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Technology and applications of Low Temperature Cofired Ceramic (LTCC) based sensors and microsystems

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Abstract. The paper presents general information on LTCC materials, manufacturing processes and properties of fired modules. A Multichip Module package has been the main application of Low Temperature Cofired Ceramic (LTCC) technology. Recently, this technology is also used for production of sensors, actuators and microsystems. The research and development on the LTCC sensors and microsystems carried out in the Laboratory of Thick Film Microsystems at Wroclaw University of Technology are presented. LTCC microfluidic system is described in detail. Moreover, a short information is given on other LTCC applications .

Key words: thick film, LTCC, sensor, microsystem, microfluidic.

1. Introduction

The Low Temperature Cofired Ceramic (LTCC) technology has been used for almost twenty years to produce Multichip Ceramic Modules MCM-C) – a multilayer substrate for packaging integrated circuits [1–6]. At the beginning, the technology was mostly used for production of high volume microwave devices. Recently, LTCC was also applied for the production of sensors and actuators thanks to its very good electrical and mechanical properties, high reliability and stability as well as possibility of making three dimensional (3D) integrated microstructures. The LTCC technology is well established both for low volume high performance application (military, space) and high volume low cost application (wireless communication, car industry). A great advantage of LTCC technology is the low temperature of cofiring. It enables the use the typical thick film materials. A great variety of these materials with different electrical properties is used to make a network of conductive paths in a package and to integrate other electronic components, sensors, actuators, microsystems, cooling and heating systems in one module. LTCC structure becomes more and more sophisticated. Using this technology it is also possible to produce MEMS and MOEMS packages.

The first sensor application of LTCC technology was presented by Bansky [7] at ISHM Conference in 1993. Since that time the number of LTCC sensor, actuator and microsystem applications as well as number of publications on these topics have been significantly growing. The first special LTCC Ceramic Microsystems Conference was organised in 2005 in Baltimore.

The LTCC technology is in production mainly in Japan, USA and Germany. In Poland a complete line for production of LTCC modules exists only in the Laboratory of Thick Film Microsystems, Wroclaw University of Technology. Most of the equipment in this Laboratory was bought using the European TEMPUS project. Research on LTCC technology has started in Wroclaw about ten years ago. The first papers on LTCC sensors were published by us in 1996 [8–10]. The research carried out in the Laboratory of Thick Film Microsystems, Faculty of Microsystem Electronics and Photonics covers two main topics: LTCC microsystems and passive LTCC components. In this paper information on the LTCC microsystems is presented, whereas the passive components investigation is described in [11].

2. LTCC technology and materials

The starting point is the green ceramic tape produced by tape casting method [12]. LTCC materials are based either on crystallizable glass or a mixture of glass and ceramics, e.g. alumina, silica or cordierite ($Mg_2Al_4Si_5O_{18}$). The properties of the ceramic tape can be modified by using materials with different electrical and physical properties (e.g: piezoelectric, ferroelectric, varistor etc.). The coefficient of thermal expansion can be adopted to match alumina, gallium arsenide or silicon.

A typical LTCC module consists of dielectric tapes, connecting vias, external and internal conductors and passive components. Standard thick film conductor, resistor and capacitor materials are used in LTCC circuits as buried (two or three dimensional 3D) or surface components.

The conductor and passive components are deposited by screen printing method which is typical for thick film technology. Thick or thin film components can be made on both sides of the fired module. Additional active or passive components are added to the top or bottom part of the fired structure using various assembling methods. Typical soldering, flip chip and wire bonding techniques are used for this purpose. The schematic crossection of the LTCC module is shown in Fig. 1.

A flow diagram of the LTCC manufacturing process is presented in Fig. 2. In the first step of the process the tape is blan-

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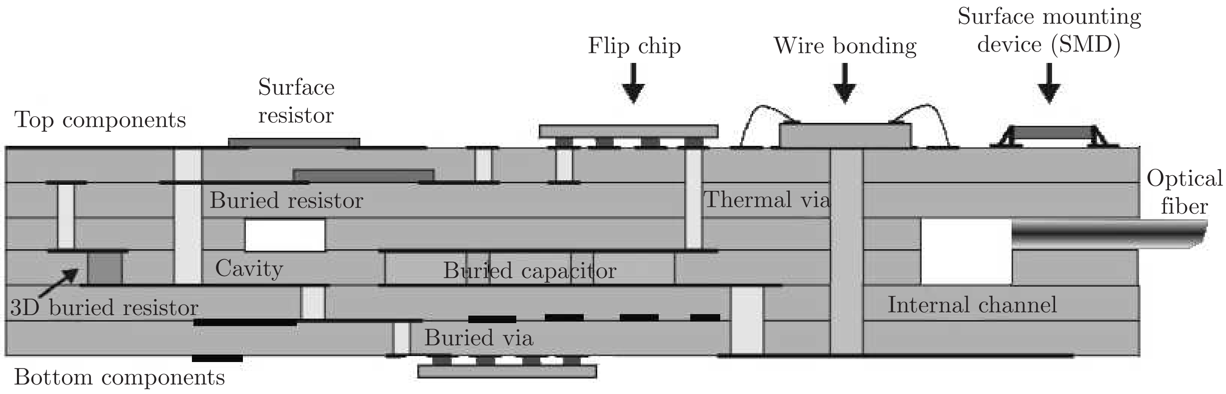

