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THICK FILM SENSING ELEMENTS ON LTCC STRUCTURES

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Key words: thick film resistors, LTCC substrates, gauge factors, electrical characteristics

Abstract: The ceramic micro electro-mechanical systems (Ceramic-MEMS) are fabricated as 3D structures in many cases by the low-temperature co-fired ceramics (LTCC). The sensors of mechanical quantities are fundamental parts of MEMS and thick-film resistor materials can be used to sense mechanical deformations in the MEMS structures. The paper deals with thick film resistors fired on LTCC structures. The microstructures of LTCC tapes were investigated. The compatibility between thick film resistor materials and LTCC tapes was studied. The possible interactions between thick film layers and LTCC substrates were thoroughly investigated by scanning electron microscope and EDX (Energy dispersive Analysis). Thick-film piezo-resistors as strain-gauges were made with 2000 series (Du Pont) resistors with a known good characteristics (i.e., low noise and "superior" stability of fired resistors) and 3414-B (ESL, high gauge factors). Electrical characteristics and gauge factors were evaluated.

Debeloplastni senzorski elementi realizirani v LTCC strukturah

Kjučne besede: debeloplastni upori, LTCC podlage, faktorji gauge, električne karakteristike

Izvleček: Tehnologija LTCC (Low Temperature Co-fired Ceramics - keramika z nizko temperaturo žganja) je zelo primerna za izdelavo keramičnih modulov – tako večplastnih elektronskih vezij kot struktur z membranami, konzolami, mostički, pokopanimi kanali in votlinami. Tipičen primer takega keramičnega mikrosistema so mikro elektro mehanski sistemi (MEMS – Micro Electro Mechanical Systems).

LTCC material se sintra do visoke gostote pri razmeroma nizkih temperaturah, okrog 850°C. Da se material lahko zgosti pri teh nizkih temperaturah, je sestavljen iz nizko taljivega kristalizirajočega stekla in keramičnega polnila, večinoma Al_2O_3. Pred žganjem je LTCC material (zmes steklenih in keramičnih delcev ter polimernega materiala) v obliki fleksibilnih folijah različnih debelin. Na posamezne folije se z metodo sitotiska lahko izdelajo različne debeloplastne strukture. Z laminacijo večjega števila tako pripravljenih folij lahko izdelamo 2D ali 3D LTCC strukture. Nato se laminirane strukture toplotno obdelajo - žgejo - pri višjih temperaturah. Med žganjem polimerni material izgori, steklo pa se zasintra v gosto in neporozno strukturo.

Za različne MEMS aplikacije, realizirane v LTCC tehnologiji, je potrebna tudi integracija senzorjev deformacije oz. tlaka. Kot senzorski elementi za te senzorje se uporabljajo debeloplastni upori z razmeroma visokimi faktorji gauge. Večina teh debeloplastnih materialov je prilagojena za žganje na razmeroma nereaktivnih oz. inertnih Al_2O_3 podlagah. Če izdelamo senzorske elemente na LTCC podlagah, materiali reagirajo s steklasto fazo v podlagah, kar spremeni - v glavnem poslabša - njihove električne karakteristike. V prispevku bomo poročali o preiskavah debeloplastnih uporovnih senzorskih elementov, realiziranih na LTCC strukturah. Podali bomo njihove karakteristike in ocenili uporabnost za senzorske aplikacije.

1. Introduction

Electro-mechanical systems (MEMS) are fabricated from different materials by various technologies. They are mainly produced by the micro-machining of silicon, but in some applications ceramic materials are a very useful alternative. The laminated 3D structures made by Low-Temperature Co-fired Ceramics (LTCC) are especially convenient for ceramic MEMS. The LTCC materials are sintered at the relatively low temperatures around 850°C. To sinter to a dense and non-porous structure at these, rather low, temperatures, it has to contain some (or a great deal) low-melting-point glass phase. LTCCs are based on mixture of crystallisable glass and ceramics filler; for example, alumina /1-5/ .Unfired LTCC tapes are a mixture of glass and ceramic particles, for example, alumina, and an organic phase. During firing, first the organics burn out at around 450°C, leaving a mixture of glass and ceramic particles. At higher temperatures the glass phase melts and the material sinters to a dense and non-porous structure.

