Electro-Ultrasonic Spectroscopy of Conducting Solids

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Abstract. The paper presents new principle of non-destructive testing of conducting solids. This method is based on ultrasonic phonons interaction with electrons in the nonlinear region caused by defect ("defect cased nonlinearity"). Tested sample is excited by harmonic AC electrical signal with frequency f_E and ultrasonic wave with frequency f_U. New harmonic signal with frequency f_i is created on the defect caused nonlinearity. The frequency f_i is given by the superposition or subtraction of exciting frequencies f_E and f_U. The advantage of this method consists in detection of electrical signal with frequency different from frequencies of excitation signals. Two ways for realisation of this principle are compared and ways to increasing of sensitivity are shown. The theoretical sensitivity of this method and its limitation by parasitic effect is also discussed. The usability and possibility of minimisation of parasitic effects are confirmed experimentally.

1. Introduction

We present new principle of non-destructive testing of conducting solids. This method is based on nonlinear effects created by anharmonic motion of atoms subjected to ultrasonic wave motion. Physical principle is based on ultrasonic phonons interaction with electrons on defect caused nonlinearity. Tested sample is excited by harmonic AC electrical signal with frequency f_E and ultrasonic wave with frequency f_U. New harmonic signal with frequency f_i is created on the defect caused nonlinearity. The frequency f_i is given by the superposition or subtraction of exciting frequencies f_E and f_U.

There are two possibilities for signal detection: (i) low frequency band for $f_i = f_E - f_U$ or (ii) high frequency band for $f_i = f_E + f_U$. The main advantage of this method is the electrical signal detection on frequency different from frequencies of excitation signals. This allows to increase sensitivity to small defects and improve signal to noise ratio. The theoretical sensitivity of this method and its limitation by parasitic effects will be discussed. The usability and possibility of minimisation of parasitic effects are confirmed experimentally.

This method belongs into the range of the non-linear ultrasonic spectroscopy, which is new progressive NDT technology ([1], [2] etc.). This method: (i) should increase a sensitivity of NDT investigation (reducing of minimum dimension of defect in relation to ultrasound wave length) (ii) allows to perform defectoscopy of samples with more complicated forms (iii) gives information on integral characteristics of tested specimen (without localization of defects and need lower time for experiment performance).

It is known that non-linear interaction of crack with ultrasonic wave propagation is sensitive indicator of material un-homogeneities caused by defects. The creation of new frequency components by non-linear effect can be relatively easy detected by the frequency spectral analysis.

On the other hand, efforts to realisation and application of these new principles bring many practical problems. There are various types of parasitic signal influences that essentially decline the theoretical sensitivity of this method [3]. This effect decreases practical sensitivity. The easiest method can be applied to samples with narrow band resonance properties where the crack induces unambiguous frequency shift of the corresponding resonance components in frequency spectrum [4].

2. Basic Principle of Proposed Method

There are more methods based on interaction of ultrasonic phonons with electrons: (i) DC electrical source and ultrasonic wave excitation. In this case the problem with parasitic transfer of the ultrasound signal appears. (ii) AC electrical signal with frequency f_E and ultrasonic wave with frequency f_U. In this case classical mixing modulation principle with two harmonic components is applied. The block diagram is shown in Fig. 1.

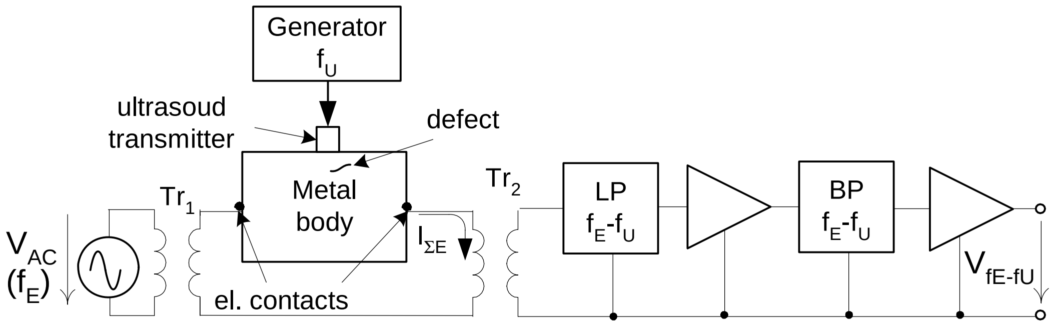

Fig. 1. Measuring set-up for electro-ultrasonic spectroscopy with AC electrical signal

