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AN AUTOMATIC SYSTEM FOR IDENTIFICATION OF RANDOM TELEGRAPH SIGNAL (RTS) NOISE IN NOISE SIGNALS

In the paper the automatic and universal system for identification of Random Telegraph Signal (RTS) noise as a non-Gaussian component of the inherent noise signal of semiconductor devices is presented. The system for data acquisition and processing is described. Histograms of the instantaneous values of the noise signals are calculated as the basis for analysis of the noise signal to determine the number of local maxima of histograms and to evaluate the number of RTS noise levels. The presented system does not need supervisor control of identification results.

Keywords: RTS noise, semiconductor devices, Noise Scattering Pattern (NSP) method, histogram

1. INTRODUCTION

Investigations carried out in the 60's of the last century showed the relation between the quality of semiconductor devices and the level of their inherent noise at low and very low frequencies. The level and character of the inherent noise of semiconductor devices allows to assess their quality, reliability and correctness of manufacture [1–4].

In the low and very low frequency range the inherent noise of semiconductor devices can contain two characteristic noise components: Gaussian noise (caused e.g. by thermal, shot, 1/f noise) and non-Gaussian noise (caused e.g. by a generation-recombination center, by avalanche noise). In the low frequency range a non-Gaussian component contains Random Telegraph Signal noise (RTS noise). It is caused by a single generation-recombination center (two-level RTS noise) or by generation-recombination centers (multilevel RTS noise). It was checked in practice that high intensity of noise and especially RTS noise which occurs in the noise signal of semiconductor devices results from defects in material from which semiconductor devices are produced and also by defects that emerged in manufacturing. The identification of devices generating RTS noise enables to eliminate these devices from application. Problems with identification of RTS noise in the inherent noise of semiconductor devices were presented, for example, in the papers [5–12].

At a low frequency the RTS noise in the inherent noise of semiconductor devices is observed as two- or multi-level impulses. Impulses are characterised by constant amplitude and random occurrence of impulses with undefined duration of up- and down time. Two-level RTS noise is caused by a single active trap (a generation-recombination centre), three and four-level RTS noise is caused by two active traps, five and six-level RTS noise is caused by three active traps. The traps are characterized by the average capture and emission times, which can be estimated on the basis of the mean time the pulses remain in the up and down state.

The presented method of an automatic RTS noise identification will be illustrated in this paper by results of low-frequency noise measurements of optoelectronic coupler devices (optocouplers) [10, 11, 12].

Typically the analysis of RTS noise is carried out in the time domain or in the frequency domain or in both. The typical two-level RTS noise is presented in Fig. 1.

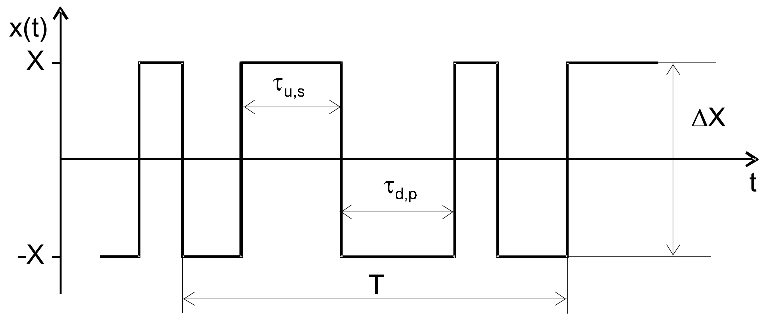

Fig. 1. Typical two-level RTS noise; $\tau_{u,s}$ – the s^{th} duration of an impulse in the up time, $\tau_{d,p}$ – the p^{th} duration of an impulse in the down time, ΔX *- the amplitude of RTS noise, T – observation time.

In the time domain, usually the noise signal is observed and the probability density function of the instantaneous values of the noise signal or the histogram are calculated – see Fig. 2. From the analysis in the time domain the following parameters of the two-level RTS noise can be evaluated:
- τ_u mean time of $\tau_{u,s}$ times (where $s = 1, 2, ..., S$) observed in time T,
- τ_d mean time of $\tau_{d,p}$ times (where $p = 1, 2, ..., P$) observed in time T,
- ΔX amplitude of RTS noise,

and subsequently the f_{RTS} frequency (or τ mean time) can be calculated:

$$f_{RTS} = \frac{1}{\tau} = \frac{1}{\overline{\tau_u}} + \frac{1}{\overline{\tau_d}}. \tag{1}$$

