STUDY OF CORRELATION AMONG DIFFERENTIAL NONLINEARITY, NONLINEARITY AND NOISE OF THICK FILM RESISTORS

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Keywords: electrical thick film resistors, nonlinearities of electrical thick film resistors, noise of electrical thick film resistors, thick resistive films, electrical conductivity of thick resistive films, I-V characteristics, current-voltage characteristics, V-I characteristics, voltage-current characteristics, linear I-V characteristics, linear current-voltage characteristics, nonlinear I-V characteristics, nonlinear voltage-current characteristics, theory of nonlinearity, differential nonlinearity of current-voltage characteristics, noise index, second harmonics index, third harmonics index correlation, laser trimming

Abstract: Typical parameters which make assessment of reliability of thick film resistors possible are noise and nonlinearity of a current vs. voltage characteristic. Both the parameters are strongly influenced by mechanisms of conductivity of the film and by mechanisms of conductivity which appear inside a transient area between the resistive film and its conductive contact. A study of correlation among nonlinearity, differential nonlinearity and noise of the thick film resistors was carried out. It was investigated an influence of the form and trimming of the resistors on these parameters. It was found that the form of the resistors influences these parameters by the same way. Trimming of the resistors influences their noise substantially but its influence on the nonlinearity is very low.

Študij povezave med diferencialno nelinearnostjo, nelinearnostjo in šumom debeloplastnih uporov

Ključne besede: upori električni debeloplastni, nelinearnosti uporov električnih debeloplastnih, šum uporov električnih debeloplastnih, plasti uporovne debele, prevodnost električna plasti debelih uporovnih, I-U karakteristike tok-napetost, U-I karakteristike napetost-tok, I-U karakteristike tok-napetost linearne, I-U karakteristike tok-napetost nelinearne, teorija nelinearnosti, nelinearnost diferencialna I-U karakteristike tok-napetost, indeks šumni, indeks harmonskih drugih, korelacija indeksov harmonskih tretjih, doravnavanje lasersko

Povzetek: Tipična parametra, s pomočjo katerih lahko ovrednotimo zanesljivost debeloplastnih uporov sta šum in nelinearnost tokovno-napetostne karakteristike. Na oba parametra močno vplivata mehanizem prevajanja znotraj filma, kakor tudi mehanizem prevajanja na prehodnem področju med uporovnim filmom in njegovim prevodnim kontaktom.

Študirali smo povezavo med nelinearnostjo, diferencialno nelinearnostjo in šumom debeloplastnih uporov, kakor tudi vpliv oblike in laserskega doravnavanja na omenjene parametre. Ugotovili smo, da oblika uporov vpliva enako na vse tri parametre, med tem ko lasersko doravnavanje močno vpliva na šum in dosti manj na nelinearnost uporov.

1. INTRODUCTION

When an electrical current is fed through a component a voltage drop appears across it. If the amplitude of the current will be changed and the voltage drop will change in proportion to the change of the current the component is linear. If the relationship between the current and the voltage drop is of an another type the component is nonlinear. It is evident that the denotation „the linear component" is related to the component with a linear current vs. voltage characteristic (C-V characteristic) and vice versa.

There are two groups of electronic components used in electronics - the nonlinear components and the linear ones. However, the basic assumption about the linear component can be accomplished theoretically only. In practice a higher or lower difference between a straight line and the C-V characteristic of the linear component can be found. Therefore the better denomination for the linear component is „the nominally linear component". The level of nonlinearity of these components is substantially lower than the level of nonlinearity of the nonlinear components. The measurement of nonlinerarity can be very useful for users as well as producers of electronic components because this parameter makes evaluation of production quality and assessment of reliability possible.

The typical linear electronic components are resistors, some types of capacitors, air cored inductors, electrical contacts and leads. The typical nonlinear components are diodes, transistors, iron-cored inductors etc. Nonlinearity of the nominally linear component is usually caused by defects inside its electrically functional part. The defects originate as a consequence of errors in a design of the component (e.g. when materials with substantially different coefficients of thermal expansivity are put together) or errors which were made during its fabrication (e.g. when cleanliness of environment is insufficient) /1/.

