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Vertical thick-film resistors as load sensors

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Abstract

A vertical thick-film resistor for a fine-pitch-array load sensor has been developed. This sensor can be used for measuring the relief (footprint) of a load force. The thick-film resistor, with a sheet resistivity of 1 Mohm/sq., is vertically oriented and terminated with a conductive layer at the bottom and on the top of the resistor layer. Sensitivity to the load (pressure) is based on the piezoresistive effect of the thick-film resistor. The experimental work on the sensing element resulted in a vertical resistor with a resistance of 2500 ohm and a sensitivity (dR/R) of about 1.3% at 6 bar pressure. Because of high density and large number of sensing elements, the whole system is divided into a number of segments. Each segment integrates 16 sensing elements (vertical thick-film resistors), 16 diodes, and 16 terminals for the inter-segment connections.

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

1. Introduction

Sensor applications and sensor technology are developing rapidly. With many years of experience in thick-film technology and sensor production we have been able to meet the market requirement to develop and produce a low-cost fine-pitch-array load sensor with a large number of sensing points (6400) for measuring the relief (footprint) of a load force. The requirements for the fine-pitch-array load sensor were to be able to measure a pressure of up to 6 bar on an area of 0.4×0.4 m with a maximum overpressure of 15 bar. The relief of the load force is measured with a large number of sensing points in a 5 mm pitch array. Each of these sensing points must be accessible with a computer-controlled measuring system.

The feasibility and capability study of the technical and economic aspects lead us to use an available and well-known thick-film technology to design the sensing element and the interconnections. The sensing element was based on thick-film resistors and takes advantage of the piezoresistive effect in these resistors, which has been characterised in previous investigations.[1–4]

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2. Experimental

As a result of a customer's demand we had to solve the following problems: a high density of sensing points, a large number of sensing points with a possibility for selective measurement of each point, mechanical construction, and not least, a low-cost product. To meet all these demands we developed a specially designed thick-film resistor. The system was also specially constructed, and the solution is based on several applications of thick-film technology in sensor fabrication techniques.[5–9]

The conventionally designed thick-film resistor is planar and is schematically shown in Fig. 1. The sensing elements in our application are realised with unusually designed thick-film resistors. The test pattern of the vertical resistor together with an expression for the resistance is shown in Fig. 2. These resistors with a sheet resistivity of 1 Mohm/sq. (Du Pont 8059) are vertically oriented and terminated with Ag/Pd conductor layers, one at the bottom and one on the top of the resistor layer. The piezoresistivity of the thick-film resistor defines the sensitivity of the sensing element.[10] To verify the sensing mechanism we designed a test pattern for the vertical resistor. The dimensions of the resistor layer are $0.6 \times 0.6 \times 0.12$ mm. The larger thickness was obtained with a thicker foil on the stainless steel screen and by repeated printing. In the case of the vertical resistor the thickness of

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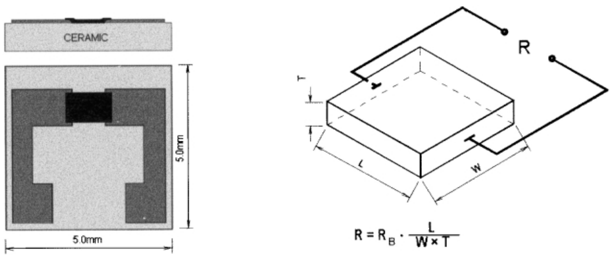

Fig. 1. Conventional (planar) thick-film resistor on the left and a schematic view of the resistor together with an expression for the resistance on the right (not to scale).

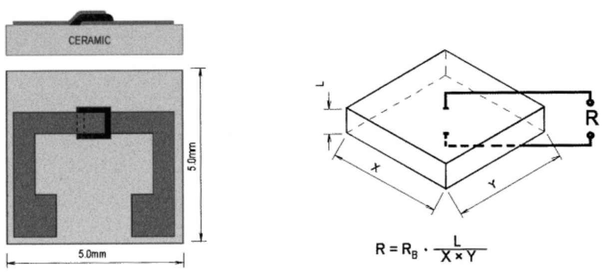

Fig. 2. Vertical thick-film resistor on the left and a schematic view of the resistor together with an expression for the resistance on the right (not to scale).

the resistor layer is the length of the resistor (120 μm). The calculated resistance value of this resistor is 3500 ohm.

Test samples of vertical resistors were produced with three different technologies denoted here with "A", "B" and "C". The technology used for the fabrication of conductive terminals was the same for all samples. First, the conductive layer was printed, dried and fired on the alumina substrate. On this bottom terminal the vertical resistor was built with three different technology procedure described in Table 1. Finally, the second conductive layer was printed, dried and fired as the upper terminal.

