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Low Frequency Noise and TCR Mechanisms in Polymer Thick Film Resistors

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Abstract—**The paper aims to propose a more realistic low frequency noise and TCR mechanisms in polymer thick film resistors. The variation of low frequency noise (also called current noise) and TCR of polymer thick film resistor, namely, PVC-graphite thick film resistor, with parameters such as high volume fraction and grain size has been studied. A model is proposed to explain the observed variations, which assumes that the texture of the polymer thick film resistor consists of densely packed conducting particles with a cavity at the center of the structure. Further, the effect of the cavity diameter of polymer thick film resistor on current noise and TCR is explained using the same model. The current noise of these resistors is controlled mainly by the average relative resistance fluctuations between the conducting particles and the number of contacts each particle has with its neighbors. The TCR of these resistors is controlled mainly by the expansion properties of the insulating medium. The variation of TCR with high voltage is also due to the change in number of contacts and the contact area between the conducting particles.**

Keywords—**Polymer thick film resistors, volume fraction, grain size, current noise, TCR**

Introduction

The study of current noise in thick film resistors has been an important subject to hybrid microcircuits because of increasing usage of thick film resistors in low noise hybrid circuits. Generally, an increase in fluctuation voltage appears when direct current (DC) is passed through the thick film resistors. The increase in fluctuation voltage is called "excess noise" or "current noise." The magnitude of the current noise is dependent upon many inherent properties of the resistor such as resistive materials and other factors such as processing, fabrication, size, and shape of the thick film resistors, and so on. Since there is no particular relationship between the current noise and many of these factors, current noise generally cannot be predicted from physical constants. Therefore, it is necessary to measure current noise to determine its magnitude. The method employed in these measurements has been designed to evaluate the noisiness or noise quality of the individual resistors in terms of noise quality index. The noise quality index, expressed in decibels, is a measure of the ratio of root mean square (rms) value of noise voltage, in microvolts, to the applied DC voltage in volts. Before any attempt is made to use these resistors, it is necessary to understand the mechanism involved in the current noise in these materials. Several investigators have proposed models to explain the current noise mechanism in these materials. Most of these models revolve around the idea of formation of relative noise of conducting chains in the insulating matrix. However, they fail to provide a reasonable quantitative analysis for the variation of current noise with high volume fraction and grain size. In view of this, a more realistic model is proposed to explain the variation of current noise with material parameters quantitatively and it assumes that the current noise is due to relative resistive fluctuations of the contacts between the conducting particles. The variation of current noise with the parameters of volume fraction and grain size is attributed to the changes in the number of relative noise fluctuations of contacts between the conducting particles. The aim of this paper is to report a more realistic low frequency noise mechanism in polymer thick film resistors.

Conductor-insulator composite materials belong to a newer class of materials that enable the conception and synthesis of materials with unusual or extraordinary characteristics. A composite material consists of two or more phases mixed in an appropriate way. These phases may be different forms of the same materials, or entirely different materials. This paper also investigates the temperature coefficient of resistance (TCR) of PVC-graphite thick film resistors with volume fraction, grain size, and high voltage. The same proposed model explained the observed variations quantitatively and it assumes that electrical conduction takes place through the contacts between the conducting particles. The variation of TCR with parameters of volume fraction, grain size, and high voltage is attributed to the change in number of contacts and the contact area. A part of the experimental results have been already published [12] and the aim of this paper is to report the proposed model.

Experimental Work

A. Resistor Fabrication

Polymer paste containing PVC and graphite was prepared by first dissolving PVC granules in cyclohexanone and then by blending graphite into it. The average grain size of graphite varied from 10-100 microns. This paste was used for printing resistors on PVC substrates with the help of a screen printer supplied by De Haart (Massachusetts, USA, model SP-SA-05). These printed resistors are processed using the usual thick film processing of polymer based films. This involves drying at

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room temperature for 15 min followed by curing at 100°C for 4 h. Various PVC-graphite compositions are taken, from 40%:60% (percent by weight of PVC:percent by weight of graphite) to 10%:90%.

