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A METHOD OF RTS NOISE IDENTIFICATION IN NOISE SIGNALS OF SEMICONDUCTOR DEVICES IN THE TIME DOMAIN

Barbara Stawarz-Graczyk, Dariusz Dokupil, Paweł Flisikowski

Gdansk University of Technology, Faculty of Electronics, Telecommunications and Informatics, G. Narutowicza 11, 80–233 Gdansk, Poland
(✉ *bstawarz@eti.pg.gda.pl*, +48 58 347 1484, *ddokupil@gmail.com, flisgd@poczta.fm*)

Abstract

In the paper a new method of Random Telegraph Signal (RTS) noise identification is presented. The method is based on a standardized histogram of instantaneous noise values and processing by Gram-Charlier series. To find a device generating RTS noise by the presented method one should count the number of significant coefficients of the Gram-Charlier series. This would allow to recognize the type of noise. There is always one (first) significant coefficient (c_0) representing Gaussian noise. If additional coefficients c_r (where $r > 0$) appear it means that RTS noise (two-level as well as multiple-level) is detected. The coefficient representing the Gaussian component always has the highest value of all. The application of this method will be presented on the example of four devices, each with different noise (pure Gaussian noise signal, noise signal with two-level RTS noise, noise signal with three-level RTS noise and noise signal with not precisely visible occurrence of RTS noise).

Keywords: RTS noise, Gram-Charlier series, semiconductor devices, optocouplers.

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1. Introduction

Noise generated in different electronic devices can be a very useful tool to inform about the quality of such a device. This information is very useful not only for semiconductor devices but also for other reasons [1–4, 21]. Many investigations carried out in the past proved that there is a strict relation between the quality of different semiconductor devices and the level of their inherent noise at low and very low frequencies [5–8]. This dependence causes the necessity of noise examination of applied devices which can be defined on the basis of identification of two components:

– a component whose instantaneous values of low frequency noise have Gaussian distribution, shortly named “Gaussian” component, caused *e.g.* by thermal, shot, $1/f$ noise;
– a component whose instantaneous values of low frequency noise have non-Gaussian distribution, shortly named “non-Gaussian” component, caused *e.g.* by RTS noise [9].

In [10] there are presented (on an example of Gaussian signal) the original relations enabling the estimation of a variance of a random signal mean square value digital estimator. Models of bias of mean square value digital estimator for different signals is described in [22].

It is obvious that a very important quality indicator would be a coefficient that detects the presence of RTS noise.

The RTS noise can be caused by a single generation-recombination center (two-level RTS noise) or by generation-recombination centers (multilevel RTS noise). A typical time record of two-level RTS noise is presented in Fig. 1.

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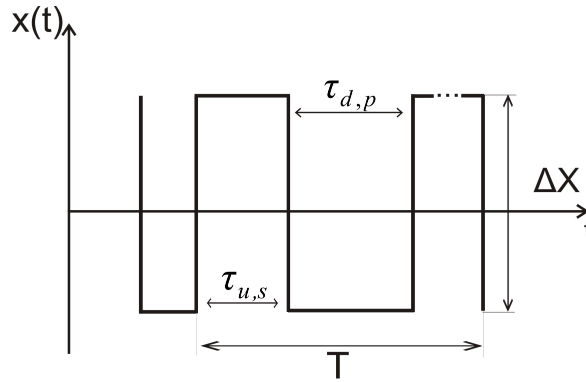

Fig. 1. Two-level RTS noise.

The RTS noise signal can be described by parameters such as:
– $\tau_{u,s}$ – the impulse duration in the up state, (s = 1, 2, ..., S);
– $\tau_{d,p}$ – the impulse duration in the down state, (p = 1, 2, ..., P);
– ΔX – the pulse amplitude;
– $\underline{\tau}$ – the mean time the impulse remains in up state;
– τ_d – the mean time the impulse remains in down state;
– f_{RTS} – the characteristic frequency.

The last parameter can be estimated from the spectrum as the frequency when the plateau comes into $1/f^2$ and is equal:

$$f_w = \frac{1}{2\pi} \cdot \frac{1}{\tau} = \frac{1}{2\pi} \cdot \left(\frac{1}{\tau_d} + \frac{1}{\tau_u}\right). \tag{1}$$

The spectrum of a pure two-level RTS signal is Lorentzian and it is given by the following relation [11]:

$$S_{RTS} = \frac{4(\Delta X)^2}{1 + \left(2\pi \frac{f}{f_{RTS}}\right)^2}. \tag{2}$$

RTS noise generation may be the result of defects in materials from which semiconductor devices are produced as well as defects during manufacturing. The problems occurring due to RTS noise presence in the inherent noise of different devices and the manners of measurements were presented *e.g.* in the following papers [12–14]. The selected RTS identification methods were proposed in [15–17].

Although there are a few methods (described below) which allow to identify devices with RTS noise in different ways, the authors propose a new one. The main advantage of this method is that RTS noise can be identified using a limited number of noise samples. Therefore, this method can be applied in industry as a completely automatic method without involvement of personnel.

Well known RTS identification methods are based on the analysis in the time or frequency domain.