The high density and large number of sensing elements in the fine-pitch-array load sensor led us to divide the whole system into a required number of segments each having 16 sensing elements. All the sensing elements are interconnected, at the level of individual segments and also between segments. One segment consists of 16 sensing elements (thick-film resistors) and 16 diodes. Therefore, the final version of the vertical thick-film resistor as a load sensor was designed within one segment of the fine-pitch-array load sensor. To enable the required interconnections of all elements in the final application the vertical thick-film resistors are integrated into a two-layer thick-film circuit on an alumina substrate (19.6 × 19.6 × 1.0 mm^3) and with a dielectric as an insulator. The vertical thick-film resistor is surrounded with a dielectric, schematically shown in Fig. 3. The use of two dielectric layers demands a technology with two additional printing, drying and firing steps.

Table 1
Three different technologies used in the fabrication of vertical resistors

Denotation	Description (P, printing, D, drying, F, firing)
"A"	1st P and D, 2nd P and D, 3rd P and D, 1st F
"B"	1st P and D, 2nd P and D, 1st F, 3rd P and D, 2nd F
"C"	1st P and D, 1st F, 2nd P and D, 2nd F, 3rd P and D, 3rd F

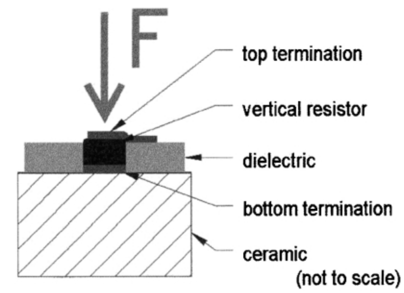

Fig. 3. Schematic drawing of the vertical thick-film resistor surrounded with dielectric.

The mechanical construction and assembly aspects have an important influence on the characteristic of the load sensor. Fig. 4 shows the details of the construction. The ceramic substrate with sensing elements (thick-film resistors), diodes and interconnections is placed on the metal base. A plastic raster matrix for positioning the small metal balls as a force interface is deposited over the ceramic substrate. The small metal balls concentrate the force on the centre of each sensing element.

3. Results and discussion

Cross-sections of the vertical thick-film resistors, realised with technology "B" are shown in Figs. 5 (test structure) and 6 (final version). Conductor, resistor and dielectric are denoted with C, R and D, respectively. Fig. 6 shows the boundary between resistor and dielectric. The thickness of the fired resistors is around 30 μm. During repeated firing the glass phase diffused from the thick-film materials into the alumina substrate to a depth of 20–30 μm. After firing the test structure four times and the final structure six times, the depth of glass diffusion is more pronounced. The conductive phase in the resistor is based on ruthenate. Dark particles in the resistor film are rich in Si and Zr and are presumably $ZrSiO_4$.[11]

Some measured characteristics of the vertical resistors made with technologies "A", "B" and "C" together with those of a conventional planar thick-film resistor are shown in Table 2. In all cases the resistance is lower than the calculated value (3500 ohm) and increases with the number of firings. The noise indices of vertical resistors are significantly higher then noise indices of

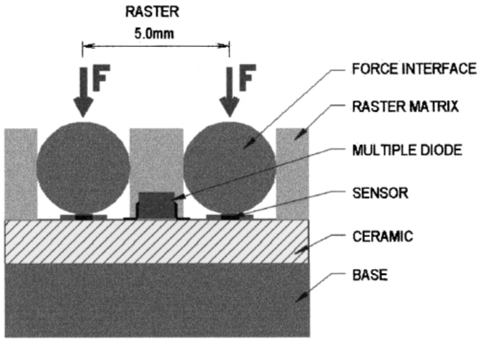

Fig. 4. Structure of the load sensor as a cross-section of two sensing elements.

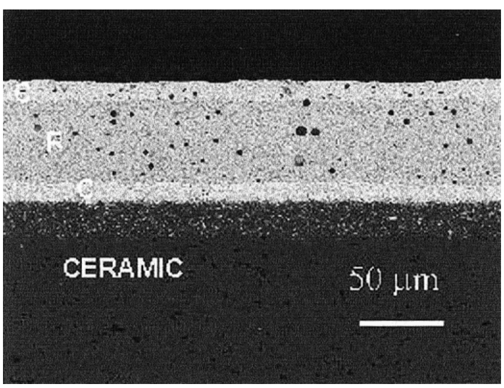

Fig. 5. Cross-section image of a test version of vertical thick-film resistor.

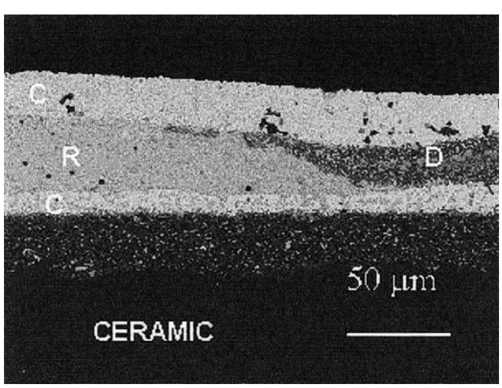

Fig. 6. Cross-section image of final version vertical thick-film resistor.