B. Electrical Measurements

The current noise index measurements of these resistors have been carried out as follows. The Quan-Tech Model 315 C resistor noise meter is used to measure the current noise index in decibels (dB). The current noise index is defined as the ratio of rms noise voltage, in microvolts, to the applied DC voltage in volts, expressed in decibels, when the bandwidth of the measurement is 1 KHz and its frequency is geometrically centered at 1 KHz. In the Quan-Tech noise meter, the noise index can be measured with these parameters under varied conditions of current. The noise index of each resistor is measured by varying the voltage across the resistor (current through the resistor). The variation of current noise is explored:

- With the volume fraction at different grain sizes.
- With the grain size at different volume fractions.

Five resistors of each type are subjected to these measurements and the average noise index is taken as the noise index for that resistor. Typical curves showing these variations are given in Figs. 1–2.

In order to obtain the TCR of samples, the resistance was measured at two temperatures, 25°C and 50°C, and the average TCR was calculated using the formula

$$\text{TCR} = R_{50} - R_{25} / (R_{25} \cdot (50°\text{C} - 25°\text{C}))$$

The average values of the grain size of the conducting particles used are 10, 45, 90, and 100 µm. The typical dimensions of the rectangular examples for measurement are length 8 mm, width 1 mm, and thickness 1000 µm. The variation of TCR was determined:

- With high volume fraction at different grain sizes.
- With grain size at different high volume fractions.
- With high voltages at different volume fractions for different grain sizes.

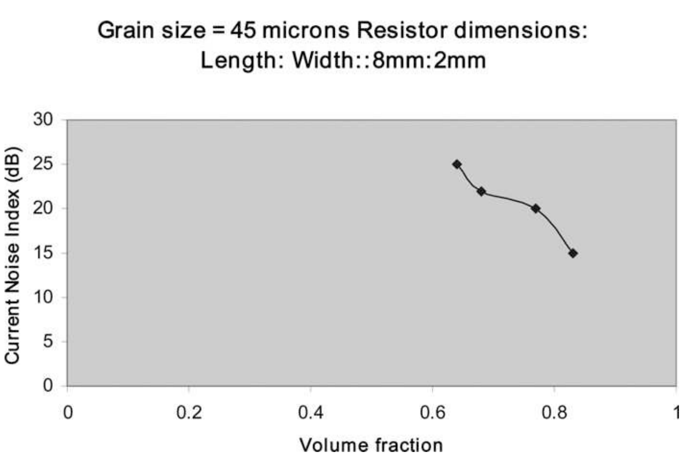

Fig. 1. Current noise index versus volume fraction for a PVC-graphite thick film resistor.

Five resistors of each type are subjected to these measurements and the average TCR is taken as the TCR for that resistor. Typical curves showing these variations are given in Figs. 3–5.

Results

A. Variation of Current Noise with Volume Fraction

The current noise variation with volume fraction of conductor (graphite) is shown in Fig. 1. Fig. 1 shows that the current

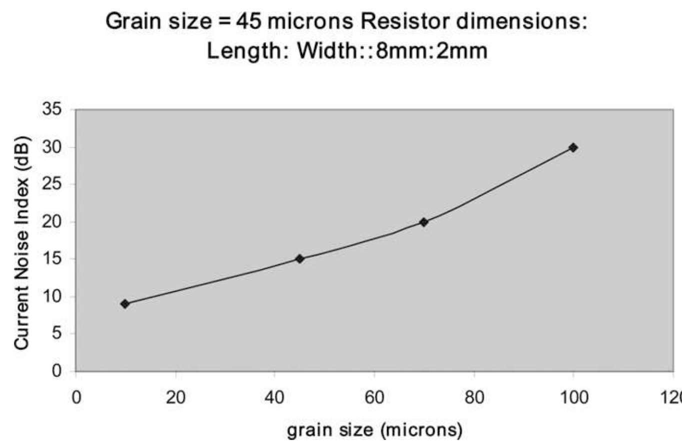

Fig. 2. Current noise index versus grain size for a PVC-graphite thick film resistor.

