DIAGNOSTICS OF NONLINEARITY OF CURRENT VS. VOLTAGE CHARACTERISTICS - THEORY AND APPLICATIONS

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Abstract: There are two groups of methods used for diagnostics of materials and components: methods, which are focused on investigation of macrophysical properties (such as resistance, dielectric constant etc.) and methods, which reflect microphysical properties (such as nonlinearity or noise). The goal of this paper is to show the use of nonlinearity as a diagnostic tool for evaluation of quality of materials and their changes. Instrumentation, theory and examples of applications of this diagnostics are presented.

Diagnosticiranje nelinearnosti tokovno-napetostne karakteristike – teorija in uporaba

Ključne besede: Materiali, deli sestavni, diagnostika materialov, diagnostika delov sestavnih, diagnostika nelinearnosti karakteristik tok - napetost električna, vrednotenje kakovosti

Izvleček: V splošnem obstajata dve skupini metod, ki ju uporabljamo za diagnosticiranje materialov in komponent: metode, ki temeljijo na preučevanju njihovih makroskopskih lastnosti (kot sta upornost, dielektrična konstanta ipd.) in metode, ki odsevajo mikroskopske lastnosti vzorca (kot sta nelinearnost in šum). Namen tega prispevka je pokazati uporabo nelinearnosti kot diagnostičnega orodja za vrednotenje kvalitete materialov in njihovih sprememb. Predstavljamo opremo, teorijo in primere uporabe tovrstne diagnostične tehnike.

1. introduction

Quality is a parameter, which appertains among basic parameters of technical components and equipment (and not technical only). Therefore a great effort is paid to development of methods, which make investigation and evaluation of quality possible with the simplest, easiest, cheapest and most reliable way.

The measurement of nonlinearity has been developed for investigation of influence of manufacturing technology on properties of thin metal films prepared by vacuum evaporation /1/. Later it has been also used for investigation of quality of production of capacitors, for testing of thick resistive films, quality of joints manufactured of electrically conductive adhesives and their aging and for evaluation of quality of technology for preparation of conductive lines with very low width.

Nonlinearity measurement has also been used for analysis of changes in electrically conductive adhesives after their thermal aging /2/ and for investigation of changes in thick film resistive structures caused by laser trimming. It seems that nonlinearity analysis has continuously growing significance in electronics diagnostics.

2. Principles of Measurement and Measuring Equipment

Two measuring principles are currently used for investigation of nonlinearity of current vs. voltage characteristics. The first principle is shown in Fig. 1. A measured component with the nonlinear I-V characteristics is powered with the sinusoidal current. As a consequence of the nonlinear shape of the I-V characteristics the voltage across the component is periodical, but it is not sinusoidal. Such the signal can be decomposed in a series of harmonics and the value of third harmonics is measured. The equipment for such the measurement is very simple and consists of three parts: a generator of the sinusoidal current, a selective voltmeter for the measurement of the first harmonics voltage and a selective voltmeter for the measurement of the third harmonics voltage. The generator must have minimum distortion of the signal and low noise (the signal to noise ratio must be higher than 150 dB). Its distortion must not change with different impedance of the measured samples. Filters of the selective voltmeters must have high quality to achieve sufficient selectivity. Therefore the equipment based on this principle is usable for one measuring frequency only; the basic frequency is usually 10 kHz the frequency of the third harmonics is 30 kHz.

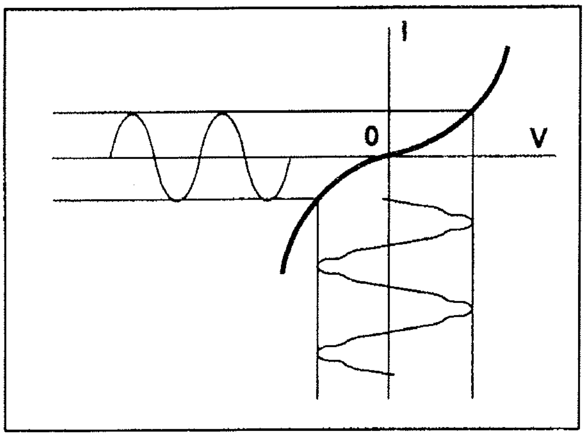

Fig. 1. Principle of measurement of nonlinearity by powering of the sample with a pure sinusoidal current

