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The application of thick-film technology in C-MEMS

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Abstract Laminated 3D structures made using low-temperature co-fired ceramic (LTCC) technology are practical for ceramic micro-electro-mechanical systems (C-MEMS). The sensors for mechanical quantities, and/or actuators, are fundamental parts of MEMS. Thick-film resistors can be used to sense the mechanical deformations, and thick-film piezoelectric materials can be used as electro-mechanical transducers in a C-MEMS structure. The integration of these thick-film materials on LTCC substrates is in some cases difficult to realise due to interactions with the rather glassy LTCC substrates. The subject of our work is an investigation of thick-film materials for electro-mechanical transducers (sensors and actuators) and their compatibility with LTCC substrates. Resistors made with commercial thick-film resistor materials for use as sensors on LTCC substrates have been investigated and evaluated. Ferroelectric ceramic materials based on solid solutions of lead zirconate titanate (PZT) with low firing temperatures around 850°C were developed for thick-film technology and evaluated on LTCC substrates.

Keywords Thick-film · LTCC substrate · Ceramic MEMS · Sensors · Actuators

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1 Introduction

The acronym MEMS stands for micro-electro-mechanical systems, and was used for the first time in the United States in the late 1980s. Around the same time, Europeans were using the phrase microsystems technology (MST). MEMS are miniature devices that convert physical quantities to or from electrical signals and which depend on the mechanical structures, materials and other parameters. MEMS refers to devices that have a characteristic length of less than 1 mm but more than 1 μm, and that combine electrical and mechanical components. A microsystem might comprise one or more sensors and/or actuators and an electronic circuit that conditions the sensor signal and/or generates an electrical signal for the actuator. MEMS can be fabricated with a variety of technologies and from a range of materials. Most MEMS are made by micro-machining silicon, but in some applications ceramic materials are a very useful alternative. These ceramic micro-electro-mechanical systems (C-MEMS) are typically larger (in the meso-size) and mostly used in a harsh environment. The laminated 3D structures made by LTCC (low temperature cofired ceramic) technology is especially suitable for C-MEMS [1–8]. Both the sensors for mechanical quantities and the actuators are fundamental parts of MEMS. The most important technology for manufacturing sensors and actuators in C-MEMS is thick-film technology. The thick-film resistor can be used to sense, and piezoelectric materials can be used to actuate, the mechanical deformations in MEMS structures. Thick-film technology can be used in C-MEMS not only to produce the sensor and actuator elements themselves but also the electronic circuits for the signal processing [3–6].

Packaging issues are very important and challenging for the applicability of MEMS because they are usually

Table 1 Some characteristics of sintered LTCC.

Characteristic	LTCC
TEC ($\times 10^{-6}$/K)	5–7
Density (g/cm^2)	2.5–3.2
Flexural strength (MPa)	170–320
Young's modulus (GPa)	90–110
Thermal cond. (W/mK)	2–4.5
Dielectric constant	7.5–8
Loss tg. ($\times 10^{-3}$)	1.5–2
Resistivity (ohm.cm)	10^{12}–10^{14}
Breakdown (V/100 μm)	>4,000

sensitive to mechanical or thermo-mechanical stresses. LTCC technology also has many benefits for the packaging of silicon-based MEMS. Firstly, it is possible to make cavities in the substrate in which the silicon-based MEMS can be bonded and hermetically sealed. Secondly, the match between the linear thermal expansion coefficient (TEC) of the ceramics and the Si is fairly good (2.6×10^{-6}/K vs. 5–7×10^{-6}/K for LTCC), which is very important for sensitive MEMS devices in wider-temperature-range applications [1, 3]. The combination of silicon- and ceramic-based MEMS formed in a hybrid structure is called a hybrid micro-electro-mechanical system (H-MEMS).