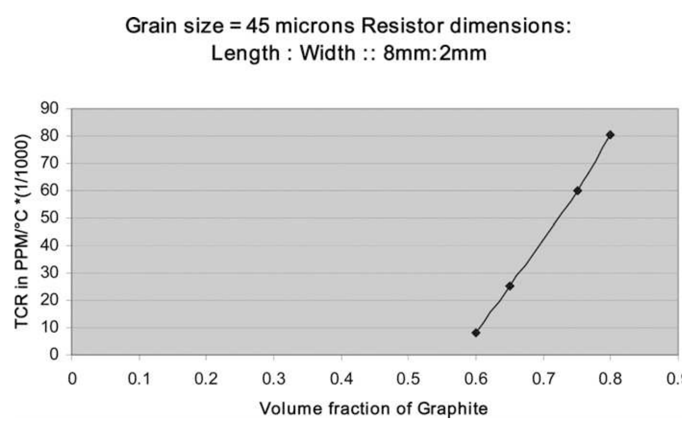

Fig. 3. TCR versus volume fraction for a PVC-graphite thick film resistor.

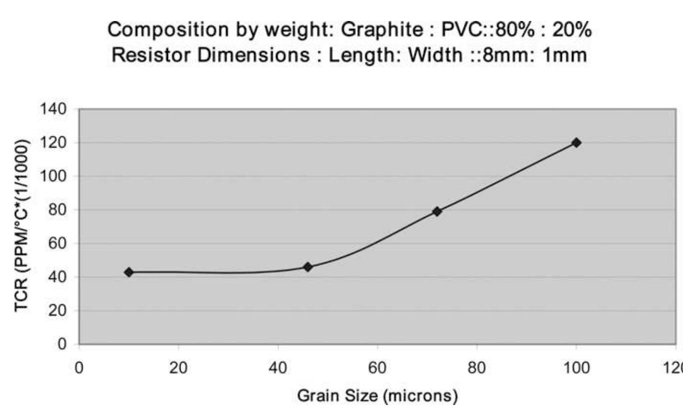

Fig. 4. TCR versus grain size for a PVC-graphite thick film resistor.

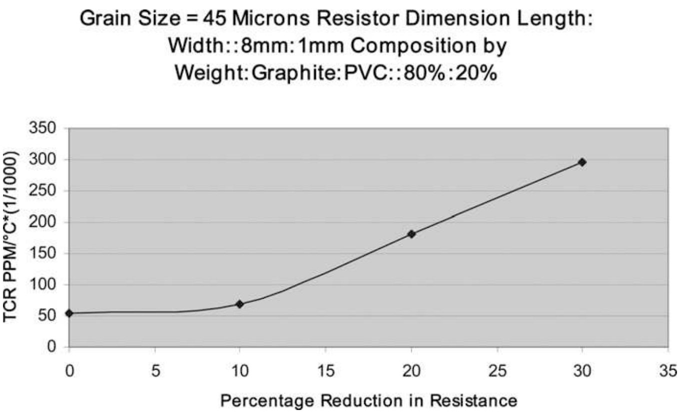

Fig 5. TCR versus high voltage for a PVC-graphite thick film resistor.

noise decreases with volume fraction for a particular grain size. From these observations, it appears that the decrease in current noise in these thick film resistors with increase in volume fraction is due to increase in number of contacts between the conducting particles and the number of conducting chains.

B. Effect of Grain Size on Current Noise

From Fig. 2, the current noise increases with grain size for a particular volume fraction. From Fig. 2, it appears that current noise in these resistors is governed by the number of contacts between the conducting particles.

C. Variation of TCR with Volume Fraction

The TCR with the percentage weight of the conductor (graphite) is shown in Fig. 3. The increase in weight of the conductor in resistor composition indicates an increase in volume fraction of the conductor in polymer thick film resistors. From Fig. 3, it may be seen that the TCR increases with volume fraction for a particular grain size. From these observations, it appears that the increase in TCR in these thick film resistors with an increase in volume fraction is due to the increase in contact resistance between the conducting particles and the number of conducting chains.

D. Effect of Grain Size on TCR

From Fig. 4, the TCR increases with grain size for a particular volume fraction. From Fig. 4, it appears that TCR in these resistors is governed by the contact resistance and the change in contact area between the conducting particles.