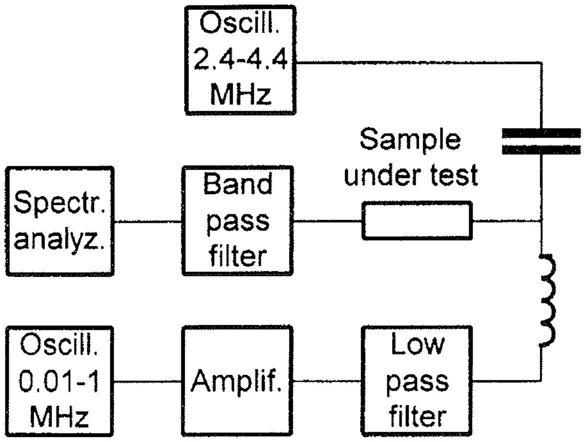

Fig. 2. Schematic diagram of an equipment for measurement of I-V characteristics nonlinearity based on modulation principle

The second principle, which has been used for design of an equipment realized at the Department of Electrotechnology of the CTU in Prague, is based on powering of the sample with two sinusoidal signals (see Fig. 2). Modulation products of third order, which are caused by nonlinearity of the I-V characteristics, are measured with a spectral analyzer. The advantage of this equipment in comparison with the previously mentioned one is ability to measure nonlinearity at the wide frequency range. The equipment has been designed with respect to minimum own noise and nonlinearitry. Therefore capacitors with very low own nonlinearity have been used (it is necessary to avoid to ceramic capacitors, which are mostly manufactured of feroelectric ceramics). As for resistors, it is not possible to use film resistors because of their high nonlinearity and noise. Wire resistors are mostly manufactured of nichrome or manganine alloys. These alloys are feromagnetic and dependence of their impedance on frequency is not linear. Therefore the wire resistors manufactured of platinum wire have been used.

3. Theory of nonlinearity

Nonlinearity of the current vs. voltage characteristics of nominally linear components is often explained by presence of nonlinear mechanisms of conductivity such as tunneling or Shottky emission, which complete the linear mechanism of phonon-electron interaction, which is the dominant one. However, according to the other theory, the main reason of nonlinearity is an increase of temperature of microscopic areas, e.g. of boundaries of grains, when the current flows through the component. Nonlinearity is also explained by magnetic properties of a material s or by thermal diffusion of vacancies.

Nonlinearity is usually joined with inhomogenities, which cause origin of potential barriers spread throughout the material. Therefore its value is substantially higher in multicomponent materials such as thick resistive films than in metals. Very often theory of potential barriers is also used for the description of nonlinearity.

Let us present short description of this theory /4/. The current I_I, which flows through the barrier, can be, in general, described by an equation:

$$I_I = A \cdot \exp\left(-\frac{e\Phi_I}{kT}\right) \quad (1)$$

Where A ... constant of the material, e ... charge of the electron, Φ_I ... height of the potential barrier, k ... Boltzman constant, T ... temperature in K.

When the voltage U will be applied in a positive direction, the value of the current will be:

$$I_I^{+} = A \cdot \exp\left(\frac{-e\Phi_I + eU}{kT}\right) \quad (2)$$

When the voltage will be applied in an opposite direction, the value of the current will be:

$$I_I^{-} = A \cdot \exp\left(\frac{-e\Phi_I - eU}{kT}\right) \quad (3)$$

The total current I_T is calculated as a sum of the currents flowing through all barriers. It is possible, after short mathematical processing, to express I_T by the equation:

$$I_T = 2N_t A \exp\left(-\frac{e\Phi_I}{kT}\right)\left[\frac{eU}{kT} + \frac{e^3U^3}{3!(kT)^3} + \frac{e^5U^5}{5!(kT)^5} + ...\right] \quad (4)$$

As follows from equation (4), potential barriers (number of these barriers is N_t) cause nonlinearity of the odd type. If the number of the barriers will increase, nonlinearity will also increase. If the hight of the potential barriers will increase, the resistance of the sample will increase (see Fig. 3).

