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$1/f$ noise in polymer thick-film resistors

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Abstract. $1/f$ noise properties of carbon black/polyesterimide and (carbon black + graphite)/polyesterimide thick-film resistors are studied. In resistive inks either high-structure carbon black or medium-structure carbon black was used. The influence of the content p of carbon black and graphite in resistive inks and curing temperature on sheet resistance $R_\square$ and noise intensity C is considered. It is shown that a higher curing temperature causes a decrease in the resistor's volume and influences $R_\square$ and C indirectly, via changes of the parameter p. It is then found that an increase in p leads to a simultaneous decrease of sheet resistance $R_\square$ and noise intensity C. The relation $C \sim (R_\square)^\eta$ is found in this case for all measured resistors. The values of noise exponent η are estimated and a comparison with the noise properties of conventional cermet thick-film resistors is made. It is shown that the noise intensities of carbon black/polyesterimide resistors are comparable to those of cermet resistors.

1. Introduction

Polymer thick-film (PTF) resistors have been used in electronics for almost 40 years. For example these compositions are widely applied as resistive tracks of 'conductive plastic' in precision potentiometers. Low-cost materials are used for their fabrication. Moreover, low-temperature processes decrease energy costs and permit the use of conventional printed circuit boards as substrates with a much larger printing area than the alumina substrates used for high-temperature cermet compositions. It is generally considered that the electrical properties of PTF resistors are not as good as those of RuO_2- or ruthenate-based resistors, so their usage is limited mainly to wide tolerance applications. However, notable progress has been made in this area over recent years (for example as the result of the application of polyimide resin as the insulating matrix) the quality of the best PTF resistors has become comparable to that of average thick-film cermet resistors.

In this paper we present new results of $1/f$ noise investigations performed on carbon black/polyesterimide thick-film resistors. On the one hand these results have practical significance because the noise index is a very important parameter of any resistor and on the other investigations of $1/f$ noise yield additional knowledge about the nature of electronic conduction which takes place in materials from which resistors are fabricated. The latter is still an open question and is an area of extensive research. The paper is organized as follows. In the next section we give details of sample preparation and the noise measurement set-up. In section 3 the results of measurements are presented and compared with data from the literature. The comparison is made both with other polymer thick-film resistors [1] and with conventional cermet thick-film resistors [2–7]. In section 4 we try to answer the question of whether $1/f$ noise phenomena observed in the system like ours may (or may not) be interpreted in terms of existing theories of $1/f$ noise. Our results are summarized in section 5.

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2. Experimental details

The inks used to prepare the sample resistors were composed of different kinds of carbon black (CB) and graphite (G) mixed together with polyesterimide resin. Three systems of inks were prepared. The first system comprised four inks of $p = 9$, 9.5, 11 and 13 vol.% medium-structure carbon black (MSCB). The second system comprised three inks which contained 20, 29 and 36 vol.% of a 50/50 blend of MSCB and flaky graphite (MSCB + G). The third set contained eight inks with 0.4, 0.6, 0.8, 1, 2, 3, 5 and 6.5 vol.% of high-structure carbon black (HSCB) [8, 9]. Resistors of dimensions 5×5 mm^2 were screen printed on alumina substrates onto which Pd–Ag contacts had been previously prepared. The films were then cured in an air-circulating box oven at temperatures of 250 °C, 300 °C or 350 °C. After curing the MSCB and MSCB + G resistors were 15 to 25 μm

