ON POSSIBILITIES OF SYNTHESIS OF A USEFUL MODEL OF THICK FILM COMPONENTS

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Received 21 March 1983; in final form 6 February 1984)

The problems in forming a useful model of a thick film component have been analysed. The need for such a model has been shown. Common features of thick film structures have been defined and, using the example of resistive film models that have been presented by previous authors, the trends in thick film structure modelling have been shown. Limitations of previous models have been described and, using the example of thick film resistors, the components of structure which should be taken into consideration in a complete model have been compiled. The problems in dealing with model verification, especially with regard to the choice of the criteria of quality and also in the choice of the measuring methods for obtaining component characteristics together with the values of the structural parameters, have been presented. Possible stages in the formation process of such a model and also research directions which could improve the process have been suggested.

1. INTRODUCTION

The application of thick film technology has been continuously expanding and this is possibly due to both the development of precise screen printing and also the improvement of thick film properties. The improvement of the electrical properties has been due to the enlargement of the useful range of the electrical parameters so that the films can be used to realise new functions in microcircuits. At present there are two trends in technological research which are resulting in an increase in the areas of applicability of thick films. One of them is concerned with improvement of the hitherto known materials while the other one is concerned with the search for new materials. This latter makes possible the preparation of films with distinctly better or new properties to those previously used. Also a reduction in the cost of production of present materials with existing properties is being obtained. In this last aspect, the development of new low cost pastes, based on base powder materials that are easily available, plays an important part. A typical example is that of resistive thick films. In the nineteen sixties pastes based on palladium and silver powders were used for the production of resistors. The properties of these materials were optimized for a certain resistance range.[1-3] At the same time research into new materials was being carried out and at the beginning of the nineteen seventies success was achieved. Resistive pastes based on conductive ruthenium oxides[4,5] were evolved and their properties were better than those based on palladium-silver. These pastes are still being improved[6,-8] but simultaneously, the investigations of new systems are being carried out.[9,10]

Development processes similar to those mentioned above have also taken place in other type of thick films which function as conductors, dielectrics, voltage variable resistors, photoresistors[10] etc. The resultant materials are demonstrated in pastes catalogues published by the producers (e.g. Du Pont Company and DeNumours[8]) who enlarge the range of the pastes offered every year.

Generally, the process of making paste compositions is relatively easy. It consists in mixing a few or at the most a dozen or so powder components (with grain sizes typically below 5 micrometers) and then, or possibly during the mixing of powders, adding an organic vehicle into the powder mixture. The fundamental powder components of the paste are glass powder together with crystalline powders of the active media. This latter can be conductive dielectric or semiconductor according to the type of paste. Other

powders at low weight % of the whole, which are called modifiers, need to be added to the pastes. These are important in enhancing specific paramters of the composition. Modifiers change the glass properties during the firing process[12,13] and they are also found to influence crystallinity.[4,7] The essence of the elaboration of a satisfactory paste, that is one which can give the required properties to the thick film component that is made from it, is related to the answer to questions as to what types of powders are used, what grain sizes distributions are involved, in what proportion they are mixed and, finally, under what technological conditions the thick film components are prepared. Up to the present all research into the relationship between the properties of the thick film component and that of paste has been carried out in a purely empirical manner using previously known premises or rules, and rarely with the use of models which explain thick film behaviour.

For characterization of the basic physico-chemical properties of a powder, a few of the parameters and characteristics must be fixed, if only approximately. For the technological processes involved, i.e. screen printing and firing, it is necessary to describe these by several parameters. Therefore, taking into consideration the number of powders in any system, together with their proportions in the pastes, it is obvious that a large number of variables and combinations of variables are obtained. Thus the optimization of new powder systems is time-consuming and consists of the investigation of a great number of pastes with properly determined compositions and a large number of trials made from each of the pastes. Since the requirements imposed by microcircuit designers on thick film components is becoming more and more demanding, the research is becoming more time consuming and more expensive.

The future alternative to the classical way of elaborating thick film materials could be the modelling of the thick film structures. Together with computer-aids this should result in a reduction in the time required to optimize thick film component properties. For this purpose an exact model of component structure needs to be worked out, i.e. a physical model must be constructed. Subsequently a mathematical model involving as many variables as possible needs to be evolved. Such a model, called in further paragraphs a full model, can be used for the optimization or programming of paste compositions and of the values of the technological process parameters. The elaboration of the full model will make possible a wide simulation of the physical phenomena occurring in thick film structures. It is possible that such a model could be used for research into the properties of other heterogeneous materials.

There are two aims in the present paper. Firstly an attempt is made to give an answer to the question as to whether it is possible to create a full model of a thick film component using hitherto existing results of both structure and conduction mechanisms. Secondly, the directions of future investigations are indicated which would help in the formation of such models.

2.   COMMON FEATURES OF THICK FILM STRUCTURES

Results of investigations into the structure and conduction mechanisms of various types of thick film components[2,3,6,7,9,11−25] have shown that independently of the functions the components are required to realise in the microcircuits, there are certain common features. The following properties can be included in these features:−

1. Thick film materials are mainly multi phase ceramics with a high degree of dispersion in the media. They are composite materials with the following microstructure. The crystalline grains of conductive dielectric or semiconductive material, with an average grain size ranging from some tens of angstroms to some tens of microns, are dispersed in a glass matrix. This matrix joins the crystalline grains together into one system on the ceramic substrate.

2. In the majority of applications of thick films an alumina ceramic substrate (96–99% Al_2O_3) with a thickness from 0.5 to 1mm is used. The thickness of the films themselves are usually in the range 10–50 microns, although in some applications, particularly those involving dielectrics and varistors, the thickness may reach 150 microns.

3. Pores or voids are present as an important component of the thick film structure. Their volume fraction can be considerable but in general does not usually exceed values of 0.35 to 0.4.[6,7] The shapes and sizes of the pores can change within wide limits, but even the greatest sizes are usually less than the thicknesses of the films themselves.

4. There is no sharp interface between the film and the alumina substrate. This is because, during the firing process, glass in the film, once it has melted, will dissolve the surface of the substrate thus allowing components of the substrate to diffuse into the film itself. Thus a transitional region is created, the thickness of which is governed by the conditions of preparation that can reach values of more than 10 microns.[12,23,26]

5. The crystalline grains are in random contact with each other and it is possible to form necks between the grains during the sintering process. Alternately the crystalline conducting grains are separated from one another by a glass film of variable thickness. The proportion of grains that are contacting one another by the formation of necks increases with the percentage of crystalline media in the film matrix — a phenomena which is particularly observable in studies on resistive and conductive films.

