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Overview of low temperature co-fired ceramics tape technology for meso-system technology (MsST)

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Abstract

For certain applications low temperature co-fired ceramic (LTCC) tape materials used in multi-layer packages offers the potential of emulating a great deal of silicon sensor/actuator technology at the meso scale level. The goal of this review is to describe meso-system technology (MsST) using LTCC, thick film and silicon technologies.

A mayor MST application being addressed today is fluid handling for miniaturized chemical analytical systems. For larger MST-3D applications, in the meso-size (from 10 to several hundred microns), it would be desirable to have a material compatible with hybrid microelectronics, with suitable thermal, mechanical and electrical properties, easy to fabricate and inexpensive to process. Such a material is the LTCC tape multilayer system.

One of the important features of LTCC technology is the possibility of fabricating 3D structures using multiple layers. In this review, we want to emphasize sensors and actuators for meso-systems exploring LTCC Tape possibilities in the following ways:

- Sensors for proximity measurement;
- Fluid media realization of vias, holes, cavities, channels and manifolds;
- Sensors for flow measurement;
- Actuators for hybrid microvalves & micropumps.

Keywords: MST; MEMS; LTCC; LTCC tapes; Hybrid microelectronics; Meso-systems; Sensors; Actuators

1. Introduction

This article presents an overview of our group contributions in the field of meso-scale LTCC ceramic tapes sensing and actuating meso-systems. We also included the results of research groups that most influenced our perspectives. A meso-system can be defined as a small package capable of handle at least two media — e.g. electricity & fluids — by means of sensors, actuators, interconnections, control & signal processing electronics. Integration is accomplished by means of devices with reduced dimensions, fabricated using the available MST or MEMS technologies [1].

MEMS developments has shown steady growth, pushing the frontiers of new materials and processes for applications like

- Microsystems for chemical analysis, e.g. fluid injection analysis (FIA).
- Microsystems for drug delivery.
- Microsystems for environmental data acquisition.
- Inertial Microsystems for disabled assistance and machine or automata stabilization.
- Hybrid Microsystems for automotive applications.

Due to the economic potential of MEMS technologies, many countries have recognized these techniques as strategic and of high priority. Therefore, a great deal of resources have been allocated for R&D in support of the following research areas [2]:

- Chemical analyses.
- Inertial systems.

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Table 1
Comparison of various MEMS technologies (modified from [6])

Merit figure	Hybrid LTCC	X-ray micro-machining	Bulk Si processing techniques	Surface processing techniques
Feature height	100 μm 10 mm using bonding	100 μm to 1 cm	500 μm to 1 mm with bonding	10–20 μm
Cross-sectional shape	Very good	Very good	Very good	Very good
Cross-sectional shape variation with depth	Fair	Fair	Limited by DREI	Limited
Materials	Wide range	New materials	Fixed	Fixed
Compatibility with integrated devices	Good	Good	Good	Excellent
Process maturity	Mature for MCM	First products	Mature	First products
Aspect ratio	Large	Large	Small	Small
Low volume production	Excellent	Poor	Fair	Poor
High volume production	Good	Good	Excellent	Excellent

- Fluid handling and control.
- Distributed sensor & actuator networks.

There are several market segments for MEMS technologies. We can expect to see growth in the following segments: pressure sensor, inertial systems, measurement and control of fluids and the chemical analysis area. It is expected that in the next decade the total MEMS market will also grow because of new applications development.

Historically, ceramic technology first appeared in ancient China [3]. Most of the relevant developments to the material contemporary use started in the sixties, where thick film Technology was introduced in the electronic industry as a method for implementing hybrids packages with thick films, and recently LTCC & HTCC for multilayer MCMs [4]. MEMS technologies take advantage of all previous microelectronics developments and deals with the new challenges of packaging, media interfacing, and interfacing with meso-scale devices and 3D structures implementation. In Table 1, one can see a comparison between basic MEMS technologies and hybrid LTCC meso-system technology as exposed in this review. One can argue that LTCC technology is already mature for MCM and compatible with several IC technologies. However, having the LTCC tapes as a basic working material, these techniques can be an interesting alternative for meso-scale MEMS and microfluidics [5].

The main purpose of this work it is to examine the current status of the hybrid LTCC technology for meso-system implementation.

1.1. Hybrid & LTCC technology

LTCC was conceived as a technology that could have the advantages of both thick film and HTCC technologies [7], as shown in Fig. 1. LTCC is a technology with excellent properties for packaging and MCM applications, rendering good conductors, low associated capacitances, simpler processes and high layer count.

LTCC tape technology has been used in the last 20 years for high reliability applications in military, avionics and automotive areas, as well as in MCMs for communications and computer applications. The main reasons for using LTCC tapes techniques as a MST technology are:

- Simplicity of tape machining in the green state with feature size of 10 μm to 10 mm.
- Mass production methods can be readily applied.
- Thermo-physical properties can be promptly modified, e.g. thermal conductivity of single layers.

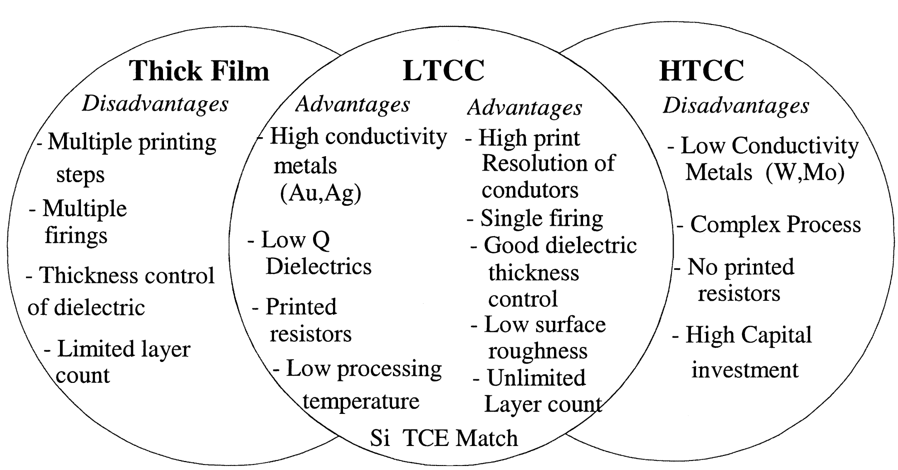


Fig. 1. Comparison of hybrid ceramic technologies [8].

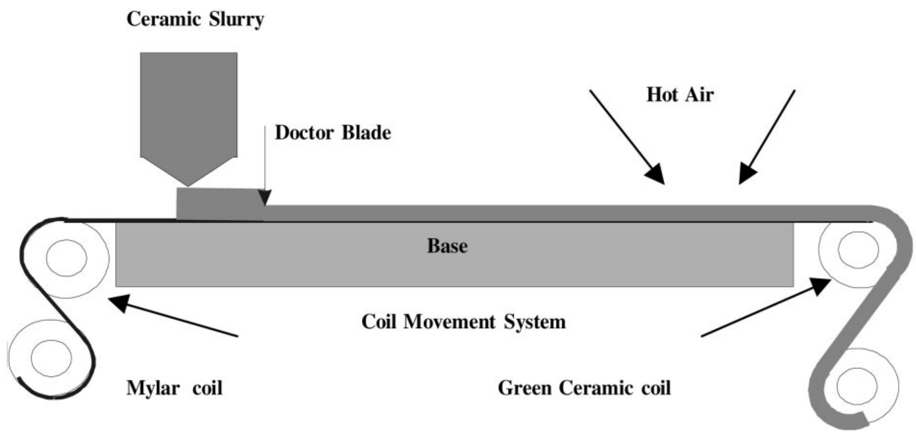


Fig. 2. Schematic depiction of a doctor blade set-up for casting LTCC tapes.

- Electronic circuits can be integrated because of its hybrid nature.
- Tapes of different compositions can be formulated to obtain desired layer properties, e.g. magnetic permeability.
- Layer count can be high.
- Possibility of auto-packed devices fabrication.
- Fabrication techniques are relatively simple, inexpensive and environmentally benign.

Tapes are easily fabricated while still in the green state; they are soft, pliable, and easily dissolved and abraded. Once the material is fired and fully sintered, it becomes tough and highly rigid. Small structures can be carved and machined once fired using diamond tools, and excimer laser can be utilized to ablade alumina within the smallest tolerances.

2. LTCC technology

We all know how versatile material silicon can be for the marriage between microelectronics and MEMS. It has the right electrical and mechanical properties, of course there is a price to pay, silicon processing is time consuming, delicate and very expensive. For larger structures, in the intermediate size (meso-structures with minimum feature size in the range from 10 to several hundred microns), it would be desirable to have a material compatible with hybrid microelectronics, with the right thermal, mechanical and electrical properties, easy to fabricate and inexpensive to process. LTCC tapes or Green Tapes[1] is such a material system.

LTCC tapes are glass-ceramic composite materials. The ceramic filler is usually alumina, Al_2O_3, but it could be any other ceramic system, including high thermal conductive BeO, Ferroelectric Perovskites, ferromagnetic spinels and ‘‘smart’’ (photovoltaic-piezoelectric) ceramics. The usual composition also includes a glass frit binder to lower processing temperature as well as rendering the material compatible with thick film technology. A third component of the composite is an organic vehicle for binding and viscosity control of the tape before sintering. They are commercially produced in flat tapes of various thicknesses but usually in the range of 100–400 μm. They are often called green ceramic tapes because they are manipulated in the green stage, which is before firing and sintering.

To obtain a controlled tape thickness, a doctor blade machine is used. Such equipment is shown in Fig. 2. Casting is accomplished by spreading the desired slurry formulation to form a paste on a moving carrier substrate (usually a film of cellulose acetate, Teflon, Mylar, or cellophane) and removing some of the volatiles. By a soft bake procedure one obtain a thin, flexible tape that can be cut and stamped to the desire configuration prior to firing.

Although the doctor blade procedure sounds simple, it requires careful control to avoid warpage, out of tolerance thickness and other defects. A variety of other additives are included in the formulation for both aqueous and non-aqueous doctor blade systems.

One of the important features of green tape technology is the possibility of fabricating 3D structures using multiple layers of green tapes [9]. Each layer is fabricated in the green (before firing) with whatever features are needed for the overall function of the 3D structure. Each layer may have vias, cavities, channels, and internal electrical elements such as capacitors, resistors and interconnections. The individual layers are then arranged in the proper order (stacked), and placed in a registry to yield the desired structure (see Fig. 3). The location holes for registry and the vias are usually punched, although they can be chemically dissolved, etched, abraded or cut.

