Int. J. Appl. Ceram. Technol., 2 [5] 345–363 (2005)

International Journal of Applied Ceramic Technology
Ceramic Product Development and Commercialization

Novel Microsystem Applications with New Techniques in Low-Temperature Co-Fired Ceramics

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Low-temperature co-fired ceramic (LTCC) enables development and testing of critical elements on microsystem boards as well as nonmicroelectronic meso-scale applications. We describe silicon-based microelectromechanical systems packaging and LTCC meso-scale applications. Microfluidic interposers permit rapid testing of varied silicon designs. The application of LTCC to micro-high-performance liquid chromatography (μ-HPLC) demonstrates performance advantages at very high pressures. At intermediate pressures, a ceramic thermal cell lyser has lysed bacteria spores without damaging the proteins. The stability and sensitivity of LTCC/chemiresistor smart channels are comparable to the performance of silicon-based chemiresistors. A variant of the use of sacrificial volume materials has created channels, suspended thick films, cavities, and techniques for pressure and flow sensing. We report on inductors, diaphragms, cantilevers, antennae, switch structures, and thermal sensors suspended in air. The development of "functional-as-released" moving parts has resulted in wheels, impellers, tethered plates, and related new LTCC mechanical roles for actuation and sensing. High-temperature metal-to-LTCC joining has been developed with metal thin films for the strong, hermetic interfaces necessary for pins, leads, and tubes.

Introduction

This article presents an overview of widely varied low-temperature co-fired ceramic (LTCC) applications to microsystems and meso-scale devices. The mere testing of silicon microfluidic chips has been complicated because of nonstandard designs in a rapidly expanding research environment. To alleviate such a problem we have developed practical solutions like the interposer/manifold/socket combination shown in Fig. 1. LTCC tubes—rolled and highly stacked—have practical uses, including smart channels, drift tubes, chemical and thermal reaction chambers, inductors, and heated fluidic headers. They can be used as chemical separators, coolers, or for other applications with longitudinal or radial channels that are spiral or serpentine. As with microfluidic boards, the serpentine can be in-plane or out of plane with the tape layers. Suspended thick films permit more sensitive thermal sensing and anemometry, as well as enabling components like air-core inductors, raised planar inductors, antennae, and electrical switch and microfluidic valve applications. Micro-total analysis

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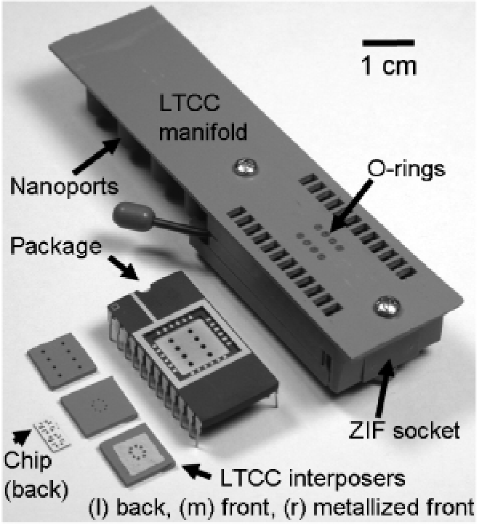

Fig. 1. Low-temperature co-fired ceramic (LTCC) microfluidic test system.

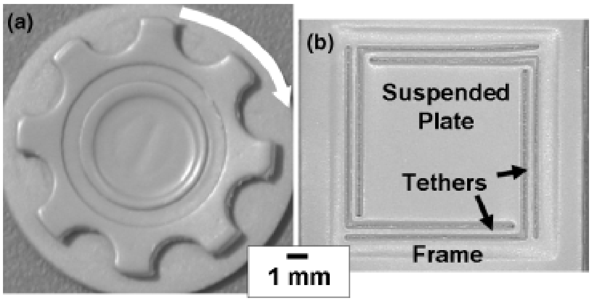

Fig. 2. (a) Freely rotating "functional-as-released" wheel. (b) Suspended square plate tethered to outer frame.