Thick film resistors are the components made of resistive paste applied on an insulating substrate by screen printing. That is to say that the material of the thick film is not the homogenous material because it consists of two components after firing: of a functional conductive component and of an insulating one. A better description of this structure is that one component has the low resistivity and the second one has the high resistivity /2/. Therefore different mechanisms of conductivity take part in the process of conducting of the current through the film. Some of these mechanisms are linear and some mechanisms are nonlinear. The combination of them influences the final shape of the C-V characteristic. When the linear mechanisms dominate (phonon-electron interaction, elastic tunneling) the characteristic is slightly nonlinear only, when the nonlinear mechanisms have a more significant influence nonlinearity of the component is higher.

Nonlinearity is usually investigated using a modulating technique. The component is powered by the sinusoidal current and the voltage drop of third harmonic component which arises across it is measured /3/. When the dependence between the fundamental voltage and the third harmonic voltage is a cubic one the relation would be said to be of the third degree. When this dependence is quadratic the component is qualified as the component with the second degree of nonlinearity. It is a limited number of electronic components only which have this type of nonlinearity, majority of the components have the third degree of nonlinearity.

Nonlinearity of the resistors is often correlated with their noise. Noise also reflects inhomogenity and defects inside the electrically functional part of the component but sources of 1/f noise probably differ from sources of nonlinearity. Nevertheless it was found a good correlation between the noise index and the nonlinearity index of thin metallic films. The results which were found for thick films are presented in this paper.

2. BASIC IDEAS ABOUT NONLINEARITY

A simplified explanation can be given concerning the basic physical mechanisms which give rise to noise. Majority of theories is centered around the modulation in conductivity which arises when current carriers pass into and out of the conduction bands.

Such the theories can not be accepted for description of nonlinearity as there is no reason why any such interchange of carriers should be dependent upon the magnitude of the applied voltage. The basic idea about a rise of nonlinearity is that it occurs due to the existence of surface states or junctions within the material. Such the idea is compatible with the structure of the thick film. However, a single junction has an asymmetrical C-V characteristic. The symmetrical characteristic can be found for the antiparallel connected junctions. This characteristic can also be synthesized by many other arrangements, e.g. by the parallel connection of the serial combinations of the opposite polarized junctions.

The basic theory of nonlinearity was given by J. C. Anderson and V. Ryšánek /4/ for the thin films but its conclusions can be generalized. This theory describes a relationship among inhomogenities and other defects inside the film, its resistivity and nonlinearity of its current vs. voltage characteristic. The basic assumption of the theory is given by the Matthiessen's rule

$$R_T = R_D + R \qquad (1)$$

where R_T is the total film resistance and R is a constant portion of it that arises from normal scattering processes. R_D represents nonlinear scattering processes due to barriers among the conductive areas which causes nonlinearity of the C-V characteristic.

If i-th boundary between two conductive cubic areas represents the potential barrier of V_i volts to conduction electrons then, under thermal equilibrium, the current I_i across the barrier in any direction will be given by equation (2) where A is a constant depending on the material of the film. It was derived that the net increase in the total current I_D across the N_t barriers can be described by equation (3) where V is the voltage applied across the barriers. It is assumed that all the barriers are of the same type.

Expanding of the sinh term in a series a dependence of the total current I_D on the harmonic components of the applied voltage can be found. The terms of the series are given by odd powers of the applied voltage only. Therefore the C-V characteristic is symmetrical and its nonlinearity can be evaluated according to the amplitude of third harmonic component.

$$I_i = A\exp\left(\frac{-eV_i}{kT}\right) \qquad (2)$$

$$I_D = 2N_t\,A\exp\left(\frac{-eV_i}{kT}\right)\sinh\left(\frac{eV}{kT}\right) \qquad (3)$$

$$I_D \approx \left(\frac{eV}{kT} + \frac{e^3V^3}{3!(kT)^3} + \ldots\right) \qquad (4)$$

Let us assume now that the insulating barrier between two conductive cubic areas is very thin and that the electron, when a voltage is applied between these areas, passes through this barrier by tunneling. There are two basic types of tunneling: elastic tunneling and inelastic one. Inelastic tunneling can be neglected as a mechanism of conductivity inside the resistive thick film because probability of an interaction of the electron with an energetic quantum inside the insulating barrier is very low here. Therefore elastic tunneling will dominate. The basic equation which describes the C-V characteristic of such the tunneling junction is as follows:

$$I_D = aV + bV^3 \qquad (5)$$

where a, b are constants. The second term of this equation is very low in comparison with the first one. Nevertheless it causes a slight cubical shape of the C-V characteristic.