The next step consists on moving the stacked blanks to the press where heat and pressure are applied to complete the lamination process. At this point the structure is ready for sintering in air furnace. The complete processing sequence for LTCC tapes is depicted in Fig. 4.

[1] Green Tape is a trade mark of DuPont Corporation.

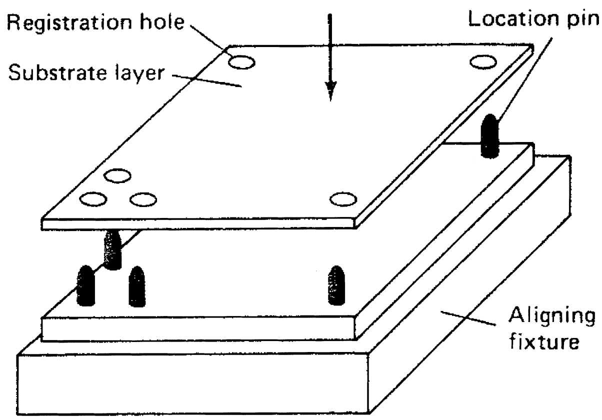


Fig. 3. Alignment fixture for ceramic tapes registration (from [10]).

The highest number of laminated layers is as high as 80, but even higher numbers are being explored. During stacking successive layer should be rotated by 90° to compensate for the texture (preferential orientation) induced by the fabrication process. The nominal thickness tolerance after casting is 1.5 μm for commercially available materials. In the green, the smallest punched cavity or via hole at this moment is of the order of 25 μm in diameter.

The LTCC ceramics shrinks upon sintering or heat-treating. A nominal DuPont alumina LTCC formulation shrinks 12% in the *x*, *y* plane and 15% in the *z*-axis. Of course the shrinkage is uniform and predictable and one can compensate for the shrinking during the design. The fracture strength of an alumina formulation is 320 MPa, which render the fired structure extremely tough. The porosity of the LTCC system is minimum due to the use of vitreous material as alumina binder. The grain size, and therefore, the

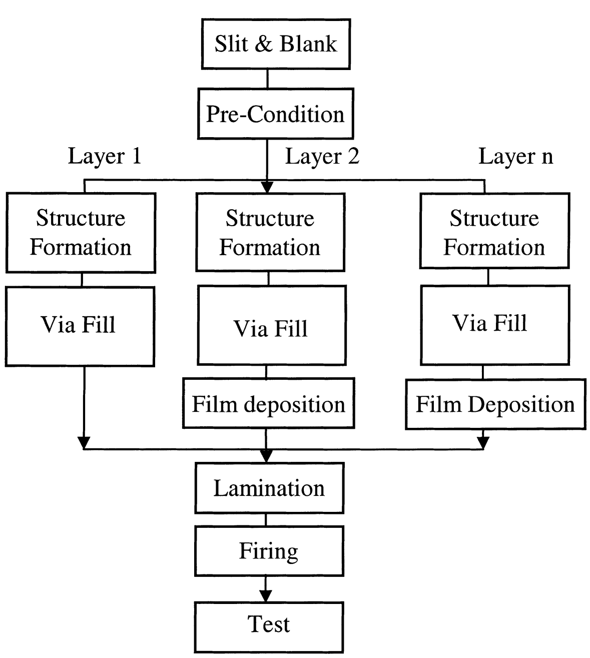


Fig. 4. LTCC tape processing.

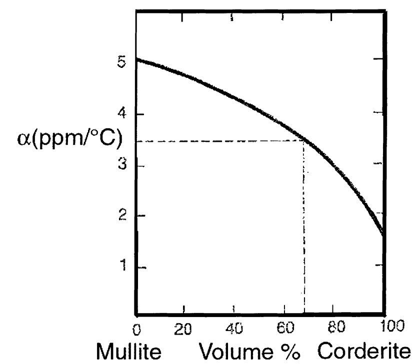


Fig. 5. TCE Variation for Mulite/Corderite system [11].

mean surface roughness of the fired ceramic is about 0.3 μm. The thermal conductivity of a nominal fired DuPont alumina formulation is 3 W/mK, and the thermal expansion coefficient is 5.8 ppm/°C. Some IBM formulations and others such as NEC (Nippon Electric Company) 55% Al_2O_3–45% glass match the thermal expansion coefficient of silicon, an important characteristic for the formation of hybrid structures.

It is important to note that most thermal properties of the LTCC materials can be adjusted by clever formulation. Microstructure designer possesses a great deal of latitude in the selection of a ceramic formulation to match either the thermal expansion coefficient or the thermal conductivity of most interested materials for hybrid integration. For example, one can see in Fig. 5 for the Mullite ($3Al_2O_3{\cdot}2SiO_2$) and Corderite ($2MgO_2{\cdot}Al_2O_3{\cdot}5SiO_2$) system that a TCE matching with Si it is attained for a 65% Corderite and 35% Mullite formulation.

One of the great advantages of LTCC technology is that allows for easy fabrication of systems with electronic and MEMS components. A typical alumina formulation such as the DuPont's LTCC 951 can be glued after firing to most transparent glasses when viewing ports are desired in a structure. The hermetic binding of other hybrid structures is accomplished with die-bonding glass formulations, epoxies or eutectic bonding.

There are multiple metallization schemes that are shrinkage matched to the LTCC tape and can be applied in the green. Metals such as Au or Ag (air fired), Cu (reducing or neutral atmospheres) are used for interconnections, electrodes and via filling. An ample gamma of resistors and dielectric formulations are available with complete shrinkage compatibility to the LTCC materials.

Due to the high fusion temperature of materials involved in LTCC tapes fabrication, a sintering process is needed to convert the LTCC tape into a solid dense material. Usually one recognizes three types of sintering process, namely: viscous flow, liquid phase and solid state. In the LTCC case, since the material is a composite glass–ceramic material the sintering is of the viscous flow type.

Assuming spherical grains of glass and alumina, a simple sintering model is shown in Fig. 6a. Vitreous grains at

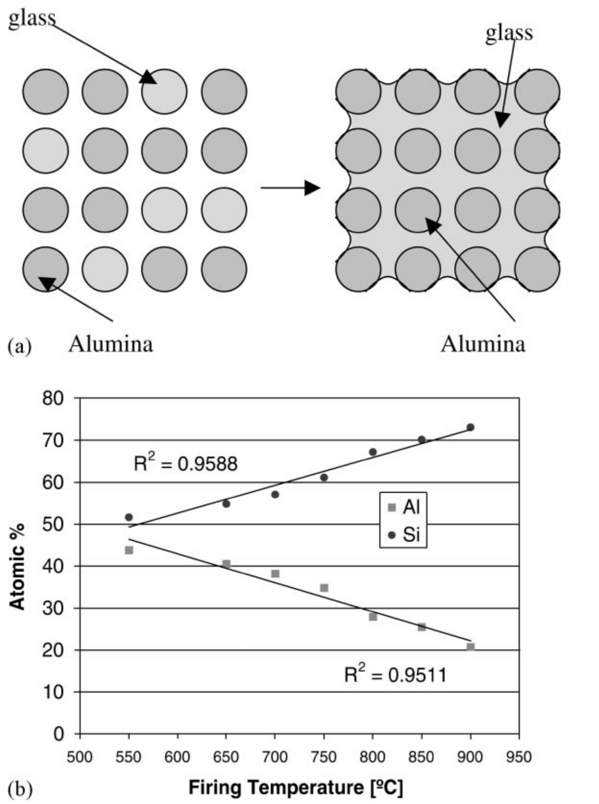


Fig. 6. (a) Sintering model for glass-ceramic system. (b) Surface concentration of aluminum and silicon as a function of firing temperature as obtained by X-ray photoelectron spectroscopy.

sintering temperature are in liquid phase and alumina grains in the solid state become wetted due to compatible surface free energies and capillary forces in the alumina grains. As temperature decrease, glass–ceramic vitrification is initiated and a dense material arises. Fig. 6b shows that the ceramic surface being covered by the glass (mainly silica and lead oxide) as the firing temperature increases.

In Fig. 7a temperature profile for LTCC tape sintering is displayed. This profile presents two plateaus. The first one is at 350°C; in order to burn out the organic components, the second is related to the viscous sintering process.

After sintering, LTCC tapes become very stiff and partially resistant to glass leaching although it is possible to deposit thick films (cermets or polymeric) and perform further sintering at a lower temperature. Finally these materials can be machined using Laser or Diamond tools, in order to position internal structures or define its final shape.

3. LTCC technology modifications for meso-scale applications

Some modifications or improvements to the usual LTCC tape process are needed in order to fulfill MsST device implementation requirements. New patterning, sagging control and lamination procedures have to be developed in order to fully utilize the potential of LTCC tapes. We have organized these modifications or improvement in eight subsections.

3.1. CNC micromachining of LTCC tapes

In order to obtain vias for electrical interconnection between layers, LTCC tapes are usually machined by punching or stamping methods. Because for MsST applications it is necessary to machine holes, cavities, channels and other structures; numerically controlled (CNC) milling methods have been used in order to obtain feature sizes of the order of 100 μm (see Fig. 8).

Using CNC machining, complex shapes are promptly obtained and dimensional tolerances are comparable to those of a general-purpose punching machine.

3.2. Jet vapor etching: a chemical machining for LTCC tapes

A technique for etching the organic part of the binder in various LTCC substrates is currently under study [12]. Using

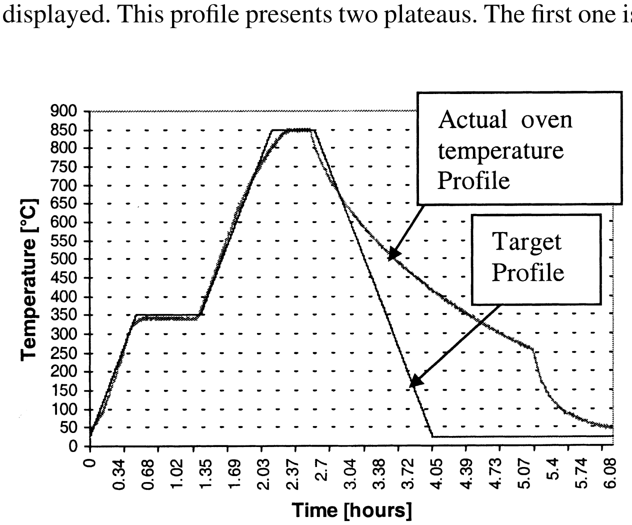


Fig. 7. Temperature profile for LTCC materials.

