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SIMULTANEOUS MEASUREMENT OF CURRENT AND VOLTAGE NOISE IN A GaN-RESISTOR

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A common working hypothesis in the analysis of 1/*f*-noise is that the spectral density of noise current and the spectral density of noise voltage in an ohmic resistor are proportional to one another. This requires that not only a deterministic voltage over a resistor is proportional to the current through it, but also that a noise-voltage is proportional to the noise current. However, no experimental evidence for this hypothesis has been given until now in the literature, since the influence of the inherent noise in the measuring equipment could not be separated from the effects produced by the resistor under test. A GaN-resistor, though, produces excessive noise in the frequency-band where 1/*f*-noise is dominant. This dominance was used to separate effects. First experimental results raise doubts above the mentioned working hypothesis.

1 Introduction

A common working hypothesis in the analysis of electronic noise is that Ohm's law does not only apply for deterministic voltages u_{det} over and currents i_{det} through an ohmic device with resistance R, but also for noise-voltages u_N and noise currents i_N. Thus, if $u = u_{det} + u_N$, with u_N being a noise process having zero-mean, then it is assumed that not only $<u> = R <i>$ holds, but also $u = R\,i$. (Brackets indicate expected value). Under these conditions and with time-invariant value of u_{det}, it follows for the spectral densities with respect to voltage and current:

$$S_I(f)\Big/\left\langle i^2\right\rangle = S_U(f)\Big/\left\langle u^2\right\rangle, \tag{1}$$

which is frequently used in literature (see for example [1]).

The assumption $u = R\,i$ is not obvious. There are strong hints that the resistance could also fluctuate, at least for some materials [2]. However, if that is true, then the relation given in equation (1) needs not to be true in every case. It appears as if no experimental evidence for the assumption $u(t) = R\,I(t)$ could be given until now. Therefore, in this paper simultaneous measurements of noise current and noise voltage will be described.

2 Simultaneous measurement of noise current and noise voltage

Fig. 1 shows the measuring system that was applied to investigate the hypothesis $u = R\,i$. It consists of an ohmic resistor R_{DUT} as the device under test, an instrumentation amplifier with gain A_U, a transimpedance amplifier with gain A_I, and a parallel resistor R_P in order to provide a closed current loop for the current to be measured. A battery with open-circuit-voltage U_S and inner resistance R_V can be connected in parallel to the device under test, in order to generate additional shot noise.

All resistors of the circuit in Fig. 1 produce electronic noise. This is indicated by the gray color of their symbols. The same applies to the amplifiers, which also generate electronic noise, and that have respective input-impedances R_U and R_I.

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For an analysis of the noise behavior, the different noisy resistors are modeled as series connections of an idealized noise-voltage source and an idealized noise-free resistor. This is shown in Fig. 2. Amplifiers are modeled with the usual model using two independent noise sources and idealized noise-free amplifiers. The idealized instrumentation amplifier is regarded to have infinitely large input impedance; the idealized transimpedance amplifier has input impedance zero.

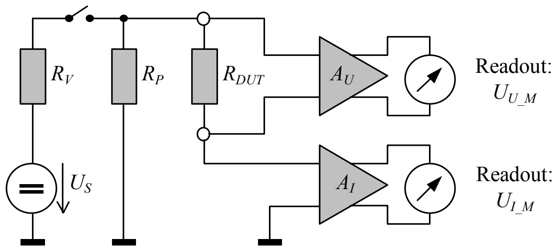

Figure 1. Current through device under test flows through transimpedance-amplifier and back through parallel resistor R_P .

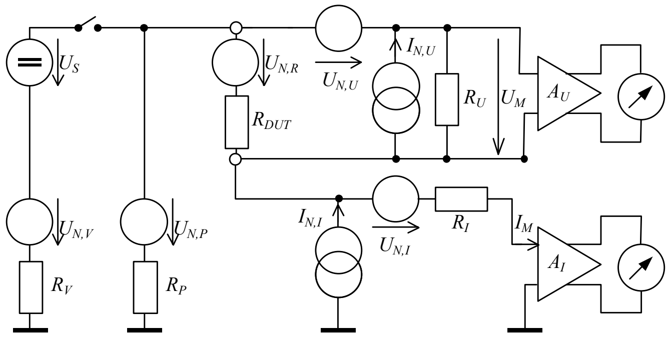

Figure 2. Equivalent circuit corresponding to Fig. 2.

Applying Norton's theorem and Thévenin's theorem, it is easy to show that under the condition $R_U >> R_{DUT} >> R_I$ and $<(R_{DUT} I_{N,U})^2> \; << \; <(U_{N,R})^2>$ the noise sources of the amplifiers are negligible with respect to measured variances.