The whole process flow of the LTCC technology is schematically shown in Fig. 1. The green tapes are cut into the required dimensions. Vias are punched and filled with a conductor material. After this the conducting layers are screen printed. The substrates are then visually examined and put together into multilayer "packets. These "packets" are laminated under a pressure at temperatures around 80°C and fired at relatively low temperatures of around 850°C, which are typically used for thick-film processing.

Sensors for mechanical quantities are often fundamental parts of MEMS, and screen printed and fired thick-film resistor can be used to sense the mechanical deformations in MEMS structures. Some characteristics of fired LTCC

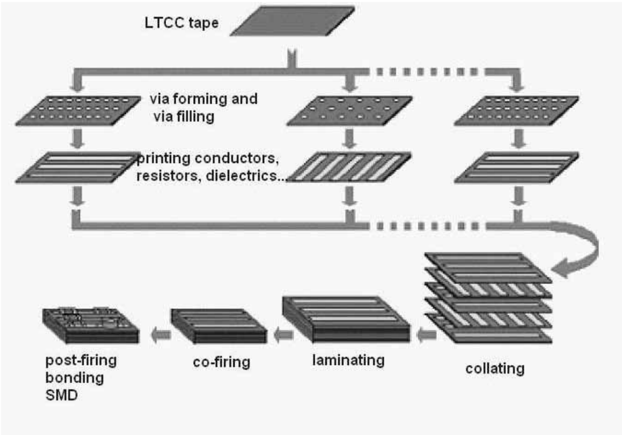

Fig. 1: Schematically presented the process flow of the LTCC technology

materials as compared with alumina for which most thick film materials are optimised are listed in Table 1.

Table 1: Some characteristics of LTCC and 94-99.5% Al_2O_3 ceramics

Property	LTCC	Al_2O_3 94-99.5%
TCE (10^{-6}K)	5.8-7	7.6-8.3
Density (g/cm^2)	2.5-3.2	3.7-3.9
Flexural strength (MPa)	170-320	300
Young modulus (GPa)	90-110	215-415
Thermal cond. (Wm/K)	2-4.5	20-26
Diel. Constant	7.5-8	9.2-9.8
Loss tg. ($x10^{-3}$)	1.5-2	0.5
Resistivity (ohm.cm)	10^{12}-10^{14}	10^{12}-10^{14}
Breakdown voltage (V/100μm)	>4000	3000-4000

Arguably the most important are relatively low elastic moduli of LTCC ceramics as compared with alumina ceramics. This means an increased sensitivity of sensing elements due to the larger deformation. In other words, for the same dimensions of the substrate / diaphragm the operating range

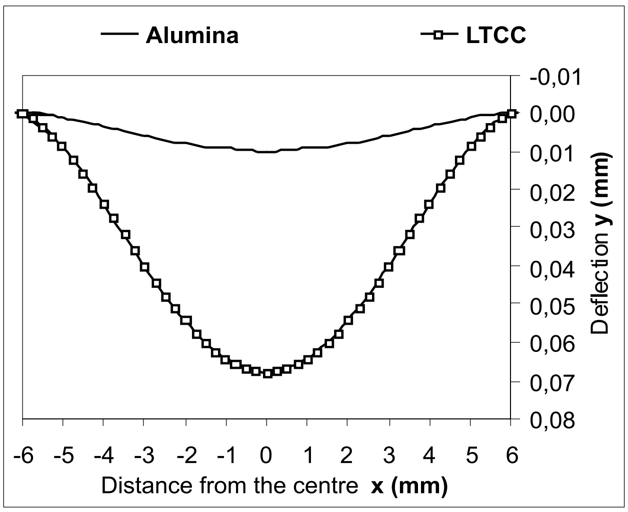

Fig. 2: The deflections of diaphragms made with the alumina and the LTCC at an applied pressure of 100 kPa

can be extended. The deformations of alumina and LTCC based membranes under same conditions are presented in Fig. 2. Some sensors and structures, realised in the LTCC technology are presented in Fig. 3.