2 Low-temperature cofired ceramics

Advanced ceramic technologies, like low-temperature cofired ceramic (LTCC), are a rapidly growing part of the hybrid electronic-module markets in Europe. More than 25% of this market in the year 2004 belonged to LTCC technology. LTCC technology is a three-dimensional ceramic technology utilizing the third dimension (*z*) for the interconnects layers, the electronic components, and the different 3D structures, such as cantilevers, bridges, diaphragms, channels and cavities. It is a mixture of thick-film and ceramic technologies. Thick-film technology contributes the lateral and vertical electrical interconnections, and the embedded and surface passive electronic components (resistors, thermistors, inductors, capacitors). Ceramic technology contributes the electrical, mechanical and dielectric properties as well as different 3D structures [7, 8].

LTCC materials in the green state (called green tapes, before sintering) are soft, flexible, and easily handled and mechanically shaped. A large number of layers can be laminated to form high-density interconnections and three-dimensional structures. The fabrication process includes several steps, which are named LTCC technology. The separate layers are the mechanical shaping of mesosize features (0.1–15 mm), and then the thick-film layers are the screen-printing. All the layers are then stacked and laminated together with hot pressing. This laminate is sintered in a one-step process (cofiring) at low temperatures (850–900°C) to form a rigid monolithic ceramic multilayer circuit (module). Some thick-film materials need to be post-fired; that means the paste needs to be screen-printed on the pre-fired laminate and has to be fired again. The whole LTCC process saves time, money and reduces the circuit's dimensions compared with conventional hybrid thick-film technology. The important advantage for MEMS applications is the lower Young's modulus (about 100 GPa) of LTCC materials in comparison with alumina (about 340 GPa). The disadvantages of LTCC technology are a lower thermal conductivity (about 2.5–4 W/mK) in comparison with alumina and the shrinking (about 10–15% in x/y-axis and about 10–45% in z-axis) of the tape during the sintering. Some of the characteristics of fired LTCC laminates are presented in Table 1.

The LTCC tape consists of alumina and glass particles suspended in an organic binder. The materials are either based on crystallisable glass or a mixture of glass and ceramics, for example, alumina, silica or cordierite ($Mg_2Al_4Si_5O_{18}$) [9]. The composition of the inorganic phase in most LTCC tapes is similar to, or the same as, materials in thick-film multilayer dielectric pastes. To sinter to a dense and non-porous structure at these, rather low, temperatures, it has to contain some low-melting-point glass phase. This glass could presumably interact with other thick-film materials, leading to changes in the electrical characteristics [9–12]. The composition of a typical LTCC material is shown in Fig. 1.

Due to the chemical composition of an LTCC material and the shrinking during sintering of an LTCC tape, special thick-film materials (conductive and resistor pastes) were developed. On the other hand, some special thick-film

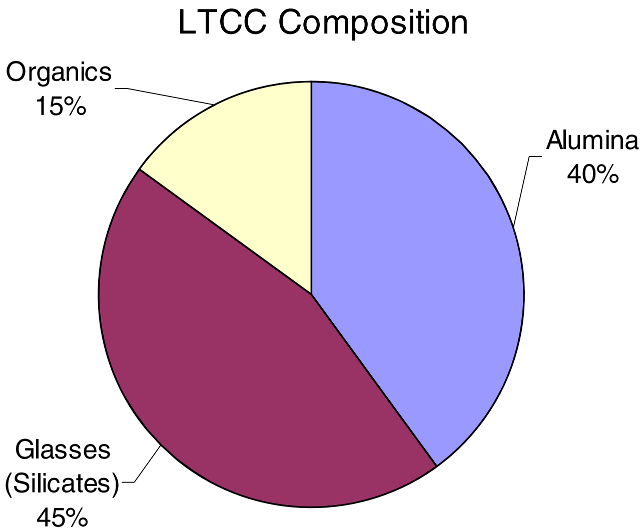

Fig. 1 The composition of a typical LTCC material (wt.%)

materials, such as thick-film sensors (thermistors, strain gauges, etc.), have not yet been developed for applications on LTCC tape. In this case some standard thick-film materials can also be used on pre-fired LTCC laminate and/or on green tape. But before their application the compatibility and characteristics of these materials must be carefully investigated and evaluated.