Fig. 1. Cross-section of the LTCC module

Table 1
Typical properties of LTCC materials

Property	DuPont DP 951	DuPont DP 943	Ferro A6M	ESL 41110-70C	Heraeus CT 2000	Heraeus HL2000
Electrical						
Dielectric constant	7.85	7.5	5.9	4.3÷4.7	9.1	7.3
Dissipation factor	0.0045	0.001	0.002	0.004	0.002	0.0026
Breakdown voltage (V/25 μm)	> 1000	> 1000	> 1000	> 1500	> 1000	> 800
Insulation resistance (Ωcm)	> 10^{12}	> 10^{12}	> 10^{12}	> 10^{12}	> 10^{13}	> 10^{13}
Dimensional						
Thickness – green (μm)	50, 112, 162, 250	125	125, 250	125	25, 50, 98, 127, 250	131
Thickness – fired (μm)	42, 95, 137, 212	112	92, 185	105	20, 40, 77, 102, 200	87÷94
Shrinkage x,y (%)	12.7 ±0.3	9.5 ±0.3	14.8 ±0.2	13 ±0.5	10.6 ±0.3	0.16÷0.24
Shrinkage z (%)	15.0 ±0.5	10.3 ±0.3	27 ±0.5	16 ±1	16.0 ±1.5	32
Thermal						
CTE (ppm/K)	5.8	4.5	7	6.4	5.6	6.1
Thermal cond. (W/m.K)	3	4.4	2	2.5÷3	3	3
Mechanical						
Density (g/cm^3)	3.1	3.2	2.45	2.3	2.45	2.45
Flexural Strength (MPa)	320	230	> 170		310	> 200
Youngs Modulus (GPa)	152		92			

The basic properties of surface and buried thick film components made in LTCC module are summarised below:

film thickness	≈5 μm
line width	≈ 100 μm (min. 15 μm)
conductor film (Au, Ag, PdAg) sheet resistance	≈5 mΩ/sq
resistor film (RuO_2 , IrO_2 , $Bi_2Ru_2O_7$)	sheet resistance R_{sq} = 10 ÷ 10^7 Ω/sq TCR ≈ 50 ppm/K

ked to a specific standard size and registration holes are made. Then vias are formed in the individual sheets of tape by mechanical punching, drilling, laser formation or photo patterning. The vias are filled with a special conductor inks (Ag or Au). In the next step, the conductors and passive components are deposited by a screen printing method. After printing, the cavities are made using automatic punch or laser. Finished sheets are stacked together and laminated in an uniaxial or isostatic laminator. The typical laminating parameters are 200 atm at 70°C for 10 minutes. After this process the structures are cofired in two step process (Fig. 3). During the first step, typically at around 500°C, the organic binder is burn out. In the second step, at 850°C, the ceramic material densifies. The fired ceramics usually shrink 12% in the x- and y- directions and about 17% in the z-direction. After cofiring the thick or thin films components can be deposited on the top and bottom surfaces and additional active or passive components are added. Before or after the cofiring process the LTCC structures are singulated using dicing saw, ultrasonic cutting or laser cutting. The properties of LTCC material from various manufacturers are presented in Table 1.

The limitations of LTCC technology are tolerance of thick film passive components, minimal width of the films, shrinkage variations and poor thermal conductivity. To eliminate shrinkage, some manufacturers have promoted a “tape-on-substrate” (called also “tape-transfer”) technology. In this method shrinkage is eliminated by laminating and firing each layer of tape on a substrate made of alumina, BeO or AlN. The tape adheres to the substrate and does not shrink in the x- or the y- direction. It shrinks only in the z- direction.

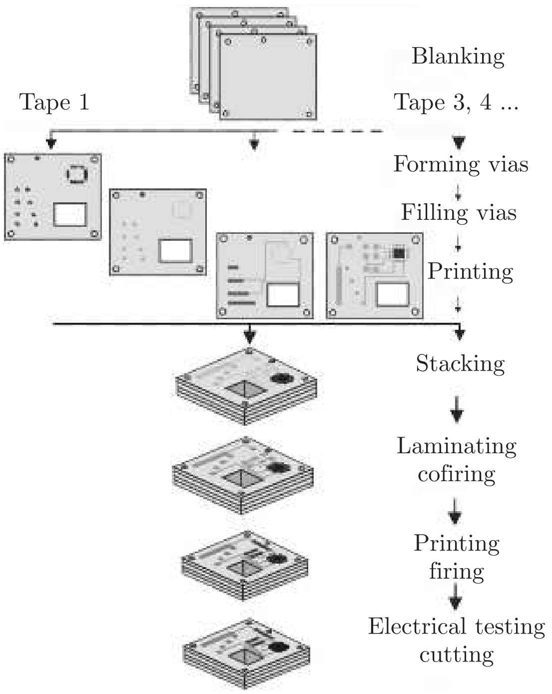

Fig. 2. LTCC manufacturing process

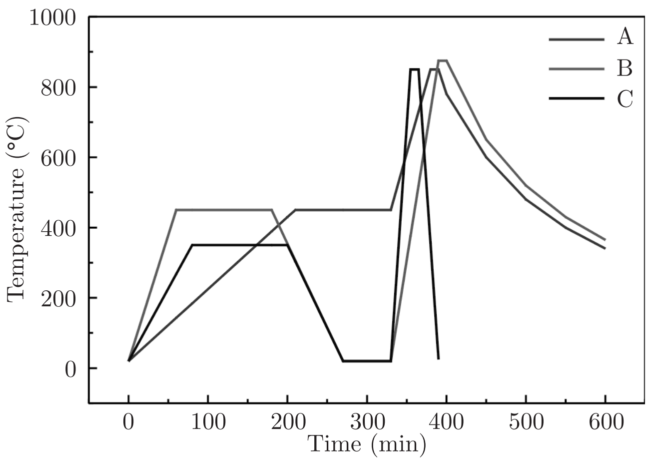

Fig. 3. Firing profiles of different LTCC tapes (A – Ferro, B – DuPont, C – Heraeus)

