Semiconductor Noise
in the Time and Frequency Domain

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Motivation

Publication:

- apply standard semiconductor parameter analyzers for also measuring low frequency noise, using Fourier Transformation
- no additional instruments like low-noise amplifier, filters, or signal analyzer required
- independently measure the input and output noise of the device

By applying Fourier Transformation to DC data, sampled over time, noise characterization becomes possible with any DC measurement system

The motivation for this paper is the publication of Hans Tuinhout, mentioned above. It describes a method to apply DC analyzers, stimulating a fixed bias voltage, for measuring a current versus time. The current also includes the noise contributed by the test device, and this current is then converted into spectral density by Fourier transform.

The beauty of the proposed method is that simply a DC analyzer is involved, and no additional equipment or instruments are required. This enables to add noise measurements to any DC measurement system.
The measurement setup consists of applying constant DC bias voltages to the (e.g. Base of a bipolar) transistor, and of re-measuring the (Base) transistor current continuously during a certain time interval. The \( i_B(t) \) current values are then Fourier-transformed into the frequency domain, and converted to spectral density [A\(^2\)/Hz].
The developed user interfaces for
1. performing the measurement and
2. applying the Fourier transform are shown above.

As a first example, a standard packaged bipolar transistor 2N2222 ‘from the shelf’ was used.

Above, on the upper left, the measured iB currents vs. time, for different vBE voltages, are shown.
Below are the zoomed-in details for three vBE bias conditions.

To the right, the spectral density result is shown for all five vBE biasings.

While for the lowest vBE bias, 0.605V, the noise spectral density declines with the expected -1decade/decade, this is not the case for higher bias voltages. A possible reason is the observed exponential drift of the iB current in the time domain, which increases with increasing vBE bias voltage.

This shows the results of a chip transistor. Again, the expected -1decade/decade slope could not be obtained independently of the applied DC biasing.
The generally observed phenomenon: slopes of ~2decades/1decade

Transistor NPN 2N2222
\[ v_{BE} = 0.60, 0.62, 0.64, 0.66, 0.68, 0.70 \]
\[ v_{CE} = 1V \]

Suspected Problems:

Device self-heating affects the freq.domain result
  > could not be avoided with increased hold time before starting the measurement
  > could not be avoided by mathematically removing self-heating exponential function
To further investigate noise signals in both, time and frequency domain, a tutorial about noise in semiconductors, overlaid by thermal drift of the operating point has been developed.

### Noise Sources in Semiconductors

#### White Noise

- **time domain**
  - (current or voltage)
- **frequency domain**
  - (power spectral density)

White noise is a time domain signal made of uncorrelated, Gaussian distributed amplitude spikes. It contains all frequencies in equal proportion and its spectrum (power spectral density $[\text{A}^2/\text{Hz}]$) is flat. This is in analogy to light, which turns white when all frequencies are summed up into a single beam. Hence its name.

#### $1/f$ Noise

- **time domain**
  - (current or voltage)
- **frequency domain**
  - (power spectral density)

#### Generation/Recombination (Popcorn) Noise

- **time domain**
  - (current or voltage)
- **frequency domain**
  - (power spectral density)
The trace of 1/f noise, in the time domain, looks a bit like the creeping of a worm, overlaid by noise. This 'flickering' trace named this kind of noise.
In the frequency domain, its spectral density characteristic is a -1decade/decade slope in a log/log plot.

Generation/Recombination noise, also called telegraph or popcorn noise because of its shape in the time domain, corresponds in a log/log plot to first a constant, then slightly increasing spectrum. After its corner frequency, it declines with a -2decades/decade slope.

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**White Noise**

A current through a resistor or a semiconductor junction generates noise due to its quantized and random flow.

**White Noise is constant over frequency, but is bias-dependent.**

Device modeling wise, white noise (resistor) or channel noise (MOS transistor) is automatically modeled by modeling the device's DC current I.
1/f Flicker Noise

This low-frequency, bias-dependent noise effect is considered attributed to traps associated with contamination and crystal defects.

Flicker Noise is bias and frequency dependent.

Flicker noise is described in electronic device models by the model parameters AF, KF and EF.

Telegraph or Popcorn Noise

This kind of noise is due to generation/recombination effects and trapping in semiconductors.

Telegraph/Popcorn Noise is bias and frequency dependent.

Note: although pretty often observed with modern sub-micron MOS transistors, this noise model is amazingly not part of modern MOS models like PSP or Hisim. The same is true also for bipolar transistors, with the exception of the simulator ADS from Keysight: it offers the modeling of this kind of noise as part of its model BJT_Model.
With the fundamentals of semiconductor noise sources recapitulated, we will now investigate the noise spectral densities, with special emphasis on being overlaid by thermal drift of the operating point.

IC-CAP of Keysight Technologies was applied for the experiment.
For the tutorial, the Time Signal of the three semiconductor noise types

- White Noise
- 1/f Noise
- Popcorn Noise

has to be synthesized, and the Corresponding Spectrum has to be calculated.

To verify the IC-CAP macros, we first inspect and verify the three individual kinds of noise.