3 Thick-film resistors on LTCC

Thick-film resistors can exhibit a rather large piezoresistive effect, a property which is usually undesirable in a standard thick-film-circuit application. Therefore, thick-film resistor materials with a higher sensitivity to strain can be used in strain-sensing applications in C-MEMS applications. The strain gauge is a device that is capable of translating a deformation (strain) into an electrical signal. The working principle is piezoresistivity: the property of some materials to change their resistivity under strain. The sensitivity to strain of a certain material is referred to as the gauge factor (GF). The gauge factor (GF) of a resistor is defined as the ratio of the relative change in resistance ($\Delta R/R$) and the strain ($\Delta l/l$):

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

Geometrical factors alone result in gauge factors of 2–2.5. Gauge factors higher than this are due to micro-structural changes, i.e., changes to the specific conductivity. The GFs of thick-film resistors are mostly between 3 and 20 [13–18]. Choosing the proper thick-film material, and the design and location of the sensing resistors, allows the MEMS designer to predict how the resistor will change in value for a given deformation. Strain-gauge thick-film sensing elements made on or within LTCC structures should have some improved characteristics in comparison with components on alumina substrates, due to their lower modulus of elasticity. For the same thickness of the layer/substrate the operating range can be extended [7–9].

In this article the evaluation of different thick-film materials for use in strain sensors on LTCC 951 (Du Pont) substrates is described. The evaluated materials for strain sensors were 10 k ohm/sq. resistors 2041 (Du Pont), 3414-B (Electro Science Labs.) and CF-041 (Du Pont). With the exception of the CF-041 resistors, these thick-film resistors are developed for firing on alumina substrates. Therefore, their compatibility and interactions with the rather glassy LTCC substrates, leading to changes in the electrical characteristics, need to be evaluated. The obtained results are compared with the characteristics of samples on alumina substrates.

4 Experimental

The LTCC substrates were made by laminating three layers of the 951 LTCC tape at 70°C and at a pressure of 20 MPa. The green LTCC tapes were fired for 1 h at 450°C (organic binder burnout) and 15 min at 875°C. The thick-film resistors were screen printed on alumina (which was used as a reference) and on green and pre-fired LTCC substrates, and then co-fired with LTCC tape or fired for 10 min at 850°C (2041 and 3414-B) or 875°C (CF-041). Test samples on LTCC and alumina substrates are shown in Fig. 2. The test pattern has five longitudinally oriented resistors in a line, with dimensions of 1.6×1.6 mm^2. All the substrates were 47.25-mm long and 7.00-mm wide.

Cold (from −25 to 25°C) and hot (from 25 to 125°C) temperature coefficients of resistivity (TCR) were calculated from resistivity measurements at −25, 25, 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). The piezoresistive property of the thick-film resistor was measured using the bending-bridge method [16]. The applied force caused a deflection of the bridge and, consequently, a change in the resistance of the thick-film resistor. This deflection and the change in the resistance were measured and the strain and gauge factor were calculated. The test samples were measured at six different temperatures (−35, −25, 25, 75, 125 and 150°C). The measurements were repeated several times on the test samples, which were unloaded and loaded with different weights. For the different loads (weights) the deflection (d) in the middle of the bridge was calculated using Eq. 2, and the following data: weight-induced force (F), bridge length (L), bridge width (W), resistor length (l), bridge thickness (a) and Young's modulus (E). Then the strains (ε) for each of the resistors, which were at different distances from the centre (x=0, ±5 and ±10 mm), were calculated using Eq. 3. Finally, the gauge factors were calculated from the resistivity changes and the strains using Eq. 1.

$$d = \frac{FL^3}{4a^3WE} \tag{2}$$

$$\varepsilon = \frac{6da}{L^2}\left(1-\frac{l}{2L}\right)\left(1-\frac{2x}{L}\right) \tag{3}$$

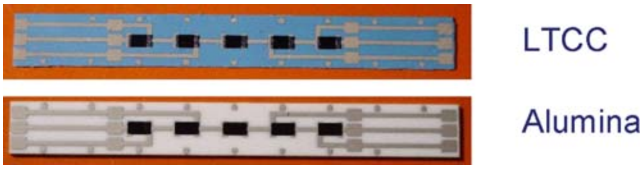

Fig. 2 Test samples of thick-film resistors on LTCC and alumina substrates

5 Results and discussion

Sheet resistivities, cold (−25 to 25°C) and hot (25–125°C) TCRs, noise indices and gauge factors are shown in Table 2. For a comparison the results for the 2041 and 3414-B resistors fired on alumina, denoted “2041 Al_2O_3” and “3414-B Al_2O_3,” are also shown.