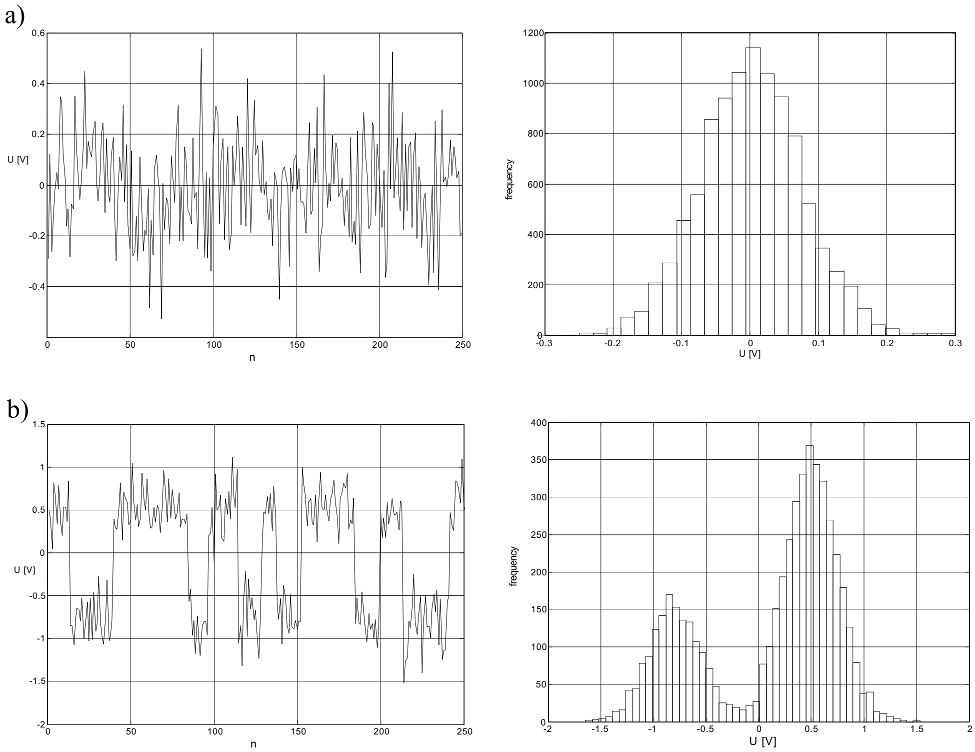

Fig. 2. The time series of inherent noise of optoelectronic coupled devices and histograms [10]; a – noise signal without RTS, b – noise signal with RTS.

Usually in the frequency domain the power spectral density function (PSD function) of the noise signal is estimated. The frequency f_{RTS} and the intensity of inherent noise at this frequency can be evaluated from $S(f)$ and from the product $f\ S(f)$.
The power spectral density function of RTS noise can be evaluated from the relation:

$$S(f) = C\frac{4(\Delta X)^2}{1 + (f/f_{RTS})^2} = \frac{A}{1 + (f/f_{RTS})^2}, \tag{2}$$

where: $C = \dfrac{1}{(\overline{\tau_u} + \overline{\tau_d})\, f_{RTS}^2}$ and $A = 4C(\Delta X)^2$.
The maximum power of noise is obtained when both mean times are equal.
Multiplying the PSD function by frequency f we have:

$$f\ S(f) = f\frac{A}{1 + (f/f_{RTS})^2} \Rightarrow \quad \text{for } f = f_{RTS} \text{ we have } \quad f_{RTS}S(f_{RTS}) = f_{RTS}\frac{A}{2}. \tag{3}$$

The product $f\ S(f)$ has a maximum at f_{RTS} frequency. Representative examples of results of investigation of inherent noise of an optoelectronic coupled device are presented in Fig. 3 [10].

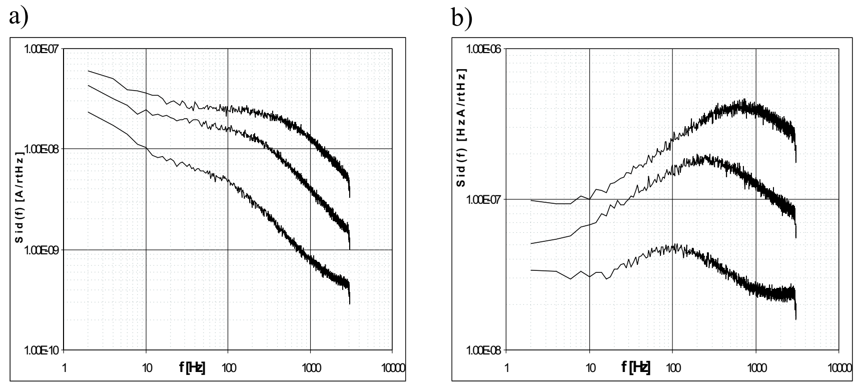

Fig. 3. The results of inherent noise analysis in the frequency domain for optocoupler device [10]; a – the current power spectral density, $S(f)$, b – the product, $f\ S(f)$, I_d – current of diode of optocoupler.

