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

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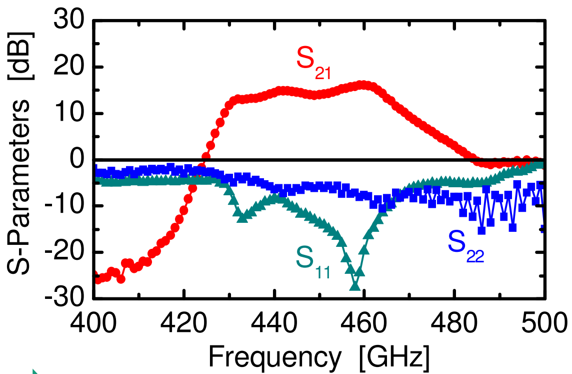
IAF Departement for High Frequency Devices and Circuits

Status

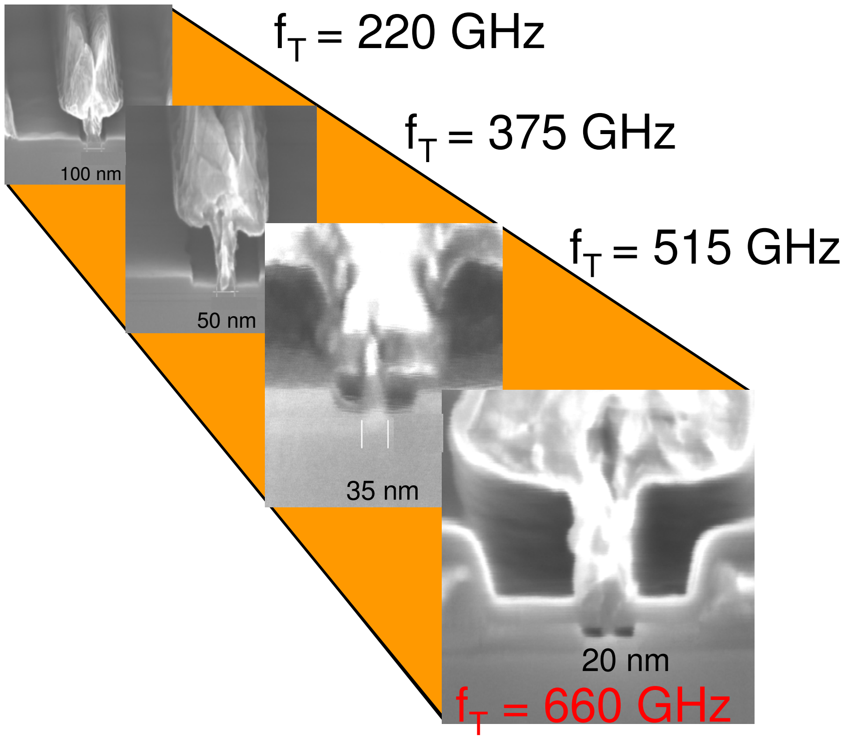
- 35 nm mHEMT
- f_T > 500 GHz
- f_{max} > 900 GHz

Target

- 20 nm mHEMT ⇒ f_{max} > 1.3 THz



Transit Frequency



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.

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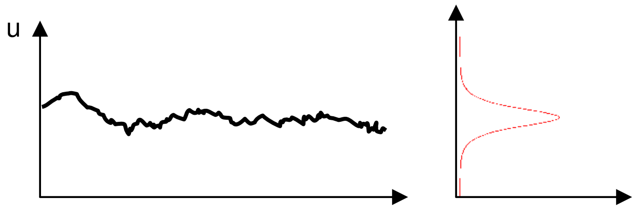
Stochastic Processes and Noise