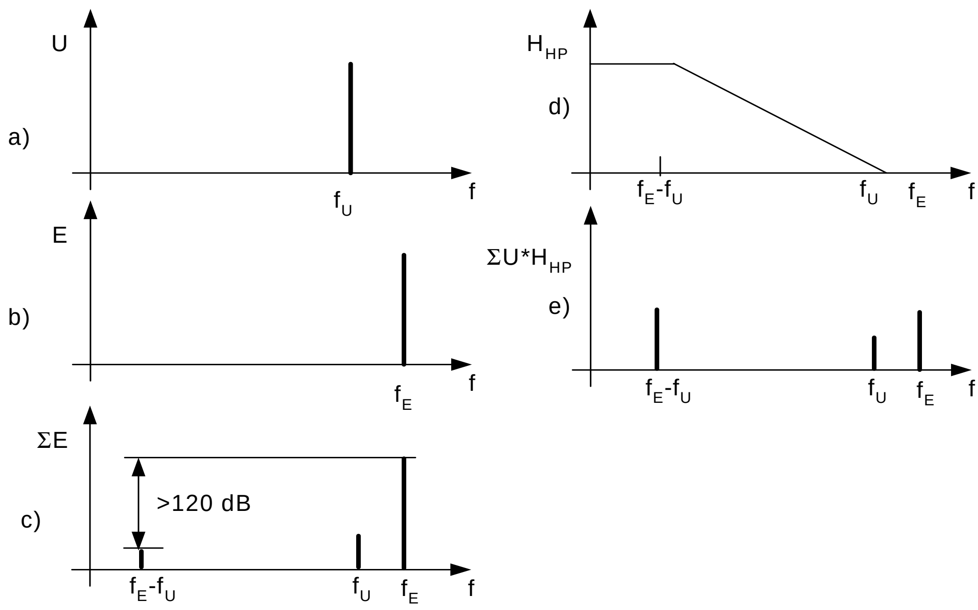

Fig. 2 Spectra of electro-ultrasonic spectroscopy signals with AC electrical source: a) ultrasonic signal, b) AC electrical signal, c) final electric current spectrum, d) frequency response of LP filter, e) final electric current signal after filtering with low dynamic range

Using AC excitation signal the current in metal sample can be increased by transformer Tr_1. The impedance matching of the signal processing is done by the transformer Tr_2. This transformer enables increase of measured voltage without increasing noise and improves the signal to noise ratio. Finally, the LC ladder LP filter is used for rejection of exciting electrical signal with frequency f_E. This special filter has high linearity for high dynamic range and high steepness for sufficient exciting signal rejection.

Spectral view of this principle is shown on Fig. 2, where Figs. 2a and 2b describe ultrasonic and electrical exciting signals, Fig.2c describes final spectrum and the dynamic ranges relation of measured current I_E and corresponding voltage of Tr_2 output. We have high value of electrical exciting signal with frequency f_E and exciting ultrasonic signal with frequency f_U, but very low level of measured signal f_E-f_U generated by nonlinearities in the device under test. There are problems with high dynamic range for signal processing. The LP filter has cut-off frequency near f_E-f_U with sufficient rejection coefficient and it have to be used as it shown in Fig. 2d. By this way we obtain frequency spectrum in lower dynamic range (Fig. 2e), which can be amplified by low noise preamplifier and filtered by band pass (BP) filter.

3. Noise Background

First experimental results of discussed system with AC electrical source show high background noise in the measured pass-band near frequency f_E-f_U. This effect corresponds to the method of AC electrical signal generation when the signal from oscillator is amplified by wide-band power amplifier. Therefore the noise background of this signal is not sufficient because signal/noise ratio (SNR) is about 100 dB and also in comparison with the preamplifier noise is also much lower (-180 dB). The LP filter attenuates only the low frequency noise at frequency band near f_E-f_U.