As seen in Fig. 3, it is easy to recognize a characteristic frequency f_{RTS} of RTS noise in particular from the product $f\ S(f)$ (Fig. 3b). The frequencies f_{RTS} estimated from formulas (1) and (3) should be equal.

If for example, four level RTS noise appears in the noise signal of a semiconductor device, it means that it is caused by two active traps and in the PSD function we find two different frequencies $f_{RTS\ i}$, and two separated mean times τ_{ui}, τ_{di}, where $i = 1, 2$.

The identification of devices generating RTS noise is a very significant issue especially in manufacturing. Quick and easy methods should be applied for the selection of devices generating the RTS noise and to reject them from a production batch. The results of an identification of this kind of noise should contain simple information:

– RTS noise occurs in the noise signal, then the number of RTS noise levels,
– RTS noise does not occur in noise signal.

A method fulfilling these rules is the Noise Scattering Pattern (NSP) described in papers [6, 8].

In our paper we propose for identification of RTS noise an automatic system based on a recognizing procedure of a number of maximal values (local maxima) in the histogram of instantaneous values of the noise signal. When the obtained histogram has only one maximal value it means that the noise signal does not contain RTS noise. When the obtained histogram has a few local maxima it means that the noise signal contains RTS noise. The number of the local maxima is equal to the number of RTS noise levels.

The advantage of this system is that the identification of RTS noise is performed automatically in a time not longer than the recording time of the investigated noise signal. Obtained results of RTS noise identification will be compared with the results gained from the NSP method.

2. THE AUTOMATIC SYSTEM FOR RTS NOISE IDENTIFICATION

Measurements of noise at low frequencies were carried out in a specially designed measurement system (Fig. 4) having three measuring heads for examining an optocoupler's LED, the phototransistor and the entire optocoupler. The system is supplied by two 12V batteries. The data were acquired with the use of a PCI-4452 National Instruments Dynamic Signal Acquisition Card with a sampling frequency of 10.24 kHz and an antialiasing low-pass filter with 1.5 kHz cutoff frequency. Data were assembled in the LabView environment. The resultant file contains one million of acquired data samples which are used during the execution of the algorithm of RTS noise identification.

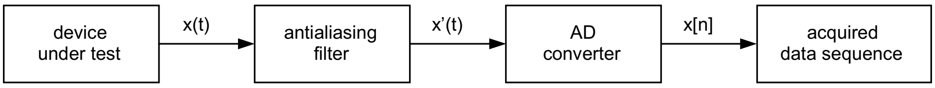

Fig. 4. Block diagram of the RTS noise measurement system.

The elaborated algorithm was written as a Matlab script. The algorithm of RTS noise identification is shown in Fig. 5. The algorithm uses 10^4 data samples which is a sufficient number of samples to observe RTS noise in optocouplers. The data set taken for analysis is interpreted as the lowest RTS noise frequency that can be detected by the algorithm. The assumed number of samples enables to identify the RTS noise signal whose f_{RTS} frequency (1) is greater than 1 Hz, but the lowest frequency response in the used measurement system is equal to 2 Hz. In order to analyze the RTS noise signal with a two times lower frequency f_{RTS} it is required to utilize double the size of data samples.

The data read from the file are filtered with a 5^{th} order median filter giving subsequence denoted as $x_f[n]$, where $n = 1, 2, \ldots, 10^4$. The median filter suppresses high-speed distortions in acquired samples.

The aim of the processing procedure of the noise signal is the identification of the maximal value (local maximum) in the histogram of instantaneous values of the noise signal.

Later, the histogram is created from the subsequence of filtered data. The Matlab command $hist(x_f[n], N)$ returns two sequences: $y[m]$ which is the distribution of $x_f[n]$ among N bins and $x_b[m]$ which stores the position of the bin centres, where

$m = 1, 2, \ldots, N$. The parameter N is the number of histogram bins and this is one of the parameters on which the procedure accuracy depends. It was assumed that $N = 25$, which means that the histogram has 25 bins.

In order to reduce differences between the minimal and maximal value of distribution of $x_f[n]$, the common logarithm of the sequence $y[m]$ is taken, giving the subsequence $y_{log}[m]$. Afterwards, elements of $y_{log}[m]$ with a small value of distribution of $x_f[n]$ are set to zero (omitted) due to the sensitivity of the local maximum detecting subprocedure. The possible maxima with small distribution of $x_f[n]$ would deteriorate the overall accuracy of maximum detection subprocedure. The level below which the elements of sequence $y_{log}[m]$ are omitted, is another parameter for tuning the procedure accuracy.