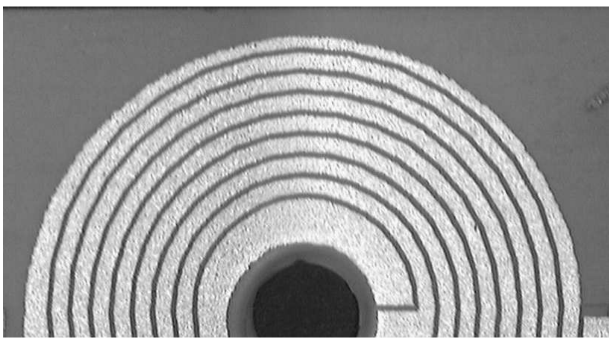

Fig. 4. LTCC inductor (pattern cut by laser), (after Ref. 16)

A new HeraLock^{TM} 2000 self-constrained LTCC tape produced by Heraeus exhibits near-zero shrinkage in the x and y directions upon firing (Table 1). However, the tape shows about 30% z-axis total shrinkage through firing [13]. HeraLock^{TM} 2000 is a lead and cadmium free formulation with properties appropriate for RF applications, automotive modules and general purpose packaging. For optoelectronic applications it is possible to make buried optical channels and fibers which remain undistorted after firing. Low x-y shrinkage also enables firing together the tape with the embedded passive devices such as ferrite transformers or chip capacitors.

LTCC's thermal conductivity of 2.0÷2.5 W/mK is a drawback of the structures dissipating many watts of power. The most common method of increasing heat transfer in the z-axis is through thermal vias. Thermal vias are holes that are filled with silver or gold and are placed beneath the hot components. The thermal conductivity in the z- axis can be improved to 120 W/mK or 70 W/mK in the case of Ag and Au, respectively.

3. Passive components

LTCC offers also a possibility of high scale integration of passive components in one module both inside (buried) and on the top (surface) of the structure, as presented in Fig. 1. The buried elements are formed as planar (2D) or three – dimensional (3D) [14,15]. Their basic electrical properties are similar.

Resistors. The electrical properties of the buried and the surface resistors are presented in [14,16,17]. The buried resistors can be trimmed by laser through a special hole in the upper foil, or through one thin layer. An other possibility of trimming is by the use of the high voltage pulses. In this case deeply buried resistors can be trimmed without making any hole. Sheet resistance values of 10 Ω/sq. to 1 MΩ/sq. are available for surface resistors and 10 Ω/sq. to 100 kΩ/sq. for the buried ones. These values depend upon the LTCC system used. For surface resistors tolerances of 1% to 2% are possible, whereas for the buried ones 10% to 20% [18].

Capacitors. The LTCC capacitors are made by the following methods:

– interdigital electrodes on one side of a tape,
– electrodes on both sides of a tape,
– vias filled with a high electrical permittivity materials,
– holes in the typical low ε tape filled with a high ε tape,
– thin tape with high ε.

Capacitors can be printed and cofired to an accuracy of 10%–20%. Capacitance value up to 70 pF/cm^2 may be achieved using standard EMCA K 7 and Du Pont K 7.8 tapes or 55 pF/cm^2 for Ferro K 5.9 A6 tape. Higher capacitance values up to 25 nF/cm^2 may be obtained by using K500 – K700 dielectric [18].

Inductors. LTCC integrated inductors can be fabricated as planar windings or multilayer structures. An example of the inductor made on LTCC tape is shown in Fig. 4. The coil pattern was cut by NAVS-30 Nd:YAG laser trimmer at dried Ag film [19,20]. The total inductance of the two level spiral inductor was equal to 2.4 μH (with air core) and 14.6 μH (with ferrite core) (at f = 100 kHz). The inductor was successfully applied to low power DC-DC converter [21].

LTCC inductors can be realized in the range of 5 nH to about 200 nH. The area required to get a certain inductance depends on the concrete design (number of available layers, layer thickness etc.).

4. Microsystems

New materials are used for tape casting (high k, piezoelectric etc.), thick films [22] and special LTCC techniques are developed for making LTCC microsystems [23,24]. These techniques include fine line patterning, micromachining of LTCC tapes, lamination, making of cavities, holes and channels, bonding of LTCC tapes to other materials.

Narrow and precise thick film lines are very important for miniaturisation of sensors and actuators. Various methods are used for fine line patterning: standard screen printing (minimal sizes line/space 100/100 μm), fine line screen printing (50/75 μm), laser patterning (25/25 μm), etched after firing (25/25 μm), gravure offset printing (15/25 μm), photo formed before firing (15/25 μm) [17,19,20]. The Aurel NAVS-30 Nd:YAG laser system is used by us for fine line patterning of thick films made from various materials. The LTCC platinum heater patterned by laser is presented in Fig. 5. A channel in the LTCC module made by laser is shown in Fig. 6.

