PROPERTIES OF THICK-FILM RESISTORS ON DIELECTRIC AND METAL SUBSTRATES FOR PIEZORESISTIVE SENSORS

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Abstract

In this paper, the resistive and piezoresistive properties of a commercial resistive composition (Du Pont 2041), often used for strain-gauge applications, are examined on several dielectric compositions, which themselves are deposited onto various ceramic and metal substrates. The choice of suitable dielectrics allows to achieve good adhesion and coverage of the metal substrate, while retaining similar properties of the resistors as on alumina. The combinations of dielectrics and substrates also allows to separately determine the contributions on the resistor properties of the thermal expansion of the substrate and those of chemical interactions between resistor and dielectric.

1. Introduction

The use of the piezoresistive properties of thick-film resistors (TFRs) in force and pressure sensors has become quite common, due to the good reliability and low cost of thick-film technology. Most thick-film sensors use standard 96% pure alumina as a substrate, in spite of its mediocre elastic properties. Indeed, alumina has only modest strength, a high elastic modulus, and suffers from static fatigue [1]. Improvements in sensor response may be attained by using resistors with a high gauge factor, but this advantage is offset by higher noise [2], and poorer stability [3]. Therefore, more standard resistive compositions such as Du Pont 2041 (10 k!), are often used in practice. Another way to increase the signal is to use substrates with better elastic properties, such as zirconia and metals – the authores recently observed extremely high responses of Du Pont 2041 on titanium alloys [4]. The use of other substrates than alumina, however, exposes TFRs to a different substrate surface chemistry and thermal expansion coefficient, both of which affect their properties. Conversely, the presence of a thick-film load cell was found to degrade the static fatigue behaviour of the whole sensor structure compared to that of the blank substrate [5]. The results of previous experiments of resistors on dielectric or on other substrates than alumina are quite scattered. Usual gauge factor values were obtained on ferritic stainless steel with various dielectrics [6], but lower ones on low-temperature cofiring ceramic (LTCC) and zirconia [7]. Extensive reactions of the resistor with porcelain enamel steel [8] and dielectrics [9] were observed. In this work, we examine the properties of Du Pont 2041 resistors on different substrate / dielectric combinations. By independently varying the chemical interactions (determined by the layer in contact with the resistor, substrate or dielectric) and the constrained thermal expansion of the resistor (determined by the substrate only), we aim to determine separately the contributions of chemistry and thermal expansion on the resistor properties.

2. Experimental

Different substrates were chosen for the experiments, with different values of the thermal expansion coefficient αs: alumina (96%, Kyocera A–476, the reference substrate, α = 6.5 ppm/K), titanium (grade 2, α = 8.5 ppm/K), zirconia (3.5% Y_2O_3, α = 10 ppm/K), ferritic stainless steel 1.4016 (X5Cr17, α =11 ppm/K), and austenitic stainless steel 1.4310 (X10CrNi17-7, α = 17 ppm/K). The following dielectric compositions were used, from Du Pont (DP), Heraeus (Her) and ElectroScience Laboratories (ESL): DP QM42, Her IP065, Her GPA 98–029, ESL 4924, ESL 4702 and ESL 4916. They were fired onto the substrate (several layers) in air using a standard thick-film profile, with a 10 min plateau at 850 C. The thick-film circuit consisted of Ag:Pd 3:1 or Au terminations (ESL 9635B or ESL 8837), followed by the DP 2041 resistors, each fired separately using the same standard profile. Resistive measurements (4 wire) were performed on 5.0 mm long, 1.5. mm wide resistors. The values are given at T_A = +25 C, with cold and hot *TCR* (*CTCR* and *HTCR*) being defined from T_A to T_C = –25 C and T_H = +100 C respectively (R_A, R_C and R_H are values at T_A, T_C and T_H respectively). Also, we define ΔTCR as the average difference of *CTCR* and *HTCR* relative to the values $CTCR_0$ and $HTCR_0$ on bare alumina:

$$CTCR = R_C - R_A/(T_C - T_A)R_A \quad \text{and} \quad HTCR = R_H - R_A/(T_H - T_A)R_A \tag{1}$$

$$\Delta TCR = 1/2\,(CTCR + HTCR - CTCR_0 - HTCR_0) \tag{2}$$

Longitudinal and transverse gauge factors K_L and K_T were measured with the layout and mounting depicted in Fig. 1. The differential measurement makes the results relatively insensitive to variations of the load point.