In the time domain one can for instance:
– observe the noise signal (Fig. 2);
– estimate the histogram of instantaneous noise values (Fig. 3);
– apply the Noise Scattering Pattern (NSP) method presented in [15] (Fig. 4).

In Figs 2–4 there are presented results of noise measurements in the time domain for two noise signals, the first (a) is noise with Gaussian component only and the second (b) is Gaussian noise with RTS noise component.

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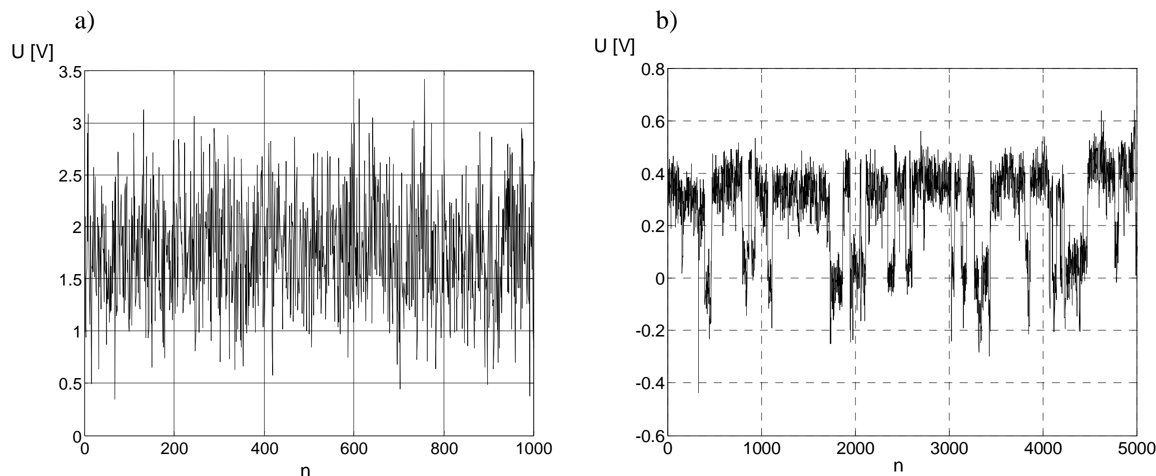

Fig. 2. The results of noise measurements: a) Gaussian noise signal without RTS noise; b) Gaussian noise signal with RTS noise component.

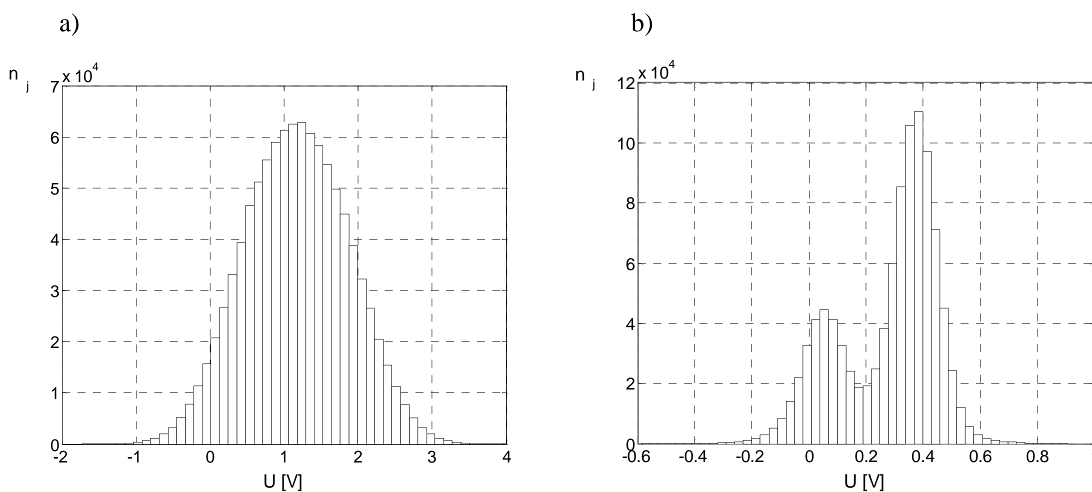

Fig. 3. The results of noise measurements: a) the estimated histogram of instantaneous noise values without RTS noise; b) the estimated histogram of instantaneous noise values with RTS noise.