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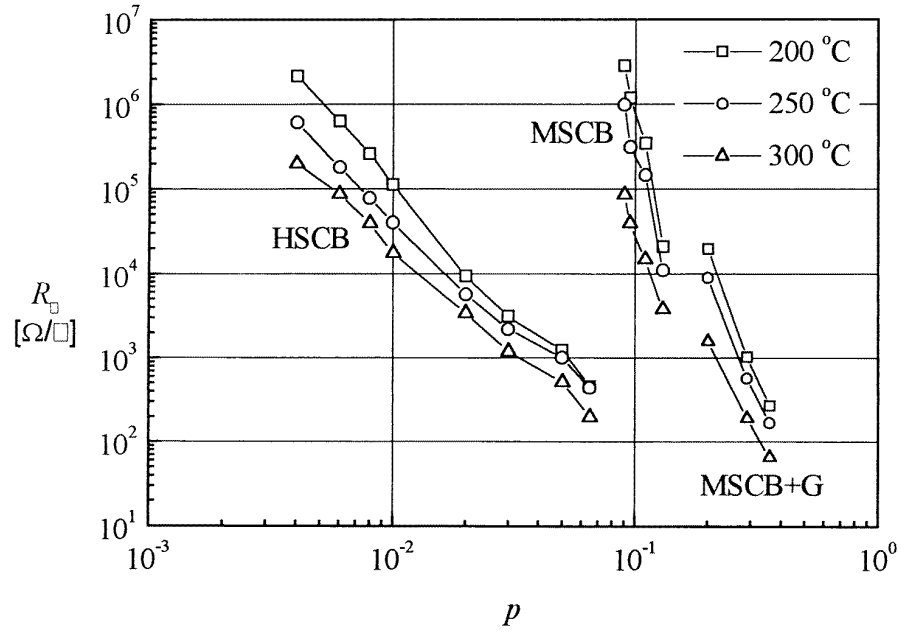

Figure 1. Sheet resistance, $R_\square$ normalized to unique thickness d = 25 μm versus volume content p of carbon black (+ graphite for MSCB + G system) in carbon black/polyesterimide thick-film resistors cured at various temperatures.

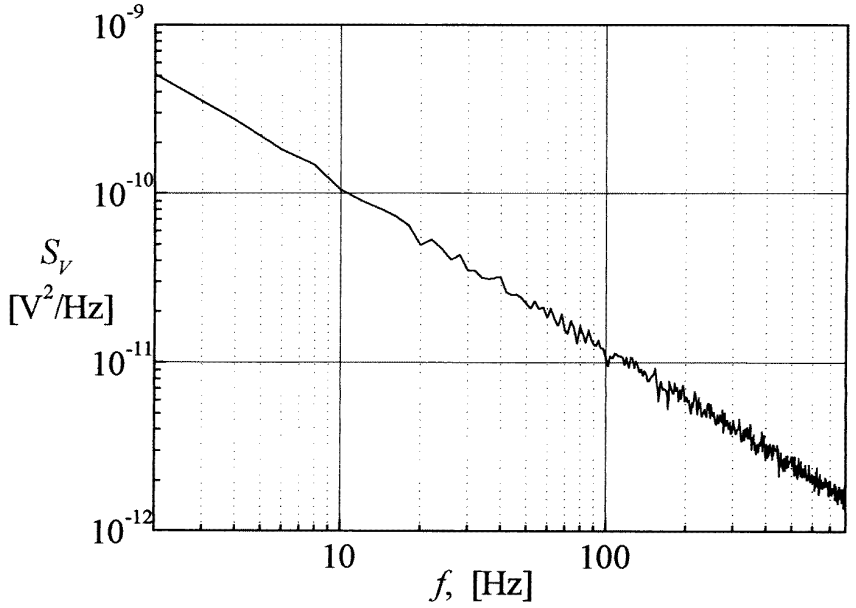

Figure 2. Power spectral density S_V of noise signal δV measured for a PTF resistor of resistance R = 123 kΩ biased by a voltage V = 24 V. In the displayed frequency range the thermal noise level of this resistor, $S_V = 4kTR \simeq 2 \times 10^{-15}$ V^2 Hz^{-1}, is not visible.

thick and the HSCB samples were 10 to 35 μm thick. For each system we observed increasing resistance with decreasing carbon black content. After normalizing to a standard unique thickness of 25 μm the sheet resistance $R_\square$ versus the volume content p of CB or (CB + G) was plotted (figure 1).

Noise measurements were performed using a standard dc technique. A sample resistor of resistance R was biased by a voltage V through a load resistor R_B from a dc source (a stack of Ni–Cd batteries). The noise signal, i.e. fluctuations δV of voltage V, was AC coupled to a wide-band (0.5 Hz–100 kHz) low-noise FET preamplifier. The output of the amplifier was sent to a HP35660A digital signal analyser in which the power spectral density S_V of voltage δV was calculated in the range 2–800 Hz. A typical plot of S_V versus f measured in such a way is shown in figure 2. The line has a slope of approximately -1, which proves that we indeed measured $1/f$ noise.