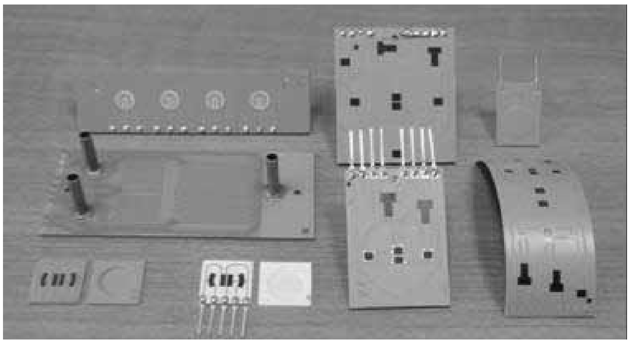

Fig. 3: Some sensors and 3D structures realised in the LTCC technology

The changes in resistance of a resistor under an applied stress are partly due to deformation, i.e. the changes in the dimensions of the resistor, and partly due to an alteration in the specific resistivity as a result of changes in the microstructure of the material /6/. The gauge factor (*GF*) of a resistor is defined as the ratio of the relative change in resistance ($\Delta R/R$) and the strain ($= \Delta l/l$):

$$GF = \frac{\Delta R/R}{\Delta l/l} \tag{1}$$

Geometrical factors alone result in gauge factors of 2-2.5. Gauge factors higher than this are due to microstructural changes, i.e. changes to the specific conductivity. The GFs of thick-film resistors are mostly between 3 and 15. Within the same resistor series the GFs and the current noise indices of thick-film resistors increase with increasing sheet resistivity /7,8/. Therefore, in most cases resistors with intermediate sheet resistivities are used for the strain sensors as a useful compromise between sensitivity and relatively low noise and also because of their relatively low power consumption. Prototypes of sensors with piezoresistive sensing elements on alumina and on LTCC are shown in Fig. 4.

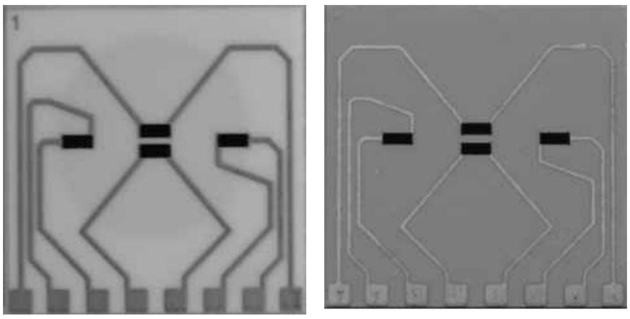

Fig. 4: Prototypes of pressure sensors with piezoresistive elements realised on alumina (left) and LTCC (right)

The Du Pont (DP) 951 LTCC tapes were evaluates as they are, at least according to the data from the literature, the material which is most widely used. For strain sensors 2041 (Du Pont, 10 kohm/sq.) and 3414-B (Electro Science Labs., 10 kohm/sq.) resistors were evaluated. The 2041 resistor was chosen because of its low noise whereas the 3414-B was developed specially for use in strain gauges /8/. As a reference resistors were printed and fired on alumina substrates.

2. Experimental

The LTCC substrates were made by laminating three layers of LTCC tape at 70°C and a pressure of 20 MPa. The laminated green tapes were fired for 1 hour at 450°C (organic binder burnout) and 15 minutes at 875°C.

Thick film resistors printed on LTCC and alumina substrates were terminated by Pd/Ag conductors and fired. The dimensions of the resistors for microstructural analysis and X-ray diffraction (XRD) analysis, which were printed and fired without conductor terminations, were 12.5x12.5 mm^2.

