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Characterisation of thick film resistor series for strain sensors

Marko Hrovat [a,*], Darko Belavič [b], Zoran Samardžija [a]

[a]Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia

[b]HIPOT, Trubarjeva 7, 8310 Sentjernej, Slovenia

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Abstract

Some 10 kohm/sq. thick film resistors based on RuO_2, ruthenates or a mixture of RuO_2 and ruthenates, were evaluated for strain gauge applications. The resistors were fired at different temperatures to estimate the influence of firing temperature on the electrical characteristics. Temperature coefficients of resistivity (TCR), noise indices and gauge factors (GF) were measured. Microstructures of the thick film resistors were analysed by SEM. The results indicate that the microstructure of thick film resistors influences the gauge factors much more significantly than the "nature" of the conductive phase. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Electrical properties; Films; Sensors; Thick film resistors

1. Introduction

The change in resistance of a resistor under an applied stress is partly due to deformation i.e. the changes in the dimensions of the resistor, and partly due to the alteration in the specific resistivity as a result of changes in the microstructure of the material.[1] The gauge factor (GF) of a resistor is defined as the ratio of the relative change in resistance($\Delta R/R$) and the strain ($\Delta 1/1$):

$$GF = (\Delta R/R)/\Delta 1/1 \quad (1)$$

Geometrical factors alone result in gauge factors of 2–2.5. Higher gauge factor values are due to microstructural changes which alter the specific conductivity. The GF values of thick film resistors are mostly between 3 and 15. Due to their stability, low values of the temperature coefficient of resistivity (TCR) below 100×10^{-6} K and relatively low cost, strain gauges realised with the thick film technology offer advantages in some applications over both metal films (low GF, low TRC, expensive) and semiconducting elements (high GF, high TRC, inexpensive).[2–4]

Thick film resistor pastes consist basically of a conducting phase, a lead borosilicate based glass phase and an organic vehicle, which burns out during high temperature processing. In most contemporary resistor compositions the conductive phase is either RuO_2 or ruthenates, mainly bismuth or sometimes lead ruthenates. Some other oxides are normally included as minor additives either as modifiers of the TCR or modifiers of the temperature coefficient of expansion of the glass phase. The GF values of thick film resistors based on ruthenates ($Bi_2Ru_2O_7$ or $Pb_2Ru_2O_{6.5}$) are reported to be usually higher than those of resistors based on RuO_2.[5–7] However, some results suggest that the GF values of thick film resistors depend not only on the composition of the conductive phase but to a greater extent on the microstructure of the thick film material.[8–10]

Four resistors, connected in a Wheatstone bridge, are usually used for the sensing element of strain sensors. For better sensitivity (greater change in the balance of the Wheatstone bridge) ordinarily two resistors are under tension (an increase of resistance) and two under compression (a decrease of resistance). Within the same resistor series the GF values and current noise indices of thick film resistors increase with increasing sheet resistance. Therefore, in most cases 10 kohm/sq. resistors are used for strain sensors as a useful compromise between sensitivity and relatively low noise.

* Corresponding author. Tel.: +386-1-477-4900; fax: +386-3426-3126.

E-mail address: marko.hrovat@ijs.si (M. Hrovat).

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In this paper the results of an evaluation of 10 kohm/sq. resistors (Du Pont 8039 and 2041, Electro Science Labs. 3414 and Heraeus 8241) are reported.

2. Experimental

The conductive phase in the thick film resistors was determined by X-ray powder diffraction analysis. 8241 is based on RuO_2, 8039 and 3414 are based on ruthenate and 2041 is based on a mixture of RuO_2 and ruthenate. The resistors were fired at three different temperatures of 750, 850 and 950°C, i.e. at the normal firing temperature of 850°C, and 100 K below and above, to estimate the influence of firing temperature on the electrical characteristics.

Thick film resistors with dimensions of 1.6×1.6 mm^2 were printed on 50×7 mm^2 alumina substrates and fired at 750, 850 and 950°C for 10 min. The resistors were terminated with a prefired Pd/Ag conductor. Cold (from −25 to 25°C) and hot (from 25 to 125°C) TCR values were calculated from resistivity measurements at −25, 25 and 125°C. Current noise was measured in dB units on resistors loaded by 100 mW using the Quan Tech method (Quan Tech Model 315-C).