It was proven in the mid 1970s that the common origin of $1/f$ noise is equilibrium resistance fluctuations [10] and

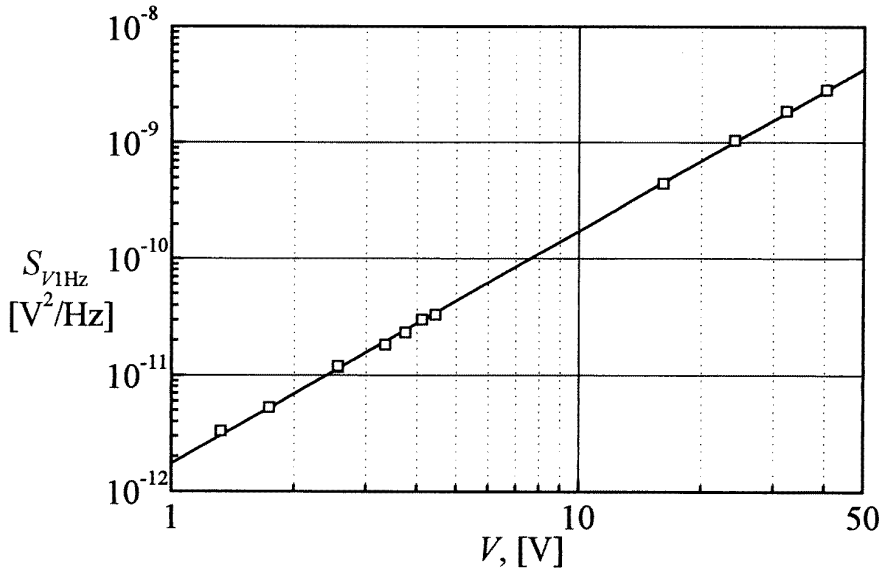

Figure 3. The dependence of power spectral density at frequency 1 Hz, S_{V1Hz}, on biasing voltage V. The data are for resistor R = 123 kΩ. The slope of the approximating line is two.

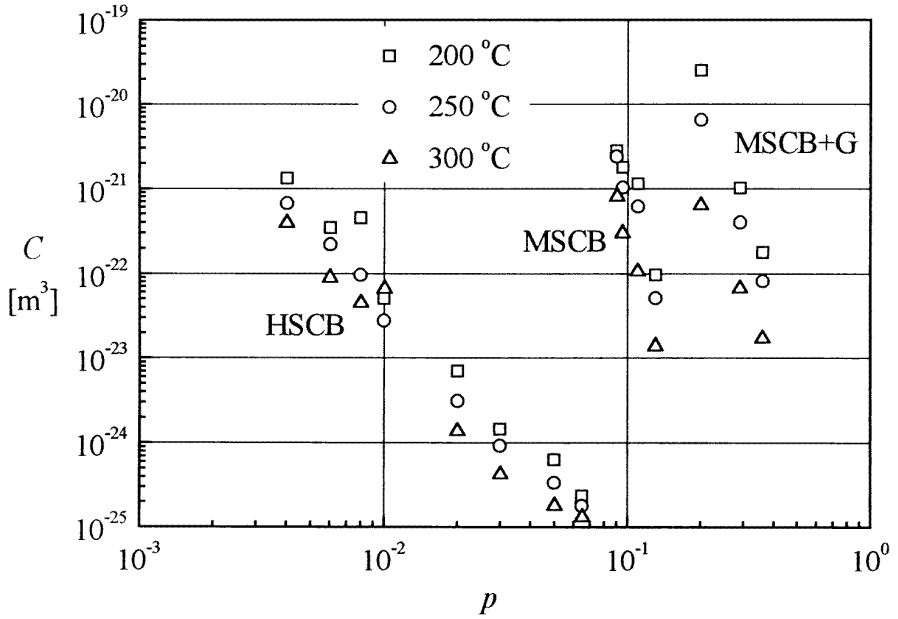

Figure 4. Noise intensity C versus content p of carbon black (+ graphite for MSCB + G system) in carbon black/polyesterimide thick-film resistors cured at various temperatures.

consequently $1/f$ noise is often called resistance noise. The direct conclusion of Ohm's law is then that for resistance noise one should observe the quadratic dependence between biasing voltage V and power spectral density S_V. On the one hand this dependence serves as one possibility to test whether the measured noise is the resistance noise. On the other hand it leads one to the conclusion that the proper quantity that should be used to characterize noisy properties of a resistor is relative power spectral density $S \equiv S_V/V^2$ which is independent of biasing voltage. In figure 3 power spectral densities at $f = 1$ Hz are plotted versus biasing voltage. A quadratic dependence is easily seen and this proves that the noise found in our PTF resistors was in fact resistance noise.