E. Variation of TCR with High Voltage

From Fig. 5, it may be seen that the TCR increases with high voltage for particular volume fraction. The variation of TCR with high voltage is due to the change in contact resistance between the conducting particles and the number of conducting chains.

The Model

In order to estimate the changes in current noise and TCR with parameters such as volume fraction and grain size, a model for the structure of polymer thick film resistive material is proposed and the effect of various parameters such as volume fraction and grain size have been evaluated. The following gives an account of this effort.

It has been first assumed that small granules of insulating phases are covered by the particles of the conducting phase, and such elemental cells constitute the entire composite material. For analytical purposes it is assumed that the insulating granules are in the form of cubes, and the conducting particles are distorted spheres. Such elemental cells constitute the entire composite material. This model is sufficient to explain the electrical properties of polymer thick film resistors with low volume fraction of the conducting phase only. This model however fails to explain the variation of electrical properties of polymer thick film resistors with material parameters such as high volume fraction of conducting phase. Polymer thick films contain a large number of cavities. A more realistic picture of a polymer thick film resistor with cavities in the structure has been introduced in order to explain the variation of electrical properties of polymer thick film resistors with a high volume fraction of the conducting phase. It has also been assumed that all the grains are connected in the form of chains and densely packed in the entire polymer thick film structure, except for the cavity.

A typical structure assumed for the material is shown in Fig. 6. It may be seen that the material is a three-dimensional rectangular structure with a spherical cavity at the center of the structure and the spherical conducting graphite grains are densely packed in the remaining part of the structure. The spherical cavity is assumed to have an insulating material with air trapped inside it. For simplicity's sake it is assumed that there is one spherical cavity at the center of the entire structure. Using this model, the variation of current noise and TCR of polymer thick film resistors with parameters such as high volume fraction of conducting phase and grain size has been evaluated. What follows is a brief account of the effort that is put in to arrive at an idea of how the current noise and TCR varies with volume fraction and grain size, and it involves the calculation of current noise and TCR of the material without cavities and with cavities, the calculation of cavity diameter, and finally the effect of grain size was evaluated.

A. Variation of Current Noise with Volume Fraction

First, the current noise of polymer thick film resistors without the cavity was calculated for a given volume fraction of conducting phase and then the current noise of these material with cavities was calculated using a technique similar to the one proposed by Murthy and Satyam [9].

1) Calculation of Current Noise of Thick Film Resistors without Cavities

For the sake of simplicity we carry out the calculations for the structure of polymer thick film resistors is shown in Fig. 6. The length of the sample between the electrode terminals is l and the breadth and thickness are given by b and d. The following assumptions are made.

1. The major part of the conduction takes place through the linking branches in the length direction.
2. The conductor-resistor interface is an ideal contact.

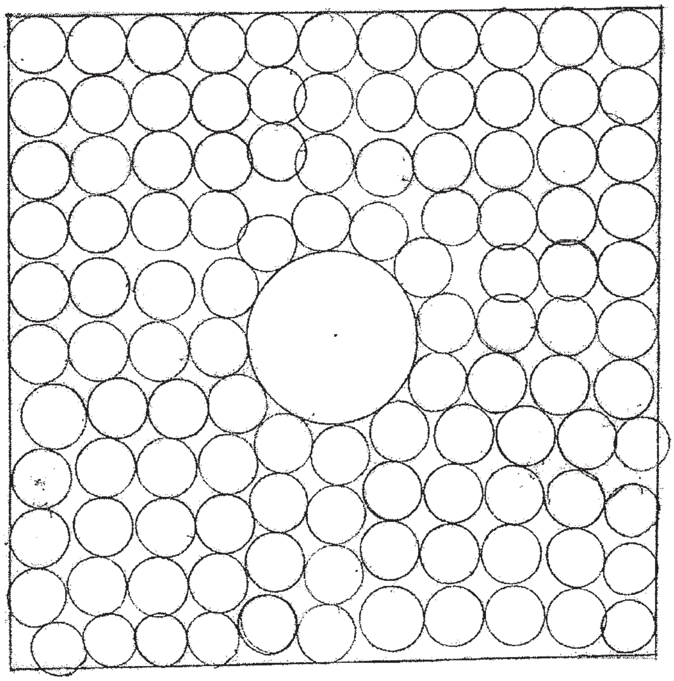

Fig. 6. Cross-sectional view of polymer thick film resistors.

