Małgorzata Jakubowska, Keith Pitt*

Institute of Electronic Materials Technology, Warsaw, Poland
*Middlesex University, London, United Kingdom

ELECTRICAL, MECHANICAL AND THERMAL PROPERTIES OF THICK FILM RESISTORS ON DIELECTRICS

This paper examines recent developments in the fabrication of compatible thick film dielectric and resistor combinations. It discusses the causes of reactions between materials and the consequent electrical changes. Results are presented showing that the newly developed ruthenium oxide based resistor series tested here has significantly better electrical and mechanical compatibility than older combinations. Piezoelectric studies show that Gauge Factors, (G.F.), of this series are significantly higher than found in earlier materials on both alumina and dielectric. Thermographic mapping and computer simulation of temperature distribution around heated resistors on alumina and on dielectric on alumina both show a significant rise on the lower conductivity layer.

Описано останні дослідження в області сумісності товстоплівкових та резистивних комбінацій. Розглянуті причини реакції між матеріалами та подальші зміни в електричних параметрах. Новорозроблені серії резисторів на основі оксиду рутенію демонструють значно кращу електричну і механічну сумісність, ніж старі комбінації. Термографічне картографування і комп'ютерне моделювання розподілу теплових полів навколо нагрітого резистора демонструють значне зростання на нижньому провідному шарі.

1. INTRODUCTION

Higher density and multilayer thick films often require resistors deposited either on or within the structure. It is well reported that problems can occur between layers of different compositions and mechanical and chemical properties[1-9].

This paper discusses some of these problems and their industrial solutions. It then examines in detail some aspects of the preparation and properties of a new thick film resistor paste series on both alumina and a selected thick film dielectric. It does not consider the case of resistors deposited within a multilayer structure.

The simplest way to combine resistors with multilayer structures is to use the structure itself as the substrate. The resistor deposition becomes the last layer to be printed and fired. This reduces the number of resistor firings to the number of different sheet resistances used and provides a reasonably flat surface. This configuration allows the laser trimming of resistors. However, since most standard resistive pastes do not react with dielectric layers in the same way as with alumina[4], careful choices must be made in order to minimize the differences in properties. In some cases the interaction of dielectric with resistor is significant.

When a resistor paste is printed onto a fired dielectric layer, interdiffusion of constituents takes place[3-6], often significantly affecting the parameters and structure of the product. Careful selection of the pastes can minimise this effect. The main objective of this work was to fabricate a compatible set of resistive and dielectric pastes and evaluate the electrical, thermal and mechanical properties of structures produced from them.

2. RESISTORS ON DIELECTRICS

Figure 1 shows a schematic resistor/conductor layer on a dielectric on alumina.

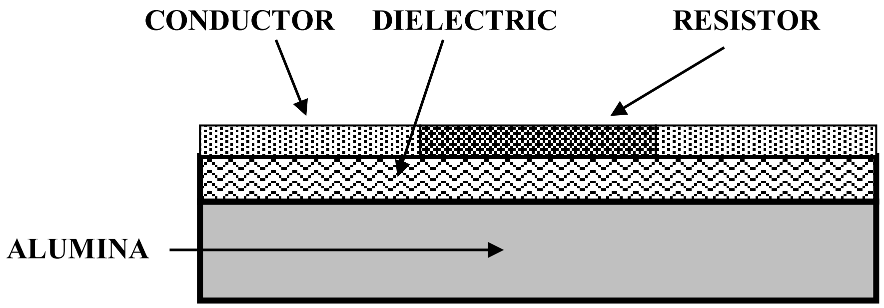


Figure 1. Schematic structure of a resistor on dielectric on alumina.

Pitt et al[3-5] examined in detail the reactions occurring during firing between selected resistors and dielectrics. Using X-ray analysis techniques, they plotted the percentage composition of selected oxides across a polished cross section. The plots for Du Pont 1730, 1000 ohms/square resistor on 96% alumina, Du Pont filled glaze dielectric, 9950 and Du Pont crystallizing dielectric 9429 are reproduced as figures 2, 3 and 4 respectively.