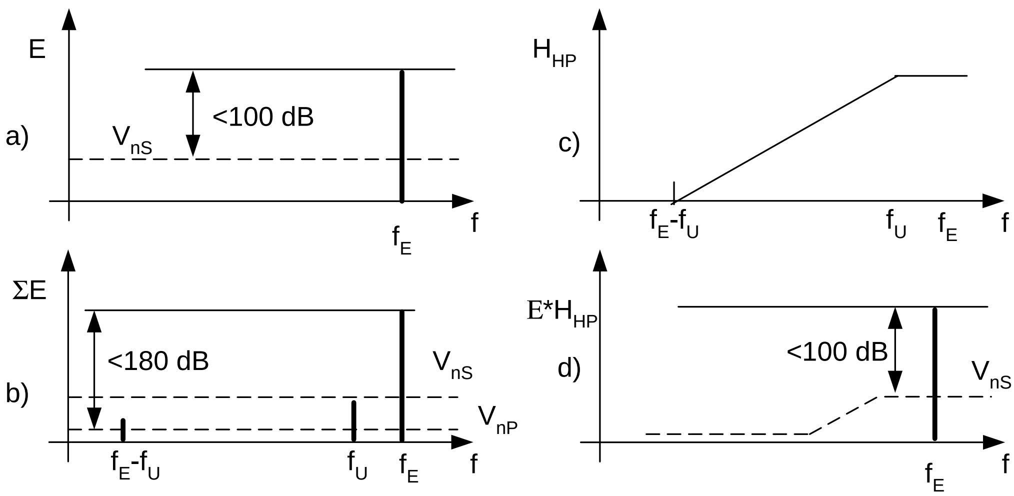

Fig. 3 Spectrum of signals and noise relation of the AC electrical source; a) source signal and noise, b) relations in tested sample, c) frequency response of AC source HP filter, d) source signal and noise after filtration

This method decreasing the noise in given frequency band shows Fig. 3. Here the frequency response of HP filter for source signal which transmits exciting signal with frequency f_E and attenuates low frequency noise is shown in Fig.3c. Spectrum of this filtered exciting signal is in Fig. 3d.

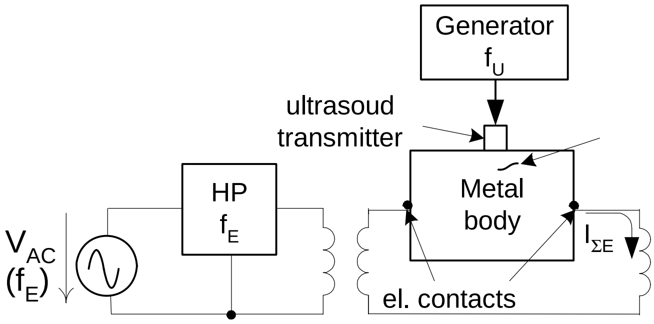

Fig. 4 Change in electrical exciting circuit of parametric ultrasound-electrical spectroscopy with AC electrical source (in comparison with Fig. 3)

Corresponding changes of measuring system from Fig. 3 is shown in Fig. 4. It is necessary to remark that the HP filer connected to power amplifier has to be designed for the high voltage and current load.

4. Experimental Results

4.1. Aluminium Plates

We start with experimental verification of this method with samples of aluminium plates without and with cracks caused by inflexion. Except of final use of band-pas filter for frequency f_E-f_U we use the spectrum analyser HP 4195A for better evaluation of measured results. We use the ultrasound transmitter with frequency 23.73 kHz. The used LP filter has cut-off frequency 6 kHz and then the exciting frequency was 29.5 kHz. The frequency of measured signal is: f_E-f_U = *29.5 – 23.73 = 5.77 kHz*. The measured value of electrical exiting signal with frequency f_E is decreased by LP filter and also the value is much higher (+70 dB) in the input of the filter.

The measured signal for sample with cracks is shown in Fig. 5. New harmonic component with frequency 5.77 kHz is observed in a frequency spectrum which corresponds to the previous discussion. Reference sample without cracks don't generate this new harmonic component.

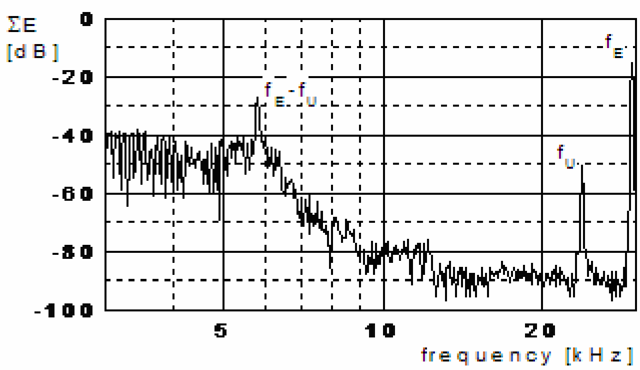

Fig. 5. Spectrum of measured signal (sample with cracks)

4.2. Thick Film Resistors

Thick conducting films were made with DuPont resistive pasta DP2041 with sheet resistance 10 kΩ/square. Samples with nominal dimensions from 0.5 × 0.5 mm^2 were screen printed on the alumina substrate. Samples were terminated with pre-fired Pd/Ag thick film conductors. Resistor test pattern is on Fig. 7.