The changes of resistivity as a function of substrate deformation (gauge factors) were measured with the simple device. The ceramic substrate is supported on both sides. The load is applied to the middle of the substrate with a micrometer and this induces a tensile strain in the resistor. The magnitude of the strain is given by the equation (2) /9/.

$$\varepsilon = \Delta l/l = \frac{6\,d\,t}{L^2}\left(1-\frac{l}{2\,L}\right)\left(1-\frac{2\,x}{L}\right) \qquad (2)$$

where d is deflection, t is substrate thickness, L is distance between support edges, l is resistor length and x is distance from the centre. The gauge factors are calculated using equations (1) and (2) from the strain and resistivity changes. The test structures with resistors (the bending test) are shown in Fig. 5.

Cold (from −25°C to 25°C) and hot (from 25°C to 125°C) TCRs were calculated from resistivity measurements at −25°C, 25°C, and 125°C. The current noise was measured in dB on 100 mW loaded resistors using the Quan Tech method (Quan Tech Model 315-C).

For the microstructural investigation the samples 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)

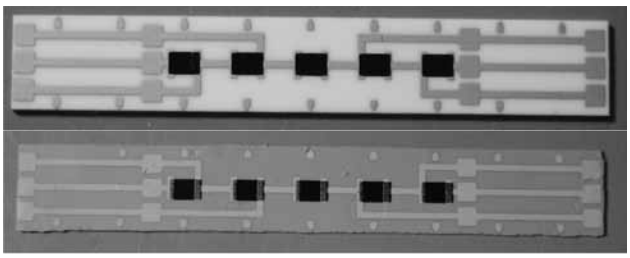

Fig. 5: Test structures for resistivity vs. deformation measurements. An alumina substrate is on the top and a LTCC substrate on the bottom

equipped with an energy-dispersive X-ray analyser (EDS) was used for the overall microstructural and compositional analysis. Prior to analysis in the SEM, the samples were coated with carbon to provide electrical conductivity and to avoid charging effects.

3. Results and discussion

The microstructures of the green and the fired LTCC material are shown in Figs. 6.a and 6.b, respectively /4,6/. The unfired material is a mixture of darker alumina and lighter glass particles. After firing the material is densely sintered with dark alumina grains in the glass matrix.