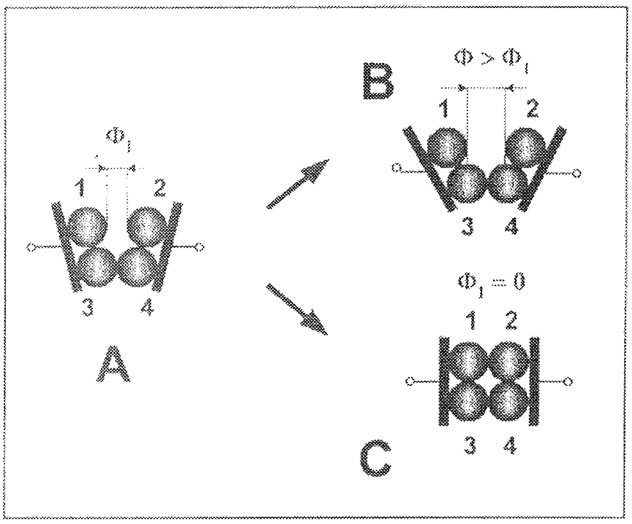

Fig. 3. Possible changes of potential barrier during the time

When the system with the barriers is arranged as shown in Fig. 3 A, there is a potential barrier Φ_l between areas 1 and 2. If we will assume, for simplicity that contacts between areas 1,3 and 2,4 have very high resistance, the total resistance of this system can be expressed as the resistance of two parallel connected resistors R' and R. The resistor R' represents the resistance of the course from the left electrode through the area 1, potential barrier Φ_l and area 2 to the right electrode and the resistor R the resistance of the course from the left electrode through the areas 3 and 4 to the right electrode. After some time the system will have configuration according to Fig. 3B or 3C. If the system will change its configuration according to Fig. 3B, the potential barrier will increase and the total resistance of the system will also increase. If the resistance R' increases to ∞, the total resistance will be equal to R. If the configuration will change as shown in Fig. 3C, the total resistance will decrease and will be equal to R/2.

For description of dependence of the number of the barriers N_t on the temperature T the Arrhenius equation is usually used.

$$N_t = N_0 \exp\left[\frac{K}{\tau}\exp\left(-\frac{E_A}{kT}\right)\right] \tag{5}$$

Here K ... constant of the material, τ ... reaction expectancy, E_A ... energy, which is necessary for reconfiguration (activation energy), N_0 ... number of barriers in balance.

Another theory of nonlinearity is based on an assumption of diffusion of vacancies /3/, which is caused by increase of the sample temperature. The current flowing through the sample causes this increase. For a rectangular thin film resistor with the length L, width b, thickness h and resistivity ρ_f, which is powered with the sinusoidal current $I_1\sin(\omega t)$, the temperature of the sample increases by ΔT:

$$\Delta T = T - T_0 = R_T P = \frac{R_T K_1 \rho_f}{h} I_1^2 \sin^2(\omega_1 t) \qquad \Delta T << T_0 \tag{6}$$

Here T ... temperature of the sample when the sample is powered by the sinusoidal current, T_0 ... temperature of the surroundings, R_T ... thermal resistance of the layer, K_1 = L/(b.h).

According to the Matthiessen rule the total resistivity of the layer ρ_f can be written as:

$$\rho_f = \rho_L(T) + \rho_D + \rho_s \tag{7}$$

Here $\rho_L(T)$ ... the part of resistivity caused by dispersion of electrons on phonons, the dependence of this part on the temperature is linear, ρ_D ... the part of the resistivity caused by dispersion of the electrons on vacancies and on other volume imperfectances, ρ_s ... the part of the resistivity caused by dispersion of the electrons on the surface of the thin film.

The change of the temperature will cause the periodical change of vacancies concentration. If it will be assumed that the increase of resistivity will be influenced by the vacancies with the energy of activation E_V only, then dependence of ρ_f on the temperature can be expressed as follows:

$$\rho_f(T) = \rho_{01}(1+\beta\Delta T) + AA_V \exp\left(-\frac{E_V}{k[T_0+\Delta T]}\right) \tag{8}$$

Here ρ_{01} ... part of the total resistivity, which is caused with dispersion of electrons on phonons and with interaction of electrons with the surface of the layer, β ... thermal coefficient of the resistivity of the layer, A ... coefficient of proportionality, A_V ... coefficient of entropy, E_V ... energy of activation of vacancies.

In equation (8) the first part represents a component, with linear dependence of resistivity on the temperature, the exponential part represents a nonlinear component. This part can be expressed as a series of harmonics. When the sample will be powered with the sinusoidal current $I_1\sin(\omega t)$, third harmonics can be expressed as:

$$U_3 = 0.25 R_T K_1^2 \rho_{01} \rho_f \left[\beta + \frac{AA_V E_V}{kT_0^2 \rho_{01}} \exp\left(-\frac{E_V}{kT_0}\right)\right] I_1^3 \tag{9}$$

4. Applications of nonlinearity measurements

Diagnostics of nonlinearity of I-V characteristics has been used in many cases. Two of them are presented in this paper.