Measurement of entity u vs. time



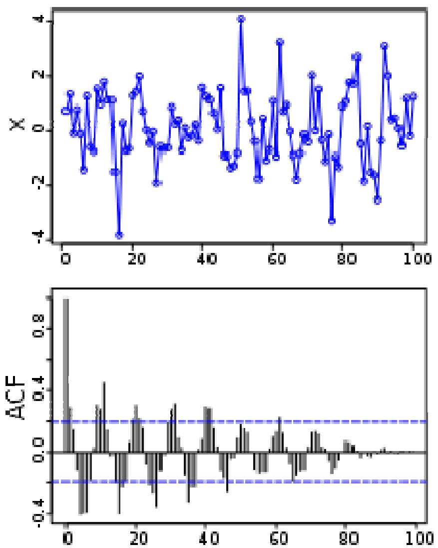
probability distribution
- expectation value
- variance

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

$$< (u - < u >)^2 > = < u^2 > - < u >^2$$

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

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

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Noise - Frequency Dependency

Autocorrelation function:

$$\rho_A(\tau) = \overline{A(t) \cdot A(t+\tau)}$$

Noise Power Density Spectrum:

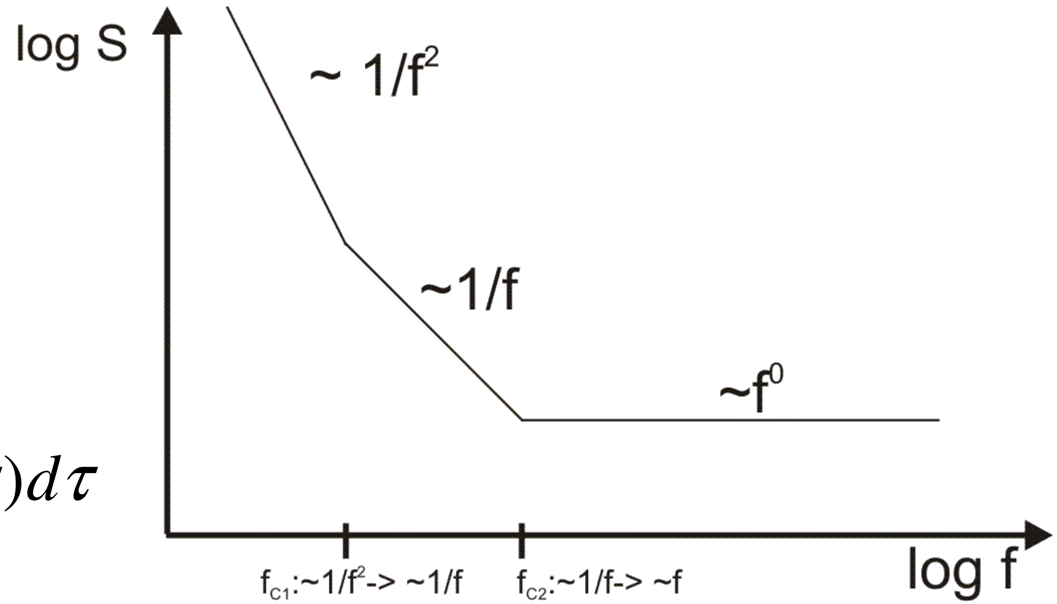
$$S(f) = 2\int_{-\infty}^{\infty} \rho_a(\tau) \exp(-2\pi j f \tau) d\tau$$

$$S(f) \propto \frac{1}{f^{\beta}}$$

$\beta = 0$: white noise

$0.5 \leq \beta \leq 1.5$: 1/f-Noise (Flicker Noise, pink noise)

$\beta \approx 2$: „Brownian“-Noise (red noise)



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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:

$$\frac{S_I(f)}{I^2} = \frac{\alpha_H}{Nf}$$

Device	α_H
GaAs MESFET**	2×10^{-4}
GaAs filament**	2×10^{-3}
N-type Silicon-Res.***	1×10^{-7} - 1×10^{-5}