6. The dispersion of the crystalline media in the film volume is not perfectly homogeneous and, on a micro scale, there can be observed regions where concentration of crystalline grains is greater than in other regions. However the sizes of these concentration regions does not usually exceed 10 to 20 microns.

7. The materials of the contact films will themselves diffuse and dissolve into the film glass. This will create regions near the contacts where the microstructure and electrical properties of the film is modified.

In figure 1 several planar schematic approximations of the structure of different thick film types are presented. These show the mutual arrangement of the phases which go to form the thick film component and demonstrate some of the features mentioned in items 1–7 above.

Basic characteristics of thick film components possess a considerable number of common features. These can best be illustrated by reference to the properties of thick film resistors since these are most easily investigated. Important characteristics have specific shapes that are vital to the resistor applications. These can be identified as:–

(i) Current-voltage relationship. I(V). These characteristics show voltage non linearity, i.e. dependence of the characteristic slope on the applied voltage.[7,19,27−30] Included in these characteristics is the dependence on current density, on electric field, resistance or conductance on voltage, and the resistivity or conductivity on electric field.

(ii) Resistance-temperature R(T). This is the dependence of resistance on temperature, sometimes referred to in terms of the temperature coefficient of resistance.[7,15,19,22,31,32]

(iii) Current noise, G(I, f), as a function of frequency and of current. G(I, f). This indicates the dependence of the noise on frequency (f), and on current (I), flowing in the element. The current function is usually measured in the low frequency range $f < 10$ kHz.
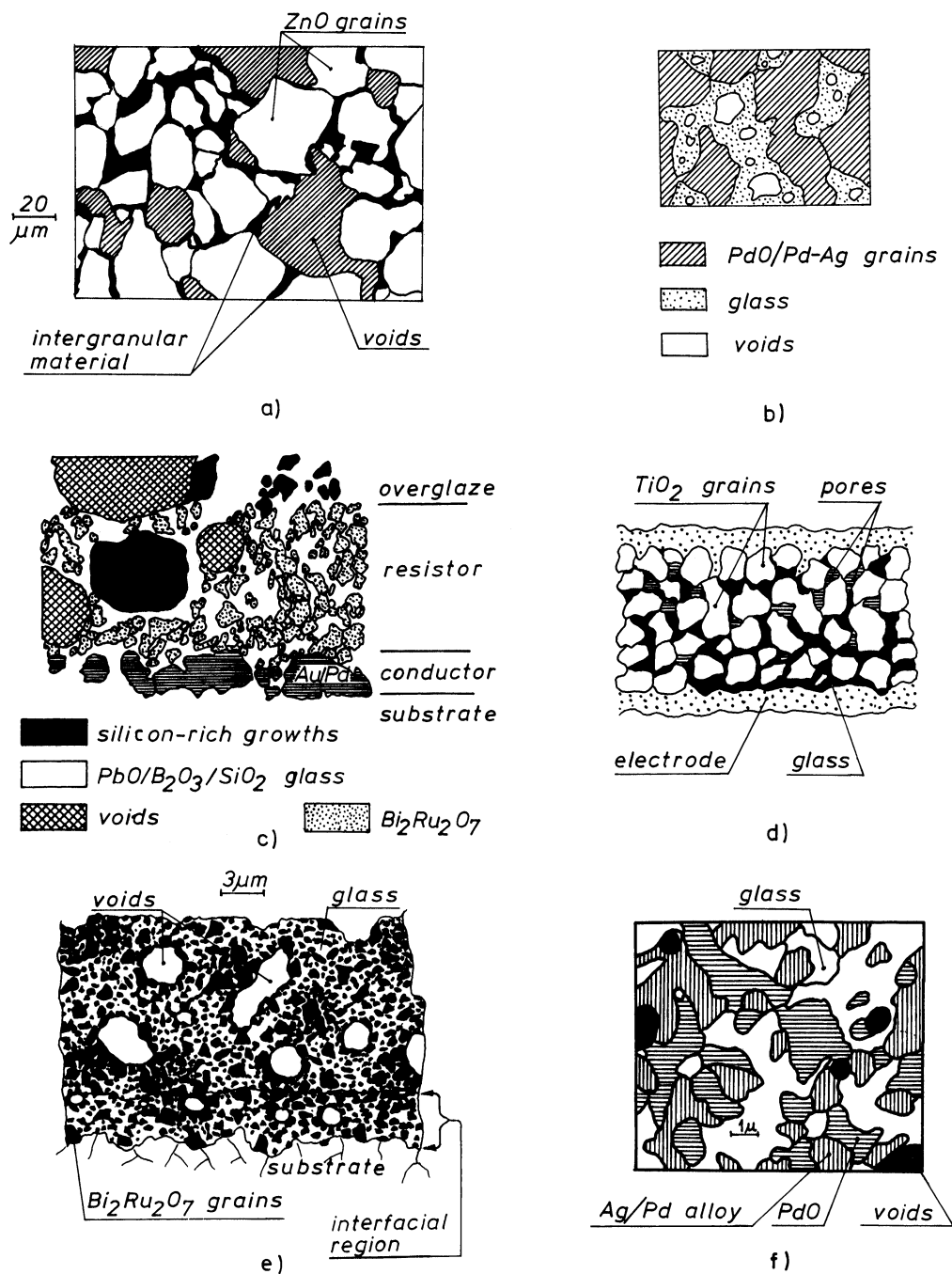
FIGURE 1   Schematic distribution of the major constituent media in some thick film structures:– (a) in varistor film,[25] (b) in resistive film, PdO/Pd-Ag type,[3] (c) across conductor resistor overglaze interfaces in Du Pont 1100 type,[24] (d) in dielectric film,[6,17] (e) in resistive ruthenate film,[7] (f) in resistive film Pd-Ag, Du Pont 7800 type.[24]
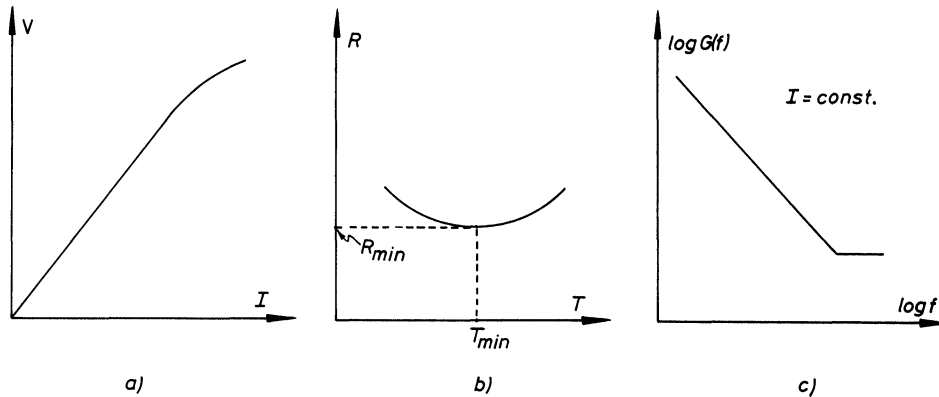
FIGURE 2 Typical shapes of some thick film-resistor characteristics: (a) current-voltage I(V), (b) temperature R(T), (c) noise density G(f).