It was also proven in the early 1980s that resistance fluctuations which produce $1/f$ noise are spatially uncorrelated [11]. Obviously, this only holds over some correlation length ξ. However, as long as all sample dimensions L are longer than the length ξ, the lack of correlation between local resistance fluctuations enables calculations of the power spectral density of voltage fluctuations on device terminals to be made. In general, if the electric field E is not uniform inside the resistor (which, for example, happens in trimmed samples) the

power spectral density S_V is given by the following integral over the resistor's volume Ω [12–15]

$$S_V = \frac{C}{f}\frac{1}{I^2\rho^2}\int\int\int E^4\,\mathrm{d}\Omega$$

where I is the current and ρ is resistivity. For a homogeneous electric field (which is the case for our rectangular-shaped resistors) one has $E = V/L$ and consequently

$$S = S_V/V^2 = C/f\Omega$$

which means that the relative power spectral density S is inversely proportional to the sample volume Ω. Careful examination of noise data has confirmed this property for cermet thick-film resistors [16]. In the case of PTF resistors this property has been confirmed only partially [1] because some deviations from a linear dependence on reciprocal volume was found for HSCB PTF resistors. According to Fu *et al* [1] such deviations should be interpreted in terms of composition inhomogeneity of resistive film resulting from interactions with substrates and/or the terminations as well as changes in film thickness.

The general reciprocal dependence of noise level on the sample volume forces one to use the product $S\Omega$ when comparing noisy properties of samples of various geometrical dimensions. This product of course has a $1/f$ frequency dependence and comparisons should be made at the same frequency (say 1 Hz). Alternatively, if power spectral densities are to be measured at different frequencies, one may use the quantity $C \equiv S\Omega f$. Thus, C appears to be the most universal quantity that should be used to characterize noisy properties. In the following we will call C the noise intensity. Figure 4 shows noise intensities measured for the PTF resistors studied in this work.

3. Discussion

$1/f$ noise data are very often presented in the form of C versus $R_\square$ plots. This has the advantage that only clearly (electrically) measurable quantities appear on both axes. Indeed, the content of carbon black (+ graphite) p used in figures 1 and 4 on horizontal axis is in fact the volume fraction of the conducting component in the resistive ink used to fabricate the resistor. But this content may differ from the 'true' volume fraction of carbon black in the resistor, for a number of reasons. Pores may exclude some regions from the conduction process and thus play the role of insulators—the true p in the resistor is then lower than that of the original ink. Another reason is that curing leads to a decrease of the volume of the polymer matrix. It was found experimentally that the higher the curing temperature the thinner the resistor [8, 9]. Thus, resistors cured at lower temperatures have a somewhat enlarged 'true' value of the conducting component volume fraction p. In view of this we must conclude that in fact the values of p in figures 1 and 4 are approximate rather than true values of carbon black volume fraction. Because they were calculated for films cured at 300 °C and on the assumption that there were no pores inside the resistors' bodies. This problem can be easily avoided if one considers noise intensity C as a function of sheet resistance $R_\square$. Both C and $R_\square$ are measured after curing and refer to the true value of p. Consequently the C versus $R_\square$ relation is unique. In figure 5 the data from figures 1 and 4 are redrawn in plots of C versus $R_\square$.

The data for HSCB, MSCB and MSCB + G systems group along different lines independently of curing temperature. One may thus note that, for a given system (say HSCB), the data for resistors with different p values but cured at fixed temperature (say 250 °C) lie approximately on the same line as those for resistors with a fixed value of p (say 0.01) but cured at different temperatures. The conclusion that one may derive from such behaviour is that in fact the change of curing temperature influences the electrical properties of a resistor simply via changes of the volume fraction p of the conducting component in the conductor–insulator mixture. Based on this conclusion we decided to treat the data from a given system altogether and performed a least-square analysis in log–log coordinates of figure 5. The slopes of the (full) lines approximating the data are 1.18 ± 0.05 for the MSCB + G system, 1.12 ± 0.04 for the HSCB system and 0.76 ± 0.07 for MSCB. These numbers represent the values of exponent η in the relation $C \sim (R_\square)^\eta$.