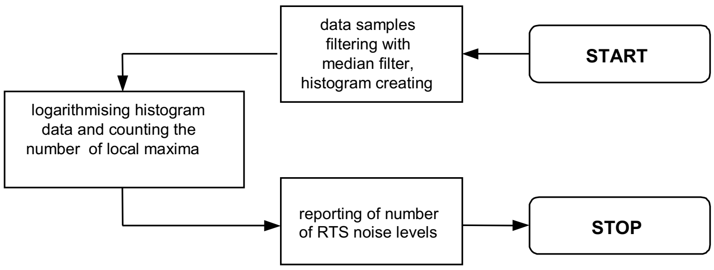

Fig. 5. The algorithm of the automatic method for RTS noise identification.

The maxima detecting procedure browses the subsequence of k elements from sequences $y_{log}[m]$. The parameter k is a natural odd number and it determines the range of neighbourhood for an element with maximal value. Increasing the value of k expands the range of neighbourhood, but deteriorates the detectability of a few of nearby maxima at the same time. It was experimentally proved that $k = 5$ is an optimal value for $N = 25$.

If the following conditions are fulfilled simultaneously, for every subsequence $\bar{y}_{\log}[k]$ of k elements taken from sequence $y_{log}[m]$ the algorithm detects the maximum.

$$\begin{cases} \forall_{l,p,q}\ \bar{y}_{\log}[l+p] < \bar{y}_{\log}[l+(k+1)/2] > \bar{y}_{\log}[l+q] \\ \forall_{l}\ \bar{y}_{\log}[l+(k+1)/2-1] \leq \bar{y}_{\log}[l+(k+1)/2] \geq \bar{y}_{\log}[l+(k+1)/2+1] \\ \prod_{i=1}^{k} \bar{y}_{\log}[i] > 0 \end{cases}, \tag{4}$$

where: $k = 2j + 1,\ j = 2, 3, \ldots;\ l = 0, 1, \ldots, N - k;\ p = 1, \ldots, (k - 1)/2 - 1;\ q = 2 + (k + 1)/2, \ldots, k$.

According to these conditions, the maximal value in k element subsequence has the element $\bar{y}_{\log}[(k+1)/2]$. The last condition prevents from detecting the maximum in the neighbourhood of previously omitted elements. The manner of maxima detection is illustrated in Fig. 6.

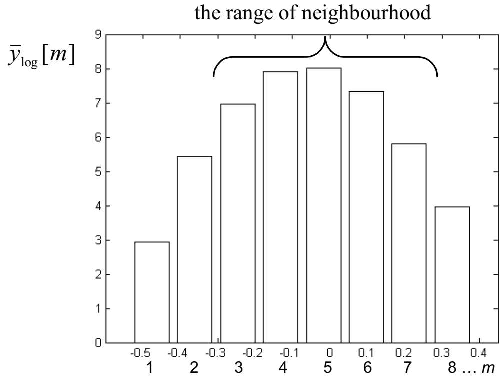

Fig. 6. Illustration of the detection manner of exemplary histogram maximum.

Let $k = 5$ and $N = 25$. Therefore: $m = 1, \ldots, 25$ $l = 0, 1, \ldots, 20$ $p = 1, 2$ $q = 4, 5$. For $l = 2$ the condition (4) is fulfilled and a maximum is detected for $\bar{y}_{log}[5]$ element, because:

$$\begin{cases} \bar{y}_{\log}[3] < \bar{y}_{\log}[5] > \bar{y}_{\log}[7] \\ \bar{y}_{\log}[4] \leq \bar{y}_{\log}[5] \geq \bar{y}_{\log}[6] \\ \bar{y}_{\log}[3]\ \bar{y}_{\log}[4]\ \bar{y}_{\log}[5]\ \bar{y}_{\log}[6]\ \bar{y}_{\log}[7] > 0 \end{cases} . \tag{5}$$

The number of detected maxima is accumulated for sequence $y_{log}[m]$ and actually this is the number of RTS noise levels in the noise signal $x(t)$, which was sampled giving sequence $x[n]$.

The information about a detected RTS noise level is displayed in the main window of Matlab. The results of recognition performed by the presented algorithm for exemplary Gaussian noise, two-level and three-level RTS noise are shown in Fig. 7 ÷ Fig. 9.

The presented method is able to detect up to ten-level RTS noise, but as it was determined upon acquired data for few CNY17 optocouplers, the highest number of RTS noise levels was not greater than three.