The use of nonlinearity evaluation for optimization of manufacturing technology of the lines with very low width is shown in Fig. 4. The lines of the width of 50 μm have been prepared by thick film technology of special photosensitive conductive pastes on alumina sub-

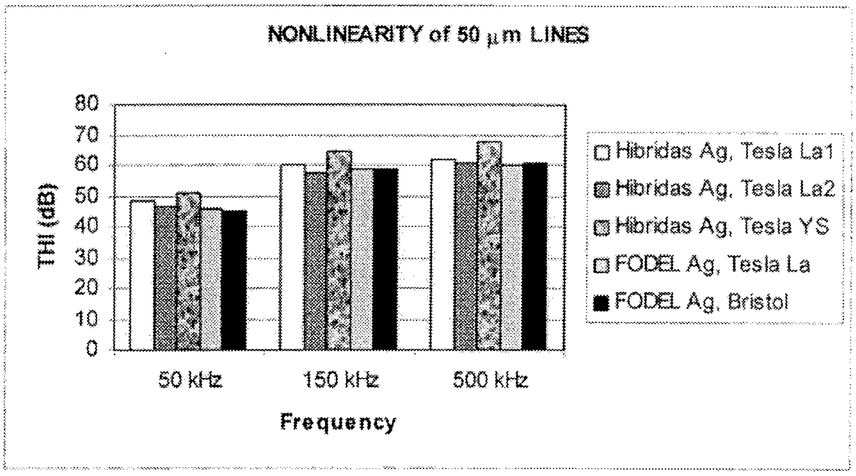

Fig. 4 *Nonlinearity (expressed as THI in dB) of 50 μm lines manufactured of photosensitive thick film pastes Hibridas and Fodel in different factories on alumina substrates*

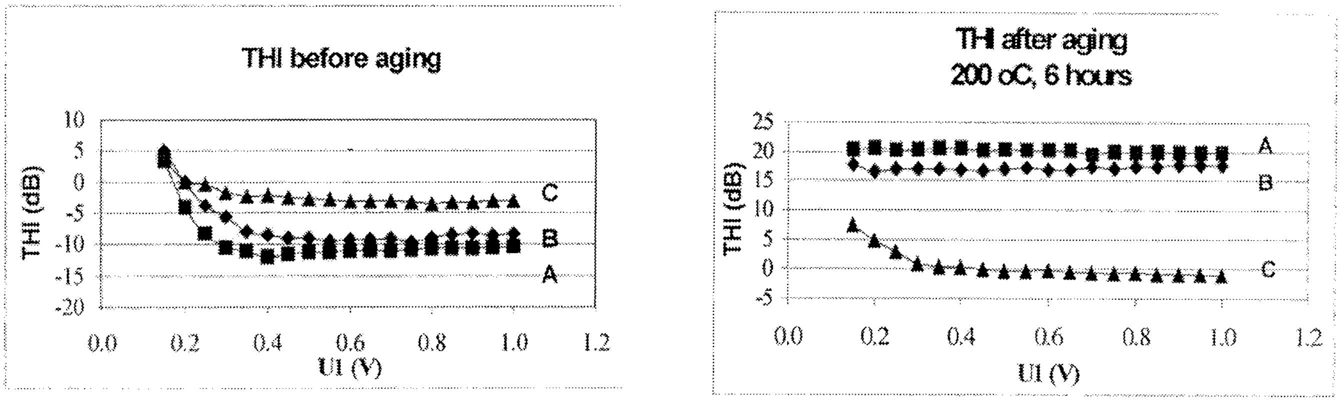

Fig. 5 *Third harmonic index (THI in dB) of joints prepared of adhesives Alpha Metals 171 (A), Alpha Metals 181 (B) and ECA 3 (C) on Cu surface before and after aging at 200 °C*

strates. The quality of the lines has been evaluated according to their resistance and nonlinearity.

Diagnostics of quality of conductive joints manufactured of electrically conductive adhesives has also been carried out by the measurement of nonlinearity of these joints. After manufacturing the joints have been measured, then at the higher temperature, measured again, and the changes of their nonlinearity have been evaluated. According to these changes the changes of a structure of the adhesives have been analyzed. The small part of these measurements is shown in Fig. 5.

5. Conclusions

It has been found that the diagnostics based on the evaluation of nonlinearity of I-V characteristics could be a very useful tool for evaluation of quality of technology and materials.

Main advantage of this type of diagnostics is its simplicity and very high sensitivity on changes in materials. These properties state it to spreading among advanced types of diagnostic methods.

6. Rererences

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