α_H :Hooge's Parameter initialy found to be: * $2\cdot10^{-3}$

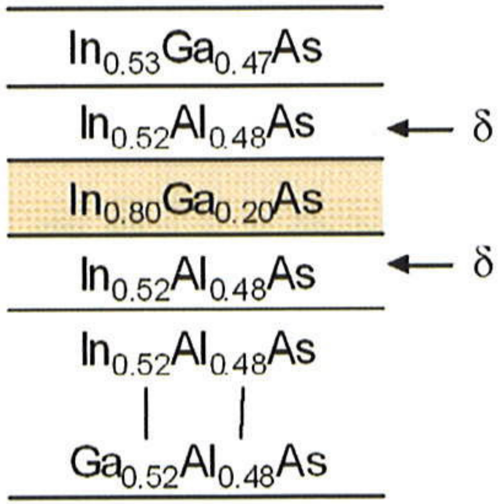
N :Number of carriers

* „1/f Noise is no surface effect", F.N. Hooge, Physics Letters A, 1969.
** „1/f Noise in GaAs Filaments" M. Tacano et. al., IEEE Transactions on Electonic Devices ,1991.
*** „Bulk and Surface 1/f", Lode Vandamme, IEEE Transactions on Electronic Devices,1989.

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

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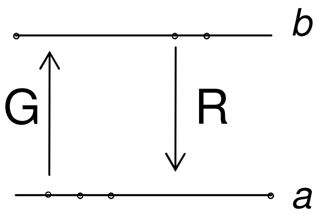
Generation-Recombination Process with two states



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: $P(j,\tau) \propto \exp\frac{-\tau}{\tau_\rho}$

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

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

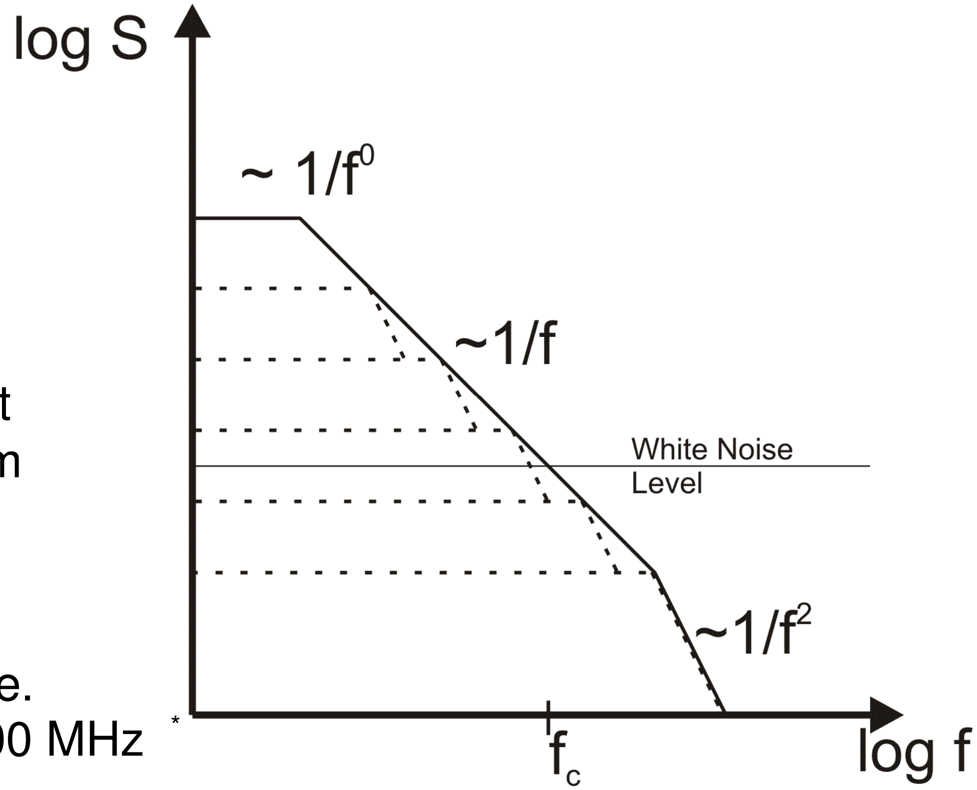
➡ $$S_{GR}(f) \propto \frac{1}{1+(2\pi\tau_\rho f)^2}$$