systems (μ-TAS), including microstructures, and micro-high performance liquid chromatography (μ-HPLC) at pressures greater than 35 MPa (5000 psi) offer new miniature analytical capabilities. LTCC lids and channels with windows from 3 mm diameter to the size of an optical fiber (125 μm) permit new optical capabilities. A cell lyser has been shown to lyse biological species without damaging the proteins. Coarse and fine manifolds are simple and have repeatedly produced functional prototypes on the first try. The requirement for planar systems has been eliminated in the case of Bourdon tube and other types of pressure sensors and manifolds. Microfluidic O-ring seals and interfaces to a range of commercial connectors have simplified connections to the outside world. The demonstrated ability to braze strong joints for pins, tubes, and custom connectors will be useful in several disciplines. Much of the current work involves the use of sacrificial volume materials (SVMs) in new and traditional ways. Commercial ceramic setter sheet has been added to our suite of SVMs, and these suggest the need for an inert-substance fill such as a setter paste for the attainment of micrometer-scale thicknesses. This new approach has enabled meso-scale "functional-as-released" moving parts including wheels, impellers, shutters, cantilevers, pressure diaphragms, tethered plates, shuttles (pistons), and others. A freely spinning wheel/impeller is shown in Fig. 2a, and a suspended spring-tethered plate is shown in Fig. 2b.

Background

LTCC technology has an increasingly important role in enabling microsystem elements and their integration, just as hybrid microcircuits integrated monolithic silicon with a mix of technologies for special performance for many years. Modular hybrid microelectronics thrived because of performance that was superior to wafer-scale integration. The term multichip module (MCM) was descriptive of a changing emphasis. First popularized by the fine feature size afforded by deposited thin-film technology (MCM-D), they soon included ceramic (MCM-C) because of the reinvention of hybrid microcircuit technology using LTCC, in particular. Performance improvements were realized, particularly for high-frequency and high-current applications. LTCC also permitted a large cross section of captive and commercial sources to use co-fired ceramics. Prototyping in LTCC even accelerated design cycles for ultimate production in high-temperature co-fired ceramics. An approach based on laminated printed circuit technology (MCM-L) also developed fine patterning capability to complement its high-conductivity metals and inexpensive, low dielectric constant polymers. Several recent requirements for inert materials in extreme environments favor ceramics. Technologies that multiplex between use of polymers, deposited films, ceramic, and other materials and methods succeed when they are solution oriented.

Integrated microsystems have now gone through some of the same phases as their microelectronic predecessors. An initial emphasis on minimum feature size in microelectromechanical systems (MEMS) is shifting to solution-oriented trade-offs considering ultimate packaged system size. Between these two scales lies the opportunity to add value with meso-scale functions. Well-known commercial entities successfully integrate surface micromachined (SMM) MEMS on the same chip with silicon integrated circuits. However, a large contingent remains interested in hybridizing the unique capabilities of microelectronic, microelectro-mechanical, microfluidic, radio frequency (RF), and optical functions while providing an interface to the outside world. LTCC provides solutions for these applications, many of which are still developing, including functions associated with health, detection of toxic or illicit materials, and security.

LTCC is a well-established commercial technology based on processing of unfired glass-ceramic tape. Processing steps are covered in detail in a comprehensive review.[1] In applications of LTCC to microsystems, it is important to understand the material properties of the available constituents (tapes, thick films, and auxiliary products). These materials, which are continuously being improved, determine the kinds of structures that can be made. These structures are, in turn, made by various methods. There is an enduring drive to look at technical needs and evaluate whether structures and methods used in other disciplines would be improved by LTCC. Some of the material properties (i.e., low thermal conductivity) that are a detriment in some applications can benefit others. A variety of devices and systems result from these materials, structures, and methods. Then come some hard questions on the selection of optimum materials for manufacturing, as some of these devices and systems critically depend upon the unique capabilities of LTCC, while others only contain LTCC.

Although the available technologies that can be used in the manufacture of systems are continually evolving, there will always be a premium on features that are completely integral, co-firable, and ''functional-as-fired'' in LTCC. The LTCC device as defined requires little additional assembly. However, the benefit of this approach must be weighed with the advantages of assembling a system of individual components that are each optimized for their intended function. As such, the complete integration of co-fired systems is a work-in-progress, and a great deal of admirable work in the literature has enhanced the acceptance of LTCC in microsystems.

Materials and Properties

The suite of tape and thick-film compositions, functions, and application techniques to LTCC is ever increasing. Studies have helped to quantify the chemical, structural, and mechanical properties of LTCC.[2] Particular attention is being given to materials interactions[3] and mechanical behavior during firing,[4,5] as well as reliability implications, including failure analysis,[6] as LTCC finds new applications as mechanical structures. Characterization of thick films in general includes applications for ceramic humidity and multifunctional sensors on alumina,[7,8] thermistors on alumina and fired LTCC,[9,10] and piezoresistors on various substrates.[11–15] Most of the work we report here uses DuPont's 951 line of LTCC tapes and DuPont thick-film compositions (Dupont Microcircuit Materials, Research Triangle Park, NC). Carbon-loaded tape and fluids and inert loaded setter tapes from Harmonics, Inc. (Seattle, WA) are also used.[16]