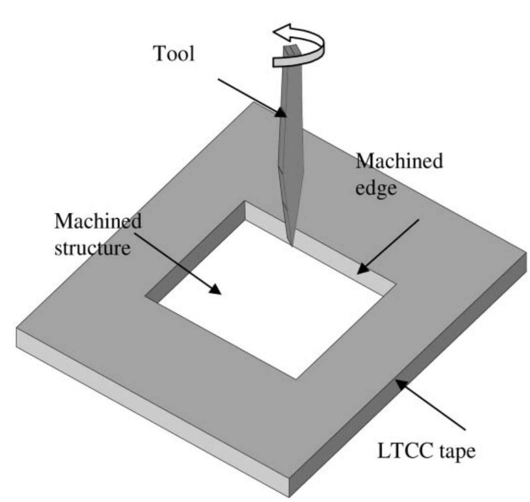


Fig. 8. CNC Machining method for LTCC.

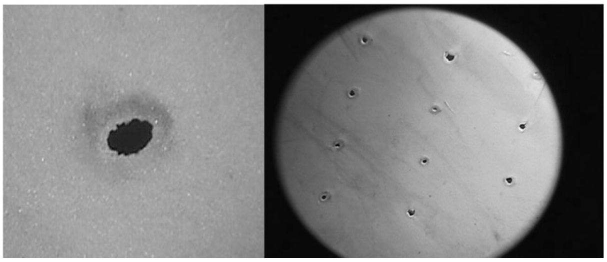


Fig. 9. Photograph of LTCC tapes machined with the atomized acetone jet.

a collimated solvent jet, it is possible to remove organic material and with the fluid flow momentum, simultaneously removing the ceramics grains of the filler. Through this technique it is possible to fabricate a wide variety of shapes.

Using acetone as the solvent of choice, we have been able to etch round holes of approximately 25 μm in diameter. Fig. 9 shows some of the fabricated vias. The processed LTCC is undamaged by the solvent vapor and can be laminated and sintered using the conventional LTCC processing.

Jet vapor etching is more flexible than the traditional punching technique because one can do partial cavities and continuous borders when machining long channels. Besides these obvious advantages in the machining of single layers, the processing and instrumentation cost are a fraction of those for the conventional punch and die process.

Fig. 10 shows the system used for jet vapor etching. The liquid solvent is heated increasing its vapor pressure. By pumping nitrogen the acetone is atomized and ejected through a microfabricated nozzle. The acetone droplets are able to dissolve the organic binder; moreover the gas mixture momentum removes the filler.

The first nozzle used has a circular cross-section with diameter of 250 μm; it was utilized in the exploration of optimal values of temperature and pressure in order obtain a sharp edge. A liquid phase temperature of about 50°C and the pressure 10 psi seems to be near optimal. Various other nozzles sizes are being tested.

3.3. Laser machining

Both Nd-Yag and excimer laser can be utilized to machine the tapes with the smallest tolerances. Laser equipment allows computer controlled x–y movement of the workpiece in order to machine complex shapes. Recent developments in the utilization of variable wavelength dye lasers for the 3D fabrication of microstructures in photosensitive glass-ceramics for aerospace applications [13] point to the possibility of utilizing this techniques in photoformable ceramic tapes.

3.4. Control of sagging and lamination deformation

Sagging of suspended or laminated structures is a common problem in the processing of LTCC materials. These composites are susceptible to plastic deformation upon lamination or under the stress of body forces once the glass transition temperature of the glass binder is reached during processing. Sagging of a suspended cavity without lamination is shown in Fig. 11. Lamination deformation prevention utilizing Mylar inserts have been described in details elsewhere [14].

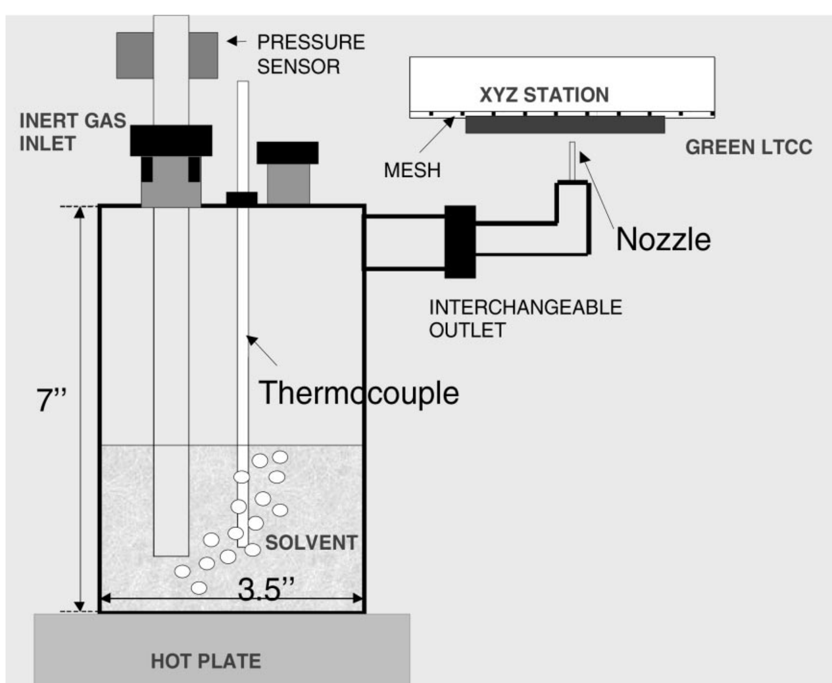


Fig. 10. Schematic diagram of the atomized acetone jet reactor.

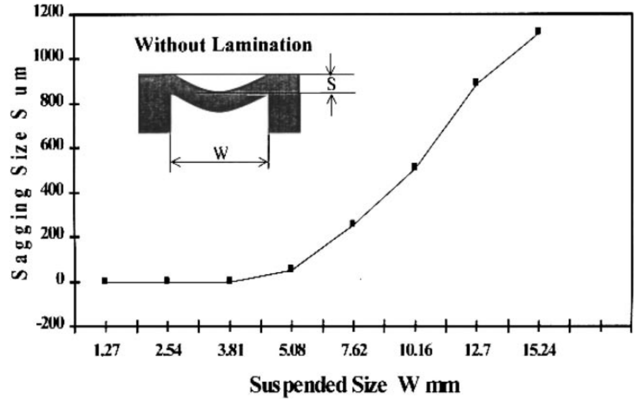


Fig. 11. Sagging for suspended cavity without lamination [15].

Among the results obtained is the fact that when an LTCC tape with holes of diameters in excess of 400 μm is laminated, the tapes above and below deform in the inside of the cavity, but for smaller diameters the deformation is negligible. It is reasonable to conclude that the main cause of sagging is a consequence of the lamination process.

There are three main strategies used to compensate or reduce the sagging problem.

3.4.1. Deposition of thick films to compensate auto-supported structures

In the case of bridging structures, one can compensate for the potential effect of body forces by screen-printing a thick film, which forms an over-layer with tensile internal stresses upon sintering [16]. This compensates for the body-force deformation and often yields straight bridges, as shown in Fig. 12.

The reason for the effectiveness of this material for sagging prevention is that the resistor paste is shrinkage match to fired alumina substrates which have a higher coefficient of thermal expansion than the glass-ceramic tape used in this study. After sintering, the resistor layer will exert a tensile force on the interface structure, preventing the sagging. Note that placement of the thick film is critical as it is important to match this tensile force to the force inducing sagging.

3.4.2. Use of sacrificial materials

In this case, the use of a lead bi-silicate frit as a sacrificial material can be useful [16]. After deposition and firing, the lead bi-silicate glass is etched in buffered hydrofluoric acid in order to remove the material from under the suspended or bridging structure. Although sacrificial materials is a good idea, and have been tested with good results, this method displays some problems:

- Etching rate is different inside cavities than in open space.
- Due to limited solubility of the glass frit, it is difficult to remove all the material.
- Ceramic green tapes are glass–ceramic composites and when exposed to BHF will etch at a rate comparable to the lead bi-silicate frit.

3.4.3. Use of fugitive phases

The use of fugitive phase materials intended to disappear during firing is another way of supporting bridging structures [16]. Several of these strategies have been explored.

The idea behind the use of the carbon black as fugitive phase is to have sintering accomplished in a neutral or just slightly oxidizing atmosphere. The gasification of the carbon (reaction with oxygen to form carbon mono, and dioxide) is slow and little carbon black is lost before the bridging or suspended ceramic structure becomes rigid. After that point, one can open the furnace to air and burn-off the carbon black. Samples were fired with structures where the feature size is large enough for the sagging to be evident and easily measured. After the carbon black gasification and sintering, the upper and lower layer in the cavity filled with the carbon black-binder mixture are parallel, see Fig. 13.

The compensation can be accomplished by changing the temperature sintering profile and the furnace atmosphere controlling the air/nitrogen ratio. Fig. 14 shows the sintering profile modification for sagging control, displaying the regions for air or nitrogen predominance and plateau for carbon black firing.

3.5. Photolithographic patterning of LTCC

These techniques are an emulation of silicon lithography. The idea is to utilize an inexpensive version of the

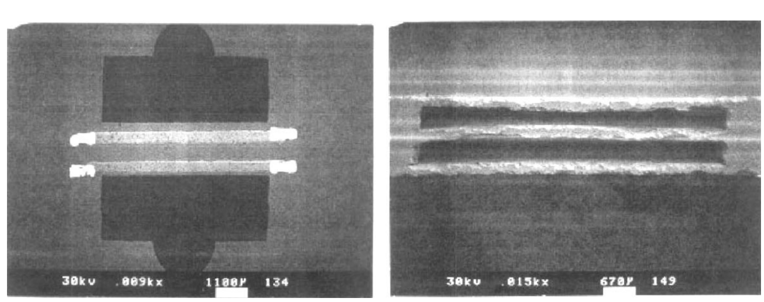


Fig. 12. Sagging control depositing film on structure.