It was shown that the overcoming of the potential barrier as well as the tunnelling through the barrier causes the slight cubical shape of the C-V characteristic. Other mechanisms also participate in the conductivity of the resistive thick films (Shottky emission, diffusion etc.) but it is possible to assume that the mechanisms mentioned above are very significant.

The conductivity of thick resistive films was also described by the use of the percolation theory, by the theory of insulating and conductive particles and by the theory of less and more conductive particles /7/, /8/. All these theories make a detailed analysis of nonlinearity possible.

3. MEASUREMENT OF NONLINEARITY AND DIFFERENTIAL NONLINEARITY

Let us assume that a component with the cubic shape of the C-V characteristic is powered by the sinusoidal current i. The periodical voltage v(t) across the component can be expressed by the Fourier series

$$v(t) = V_0 + \sum_{1}^{\infty} V_n \cos n\omega t \tag{6}$$

where n = 1, 3, 5, ... The amplitude of third hamonic component V_3 is used for evaluation of nonlinearity of the C-V characteristic.

An arrangement for measurement of nonlinearity is very simple. The sinusoidal current applied to the component shall be provided by an oscillator having minimum distortion of the signal. The amplitude of the current is changed and the voltage of third harmonic component is measured by a selective voltmeter or by a lock-in amplifier.

Differential nonlinearity is measured by the use of modulating technique. The component under test is powered by the pure sinusoidal current of a constant low amplitude (the amplitude of the current is chosen to achieve the amplitude of the voltage drop across the component of 20-50 mV). This sinusoidal signal is added with the dc offset voltage. The dc voltage and its polarity is changed to investigate nonlinearity of the C-V characteristic in different working points in a whole range of the accepted voltage. The differential nonlinearity is investigated according to the level of the second harmonic component of the periodical voltage drop which is measured across the component during its powering by the sinusoidal current. When the characteristic is symmetrical the level of the measured harmonic component has to be the same for both the polarities of the bias voltage. The specimens are measured in a four-point arrangement.

4. EXPERIMENTAL

Samples were prepared on alumina substrates of paste HS 8031 (10^3 Ω/□). The topology of the specimens was chosen with respect to the request to have the samples of oblong form of the same resistance (that means with the same ratio of length/width) but with the different area. It makes evaluation of influence of sample area on noise, nonlinearity and differential nonlinearity possible. The measurements were carried out by the equipment Quantec (measurement of noise) and CLT 1 (measurement of nonlinearity). Differential nonlinearity was measured on a special nonlinearity meter designed and realized at the CTU in Prague, Department of Electrotechnology. The basic arrangement described above was completed by the Wien bridge to achieve higher quality of the sinusoidal current and by the Wheatstone bridge to avoid problems caused by a limited dynamic range of the lock-in amplifier.

The nonlinearity meter consists of the Wien bridge, the Wheatstone bridge, a lock-in amplifier (EG&G SR 830), a programmable DC supply (HP E3631A) and a sinusoidal oscillator with the very low distortion (G 212). The measured component is connected in one branch of the Wheatstone bridge and powered by the sinusoidal current. Current bonds of the component are separated from voltage bonds (four-point arrangement). The Wheatstone bridge is connected in a diagonal of the Wien bridge. The level of the second or third harmonics is measured in a diagonal of the Wheatstone bridge by the lock-in amplifier. All equipment except of the generator of the sinusoidal signal are controlled by the use of a GPIB interface and a SW product HP VEE and are carefully screened. Earth connections are made to avoid to earth loops. A schematic diagram of this equipment was published elsewhere /5/, /9/.

5. MEASURED RESULTS

Groups of 30 thick film resistors with different topology were measured with the aim to analyze influence of the shape and area of the resistors on noise, nonlinearity and differential nonlinearity. The typical characteristics of the noise index are shown in Fig. 1.

Nonlinearity of the same groups of the resistors was also investigated. The level of the measuring voltage U1 was carefully controlled to avoid to nonlinearity caused by increasing of the temperature of the resistors by measuring voltage. The maximum amplitude of U1 was calculated according to the value of the resistor and its estimated maximum load. The used voltage was substantially lower. The fact that the measuring voltage does not influence the temperature of the resistor during its measurement was verified by the measurement when the value of the voltage of the third harmonic component was measured for more than 20 sec. When this value did not change for the whole time of this measurement it was assumed that the measuring signal is sufficiently low and does not influence the temperature of the resistor under test.