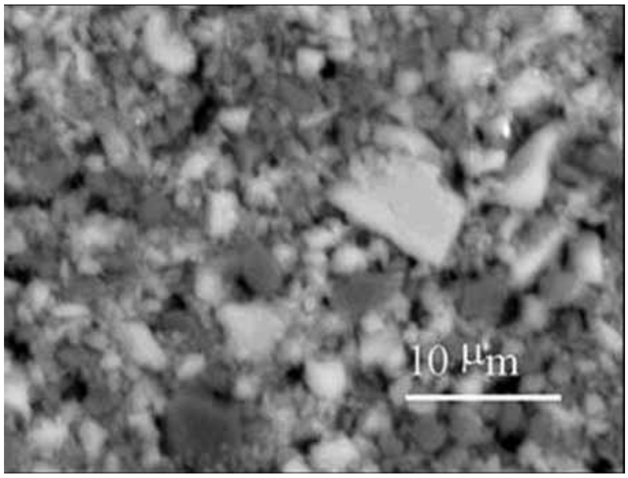

Fig. 6a: Microstructure of a green LTCC tape

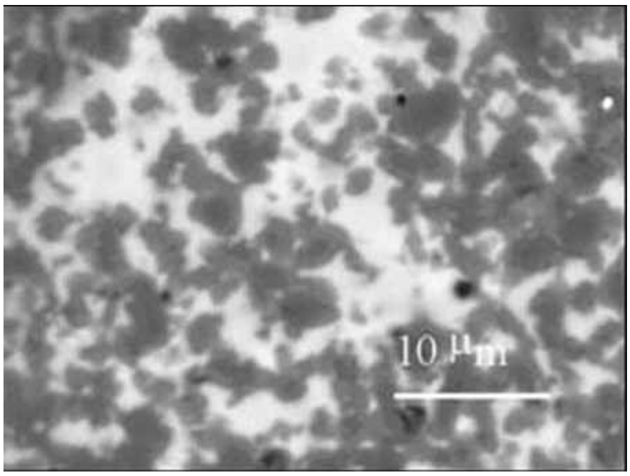

Fig. 6b: Microstructure of a LTCC tape fired at 875°C

Electrical characteristics of thick film resistors fired on alumina (used as a reference) and LTCC substrates, i.e. sheet resistivities, cold (from -25°C to 25°C) and hot (from 25°C to 125°C) TCRs, noise indices and gauge factors are presented in Table 2. Noise indices are given in dB and in uV/V.Resistivities vs. temperature are shown in Figs. 7.a and 7.b for 2041 and 3414 resistors, respectively. Gauge factors of resistors which are important for “sensing” characteristics are more or less independent of substrates and are between 10 and 11 for 2041 and around 19 for 3414

Table 2: Sheet resistivities, cold and hot TCRs, noise indices and gauge factors

Resistor	Substrate	Sheet resistivity (kohm/sq.)	CTCR (10^{-6}/K)	HTCR (10^{-6}/K)	Noise (dB)	Noise (μV/V)	GF
2041	Al_2O_3	8.0	-55	15	-21	0.09	10.5
	DP 951	12.5	-40	20	-20	0.10	11.4
3414-B	Al_2O_3	2.9	-45	-15	-4	0.63	19.1
	DP 951	9.3	-430	-360	5	1.74	18.8

resistors. In the case of 2041 resistors the other electrical characteristics are not changed too much when fired on LTCC substrates. In the case of 3414-B resistors sheet resistivities, TCRs and noise indices increased significantly indicating that characteristics of this material "sensitive" to reactions between glassy LTCC substrates and active layers. The results indicate that the 2041 resistors could be used as sensing elements when fired on Du Pont 951 LTCC substrates while 3414 resistors are still useful due the high gauge factors but high noise indices and very high TCRs must be taken in the consideration.

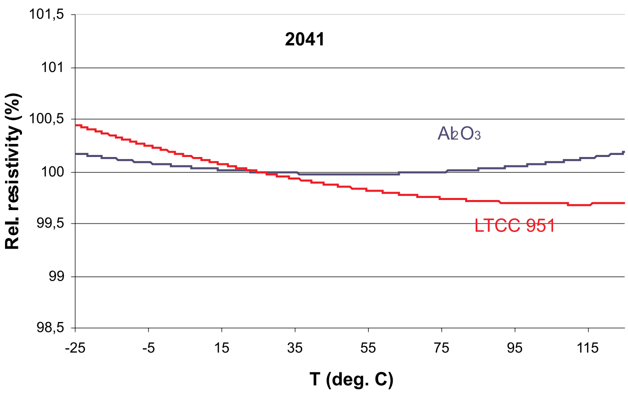

Fig. 7a: Resistivities vs. temperature for 2041 resistors fired on alumina and LTCC substrates

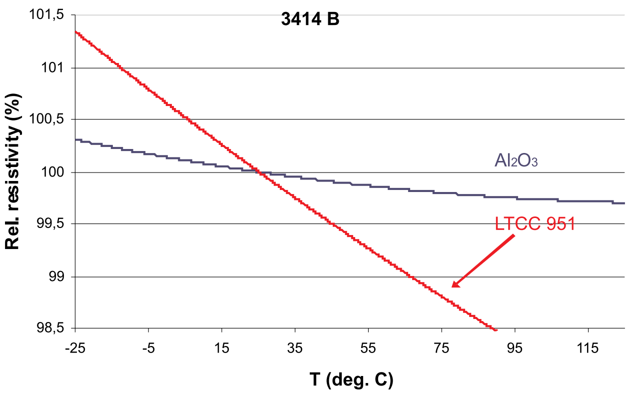

Fig. 7b: Resistivities vs. temperature for 3414 resistors fired on alumina and LTCC substrates