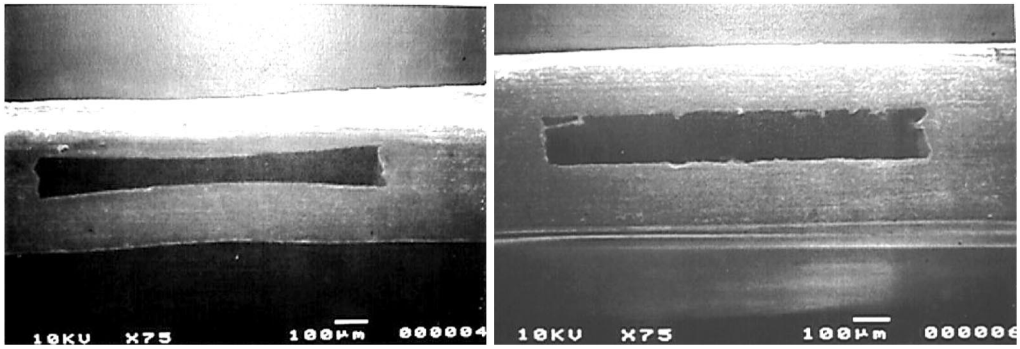


Fig. 13. Sintered cavity without and with carbon black paste.

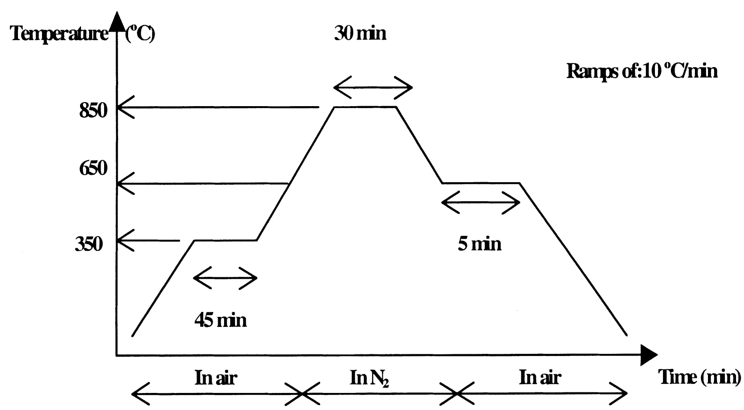


Fig. 14. Temperature sintering profile modification for sagging control using sacrificial materials.

instrumentation utilized in Si lithography (since high resolution is not needed) and to operate in batch mode. This approach also opens the possibility of patterning features smaller than 10 μm for tapes with optimal grain size distribution.

For this technique a dry photoresist is laminated at 70°C with the partially sintered tape. Using contact UV photolithography the patterns are transferred. The dry photoresist must be developed using sodium carbonate and finally a post exposure ensures good etchant resistance.

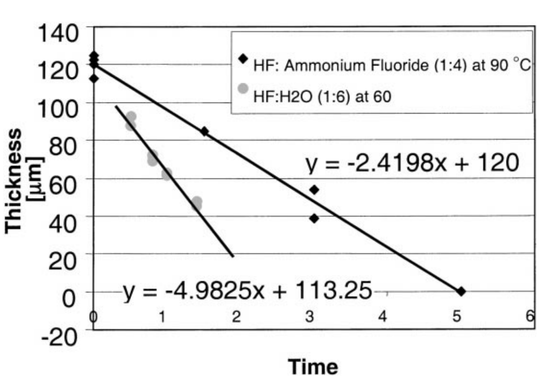


Fig. 15. Etching rate of partially sintered tape.

A fundamental aspect of this procedure is that the tape must be partially sintered. The second plateau in the target firing profile is reduced from 30 to 2 min. That is equivalent to reduction of the actual maximum temperature to 810°C because of the time lag between the targeted temperature and the actual temperature of the kiln. With this alteration of the sintering process the tape is not fully fired and it is realistic to etch the glass grains using hydrofluric acid. Fig. 15 shows that the etching rate on diluted hydrofluoric acid is larger than that of buffer HF even when the temperature and concentration of the diluted HF are smaller. Fig. 16 shows examples of fabricated patterns for the

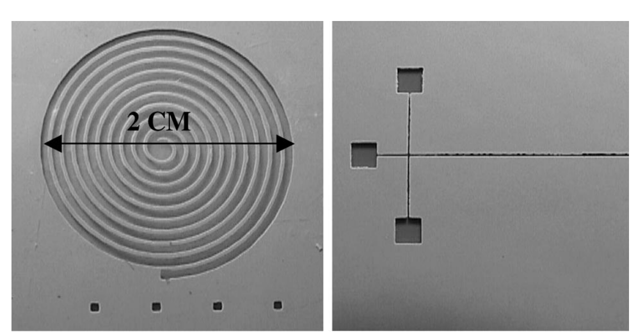


Fig. 16. Patterns fabricated using a dry photoresist film (Riston^{TM}).

development of a multilayer coil and an eletrophoretic channel utilizing this technique.

Multilayer structures can be accomplished modifying the standard lamination process as follows:

- Stack, alignment (using registration marks previously patterned).
- Sintering of the assembly using a low-pressure jig.

3.6. Chemical exfoliation of partially sintered low temperature co-fired ceramics

By immersing a partially sintered LTCC tape in aqueous solution of hydrofluoric acid at room temperature it is possible to split the nominal single layer of 10 mils thickness into three distinct layers. This phenomenon could be a consequence of casting induced texture (preferential orientation). Texture could be induced when the ceramic slip is cast by the doctor's blade if the aspect ratio of the alumina particles in these materials is larger than one [17]. However, recent studies suggest that tape casting probably induces a negligible anisotropy, so this phenomenon may be induced by the tape drying process.

As a consequence, three layers tape are produced with a textured top and bottom layer and a homogeneous (or nearly so) middle layer. Exfoliation process can be visualized in Fig. 17.

An HF solution is used to process exfoliation in a partially sintered LTCC tape, in this case a temperature of 85°C. A partially sintered tape is obtained firing the material with a temperature profile as shown in Fig. 7 modifying the second plateau time to 2 min.

Exfoliation process obeys Fick's law, so its kinetics could be controlled by diffusion. This technique renders very good membranes of thickness between 50 and 100 μm, suitable for high temperature pressure sensor fabrication [19].

3.7. Cavity realization for MST technology

In MsST or MEMS there is a need for 3D structures. In the case of an elemental 3D structure such as a cavity in LTCC tapes, the steps to follow are:

- Machine cavity in tape or laminate.

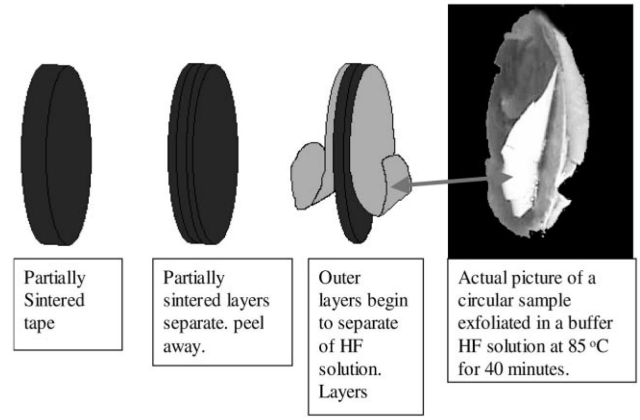


Fig. 17. Partially sintered green tape exfoliation technique [18].

- Use of some sagging control scheme.
- Join patterned tapes and laminate parts.
- Co-fire laminate.

Top layer cavities found applications as sensor carriers to pressure sensors as shown in Table 2. The main requirement is edge quality (vertical walls) that can be obtained using uniaxial or isostatic lamination. As we note in that illustration, the first type of cavity in row one, with inclined walls is ideal for inexpensive self-assembly. One can vibrate the substrate until a die or chip falls in place. The second row illustrates the need for vertical edges when trying to minimize real state (substrate area) and a robotic arm is utilized for chip placement. The third row shows a self-packaged membrane type pressure sensor with the membrane on top.

Inner layer cavities are used to implement sensors, cooling and microfluidic applications as shown in Table 3. Sometimes it is possible to use insert techniques to solve lamination problems, but for more complicated structures fugitive phase techniques are indicated.

In Fig. 18 a silicon die packaging scheme is shown. Remember that both silicon and the ceramic are brittle materials which will not accommodate strain (and stresses) by plastic deformation, therefore in this case it is fundamental to match the die geometry to LTCC material shrinkage.

Table 2
Top layer cavities in LTCC technology from [14]

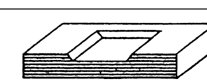
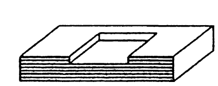
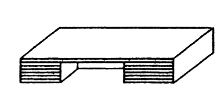
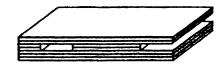
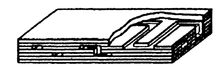
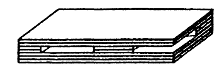
Cavity requirements	Application examples	View of set-up
No special requirements	Sensor carrier Actuator carrier Gas sensor	
High edge quality	Sensor carrier Pressure sensor Dies for innerlayer cavities	
Thin membrane under/over cavity	Pressure sensor	

Table 3
Inner layer cavities in LTCC technology from [14]

Cavity requirements	Application examples	View of set-up
Simple through holes (*x*- or *y*-direction)	Flow sensor Cooling functions	
Small capillary tubes Capillary systems	Chemical sensor Cooling systems Microfluidic systems	
Expanded innerlayer cavities	Pressure sensor Chemical sensor	

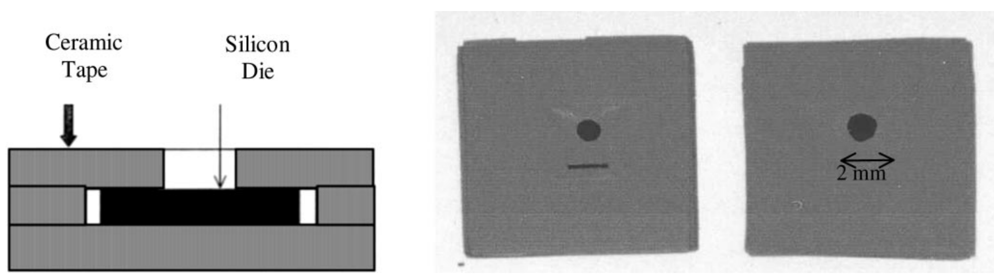


Fig. 18. Schematic and samples for packaging of silicon dies in LTCC tapes.

3.8. Bonding of LTCC tapes with other materials

It is possible to bond LTCC Tapes to other materials, like, glass, ceramics, metals and silicon, using a co-fired or post-fired scheme. This technology is fully compatible with thick film and some thin film technologies.

Glass is bonded using a co-fired scheme or through post-fired glass frits and lower sintering temperatures. Several epoxides could also be used in some applications. For ceramics in particular, one can bond using co-firing frits and glazes, epoxy or brazing techniques. Silicon can be co-fired or post-fired using metallic die-attaching pastes.