Typical values of the characteristic discussed above are shown in figure 2.

The greater the value of the sheet resistivity (R_s), which results from increases in the volume fraction of glass in the film, the greater is the voltage non linearity of the I(V) resistor characteristics (cf figure 2a). Irreversible changes of resistance can occur according to the range of the supply voltage used and the measuring method applied. For high values of R_s (i.e. $R_s > 100K\Omega/sq$), the resistance decreases with voltage increase. However, in the case of resistors with low values of sheet resistivity ($R_s < 10K\Omega/sq$), non linearity is practically negligible at least up to a critical value of voltage. Above this critical voltage irreversible changes of resistance occur, changes which, depending on the type of material and the measuring pulse parameters, can be both positive, (i.e. increase of resistance) as is generally observed in resistors using conducting ruthenium oxides, or negative.[34] The occurence of this phenomena testifies to the complicated nature of the thick film resistor conducting mechanism and shows that it must be composed of at least two basic mechanisms in which both the conductive medium and the glass take part. The irreversible changes of resistance occurring above the critical voltage values show that energy barriers exist in the resistor structure which determine the current passage and these can be destroyed or changed by the application of a strong electrical field.

With regard to the resistance-temperature characteristics, thick film materials are almost unparalleled in having minima (cf figure 2b), at temperatures generally lying in the range 100K–500K. The temperature, T_m in, at which the resistance is a minimum, depends, among other things on:–

(a) The type and contents of the modifier used.[7,35]

(b) The type of substrate employed.[32]

(c) The parameters of the firing process.[7]

(d) The type of contact films used.[20]

(e) The resistor sizes.[20]

Up to date no influence has been found of external stresses on the minimum temperature value, T_{min}.[37]

The noise characteristics of thick film resistors at low frequency can be approximated by the formulae[33]:–

$$G(f, I) = cf^{-\nu} I^{\alpha}$$

where v and α are constants equal to approximately 1 and 2 respectively, and c is a material constant.

Thus, the noise existing in thick film resistors is typical $1/f$ noise, common in electronic components during the passage of current. However in thick film resistors the level is rather high and increases with sheet resistivity increase.

Other characteristics of thick film resistors also possess many common features. For example, resistance dependence on stresses $R(\sigma)$, which is linear below destructive stress, with tension stresses causing resistance increase.[37,26,37,38] The slope of this characteristic depends on the type of resistor and its sheet resistivity. This phenomenon makes the use of thick film resistors as strain gauges and pressure transducers[39] possible.

Similar specification of common properties of characteristics could be done for other types of thick film components which are used in other functions in microcircuits, e.g. varistors or thermistors. However the number of papers published in these areas is considerably smaller than the number of the papers dealing with thick film resistors and conductors.

Generalization concerning all types of thick film components and their basic electrical characteristics should be possible. Since future development of films with other electrical properties, one ought to expect that the interest in them as well as the knowledge about them will constantly increase.

3. MODELS OF THICK FILM STRUCTURES

Up till now many simple physical and mathematical models of thick film structures have been worked out. Models elaborated for other heterogeneous materials have also been adopted for this purpose. Since most of the models concern descriptions of thick film resistor properties, the field and trends of hitherto existing models will be discussed using the example of this group of models. In Figure 3 some of the most useful models for thick film resistor microstructure are summarized.

3.1 Percolation Models

Figures 3a and 3b show examples of resistive film models built for describing the $R_s(v)$ characteristic (or $\rho(v)$, where ρ — resistivity of the film), where v is the volume fraction of the conductive medium. These models use percolation theory. The model of a two-phase random mixture of conductive and nonconductive media (Figure 3a) gave a dependence $R_s(v)$ whose generalized form (with the band — percolation approach) is given by[16,40,41]:–

$$R_s(v) = R_{so}(v - v_c)^{-h} \qquad (\text{for } v > v_c). \qquad (1)$$

where R_{so}, v_c, h are parameters whose values depend on the type of material and the technological process. Approximations of the $R_s(v)$ characteristic of different types of thick film resistors using formula (1), show that, practically, h varies between 2 and 5 and $v_c > 0.02$, although in percolative systems h ought to be constant and equal $h \cong 1.7$. Analytical dependences between the model parameters and the structure parameters of the film have not been found to date though some quantitative dependences are known. It is known for example that the smaller the average grain size of the conductive medium, the smaller v_c.