The sheet resistivities of the 2041 resistors on both substrates are comparable and in the range ±30%. The TCRs are about or under 50×10^{-6}/K on both substrates. The noise indices have relatively low values on both substrates. The gauge factors are about 12 on the alumina substrate and about 10% lower on the LTCC substrate. The temperature coefficients of the gauge factor (TCGF) are negative and are under -200×10^{-6}/K.

The sheet resistivities of the 3414-B resistors on the LTCC increase by more than 200% in comparison with the alumina substrate. These results indicate an interaction between the 3414-B resistors and the LTCC substrates. One of the possibilities is the diffusion of the glass phase from the LTCC into the resistor during firing, which could dilute the concentration of the conductive phase in the resistor, so leading to higher sheet resistivities. The TCRs of the 3414-B resistors are negative. The TCRs on the alumina substrate are lower than 100×10^{-6}/K, while the TCR values on the LTCC substrates are six times higher. We presume that the high and negative TCRs are due to two factors: first, the lower concentration of the conductive phase in the resistor material because of the diffusion of the glass phase from the LTCC; and second, the lower thermal expansion coefficient of the LTCC. The noise indices of the 3414-B resistors on the alumina substrate are relatively high, but they are as much as five times higher on the LTCC substrates. The TCGFs of the 3414-B resistors on the alumina substrate are about -100×10^{-6}/K, and two to three times higher on the LTCC substrates.

The CF-041 resistor material was developed for screen-printing on green LTCC tape and then co-firing. We investigated these resistors only on co-fired LTCC substrates. The results show a very low sensitivity to strain—the gauge factors are about 3. Therefore, the CF-041 resistor material is not suitable for sensor applications.

6 Thick-film PZT layers on LTCC

Piezoelectric ceramics are used in a wide range of sensors, actuators and transducers that are important in diverse fields such as industrial process control, environmental monitoring, communications, information systems, and medical instrumentation. Thick-film technology, i.e., the deposition of thick-film pastes by screen printing, primarily on alumina substrates, is a relatively simple and convenient method for producing piezoelectric layers with a thickness of up to 100 μm. The characteristics of thick-film ferroelectrics are similar to those of bulk materials [19]. The compositions of piezoelectric thick-films are almost exclusively based on $Pb(Zr_{1-x}Ti_x)O_3$ solid solutions, often referred to as PZT. The PZT material for actuators was a ferroelectric thick-film paste based on PZT 53/47 powder ($PbZr_{0.53}Ti_{0.47}O_3$). This composition was chosen because it is at the morphotropic phase boundary (MPB) between rhombohedral (ZrO_2 rich) and tetragonal (TiO_2 rich) PZT solid solutions. The PZT ceramics with the composition at the MPB have enhanced piezo electric and ferro electric characteristics [20]. The material was made at the Joef Stefan Institute. Preliminary experiments indicated that due to the interaction between the printed PZT layers and the LTCC substrates during firing the electrical characteristics deteriorate significantly [21, 22].

7 Experimental

PZT 53/47 powder ($PbZr_{0.53}Ti_{0.47}O_3$) with an excess of 6 mol% PbO was prepared by mixed-oxide synthesis at 900°C for 1 h from high-purity oxides: PbO (litharge) 99.9% (Fluka), ZrO_2 99% (Tosoh), and TiO_2 99% (Fluka). To this was added 2 wt.% of lead germanate, with the composition $Pb_5Ge_3O_{11}$ (melting point 738°C) as a sintering aid. Lead germanate (PGO) was also prepared by mixed-oxide synthesis from PbO and GeO_2 99% (Ventron) at 700°C. After the synthesis, both compositions were ball milled in acetone for 1 h and dried. A thick-film paste was prepared from the PZT (2% PGO) and an organic vehicle

Table 2 Sheet resistivities, cold (−25 to 25°C) and hot (25–125°C) TCRs, noise indices, gauge factors and temperature coefficients of the gauge factor of the 2041, 3414-B and CF-041 resistors on different substrates.