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 *



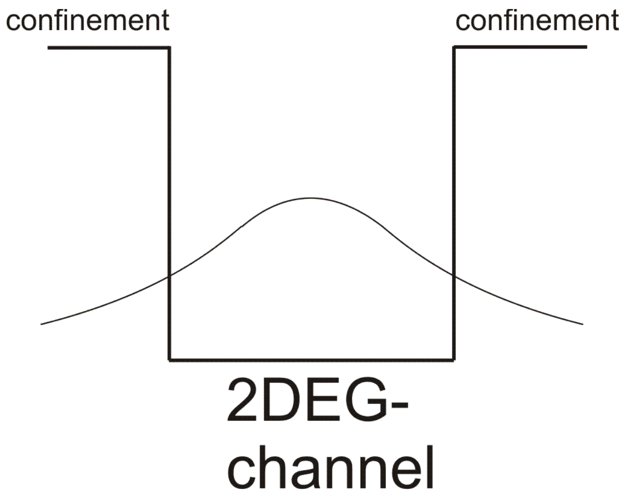
*„Low-Frequency Noise Characterisitcs of Lattice-Matched (x = 0.53) And Strained (x > 0.53l InAlAs/InGaAs HEMT‘s“ G.I. Ng et. al., 1992, IEEE Transactions on Electron Devices.

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.:

$\delta-$, 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:

$$S_j(f) = 2\alpha A / f$$

α : Sommerfield's fine structure constant $\frac{e^2}{\hbar c}$

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

➡ f_{knee} ~ 100 kHz

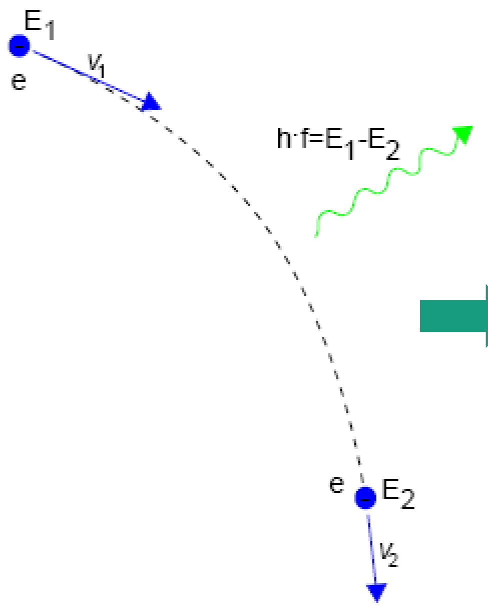
Hooge's Parameter predicting quantum 1/f noise: $$\alpha_H = \frac{4e^2}{3\pi\hbar \cdot c}\left(\frac{\overline{\Delta v^2}}{c^2}\right)$$

$\overline{\Delta v}$: average change in velocity

*„Fundamental Quantum 1/f Noise in Semiconductor Devices"
P. Handel, 1994, IEEE Transactions on Electron Devices.

Bremsstrahlung due to Scattering

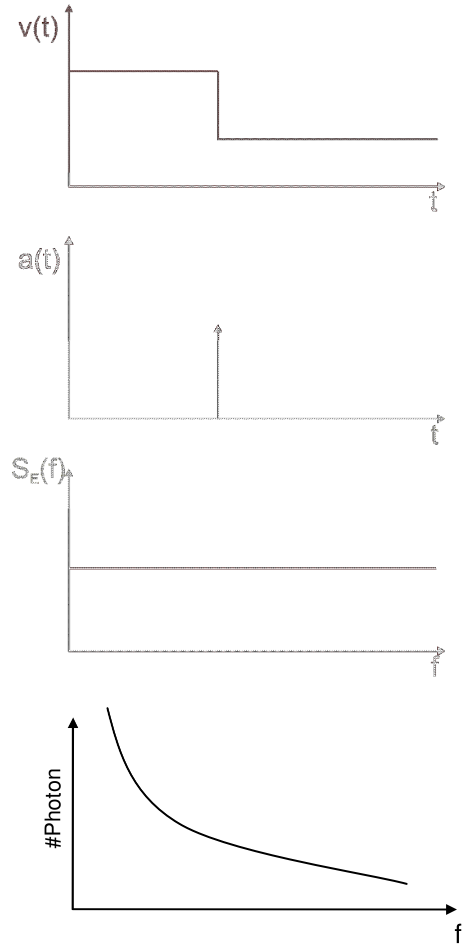
Scattering at impurities, phonons, interface roughness, etc.