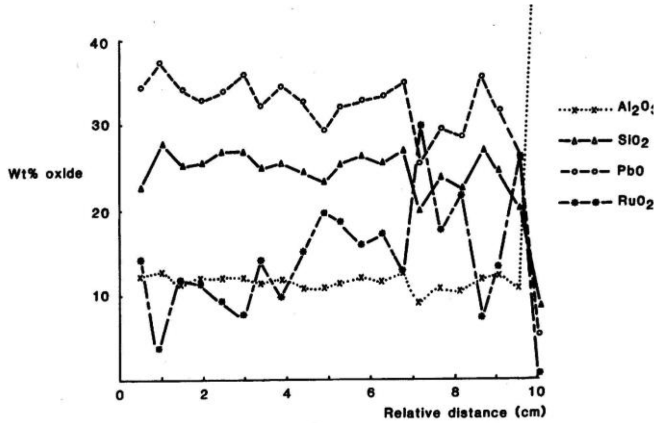


Figure 2 DP1730 on alumina

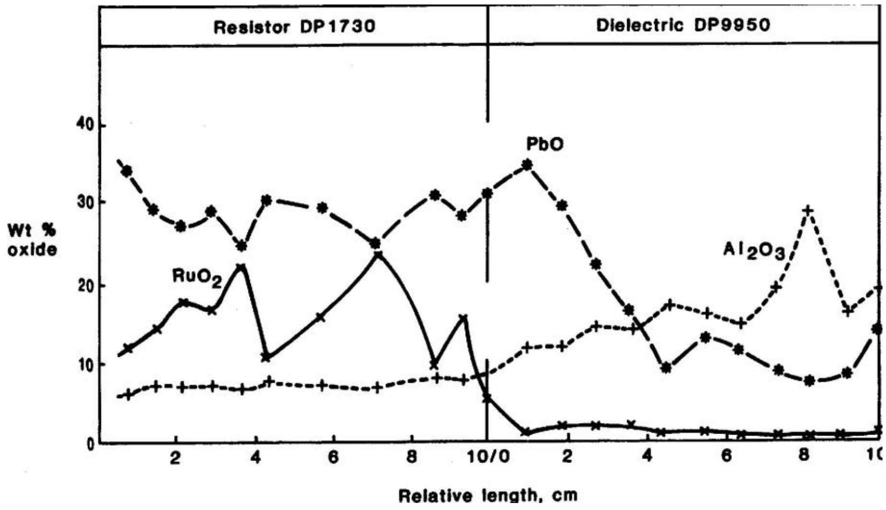


Figure 3 DP1730 on DP9950 filled glaze dielectric

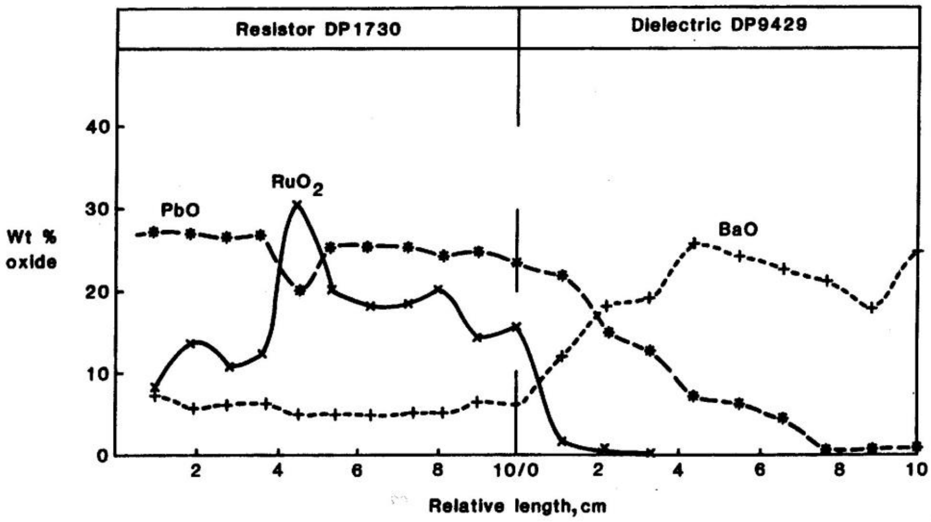


Figure 4 DP1730 on DP9429 crystallising dielectric

They found that while the electrical differences in resistors on alumina and filled glaze dielectric DP9950 were relatively small, on crystallising glaze DP9429, they were very significant, both in measured sheet resistance and temperature coefficient of resistance. They concluded that there were marked reactions taking place during firing on DP9429 which were absent on DP9950 and alumina.

Analysis of the cross sections indicated that the constitutional changes to the resistor compared with those on alumina were quite small on DP9950. On an alumina substrate the alumina content of the film is almost constant across the section. RuO_2, PbO and SiO_2 are fairly evenly distributed, except where the probe hit regions where the particle distribution of the conducting phase was abnormal, i.e. where the constituent was either mainly conductor or mainly glass. DP9950 contains lead oxide and there is a gradient of composition across the boundary suggesting some of the glass content had migrated across the boundary, slightly increasing the conductivity. A trace of RuO_2 was observed across the dielectric. This was concluded to be contamination during polishing.

However, on DP9429 there were very noticeable changes. This dielectric contains barium oxide, but no lead oxide. The ionic sizes are similar and the two oxides readily interdiffuse. With a much lower lead content, the conduction mechanisms change since BaO is always stoichiometric, while lead oxide is not[10]. The authors concluded that the cause was changes in conduction type due to a loss of part of the PbO content and its replacement by BaO. They also concluded that the presence of BaO alone in the dielectric was a prime contributor and that problems were more likely to arise when the dielectric was crystallising rather than filled.

Recent developments in thick film resistors and dielectrics have taken place in parallel in order to ensure that the differences in properties observed when the substrate is changed are reduced to a minimum. Higher melting point glasses and careful control of fillers now ensure high density dielectric layers which are much less sensitive to reactions during firing. Ensuring that there are few significant diffusion gradients during firing also helps to minimise the changes. Most of the dielectrics now used with resistors are filled glazes. In some cases it is necessary for barium compounds, such as barium titanate to be present. However, the presence of lead oxide in the paste also will tend to minimize diffusion of barium into the resistor in exchange for lead.