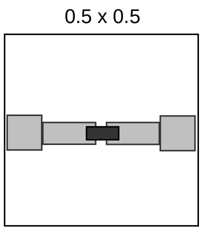

Fig.7. Resistor test pattern, resistor size 0.5 x 0.5 mm^2

Square of amplitude of intermodulation component for ultrasonic excitation f_U = 20 kHz , U_U = 28V and electric excitation f_E = 22 kHz, U_E = 10V is in Fig. 8, where f_E-f_U = 22 – 20 = 2 kHz, second harmonic 2(f_E-f_U) = 4 kHz, PS denotes parasitic signals and BN is background noise spectral density of sample and measuring set up. Electrical filter frequency is 3 kHz. More details of this frequency characteristic in region of 2 kHz is in Fig.9.

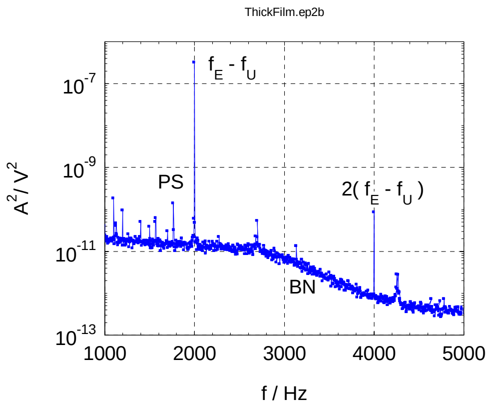

Fig.8. Square of amplitude of intermodulation component A^2 vs. frequency for ultrasonic excitation f_U = 20 kHz , U_U = 28V and electric excitation f_E = 22 kHz, U_E = 10V

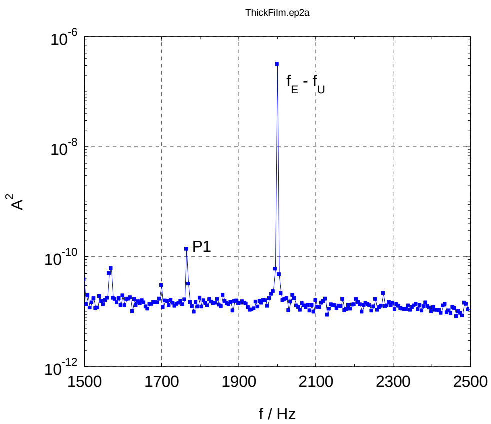

Fig.9. Square of amplitude of intermodulation component A^2 vs. frequency for ultrasonic excitation f_U = 20 kHz , U_U = 28V and electric excitation f_E = 22 kHz, U_E = 10V

Amplitude of intermodulation component A_i is linear function of ultrasonic excitation A_U as is shown in Fig. 10. Without ultrasonic signal the intermodulation component is zero.

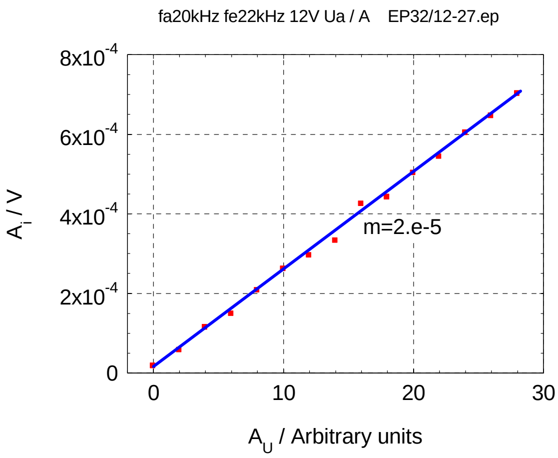

Fig.10. Amplitude of intermodulation component A_i vs. ultrasonic excitation A_U for U_E = 12 V at frequency f_U = 20 kHz and f_E = 22 kHz

Amplitude of intermodulation component A_i vs. electric excitation U_E for constant ultrasonic excitation A_U = 14 V is shown in Fig. 11. Exponential dependence was found for low voltage while saturation appears at voltage higher than 10V.