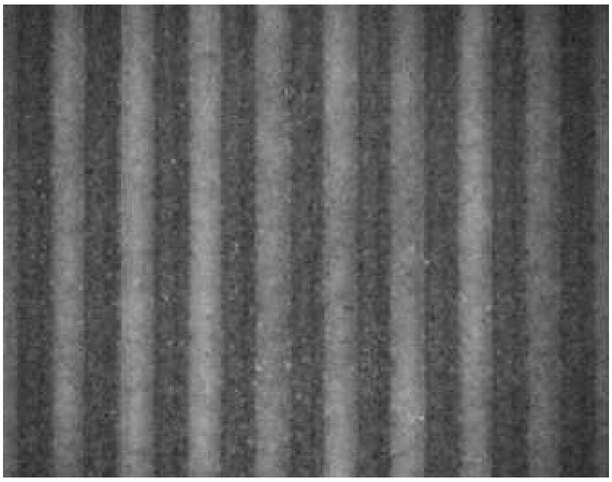

Fig. 5. Heater pattern cut by laser (line width 100 μm), (after Ref. 27)

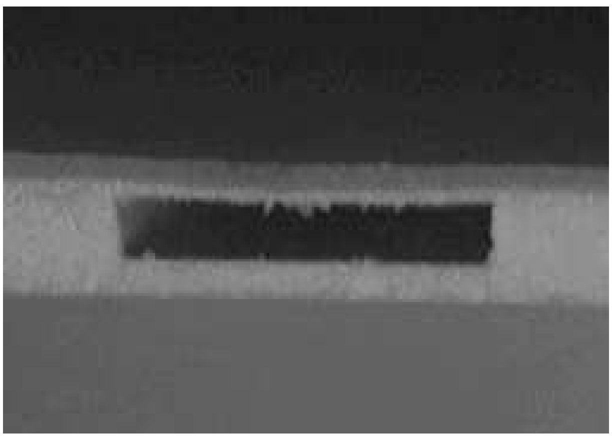

Fig. 6. LTCC structure with 2 mm wide channel cut by laser (after Ref. 17)

Special methods are used for making three dimensional structures, channels and cavities in the LTCC module. The most frequently used methods are: laser micromachining [17,19], numerically controlled milling method, jet vapour etching, photolithographic patterning, using of photoformable LTCC tapes, casting, embossing.

4.1. Heating and cooling system. Heating or cooling systems are very often used in LTCC modules [20,25–32]. The sensor and microsystem properties depend strongly on the temperature and its distribution. The heaters are made of typical resistor or conductor inks printed in the meander pattern. The Pt based heater can be additionally used for temperature measurements due to its high TCR.

The example of LTCC platinum heater cut by laser is presented in Fig. 7 [26]. The modelling of temperature distribution inside LTCC module is a very important tool for designing heater construction for proper temperature distribution [26,27]. Active liquid cooling systems [17] or heat pipe [31] are used in LTCC modules to decrease temperature. Basic construction of LTCC liquid cooling system is shown in Fig. 8.

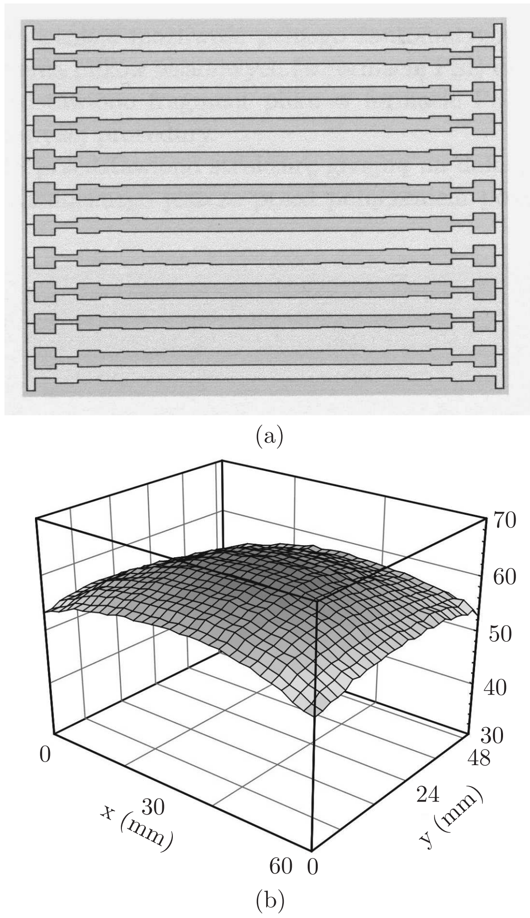

Fig. 7. PdAg heater used in LTCC microfluidic system. (a) optimized pattern, (b) temperature field of the heater measured by IR thermoscanner (after Ref. 26)

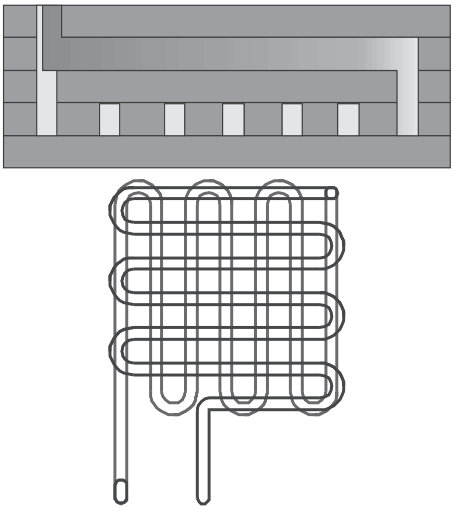

Fig. 8. Construction of LTCC cooling system (top – cross-section, bottom – top view of channel meander), (after Ref. 17)

4.2. Sensors and actuators. The following kinds of LTCC sensors and actuators are made in LTCC microsystems: temperature sensor [33,34], pressure sensor [35,36], proximity sensor [37], gas and liquid flow sensor [38], gas sensors [39], microvalve, micropump. RTDs (Pt), thermistors and thermocouples are typical LTCC temperature sensors. An example of thermistor array for temperature measurements at different levels of LTCC module is shown in Fig. 9 [34].