Resistors/substrate	T fir. (°C)	$R_{sq.}$ (ohm)	CTCR (10^{-6}/K)	HTCR (10^{-6}/K)	Noise (dB)	GF	TCGF (10^{-6}/K)
2041/Al_2O_3	850	9.0 k	−10	35	−23	11.5	−170
2041/Cofired LTCC	850	6.2 k	20	60	−19	10.0	−140
2041/Prefired LTCC	850	10.8 k	−30	15	−19	10.5	−140
3414-B Al_2O_3	850	3,0 k	55	70	8	24.0	−100
3414-B/Cofired LTCC	850	88.1 k	−360	−330	>33	21.5	−300
3414-B/Prefired LTCC	850	64.8 k	−360	−310	>33	20.5	−220
CF-041/Cofired LTCC	875	19.6 k	200	235	−5	3.0	/

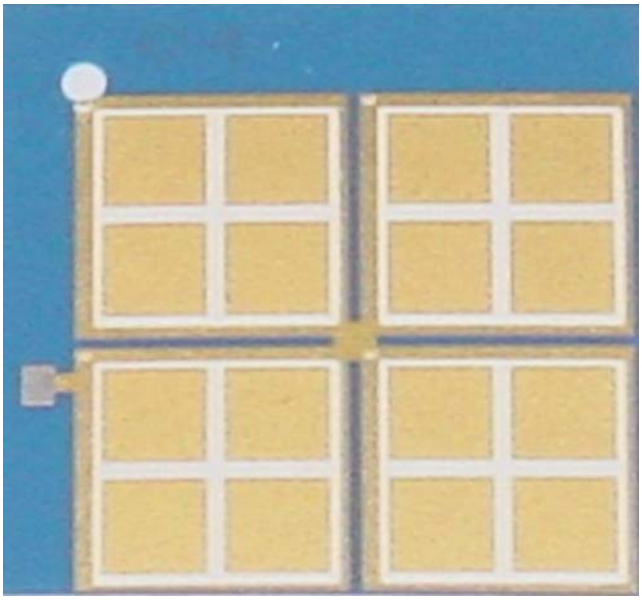

Fig. 3 The test sample of 16 elements (capacitors)

(ethyl cellulose, alpha-terpineol and butil carbitol acetate) by mixing on a three-roller mill.

The test pattern consists of 16 elements (capacitors) with lateral dimension 4.7×4.7 mm. The test sample is shown in Fig. 3. The thick-film structures shown in Fig. 4 were made on alumina (which was used as a reference) and on pre-fired LTCC substrates by first printing a bottom electrode (gold thick-film conductor) and fired for 10 min. The PZT paste was printed twice and fired, and then again printed twice and fired for 18 min. Then the upper gold electrode was printed and fired. The firing temperature for all the layers was 850°C. Some samples had an intermediate barrier layer, based on PZT, between the LTCC substrate and the PZT structure. The thickness of the PZT films after the thermal treatment was around 50 μm. The dielectric permittivity and the dielectric losses were measured with an HP-4284 Precision LCR Meter at 1 kHz. The samples were heated to 160°C and polarised with an electrical field of 100 kV/cm for 20 min and then cooled to room temperature. The values of the piezoelectric coefficient d_{33} were estimated by using the conventional Berlincourt method at 100 Hz with a "Piezometer system PM 10." The standard samples for this method are bulk pellets with defined dimensions. However, for a measurement of the piezoelectric properties of thin and thick films one has to keep in mind that the film is always clamped to a substrate. Therefore, the measured values do not represent the piezoelectric coefficient d_{33}, of the free samples, but an effective coefficient and the obtained values are only used for the benchmarking of different technologies.

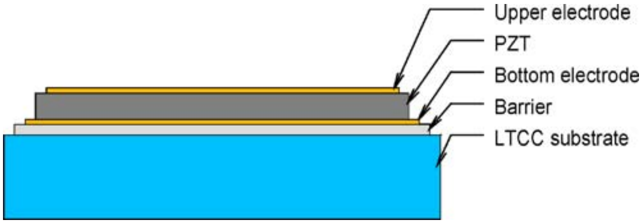

Fig. 4 Basic PZT/LTCC structure (schematics-not to scale)

Table 3 Electrical characteristics (dielectric constant ε', dielectric loss tg δ, and piezoelectric constant d_{33}) of the PZT layers an alumina and LTCC substrates.