„Loss" of energy (Larmor)

$$P = 2e^2 a^2 /(3c^3)$$

e: charge of electron
a: acceleration (approximated by Δ function)
c: speed of light



Fundamental 1/f Noise

- 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: $\frac{4q^2(\Delta v)^2}{3 \cdot c^3} = const.$

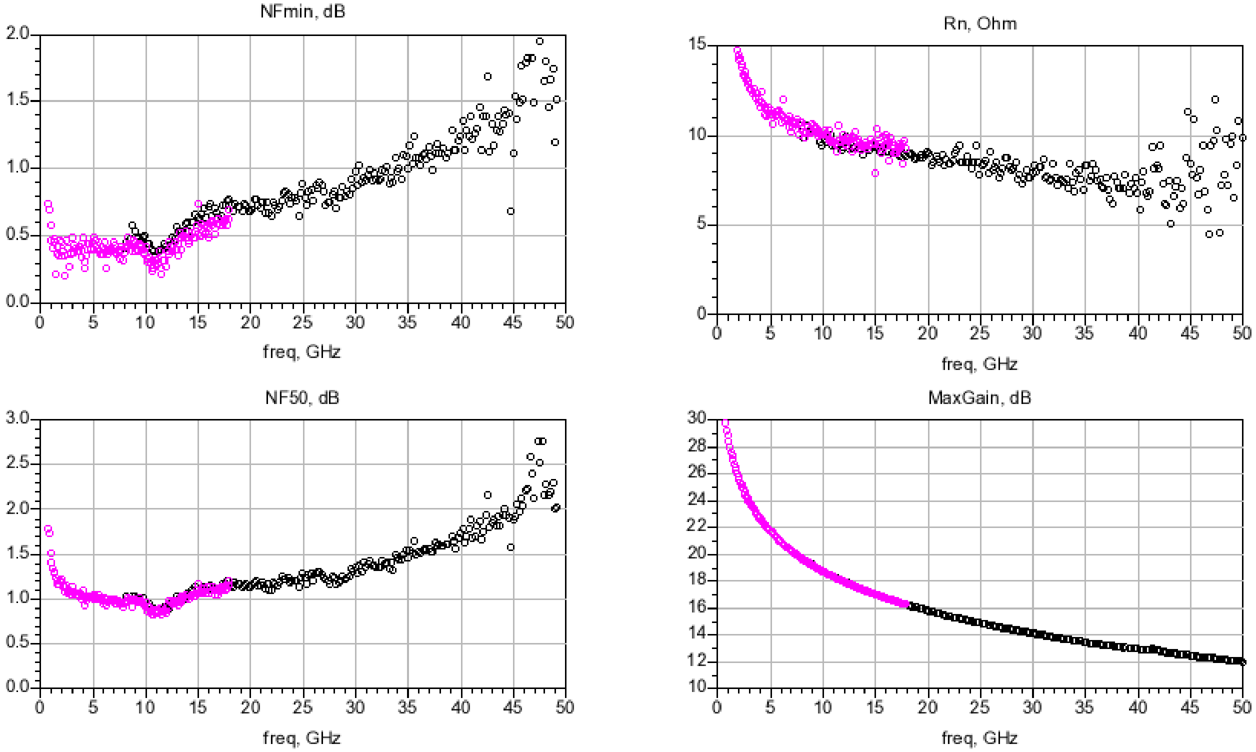
- $NoP = \frac{4q^2(\Delta v)^2}{3 \cdot h \cdot f \cdot c^3}$: Number of Photons

