COMMUNICATIONS

METHOD OF MEASUREMENT OF THERMAL CONDUCTIVITY OF RESISTIVE LAYERS IN THICK-FILM STRUCTURE

Włodzimierz Kalita* — Mariusz Węglarski* — Stanislav Slosarcík**

Resistive layers are usually the main heat sources in thick-film structures. For accurate analysis of stationary and non-stationary temperature fields in structures of this kind it is necessary to know the thermal conductivity of resistive layers printed on the ceramic substrate. An unconventional method of measurement of the thermal conductivity of the resistive layer and transient region between the layer and substrate has been described. The results of measurements of the conductivity with the use of scanning electron microscopy for identification of the transient region and X-ray diffraction for measurement of temperature into the substrate have been presented.

Key words: hybrid microcircuits, thermal conductivity, thick-film resistor, simulation of temperature states

1 INTRODUCTION

A resistor made in thick-film technology in principle consists of two layers. The first is the resistive (active) layer, which determines the thermal properties of the element. The second layer - substrate - plays a protective and isolation role as well as it takes part in heat dissipation. Moreover, as a result of interaction between these two layers in the firing process a transient region (with different properties) is observed. The resistive layer has structure dissimilarity in the transient region in direct neighbourhood with the substrate (Fig. 1).

![Fig. 1. Transient region: a) after firing (1-resistive layer, 2-transient region with PbO Al₂O₃ B₂O₃ SiO₂ glaze, 3-substrate, b) distribution of Al and Pb](image)

This is the effect of partial dissolving (in the firing process) of the substrate material in the resistive layer glaze (10-15% Al₂O₃ for corundum substrate) and penetration of this glaze in the substrate structure. This mutual penetration of material layers is heterogeneous and takes place to a depth of 10μm [1]. So, this value is relatively high in relation to layer thickness. Because of significant structural differences of the transient layer (relatively to the resistive layer or substrate) it is necessary to determine the thermal resistance of this region. The thermal resistance of the resistive layer printed on the corundum substrate has two components: thermal resistance of the main layer and thermal resistance of the transient region.

2 THERMAL CONDUCTIVITY IN TEMPERATURE FIELD ANALYSIS

For determining the heat resistance (Fig. 2a) the Wanczews method of elementary balances was used. It consists in heat balancing in single separate elements of the thick-film device. Because the dimensions of layers areas are much bigger than their thickness (hr << a, hr << b, hs << a, hs << b) it can be assumed that the sides of elementary regions are adiabatic areas and heat flow Q is along z-axis only (\(\partial T/\partial x = \partial T/\partial y = 0\)) (Fig. 2b), as well as the principal layer region is homogeneous and isotropic as regards thermal properties. With those assumptions the boundary problem can be treated as 1-D [2].

Flux Q, which penetrates from the substrate through the resistive layer (with thermal resistance \(R_r\), area \(S\) and thermal conductivity \(\lambda\); no generated heat) creates a temperature distribution in the cross-section (along z-axis) illustrated in Fig. 2c. The temperature differences \(T_2 - T_1\) and \(T_3 - T_2\) are expressed by

\[
T_2 - T_1 = QR_r, \quad \text{where} \quad R_r = \frac{h_r}{S\lambda_r} \quad (1)
\]

\[
T_3 - T_2 = QR_t, \quad \text{where} \quad R_t = \frac{h_t}{S\lambda_t}
\]
Equation (1) can be the basis to experimental estimation

\[ q = -\lambda \nabla T, \quad \text{where} \quad \nabla T = \frac{\partial T}{\partial z} \quad (2) \]

of the \( R_r \) and \( R_t \) value but determination of temperature \( T_2 \) (directly over transient layer) is a big problem.

Also knowing the material thermal conductivity is insufficient because of geometrical-structural heterogeneity of the transient region. For those reasons two circuits with different thickness of resistive layer \( h_r' \) and \( h_r'' \) have been considered to determine the above mentioned thermal resistances. It was assumed that in both cases the heat flux as well as temperature of layer surface have the same values: \( Q' = Q'' = Q; T_1' = T_1'' = T \) (indexes ' and '' refer to particular values of layers with thickness \( h_r' \) and \( h_r'' \), respectively). From the systems of equations (1) for \( h_r' \) and \( h_r'' \) the following expression can be obtained

\[ T_3' - T_3'' = Q(R_r' - R_r'') \quad (3) \]

which after taking account the relation \( R_r'' = R_r' \cdot \frac{h_r''}{h_r'} \) leads to equation

\[ R_r' = \frac{h_r' (T_3' - T_1')}{Q (h_r' - h_r'')} \quad (4) \]