Ewen's and Robertson's model[42] (Figure 3b) takes into consideration the segregation of the media in the thick film resistor structures caused especially by the considerable differences between the sizes of the conductive and the glass grains in the pastes and by
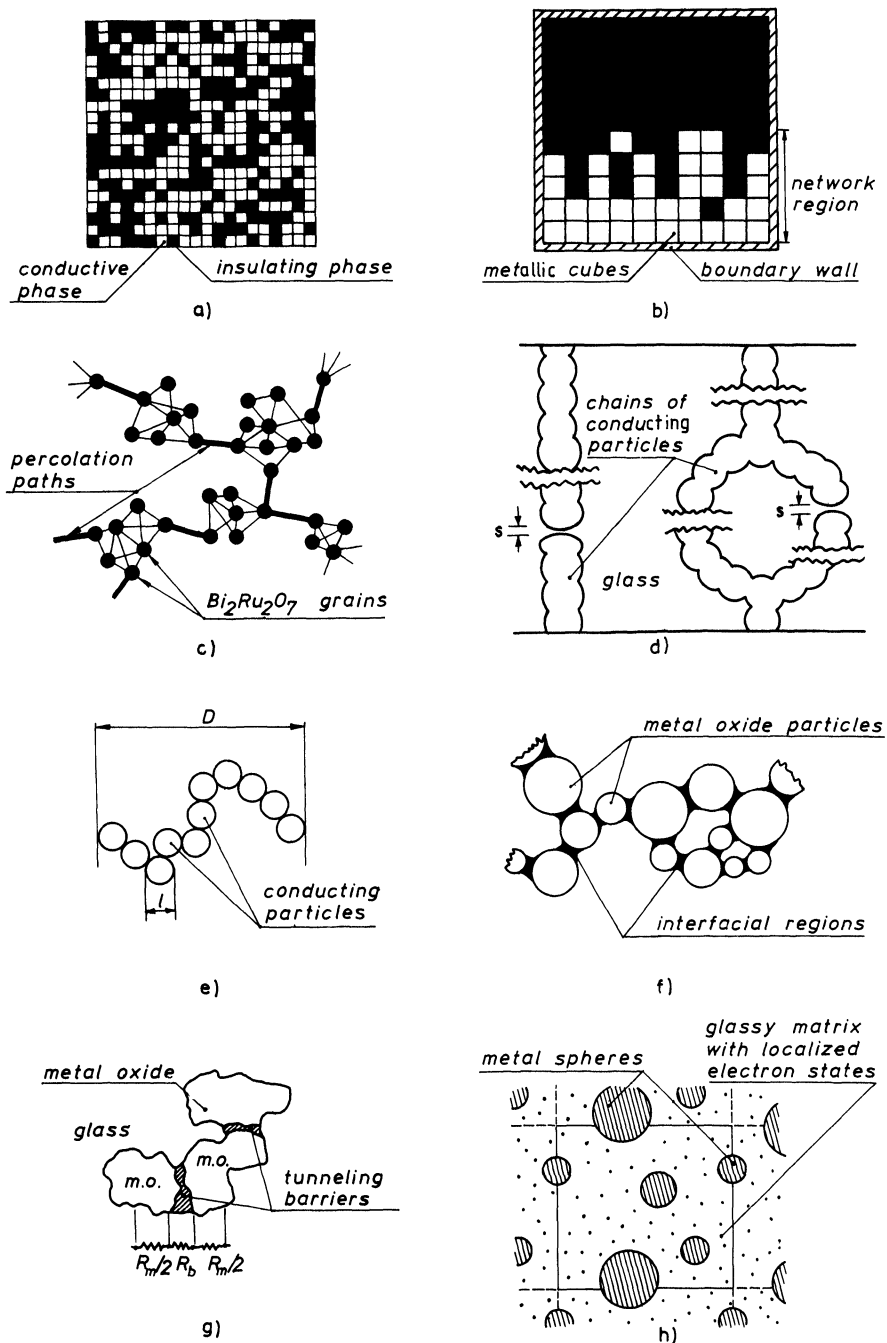
FIGURE 3 Some models of resistive thick film: (a) percolation model;[16,40,41] (b) percolation model;[42] (c) percolation model;[20] (d) conducting chain model;[43] (e) conducting chain model;[45,46] (f) model with tunnelling barrier;[27] (g) model with tunnelling barrier;[14] (h) model based on hopping conduction.[31]

such phenomena as glass melting, media re-arrangement processes, influence of surface tensions, etc.[43] that occur during the forming of the film structure. Analysing this model, the authors obtained a general formula for $\rho(v)$ in the form:-

$$\rho = \frac{\rho_0}{[(\{v/[f_m(1 - f_g)]\}^n + p_c^n)^{1/n} - p_c]^{1.7}} \qquad (2)$$

where ρ_0, f_m, f_g, p_c, n are parameters depending on the powders system and the technological process. p_c means the probability of percolation threshold (for a square lattice, $p_c = 0.59$). The parameter n, varying from 1 to ∞, and parameters f_g and f_m are segregation coefficients of the nonconductive and the conductive media respectively. Taking $p_c = 0.24$ (for randomly packed spheres) the authors showed that formula (2) was a good approximation to the real characteristics, $\rho(v)$, of the conductive and the nonconductive media mixture and thus of the resistive films. Physical interpretation of the model parameters shows that there will be a possible analytical dependence of the parameters f_m, f_g, ρ_0 on the thick film structure. However this seems less probable for the parameter n as it is variable over such a wide range. Interpretation of ρ_0 as an effective resistivity of a so-called complex particle of the film involved in conduction (taking into consideration the thin layer of surrounding glass as its influence on the contact resistance of the grains) is very interesting but there are definite relations with any real film stsructure. Smith's and Anderson's research[44] in this field, with the use of effective medium theory, may resolve the situation.

Figure 3c[20] shows some exact models of resistor networks existing in thick film resistor structures which consists of groups of conductive grains with purely ohmic contact between them, of grains or groups of grains in electrical contact with contact resistances having a non-zero value and of grains or groups of grains with high resistance contacts. The resistance of the percolation paths dominates the resistance of the network. Relatively low contact resistances are due to electron tunneling between the adjacent grains. The authors did not attempt to give a mathematical description of this model but utilized it for quantitative interpretation of some observed resistor properties.

3.2 Model of Conductive Chains

In Figures 3d and 3e models of resistive film microstructure, assuming the existence of conductive particle chains in a film, are presented. Possible forms of such conductive chains are shown in Fig. 3d.[43] There are chains with both linear and loop configurations. Chains are composed of segments with ohmic contacts between conductive particles and also of ones where the conductive particles are insulated by a very thin glass layer with thickness s. The author assumes that in the real structure there are two types of contacts with the glass film. Some with small values of s are characterized by tunnel conduction, the others with high values of s possess conduction mechanisms the same as in glass. Based on this, the author has obtained a good agreement between the parameters of resistors using ruthenium dioxide, particularly with regard to the temperature coefficients of resistance (TCR).

In Figure 3c a model of random conducting chains composed of identical particles is shown. Kusy[45] based on Scarisbrick's research,[46] deduced an expression for $\rho(v)$ for thick film resistors such that:-

$$\rho = \frac{\rho_c}{v \, v^{\phi(k,m)v^{-2/3}} \, L(v)^2} \qquad (3)$$

where ρ_c is the conducting phase resistivity, $\phi(k, m) = 3(km)^{2/3}/(1+k^2+m^2)$ is the so-called order function whose value depends on k and m parameters and can lie in the

range from 1 to 0 according to the film microstructure, and L(v) is the parameter defined by the equation $3L^2 - 2L^3 = v$.