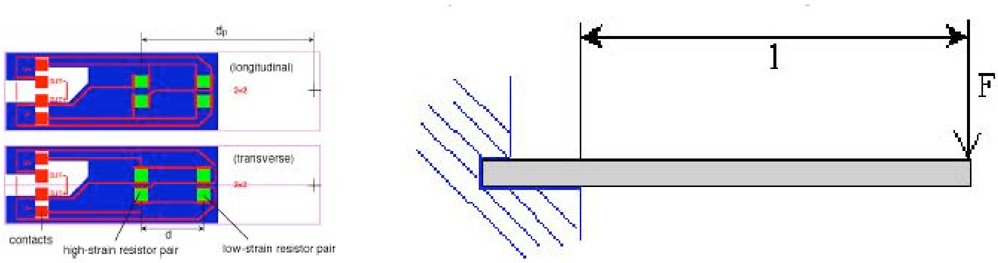

Fig. 1. Layout and set-up for the gauge factor measurements. l = 40, dp = 27.8 and d = 10.1 mm.

3. Results and discussions

3.1. Properties on alumina, bare or coated with various dielectrics

Since the dielectrics have negligible effects on the overall thermal expansion, one can assume that differences in value and *TCR* compared to alumina are only due to differences in chemical interaction between resistor and underlying surface (substrate or dielectric). Table 1 gives the measured properties of DP 2041 on the different dielectrics. Most dielectrics have little effects on value, except ESL 4702 (high value on DP QM42 was due to low thickness). Gauge factors *K* and *TCR* provide a more intrinsic measure of the effect of chemical interactions. While *K* remains essentially constant, some shifts of *TCR*, within ±30 ppm/K, are observed. Interestingly, DP QM42 and Her GPA 98–029 are quite neutral, with shifts of +2 and –11 ppm/K.

Table 1. Properties of DP 2041 on alumina + dielectric.

Dielectric	R_A [kOhm/sq.]	CTCR [ppm/K]	HTCR [ppm/K]	ΔTCR [ppm/K]	K_L	K_T
(alumina)	10.58 ± 0.15	–2 ± 3	+49 ± 1	(0)	12.6	8.5
ESL 4702	13.89 ± 0.90	–29 ± 7	+21 ± 4	–27	12.4	8.4
Heraeus	10.71 ± 0.17	–28 ± 2	+27 ± 1	–24	12.5	8.4
Her GPA 98–029	10.07 ± 0.23	–11 ± 6	+35 ± 1	–11	12.3	8.0
DP QM42	13.86 ± 0.39	–2 ± 7	+46 ± 5	–2		
ESL 4924	11.71 ± 0.43	+21 ± 7	+63 ± 5	+19		

3.2. Properties on other substrates.

The properties measured on other substrates, with different dielectrics, are shown in Table 2. Some samples failed due to bad dielectric-substrate adhesion, and other dielectrics had to be used as adhesion layers. Also, due to substrate warpage, considerable thickness variations of the resistors occurred – one therefore cannot draw conclusion from the value of the sheet resistance. *TCR* values follow in most cases the same trend as on alumina, but shifted upward as the thermal expansion of the substrate increases (see below). The gauge factors, when measured, tend to be slightly lower than on alumina. However, this could also be an artefact due to the width of the cantilevers combined with warpage of the substrate. On titanium, moreover, considerable oxidation of bare substrate regions took place, which can alter the substrate elastic properties.

Table 2. Properties of DP 2041 on other substrates + dielectric.