The measurement of temperature \( T_3' \) and \( T_3'' \) (on the substrate under resistive layer) and determination of the heat flux power on the basis of the product \( Q = g \cdot S \) (g - is power density) allows to calculate the heat conductivity

\[ \lambda_r = \frac{h_r' (T_3' - T_1') - h_r'' (T_3'' - T_1'')}{Q (h_r' - h_r'')} \quad (5) \]

\[ R_t = \frac{h_r (T_3' - T_1') - h_r'' (T_3'' - T_1'')}{Q (h_r' - h_r'')} \quad (6) \]

\[ \lambda_t = \frac{g h_t (h_r' - h_r'')}{h_r (T_3' - T_1') - h_r'' (T_3'' - T_1'')} \]

After similar transformations of equation (1) expression can be established which describes the thermal resistance of the transient region.

3 EXPERIMENTS

Expressions (5) and (6) are the basis for determining the thermal resistance value of the resistive layer referred to the substrate. It requires establishing of the values \( h_r \) and \( T_1 \). In the experimental investigations the layer thickness \( h_r \) was established using the gravimetric method [3], which guarantees high accuracy with taking into account irregularity of the surface. Temperature \( T_1 \) was measured using a point IR method. Another problem is the measurement of substrate temperature under resistive layer \( T_3 \). A special test method has been elaborated on the basis of X-ray diffraction. It is based on the determination of the changes of crystal lattice in the substrate material (using diffraction method) under temperature changes. It requires establishing X-ray penetration depth in the tested region and layer thickness (which is the source of information in the form of diffraction lines). The calibration of the diffractometer should be also made before tests. It consists in establishing of a unique dependence between the diffraction lines and temperature value of the examined material layer. The intensity of the radiation beam \( I_z \) after transition through the material layer with thickness \( z \) can be described by formula [4]

\[ I_z = I_0 e^{-\mu z} \quad (7) \]

where \( I_0 \) means the intensity of the incident beam and \( \mu \) is the coefficient of linear absorption. Analogous methods of \( \mu \) coefficient determination are not useful for a heterogeneous structure of the resistive layer. For those reasons an indirect experimental method was used. It consists in measuring the intensity of diffraction lines \( I_{xz} \) from the substrate without a resistive layer and measuring the same line \( I_{xr} \) with the resistive layer (Fig.3).
The intensity of the diffraction line can be determined on the basis of expression (7) and for the first and second case is given by equations

\[ I_{zs} = I_o \exp \left( \frac{-2\mu\sin\Theta}{z_s} \right) \]  
\[ I_{zr} = I_o \exp \left( \frac{-2\mu}{\sin\Theta} \right) \frac{z_s}{z_r} \]  

where \( \Theta \) means the Bragg angle, \( \mu \) is the linear absorption coefficient of the substrate material, \( z_s \) is the depth of penetration of radiation in the substrate and \( z_r \) is the known thickness of the resistive layer. Simple transformations of equations (8) lead to formula

\[ \mu = \frac{\sin\Theta}{2z_r} \ln \frac{I_{zs}}{I_{zr}} \]  

which allows to determine coefficient \( \mu \) from diffraction measurements of \( I_{zs} \) and \( I_{zr} \). The measurement of the linear absorption coefficient allows establishing the effective depth of penetration of radiation in resistive layer and substrate from equation

\[ G_z = 1 - \exp \left( \frac{-2\mu}{\sin\Theta} \right) \]  

which describes part \( G_z \) of the total intensity of radiation beam from the material layer with depth \( z \). It allows to determine the thickness of the resistive layer and diffraction angles where are possible reflections from the substrate carrying information about the temperature directly under layer.

The above-mentioned analysis is the basis to using the X-ray diffractometer for temperature measurements. The temperature change causes a volume change of the crystal lattice cells in the analysed region. As a result, displacement of diffraction lines is observed. For this reason the measurement of temperature \( T_3 \) was based on the determination of displacement of one diffraction line. It required calibration of the diffractometer for the mentioned line in accordance with expression

\[ \Theta = f(T) \]  

Experimental investigations for determination of the heat resistance of the resistive layer consist of four steps: preparation of samples, calibration of the diffractometer, measurement of temperature in samples and establishing of heat resistance.