For microstructural investigation the resistors, printed and fired on alumina ceramics, were mounted in epoxy in a cross-sectional orientation and then cut and polished using standard metallographic techniques. A JEOL JSM 5800 scanning electron microscope (SEM) was used for the microstructural analysis. For SEM imaging, the samples were coated with carbon to provide electrical conductivity and to avoid charging effects.

The changes of resistivity as a function of substrate deformation were measured with the simple device described in Ref. 11. The ceramic substrate with printed and fired thick film resistor was supported on both sides. The load was applied to the middle of the substrate with a micrometer and which induced a tensile strain in the resistor. The magnitude of the strain ($\Delta 1/1$) is given by Eq. (2).[12]

$$\Delta 1/1 = (d^* t^* 6)/L^2 \qquad (2)$$

where d is the deflection (m), t the substrate thickness (m) and L the distance between support edges (m). GF values are calculated from Eqs. (1) and (2).

3. Results and discussion

Sheet resistivities, together with cold and hot TCR values of the investigated thick film resistors, fired at different temperatures, are given in Table 1, and the noise indices and GF values are given in Table 2. The experimental GF values are rounded up to 0.5, e.g. to 12.0 or 12.5. The noise indices of the resistors are also shown graphically in Fig. 1. Note that in Fig. 1 the noise indices are given in μV/V units while in Table 2 they are given as dB units.

Table 1
Sheet resistivities, cold and hot TCR values of thick film resistors, fired at three different temperatures

Resistor	T firing (°C)	Resistivity (ohm/sq.)	Cold TCR (−25–25°C) (10^{-6} k)	Hot TCR (25–125°C) (10^{-6} k)
8241	750	7.4 k	20	60
	850	5.4 k	20	60
	950	4.8 k	5	40
3414	750	410 k	−690	−505
	850	6.6 k	−45	15
	950	1.5 k	180	205
8039	750	3.4 k	−5	75
	850	7.3 k	50	90
	950	310	1730	1635
2041	750	3.0 k	140	175
	850	6.6 k	−35	20
	950	680	155	175

Table 2
Noise index and gauge factor values of thick film resistors fired at three different temperatures

Resistor	T firing (°C)	Noise (dB)	GF
8241	750	−8.1	17.0
	850	−4.5	15.5
	950	−6.2	15.5
3414	750	–[a]	???[b]
	850	2.0	20.0
	950	−7.4	19.5
8039	750	−15.8	9.5
	850	−14.3	11.0
	950	−25.6	2.0
2041	750	−18.9	9.0
	850	−23.3	11.0
	950	−22.6	9.0

[a] Noise too high to measure with the Quan Tech Model 315-C (over 30 dB).
[b] Measured gauge factors varied between 25 and 50.

After firing at 950°C, sheet resistivities of all resistors decreased. The resistivities of 2041 and 8039 resistors were only around 10 and 5%, respectively, of the resistivities after firing at 850°C. TCR values of resistors after firing at the "normal" temperature of 850°C are below 100×10^{-6} K. After firing at 950°C, the absolute TCR values of all resistors, with an exception of the 8241 resistor, increased and the dependence of resistivity on temperature was positive. The TCR values of the 8039 resistors were over 1600×10^{-6} K.

The noise index of the 3414 resistors, fired at 750°C, is very high and could not be measured within the upper range of the Quan Tech Model 315-C instrument, which

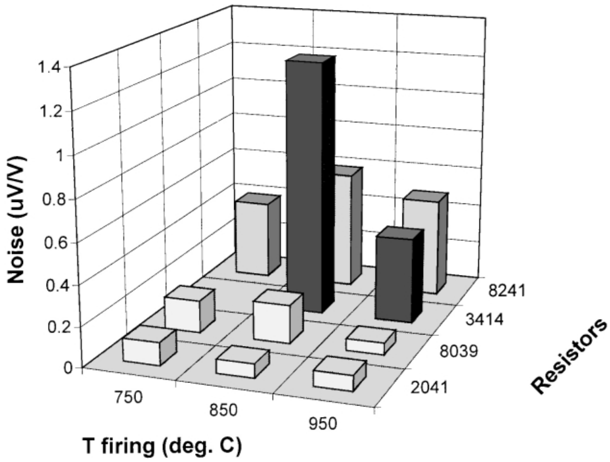

Fig. 1. Noise index values of thick film resistors fired at three different temperatures.