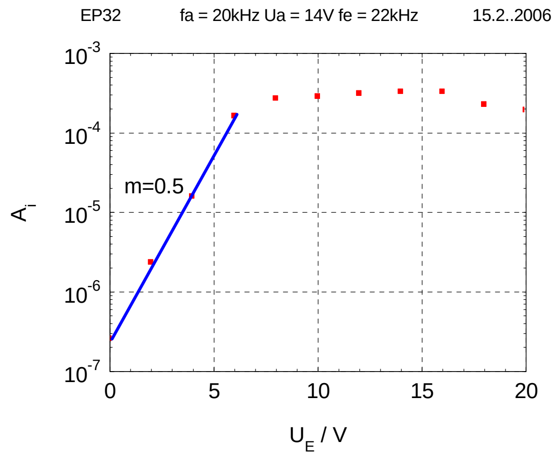

Fig.11. Amplitude of intermodulation component A_i vs. electric excitation U_E for A_U =14 V at frequency f_U = 20 kHz and f_E = 22 kHz,

We have used short current pulse from capacitor discharge as a stressing method for resistor degradation [5, 6]. The high current density value leads to power density increase in the vicinity of defects and other imperfections. This creates destructive local changes in these sites. A minimization of this destructed area can be supposed with shortening of pulse time. This principle of local destruction by pulse stressing corresponds to accelerated destructive process in a resistor with low reliability.

The stressing circuit is shown in Fig.12. The capacitor C is used as a source of constant energy pulse. The high voltage stress is applied by switching of tested resistor R_x to capacitor C. The total pulse energy is $E = ½C_T.U_0^2$, where C_T is capacitance of capacitor C, U_0 is the voltage on capacitor C before it's switching on tested resistor. Current peak value is $I_{max} = U_0/R_x$. Sample stressing depends both on the total energy and current peak value.

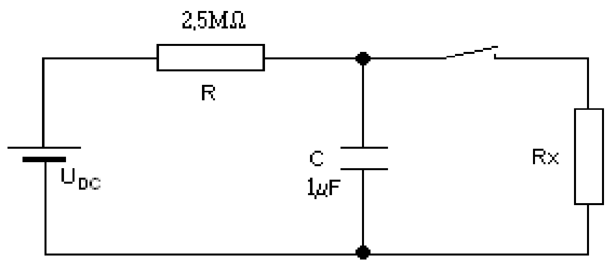

Fig.12. Testing circuit for current pulse stressing

The value of amplitude of intermodulation component A_i after the pulse stressing is shown in Fig.13. We have applied 3 pulses, the voltage U_0 was 280 V for the first and second pulse, and 320 V for the third pulse, respectively. Resistance of measured sample was 8.6 kΩ. The highest change of amplitude of intermodulation component A_i is induced by the first testing pulse as is shown in Fig. 13.

Standard measuring method of resistor quality is based on the distortion of pure harmonic signal by nonlinearity of resistance. We applied signal of frequency 10 kHz and we measured the response on frequency 30 kHz. The value of the third harmonic voltage (THV) before and after the pulse stressing is shown in Fig.14. We can see that the highest change of THV is induced by the first current pulse. Comparing results shown in Figs. 13 and 14 we can see, that the amplitude of intermodulation component A_i increases approximately 6times, while the THV value changes for less than 5%. Current pulse stressing and subsequent nonlinearity measurement is used as a method for resistors quality screening [5, 6]. The application of new method where the amplitude of intermodulation component A_i is measured allows using lower stressing pulse energy to evaluate quality and reliability of thick film resistors.