The characteristics of $| \rho(v) |$ for thick resistive films of types, Pd-Ag, and Bi-ruthenate, could be approximated by formula (3) for variable v in the range from 0.08 to 0.55. It is characteristic for this model that all the parameters have reliable physical interpretations and correlate with real parameters of resistor microstructure.[43,45]

3.3 Models with Tunnelling Type Barriers

Many authors who investigate the conduction mechanism of thick resistive films base their interpretation of observed properties on models in which the fundamental assumption is the existence of tunnelling type barriers between grains of conductive medium. In Fig. 3f[27] is shown such a model of resistor structure network segments. It is characterized by spherical conductive particle with various sizes and by interparticle regions which condition the conduction mechanism.

The model shown in Figure 3g[14] is similar in character. It considers a varietay of conductive particles shapes and because of that is more general.

The models shown, with intergrain barriers, were used with good results for interpretation of some resistors characteristics, particularly the dependences of resistance on temperature and on electrical field intensity for films with high values of sheet resistivity.

3.4 Other Models

As an example of the model formed for the interpretation of the shape of one particular resistor characteristics, namely conductivity dependence on temperature, is the model shown in Figure 3h.[31] In a certain range of concentrations of metallic grains and postulating localized energy states in the glass together with hopping conduction between the metallic grains and localized states (an assumption), the authors obtained, with computer-aid, a maximum in conductivity as a function of temperature. Since, in making the computations, arbitrary values of several parameters were taken without comparison with the real parameters of the resistor structure. It is difficult to estimate the quality and usefulness of the model.

There are a number of papers published in which some of the earlier models, suitably modified, are utilized to give a description of resistor properties observed. An example of such a model is given in Thust's[47] paper where the description of the dependence of thick film resistor impedance on frequency depends on the model of conducting particle chains which was used. The model was expanded by involving intergrain capacitances and conductive grains inductances.

4. LIMITATIONS OF THE EXISTING THICK FILM MODELS

All thick film models to date, independent of the type of film, can approximate or interpret at the most only two characteristics of a film, with severely limited technological process parameters or with their invariability. The parameters in analytical expressions obtained often do not have any clear relations to the parameters of the real film structure. The existing dependences are usually qualitative without concrete analytical expressions. Mathematical models of thick film formed up to the present are based on very simplified models of the film structure. Mostly the homogeneity of the film in volume and the infinity of its sizes are assumed without taking into consideration many important aspects of the microstructure which have allowed the film to become a useful component of a thick film microcircuit.

Comparison of the most important components of thick film components microstructure with previous resistive film models allows one to note that present models generally do not take into account the following:-

(i) pores are the third most important component of the film besides the crystalline and glass media,

(ii) the transitional region between the proper film and the substrate, whose properties can be diametrically opposed to the film properties and the thickness of the region can be comparable with the thickness of the film.

(iii) the substrate and its influence, particularly with regard to the state of internal stress in the film,

(iv) regions of the film in which the influence of the contact film which diffuses into the film is observable,

(v) the average sizes of crystalline grains and the distributions of its sizes and the shapes.

The influence of the above factors on the thick film comopnent properties and the quality of models will be analysed using the example of the thick film resistors, although this analysis has in many aspects a more general application and can be related to other thick film components.

4.1 Pores and their Importance

Investigations of multiphase ceramic materials to which class thick film resistors belong, show that the pores existing in these structures possess an important influence on their mechanical properties and because they cause discharge of internal stresses occuring in the materials, they generally change the elastic modulus (E). This influence can be described by the general expression[48,49]

$$E = E_o(v, E_c, E_g) \exp(-mv_p) \tag{4}$$

where E_o is the elastic modulus of the nonporous film, m is a material constant, (typically m ranges from 4 to 7), E_c, E_g are elastic moduli of the conductive medium and glass respectively, and v_p is pore volume fraction in the film.

The research done by the author by the method of analysis of polished film surface photos[50] shows that dependence of pores volume fraction, v_p, in resistive ruthenate films on ruthenium volume fraction, v_r, is given by:-

$$v_p = a(v_r)^2 \tag{5}$$

where a is a constant dependent on the technological process and having for the investigated system values between 0.5 and 1.2, while v_r was estimated analytically with the assumption $v_p = 0$.

Equation (5) shows that the calculation of the film resistivity, $\rho(v_r)$, based on sheet resistivity (R_s) and average thickness ($\overline{d}$), ($\rho = R_s\overline{d}$) measured, when disregarding pore volume fraction, causes an error of some tens per cent, independently of other possible errors of the models built for this characteristic description. Inserting equation (5) into equation (4) we obtain

$$E = E_o(v_r, E_r, E_g) \exp(-mav_r^2) \tag{6}$$

This equation shows that the elastic modulus of the film, with weak E_o dependence on

v_r, decreases with v_r increase. This means that in the films with low sheet resistivities, (i.e. high values of v_r), the state of stress will considerably differ from the state of stress in films with high sheet resistivities. Similarly influence of pore volume fraction on the other mechanical properties of the film, e.g. strength, could be analysed.

Up to now we have been unacquainted with the influence of pores on the non-random dispersion of conductive particles in the film volume. Considering the formation and growth of the pores mechanisms in relationship to the rearrangement of the conducting media in the film, such influence must exist, and thus there will be an influence of pores on the conduction mechanism of the film.

4.2 Effects of Reactions of Resistors Forming Media During the Firing Process

Investigations of paste constituents and substrate interaction during the firing process show that there are three main phenomena which condition resistor structure giving results which have not been taken into consideration in modelling.

The first of these is the reducing-oxidizing chemical reactions between the products of burning off of the organic binder vehicle and the conductive medium. These will affect the conductive medium, dissolve in the molten glass and also chemically react with the glass.[3,35] The new compounds found can also be of a conductive type. In the case of a film where the initial conductive material is bismuth ruthenate, $(Bi_2Ru_2O_7)$, such conductive compounds as ruthenium dioxide, (RuO_2), and ruthenium, (Ru), can exist additionally in the film after firing. Generalizing the problem, the volume fraction of conductive medium in the film, ought to be calculated from the equation:−

$$v = \sum_{i=1}^{n} v_i \tag{7}$$

where v_i is the volume fraction of the i-th material existing in the film conductive medium. It should not be calculated from the paste composition.

Even though resistivities and other electrical properties of conductive media in the film can differ considerably from another (e.g. in the case of $Bi_2Ru_2O_7$, RuO_2 and Ru), the influence on parameter such as resistance or temperature coefficients of resistance cannot be ignored and can cause essential divergences between the observed film properties and those resulting from simplified models. This is true although the volume fractions of additionally formed material are usually much smaller than the volume fraction of the initial medium.