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

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

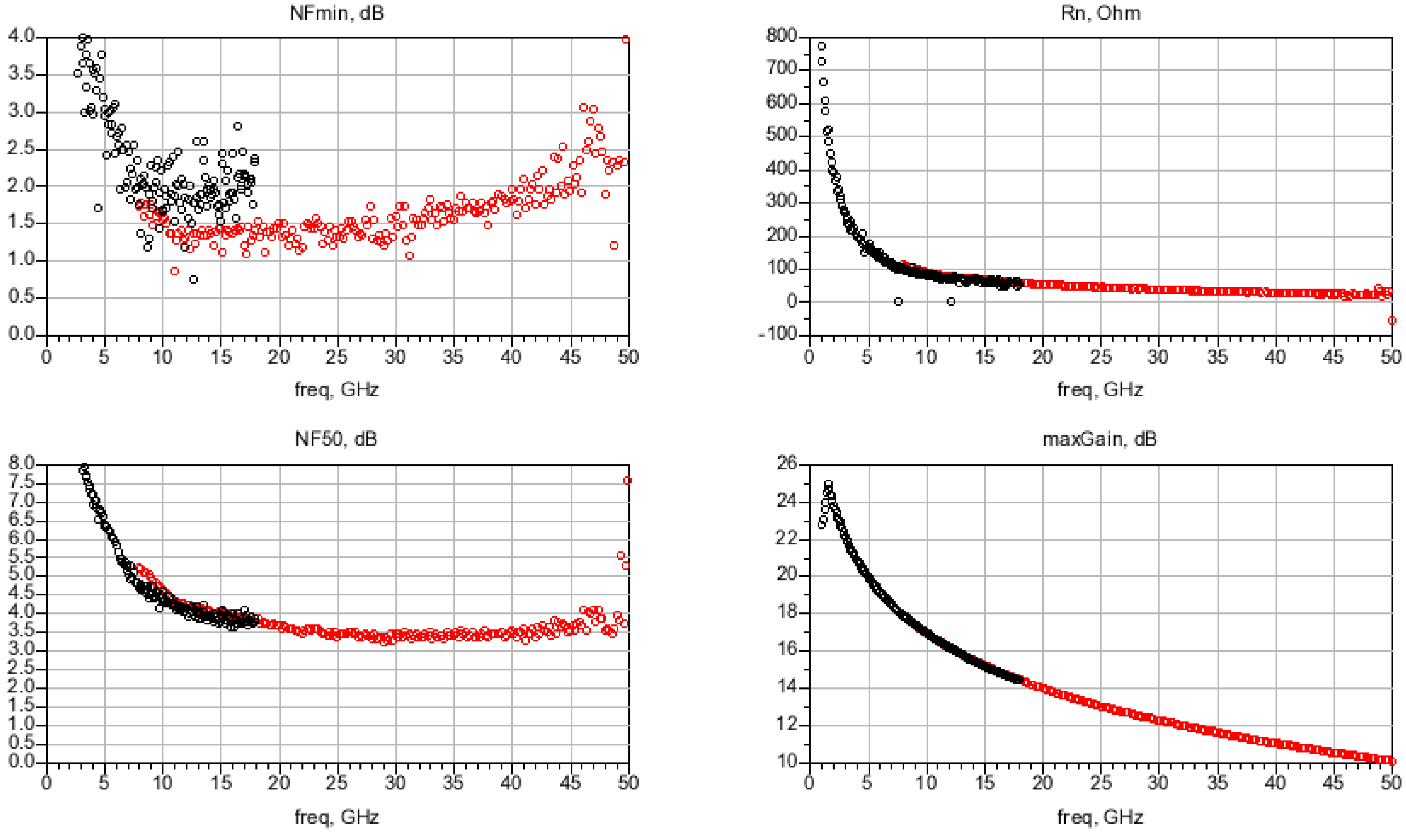
Measurement Observations