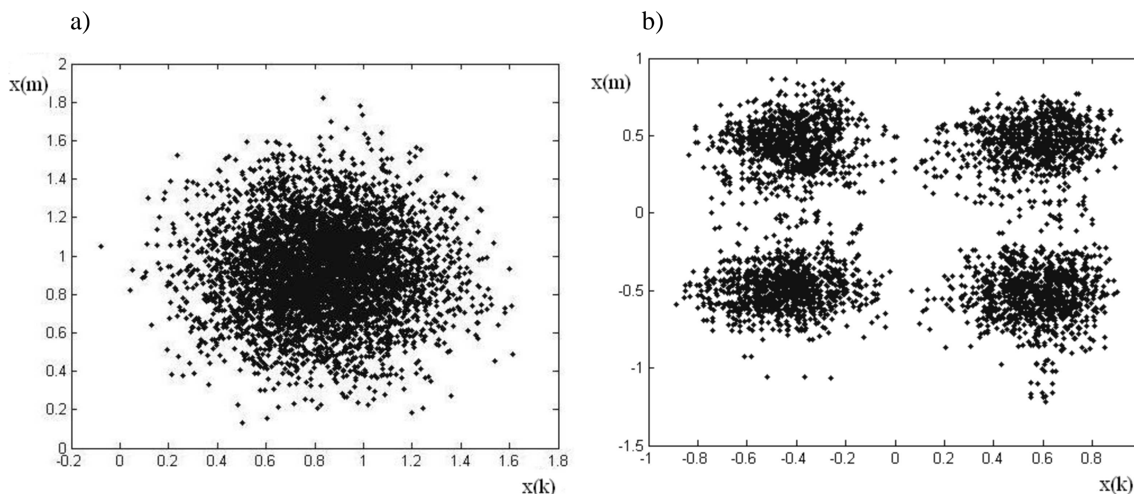

Fig. 4. The results of noise measurements: a) the NSP of noise without RTS; b) the NSP of noise with RTS; sequence x(m) are values of the first half of the noise signal and x(k) are values of the second half of the noise signal.

In the frequency domain one can:

– estimate the power spectral density (PSD) function of a noise signal (Fig. 5);
– estimate the product of PSD and a frequency (Fig. 6).

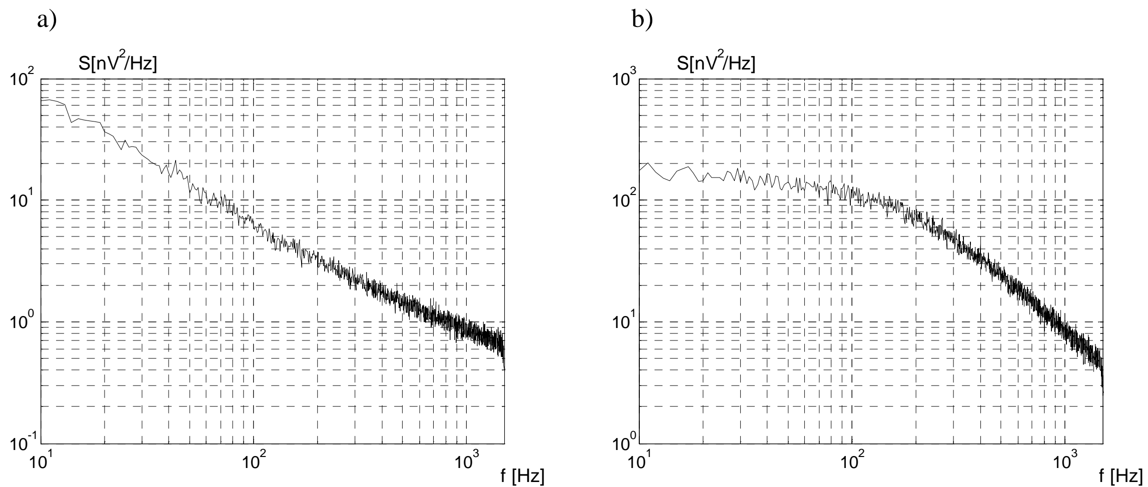

Fig. 5. The results of noise measurements and processing: a) the estimated PSD function of a noise signal without RTS; b) the estimated PSD function of a noise signal with RTS.

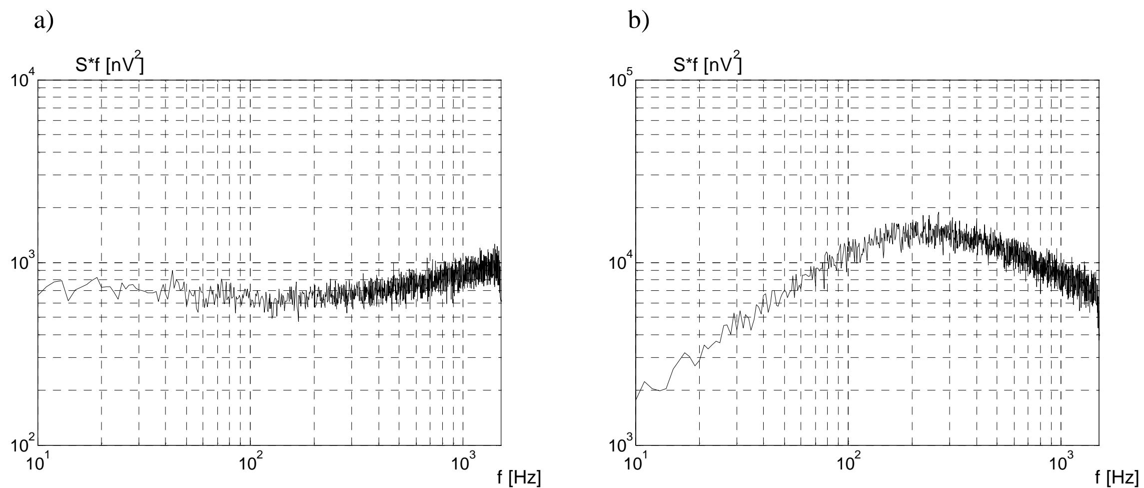

Fig. 6. The results of noise measurements and processing: a) the estimated product of PSD and a frequency for signal without RTS; b) the estimated product of PSD and frequency for a signal with RTS.