The second important phenomenon occurring during the film firing is the dissolution of the surface region of the substrate in the film glass[7,23] which causes simultaneous penetration of the film into the substrate. The thickness of the transitional region formed generally depends on the maximum firing temperature, time at this temperature and also on physico-chemical properties of the glass and substrate. In the case of ruthenate films with lead-boro-silicate glaze on an alumina substrate this region thickness can be even a dozen or so microns thick.[23,26] Because the glass properties in the transitional region will differ considerably, (as a result of the high content of Al_2O_3), from glass in the normal film, so both the electrical and mechanical properties of this region will be different from those of the normal film. Thus formation of the transitional region means that the resistive film is composed of two interreacting parallel films with different properties. Thus, making assumptions in models about the independence of the film structure properties on thickness is a serious error, while the methods of measuring the film thickness that do not take into account penetration of the film into the substrate are inadequate.

Protective overglaze films that are more and more becoming an additional component of the thick film resistor system will have a similar influence on the

microstructure of the resistor. However, taking into consideration that the protective glass is fired at a lower temperature than the firing temperature of the resistive film, the top transitional region is thinner and therefore its importance is smaller. However the protective film can influence the stresses in the resistive film.

Thus the interaction of the film and the substrate during the firing process are of great importance in multilayer elements. In relation to resistive films these elements are more and more often utilizing RC elements with distributed parameters.

The third significant phenomenon occuring during the firing process is the reaction of the contact films and the resistive film in adjacent regions. Due to migration and diffusion of the contact films into the resistive film[20] significant additional hetero-geneity of the resistive film occurs which is a function of the resistor length. The importance of this heterogeneity and thus of the type of the contact film on the resistor properties will increase with the decrease of the resistor length. However, the influence of the contact film on sheet resistivity and other electrical properties of the resistive film can be eliminated by using suitable preparation method. In a practical resistor these transitional regions will take part in the conduction and the properties of the transmission region will add to the properties of other parts of the resistive film. Thus the model of the real structure of the thick film component must take into account these transitional regions in the resistor.

4.3   Stresses in the Film and Due to the Substrate

Most of the up-to-date worked models of thick resistive films do not take into consideration temperature stresses in resistor structure which is caused by mismatch of the thermal expansion coefficients of the phases forming the resistor. These stresses may be listed in two groups:–

(i) Stresses caused by mismatch of the thermal expansion coefficients of conductive medium (α_c) and glass (α_g),

(ii) stresses caused by mismatch of thermal expansion coefficients of the resistive film (α_f) and the substrate (α_s) and, in certain cases, also of the protective overglaze film.

Since the thermal expansion coefficients of the conductive medium and glass can differ considerably in values- (e.g. $\alpha_{Bi_2Ru_2O_7} \cong 11.6 \times 10^{-6}/°C$, $\alpha_g \cong \alpha_{Al_2O_3} \cong 6.6 \times 10^{-6}/°C$ for temperatures ranging from 20°C to 300°C[7]), the first type stresses can exceed the strength of one of the phases and can cause microcracks,[51] thus influencing the conducting mechanism of the film.

The stresses of the second type can cause cracking of the film, increasing the nonstability of its parameters, particularly after the trimming process, which itself initiates the propagation of microcracks,[26] and can change the temperature characteristics.[32] In consequence of counter-reaction of the film, the stresses induced in the substrate (especially if the thickness of the film and occupied area of the substrate are considerable) can cause bowing. This makes the proper printing and packaging of the microcircuit difficult.

4.4   Sizes of Conductive Medium Grains

A number of studies of the solubility of thick film resistor conductive media in lead-boro-silicate glasses have been made. Such studies have provided information that solubility is insignificant, and in principle average sizes and size distributions of the grains of resistive media in pastes and films do not differ very much. However it is known that the properties of the grains with sizes below about 0.1 μm will already differ from the properties of big crystals[52] due to the influence of their surface. Thus the
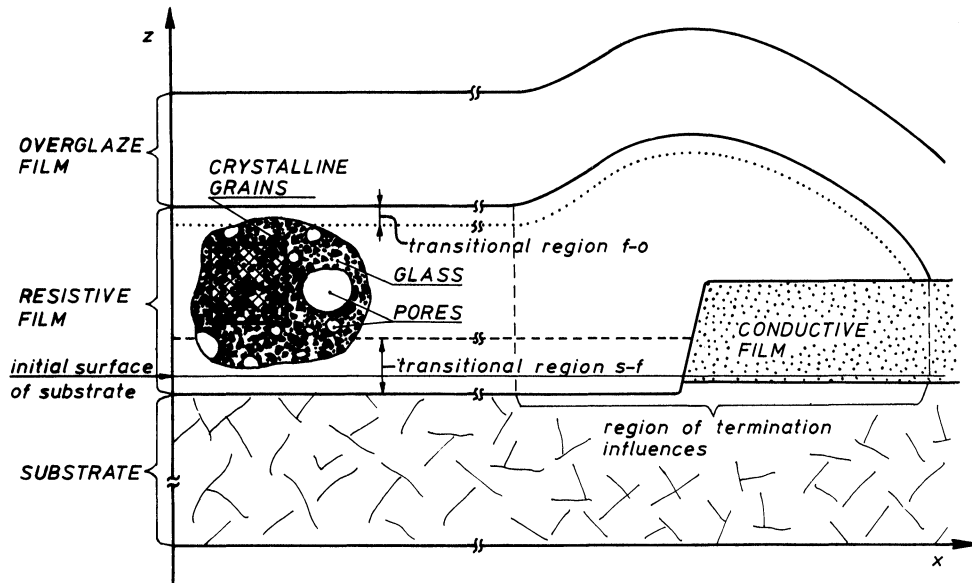
FIGURE 4   Schematic cross-section of half of a thick film resistor showing the most important components of the structure which influence electrical properties.

insensitivity of the models evolved on the sizes of the conductive medium grains is suspect. Similarly, not regarding the distributions of grain sizes, may lead to considerable errors in the defining of the model parameters. This effect concerns such parameters as coordination numbers of grains, segregation coefficients, etc. These parameters are usually fixed without taking into consideration the distribution of grain sizes.