3. The derived noise formula refers to the resistive material between the conductors.
4. The average resistance fluctuations $<(\Delta r/r)^2>$ for all linking branches have the same value.
5. The fluctuations produced for all linking branches are uncorrelated.

It is proposed that the average relative resistance fluctuations between the conducting particles controls the current noise of the thick film resistor. A further assumption is made.

6. The resistance R_0 of the type represented in Fig. 6 by the label 1 are assumed to carry no net current.

The influence of side paths carrying net current can be taken into account by considering $<(\Delta r/r)^2>$ in parallel. In this way, a new $<(\Delta R/R)^2>$ is obtained.

If n is the number of conducting particles in a row extending over a length l, its average resistance fluctuation $<(\Delta R_l/R_l)^2>$ is given by

$$<(\Delta R_l/R_l)^2> = <(\Delta r/r)^2> (n-1) \tag{1}$$

where $<(\Delta r/r)^2>$ is the average resistance fluctuation between two conducting particles. Since $n \gg 1$, $<(\Delta R_l/R_l)^2>$ can also be written as

$$<(\Delta R_l/R_l)^2> = <(\Delta r/r)^2> n \tag{2}$$

When there are n conducting particles in the breadth b, then the average resistance fluctuations of all conducting paths in a conducting layer perpendicular to thickness $<(\Delta R_{ll}/R_{ll})^2>$ is given by

$$<(\Delta R_{ll}/R_{ll})^2> = <(\Delta r/r)^2> n/(n-1) \tag{3}$$

When there are p conducting particles along the direction of thickness d, then the average resistance fluctuation of all conducting layers along the direction of thickness $<(\Delta R/R)^2>$ is given by

$$<(\Delta R/R)^2> = <(\Delta r/r)^2> n/[(n-1)(p-1)] = <(\Delta r/r)^2> n[(n-1)(\mathrm{p}-1)]^{-1} \tag{4}$$

The volume of the conducting phase of the polymer thick film resistor is given by

$$V_g = (4/3)\Pi R^3(l^2/\Pi R^2)(p-1) \tag{5}$$

Where R is the radius of the conducting particle.

The volume of the structure is

$$V_g + V_I = lbd \tag{6}$$

Where V_I is the volume of the insulating phase.

Using eqs. (5) and (6) yields

$$p-1 = 3V_f d/2D \tag{7}$$

where D is the average diameter of the conducting particles, which is also considered as the grain size of the conducting particle, and V_f is the volume fraction of the conducting phase. The value of n can be written as $n = l/D$. Substituting for $(p-1)$ and n in eq. (4):

$$<(\Delta R/R)^2> = <(\Delta r/r)^2> 1/D[(l/D-1)3V_f d/2D]^{-1} \tag{8}$$

The average noise fluctuations between two spherical particles is given by [6]

$$<(\Delta r/r)^2> = (\alpha\Pi^3 r^3 \Delta f)/(20n\rho^3 f) \tag{9}$$

where r is the resistance between two conducting particles, ρ is the resistivity of the conducting particles, n is the free charge carrier concentration, and α is about 2×10^{-3}, $<(\Delta r/r)^2>$ is the average of the squared relative resistance fluctuations observed in a band Δf centered at frequency f.

Note that eq. (8) was derived by considering the total number of contacts that come into the picture for electrical conduction. The total number of contacts has been calculated by considering the number of contacts in a layer and the number of layers between the contacts of the polymer thick film resistors. Writing

$$1/D = 1/k \tag{10}$$

one obtains for the average resistance fluctuation $<(\Delta R/R)^2>$:

$$<(\Delta R/R)^2> = 2/3<(\Delta r/r)^2>Kl[(1-K)V_f]^{-1} \tag{11}$$

Thus eq. (11) can also be written as

$$<(\Delta R/R)^2> = K_0/(1-K)V_f \tag{12}$$

Where $K_0 = 2/3 <(\Delta r/r)^2>Kl$, K being the constant of a material that depends upon the grain size D.