The microstructures of 2041 and 3414 resistors on LTCC substrates are shown in Figs. 8.a and 8.b, respectively. The formation of a new phase at the 2041 / LTCC interface can not be observed. .In the case of the 3414 resistor the lighter layer formed at the resistor / LTCC interface. The light phase in this layer contains over 12 mol. % of PbO which indicates the diffusion of a PbO rich glass from the resistor into the LTCC during firing. That means more extensive interactions between 3414 resistors and glassy LTCC substrates and thereof more significant influence on resistors' characteristics.

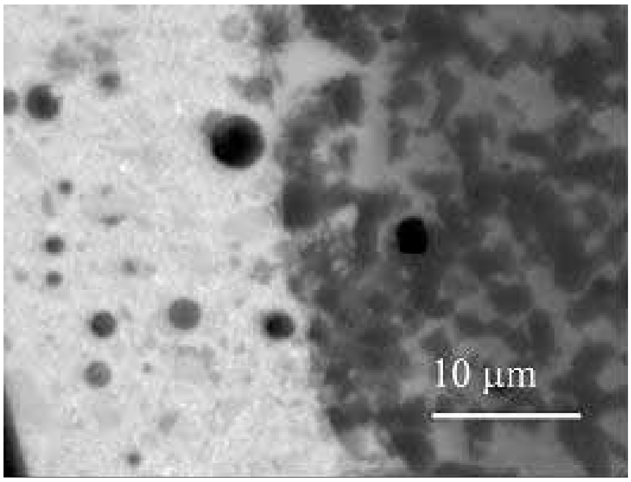

Fig. 8a: Cross-section of the 2041 resistor fired at 875°C on the LTCC substrate

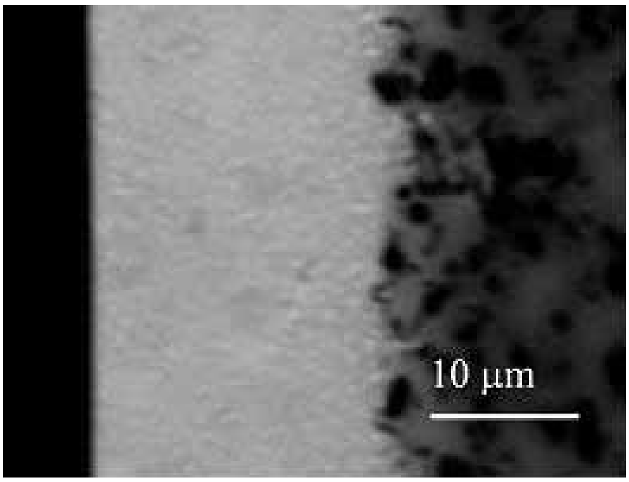

Fig. 8b: Cross-section of the 3414 resistor fired at 875°C on the LTCC substrate

4. Conclusions

Thick film resistors 2041 (Du Pont, 10 kohm/sq.) and 3414-B (Electro Science Labs., 10 kohm/sq.) resistors were printed and fired on alumina and LTCC substrates. Electrical characteristics and gauge factors were measured. The interactions between glassy LTCC materials and resistors were investigated by SEM and EDS. Gauge factors of resistors which are important for "sensing" characteristics are more or less independent of the substrates and are between 10 and 11 for 2041 and around 19 for 3414 resistors. In the case of 3414-B resistors sheet resistivities, TCRs and noise indices increased significantly indicating that characteristics of this material "sensitive" to reactions between glassy LTCC substrates and active layers. SEM and EDS analysis did not detect he formation of a new phase at the 2041 / LTCC interface. .In the case of the 3414 resistor the lighter PbO rich layer formed at the resistor / LTCC interface. These results indicate interactions between 3414 resistors and glassy LTCC substrates which influence the resistors' electrical characteristics.

Acknowledgments

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