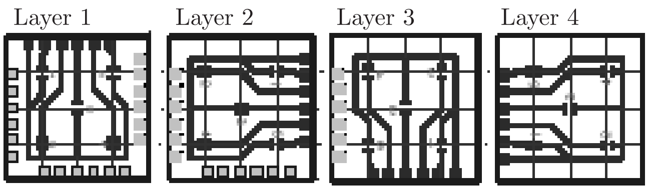

Fig. 9. Thermistor configuration inside module on different LTCC layers (after Ref. 34)

An example of pressure sensor with thick film piezoresistors on the LTCC membrane is shown in Fig. 10 [35]. The sensor consists of eight green tapes. The three lowest tapes form the membrane. The thick film piezoresistors are made on the tape 3. They are connected in a Wheatstone's bridge configuration. The central holes made in the tapes 4–6 determine the membrane diameter. Four vias are made in the tapes 4–8. They are filled with conduction ink. The vias provide electric supply to the bridge input, and the signal from the bridge output to the electronic transducer on the highest tape. In order to convert an output signal from the sensor into linearly proportional current signal the electronic circuitry are used. The circuitry is fabricated on the top of LTCC ceramics in SMT technology. The pressure sensor described in [35] works in the range of differential pressure from 0 down to –100 kPa.

The LTCC gas sensors are based on the measurement of the electrical conductivity of thick film tin oxide [39] or electrochemical processes.

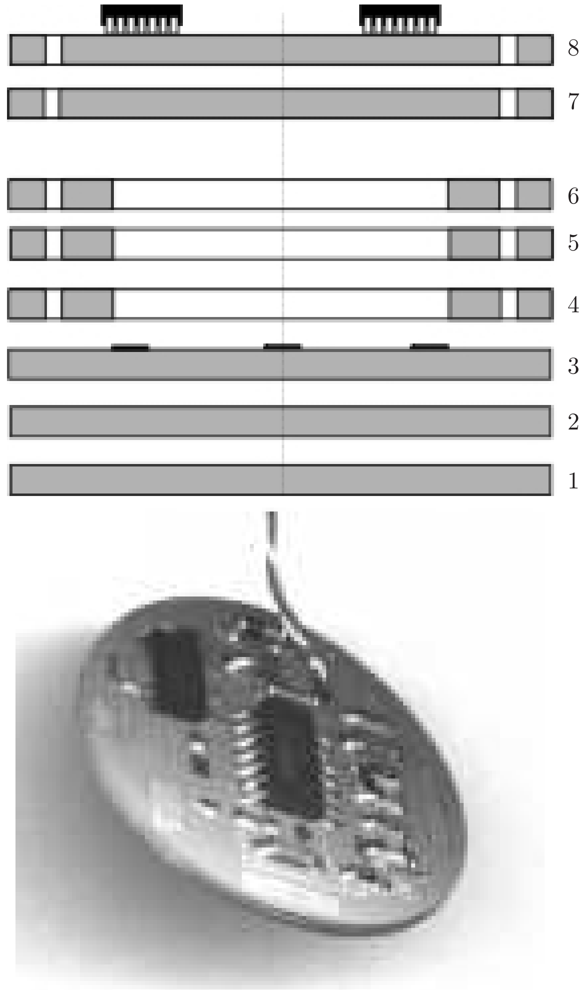

Fig. 10. LTCC pressure sensor (a) – crossection, (b) picture of the sensor with SMD components

Different types of LTCC microvalves and micropumps are investigated. Movement of the valve can be generated by temperature expansion of heated liquid or by piezoelectric effect. The hybrid micropump containing silicon membrane with magnet and LTCC coil is described in [37]. Moreover, magneto hydro dynamic MHD) effect is utilized in LTCC liquid mixer and pump [40].

4.3. LTCC microfluidic system. Low temperature cofired ceramic enables development of channels and cavities for microfluidics systems. Properties of the systems are similar to these of silicon ones. The fabrication process of LTCC detectors is much simple, faster and cheaper. An example of LTCC liquid conductivity detector is described in [41]. Four and two electrode detectors were used for determining the conductivity of the KCl solution in water in the concentration range 1 mM to 100 mM. The LTCC detectors exhibit the same properties as silicon one. The detector can be used in μTAS devices due to small working volume. The volume is equal to 6.5 nl and 13.5 nl for four and two electrode detectors, respectively.

