noise, flicker noise, burst noise
- **MOSFETs** - flicker noise, thermal noise in strong inversion, shot noise in weak inversion, burst noise

Shot noise occurs due to various reasons - random emission of carriers across a barrier, random tunneling of carriers, generation/recombination processes in bulk and depletion region, thermal fluctuations triggering a relaxation current through diffusion. The PSD of shot noise is proportional to the current.

Some controversy on origin of flicker noise - whether it occurs due to number (of carriers) or mobility fluctuations. Models are empirical models.

Burst noise (or random telegraph signal) is seen as random “bursts” of noise in the time domain - occurs due to charging/discharging of a single defect.
Diodes

- Shot noise occurs because the minority carrier density in the bulk fluctuates due to thermal motion and generation/recombination of carriers. This triggers a relaxation current - the current flow is by diffusion.

- The noise spectral density is given as

  \[ S_I(f) = 2q(I + 2I_s) \]

- A more accurate expression includes a frequency dependent term.
Bipolar Junction transistor

- Shot noise - mechanism is similar to diodes (narrow diodes)
- The spectral densities are given by

\[ S_{I_E} = 2qI_E, \quad S_{I_B} = 2qI_B, \quad S_{I_C} = 2qI_C \]
The three noise current sources are correlated

\[ S_{CE} = -2qI_c \Rightarrow c_{CE} = -\sqrt{\alpha} \]

\[ S_{BE} = -2qI_B \Rightarrow c_{BE} = -\sqrt{\frac{\alpha}{\beta}} \]

The collector base correlation occurs due to charging and discharging of the diffusion capacitance

\[ S_{CB} = -2qI_c \frac{j\omega \tau_t}{3} \Rightarrow c_{CB} = -\sqrt{\beta} \frac{j\omega \tau_t}{3} \]

where \( \tau_t \) is the base transit time
MOSFET - strong inversion

- Random thermal motion of carriers in the inversion layer
- Modelled as a voltage dependent nonlinear resistor
- The noise in the drain current is

\[ i_d^2 = 4kT \frac{\mu}{L^2} |Q_{inv}| \Delta f \]

where \( Q_{inv} \) is the total inversion charge in the MOSFET
- In a simple model, ignoring channel length modulation,

\[ Q_{inv} = \frac{2}{3} WLC_{ox}(V_{GS} - V_T) \frac{1 + \alpha + \alpha^2}{1 + \alpha} \]

where

\[ \alpha = 1 - \frac{V_{DS}}{V_{GS} - V_T} \]

- More complex models take into account velocity saturation
Induced gate noise

- Voltage fluctuations in the channel coupled to the gate through $C_g$
- Induced gate noise correlated to the drain noise
- A potential fluctuation at $v(x)$ causes a gate current $i_g$ given by

$$i_g = -j\omega W \int_0^L C_g(x)v(x)dx$$
For long channel devices in saturation ($V_{Dsat} = V_{GS} - V_T$), the PSDs of the drain current and induced gate current are

$$S_{id} = 4kT \frac{2}{3} g_m, \quad S_{ig} = 4kT \frac{16}{135} \omega^2 (W/LC_{ox})^2 \frac{1}{g_m}$$
The drain and gate noise are correlated and the cross spectral density is

\[ S_{igid^*} = 4kT \frac{1}{9} j\omega C_{ox} WL \]

The correlation coefficient (coherence function) is therefore

\[ c = \frac{S_{igid^*}}{\sqrt{S_i d S_{ig}}} \approx 0.395j \]
1/f Noise

- Fluctuations in the current due to trapping/detrapping by interfacial defects
- A simple model is

\[
\frac{i_{df}^2}{f} = \frac{K_\text{g}_m^2}{WLC_{\text{ox}}^2} \frac{1}{f} \Delta f
\]

- Often just modelled as

\[
\frac{i_{df}^2}{f} = K' \frac{l_{\text{DS}}^a}{f}
\]

where \(a\) is left as a parameter
- \(K\) depends on device type and processing
Other noise sources

- Thermal noise due to the distributed gate resistance ($R_g$)
- Thermal noise due to source and drain resistances $R_s$ and $R_d$
- Shot noise due to gate tunneling current and junction diodes
- Noise due to hot electrons (in submicron devices)
- Substrate noise
- RTS noise
References

1. A. van der ziel “Noise in solid state devices and circuits”
2. A good introduction to noise in MOSFETs is contained in the book “Analysis and modelling of MOS transistors” by Y. Tsividis