3.8.1. Constrained lamination and sintering

When a green LTCC tape is laminated to a rigid substrate (e.g. metal, ceramic or others) the *xy* shrinkage is negligible. All the change in volume is accomplished by shrinkage in the *z*-direction. Fig. 19 depicts five fired layers laminated to a rigid alumina substrate. Note the asymptotic behavior toward the nominal percentage shrinkage value as we move further away from the substrate.

4. Photoformable LTCC tapes

We would like to report some results on a photosensitive dielectric ceramic tape prototype. The photoformable ceramic incorporates a photopolymer in the organic binder. This material is a glass ceramic composite with a conventional nominal composition except that in the organics, besides the plasticizers and anifloculants, a negative photoresist is included. The photosensitive tape we utilized was 150 μm thick.

The processing sequence for photoformable LTCC tape is depicted in Fig. 20.

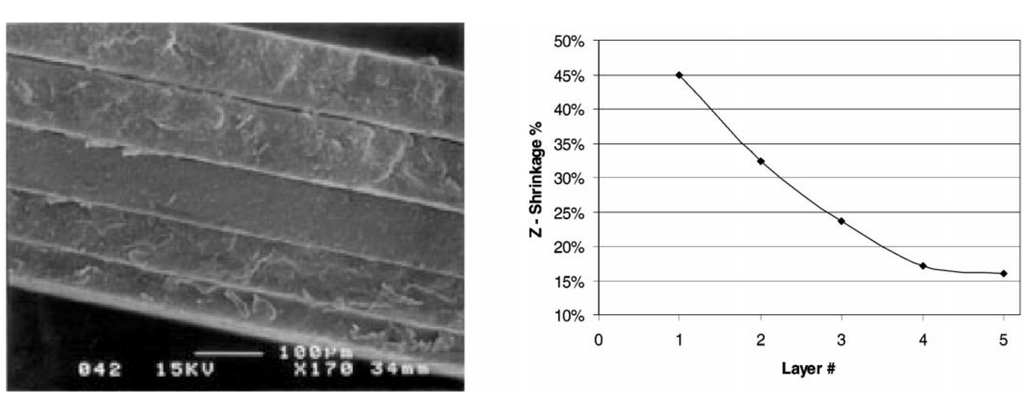


Fig. 19. Z-shrinkage behavior in a multilayer structure under constrained lamination and sintering.

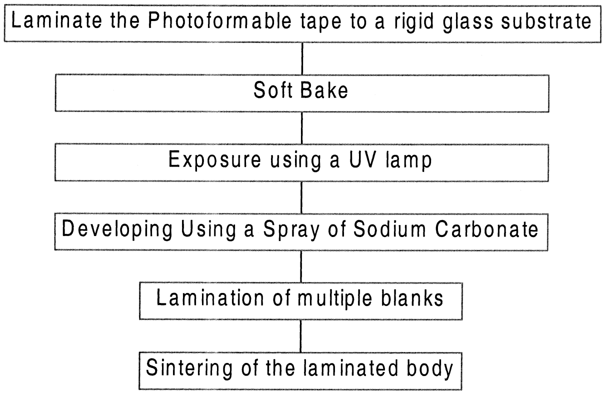


Fig. 20. Photoformable process sequence.

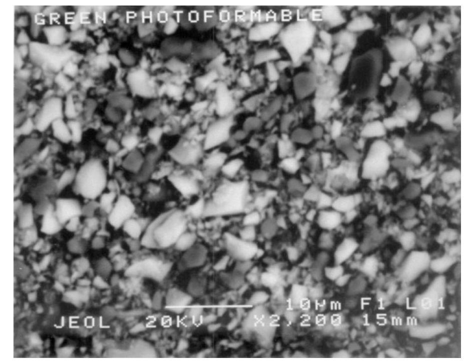


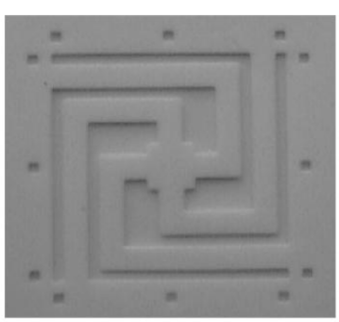
Fig. 22. This micrograph of secondary electrons of a green photoformable tape shows that the mean particle size is 1.84 μm with a standard deviation of approximately 0.9 μm.

The tape is exposed using contact photolithography. In order to develop the tape, a sodium carbonate spray shower is used. After developing, the tape is removed from the glass and finally laminated and fired.

One can control the partial etching depth modifying the process parameters like shower pressure and developing time as shown in Fig. 21.

We found that the larger the energy dosage the smaller the actual feature in the tape [20]. This is due to the scattering of the UV photons by the large particles (Fig. 22). However, if the dosage is too small only the surface of the tape photosensitive organics is exposed and the tape is developed in undesired areas.

(a)



(b)

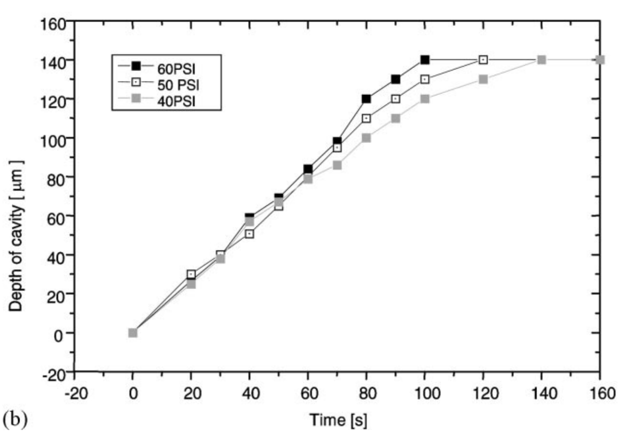


Fig. 21. (a) Partial etching has been achieved at our lab. (b) Depth of cavity vs. development time and shower pressure.

Feature sizes smaller than 30 μm may be achievable, but the resolution limit in a turbid media such as this one seems to be imposed by the diffusive nature of the light scattering within the filler alumina grains. Several workers have shown that the diffusion equation may be an appropriate model for transport of light in turbid media [21–24]. In the case of the photosensitive material that we are using we must consider the scattering of light due to the alumina grains and the glass in the material. Note that most of the absorption will occur on the photosensitive polymer used as resist in the tape.

However, the description used, leads to an integral equation, the Boltzman equation used in neutron transport theory [25]. A simpler solution can be achieved using the average over the solid angle of the reduced diffused intensity. If we assume that the photons are scattered almost uniformly in all the directions we obtain the diffusion equation. We numerically solved it for a finite slab using a Green's function formulation and also using finite element.

One of our results, for example, deals with the influence of number density on the scattering profile. Fig. 23 depicts the normalized average diffuse intensity as a function of position, where the position is defined as in Fig. 24.

5. Sensor applications

As an illustration of the capabilities of the LTCC technology, we briefly describe the following meso-scale sensors:

- Eddy current proximity sensor.
- Gas flow sensor.
- Gas detection sensor.
- Electrochemical sensor.
- Pressure sensors.

5.1. Multilayer eddy current proximity sensor

Non-contact displacement sensors are generally grouped in three categories: eddy current [1], capacitive and optical

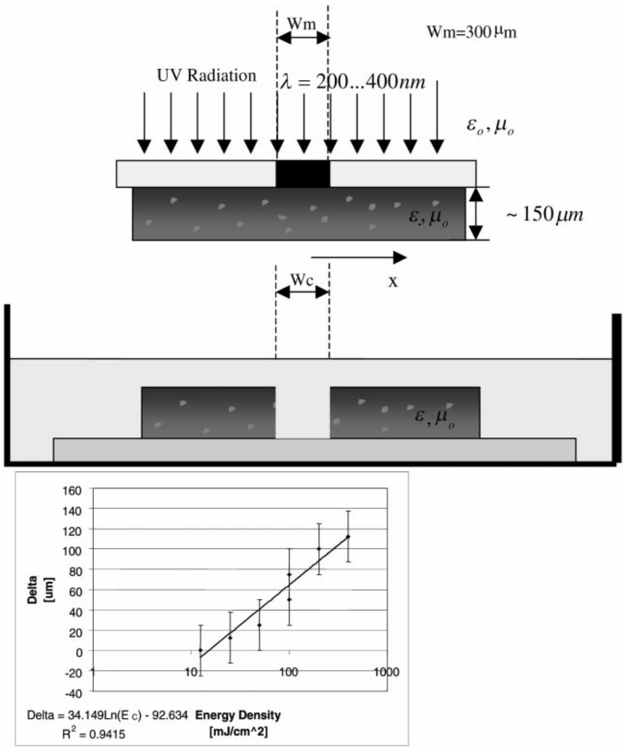


Fig. 23. The larger the numbers density the more steep side-walls.

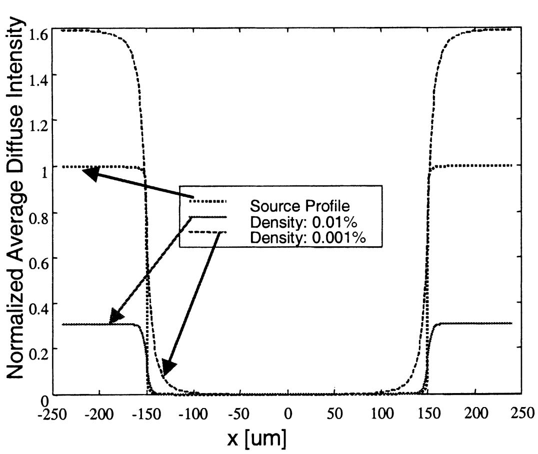


Fig. 24. Undercut: delta represents the difference between the mask size (W_m) and the actual feature size after developing (W_c), $\text{Delta} = (W_m - W_c)/2$.

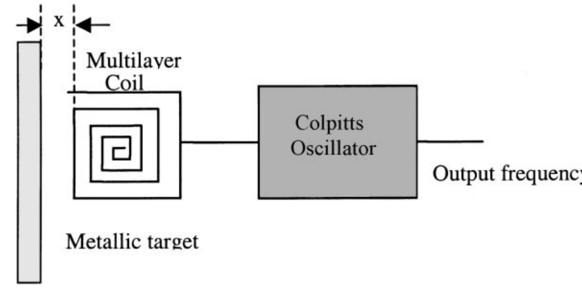


Fig. 25. Block diagram of proximity sensor.

sensors. Eddy current proximity sensors [26], in particular ceramic ones, could be used in many industrial applications because their ability to work in harsh environments. Applications range from metallic target positioning, detection of holes, rivets or screws, profiling of metallic surfaces for automatic teller machines, to the precise measurement of automobile wheel position in ABS braking systems. An approach for implementing 3D multilayer coils for eddy current proximity sensors using low temperature co-fired ceramics (LTCC) technology is briefly described. The eddy current proximity sensor has a multilayer coil incorporated in a LC oscillator as shown in Figs. 25 and 26.