Substrate	Dielectric	R_A [kOhm/sq]	CTCR [ppm/K]	HTCR [ppm/K]	TCR [ppm/K]	K_L	K_T
Titanium	ESL 4702					10.0	5.6
Titanium	Her IP065	41.3	-150	-95	-143	10.7	6.2
Titanium	Her GPA 98-029	18.4	20	60	18	9.3	5.5
Zirconia						10.6	7.2
Zirconia	ESL 4702	18.5	66	106	65		
Zirconia	Her IP065	8.2	98	144	99		
Zirconia	DP QM42	12.2	89	130	88		
Zirconia	ESL 4924	17.1	119	152	114		
Steel 1.4016	ESL 4702	33.6	10	57	10	11.2	7.0
Steel 1.4016	Her IP065	13.3	53	99	53	11.3	6.7
Steel 1.4016	Her GPA 98-029	13.9	66	110	65	10.4	6.7
Steel 1.4016	DP QM42	14.6	120	158	115		
Steel 1.4016	ESL 4924	14.8	113	149	104		
Steel 1.4310	ESL 4702	19.4	167	217	168		
Steel 1.4310	Her GPA 98-029	13.6	195	246	197		
Steel 1.4310	ESL 4924	19.6	240	285	239		

3.3. Separation of thermal expansion and chemistry

The effect of the substrate thermal coefficient of expansion on a constrained piezoresistor has been analysed previously [10], albeit in terms of the piezoresistive coefficients instead of the more commonly used gauge factors, and assuming that piezoresistivity is temperature independent:

$$TCR = \chi - \alpha + \left[\Gamma_L + 1 + (\Gamma_T - 1)\left((1-3\nu)/(1-\nu)\right)\right](\alpha_S - \alpha) \quad (3)$$

G_L and G_T are the longitudinal and transverse piezoresistive coefficients, c the temperature coefficient of resistivity, a and a_S the resistor and substrate thermal expansion coefficients, and n the Poisson's ratio of the resistor. In practice, TFRs are almost never free-standing, and it is more practical to compare *TCR* on different substrates, taking for instance alumina as a reference (a_0). By also using the definitions of the longitudinal and transverse gauge factors K_L and K_T, and assuming they are equal on both substrates, one can show (will be part of a future paper) that the above expression then translates to:

$$\Delta TCR_{thermal} = (K_L + K_T)(\alpha_S - \alpha_0) \quad (4)$$

If one considers that the gauge factors are only little altered in reality, we can substract this value from the total *!TCR*, giving the shift due to chemical effects. This is attempted for all our results in Fig. 2 below.

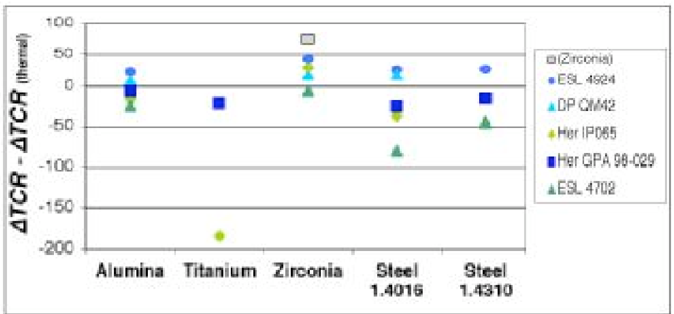

Fig. 2. *TCR* of DP 2041 on different substrates / dielectrics, after removing thermal contribution.

This approach works well for ESL 4924, DP QM42 and Her GPA 98, which are modern cristallising dielectrics and seem to have little reaction with DP 2041. On the other hand, Her IP065 (glass) and ESL 4702 (cristallising dielectric) induce strong *TCR* variations, due either to strong reactions with the resistor or to an insufficient barrier effect against diffusion from the underlying substrate. Finally, we note the very strong positive shift of *TCR* directly on zirconia.

Conclusions

– DP 2041 piezoresistive composition is compatible with modern cristallising dielectrics such as DP QM42, ESL 4924 and Her GPA 98–029, which cause only slight property changes compared to alumina. In this case, the *TCR* shift on a given substrate / dielectric combination can be expressed as the sum of the thermal and chemical contributions.

– Compatibility problems (Her IP065 and ESL 4702) can arise due to too strong reactions of the dielectric and resistor, or to insufficient barrier properties of the dielectric, exposing the resistor to interactions with the substrate.

– Zirconia causes strong positive chemical shifting of the *TCR* of DP 2041.

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