Let us now compare our results with data from other experiments. To our knowledge the only experimental study of $1/f$ noise in model PTF resistors is that carried out by Fu *et al* [1] who studied resistors made of different kinds of carbon black mixed with either epoxy resin or polyimide resin. Their data for samples with a polyimide matrix, recalculated to give noise intensities C, are also shown in figure 5 in the useful form of C versus $R_\square$ plots. As in our experiments the sheet resistance in [1] was changed by the amount of carbon black in resistive inks. Except for the low-resistivity samples this led to a simultaneous increase of both the sheet resistance $R_\square$ and noise intensity C. The mentioned exception was attributed by Fu *et al* [1] to cracks which appeared on surfaces of resistors with a high CB content. The (broken) lines, representing the data for resistors in which no cracks were observed, have the following approximate slopes: 2.4 for the HSCB series, HS 500 (see figure 5(a)); 1.4 for both MSCB series, MA 600 and MA 100 (see figure 5(b)); and 2.1 for #45 series. These slope values are larger than those found for our polyesterimide thick film resistors. Another difference is that Fu *et al* [1] found higher noise intensities for resistors with a higher structure index of carbon black used in original resistive inks. However, as we have already mentioned noise measurements performed on the HS 500 system do not give the correct volume dependence which means that an inaccuracy occurred in their experiment. This conclusion seems to be confirmed if we compare absolute values of noise intensities. For MSCB systems our data and those of Fu *et al* [1] are of the same order of magnitude and group along the same line, as one can see in figure 5(b). This is not true for the HSCB series. It is clearly seen in figure 5(a) that our data are almost two orders of magnitude lower than those of Fu *et al*.

In view of the comparison made in figure 5 the difference between the values of η found for MSCB by

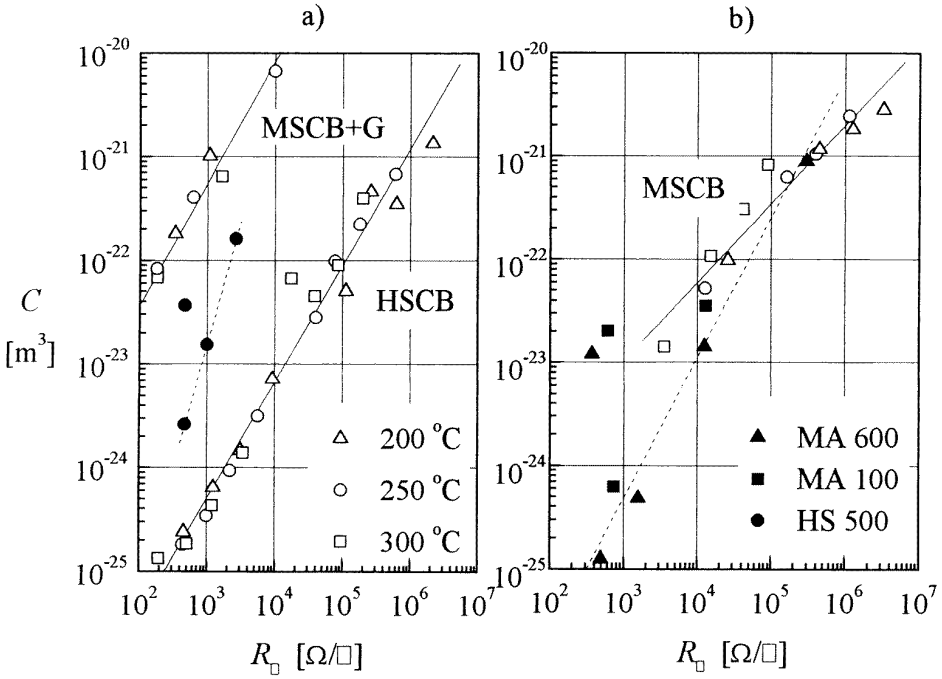

Figure 5. Noise intensity C versus sheet resistance normalized to a film thickness of 25 μm, $R_\square$, of carbon black/polyesterimide (open symbols) and carbon black/polyimide (full symbols) resistors. The full symbols refer to data of Fu *et al* [1] for carbon black/polyimide resistors. The data in (a) and (b) refer to high- and medium-structure carbon black used in resistive inks respectively. (a) also shows our data for the MSCB + G system.