Sometimes the methods presented above are not precise enough to identify RTS noise. The easiest method of RTS noise identification is the method of noise signal observation using *e.g.* an oscilloscope, but it is very time-consuming. The method of estimating the histogram of instantaneous noise values can give false results. For example, if $\tau_u << \tau_d$ then a histogram may seem to have only one local maximum and the other cannot be seen. A similar situation is for identification by the NSP method. In the frequency domain, RTS noise identification consists in finding a characteristic swelling in a PSD function (Fig. 5b) or finding the maximum in a product function of PSD and frequency (as one can see in Fig. 6b). Also in these cases the identification may be misleading because of invisible swelling or maximum. For proper RTS identification in the frequency domain one can use the method of spectra composing presented in [17] which is based on composing estimators of two spectra, corresponding to $1/f$ type of noise (Gaussian component) and RTS noise (non-Gaussian component).

The method proposed in this paper utilizes a standardised histogram estimated in the time domain and the Gram-Charlier series. The method identifies the presence of RTS noise but does not provide information about its level. All results presented in the paper were collected during low frequency noise measurements of CNY 17 optocouplers.

2. The method of RTS identification based on the Gram-Charlier series

As mentioned above, the Gram-Charlier series can give a satisfactory characterization of the tested distribution in order to find the devices that generate RTS noise. This way gives very precise results presented at the end of the chapter. Firstly, the most important theoretical information about the Gram-Charlier series will be presented [18], for more see [19, 20].

Let us take under consideration a standard normal deviate z:

$$z = \frac{x - \alpha_1}{\sigma}, \tag{3}$$

where α_1, σ are mean lifetime and standard deviation, respectively and x is a random variable. The law of formation of Gram-Charlier series terms involves the Gaussian probability density function $\varphi(z)$ and its consecutive derivatives $\frac{d^r \varphi(z)}{d z^r}$:

$$f^{(k)}(z) = c_o \cdot \varphi(z) + \sum_{r=1}^{\infty} \frac{c_r}{r!} \frac{d^r \varphi(z)}{dz^r}, \tag{4}$$

where:

$$\varphi(z) = \frac{1}{\sqrt{2\pi}} \cdot \exp\left[-\frac{1}{2} \cdot z^2 \right]. \tag{5}$$

Derivatives $\frac{d^r \varphi(z)}{d z^r}$ are expressed:

$$\frac{d^r \varphi(z)}{dz^r} = (-1)^r \cdot H_r(z) \cdot \varphi(z). \tag{6}$$

Values of coefficients c_r in expression (4) are derived from integration (7):

$$c_r = \int_{-\infty}^{\infty} H_r(z) f(z) dz, \tag{7}$$

where we have denoted Hermite polynomials by $H_r(z)$. In practical application we limited calculations to the proper value (3σ interval). There was also no need to generate more than first twenty six coefficients because its values decreased rapidly with growth of the index.

To generate the required Hermite polynomials one should use the recurrent formula (8):

$$\begin{gathered} H_{r+1}(z) = z \cdot H_r(z) - r \cdot H_{r-1}(z), \\ H_o(z) \overset{def}{=} 1, \quad H_1(z) \overset{def}{=} z. \end{gathered} \tag{8}$$

Equations presented above were applied in the Mathcad program to perform few calculations for which we chose four devices with different noise. The calculations were supposed to check how well the method based on the Gram-Charlier series can detect RTS noise. To check this, after each calculation we reconstructed the histogram from calculated coefficients and compared it with the original one if both were similar.

The method bases on counting the number of significant coefficients which allows to recognize the type of noise. The assumption was as follows: there is always one significant coefficient (c_0) representing Gaussian noise. Additional coefficients c_r (where $r > 0$) appear when RTS noise (two-level RTS noise as well as multiple-level RTS noise) is detected. The coefficient representing the Gaussian component always has the highest value of all. By writing "significant" we mean that after reconstructing the histogram it would be very similar to the original one. The assumptions of coefficients significance will be presented for each case separately.

In the next chapter the authors present the results of RTS identification for chosen devices.

3. Results of Gram-Charlier series application for RTS noise identification

The calculations were carried out for four type CNY 17 optocouplers (a pair consisting of a gallium arsenide infrared emitting diode optically coupled to a silicon npn phototransistor). The chosen devices were:

- **Device A** (low frequency noise without RTS noise);
- **Device B** (low frequency noise consists of $1/f$ type of noise and two-level RTS noise);
- **Device C** (low frequency noise consists of $1/f$ type of noise and three-level RTS noise);
- **Device D** (low frequency noise data (histogram and spectrum) of this device with not obvious presence of RTS noise).

3.1. The RTS identification results for device A

The histogram of instantaneous noise values for device A is presented in Fig. 7 (the samples number was 10^6).