DC-source and parallel resistor R_P can be jointly described by a new voltage source with open-circuit voltage $U'_{N,P}$ and inner resistance $R'_{N,P}$:

$$U'_{N,P} = \begin{cases} U_{N,P} & \text{switch open} \\ \left\{R_P\left(U_S + U_{N,V}\right) + R_V U_{N,P}\right\} / \left(R_V + R_P\right) & \text{switch closed} \end{cases}, \tag{2}$$

$$R'_{N,P} = \begin{cases} R_P & \text{switch open} \\ R_V R_P / \left(R_V + R_P\right) & \text{switch closed} \end{cases}. \tag{3}$$

If it is assumed that the influence of the amplifiers can be neglected, then a circuit as in Fig. 3 is to be analyzed. An elementary analysis then reveals that

$$U_{DUT} = \frac{R_{DUT}}{R'_P + R_{DUT}} U'_{N,P} + \frac{R'_P}{R'_P + R_{DUT}} U_{N,R} \quad ; \quad I_{DUT} = \frac{U'_{N,P} - U_{N,R}}{R'_P + R_{DUT}}. \tag{4}$$

A noise-voltage U_N can be approached arbitrarily well by Rice's second noise sum [3], [4]:

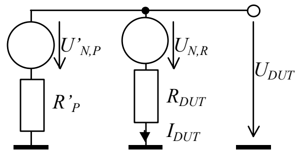

Figure 3. Simplified equivalent circuit corresponding to Fig. 2.

$$U_N = \sum_{n=1}^{N} \sqrt{2}\, U_{N,n} \cos\left(n\, 2\pi\, \Delta f\, t + \theta_{N,n}\right), \tag{5}$$

where the $U_{N,n}$ are deterministic (!) quantities with

$$U_{N,n} = \sqrt{S_U\left(n\,\Delta f\right)\Delta f}\ , \tag{6}$$

and where the $\theta_{N,n}$ are random variables that are uniformly distributed in $[0,2\pi)$. In case of thermal noise generated by a resistor that is on the physical temperature T and with resistance R, it follows

$$U_{N,n} = \sqrt{4 k_B T\, \Delta f\, R}\ . \tag{7}$$

Thus, if all resistors are assumed to generate thermal noise only, then equation (4) in combination with equation (7) yields

$$U_{DUT} = \frac{\sqrt{4 k_B\, T\, \Delta f\, R_{DUT} R'_P}}{R'_P + R_{DUT}} \sum_{n=1}^{N} \left\{ \sqrt{R_{DUT}} \cos\left(n\,\Delta\omega\, t + \theta'_{N,P,n}\right) + \sqrt{R'_P} \cos\left(n\,\Delta\omega\, t + \theta_{N,R,n}\right) \right\},$$

$$I_{DUT} = \frac{\sqrt{8 k_B\, T\, \Delta f}}{R'_P + R_{DUT}} \sum_{n=1}^{N} \left\{ \sqrt{R'_P} \cos\left(n\,\Delta\omega\, t + \theta'_{N,P,n}\right) - \sqrt{R_{DUT}} \cos\left(n\,\Delta\omega\, t + \theta_{N,R,n}\right) \right\} \quad .(8)$$

Therefore, would R_{DUT} be very large compared to R_P, then the measured voltage U_{DUT} would be dominated by the noise voltage of the parallel resistor R'_P and the measured current would be dominated by the noise produced in the device under test. I.e.: the measured outcomes would not both refer to the same device. The latter is also true, if R_{DUT} is very small compared to R_P. The effects of the noise sources even cannot be separated. This was already pointed out by L.B. Kish [5].

Consequently, with thermal noise alone, the measurement cannot be done. If, however, a GaN-resistor is used as device under test, and if this resistor will be used in a frequency range, where 1/*f*-noise is predominant over thermal noise, and if finally R'_P is sufficiently large, the situation changes completely, which is seen from equation (4). This arrangement was implemented for measurements.

3 Measurements

Spectral measurements showed the expected 1/*f*-noise spectrum, when all resistors but the device under test were realized as metal-film resistors, while the device under test was implemented as a GaN-resistor that was fed by a DC-source. Control measurements (shorted input of instrumentation amplifier, open input for transimpedance amplifier) demonstrated that the measured noise from the GaN-device was well above the noise-floor of the amplifiers (20 dB for the instrumentation amplifier, 35 dB for the transimpedance amplifier, both for frequencies between 5 Hz and 100 Hz).

Fig. 4 shows a typical example of *simultaneously measured* AC-voltage U_{DUT} (fat curve) and AC-current I_{DUT} times R_{DUT} (thin curve).

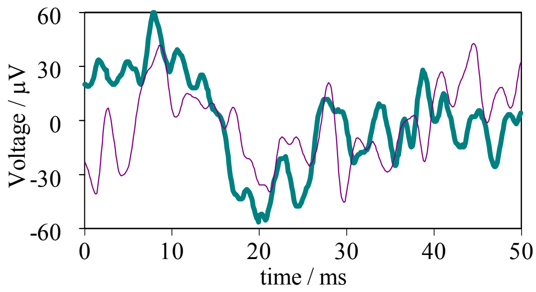

Figure 4. Typical curves for U_{DUT} (bold curve) and $I_{DUT}R_{DUT}$ (thin curve)

The curves do not coincide. In the measured curves, it appears as if there were even phase reversals between the voltage curve and the curve proportional to the current.

Cross-correlation of the curve-pairs (U_{DUT} , I_{DUT} R_{DUT}) were performed for many experiments. The absolute values of the correlation coefficients were in the range of 0 … 0.5. There are two possible explanations:

1. The influence of the residual noise (measuring equipment) is too strong [5], [6].
2. The resistance value of the device under test is fluctuating [6].

Further experiments must be performed to improve the resolution and to increase the duration of observation intervals.

4 Conclusions

Measurements seem to show that the spectral densities of current through and voltage over a resistor do *not* always vary in linear proportion, which means that the spectrum of UI could be different from U^2 or from I^2. In summary, the performed experiments could give rise to the experimental investigation of some new aspects of 1/*f*-noise in electron devices.

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