Fu *et al* [1] and by us is not so surprising. As one can see in figure 5(b), in the low-resistance range which is covered by the data of [1] the average value of $\eta \simeq 1.4$ is characteristic. It drops to $\eta \simeq 0.8$ as $R_\square$ crosses over to the high-resistance region covered by our data. No such crossover is observed in figure 5(a) for the HSCB system; $\eta \simeq 1.1$ is characteristic for the whole resistance range.

It is interesting to compare the $1/f$ noise properties of PTF resistors with cermet thick-film resistors. On the one hand $1/f$ has practical meaning since the noise index of a resistor is important in many industrial applications. On the other hand such comparisons may help to answer the question of how to extend the mechanisms responsible for electrical transport in these two kinds of metal–insulator composites. From the latter point of view it is important to consider only 'model' cermet systems with well defined and controlled stages of resistor's fabrication. We therefore must exclude all the commercially available systems because of their hidden technology. Consequently, we limit ourselves to laboratory prepared RuO_2- and ruthenate-based thick-film resistors. Since in most works the dimensions of test resistors are different it is possible to compare only values of the noise exponent η in the C versus $R_\square$ relation. From the data of de Jeu *et al* [2] one may estimate $\eta \simeq 1.3$ for $Pb_3Rh_7O_{15}$-based thick resistive films and 0.6 for $Pb_2Ru_2O_7$ ones (see figure 6 broken lines). Müller and Wolf [7] found $\eta \simeq 1$ for $Bi_2Ru_2O_7$-based resistors. For RuO_2-based resistors from the data of Inokuma *et al* [5] one may estimate $\eta \simeq 0.5$, $\eta \simeq 0.6$ and $\eta \simeq 1.1$ for resistive pastes made of various sizes of glass and/or RuO_2 particles (see figure 6, full lines). Kusy and Szpytma [3] found $\eta \simeq 0.8$ (see figure 6, dash-dot line) and $\eta \simeq 1.5$ for pastes made of RuO_2 particles of average size 10 nm and 300 nm respectively. Finally, for a resistive system made of RuO_2 particles of average size 40 nm, Bobran and Kusy [4] found $\eta \simeq 1.9$ in the low-resistance range and a very weak dependence of noise intensity on sheet resistance in the high-resistance region. Very recently Tamborin *et al* [6] reported $1/f$ noise measurements performed on RuO_2-based model resistors prepared with some glass frit and RuO_2 powders covering a particle size range from a few nanometres up to several micrometres. No systematic correlations were found between noise intensity and RuO_2 grain size in resistors of equivalent sheet resistance. The average value of exponent η that may be deduced from their data is 1.4 (see figure 6, dotted line). In general we may thus conclude that the exponent η lies in the range 0.5–2 for cermet resistive films. Most values of η found for PTF resistors also lie in this range—from the 'η point of view' cermet and PTF resistors thus do not differ significantly.

In some cases it is also possible to compare absolute values of noise intensities. Figure 6 shows the noise intensities of both polymer and cermet resistors. As one can see $1/f$ noise intensities of our polymer resistors from HSCB and MSCB systems are almost never larger than the $1/f$ noise intensities of cermet resistors of equivalent sheet resistance. This is important for practical applications. From the point of view of resistor noise index, polymer resistors provide a completely equivalent substitution of cermet resistors. This conclusion has quite important practical meaning since PTF resistors are much cheaper than cermets. The main reasons for this are that PTF resistors can be fabricated at much lower temperatures and can be printed on a much wider class of substrates.