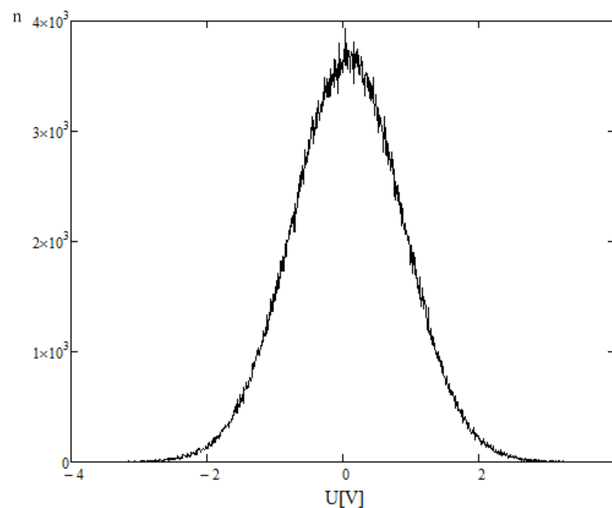

Fig. 7. The histogram of instantaneous noise values (device A).

In our simulation we took into account first twenty six terms of equation (6) namely for r = 0, 1, …, 25. Substituting recursive polynomials generated from (6) into (7) and performing integration, one receives values displayed in Fig. 8a. We took under consideration only significant coefficients, in this case only coefficient c_0, presented in Fig. 8b.

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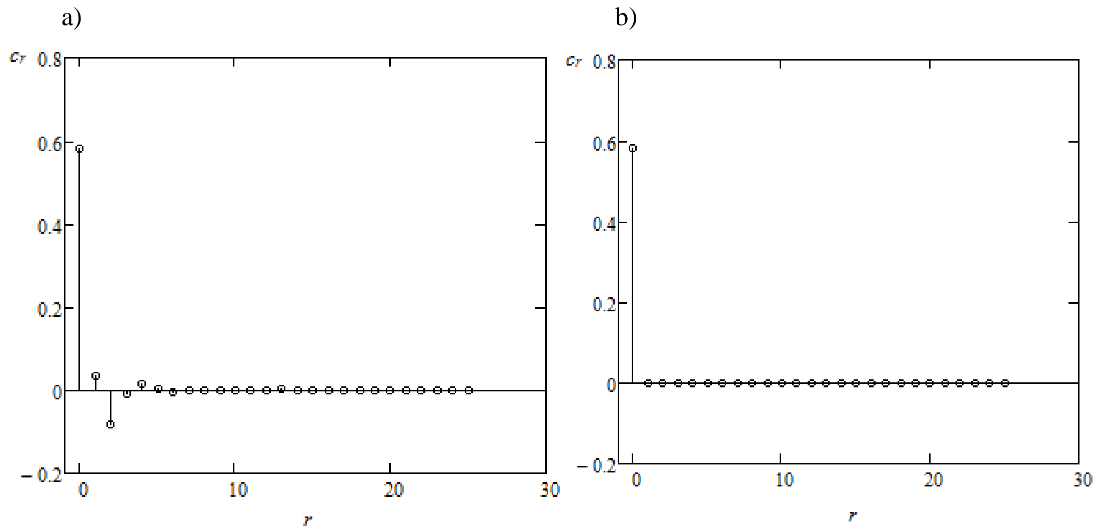

Fig. 8. Device A: a) received values of coefficients c_r; b) significant values of coefficients c_r.

In Fig. 9 the reconstructed histogram is presented.

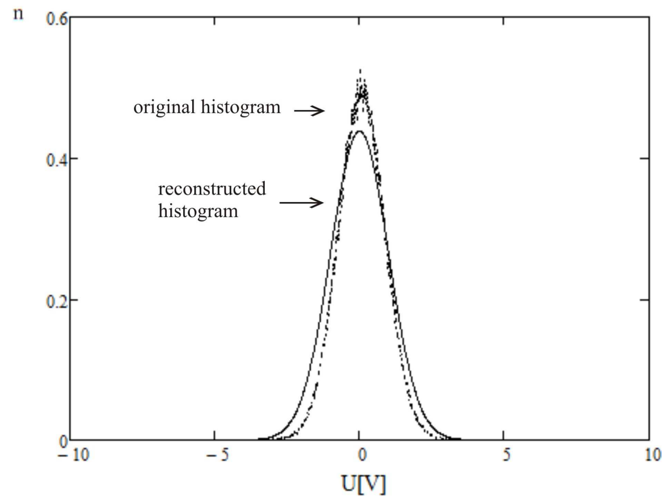

Fig. 9. Original and reconstructed histogram of instantaneous noise values (device A).

A single coefficient appears to be the only one required for the reconstructed histogram to be similar to the original one and means that the device generates only $1/f$ type of noise.

3.2. The RTS identification results for device B

The histogram of instantaneous noise values for device B is presented in Fig. 10 (the samples number was 10^6).

Again we took into account only twenty six terms of expression (6). The received coefficients are displayed in Fig. 11a. Even at this stage it is obvious that more than one coefficient is significant. To extract significant coefficients we removed those whose absolute values are less than 0.1 (Fig. 11b).

Coefficient c_0 proves that the low frequency noise generated in this device contains $1/f$ type of noise and coefficients c_1 and c_3 prove it to contain also a two-level RTS noise. In Fig. 12 the reconstructed histogram for device B is shown. After reconstruction some of histogram values had to be equalled to zero because of their negative values.