4.5   Recapitulation

In Figure 4 is shown the schematic cross-section of half a thick film resistor. The most significant features of the structure are shown and these need to be taken into consideration in building models of structure, in order to create a useful and full model of a resistor basing on them. It follows from Figure 4 that, from the point of view of resistor conduction mechanism, important parameters such as resistivity, elasticity modulus, thermal expansion coefficient, stresses and others depend on at least two co-ordinates (in a rectangular resistor) and, in general, on all three. The average observed values of these parameters will be conditioned by resistor sizes, especially thickness and length. The lined area (Figure 4) shows which segment of the resistor structure has been modelled in the past and shows the considerable idealization of these models.

5.   PROBLEMS DEALING WITH BUILDING AND DETERMINING OF A THICK FILM COMPONENT MODEL

The procedure of full model creation and verification ought to contain a few stages and the most important of them, are those shown as a block diagram in Figure 5. One possible use of the model, after verification, is shown by the dashed line. A mathematical model is proposed as a many variable function $P(F, H, C)$ where P is one
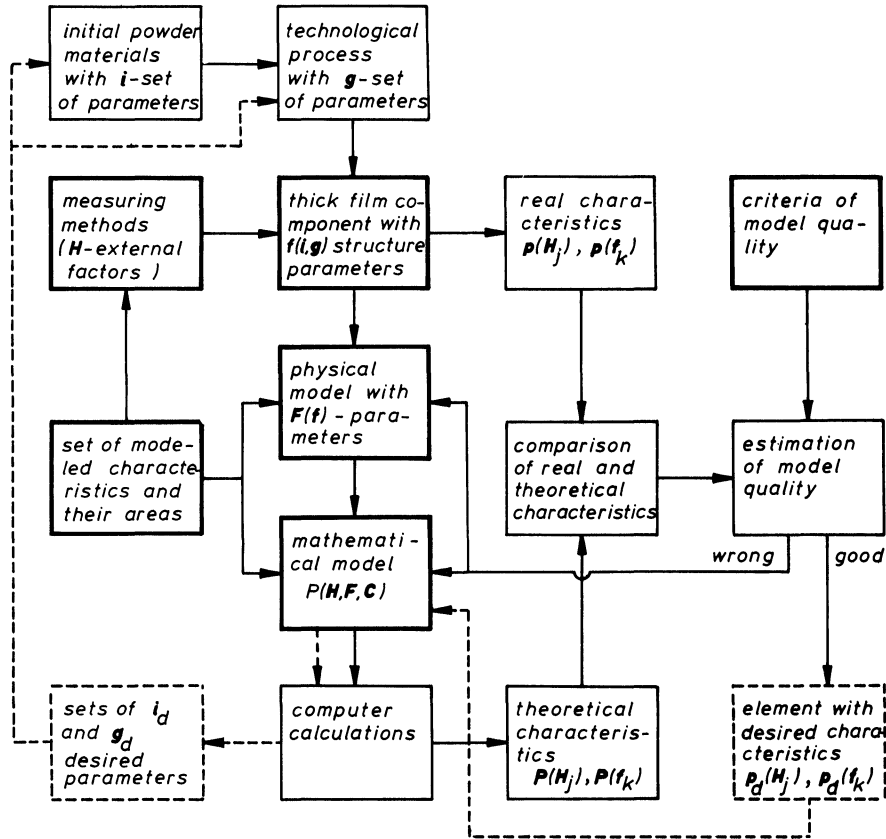
FIGURE 5 Block diagram showing the most important stages in the creation process of a thick film component model. One of the possible uses of the model is shown by the dashed line.

of the important parameters of the component (it could be resistance R in resistors, B-constant in thermistors defined by equation $B = Tln(R_T/R_o)$, etc, F is a set of parameters of the physical model (i.e. structure model), H is a set of external agents which influence a component (e.g. T — temperature, V — voltage, etc.), C is a set of other arbitrary constants. In general this function could be an implicit one. Assuming that there exist an analytical expression $F[f(i, g)]$ where f is a set of structural component parameters, i is a set of initial powders parameters and g is a set of technological processes parameters, such a model given by $P[f(i, g) H, C]$ could give agreement with the observed properties of the thick film components. Obviously such a full model could exist only for exactly defined fields of the variables H, f, g and i.

The check of the thick film component model quality is an inseparable component of its forming process and must be done by comparison of the results received with the use of the model and the measured parameters and characteristics. The quality and usefulness of the model will depend on many factors, especially on the fixed criteria of model quality and set of modelled characteristics i.e. $p(H)$ and $p(f)$. The greater the number of these characteristics, as well as the larger the intervals of their variability (i.e. field of characteristics) will be, the greater will be the usefulness of the model. The selected set of modelled characteristics and parameters is, in other words, a mathematical picture of a real component which can be transformed into number sets

and is of interest to investigators. In practice a number of characteristics which can be used for construction and verification of the model will be considerably limited due to the user's real needs, time limitations of the measures and the cost of the whole process.

The model quality should be estimated on the ground of divergences between the measured characteristics and the theoretical ones obtained on the basis of the model though it seems logical to fix an additional criterion which will concern a number of parameters C in the model which cannot be related to the parameters of the real component structure. The lower the number of parameters in C, the better the model will be. The number of F parameters should have secondary significance due to the great calculation capability of present computers. The minimalization of the number of C parameters is important because each limited characteristic can be approximated by many different functions whose relation to the real structure of the component can be either little or great with the same errors of approximations.

The set of the selected characteristics used to build a mathematical model of the thick film component should result from real working conditions of the component and from requirements specified by the designer of the microcircuits. It is important to fix a hierarchy of the importance of these characteristics.

One of the next, equally important problems which occurs during the determination of the model is the proper identification of characteristics, i.e. choice and use of adequate measuring methods. These problems will be discussed shortly in terms of the example of possibilities of simple measurement of the I(V) characteristics of thick film resistors. This depends on the measursing method, especially on the parameters of the measuring pulse train, (in pulse methods), or on the speed of voltage increase in continuous methods. Figure 6 shows the results of the author's research concerning the shape changes of the I(V) characteristic of ruthenate resistors, with sheet resistivity $R_s \cong$ 2MΩ/sq, after repeated measuring cycles. A pulse voltage was applied. After each pulse the amplitude was changed by 1V. Pulse duration and pulse time ratio were 50 ms and 10^{-3} respectively. Hysteresis occurred which showed that exceeding a certain value of electric field intensity caused irreversible changes of the resistor resistance. and thus its microstructure. The influence of pulse number at high electric field intensity with the constant amplitude and duration on the resistance of ruthenate resistor ($R_s \cong 2M\Omega$/sq) is shown in Figure 7. The number of pulses which can stabilise the resistance at new level depends on the type of the film and the pulse parameters. A similar shape to these characteristics was achieved by Stevens et al[27] for resistors made of Birox 1451
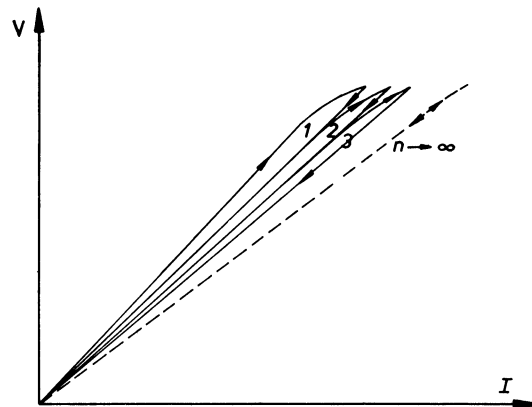