For the laboratory tests three resistive compositions based on ruthenate (with different gravimetric compositions and sheet resistances) were selected (Tab.1).

For those compositions the linear absorption coefficient and thickness of investigated layers have been determined. After this, the depth of radiation penetration (for selected line with deflection angle \( 2\Theta = 150 \) deg) in layers on the basis of particular composition was established (Fig.4).

![Fig. 4. \( G_z \) vs \( z \) for composition with \( \mu \) from Table 1 and \( 2\Theta = 150 \) deg](image)

![Fig. 5. Idea of making of the test samples](image)

Table 1. Compositions of samples

<table>
<thead>
<tr>
<th>No</th>
<th>Ruthenate</th>
<th>Glaze</th>
<th>( R_0 )</th>
<th>( \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>49</td>
<td>51</td>
<td>0.3</td>
<td>1000</td>
</tr>
<tr>
<td>2</td>
<td>37</td>
<td>63</td>
<td>1.7</td>
<td>960</td>
</tr>
<tr>
<td>3</td>
<td>18</td>
<td>82</td>
<td>230.0</td>
<td>940</td>
</tr>
</tbody>
</table>
The symmetry of the tested samples allowed direct flux from layer 3 to investigated area.

The substrate temperature $T_3$ (directly under resistive layer) was established on the basis of dependence (11) determined during scaling of the diffractometer. The obtained results of calculations and measurements are presented in Tab.2.

<table>
<thead>
<tr>
<th>No</th>
<th>$\lambda_r$ (W/(mK))</th>
<th>$R_t$ (K/W)</th>
<th>$R_{rt}$ (K/W)</th>
<th>$R_{rt}'$ (K/W)</th>
<th>$h_r$ (W/mK)</th>
<th>$h_r'$ (W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.16</td>
<td>0.10</td>
<td>3.0</td>
<td>1.9</td>
<td>15.5</td>
<td>10.0</td>
</tr>
<tr>
<td>2</td>
<td>0.18</td>
<td>0.08</td>
<td>2.5</td>
<td>2.1</td>
<td>14.3</td>
<td>12.4</td>
</tr>
<tr>
<td>3</td>
<td>0.28</td>
<td>0.16</td>
<td>12.6</td>
<td>11.0</td>
<td>15.6</td>
<td>13.7</td>
</tr>
</tbody>
</table>

Because the value of thermal conductivity $\lambda_r$ of resistive layer is established on the basis of dependence (5), the maximal relative error was assumed as the accuracy of measuring the average value (it is equal to 1%).

### 4 CONCLUSIONS

The analysis of value $\lambda_r$ for particular resistive compositions (with considerable differences of the sheet resistance) leads to conclusion that the heterogeneous structure - to a large extent - equalizes their thermal properties in macroregions. The existence of a separate transient layer (with thermal conductivity about two times higher than the resistive layer) was confirmed. Two phases are interpenetrating: from one side - glaze, ruthenate and air, from the other - $Al_2O_3$ ceramic.

The obtained results confirmed usefulness of the presented X-ray method of temperature measurement for determination of the thermal resistance of resistive layers. It plays a very important role in the identification of heat exchange processes in hybrid microcircuits. The used method has a universal character and can be also applied in other branches of technology.

### REFERENCES


Włodzimierz Kalita was born in Poland in 1933. He graduated in electronics engineering from the Technical University of Wrocław in 1958 and received a doctorate in electronics engineering and a doctorate in sciences from the Technical University of Gdańsk in 1972 and from the Technical University of Lvov, Ukraine in 1992, respectively. Between 1958 and 1965 he worked at Transport Equipment Mfrg Centre, PZL-Mielec, Poland as the head of Avionics Department. Since 1965 he has been at Rzeszów University of Technology, where he is at present Professor and head of Electronic and Telecommunication Systems Department. His major research interests are in the area of hybrid microelectronics, especially, analysis of temperature fields, tolerance, reliability and electromagnetic compatibility of microcircuits. Professor Kalita has published over 140 articles and contributed to 3 books on sensors. He is a supervisor of 5 doctoral dissertations and member of the International Microelectronics and Packaging Society and Editorial Boards of ”Elektronizacja” and ”Elements of Theory and Applications of Solid-state Electronics (Ukrainian)” Journals

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