When this circuit is powered-up it creates a weak electromagnetic field near the coil. If metallic targets are introduced in this field, eddy currents are induced in the target changing the circuit output frequency by the modification of the coil inductance.

The fabricated proximity sensor exhibits the following characteristics:

- Non-contact device.
- Full scale of hundreds of microns.
- Could work with gap regions with variable dielectric constants.
- Sensor can work in high temperature environments.

A multilayer square spiral coil of $1\,\text{cm} \times 1\,\text{cm}$ was designed with special geometry in order to have small quantity of interconnection vias.

A single layer was designed to have silver conductors of 80 μm lines and 10 μm thickness with 80 μm space between lines, rendering a 20-turn single layer coil. Typical fabricated layers and details of conductors can be seen in Fig. 27.

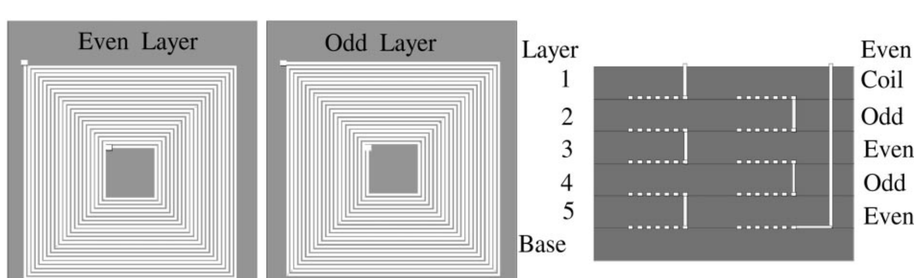


Fig. 26. Coil geometry and interconnection for proximity sensor.

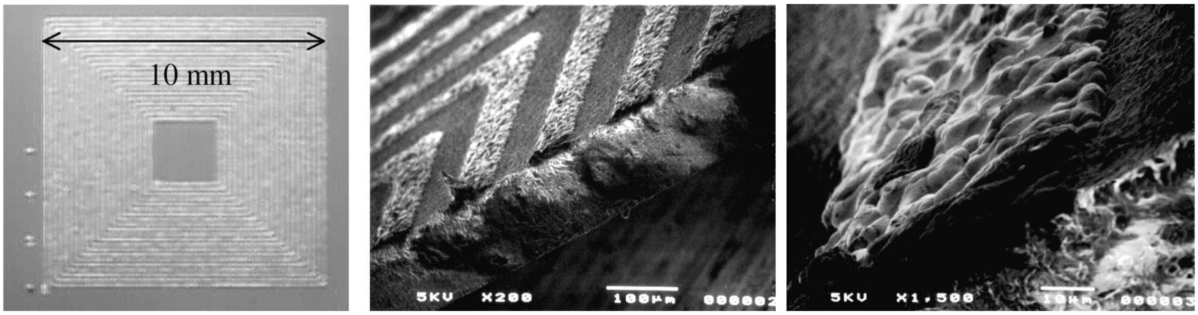


Fig. 27. Typical single layer and conductor details.

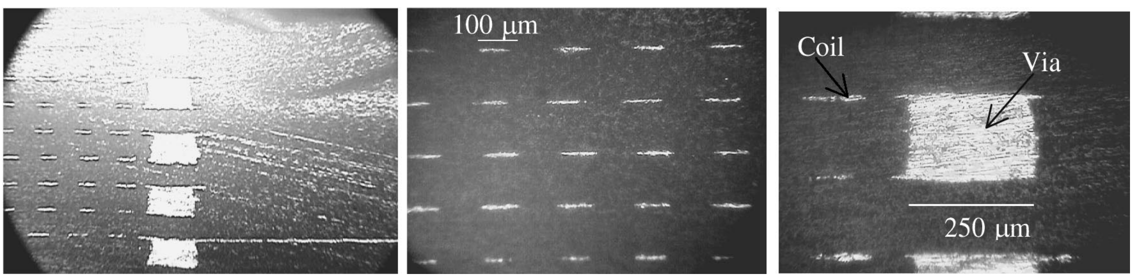


Fig. 28. Cross-section of central part of sensor and details of coil turns and vias.

A five-layer proximity sensor coil was fabricated using DuPont 951 LTCC ceramic system following typical process sequence, using interconnecting vias of 250 µm as visualized in Fig. 28.

The approach utilized, using LTCC technology, provides 3D planar non-contact proximity sensors with low internal capacitance allowing the use of higher frequency in the associated oscillator.

In addition it allows reduced dimensions for better target tracking, 3 mm full-scale measurements, moderately temperature operation and it is fully compatible with all hybrid electronics.

5.2. Gas flow sensor

A meso-scale gas flow sensor was fabricated [27]. The basic sensor structure consists of a thick film resistive heater and two thermistors printed on a thermally isolated bridge in a cavity. The device was fabricated following conventional LTCC technology process and sagging prevention method.

The basic sensor measures the mean temperature in bridge using two thermistors; this temperature is related to flow in the cavity. This configuration utilized five layers of 200 µm thick alumina ceramic DuPont 951. DuPont formulations for the NTC thermistor with high β constant ($\cong$2000) [28], together with a ruthenium-based resistor for the heater were screen-printed on the bridge (see Fig. 29). Fig. 30 depicts various layers of the basic sensor schematically and Fig. 29 is a SEM micrograph of the device cross-section.

It was investigated some sensor characteristics as flow range, sensitivity, temperature excitation, and response time of the device. Temperature difference between bridge and

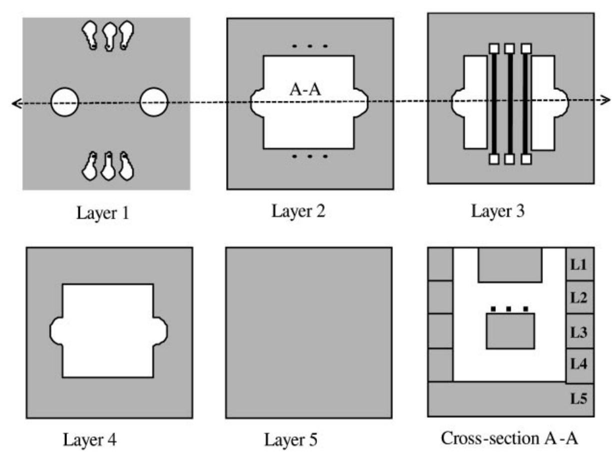


Fig. 29. Cross-section of basic flow sensor.

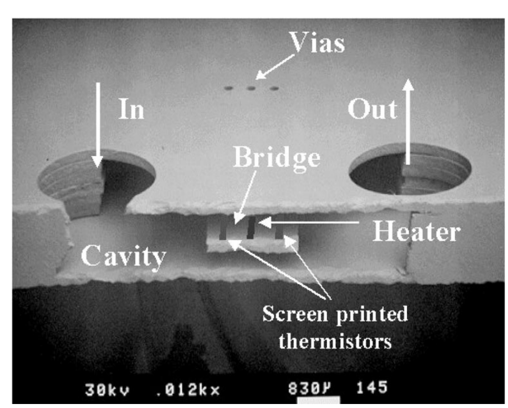


Fig. 30. Schematics: flow sensor layers and cross-section.

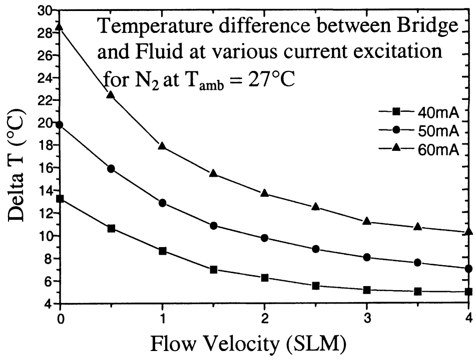


Fig. 31. Delta T vs. flow with parameter I_p.

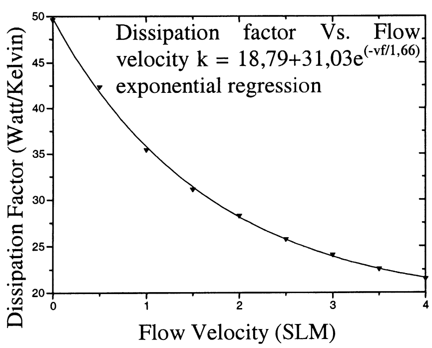


Fig. 32. Dissipation factor vs. flow.

fluid temperature as a function of the heater current is displayed in Fig. 31. Fig. 32 indicates dissipation factor of the fabricated device to diverse flow velocities [29].

5.3. Gas detection sensor

Gas sensor devices using SnO_2 has been implemented using LTCC technology by Teterycz et al. [30]. Sensors were made using LTCC techniques with a platinum heater buried inside the multilayer structure. Tin oxide or thick films SnO_2 with Pd as catalyst were used as gas sensitive materials. The properties of the gas sensors were measured with methane and carbon monoxide.

5.4. Electrochemical sensor

A new electrochemical technique, temperature pulse voltammetry (TPV), was recently introduced using an electrode array fabricated with LTCC technology [31]. Working, counter and reference electrodes were screen-printed on an LTCC tape using Au, Pt, and Ag/AgCl pastes, respectively. The thermal conductivity of the ceramic substrate is five times higher than that of water, which helps to better control the electrode temperatures.

5.5. Pressure sensors

LTCC tape based pressure sensors of the membrane type have also been developed. In our case, to obtain the membrane we utilize the LTCC tape exfoliation process described in Section 3. The sensing device uses piezoresistors from hybrid pastes. These sensors have the advantage of being selfpackaged and to withstand high temperatures [32]. LTCC tapes also allows for onboard electronics [33].

6. Some microfluidic devices

Simplicity to implement channels is one of LTCC technology characteristics. Cavities with reduced dimension and without geometrical limitations can be achieved [34]. In this section some basic applications in the microfluidics area are presented, specifically microchannel, a critical orifice and a gas flow sensor fabrication.