2) Calculation of Current Noise of Polymer Thick Film Resistors with Cavities

The variation in current noise with diameter of the cavity has been calculated following similar lines described by

Murthy and Satyam [4]. The variation of normalized current noise with cavity diameter of polymer thick film resistors was derived from that work. Using this technique, the current noise of the polymer thick film resistor with a cavity was calculated. The calculation of the cavity diameter of the polymer thick film resistor for a particular volume fraction of the conducting phase was already derived in our previous work [8].

B. Effect of Grain Size on Current Noise

The current noise variation with grain size is expected to arise from the change in number of conducting particles in a layer and number of such layers between the electrodes. The current noise increases with increase in grain size for a particular volume fraction is due to both reduction in number of conducting particles in a layer and in number of layers between the electrodes.

C. Variation of TCR with Volume Fraction

First, the TCR of polymer thick film resistors was calculated without a cavity for a given volume fraction of conducting phase. Next, the TCR of the materials with cavities was calculated using a technique similar to that proposed by Murthy and Satyam [9].

1) Calculation of TCR of Thick Film Resistors without Cavities

For the sake of simplicity, we carry out the calculations for the structure of polymer thick film resistors as shown in Fig. 6. The length of the sample between the electrode terminals is l and the breadth and thickness are given by b and d. The following assumptions are made.

1. The major part of the conduction takes place through the linking branches in the length direction.
2. The conductor-resistor interface is an ideal contact.
3. The derived resistivity formula refers to the resistive material between the conductors.
4. The contact resistance R_0 for all linking branches has the same value.
5. The resistance R_0 of the type represented in Fig. 6 by the label 1 is assumed to carry no net current.

The influence of side paths carrying net current can be taken into account by considering R_0 in parallel. In this way, a new R_{eff} is obtained in a procedure similar to that shown in the calculation of current noise in the previous section.

$$R_{\mathrm{eff}} = R_0 l/D[(l/D-1)3V_{\mathrm{f}}d/2D]^{-1} \tag{13}$$

Note that eq. (13) was derived by considering the total number of contacts that come into the picture for electrical conduction. The total number of contacts has been calculated by considering the number of contacts in a layer and the number of layers between the contacts of the polymer thick film resistors.

The resistivity ρ can be shown to be

$$\rho = R_{\mathrm{eff}} l \tag{14}$$

The resistivity variation with temperature is expected to arise from the change contact area between the conducting particles. This change in the contact area arises because of the expansion of the insulating phase between the two conducting particles and can be related to the expansion coefficient of the insulating phase.

Differentiating eq. (14) with respect to temperature we obtain:

$$d\rho/dT = (\rho/R_0)(dR_0/dT) \tag{15}$$

The contact resistance R_0 is given by

$$R_0 = \rho_{\mathrm{g}}/2r \tag{16}$$

where ρ_{g} is the resistivity of the conducting phase and r is the radius of the contact area.

The change in the total volume of the conducting medium per conducting particle is equal to the change in the volume of the interstitial insulating medium per particle and is already calculated by Rajagopal and Satyam [3].

$$V_{\mathrm{I}} = (D-2m)^3 - 4/3\,4R^3 + 6R^3[(1-\mathrm{r}^2/\mathrm{R}^2)^{1/2} - 1/3(1-r^2/R^2)^{3/2} - 2/3] \tag{17}$$

where D is grain size of the conducting particle, $m = r^2/D$, and R is the radius of the conducting particle.