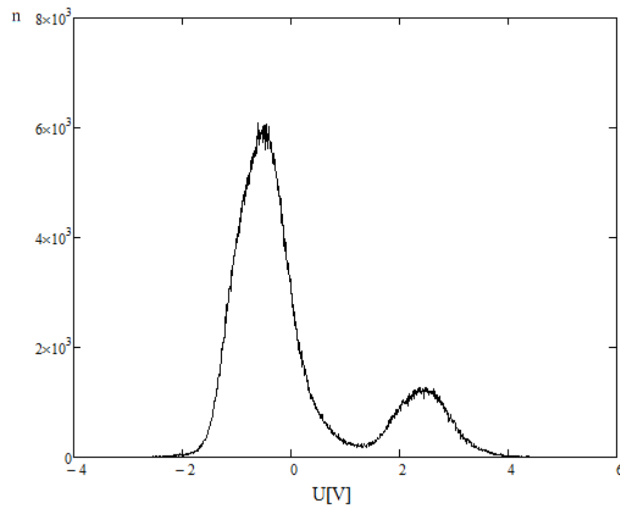

Fig. 10. The histogram of instantaneous noise values (device B).

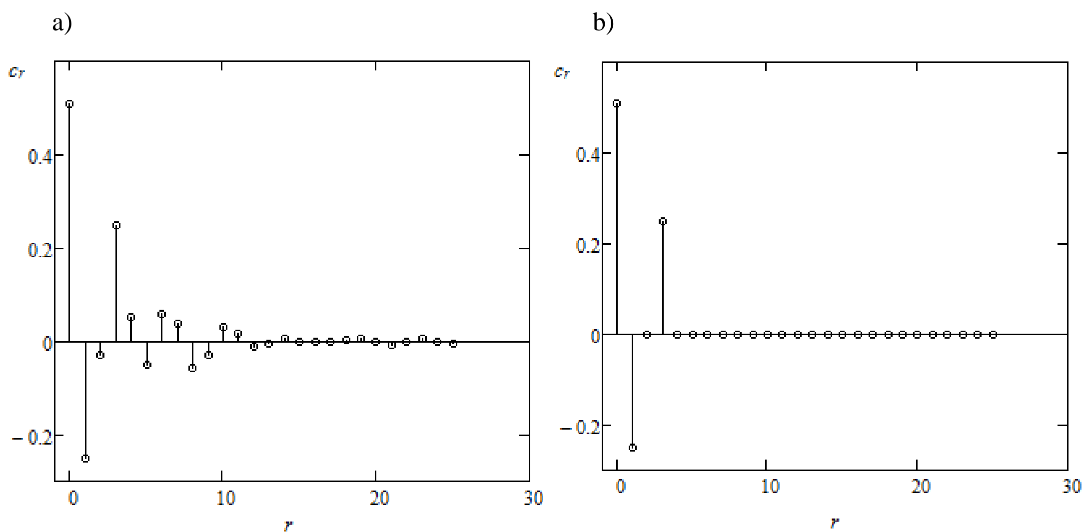

Fig. 11. Device B: a) received values of coefficients c_r; b) significant values of coefficients c_r.

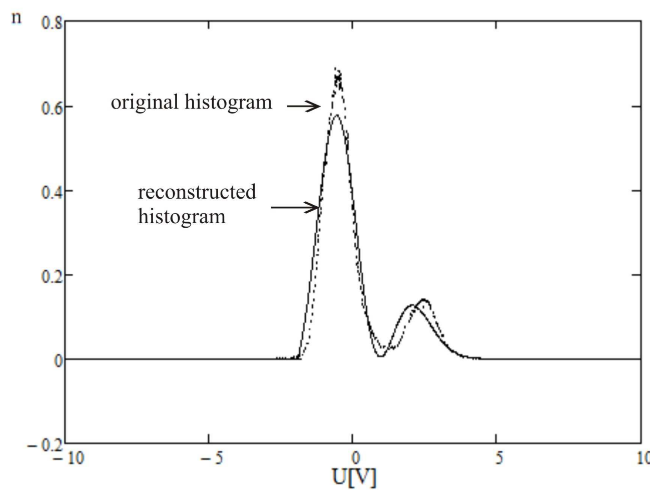

Fig. 12. Original and reconstructed histogram of instantaneous noise values (device B).

Again, taking under consideration only significant coefficients, the reconstructed histogram only slightly diverges from the original one.

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3.3. The RTS identification results for device C

The histogram of instantaneous noise values for device C is presented in Fig. 13 (the samples number was 10^6).