6.1. Microchannels

First studies on microchannels were performed by Poiseuille [35] in 1846. He managed to do some experiments using glass capillaries with diameters in the hundreds of microns. From this study the classical expression that relates pressure drop with volumetric flow rate was obtained. Microchannels on silicon substrates were studied by Phaler [36] and Harley et al. [37] to relate hydraulic diameter with liquid and gas behavior. Fig. 33 illustrate a simple way to

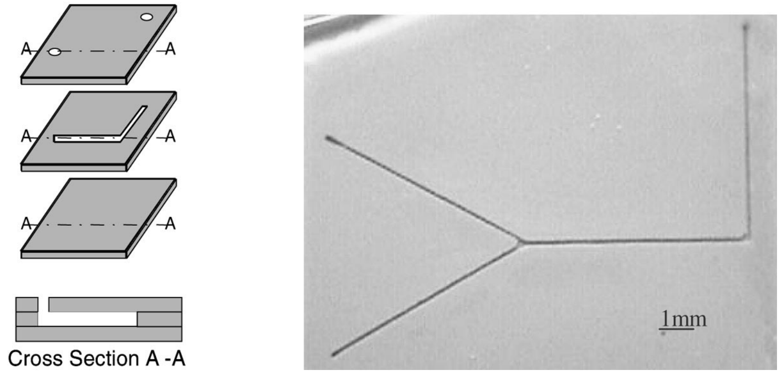
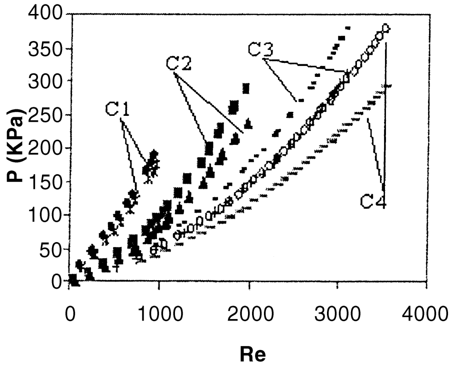


Fig. 33. L microchannel and implementation of Y microchannel using LTCC technology.



The Dimensions of the straight conduits used in the experiments and the Poiseuille number

Conduit's Designation	C1	C2	C3	C4
Conduit's Height (mm)	200	200	200	200
Conduit's Width (mm)	220	210	410	400
Conduit's Length, L (mm)	44	10.5	21.5	10.6
$L_1^+ = (D_H \mathrm{Re}_1)^{-1} L$	1.43	.78	.15	.05
$L_2^+ = (D_H \mathrm{Re}_2)^{-1} L$	.22	.026	.027	.011
Experimentally determined Po # at L_1^+	56.4	62.1	71.8	120.4
Theoretically determined Po # at L_1^+	58.1	58.8	70.9	87.8
Relative difference between theory and experiment (%)	3	5.6	1.3	37
Theoretical, fully developed, Po Number	57.06	56.94	62.45	62.19

Fig. 34. Pressure drop vs. Reynolds number for straight channels.

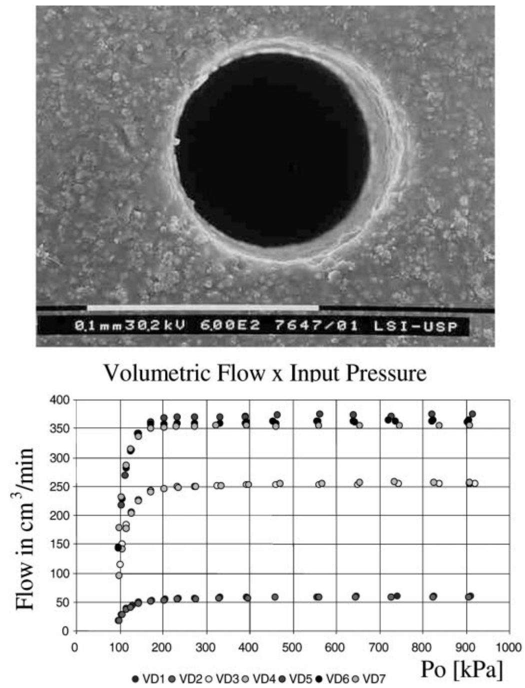


Fig. 35. Critical orifices and its input pressure vs. flow behavior.

implement microchannels using LTCC tape technology; in this case three layers are enough to fabricate the channel. Top layer makes media interconnection, middle layer makes the channel itself (that could be straight, in L, Y, U, spiral or any desired complex shape), and bottom layer makes the device base. A Y-shaped microchannel fabricated using LTCC tapes and glass, it is also presented.

Measurements performed by Moon et al. [38] in straight conduits with dimensions shown in Fig. 34 display linear pressure drop for low Reynolds numbers.

6.2. Critical orifices

Critical orifices as nozzles are passive devices for gas flow control, using Choked flow phenomena. Choked flow occurs when gas reaches sound velocity in the nozzle or orifice. At certain critical input pressure this phenomena arises and volumetric flow remains constant despite output pressure variations [39]. Critical orifices do not have moving parts and can control volumetric flow passively with accuracy.

There are several microfluidics applications for these devices. Fig. 35 depicts a critical orifice fabricated using LTCC materials and machined using CNC techniques. In addition, critical orifice behavior for input pressure versus volumetric flow and different orifice diameters is displayed.

7. Actuator applications

Sensors and actuators with promising characteristics in aggressive environments and high temperatures have been developed using LTCC tape technology [34,40].

7.1. Hybrid microvalve

Microvalves are necessary to execute fluid control functions in microfluidic applications, some advantages of miniaturization of this devices are:

- Small sizes.
- Short response time.
- Low power consumption.
- Low inactive volume.
- Good dynamic characteristics.

In this review, a non-moving parts hybrid electromagnetic microvalve is presented, fabricated using LTCC, thick film and silicon technologies. Forces of magnetic origin can be generated by the interaction of a magnetic field intensity H with an electrical current I [41]. For a vertical actuator the force generated by the interaction of a magnetic field intensity H_z created by a current I in a coil and a permanent magnet with magnetization M_z is

$$dF = M_z \frac{d}{dz} H_z \, dV$$

So the force generated in this scheme depends on the H_z rate of change. So if the magnet is placed in a flexible spring, the applied force will be [42]

$$F_z = M_z \int \frac{d}{dz} H_z \, dV$$

H_z for given geometry can be calculated integrating the Biot–Savart law. As a result of this force, the spring generate a displacement proportional to the force divided by the equivalent spring constant k.

$$\Delta z = F_z k^{-1}$$

Electromagnetic techniques are suitable to hybrid meso-systems, [43,44] because:

- Can generate large forces.
- Can produce large displacements.
- Good performance with temperature.
- Adequate velocity response.
- Robust and inexpensive technique.

A hybrid microvalve was implemented using LTCC. This device has a multilayer coil, a fluidic system and a flexible diaphragm with a permanent magnet bonded in its topside, as shown in Fig. 36.

The multilayer coil fabrication is similar to that used in the proximity sensor presented above. The fluidic part of the system can be implemented with three LTCC tapes as presented in Fig. 37.

Flexible diaphragm with a rare earth magnet attached allows for electromagnetic actuation; the diaphragm was implemented using silicon technology for a planar spiral spring that is covered with an RTV film. Fig. 38 depicts the flexible diaphragm fabrication process. Fig. 39 illustrates the actual microfabricated flexible diaphragms (planar spring); one can also see the complete devices after bonding the rare earth magnet.

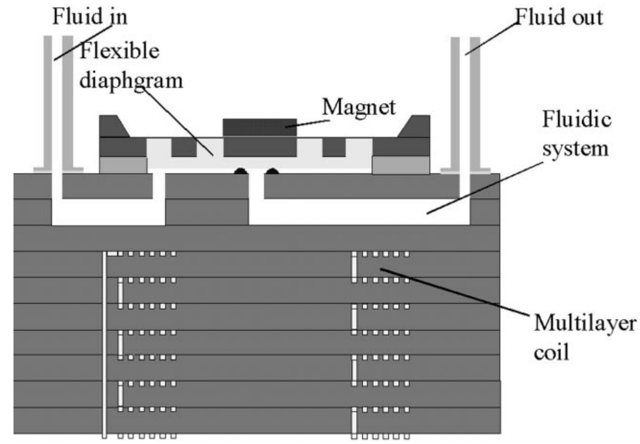


Fig. 36. Conception of a hybrid microvalve.

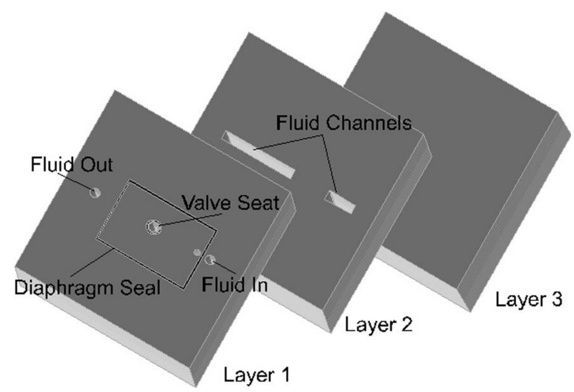


Fig. 37. Microvalve fluidic system.

The fabricated microvalve is shown in Fig. 40. This is a hybrid device that utilizes LTCC tape, an electro-magnet, a fluid flow manifold, an anisotropically etched silicon

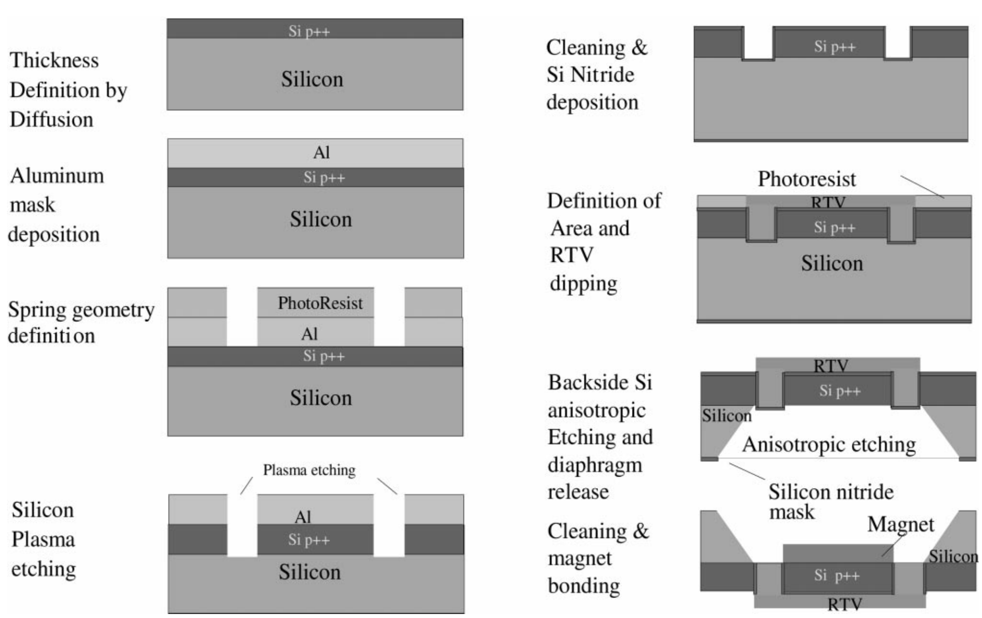


Fig. 38. Flexible-diaphragm fabrication process.