Structures

Cavities have been used since the inception of LTCC, and interest in enclosed unfilled volumes (channels, chambers, etc.) was anticipated. In fact, microfluidic applications are given their own section below. LTCC unsupported bridges have been used to carry thick-film structures for rapid thermal response,[17] coils,[18] and for an air core microstrip.[19] Suspended thick films have been fabricated that would enhance both of these applications.[20] Thick-film diaphragms have also been demonstrated,[20,21] as have thick conductor heat-spreading columns and tapes in cooling channels.[22]

Devices

There are several examples in the literature where a hybrid approach has been used to integrate microsystems in LTCC,[1] as with valves and windows in a microfluidic LTCC board,[23] and silicon or ceramic membranes in an LTCC valve.[24] Partially sintered membranes and bodies were joined with a glass frit for an all-ceramic pressure transducer.[25] Other distinctive devices include rolled tubes formed prior to firing (ion mobility spectrometer (IMS) drift tube),[26] stacked thick-walled IMS drift tubes,[27] micro-heat pipes,[28] and micronozzles.[29]

Methods

LTCC tapes can be perforated and deformed. Thick-film materials can be screen printed, stenciled, dry transferred, or can be written directly on surfaces and into vias. When collated, laminated, and co-fired, monolithic microsystem structures are the product. Collating can include unusual approaches such as rolling or fixturing for viscoplastic formation.

Our interest in novel capabilities of LTCC predated our work in rolled tape techniques, for cavity lids with three-dimensional (3-D) relief. Whether by laminating complex layer stacks,[30,31] deforming prior to firing,[26] slumping during firing,[32] or use of thick-film loading,[4] the 3-D capability of LTCC has been appealing for a long time.

Shaping of LTCC

Shaping of LTCC has been used in designs such as the rolled IMS drift tube reported elsewhere (Fig. 3a).[33] This device included an embedded heater and surface co-fired resistor networks (we have recently added thick-film thermistors to the device). Tubes have been rolled on a 1.43 cm (0.563 in.) mandrel to a layer count of 17 using 250 μm (0.010 in.) tape layers. Firing was performed with the tube standing on end using our normal temperature profile. Two orthogonal cross sections revealed no apparent defects.

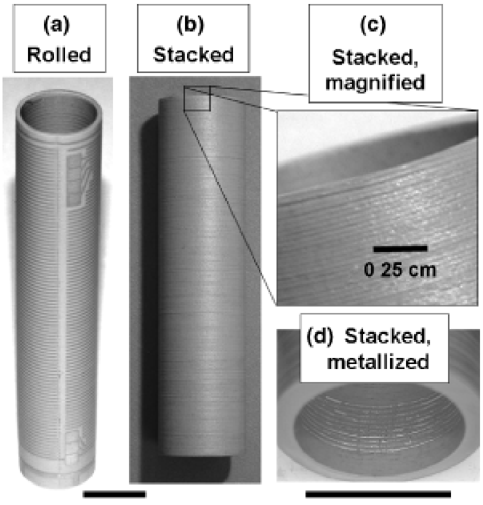

Fig. 3. Fired low-temperature co-fired ceramic tubes: (a) rolled, (b, c) stacked, (d) metallized and stacked.

As a demonstration, a device of similar wall thickness was fabricated by stacking, as cracking had temporarily stalled previous efforts to build a stacked drift tube. The tube shown in Fig. 3b was stacked to a layer count of 300 using 250 μm (0.010 in.) tape. Stacking of washers maximized the availability of air to inner volumes during burnout and firing. All stacked parts made in this way were hermetic. Metallization on the face of the washer connected external traces to internal traces, whether they consisted of a thick-film conductor on the edge or on the inner bore surface of alternate washers (Fig. 3d). All such interior electrodes were electrically continuous to the exterior. Lamination was performed in either 20.7 MPa (3000 psi) or in 207 MPa (30,000 psi) isostatic laminators. The inner bore, which was laminated to a mandrel, was quite smooth. The outer surface, which was wrapped in a buffer, could be smoothed, if required. The availability of tapes as thin as 50 μm (0.002 in.) means the electrode size and separation could be very small. This was not necessary in the current drift tube design. The quality of the internal electrodes for face-metallized washers was degraded by tape edge deformation at the mandrel, and would have been improved by reaming before firing.[27]

Another rolled tube application to replace an inert ceramic feed tube for a gas sample has been prototyped. The existing alumina tube had been fitted with a discrete heater and temperature sensor that were quite bulky. An LTCC tube was fabricated with a buried gold thick-film heater and a surface thick-film thermistor (Fig. 4). This tube was lightweight and functional, actually melting the soft solder joints on its first trial. The smallest diameter mandrel used for this tube approach was about 2 mm diameter, and the fired outer diameter 3 mm.