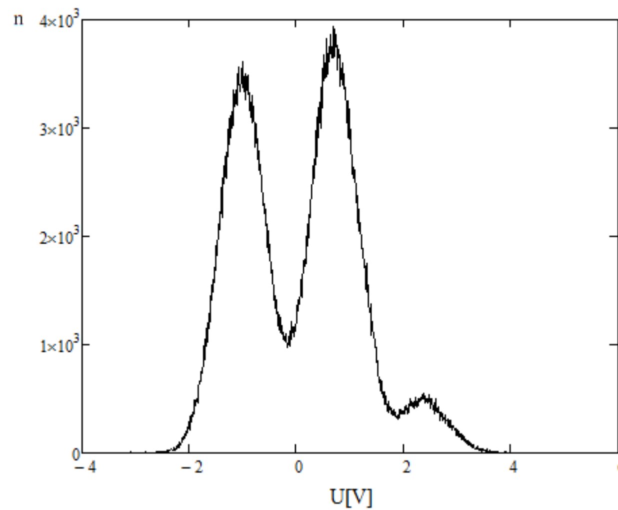

Fig. 13. The histogram of instantaneous noise values (device C).

The same procedure was applied to device C with only one exception that the absolute values of significant coefficients could not be less than 0.08. The received values of coefficients c_r are presented in Fig. 14a and the significant values of coefficients c_r are shown in Fig. 14b.

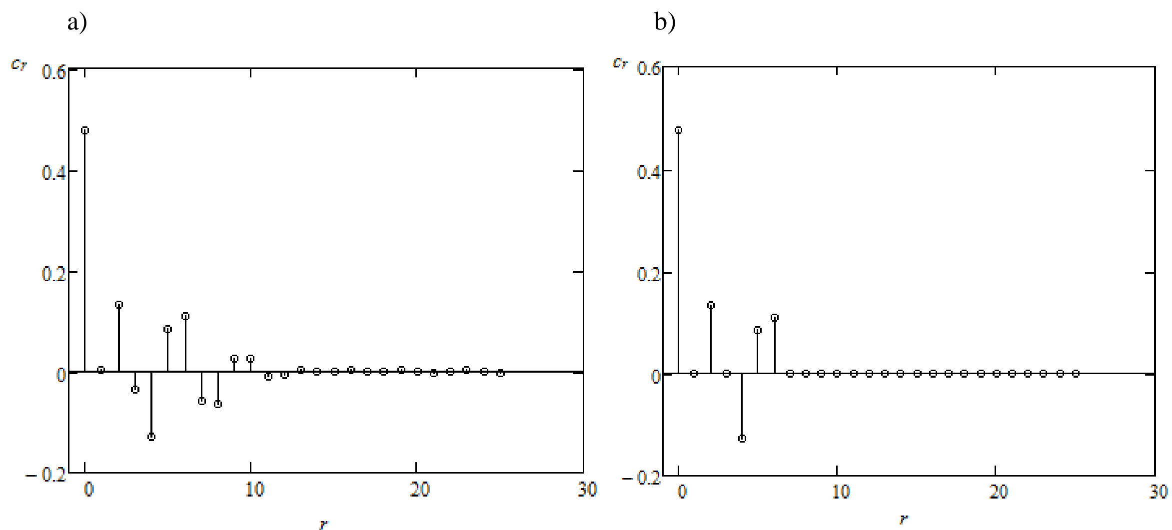

Fig. 14. Device C: a) received values of coefficients c_r; b) significant values of coefficients c_r.

The value of 0.08 is set as a required value of coefficients to prevent the reconstructed histogram (Fig. 15) from being deformed significantly, but even if the border value was left at 0.1, the RTS noise would be detectable.

Just like the original histogram, the reconstructed one consists of three distinctive maxima. Also in this case after reconstruction some of histogram values had to be equalled to zero because of their negative values.

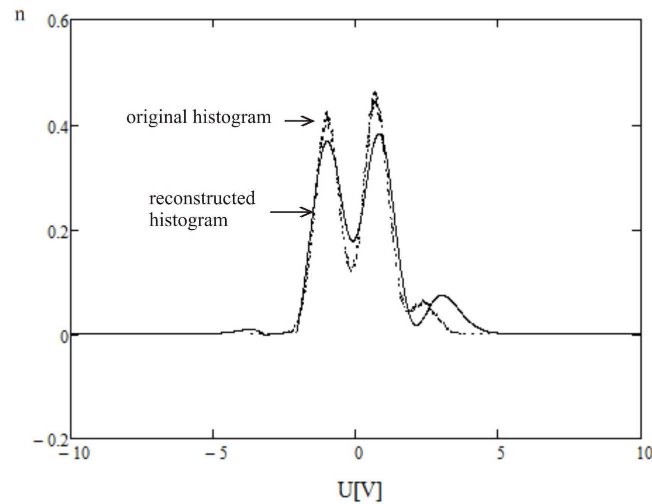

Fig. 15. Original and reconstructed histogram of instantaneous noise values (device C).

3.4. The RTS identification results for device D

The histogram of instantaneous noise values for device D is presented in Fig. 16 (the samples number was 10^6).

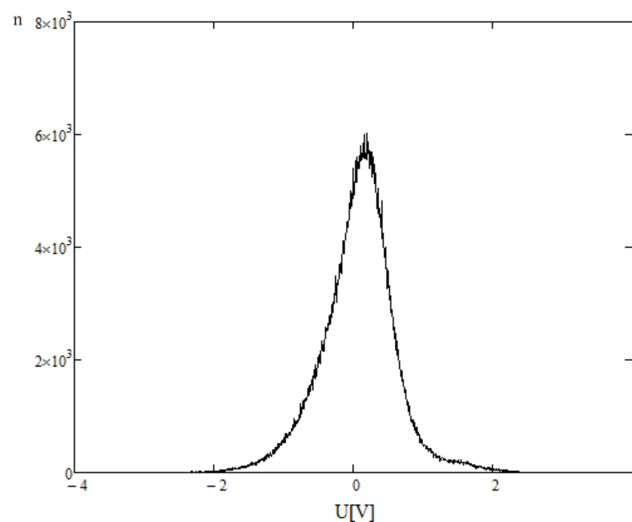

Fig. 16. The histogram of instantaneous noise values (device D).