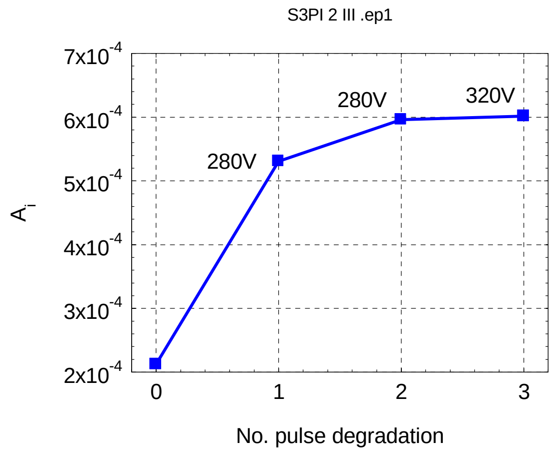

Fig.13. Amplitude of intermodulation component A^2 vs. the number of testing pulses for A_U =28 V at frequency f_U = 20 kHz, f_E = 22 kHz and U_E = 10V

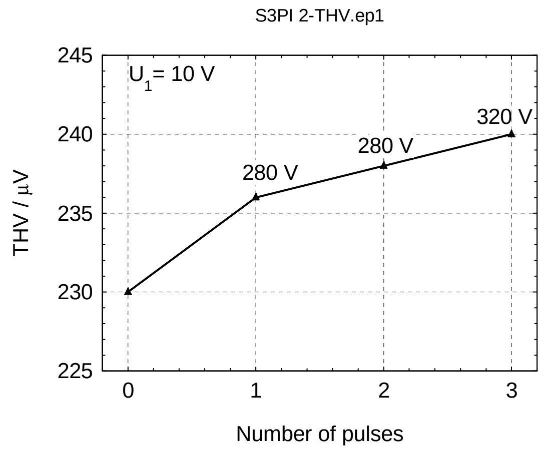

Fig.14. Third harmonic voltage vs. the number of testing pulses for applied first harmonic voltage U_1 = 10V

5. Conclusions

This paper describes new non-destructive testing method of conducting solids with defects or cracks. This method is based on nonlinear effects created by anharmonic motion of atoms subjected to ultrasonic vibrations. Physical principle follows from ultrasonic phonons interaction with electrons on defect caused nonlinearity. Tested sample is excited by harmonic electrical and ultrasonic signals with different frequencies. On the defect caused nonlinearity new harmonic signal is created with frequency given by subtraction of excited frequencies f_E and f_U. It was found that amplitude of intermodulation component A_i is linear function of ultrasonic excitation A_U.

High sensitivity of this method follows from this fact that signal giving information on tested sample quality has frequency different from exciting signals ones. The signal to noise ratio and high sensitivity for NDT analyses is based on application of special electrical filters. Experimental verification of this method was performed on samples of aluminium plates and thick conducting films both without and with cracks prepared artificially. Application of standard testing for thick film resistors shown that the amplitude of intermodulation component A_i increases approximately 6times, while the third harmonic voltage (THV) value changes for less than 5%. The application of new method where the amplitude of intermodulation component Ai is measured allows using lower stressing pulse energy to evaluate quality and reliability of thick film resistors.

Acknowledgement

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Reference

[1] Johnson, P., Ten Cate J. A.: Non-destructive Testing of Materials By Nonlinear Elastic Wave Spectroscopy. ttp://www.ees.lanl.gov/ees11/nonlinear/diagnostics.html

[2] Zaitsev, V.Yu., Sas, P.: Nonlinear response of a weakly damaged metal sample: a dissipative mechanism of vibroacoustic interaction, Journal of Vibration and Control, 2000.

[3] Hájek, K., Šikula, J., Sedlák, P.: Improving of practical sensitivity of nonlinear ultrasound spectroscopy for one exciting signal (in Czech). Defektoskopie'04, Špindlerův mlýn, listopad 2004, s. 51-58. ISBN 80-214-2749-3.

[4] Van Den Abeele, K., Carmeliet, J.: Single Mode Nonlinear Resonant Acoustic Spectroscopy (SIMONRAS) for damage detection in quasi-brittle materials. http://www.bwk.kuleuven.ac.be/bwk/sr99/bwf.htm#bfE.1

[5] Sedlakova, V., Melkes F., Dobis, P., Sikula, J. Tacano, M., Hashiguchi, S. Non-linearity changes induced by current stress in thick film resistors. In Proceedings of CARTS 2004, San Antonio, Texas, (U.S.A.), 2004, pp. 154 – 157, ISSN 0887-7491.

[6] Hajek, K., Sedlakova, V., Majzner, J., Hefner, S., Sikula, J. Non-linearity and noise characterisation of thick-film resistors after high voltage stress. In Proceedings of 3rd European Microelectronics and Packaging Symposium. Prague (Czech Republic), 2004, June 16 – 18, pp. 421 – 426, ISBN 80-239-2835-X.