Sample	ε	tg δ	d_{33} (pC/N)
Alumina	520	0.016	120
LTCC	180	0.014	55
LTCC+B	230	0.011	65

8 Results and discussion

In Table 3 the electrical parameters, i.e., the dielectric constant ε', the dielectric loss tan δ, and the piezoelectric constant d_{33}, of the thick-film structures fired at 850°C on alumina and LTCC substrates are presented. The electrical parameters are shown graphically in Fig. 5. The samples are denoted according to the substrates as "alumina," "LTCC" and "LTCC+B" (samples with an interposed PZT barrier). The value of the dielectric constant of the thick-film PZT layers on alumina is 520, and the value of the piezoelectric constant is 120 pC/N. For comparison, the dielectric constant and the piezoelectric constant d_{33} of the bulk PZT 53/47 ceramic are around 1,000 and 200 pC/N, respectively [23]. The electrical characteristics of the PZT fired on the LTCC substrate deteriorated due to interactions between the LTCC substrate and the PZT layer. The dielectric and piezoelectric constants of the samples are considerably lower than those on the alumina substrates. The dielectric constants of the samples without the PZT

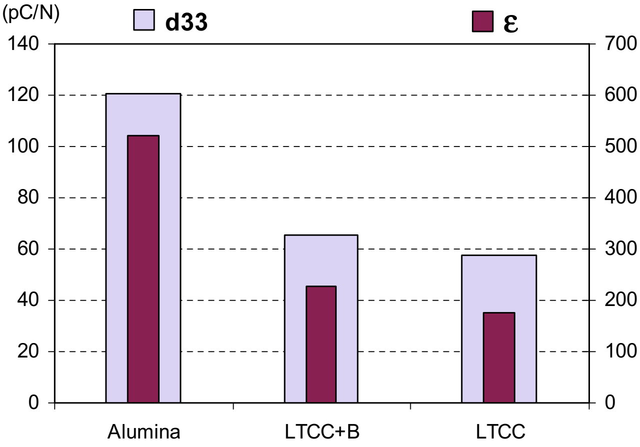

Fig. 5 Dielectric and piezoelectric constants d_{33} of PZT layers on alumina and LTCC substrates. Samples with the PZT barrier are denoted LTCC+B

barrier are 180, and for those samples with the barrier the value is 230. Both sets of samples have values of the piezoelectric constant d_{33} about two times lower than those on the alumina substrates. The low dielectric constants of the PZT on the LTCC substrate are attributed to the diffusion of SiO_2 from the LTCC into the active PZT layer. The silica presumably reacts with the PZT, forming low-permittivity lead-based silicates resulting in a lower dielectric constant. The additional barrier layer improves the parameters by about 20%, but this layer does not hinder the diffusion of silica, but it prevents the loss of lead oxide from the active PZT layer.

9 Conclusions

The compatibility of thick-film materials with LTCC substrates was studied. Thick-film resistors were evaluated as sensors of mechanical quantities in C-MEMS. The comparison of two thick-film materials—2041 (Du Pont) and 3414-B (ESL)—suggested a better cost-performance ratio for the 2041 resistor material. This material is also less sensitive to the manufacturing process and the type of substrate. The third resistor material—CF-041—has a very low sensitivity to strain and therefore is not suitable for sensor applications. Thick-film PZT material was evaluated as a possible actuator in C-MEMS. For the investigation of properties the thick-film PZT ($Pb(Zr_{0.53}Ti_{0.47})O_3$) paste was screen-printed and fired on alumina and LTCC substrates. The values of the dielectric constant and the piezoelectric constant (d_{33}) of the PZT films on LTCC substrates were less than half those of the values on alumina. The additional PZT barrier layer improves these values by about 20%. The future work will be aimed to optimise the characteristics of active PZT layers with improved processing.

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