Finally, the unchanged procedure was applied to the last of devices. Coefficient values for this device are as shown in Fig. 17a and significant values of these coefficients are presented in Fig. 17b.

More than one significant coefficient proves that the low frequency noise data contain RTS noise.

Reconstructing the histogram from significant coefficients proves the process to be accurate (Fig. 18). Also in this case after reconstruction some of histogram values had to be equalled to zero because of their negative values.

As it was proved above this method detects the RTS noise very well.

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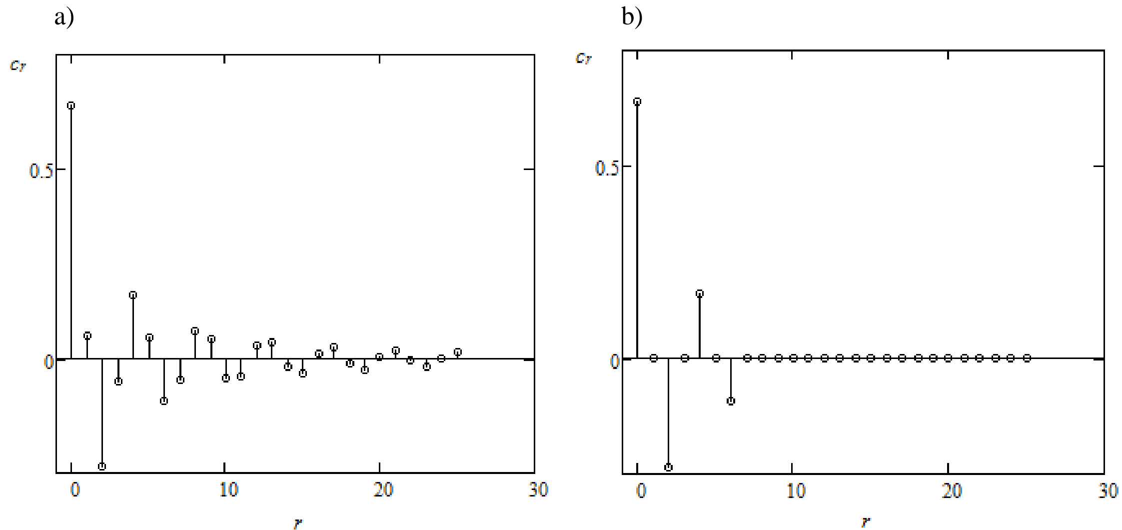

Fig. 17. Device D: a) received values of coefficients c_r; b) significant values of coefficients c_r.

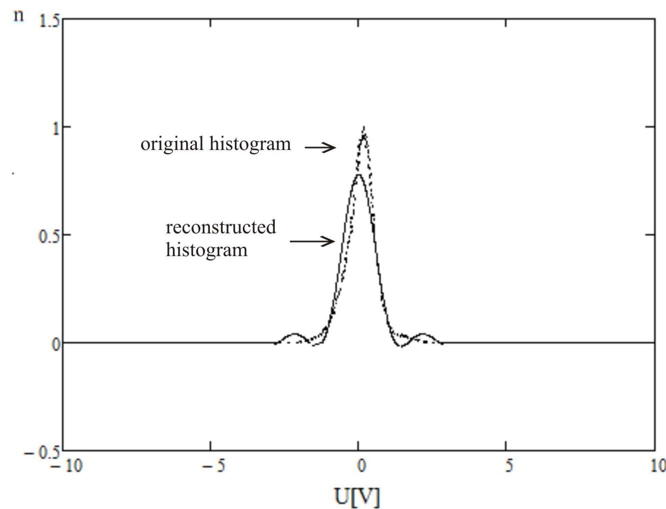

Fig. 18. Original and reconstructed histogram of instantaneous noise values (device D).

4. Conclusions

In the paper a new method of RTS noise component identification in the inherent noise of semiconductor devices was proposed. The method is based on the Gram-Charlier series. Four devices with different noise (pure Gaussian noise signal, noise signal with two-level RTS noise, noise signal with three-level RTS noise and noise signal with not precisely visible occurrence of RTS noise) were selected to present how to apply the Gram-Charlier series for RTS noise detection. The calculations showed that there is always a first coefficient informing about the occurrence of a Gaussian component (which is much higher than the rest). More than one term in the Gram-Charlier series should be interpreted as a device generating RTS noise. It was sufficient to analyze the first 26 terms in each investigated case. The results of identification for the presented examples were very satisfactory. Even in the inherent noise of device D, where the RTS noise component had very low intensity (weakly visible in the histogram or in the spectrum), RTS noise was properly identified due to this method.

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