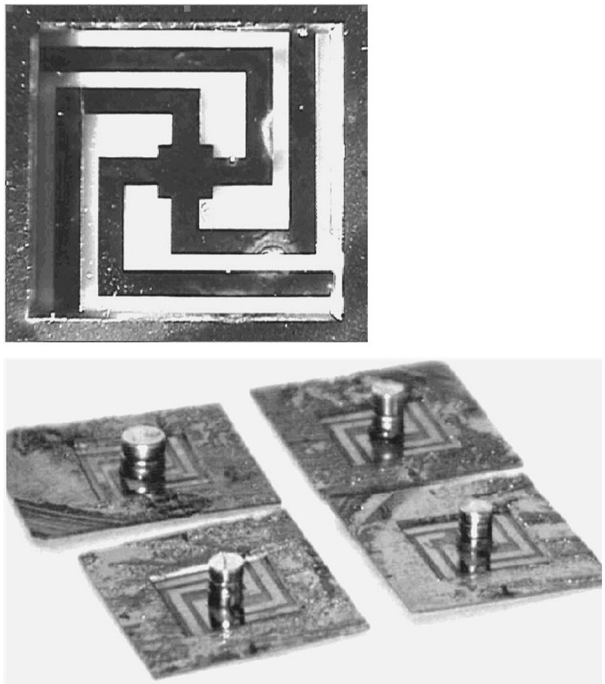


Fig. 39. Flexible diaphragms.

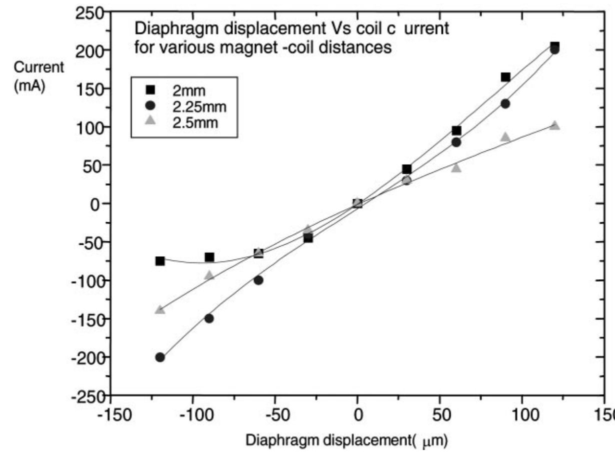


Fig. 41. Flexible diaphragm displacement vs. coil current.

rectangular planar spring, and a high energy product SmCo mini-permanent magnet. Device dimensions are in the meso (intermediate) range with the smallest features (fluid conduit in the manifold) of 400 μm and the largest (the electromagnet, coil) of 12 mm. All parts of the electromagnet and the channels were machined from DuPont 951 series utilizing either a numerically controlled milling machine, a puncher or an isotropic etching technique involving the glassy binder of a partially sintered LTCC tape. The coil consists of five layers of planar spiral. The total coil resistance is high (120 Ω) and thermal considerations limit the current to 150 mA.

Using SmCo magnet (1 mm diameter) we obtained 200 μm deflection of the 30 μm thick silicon rectangular planar spring with a polysiloxane-sealing element. Fig. 41 shows diaphragm displacement versus current coil. This is an inexpensive, easy to fabricate meso-scale valve realized in the same material as many IC packaging systems. This may lead to fluidic systems where the fluidic devices can simultaneously serve as part of the IC package (self-packaged devices).

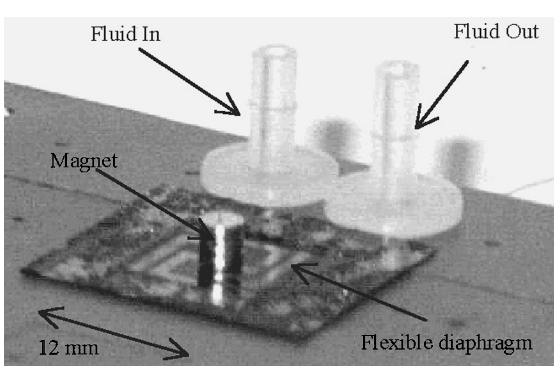


Fig. 40. Hybrid microvalve fabricated.

8. Possible meso-system applications

Meso-systems for drug delivery, biological parameter monitoring, gas or liquid chromatographs, cooling and heat exchangers, particle separators, electrophoretic cells, PCR and SDA reactors, micro combustion chambers and chemical microreactors, could be implemented using the techniques presented in this work. Let us take as an example the LTCC hybrid technology application in meso-systems, a well known analytical technique: flow injection analysis (FIA), [45]. In this technique, a sample is injected in a continuous flowing carrier and is transported downstream into a detector. On its way to the detector, the sample fluid is mixed with the carrier and reagent solutions and is dispersed in a reaction coil. A detector measures the result of this reaction by optical or electrochemical sensing in a continuous flow. Block diagram of the FIA system is presented in Fig. 42.

There are several advantages for FIA miniaturization [46]:

- Sensor can have its sensibility and selectivity optimized.
- Time for analysis is 10–100 s, allowing up to 300 analysis per hour.
- Waste and sample size are minimized.

In Fig. 43, our basic FIA meso-system conception is depicted, using the devices presented in this work. In this case a hybrid pump, two hybrid valves as well as channels and cavities for fluid flow and mixing, are fabricated using LTCC technology. All this is associated to a silicon

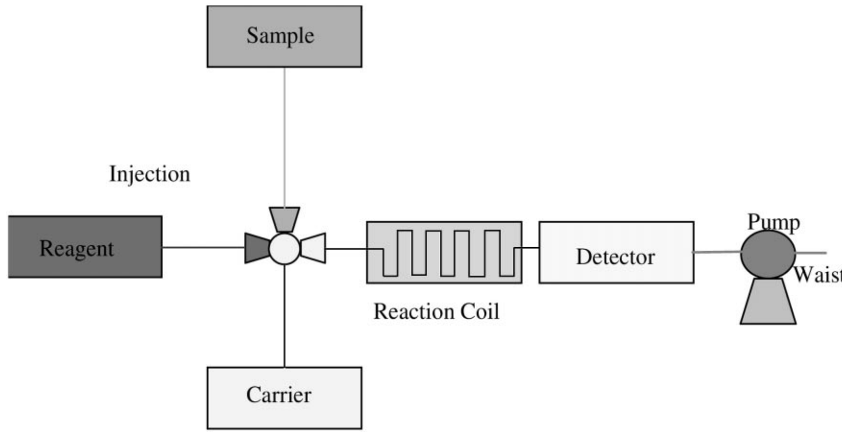


Fig. 42. Basic FIA block diagram.

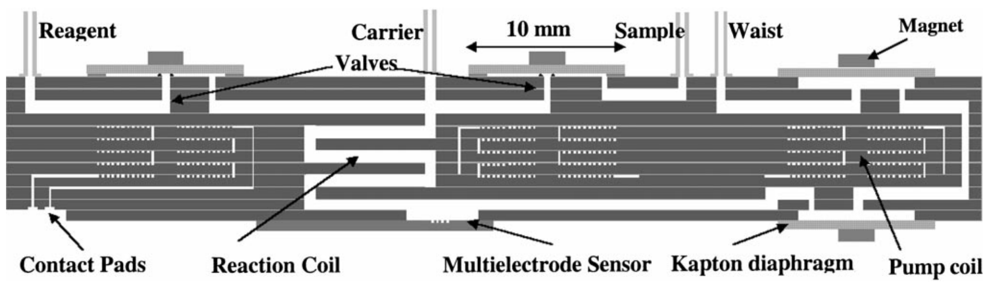


Fig. 43. Conception of FIA meso-system using LTCC hybrid technology.

electro-chemical sensor bonded to the ceramic body after firing.

A multi-electrode sensor for electro-chemical measurement is available as depicted in Fig. 44. This sort of general purpose electrochemical sensor fabricated using silicon technology [47], displays suitable characteristics for doing static or dynamic analysis, multipoint and multi-species measurements.

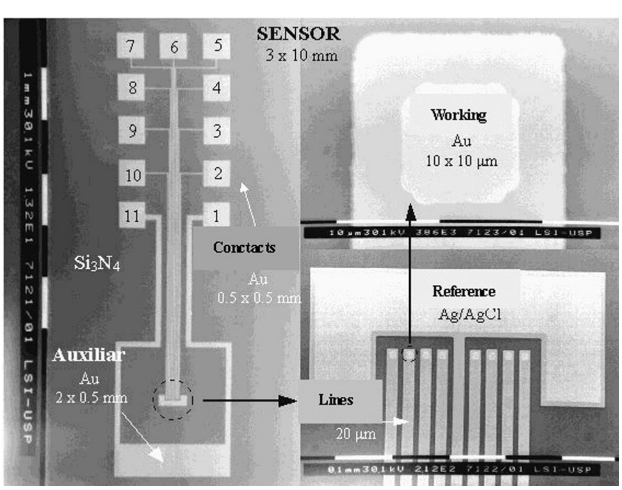


Fig. 44. Silicon multi-electrode sensor.

9. Conclusions

One of the important features of LTCC technology is the possibility of fabricating 3D structures using multiple layers of LTCC tapes. In spite of all their attractive features, LTCC tapes are not well known in the sensor community. In this review we show the potential of ceramic tape technology for the implementation of sensors and actuators suitable for meso-systems. The brief description given here demonstrates how LTCC tape is a suitable material for the fabrication of devices for MsST.

Most of the modules needed for detection systems and hydraulic interconnects can be fabricated and integrated in green tapes. In this review we show a sample of the growing number of applications and potential applications of LTCC tapes to MsST. Studies of more such applications and the development of appropriate processes for production we are sure will be pursued. This area is at present in a development flux, and considering the early results so far obtained; we think that LTCC tape hybrid meso-system technology has a promising future.

Acknowledgements

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