Another example of microfluidic device is an LTCC system with optical detection for chemical analysis of liquids. Investigation of the system is carried out in a collaboration with the Department of Analytical Chemistry, Warsaw University of Technology. The work is supported by Polish Ministry of Science and the Information Society Technologies, Grant no 4 T11B 047 25. The LTCC system is presented in Fig. 11. The device consists of a mixing meander, a Y-shape reagents junction, a channel for optical detection, optical fibers, fluid inlets/outlet, heater, temperature sensor and dedicated temperature controller [42]. The optical fibers allow to perform measurements of light transmittance and fluorescence. The constructed structure can be applied to chemical analysis of liquids. The microfluidic system is connected via long optical fibers to UV-Vis and spectrofluorimetric analytical apparatus. Results of measurements of light transmittance and fluorescence in the system were presented in [42]. The fluidic module was modified by integrating into it the whole optoelectronic part. The modified LTCC microfluidic module (Fig. 12) with two very short standard multimode 62.5/125 optical quartz fibers integrated with SMD light source (LED) and a light detector (light to voltage converter) for light absorbance measurements were described in [43]. As a light source electroluminescence diode EL-12-21-UBGC LED (wavelength 502 nm) was used. The light detection circuit is consisted of high-sensitivity light to voltage converter TSLG 257.

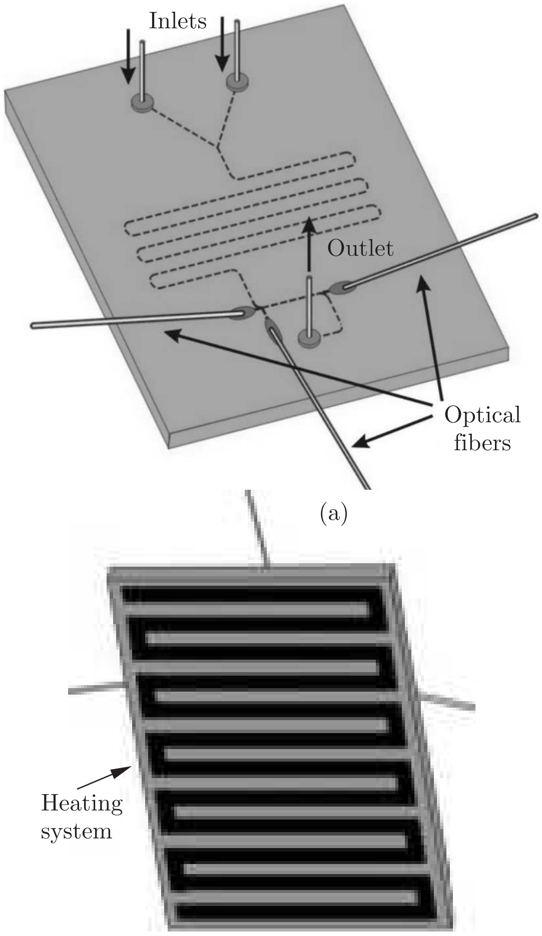

Fig. 11. LTCC microfluidic system (a) top surface, (b) bottom heater, (after Ref. 46)

Fig. 12. Picture of LTCC microfluidic system with integrated optical fibers and SMD light source and detector

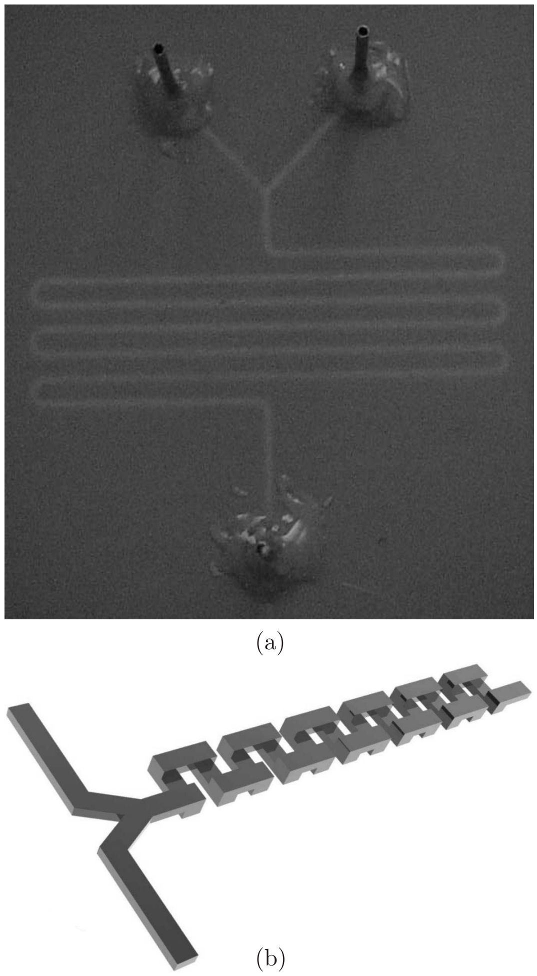

Fig. 13. Mixer made in LTCC microfluidic system (a) 2D and (b) 3D (after Ref. 47)

Various designs of microfluidic channel and optical detection part of LTCC microfluidic module with polymer optical fibers (diameter 750 μm) for transmittance measurements were investigated (Figs. 13–15). The results of experiments were presented in [44,45]. An output signal from the microdetector with integrated polymer fibers was much higher than in the case of the microsystem with quartz fibers. The best construction of LTCC microfluidic optical detector examined in [45] was modified by adding an optical fiber for fluorescence measurement and changing liquid inlet/outlet construction (Figs. 14 and 15). The results of light absorbance and fluorescence measurements were described in [46].