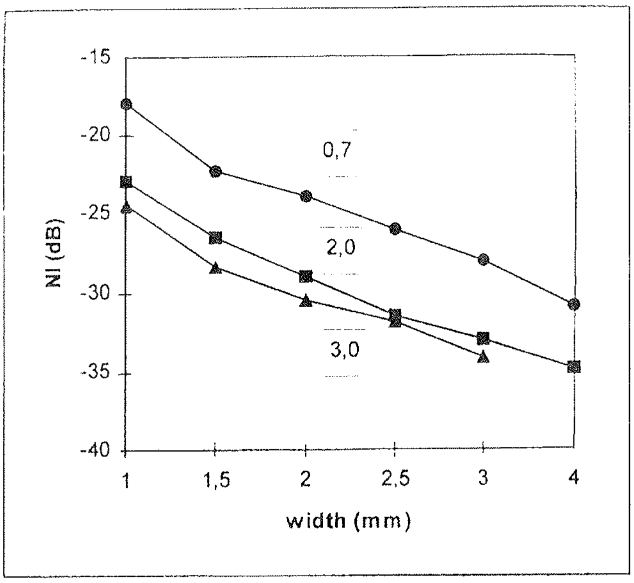

Fig. 1. Noise index of the resistors with the same ratio of length/width and with the different width. The characteristics for the ratio 0,7; 2,0 and 3,0 are shown.

The measurement of nonlinearity is more comfort than the measurement of noise and it is also less time consuming /6/. The price of the equipment for measurement of nonlinearity is comparable with the price of the equipment for measurement of noise.

The comparison of the results obtained by the measurement both the parameters could be interesting. Nonlinearity of the resistors expressed in THI is shown in Fig. 2

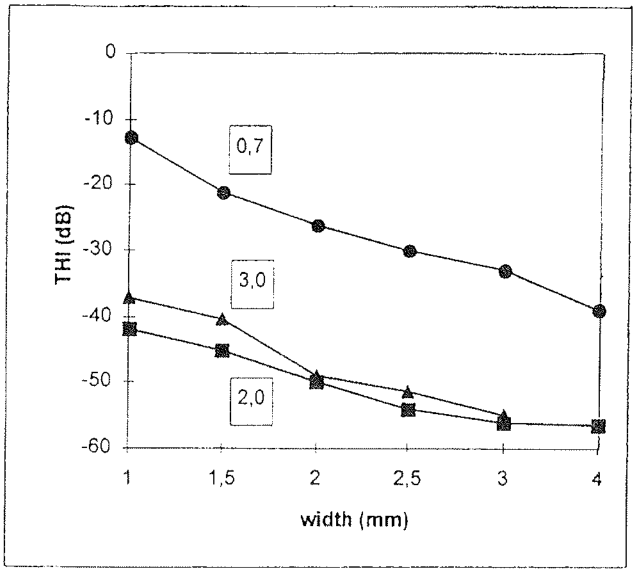

Fig. 2. Third harmonics index of the resistors with the same ratio of length/width and with the different width. The characteristics for the ratio 0,7; 2,0 and 3,0 are shown. The amplitude of the voltage U_1 was 5V.

Differential nonlinearity was investigated by the measurement of the second harmonic component of the periodical voltage generated by the sinusoidal current flowing through the resistor. The amplitude of the current was adjusted to achieve the voltage drop 50 mV across the resistor. This signal was added by the bias voltage 5 V. In contrast to the measurement of the THI the measured part of the C-V characteristic is nonsymmetrical. Even terms will dominate in the Fourier series for this type of nonlinearity. Therefore the second harmonic component was measured. We did not meet such the measurement in the literature. Therefore we defined for evaluation of this measurement a "Second harmonic index" (SHI) by the equation:

$$SHI = 20 \log \frac{U_2}{U_1^2} \qquad (7)$$

where U_2 is the amplitude of the second harmonic component in µV and U_1 is the voltage of the first harmonic component in mV. This definition corresponds to the definition of the "Third harmonic index" (THI) which is used for evaluation of the nonlinerarity measurement when the third harmonic component is evaluated. In eq. (7) the second harmonic component U_2 is evaluated and instead the third power of U_1 used for calculation of THI the second power of U_1 is used here. The results of this measurement are shown in Fig. 3.