3 EXPERIMENTAL WORK

3.1 Preparation of Samples

A standard ITME dielectric, D-421[11], was selected for this investigation together with palladium silver 3:1 conductor, P-202, fired at 850°C, and 96% alumina substrates. The experimental resistor paste for approximately 20KΩ/□. was based on ruthenium dioxide and a lead-silica-aluminium glass and designated R20 KΩ□. Its vehicle was ethyl cellulose in terpineol. This specific paste was chosen as a mid range member of the series for detailed physical analysis.

Table 1 Basic Parameters of Dielectric D-421

a) Glass properties

Property	Parameter
Composition	PbO, $A1_20_3$,SiO_2, $BaTiO_3$, ZnO, TiO_2
TCE (glass) x 10^{-6}/°C	5.52
Density, g/cm^3	3.65
DTM	720°C
T_g	590°C

b) Dielectric Paste Composition and Fired Properties

Property		Parameter
Composition (%)	Glass	90.7
	$A1_20_3$	4.8
	Pigment	4.5
Firing temperature		850°C
Thickness of triple layer		66 µm
Dielectric constant		8-10
Loss tangent		0.0066
Breakdown voltage 30 µm thick		> 800 V

Table 2 Basic Parameters of Resistor Layer R20KΩ/ □

Property		Parameter
Composition (%)	Glass	63
	RuO_2	37
Firing temperature		850°C
Firing time		60 min.

The printing and firing sequence was:
Dielectric: print, dry, fire
Dielectric: print, dry, fire
Conductor: print, dry, fire
Resistor: print, dry, fire

The test pattern held 9 resistors ranging in length from 1-9mm and width 1mm. The three pastes used in this investigation were carefully selected and designed for minimum reaction between layers. The experimental work investigated the extent of the actual reactions and its effect on resistor properties.

3.2: Preliminary Measurements

Examination of Table 3 shows that the properties of the conductor are very similar on both surfaces, although the solderability is slightly reduced.

Table 3 Fired Conductor Properties

Conductor	Substrate	Sheet Resistance $m\Omega/\square$	Solderability %	Adhesion $N/4mm^2$
PdAg 3:1 ITME P-202	Al_2O_3	20.4	100	19
	D-421	23.1	90	18

Table 4 shows the results for the resistors. There is a small increase in sheet resistance on the dielectric with a corresponding decrease in TCR.

Table 4 Fired Resistor Properties

Substrate	Sheet Resistance $K\Omega/\square$	TCR ppm/K
Al_2O_3	18.2	83
D-421	20.1	61

4. FURTHER INVESTIGATIONS

4.1 Sheet Resistance Effects

Initially, the compatibility of the resistor and its terminations was examined. Normally, short resistors are affected to a greater extent than longer ones by diffusion of silver and other ions into the resistor body at the contacts. In addition slight thickness increases near the contacts also become more significant in shorter tracks. The resulting sheet resistance is, thus, lower than for longer tracks. In this case, however, short resistors were seen to be higher in sheet resistance both relative to those on alumina and to the longer ones on dielectric. This may be due to diffusion of glass during firing through the conductor into the termination regions of the resistor. The general higher sheet resistance of the resistors on dielectric compared with alumina is discussed below.

Figure 5 shows an SEM view at x500 of the top surface of a resistor layer on dielectric D-421. The structure is homogenous, dense and without micro cracks. This is confirmed by profilographs of the dielectric layer (Figure 6a) and of the resistor on the dielectric (Figure 6b) and by figure 7 which shows an SEM image of the cross-section of an RuO_2 resistor deposited on dielectric D-421. (Figure 6c shows the profile of the resistor deposited on a dielectric layer containing cubic boron nitride.) The section was broken, not polished. An interlayer, thickness about 7μm, between the resistive and dielectric layers can be seen. This is caused by interdiffusion between the resistive and dielectric layers. These diffusion effects appear to be the main cause of the higher resistivity observed when the resistor is on dielectric rather than alumina.

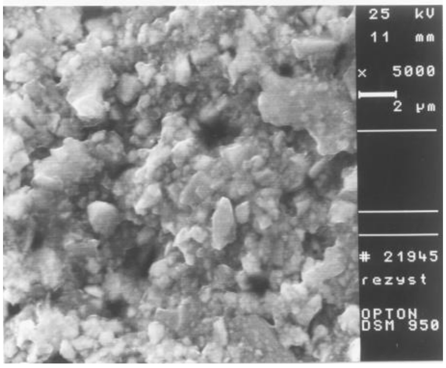
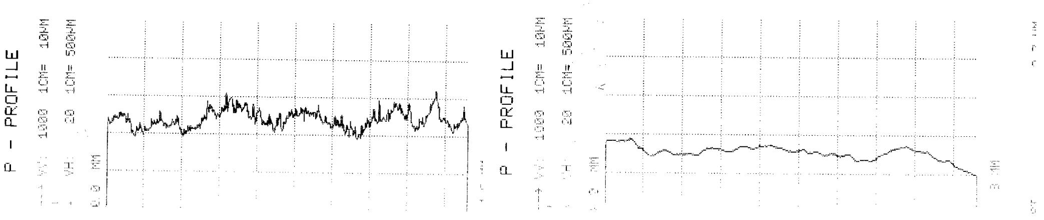