Smart Channels

Feasibility demonstrations for smart channels were fabricated from rolled LTCC tubes. As with the rolled IMS, the electrodes on the concave surface were rolled into contact with the electrodes on the convex surface, which were electrically terminated on the exterior of the tube with solderable thick-film pads.

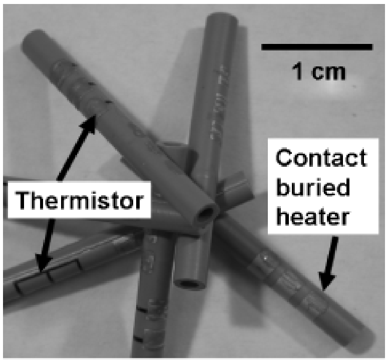

Fig. 4. Miniature heated tubes with thermistors simplify point-of-use heating.

The smart channel integrates several sensors using the LTCC as a common substrate for (1) a chemical sensor, (2) temperature sensors, and (3) a flow sensor. The tube has provisions for internal surface thermistors, precision thick-film electrodes for the sensing medium, and a small multipurpose heater embedded in the tube wall. Figure 5 shows the rolled LTCC tube, with electrodes both on the exterior and interior surfaces, during testing.

Chemical Sensing

A chemical sensor (chemiresistor) was fabricated by depositing a conductive polymer "ink" across a pair of electrodes along the interior of the LTCC tube. In the current method, the "ink" was deposited inside the tube in the desired location using a micropipette. Volatile organic compounds can be absorbed into the polymers, causing them to swell and change in electrical resistance. The change in resistance is proportional to the concentration, so these devices can be calibrated. The unique aspect of this device is that the sensors are integrated within the channel/tube, eliminating the need for extensive plumbing to introduce the fluid sample into the sensors. The location of electrodes at the end of the tube was ideal for applying the polymer.

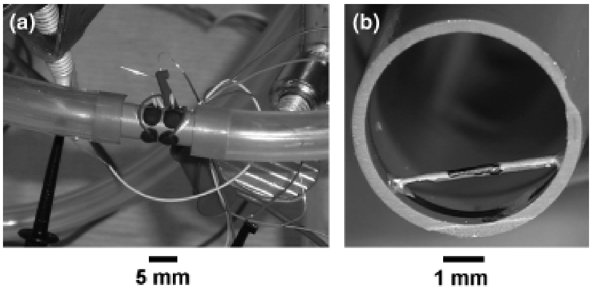

Fig. 5. (a) Measuring chemical concentration, air flow, and temperature through the low-temperature co-fired ceramic chemiresistor smart channel with integrated anemometry. (b) Suspended thermistor assembly.

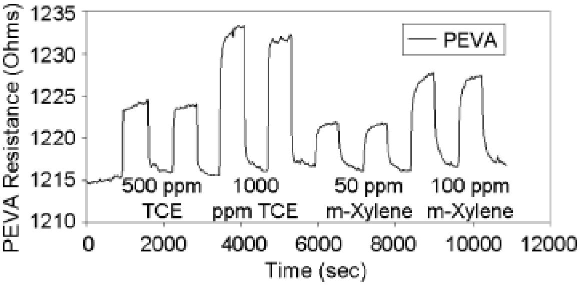

Fig. 6. Response of the low-temperature co-fired ceramic chemiresistor to different concentrations of trichloroethylene (TCE) and m-xylene.

The ends of the LTCC smart channel were connected to 6 mm (0.25 in.) Flexible tubing, and dry air, trichloroethylene (TCE), and m-xylene gas were passed through the tube at known concentrations. A noise/stability analysis showed that the LTCC chemiresistor exhibited noise that was comparable (or lower) to conventional chemiresistors made from a silicon substrate. Results also showed that the LTCC chemiresistor responded well when poly(ethylene-vinyl acetate) was exposed to cycles of TCE and m-xylene (Fig. 6). The response was approximately linear up to 1000 ppm of TCE and 100 ppm of m-xylene. A new design will increase the number of electrode pairs for the chemiresistors so several polymers can be simultaneously evaluated for discrimination of different chemicals.