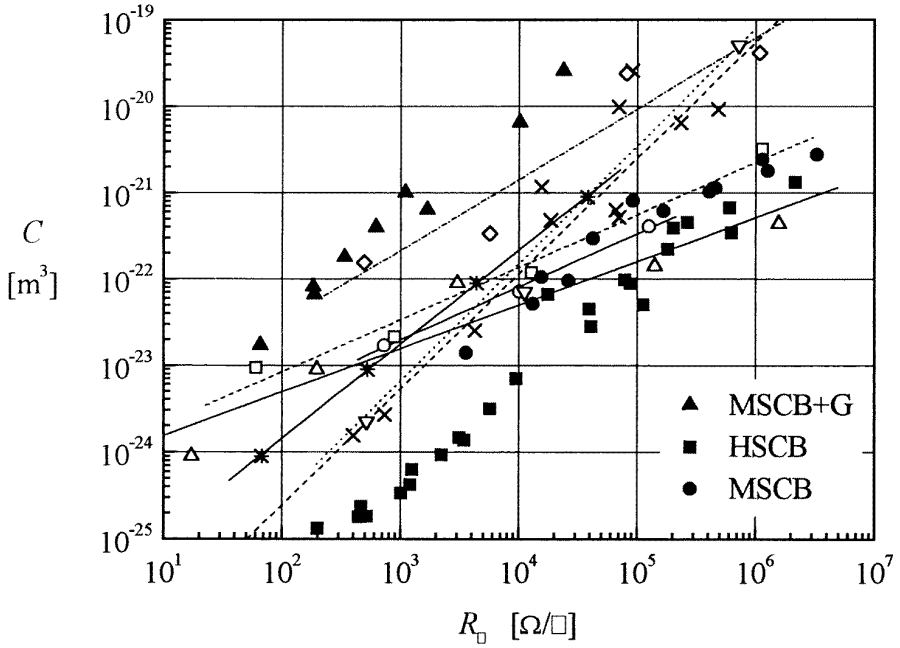

Figure 6. Comparison of $1/f$ noise intensities of polymers (this work, full symbols) and cermet thick-film resistors (open symbols): RuO_2/glass of 10/120 nm particle size [5], up triangles; RuO_2/glass of 3.7/120 nm particle size [5], circles; RuO_2/glass of 3.7/310 nm particle size [5], stars; RuO_2/glass of 30/160 nm particle size [3], diamonds; RuO_2/glass of various RuO_2 particles sizes [6], crosses; $Pb_2Ru_2O_7$/glass [2], squares; $Pb_3Rh_7O_{15}$/glass [2], down triangles. The sheet resistance $R_\square$ on the horizontal axis was normalized to a film thickness of 25 μm.

One should bear in mind, however, that this conclusion is derived for model thick resistive systems. Commercially available inks for cermet resistors contain some noise modifiers (e.g. MnO_2) which make the noise index of a resistor an order of magnitude lower than that for a pure model system. We believe that there are modifiers which could also reduce the noise index in PTF resistors.

Let us now employ some theory to explain $1/f$ noise properties found for our PTF resistors. Our data fit a power-law dependence $C \sim (R_\square)^\eta$ with exponent η equal to 1.12 for a HSCB system, 1.18 for MSCB + G and 0.76 for MSCB. Completing these data with those of Fu *et al* [1] one may expect that for a MSCB system a crossover from $\eta = 1.4$ for a low-$R_\square$ region to $\eta = 0.76$ for a high-$R_\square$ region should be observed. The simplest model that can explain the relation $C \sim (R_\square)^\eta$ in thick-film resistors was proposed by de Jeu *et al* [2] and Wolf *et al* [17]. In this model parallel chains of elementary resistors are responsible for electrical conduction. When spatially uncorrelated fluctuations are attributed to each elementary resistance, simple calculations yield a linear dependence between noise intensity and sheet resistance, i.e. $\eta = 1$ is proposed. Let us note that in this model all the chains are identical and all elementary resistors carry currents of the same value. No disorder is present on any macroscopic scale. It is hardly probable that the conductors are arranged along ordered parallel chains inside a resistor. One rather expects the presence of tortuous multiply convoluted chains, which certainly carry currents of different ampage. Consequently, the chain model is hardly an acceptable explanation of transport processes that take place in thick-film resistors. For the same reason, explanations based on the formula of Hooge *et al* [18] are not acceptable in this case. They are based on the relation $C = \alpha/n$ where α is the so-called Hooge parameter and n the concentration of charge carriers. When combined with Ohm conductivity $\sigma = en\mu$, where μ is the mobility of charge carriers it can be immediately rewritten as $C \sim \sigma^{-1} \sim R_\square$. However, both Hooge's formula and the Ohm conductivity are for homogenous transport and cannot be applied in a system like ours. However, if they are applied they lead to unreasonable physical quantities. For example, the use of such a scheme for bismuth–ruthenate-based thick-film resistors led Peled *et al* [19] to values of charge carrier mobility as high as 400–2000 $cm^2\ V^{-1}\ s^{-1}$, whereas for these kinds of resistors the upper limit of Hall mobility was experimentally found not to exceed 10^{-3}–10^{-2} $cm^2\ V^{-1}\ s^{-1}$ [20].