Figure 5: View of the top surface of a resistor layer on D-421 dielectric (x5000).



a) b)

Figure 6: Surface profiles of a) dielectric D-421 on alumina, b) a resistor on D-421 and c) a resistor on cBN

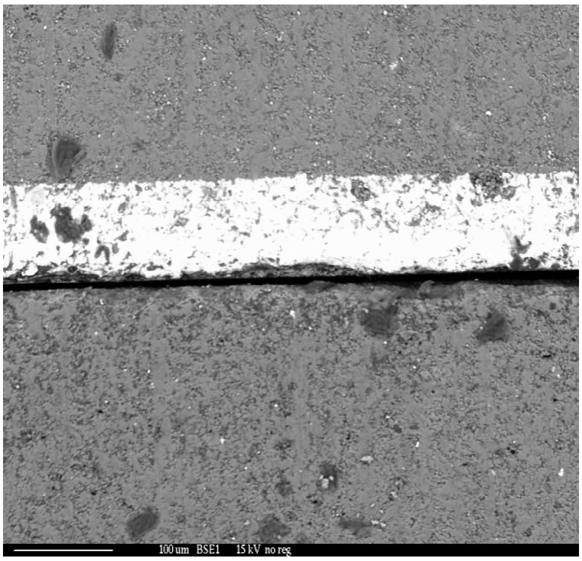


Figure 7: Cross-section of a resistor deposited on dielectric D-421 on alumina (x700).

4.3. Piezoresistive properties of resistors on dielectric

Piezoresistivity in thick film resistors is characterised by a gauge factor (GF), which can be defined as:

$$GF = (\Delta R/R_0)/(\Delta L/L_0) \quad = \quad (\Delta R/\varepsilon R_0)$$

where:

ε = strain in resistor, (elongation/unit length).

The relative change in resistance due to the strain is given by ($\Delta R/R_0$)

Belavic et al[12] review piezoresistivity and gauge factors in the context of applications.

In order to investigate piezoresistivity in thick film resistors, a simple measurement method has been designed and applied. Szczepański and Jakubowska describe the measurement method in detail[13]. It uses a ceramic substrate with longitudinal and transverse resistors. One end of the substrate is clamped and the free end is subjected to an external load which deflects it. In the current work 4 resistors each 1mm square were used. In two the contacts were longitudinal, (R_3 and R_4) and in the remainder, (R_1 and R_2) transverse. Deflection is applied so that the strain in R_1 and R_4, closer to the clamp, is greater than in R_2 and R_3.

This results in two types of gauge factor: longitudinal gauge factor, GF_L and transverse gauge factor, GF_T. By reversing the mounting of the test substrate so that the resistors can be either on the top or the bottom side, both tensile and compressive strains can be achieved.

A lower member of the new paste family, R1K, was used for the investigation of gauge factor, approximately 1 Kohm/□ on alumina and 2.5 Kohm/ □n the dielectric in order to compare the results with those for a known bismuth ruthenate resistor (R342). Results for Du Pont 1431, also containing bismuth ruthenate, on alumina and DP9950 are also included in the table for longitudinal strain only[14].

Table 5 Piezoresistive properties of selected pastes

Paste	Substrate	R_s Kohm/□	GF_L	GF_T	Hot side TCR
R1K	Alumina	0.9	18	12	53
R1K	D-421	2.5	22	15	25
R342	Alumina	2.5	10.5	8.1	23
DP1431	Alumina	Approx 1K	10.6	-	66
DP1431	DP9950	Approx 0.7K	10.4	-	91

These results show that the new structures exhibit higher gauge factors than those seen with equivalent bismuth ruthenate resistors on alumina or the Du Pont filled glaze, DP9950. This is thought to be due to stresses caused by the difference of thermal expansion coefficients between the alumina substrate and the dielectric and resistive layers. The thermal expansion coefficients, (TCE), for these layers are given in Table 6.

Table 6 Thermal expansion coefficients of constituent layers.

Material	TCR (ppm/k) x 10^{-6}
Alumina	6.8
D-421	5
R1KΩ/□	5.8

Reports of gauge factors as high as 30 appear to have been related to microcracks in the structure and are discounted here. However, figure 5 shows that micro-cracks appear to be absent in these new structures and the results in Table 5 indicate that the RuO_2 based resistor has a higher gauge factor on both surfaces than two examples based on bismuth ruthenate. Pitt et al.[14] examined 4 members of the DP1400 series on alumina and 3 on DP 9950 from 100 to 100k ohms/ . They□und that GF increases with sheet resistance. The value on alumina for 100 ohms/ is 8.2. □

4.4 Thermal properties of resistors on dielectrics

One of the potential disadvantages of a structure using resistors on the surface of a dielectric is that the electrical insulator is also of high thermal impedance. A thermovision camera and computer simulations[16,17] were both used to evaluate these effects. The resistor test pattern is shown as figure 8.

