Modelling and simulation of standard TFRs as strain sensing elements

Ivanka Stanimirović and Zdravko Stanimirović

Abstract - In this paper modelling and simulation of standard thick-film resistors as strain sensing elements are presented. Thick-film resistors are described using a model that incorporates both deterministic model and percolation model with double percolation. The model served as a base for computer simulation of resistor behaviour under applied mechanical straining. It is shown that obtained results are in accordance with experimental ones confirming that standard thick-film resistors can be used as strain sensing elements and that presented model can be used as a tool in prediction of behaviour of mechanically strained resistors.

Keywords – Thick-film resistor (TFR), computer simulation, mechanical straining, conducting mechanisms, glass barrier width.

I. Introduction

Thick film resistors (TFRs) have been used for decades but due to their reliable performances they are still commonly used in both commercial and specialized electronics. For years they have been used in sensitive telecommunications equipment and various sensing applications. However, when micro-electro-mechanical systems (MEMS) technology emerged, thick-film technology became useful alternative for micro-machining silicon. The most MEMS are made of micro-machining silicon combining electrical and mechanical components. Such micro system might comprise one or more sensors and actuators and adequate electronic circuitry to condition the sensor signal and generate an electrical signal for actuator. Nowadays, some MEMS applications require ceramic materials in combination with thick-film technology. These MEMS are usually larger than standard and they can often be used in harsh conditions. The fact that thick-film technology can be used not only to produce the sensor and actuator elements, but to form electronic circuits for signal processing makes room for this technology in fast-growing MEMS market. When sensor applications are in question, piezoresistive effect in TFRs has been used since 1970s and over the past decade the most published papers dealt with different problems of understanding the effects of mechanical straining on TFRs [1-4] and novel thick-film compositions specifically developed for strain sensing purposes [5, 6]. However, there is a possibility that standard TFRs due to their strain sensitivity can be used in up-to-date strain-sensing applications. Standard TFRs can exhibit a rather large piezoresisitve effect that is usually undesirable property when conventional thick-film applications are in question and for this reason behaviour of thick-film under mechanical straining conditions still induces significant interest. In this paper we have performed computer simulation of changes in thick-film resistor properties caused by mechanical straining based on our previous experimental and theoretical investigations of mechanically strained standard TFRs [7] in order to predict their behaviour under applied strain.

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II. Mechanical straining of TFRs

The change of resistance in TFR under applied mechanical strain is partly due to deformation (changes in resistor dimensions), and partly due to micro structural changes resulting in specific resistivity alterations. The applied strain, ε, is defined as the relative change in the length of the resistor, while the gauge factor, GF, is defined as the ratio of the relative change in resistance and the applied strain:

$$GF = \frac{\Delta R/R}{\varepsilon} = \frac{\Delta R/R}{\Delta l/l} \quad (1)$$

The GF values for TFRs are mostly between 3 and 15. It is known that gauge factors of 2-2,5 are due to geometrical factors alone. Higher GF factors are due to micro structural changes [6]. Transport of electrical charges in TFRs takes place via complex conductive network formed during firing by sintering metal-oxide particles surrounded by glass. Our previous investigations resulted in the model of the random resistor network that was developed using the deterministic model in combination with the site percolation model with double percolation [8]. Deterministic model describes TFR as a network of conducting chains where some particles are in contact and others are separated by thin glass barriers thus forming metal-insulator-metal structures. Therefore the current flow through resistor is determined by metallic conduction through conducting particles and sintered contacts between them and tunnelling through glass barriers. Under assumption that TFR consists of M parallel conducting chains the total resistance of TFR can be given as [9]:

$$R = \frac{K_B}{M} R_B + \frac{K_C}{M} R_C \quad (2)$$

where K_B is the number of barriers and K_C the number of contacts. R_B and R_C are barrier and contact resistances, respectively:

$$R_B = \frac{h^2 s}{q^2 A (2mq\Phi_B)^{1/2}} \exp\left[\left(\frac{32\pi^2 mqs^2 \Phi_B}{h^2} \right)^{1/2} \right] \quad (3)$$

$$R_c = \frac{\rho}{\pi a} \quad (4)$$

where q and m the absolute electron charge and its effective mass respectively, h Planck's constant, s and Φ_B the potential barrier width and height respectively, $A = \pi a^2$ the barrier cross section and ρ the specific resistance of the contact. Site percolation model with double percolation introduced two percolation problems [8]:

- any lattice site can be occupied by a conducting particle with probability p or unoccupied with probability 1-p
- two neighbouring sites can be connecting by contact resistance R_C with probability p_1 or by barrier resistance R_B with probability $1-p_1$ where

$$p_1 = \frac{N_C}{N_C + N_B} \quad (5)$$

where N_C is the number of contact resistances and N_B the number of barrier resistances in TFR. Resistor, depending on its dimensions, consists of a number of elemental cells – elemental two-dimensional matrixes with N^2 elements. Within an elemental cell random occupancy of any bond between two neighbouring sites by R_B or R_C is obtained using random number generator with uniform distribution from (0,1) range – the second percolation problem. If the generated number is $\leq p_1$ then the bond is occupied by contact resistance R_C. If it is $>p_1$ the bond is occupied by barrier resistance R_B. Glass particles are being introduced using random number generator with uniform distribution to generate coordinates of glass particle centres thus removing contact and barrier resistances within the glass particle diameters D – the first percolation problem. Glass particle diameter is being obtained using random number generator with normal distribution and defined upper and lower diameter limit (3μm and 0,1μm, respectively). Diameter of the conducting particle d=150nm is being taken from the deterministic model. Such a representation of TFR incorporates both micro and macro structural characteristics of the resistor.

III. SIMULATION RESULTS AND DISCUSSION

Simulation of standard TFRs as strain sensing elements was performed using model described in section II in combination with experimental results obtained during series of experimental investigations related to behavioral analysis of thick-film resistors subjected to mechanical and electrical straining. Detailed description of performed experiments can be found in [7]. These investigations confirmed assumption that the tunneling process through glass barriers gets higher strain sensitivity than metallic conduction. This means that this type of straining can only influence the barrier resistance changing the glass barrier width since numbers of contacts, barriers and barrier height cannot be influenced by this type of straining. For simulation purposes we chose to evaluate 1mm wide and 2, 4 and 6mm long resistors centrally positioned on the substrate with fixed edges (Fig. 1) subjected to maximal mechanical straining of 400μm resulting in changes of resistor physical dimensions shown in Table I.

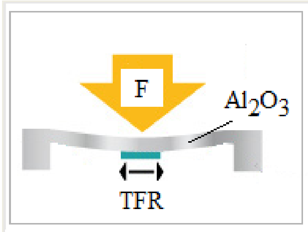

Fig. 1. Schematic presentation of experimental settings

Sheet resistances of 10kΩ/sq and 100kΩ/sq (Fig. 2) were selected with 0,2 and 0,1 volume fractions of conductive phase respectively. Resistor composition with sheet resistance of 1kΩ/sq was excluded because of the small conducting/isolating phase ratio that determines dominant conducting mechanism – conduction through clusters of particles that cannot be affected by mechanical straining [7].

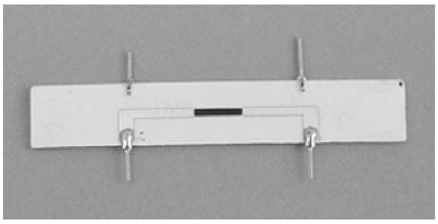

Fig 2. One of TFRs used in the experiment (w=1mm, l=6mm, R_{sq}=100kΩ/sq)

Potential barrier height Φ_B=1V and initial value of barrier width s=1,33nm were taken into account. These values were used, along with experimentally obtained resistance values for unstrained TFRs [7], to simulate resistor microstructure – number and spatial distribution of contact and barrier resistances. Then, microstructure of strained resistor was being simulated based on experimentally obtained percentual changes in resistance values after performed mechanical straining. Having in mind that mechanical straining affects the charge transport by changing glass barrier widths, as an illustration of performed simulations relative changes of barrier widths due to mechanical straining are presented in Fig. 3 and 4.

TABLE I

EXPERIMENTAL VALUES USED IN SIMULATIONS [7]

R_{sq} (kΩ/sq)	10	10	10	100	100	100
R_i (kΩ)	16,59	32,81	50,64	276,51	495,83	704,3
l (mm)	2	4	6	2	4	6
$\|\Delta R\|$ (%)	0,958	0,945	0,918	1,381	1,266	1,136
Δl (μm)	1,905	3,81	5,175	1,905	3,81	5,715

In Fig. 3 relative changes of barrier widths vs. relative changes of resistor lengths for mechanically strained TFRs of the identical initial length and different sheet resistances are given. It is shown that higher sheet resistance suffers grater barrier width change due to lower conductive/glass phase ratio and therefore more dominant tunnelling mechanism. Also, barrier width increases with the increase in length of the strained resistor (Fig. 3).