In view of the above, models which assume the presence of macroscopic disorder are more appropriate to explain our results. The simplest of these is a two-component disordered system. Effective medium approximation applied to such a system again leads to a linear C versus $R_\square$ dependence [21]. Numerical simulations confirm such a dependence in a weak disorder regime. As disorder increases a percolation critical exponent $\eta \simeq 0.8$ is expected [22] (in 3D) rather than $\eta = 1$. Note that a number of cermet as well as polymer resistor systems give exponents which are close to these theoretical values. There are, however, experiments that give values of η as large as two and cannot be explained in terms of a two-component percolation system. In these cases the so-called continuum percolation models can be applied [23] in which special attention is paid to the microscopic details of the disordered system. It was

shown [24] that η values of 2.1 or 2.4 are characteristic for the so-called random void or inverted random void models. The most important conclusion to be derived from the analysis of continuum percolation models is that some percolation critical exponents (for example exponent η) are micro-geometry sensitive. Consequently, one may expect that the different values of η found for polymer and/or cermet resistor are caused by microscopic details of the composite systems, which are formed during resistor fabrication. Thus, it seems that continuum percolation theory gives an explanation of the dependence $C \sim (R_\square)^\eta$ which has been found in many experiments on thick-film resistors. However, this dependence reflects only the influence of the metal volume fraction on the noise intensity. If sheet resistance is varied by another parameter, say the grain size, the exponent in the C versus $R_\square$ relation may be quite different. It is also important to note that although the percolation theory is used to explain our $C \sim (R_\square)^\eta$ dependence, it does not mean that microscopic mechanisms that are involved in electrical transport are described definitely. Metallic conduction, thermally activated tunnelling [20], metallic contacts in either Maxwell or Sharvin regimes [25] and fluctuation induced tunnelling [26] are examples of microscopic mechanisms that can occur in carbon black grain-to-grain (or aggregate-to-aggregate) interfaces. Interestingly, if a Sharvin-type contact is assumed as a microscopic mechanism between carbon black grains in a two-component model, the crossover observed on C versus $R_\square$ plots for MSCB systems can be explained. The low-resistance region in such plots refers to weak disorder where the effective medium theory works well. An exponent $\eta = 1$ seems to be expected. However, the distribution of contact diameters changes the value of η to 1.5; this was shown by use of the effective medium approximation in [25], where Sharvin-type contacts were proposed to appear in polymer–copper-particle composites. Thus, the value $\eta \simeq 1.4$ found in the low-resistance region of figure 5(b) can be explained. The high-resistance region in figure 5(b) corresponds to large disorder. In this region the value $\eta \simeq 0.8$—the ordinary critical exponent in two-component percolation—is expected. Of course, this picture should be regarded as one possible explanation rather than rigorous proof that Sharvin-type contacts appear in MSCB-polymer systems. More systematic studies to cover more than noise properties are needed to prove the latter point. For example more knowledge about microscopic mechanisms could be gained from studying the influence of temperature and/or magnetic field on various resistor parameters.

4. Summary

$1/f$ properties of carbon black/polyesterimide and (carbon black + graphite)/polyesterimide thick-film resistors have been studied. It has been shown that the noise intensity of carbon black/polyesterimide resistors is almost always lower than that of model cermet thick-film resistors of equivalent sheet resistance. On the contrary the noise intensity of (carbon black + graphite)/polyesterimide resistors was found to be more than two orders of magnitude larger than the noise intensity of polyesterimide/carbon black resistors and usually also larger than the noise intensity of cermet resistors. It was also noted that if the sheet resistance is varied by the content p of carbon black in resistive inks both the sheet resistance $R_\square$ and noise intensity C increase. The relation $C \sim (R_\square)^\eta$ was found for this case. The values of noise exponent η estimated by reconciling experimental data to this equation are 1.12 for high-structure carbon black and 0.76 for medium-structure carbon black. Such behaviour may be interpreted in terms of percolation transport through the disordered structure of a composite resistor.

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