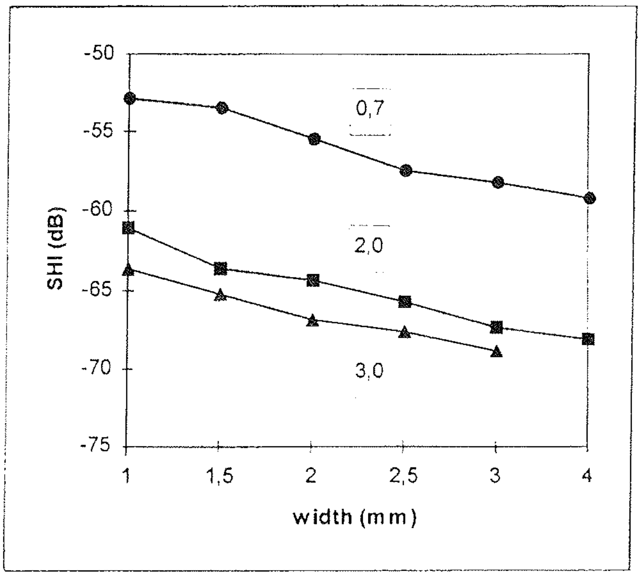

Fig. 3. Second harmonics index of the resistors with the same ratio of length/width and with the different width. The characteristics for the ratio 0,7; 2,0 and 3,0 are shown The amplitude of the modulating voltage U_1 was 50 m V. The bias voltage was 5V.

The influence of laser trimming of the resistors on values of NI and THI was also investigated. Trimming was carried out by a YAG laser, the resistance value increased by 50 % by trimming. NI and THI were compared before and after trimming. A typical example of their changes is presented in Fig. 4. It was found that

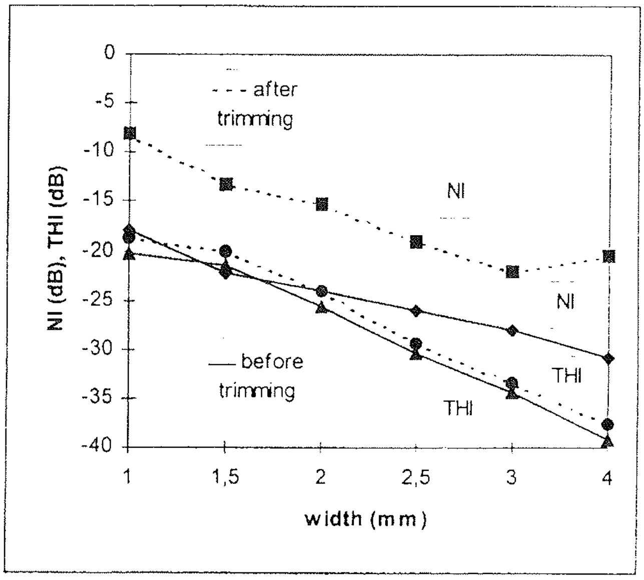

Fig. 4. Typical dependence of noise index NI and third harmonics index THI before and after trimming of the resistors. The resistance change after trimming was 50 %.

noise is substantially more influenced by trimming than nonlinearity of the resistors.

6. CONCLUSIONS

It was found that the noise index, the third harmonics index as well as the second harmonics index depend on the ratio of length/width of the resistors. All these parameters increase when the ratio length/width decreases. It could be caused by the higher influence of a transient area between the resistive thick film of the resistor and the conductive thick film of the contact. Therefore it is possible to recommend, from the point of view of investigated parameters, to prefer a higher ratio of length/width in the topology of the resistors when the resistors are an oblong form.

It was also found that the all investigated parameters of the resistors (NI, THI and SHI) reflect to the shape of the resistors with a comparable sensitivity. It makes the use of them with comparable efficiency possible.

Noise and nonlinearity differ in their sensitivity to laser trimming of the resistors. Noise increases after laser trimming, the changes of nonlinearity caused by laser trimming can be neglected. The matter of trimming is evaporation of the film from the area of an incidence of the laser beam. Borders of the laser beam track which were not evaporated were melted during trimming and therefore their structure, and probably distribution of conductive particles in the insulating matrix, differs in comparison with the structure of the film. This situation could contribute to the increase of the noise level of trimmed resistors. On the other hand nonlinearity could be also influenced by trimming from the same reason, but we found low changes of nonlinearity only.

The authors assume that the investigation of relations among NI, THI a SHI could contribute to deeper understanding of the mechanisms /7/ of thick resistive films conductivity.

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