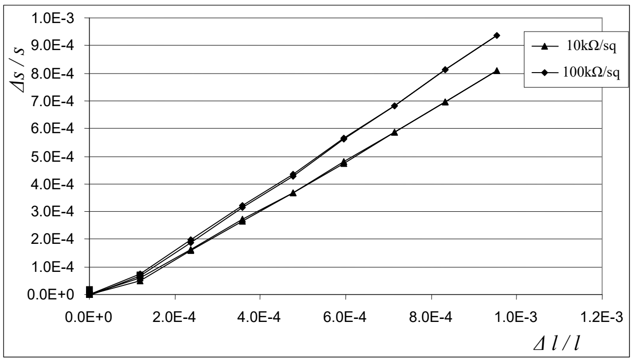

Fig. 3. Relative change of barrier widths vs. relative change of resistor lengths for 4mm long mechanically strained TFRs with nominal sheet resistances of 10kΩ/sq and 100kΩ/sq and initial value of barrier width s=1,33nm

Relative changes of barrier widths for TFRs with different initial lengths and sheet resistances are given in Fig. 4. It can be seen that that shorter resistors exhibit greater barrier width changes. In order to prove that these results are in accordance with experimental results GF values were calculated (Fig. 5). Experimental results show that resistor compositions with smaller volume fractions of conducting phase have greater GF values. TFRs based on 100kΩ/sq composition have lower volume fraction of conductive phase than 10kΩ/sq composition and therefore its charge transport is predominantly limited by conduction through glass barriers. TFRs based on 10kΩ/sq composition incorporate approximately equally tunneling through glass barriers and conducting through conducting particles and sintered contacts. Fig. 5 shows that obtained GF values are greater for resistors realized using compositions with higher sheet resistance but decrease with increase in length for resistors with identical nominal sheet resistance. It can be noticed that TFRs realized using 10kΩ/sq composition have GF~10 and therefore can be used as strain sensing elements.

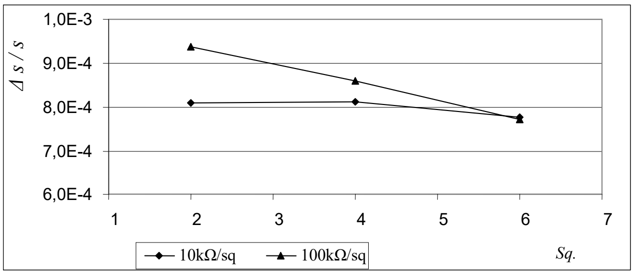

Fig. 4. Relative change of barrier widths vs. resistor area for mechanically strained TFRs with different initial lengths and nominal sheet resistances of 10kΩ/sq and 100kΩ/sq

Simulation results proved to be in accordance with experimental results proving that applied model can provide adequate analysis of mechanically strained TFRs. Depending on the application, data basis could be formed that would incorporate all necessary data about the resistor composition to be used, straining conditions that are to be applied and expected percentual resistance change for every composition. In that way behavior of strained TFRs can be predicted and used during the design phase of the device or in reliability assessment. Another potential use of this simulation process is analysis of degradation processes and failure mechanisms in TFRs subjected to various types of straining. It may be possible to introduce presence of defects in the model of TFR structure thus predicting its behavior under various straining conditions both mechanical and electrical. Such an analysis could be of use in performance optimization and elimination of potential reliability issues.

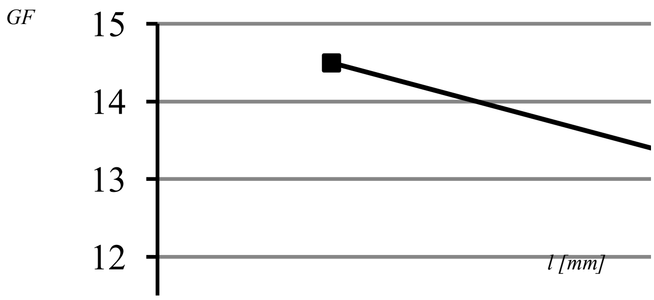

Fig. 5. Mean values of gage factors for TFRs with different lengths and sheet resistances of 10kΩ/sq and 100kΩ/sq

IV. CONCLUSION

In this paper modelling and simulation of standard TFRs as strain sensing elements are presented. A model that incorporates both deterministic model and model based on percolation theory is being used in order to represent spatial distribution of conducting and isolation phase within the volume of these complex heterogeneous structures that determines types of conducting mechanisms and basic characteristics of resistive layers. Deterministic model introduced micro structural and percolation theory introduced macro structural characteristics of the resistor into the model. In order to investigate whether standard TFRs can be used as strain sensing elements described model was used for computer simulation of thick film resistors subjected to mechanical straining. Resistors with sheet resistances of 10kΩ/sq and 100kΩ/sq, previously used for experimental investigations [7], were simulated. Obtained results were compared with the results of experimental analysis and it is proved that mechanical straining causes reversible resistance change due to change in conduction conditions. It causes the barrier width change thus affecting conducting through glass barriers. It is shown that standard resistors can be used as strain sensing elements, particularly TFRs based on 10kΩ/sq composition and that presented model can be used in prediction of behavior of mechanically strained TFRs. That can be of use in various stages of device design as well as in reliability analysis. Because the applied model incorporates both micro and macro structural characteristic of TFRs, further investigations may be directed to simulation of degradation processes in resistors caused by different types of unwanted straining in order to study these processes.

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