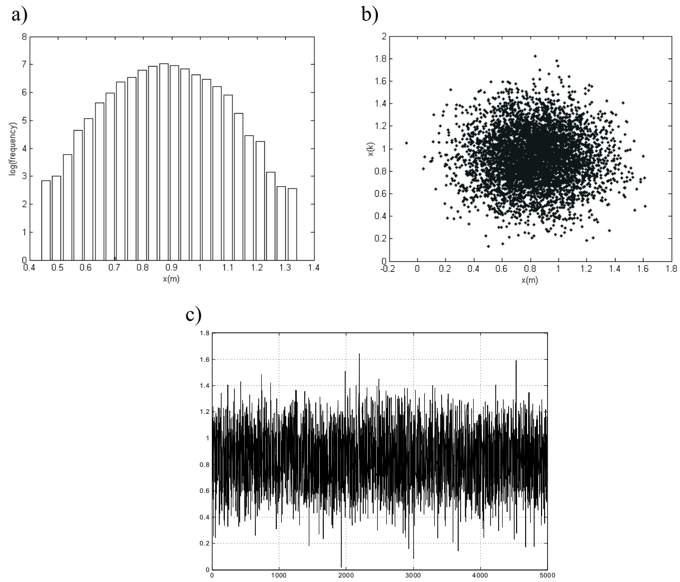

Fig. 7. The data histogram (a), NSP image (b) and waveform of Gaussian noise.

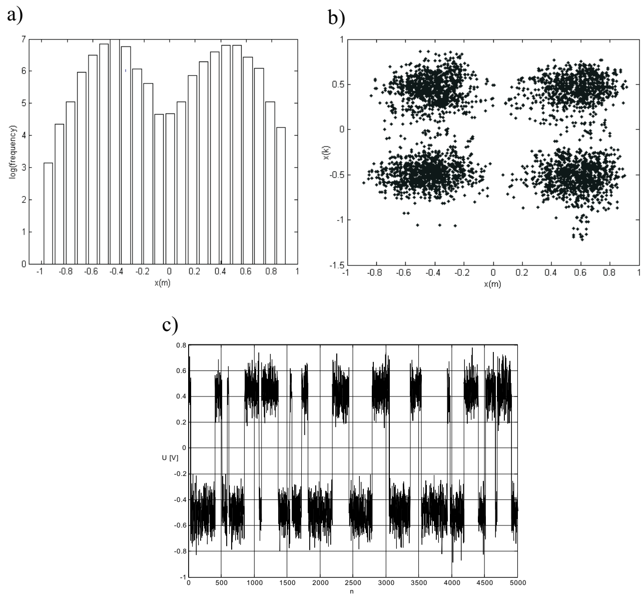

Fig. 8. The data histogram (a), NSP image (b) and waveform (c) of two-level RTS noise.

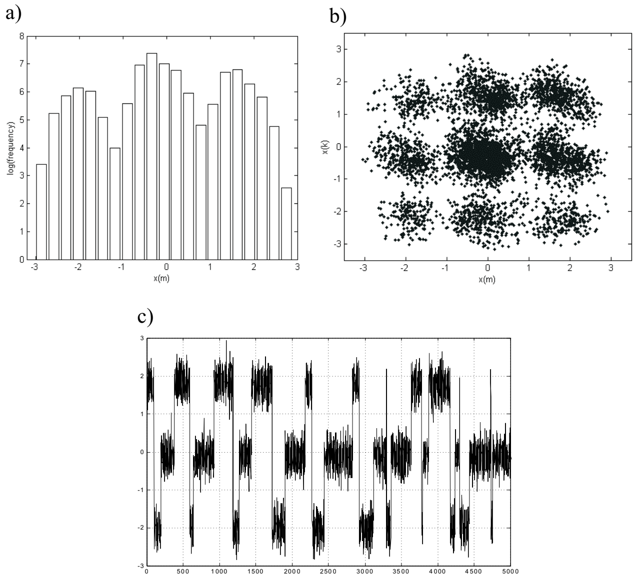

Fig. 9. The data histogram (a), NSP image (b) and waveform (c) of three-level RTS noise.

3. DISCUSSION OF RESULTS

The presented system for the identification of the character of low frequency noise is very fast and flexible. Results of RTS noise identification gained from the presented method are equal to results obtained from the NSP method [6] for the same noise signals.

The presented method is still in development and improvement, in order to utilize it for automatic non-supervised batch processing of files containing measurement samples of “device under test” noise and minimize recognition defects resulting as RTS noise in the inherent noise signal of semiconductor devices.

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