Table 2
Resistance (R), noise index (NI), and cold (−25–25°C) and hot (25–125°C) TCR of thick-film resistors with sheet resistivity of 1 Mohm/sq

Technology		R (kΩ)	NI (dB)	TCR(10^{-6}/K)	
				(−25–25°C)	(25–125°C)
Vertical resistor	"A"	2.0	31	+135	+180
	"B"	2.5	30	+130	+170
	"C"	2.6	32	80	+100
Planar resistor (1.0×2.5 mm²)		350	11	−20	+40

planar resistors. The results of the resistance (R), sensitivity (dR/R/bar) and linearity (R-squared) measurements on the test samples of the sensing elements are shown in Table 3. The sensitivity (change in resistance as a function of pressure) is about−0.2%/bar and is higher for the higher resistances. The measured resistances of the sensing elements produced with technologies "A", "B" and "C" as a function of pressure are shown in Fig. 7. R-squared values for the linearity of the sensing elements are shown in Table 3 as an R-squared value. R-squared values close to 1 indicate a good linear fit. The results show that the linearity is not very good. A reason for this is perhaps in the relative inaccuracy of the load-pressure measurement. The temperature coefficient of resistance (TCR) is around $+100\ \times 10^{-6}$/K in the temperature range between +25 and +50°C. The temperature dependence of means that at higher temperatures the sensitivity is decreases.

Fig. 8 shows the resistance as a function of load pressure measured at temperatures of 25 and 50°C. The samples were produced with the technology "B". The nonlinearity increases with increasing temperature.

The obtained results show that the sensing elements which were produced with the technology "C" have better characteristics in comparison with those produced with the technology "A" (20% higher sensitivity and 30% higher resistance). But, on the other hand, the thick-film processing time of the technology "C" is about 20% longer.

Table 3
Resistance at 25 and 50°C, sensitivity at 25 and 50°C, and linearity of sensing elements

Technology	R (kΩ)		dR/R (%/bar)		Linearity R-squared
	At 25°C	At 50°C	At 25°C	At 50°C	
"A"	2.030	–	−0.190	–	0.9856
"B"	2.519	2.528	−0.215	−0.205	0.9850
"C"	2.596	–	−0.231	–	0.9895

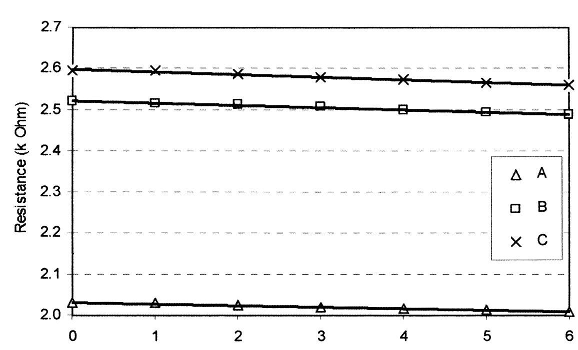

Fig. 7. Resistance of sensing elements produced with three different technologies ("A", "B", "C") as a function of pressure.

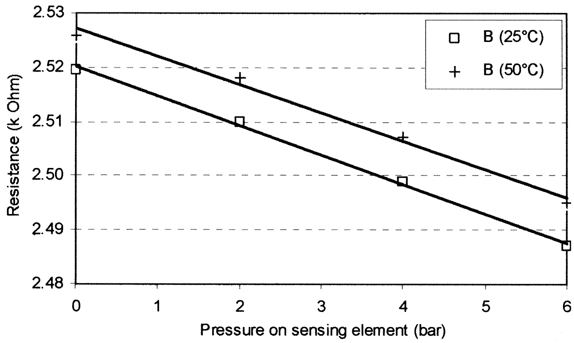

Fig. 8. Resistance of a sensing element produced with technology "B" measured at two different temperatures as a function of pressure.

4. Conclusions

In this contribution we demonstrate that a non-conventional structure of thick-film resistors can be successfully used in a sensor application. For a low-cost fine-pitch-array (multipoint) load-sensor application we developed a special construction of the thick-film resistor as a sensing element. The design is non-conventional in the way that the thick-film resistor is not planar but vertically oriented. In addition, the sensing element was developed to function on the basis of the piezoresistive effect in thick-film resistors, which is an undesirable property in conventional resistor applications. The final design of the vertical thick-film resistor enabled to fabricate a high-density multipoint load sensor with sensing resistor resistances of 2500 ohm and sensitivities (dR/R) of about 1.3% at 6 bar pressure.

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