Figure 8: Test pattern for infrared thermography

4.4.1 Infrared thermography

Figure 9a shows a grey-scale thermal image of a 1mm square resistor on 96% D-421 on 96% alumina and Figure 10b (right) its equivalent on alumina. The peak temperature is approximately doubled. An experimental boron nitride based paste was also used as an underlayer and the resulting photograph is reduced on the left in figure 9b. The power dissipation was 500mW in each case.

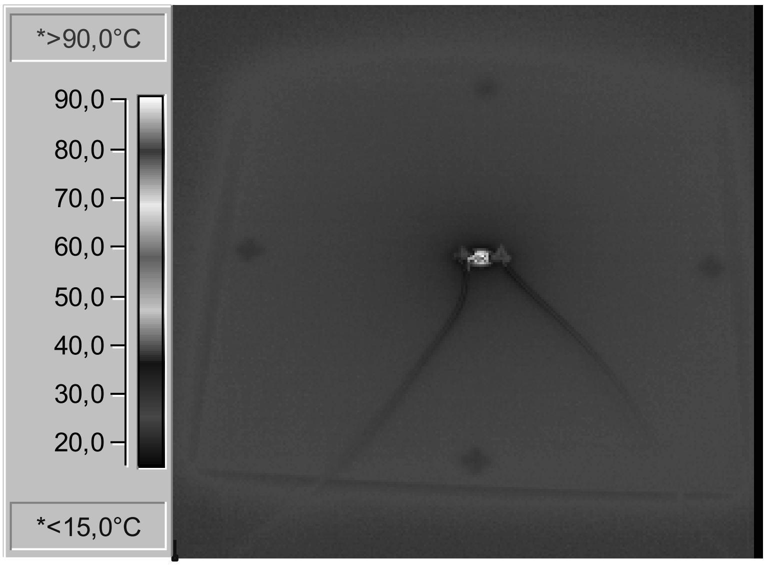


Figure 9a: Thermal camera images of 1mm square resistors on D-421 on alumina.

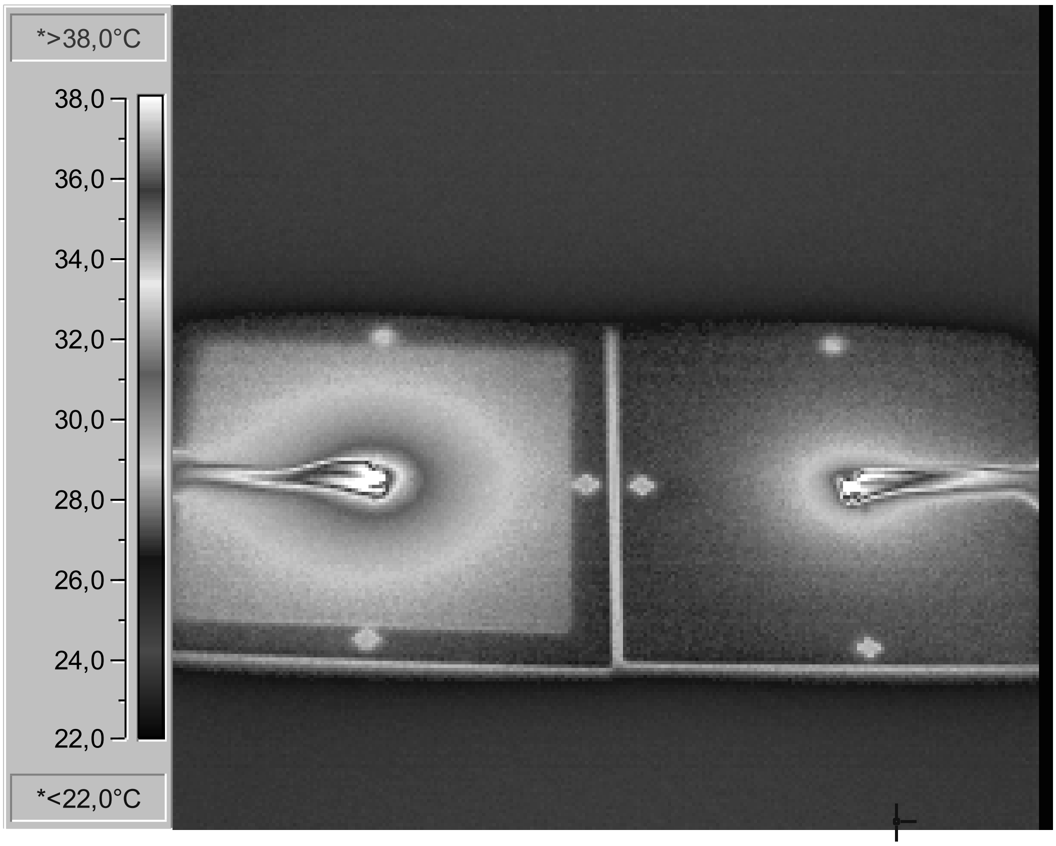
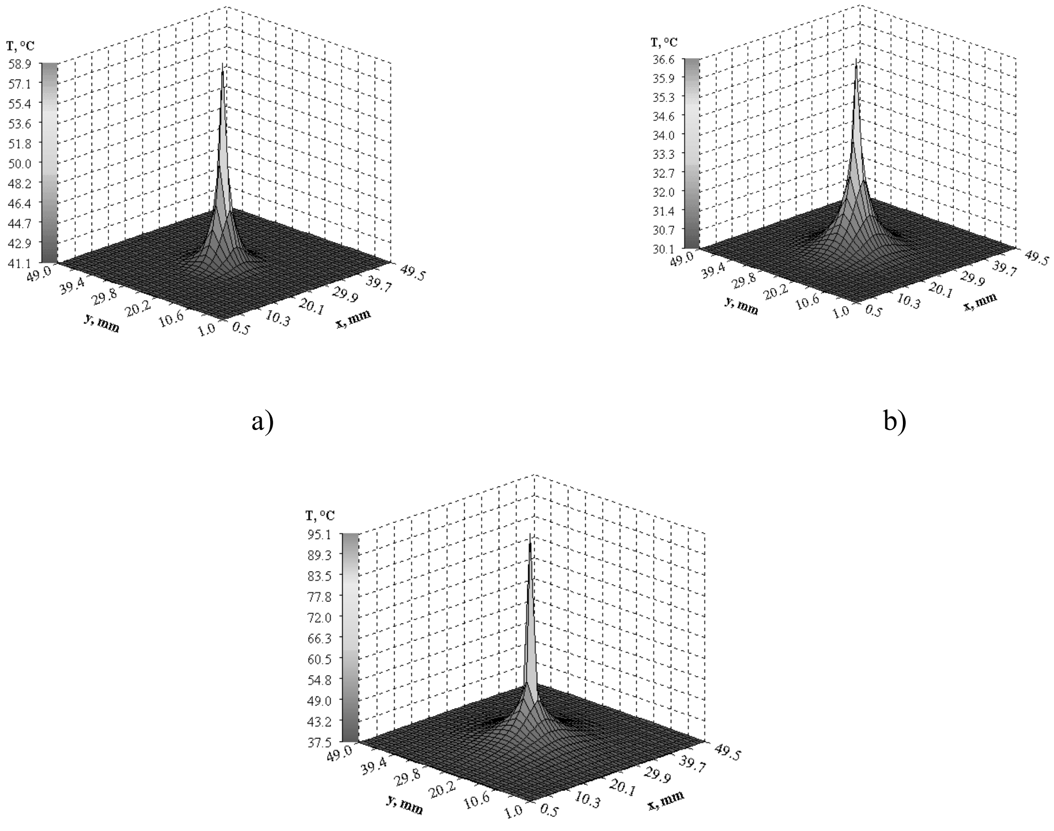