White (Gaussian) Noise

White (Gaussian) noise corresponds to a flat power spectral density, which is independent of the frequency.
The power level depends on the magnitude of the Gaussian noise.
The 1/f noise is created from Gaussian white noise, filtered by a low pass to obtain the characteristic -1decade/decade slope of the spectral density. This explains why in the time domain, for small time intervals, the random spikes are overlaid by flickering directions (the low-frequency part of the power spectral density, dominating its high-frequency part).
As mentioned before, 1/f noise can be composed from white Gaussian noise (with its power spectral density constant over frequency) when sent across a lowpass filter.

This is investigated by the three slides of this intermediate investigation. In a first investigation, above on the upper right, the Gaussian noise (blue curve) is sent across a lowpass filter with a too big a corner frequency of \( f_{3dB} = 1MHz \) (green curve). Such a 1MHz lowpass filter is represented in the time domain by the impulse response function:

\[
    f(t) = \exp\left(-\frac{t}{\tau_{\text{LowPass}}}\right) \quad \text{with} \quad \tau_{\text{LowPass}} = \frac{1}{f_{3dB}}
\]

In other words, the Gaussian noise, in the time domain, has to be convoluted with the lowpass impulse response \( f(t) \), to give flicker noise (red curve on the upper right). Since the lowpass has a too large a corner frequency, and hence, its \( f(t) \) impulse response corresponds nearly to a Dirac impulse function, the convolution result (flicker noise) is nearly equal to the original Gaussian noise.

On the upper left, the autocorrelation of the resulting flicker noise is shown. Due to the much too small \( \tau_{\text{LowPass}} \) of the lowpass filter impulse response with, the resulting noise is not autocorrelated at all (visible by the single Dirac impulse at time=0sec).

As mentioned, this results in synthesized 'flicker' noise which basically still is Gaussian noise.

Another interpretation of this scenario is that the lowpass filter lets pass all frequencies which are relevant for this experiment.
In this scenario, with a lower corner frequency of the lowpass filter \(f_{3\text{dB}} = 25\text{kHz}\), and the corresponding \(\text{Tau}_{\text{Lowpass}} = 40\text{us}\), the resulting flicker noise (red curve in the upper right plot) exhibits a small autocorrelation (upper left). After the Fourier transform, the resulting noise power spectral density shows the expected -1decade/decade slope.

With a too big a corner frequency of the lowpass filter \(f_{3\text{dB}} = 1\text{kHz}\), the resulting time-domain 'flicker' noise shows a large autocorrelation.

The corresponding power density spectrum has a slope of -2decades/decade.
After its corner frequency FB, the slope of Popcorn noise falls with -2 decades/decade.

A Quick Side Aspekt: This looks like noise but isn't

This experiment, with an artificially created signal that 'looks like noise', points to a critical measurement correction trap: it clearly dissuades to apply mathematical tricks to correct bad time-
domain measurement results (unless you know what you do ;-) )

-> A -2decades/decade noise power density spectrum slope is not physical!

Thermal Drift in Time and Frequency Domain

When the bias point is drifting over time during the noise measurements, this corresponds to a -2decades/decade slope in the spectral density plot.
Thermal drift during noise measurements can badly affect the noise measurement result. The following slides depict the effects.

In the above example, the magnitude of thermal drift is in the same range like the white noise peaks. The slope, in the frequency domain, is only slightly affected.
The power spectral density of white noise can exhibit a slope of \(-2\) decades/decades (!!!) if the thermal drift of the device's bias point is large compared to the noise peaks.

In this example, the magnitude of thermal drift is in the same range like the \(1/f\) noise peaks. As a result, the slope, in the frequency domain, is 20% larger than its theoretical value of \(-1\) decade/decade.
When small compared to the thermal drift, its own -1 decade/decade slope is overlaid and dominated by the -2 decades/decade slope (!!) of the bias drift.
Popcorn noise is represented by a -2decades/decade slope for frequencies above its corner frequency FB, and the same slope corresponds also to the (1-exp) thermal drift function overlaid in the time domain: the resulting slope is again -2decades/decade.

Compared to the previous scenario, the popcorn noise level is now small compared to the thermal drift. Therefore, the popcorn spectrum with its characteristic corner frequency has sunk below the thermal drift spectrum.
Tutorial Conclusions

- It has been found that thermal drift of the operating point, during noise measurements, can badly affect the noise power spectral density.

- Noise spectra, measured under such conditions, can exhibit a -2 decades/decade slope, what does not correspond to physical noise power spectral densities.

Findings and Suggestions for Further Investigations on Applying DC-Analyzers to 1/f Noise Measurements

- The noise measurement principle suffers from the coupling of the (drifting) DC bias and the noise.
  
  Note: in conventional noise meas. systems, a band filter (typ. 1Hz ... 1MHz) is applied, and this decouples the DC bias and the noise measurement.

  - offstripping of the exponential drift function disturbs the noise properties
  - also long delay times before sampling start did not work really well

- Due to the auto-correlation property of 1/f noise, the time-domain sampling should be done fast i.e. within the auto-correlation time.

  Probably best using the internal programming feature of some DC analyzers (e.g. Agilent 415x series)

- to improve the shape of the frequency-domain curves, the averaging should be done in the frequency domain, and not in the time domain.