On differentiating eq. (17), it reduces to

$$dV = dV_{\mathrm{I}} = -3(\mathrm{D}-2m)^2 2dm + 6R^3[(-rdr/R^2)(1-r^2/R^2)^{-1/2} - (rdr/R^2)(1-r^2/R^2)^{1/2} \tag{18}$$

$$dV = \nu dV_{\mathrm{I}} dT \tag{19}$$

where ν is the volume coefficient of expansion of the insulating phase.

$$dr/dT = \nu dV_{\mathrm{I}}/\{-3(\mathrm{D}-2m)^2 2dm + 6R^3[(-rdr/R^2)(1-r^2/R^2)^{-1/2} - (rdr/R^2)(1-r^2/R^2)^{1/2}\} \tag{20}$$

Differentiating eq. (20) yields

$$dR_0/dT = -(\rho g/2r^2)dr/dT \tag{21}$$

Finally, from eqs. (10) and (16), we obtain

$$d\rho/dT = (\rho/R_0)(\rho g/2r^2)dr/dT \tag{22}$$

From eq. (17), the variation of resistivity of a polymer thick film resistors with temperature depends on the resistivity of the composite material, the resistivity of the conducting phase, and finally on the radius of the conducting particle.

2) Calculation of TCR of Polymer Thick Film Resistors with Cavities

The variation in TCR with diameter of the cavity was calculated following similar lines described by Murthy and Satyam [1]. The variation of normalized TCR with cavity diameter of polymer thick film resistors was also derived from that work. Using this technique, the TCR of the polymer thick film resistor with a cavity has been calculated. The calculation of cavity diameter of a polymer thick film resistor for a particular volume fraction of conducting phase was already derived in our previous work [5].

B. Effect of Grain Size on TCR

The TCR variation with grain size is expected to arise from the change in contact resistance between the conducting particles that is due to the change in contact area between them. The TCR increases with increase in grain size for a particular volume fraction are due to both reduction in number of conducting particles in a layer and in number of layers between the electrodes.

C. Effect of High Voltage on TCR

The TCR variation with high voltage is expected to arise from the change in contact resistance between the conducting particle, which is due to the change in contact area between them and the change in number of conducting chains. TCR increases with high voltage for a particular grain size and a particular volume fraction is due to both changes in contact resistance between the conducting particles and number of conducting chains.

Conclusions

The variation of current noise and TCR of typical polymer thick film resistors, namely PVC-graphite thick film resistors with parameters such as volume fraction and grain size, has been studied. An expression for the current noise of the polymer thick film resistors in terms of high volume fraction of the conducting phase, grain size of the conducting particles, and the average relative noise fluctuations has been derived. The effect of cavity diameter of polymer thick film resistor on current noise has also been evaluated. The variation of current noise with volume fraction and grain size is due to the change in number of contacts between the conducting particles. An expression for the TCR of the polymer thick film resistors in terms of high volume fraction of the conducting phase, grain size of the conducting particles, and the contact resistance has been derived. The effect of cavity diameter of polymer thick film resistor on TCR has also been evaluated. The variation of TCR with volume fraction and grain size is due to the change in number of contacts between the conducting particles and also due to the change in contact area between them.

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Biography

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Y. Srinivasa Rao received his Ph.D. in Electrical Communication Engineering from Indian Institute of Science, Bangalore in 1998. At present, he is a Senior Associate Professor in the Instrument Technology Department, AU College of Engineering, Andhra University, Visakhapatnam, AP, India. He was with Eritrean Institute of Technology, Asmara, Eritrea for one year on academic assignment. He has 14 years of teaching and research experience, he has completed two major research projects, and he has published 30 research papers in international journals and presented a few of these works at international conferences. He will be Visiting Researcher, Microelectronics Division, EEE Department, Nanyang Technological University, Singpore, for the period of July 1st to December 31st. Awards he has received include the "Emerald Literati Network 2008 Outstanding Paper Award (UK)," the "Best Paper Award," the "Best Student Paper Award," and at the ICSCI International Conference in 2007, he was awarded the "Vignan Pratibha Award—2006" from Andhra University and selected as "Science Researcher" for the Asia-Pacific region in 2005 by UNESCO and the Australian Expert group in Industry Studies (AEGIS) at the University of Western Sydney (UWS); and he received the "Young Scientist Award" from the Department of Science and Technology, Government of India, in 2002. His present research focuses on carbon nanotube electronics, VLSI, and thick film technology. He is a life member of ISTE and member of IMAPS (India).