Figure 9b: Thermal camera images of 1mm square resistors on c-BN (left) and directly on alumina (right).

It was necessary to use wires soldered directly to the contacts in (a) which is on dielectric, while they were at the substrate edges on alumina. Despite the additional heat paths, the peak temperatures were approximately 80°C and 40°C respectively.

4.4.2 Computer simulation of thermal profiles

Computer simulation of the thermal profiles of a 1mm resistor on alumina and layers containing the highly conductive compound cubic boron nitride, c-BN, were made with the use of a programme Hybterm[17] and the contrast between the profiles is very clear. Unlike a normal dielectric such as D-421, the layer containing c-BN acts as a heat spreader and although there is no change in the heat actually leaving the substrate, the hot spot is sharply reduced. Figure 10 (a) and (b) respectively show in 3 dimensions the change in peak temperature between the resistor on alumina and on a c-BN layer containing 10% glass. Results on a layer of dielectric D-421 are shown in figure 10(c).



a)

b)

c)

Figure 10 Simulation of 3 dimensional heat distribution for a resistor dissipating 0.75W on a) 96% alumina, b) a layer of cubic boron nitride, (c-BN), containing 10% glass on 96% alumina and c) dielectric D-421.

5 EXAMPLES OF APPLICATIONS OF RESISTORS ON DIELECTRICS

In contrast to the efficient heat spreading observed when a thermally conducting filler is used in a dielectric, applications exist where the presence of a thermal barrier becomes necessary to minimise power consumption due to heat losses behind the substrate. For example, between resistors acting as a heater for paper and the alumina substrate. A thermal overhead for a laser printer was used as a possible example application for the use of thick film resistors on dielectric. The resistors are designed to heat the paper in selected places and the dielectric acts as a thermal barrier to heat loss out of the back, thus minimizing power use.

Conversely, there is potential for the development of highly conducting layers compatible with resistors in order to minimise hot spots and improve system reliability. C-BN layers investigated here show promise.

6 DISCUSSIONS

Earlier work has shown that the properties of resistors printed and fired on thick film dielectrics are very sensitive to the process conditions and compositions of the two adjacent layers. In any thermally induced process, there is potential for composition gradients at interfaces between materials of different composition or structure. In most thick film precious metal based resistor systems the presence of lead oxide at the interface between conducting particles is a significant contributor to the conduction mechanisms. Previous investigations[3-6] have shown that diffusion of metal ions can take place causing the background glass composition to change. It was observed that the changes were minimised if, for example, lead oxide were present in both layers, such as DP1730 on DP9950. In contrast, the DP9429 dielectric is lead free and its filler contains barium oxide BaO[10]. Diffusion of lead oxide into the dielectric is compensated for by its replacement by barium oxide in which the ion Ba^{++} can not change its oxidation state from 2 unlike Pb^{++} which can readily do so.