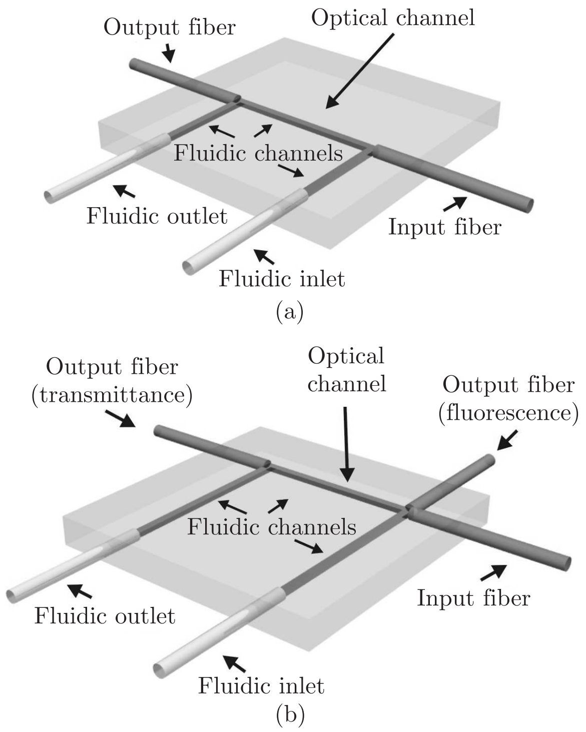

Fig. 14. Schematic view of theLTCC microfluidic structure with optical fibers for measurements of light (a) transmittance, (b) transmittance and fluorescence. (after Ref. 46)

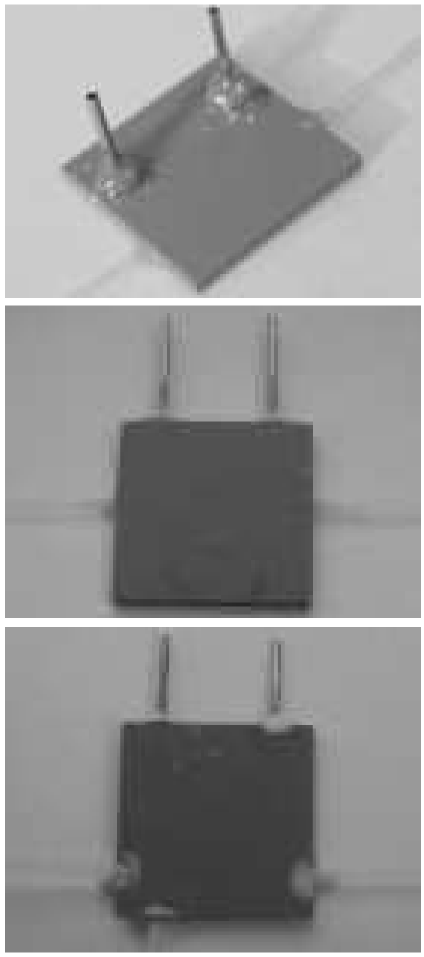

Fig. 15. LTCC based microfluidic optical detectors

Light absorbance is proportional to the concentration of the compound in solution. It was assumed that measured output signal from lock-in amplifier was proportional to the light intensity coming to the light detector device. So it was possible to measure light absorbance $A(c)$ versus concentration of colour dye in distilled water utilizing the following formula:

$$A(c) \equiv \log\left(\frac{I_o}{I(c)}\right) = \log\left(\frac{U_o}{U(c)}\right)$$

where U_o is the output voltage for pure water and $U(c)$ is voltage level related to concentration c [45].

A solution of Sunset Yellow colour dye was used to test the light absorbance part of the detector. A high-efficiency LED UBC21-11 was applied as a light source. It transmitted light via one optical fiber to the detection channel. The opposite fiber was connected to the integrated high-sensitivity light to voltage converter TSLB 257. Results of the light absorbance measurements are shown in Fig. 16. The spectrofluorimetric detection system (perpendicular configuration of optical fibres) was evaluated by fluorescein test measurements (Fig. 17) [46]. The fluorescence measurements were carried out at the Department of Analytical Chemistry, Warsaw University of Technology.

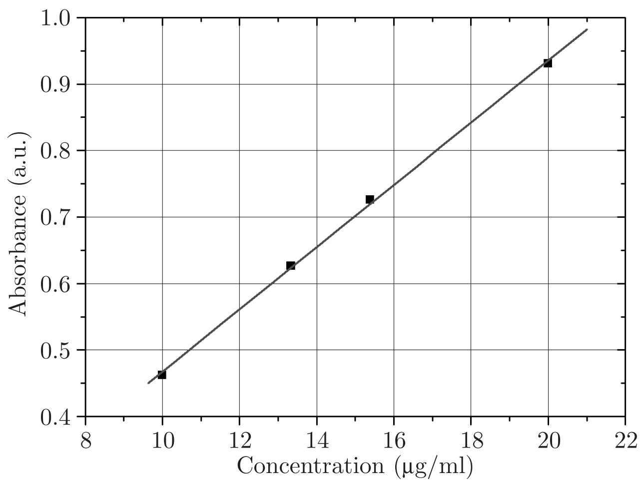

Fig. 16. Light absorbance vs. concentration of Sunset Yellow dye measured at wavelength λ = 468 nm (after Ref. 46)

The mixing part of the LTCC was also modified to achieve better mixing properties at a much smaller area of the LTCC structure [47]. The 3D structure made in LTCC was found to be the most efficient one. The construction of 3D LTCC mixer is presented in Fig. 13b.