FIGURE 6   The irreversible changes of shape of I(V) thick film ruthenate resistor characteristic in succeeding measuring cycles ($R_s = 2M\Omega$/sq).
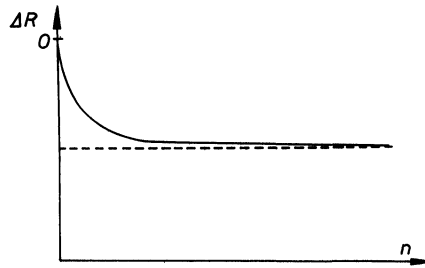
FIGURE 7   Typical shape of resistance increase versus pulse number for high electric field for ruthenate resistors with film resistivity greater than 10 Ωm.

($R_s = 100$ kΩ/sq), paste. In general, irreversible changes of the thick film resistor resistance caused by high values of electric field intensity can be both positive and negative dependent on R_s value of the type of material. The problems of choice of the measuring method in this case may be analysed based on the characteristic shown in Figure 8. This is a typical dependence of current amplitude in ruthenate high value R_s resistors, on constant amplitude voltage pulse duration. Fast dynamic methods with pulse duration $t_m < t_d$ ensure the information is obtained without irreversible changes of the resistor structure, due to the small pulse energy. Static methods with $t_m > t_s$ cause irreversible changes in the resistor structure and, in general, contribute additional errors due to noticeable increase of the temperature of the film. The methods in which $t_d < t_m < t_s$, give intermediate results, with partial irreversible changes in film structure. An analysis of the possibility of a single measurement of R(T) resistor characteristics especially at higher temperatures were irreversible changes of the resistor structure may also occur, would look similar. Thus the choice of an adequate measuring method is important in that in many cases the method used and characteristic obtained, are interdependent. The quality of the selected method should be estimated by considering the degree of identification of the real characteristic and what changes are caused by its utilization in the structure of the test component, and if these changes have a realization in the model of the component structure.

In summary it can be stated that the select measuring method is an inseparable part of the model verification process and thus of the model. It is difficult to specify the criteria of the method selection because they will depend on the model construction and its actual application.

As equally important as the problem above mentioned is the problem of obtaining reliable values of the parameters describing the structure of the element for analysis. This reliability will be ensured again by appropriate measuring methods which will identify these parameters and will allow the measure of them with sufficient accuracy.
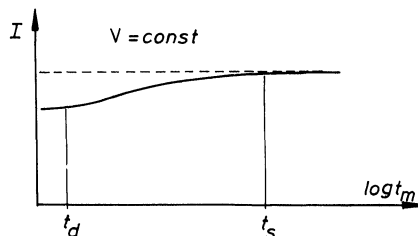

FIGURE 8   Current versus time of voltage pulse duration with constant amplitude for ruthenate resistors with $R_s > 100$ kΩ/sq.

Such a parameter is the thickness of the film which was initially measured with the use of profilograph. At present, in high accuracy research, the weight method basing on theoretical film density is used. Since there is a transitional region between the proper film and the substrate, and because of penetration of the film into the substrate, with the existing film porosity causing the density of the film to be considerably smaller than the theoretical one; the method in its present form will not be useful for the verification of the full model. It needs to be modified using microscopic methods. Similar problems arise in the evaluation of real volume fractions of the media in the film and segregation coefficients of the media.

6. SUMMARY REMARKS AND CONCLUSIONS

A short review has been given of previous thick film models. These have used, as an example, thick film resistors, as they are the ones most often used for model analysis work. It has been shown, in the context of the need for building a complete thick film component model, that present models are generally concerned only with a part of a component structure and therefore their simplification is relatively high. In the case of thick film resistors they are most often built in order to model only one specific characteristic of the resistor. This is generally the relationship between the resistance of the film and the volume fraction of the conductive medium in the material. The application of modelling to other types of thick film component has been much less extensive and, due to many reasons, worked out models for other thick film components are not satisfactory as full models either. Generally in existing models effect of pores, transitional regions between film and substrate, film and protective layer and film and contact film have not been taken into account. These components and the structure of thick film resistors are important for defining the shapes of several characteristics.

Very important problems occur in forming thick film component models as a process of model verification. In practice this had best be done using a thick film resistor system using one set of powders prepared under constant technological conditions. In order to completely define the resistor the following problems should be identified:–

1. The need to designate the stress distribution in the film and their influence on resistor electrical characteristics.

2. Investigation of the type of conducting grain contact whether by direct contact or by conduction through thin isolating layers of glass.

3. Investigation of the influence of average grain sizes and of distribution of sizes including that of the effect of modifiers, on resistor characteristics.

4. Research into the physiochemical changes in the media of the resistor produced during the technological processes, particularly with regard to the part played by modifiers in these reactions.

5. The application of the above data towards the improvement of previous analyses.

The characteristics of the resistor which a thick film model must satisfy can be identified as:–

1. The temperature characteristic, R(T)

2. The current-voltage characteristic — possibly using a frequency as a parameter.

3. The influence of the technological processes, such as resistor dimensions and top firing temperature.

4. Noise behaviour at low frequencies, G(f, I).

5. Effect of machanical stress on resistance.

6. Stability of the resistor as a function of time.

In summary it can be stated that a full model of a thick film resistor with its associated computer analysis could result both in a quicker identification of new resistive compositions to give resistors with desired properties and also an advancement in the speed in which previously known materials could be optimised. Models would also give a considerable enlargement to our knowledge concerning conduction mechanisms in such components. Finally, studies of full models of resistors would enable full models on thick film components, whose application areas are increasing very rapidly at the present time, to be worked out.

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