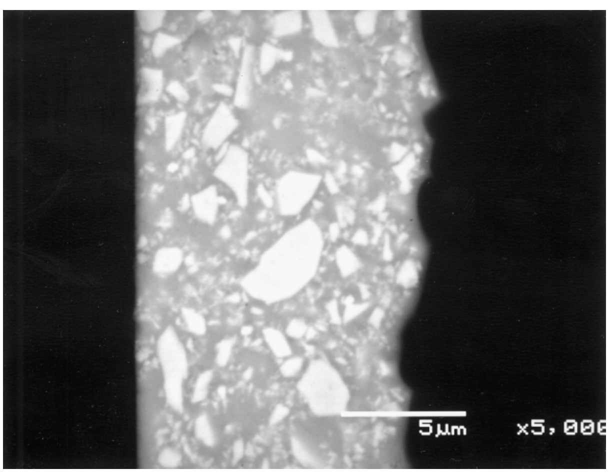

Fig. 2. Microstructure of a cross-section of the ruthenate based 3414 thick film resistor fired at 850°C. Alumina substrate is on the right.

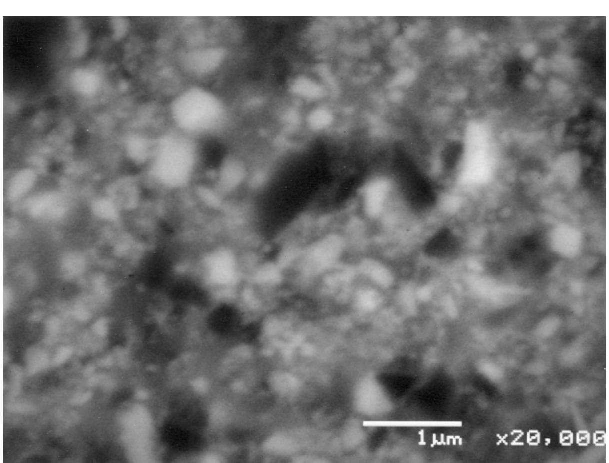

Fig. 3. Microstructure of a cross-section of the ruthenate based 8039 thick film resistor fired at 850°C.

is +30 dB. For all resistors the noise indices decrease with increasing firing temperature. The 2041 resistor had, after firing at all these temperatures, the lowest noise, which was about or below −20 dB. From all resistors fired at 850°C, the 3414 resistor had the highest noise of 2 dB (1.27 μV/V).

The highest GF values of around 20, were measured for resistors made from 3414 resistor paste, which was developed by Electro Science Labs. For use in strain gauge applications.[13] However, the wide scatter of measured GF values of the 3414 resistors, fired at 750°C, in the range from 25 to 50, is presumably due to the micro-cracks in the under-fired resistor films, as described by Prudenziati et al.[14] The GF values of the 8241 resistors were around 15 and the GF values of the 2041 resistors around 10, regardless of the firing temperature. For the 8039 resistors the values of GF decreased from 11 to 2 when the resistors were fired at 850 and 950°C, respectively.

The microstructures of ruthenate-based 3414 and 8039 resistors fired at 850°C are shown in Figs. 2 and 3, respectively. Note different magnifications in the two figures. The microstructure of the 3414 resistor consists of rather large light grains of conductive phase in a glass matrix, whereas the microstructure of the 8039 resistor consists of small, submicometer size conductive grains or clusters of particles, imbedded in a grey glass phase. As both resistor materials are ruthenate based, their different GF values can be ascribed to the different microstructures. This indicates that the microstructure of the thick film resistors influences the gauge factors much more significantly than the "nature" of the conductive phase.

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