A microchamber Polymerase Chain Reaction (PCR) device was another microfluidic system investigated in our laboratory [48,49]. The PCR is one of the powerful techniques, by which DNA segments may be amplified. A new construction of a microchamber PCR system in Low Temperature Cofired Ceramics (LTCC) technology has been developed. The device is comprised of 12 μl volume reaction chamber with special outlet and integrated thick film platinum heater which constitutes a heating source as well as temperature sensor [49]. The construction of the device is shown in Fig. 18.

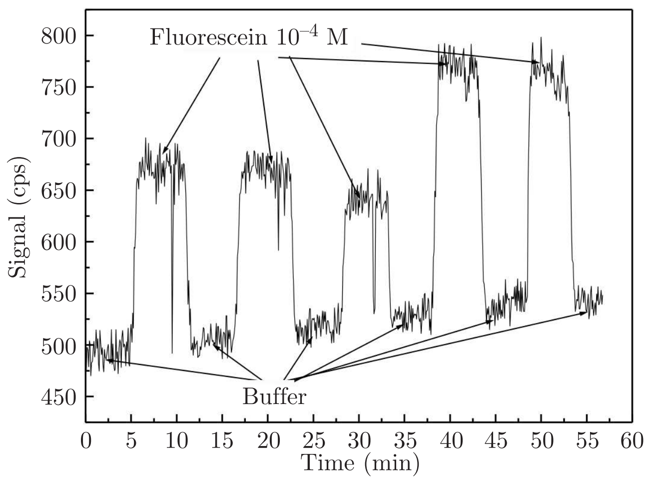

Fig. 17. Single wavelength fluorescence measurements of fluorescein solution (λ_{ex} = 488 nm, λ_{em} = 520 nm), (after Ref. 46)

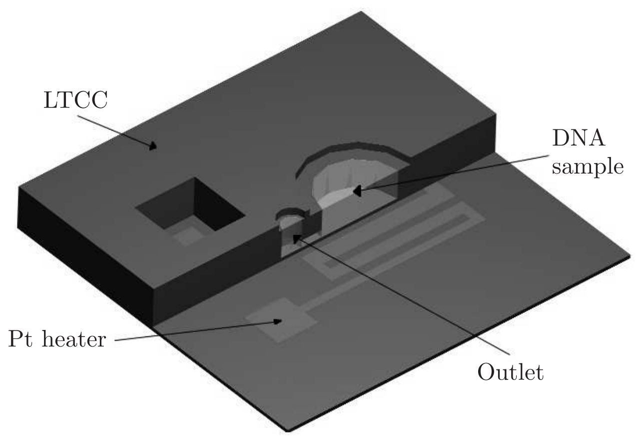

Fig. 18. Schematic view of the PCR microchamber device (after Ref. 49)

5. Other applications

Nowadays there are many new microelectronics and non-microelectronics meso scale applications of the LTCC technology. LTCC is very good for high voltage [50], high pressure or vacuum applications. The technology is applied to build microsystems for miniature fuel cell energy conversion systems, drug delivery, biological parameter monitoring, gas or liquid chromatographs, cooling and heat exchangers, particle separators, polymerase chain reaction (PCR) [48,51], Micro Total Analysis Systems (μTAS), photonic devices, MOEMS and MEMS packaging [52–54].

Important new applications of LTCC are microfluidic systems [24,35,57] used mostly for chemical analysis [42,56,58,59].

Micro-high performance liquid chromatography (μ-HPLC) made in LTCC demonstrates very good properties of ceramics at high pressures. A ceramic thermal cell lyser has lysed bacteria spores without damaging the proteins. The properties of LTCC/chemiresistor smart channels are comparable to the performance of silicon-based ones [72].

An LTCC microdischarge device has been developed and operated in Ne gas [60,61]. The device can be used as UV source in biomolecule assay operations where the target molecule is fluoresced in the UV light. LTCC structure can be used as a focusing electrode in the field emitter arrays [62]. Recently, a new design of the LTCC plasma generator was described [63].

LTCC materials are applied for fiber optic and electro-optic packages [52,64–67]. The opto-electronic MEMS packaging and laser alignment based on an LTCC structure are described in [68,69]. Silicon MEMS packaging is another very wide field of LTCC application [52,53,70–72].

Interesting application of LTCC are three-dimensional shells used for example in spherical stepper motor [73] or radar sensor [74].

6. Summary

An information on LTCC materials, manufacturing processes and properties of fired modules was given in the paper. The results of research on the LTCC sensors and microsystems carried out in the Laboratory of Thick Film Microsystems were shortly presented. Our work on the LTCC microfluidic system with optical detection for chemical analysis of liquids was described in detail. The system was examined in collaboration with Warsaw University of Technology.

The latest non-conventional applications of LTCC technology are very interesting. There are many new microelectronics and non-microelectronics meso scale applications of the technology. The market is growing very fast because of low cost of investment, short development time, interesting properties of the ceramics and flexibility of the technology.

The following advantages of the LTCC ceramic are responsible for a success on the market: good electrical and mechanical parameters, high reliability and stability, possibility of making 3 dimensional (3D) microstructures with cavities and channels, high level of integration (sensors, actuators, heating, cooling, microfluidic, electronic and photonic systems in one LTCC module), very good properties at high voltage, high pressure and high vacuum.

The fabrication process of LTCC systems is simple, fast and inexpensive. Cost of investment is much lower than in silicon or thin film industry. Short production series are profitable. The technology is suitable for small and medium enterprise.

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