„Well behaved“ 100nm Transistor
Size: 4x30 µm

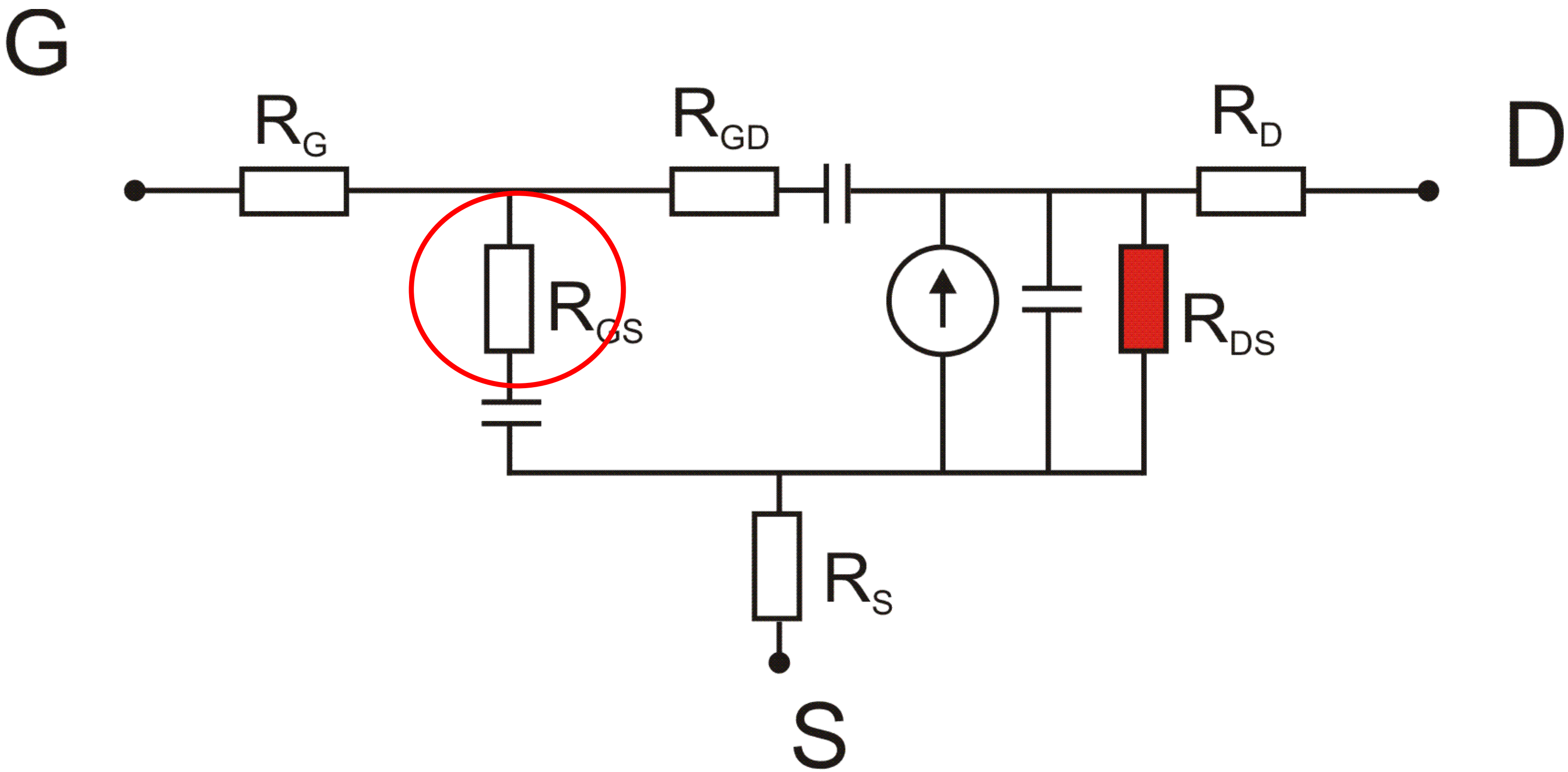


Measurement Observations

„Bad behaved“ 50nm Transistor
Size: 2x30 µm



Model Extension: 1/f-Noisesource



Thank You!