Mechanisms of 1/f noise and Gain Instabilities in metamorphic HEMTS

D. Bruch; M. Seelmann-Eggebert; S. Guha

Fraunhofer Institute for Applied Solid State Physics IAF
Tullastrasse 72
79108 Freiburg Germany
IAF Departement for High Frequency Devices and Circuits

Status
- 35 nm mHEMT
- $f_T > 500$ GHz
- $f_{\text{max}} > 900$ GHz

Target
- 20 nm mHEMT $\Rightarrow f_{\text{max}} > 1.3$ THz

Good RF performance (e.g. Gain and Noise properties)

But Low frequency noise comes into play for frequency converting (non-linear) circuits (e.g. Mixers, oscillators) and (Low-Frequency) Amplifiers.
Stochastic Processes and Noise

Measurement of entity $u$ vs. time

- Probability distribution
- Expectation value
- Variance

$$<u> = \frac{1}{T} \int_0^T u(t) dt$$
$$<(u - <u>)^2> = <u^2> - <u>^2$$

Autocorrelation function (ACF)

$$\rho_A(\tau) = \frac{1}{T} \int_0^T u(t) u(t+\tau) dt$$

- Constant for static process
- Contains information on deterministic dynamics

⇒ Dynamics underlying stochastic process

Noise = power density spectrum
= fourier transform of ACF

$$S(f) = \int_{-\infty}^{\infty} e^{-j2\pi f} \rho_A(\tau) d\tau$$
Noise - Frequency Dependency

Autocorrelation function:
\[ \rho_A(\tau) = A(t) \cdot A(t + \tau) \]

Noise Power Density Spectrum:
\[ S(f) = 2 \int_{-\infty}^{\infty} \rho_a(\tau) \exp(-2\pi jf\tau) d\tau \]
\[ S(f) \propto \frac{1}{f^\beta} \]

\[ \beta = 0 : \text{white noise} \]
\[ 0.5 \leq \beta \leq 1.5 : 1/f\text{-Noise (Flicker Noise, pink noise)} \]
\[ \beta \approx 2 : \text{“Brownian“-Noise (red noise)} \]
Hooge‘s Parameter

Empirical Approach to define 1/f Noise, independent of noise origin:

If a 1/f Noise-Spectrum is observed it can be described by:

\[
\frac{S_I(f)}{I^2} = \frac{\alpha_H}{N_f}
\]

<table>
<thead>
<tr>
<th>Device</th>
<th>(\alpha_H)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs MESFET**</td>
<td>(2 \times 10^{-4})</td>
</tr>
<tr>
<td>GaAs filament**</td>
<td>(2 \times 10^{-3})</td>
</tr>
<tr>
<td>N-type Silicon-Res.***</td>
<td>(1 \times 10^{-7}) - (1 \times 10^{-5})</td>
</tr>
</tbody>
</table>

\(\alpha_H\) : Hooge‘s Parameter initially found to be: \(\approx 2 \cdot 10^{-3}\)

N : Number of carriers

Low-frequency noise: Dynamic processes with long time constants

- Generation-Recombination Processes
- Typical for deep traps and lattice mismatch

The high electron mobility transistor (HEMT) is a “surface” component

Layer composition of Fraunhofer IAF’s 35nm mHEMT
**Generation-Recombination Process with two states**

Probability for $j$ carriers at state $b$ at time $t = \tau + d\tau$ under the assumption that only one transition is possible during $d\tau$

\[
P(j, \tau + d\tau) = G(j-1)P(j-1, \tau)d\tau + R(j+1, \tau)P(j+1, \tau)d\tau + [1-G(j)][1-R(j)]P(j, \tau)d\tau
\]

\[
\frac{d}{d\tau} P(j, \tau) = -[G(j)+R(j)]P(j, \tau) + R(j+1, \tau)P(j+1, \tau) + G(j-1)P(j-1, \tau)
\]

Which is solved by: $P(j, \tau) \propto \exp \left( -\frac{\tau}{\tau_\rho} \right)$

The Autocorrelation $\rho_A(\tau) = \frac{A(t) \cdot A(t+\tau)}{\langle A(t)^2 \rangle}$ is given by an Expectation (value) and hence depending on $P(j, \tau)$

With $\tau_\rho = \frac{1}{R' - G'}$ this leads to: $\rho(\tau) = \frac{R}{R' - G'} \exp \left( -\frac{\tau}{\tau_\rho} \right)$

\[
S_{GR}(f) \propto \frac{1}{1 + (2\pi\tau_\rho f)^2}
\]
Generation-Recombination Process and the McWhorter-Model

This does not give a 1/f noise spectrum by itself!

But the superposition of plenty of GR-processes featuring different Time constants leads to a spectrum which behaves LIKE 1/f noise.

„Non-fundamental“ 1/f noise. With reported $f_c$ up to ~700 MHz

*Low-Frequency Noise Characteristics of Lattice-Matched ($x = 0.53$) And Strained ($x > 0.53$) InAlAs/InGaAs HEMT's* G.I. Ng et. al., 1992, IEEE Transactions on Electron Devices.
Fundamental Quantum 1/f Noise

Voltage and current fluctuations not only due to carrier density but also due to carrier velocity.

„Random“ change in carrier velocity/mobility caused by scattering mechanisms.

Scattering of carriers in HEMTs:

Confinement layers e.g.:
\[ \delta - \text{ Spacer, Buffer, …} \]

Scattering in the channel, the confinement layers or the interface.
Fundamental Quantum 1/f noise

The Photons generated by the decelerated charge carriers influence the carriers themself (feedback mechanism).

After P.H. Handel this leads to a spectrum density of:

\[ S_j(f) = \frac{2\alpha A}{f} \]

\( \alpha \): Sommerfield's fine structure constant \( \frac{e^2}{\hbar c} \)

\( A \): proportional constant \( \frac{2\pi 2a^2}{3c^2} \)

Hooge’s Parameter predicting quantum 1/f noise:

\[ \alpha_H = \frac{4e^2}{3\pi\hbar c} \left( \frac{\overline{\Delta v}^2}{c^2} \right) \]

\( \overline{\Delta v} \): average change in velocity

\( f_{\text{knee}} \sim 100 \text{ kHz} \)

*"Fundamental Quantum 1/f Noise in Semiconductor Devices"

Bremsstrahlung due to Scattering

Scattering at impurities, phonons, interface roughness, etc.

"Loss" of energy (Larmor)

\[ P = \frac{2e^2a^2}{(3c^3)} \]

- e: charge of electron
- a: acceleration (approximated by \( \Delta \) function)
- c: speed of light
Generation of "soft"-Photons with \( E = h \cdot f \) shifting a part of the DeBroglie waves to lower frequencies, resulting in a beat term.

Spectral density of the emitted Bremsstrahlung energy:

\[
\frac{4q^2(\Delta v)^2}{3 \cdot c^3} = \text{const.}
\]

\( NoP = \frac{4q^2(\Delta v)^2}{3 \cdot h \cdot f \cdot c^3} \) : Number of Photons

The resulting spectral density of the beat term is then given by:

\[
S_j(f) = 2 \cdot \frac{4q^2(\Delta v)^2}{3 \cdot h \cdot c^3 \cdot f \cdot N}
\]
Measurement Observations

"Well behaved" 100nm Transistor
Size: 4x30 µm
Measurement Observations

“Bad behaved” 50nm Transistor
Size: 2x30 µm
Model Extension: 1/f-Noisesource
Thank You!