An investigation into distributed thick film filters[18] had earlier indicated that many commercial dielectrics had a very open structure which caused glass from the resistor layer to be withdrawn, leaving the ratio of the conductor phase to the resistor phase in the final product markedly lower than for the same paste on alumina.

As a result of these and many similar observations, industrial development of thick film dielectrics for both multilayer and multilayer with resistor applications concentrated on the development of glasses which had much higher flow temperatures, but which, at the same time, wetted the filler efficiently and minimised the porosity. D-421[11] is an example of this newer type of filled dielectric.

Although the dielectric does contain barium titanate and, hence, the Ba^{++} ion, it also contain PbO. Both at 20Kohm/square and at 1Kohm/square, there is some increase in sheet resistance. In neither case does it lead to very large negative changes in TCR such as observed by Joshi et al[2]. The use of Matthiessen's Rule[4,10] indicates that, here, there is no significant change in the conduction mechanisms.

Belavic et al.[12] and Licznerski et al[19] both discuss the physical causes of parameters in film resistors. Belavic examined the dimensional effects in the context of applications. Licznerski used the effective medium theory to examine the causes of the changes in properties of the resistors produced by Pitt[4]. These workers concluded that some of the temperature coefficient changes observed could be related to the difference in physical properties of the resistor on different surfaces. However, they concluded that the chemical changes occurring on dielectric DP9429 were also very significant.

Thick film resistors are a convenient class of strain gauge and have medium value gauge factors, typically close to 10 longitudinally. This work has shown that the 1000 ohms/□ resistor used here has a significantly higher gauge factor, both on alumina and dielectric. The slightly higher figure on dielectric suggests that thermal mismatch of the three layers during firing has affected the gauge factor more than that occurring between two layers only on alumina.

The resistor series shows only minimal interaction and no cracking between layers shown in the examples in figures 5, 6 and 7. The electrical changes are low and indicate that there is much less interaction between layers during firing than with earlier types of dielectric. As a result, potential applications arise where a 'hermetic' type dielectric, such as D-421 can be applied as a heat blocker. This is illustrated by figure 11. Figure 11a) shows the simulated temperature profile across an alumina substrate for, above, bare alumina and below, a cubic boron nitride layer. Figure 11b) shows, in contrast, the very much higher temperature predicted for a resistor on D-421 on alumina. Infrared measurements[16] of resistor temperatures across a substrate on cBN layers on alumina containing several different proportions of glass binder show that the peak temperature is strongly dependent on the glass content.

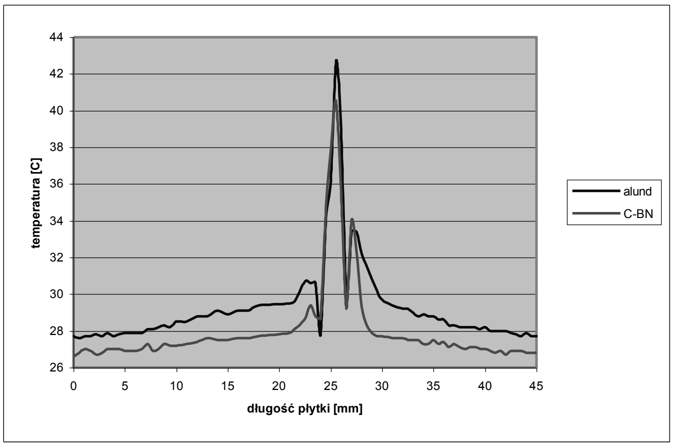


Figure 11a Temperature distribution across the substrate for resistor deposited on c-BN layer and on bare alumina substrate. Resistor powered with 500 mW.

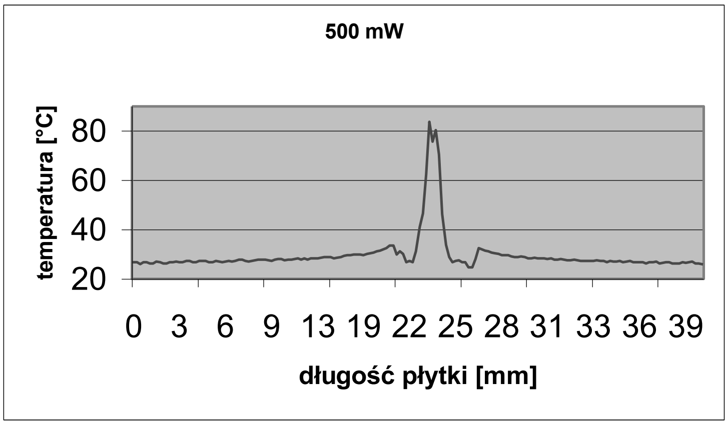


Figure 11b Temperature distribution across the substrate for resistor deposited on *D-421 layer. Resistor powered with 500 mW.*

In contrast, the potential arises for the development of resistors compatible with highly thermally conductive dielectrics such as those containing cubic boron nitride and up to 15% of glass. Preliminary results and computer simulations both suggest that potential uses for this combination of pastes may be found. Further evaluation of the interactions between resistors and cBN dielectric layers will be necessary before such applications can be realised. Examination of electrical aspects of combinations using cBN show that attempts at measuring the breakdown voltages of the films produce a semiconductor diode curve[20,21]. Cubic boron nitride is a 3-5 compound isoelectronic with diamond and is very similar in its properties.

7 CONCLUSIONS

This investigation has confirmed that the use of filled glazes with a high hermeticity has greatly reduced the interactions with resistors which occurred during the firing stage in earlier classes of dielectrics. The ruthenium dioxide based resistors series used here shows a significantly higher gauge factor than earlier bismuth ruthenate based structures. The gauge factor is further enhanced by deposition on a dielectric.

Stable and non-reactive combinations of thick film resistors and dielectrics may also have applications where heat loss through or into a substrate must be kept to a minimum.

Preliminary examination of resistors in combination with dielectrics of high thermal conductivity indicate a potential for use in heat spreading. Further development work is necessary in order to evaluate whether there are materials interactions affecting the resistor properties in this case also.

1. Vest R.W., Conduction Mechanisms in Thick Film Microcircuits, Final Report, DAHC15-70-97, 1975.

2. Joshi B., Pitt K. E. G., Winster A.E., The properties of thick film resistors on dielectrics, Microelectronics J., 13, no. 5, 1982. – pp.4–11.

3. Adie G., Hołodnik B., Pitt K., SEM/EDX analyses of some interactions between thick film resistors and dielectrics, Microelectronics J., 15,1984, no 2. – pp.38–43.

4. Pitt K. E. G., Thick Film Resistors on Dielectrics, M.Phil Thesis, CNAA, Middlesex Polytechnic 1987.

5. Bober B., Pitt K. E.G., Further studies of the interaction between thick film resistors and dielectric, Microelectronics J., 18, 1987, no 1, – pp.35–43.

6. Bober B., Pitt K.E.G., Licznerski B.W., Bober Z., The effect of constituent exchange on the conduction mechanisms of thick film resistors on dielectrics, Mat. Sci., 1987, no 3–4, – pp.193–198.

7. Cattaneo A., Pirozzi L., Morten B., Prudenziati M., Influence of the substrate on electrical properties of thick film resistors, Electrocomp. Sci. and Techn., 6, 1980, – pp.247–251.

8. Cattaneo A., Pirozzi L., Morten B., Prudenziati M., Influence of the substrate on electrical properties of thick film resistors, IEEE Trans. on CHMT, 3, 1980, no 1, – pp.181–186.

9. Coleman MV., Ageing mechanism and stability in thick film resistors, Hybrid Circuits, 4, 1984, – pp.36–41.

10. Pitt K.E.G., Chemical constitution and conduction mechanisms in thick film resistors, Journal of Materials Science: Materials in Electronics, 7 (1996), 187–190.

11. Achmatowicz S., Jakubowska M., Zwierkowska E., Szczytko B., Szymański D., Insulating paste, Pat. No. RP 162992, (In Polish)

12. Belavic D., Pavlin M., Grame S., Santo-Zarnik M., Hrovat M., Some Applications of Thick-Film Strain Gauge, Proc. IMAPS Poland , Rytro, September 2000. – pp.85–91

13. Szczepański Z., Jakubowska M., Materials and Piezoresistivity Measurement Method for Thick Film Pressure Sensors, Trans. on the Precision and Electronic Technology, vol.4 (1999), – pp. 51–56.

14. Pitt K. E. G., Hołodnik B., Whitaker R., Piezoelectric effects in resistors on dielectrics, Internepcon UK, 1985. – pp. 217–227.

16. Achmatowicz S., Jakubowska M., Zwierkowska E., Gielisse P., Niculescu H., Tremblay J., Golonka L., Zawada T., Shipilo V., Shishinik E., Gameza L., High Thermal Conductivity Cubic Boron Nitride Thick Films, Proc. IMAPS 2001, 34th Int. Symp. on Microelectronics, Oct.9-1 1, 2001, Baltimore USA, – pp. 379–383

October 1989. – pp.107–110.

17. Jakubowska M., Hotra Z., Klepacki D., Modelling of Thermal properties of thick film resistors on dielectric multilayer structure, Technical News, No 1-2 (12-13), 2001, pp.149-151. [20] Pitt K. E. G., Thick film distributed notch filters, Microelectronics J., 9, 1, 18–21, 1978.

18. Pitt K. E. G., Thick film distributed notch filters, Microelectronics J., 9, 1, 18–21, 1978.

19. Licznerski B. W., Pitt K. E. G., Seweryn A., Analysis of strain induced properties of thick film resistors on dielectrics., Pro. 13th Conf. ISHM Poland, Szklarska Poręba,

20. Pitt K. E. G., personal communication to P. Gielisse, September 2000

21. Niculescu H., Gielisse P. J., Tremblay J. P., Achmatowicz S., Jakubowska M., Zwierkowska E., Current-Voltage characteristics of co-fired cubic boron nitride, Proc. 26th Conf. IMAPS Poland, Warsaw 25-27, 2002, – pp. 185–190.