Flow and Temperature Sensing

Thermistors were fabricated and co-fired in the LTCC smart channel to provide temperature sensing and anemometry (Fig. 5). Heating elements were also integrated with the smart channel to allow temperature control for the chemiresistors and for the flow measurement. The thermistors in the LTCC smart channel were first calibrated in an oven to yield a resistance/temperature coefficient. Air was then passed through the channel at different flow rates, and the thermistor temperatures were recorded while the heating element was maintained at a constant temperature. The thermistors were positioned at several locations in the channel to monitor the spatial temperature distribution. Preliminary results showed that flow rates above 100 mL/min could be measured with thermistors printed on the inner surface. We anticipate that with suspended thermistor structures (Fig. 5b) the sensitivity can be significantly increased.

SVMs

Enclosed unfilled volumes have been formed by a number of different techniques.[1] Frequently, channels are left open and are closed later with a cover—transparent if desired. They can be formed in an unfired ceramic surface, fired, and joined to a second surface. Openings can be made through all or part of the full thickness of unfired tape layers by machining, punching, solvent jetting, laser ablation, stamping,[34] or other means. These volumes can be preserved in high-pressure lamination using uniaxial pressing, fine geometries,[35] or selective protection during isostatic lamination (used by authors). Sagging in firing has been studied and thick-film overlayers were used for shape compensation during firing.[4] Increasing the thickness of overlying unfired tape can also mitigate the closing of these volumes during firing. Low-pressure lamination with an adhesive has also been used.[36,37]

Another technique for preserving enclosed unfilled volumes involves a temporary insert,[38] as might be used for component cavities. Cracking has been seen to result from differences in density following lamination.[28] Friction against an insert or fixture can result in such density differences.

Enclosed unfilled volumes can also be protected by inserts that are etched away after firing,[4,21] or an insert that would dissociate during burnout and firing.[4,28] In some cases, this insert is cast in place.[39] In most other instances, the insert is a discrete layer or stack matching the appropriate opening in a corresponding ceramic tape structure.[40] Another insert has been described that could be poured, shaken, or flowed out after firing.[41] We and others have referred to these volumes as sacrificial and to the materials used to make them as SVM. The term "fugitive phase" is also used in the literature for a subset of these.

While SVMs are not new, as referenced above, they have greatly enhanced the versatility and manufacturability of specialty LTCC applications. We previously described our use of SVMs in detail.[20] A distinct feature of one aspect of our use of SVM is that we do not require a pre-existing volume, but rather form the volume upon lamination according to the placement of the SVM. This technique is integrable with the existing infrastructure in industry, which can regard SVM as a unique thick-film or tape material.

We have used a variety of materials as SVM including polymer sheets and fluids, and commercial carbon-loaded tapes and pastes. We will also describe our use of inert loaded setter material in this article.[16] A combined thermogravimetric analysis (TGA)/differential scanning calorimetry curve is shown in Fig. 7 for a 2 mm diameter button of the carbon tape enclosed in 3 mm diameter LTCC tape wraps. Temperature is plotted versus time, as the light line, for a steady heating rate burnout and firing process (3°C/min). The heavy dotted line—the calorimetry curve—indicates measured heat flow. Sample weight is shown as the heavy solid line. Both curves show the enclosed carbon-filled SVM "burnout" in a range around 650°C.

Figure 8a illustrates the use of SVM tape or a fluid-defined layer, including its use as a substrate level for other thick-film materials. This ability to print on a material of various thicknesses that is essentially going to disappear is very useful. It compares with dry transfer of thick film we have performed in our lab and with thin-film lamination described by others.[42] Plugs or thick film via fills, that are dielectric, conductor, or other, as shown in Fig. 8a, become z-axis supports. Use of SVM in conjunction with unfired ceramic tape is illustrated in Fig. 8b. SVM tape, fluid, and other forms can be incorporated by a large number of techniques summarized in prior work.[20] It can be vanishingly thin ($\ll 1\,\mu\text{m}$) or remarkably thick ($\gg 1$ mm) as dictated by the particular application. Just as vias can be filled with SVM in Fig. 8b, the ability to route SVM anywhere on a layer or between layers complements its addition to the suite of available thick-film materials. Several structures from Fig. 8 are listed in Table I. Features i and ii can be laminated to other areas shown on SVM or on LTCC tape. Feature iii is a raised conductor with conductive and/or insulating supports. Other structures shown in Fig. 8a can be laminated as well. An example of such a method is shown in Fig. 9, where feature iv, an SVM-defined serpentine channel, has been incorporat-

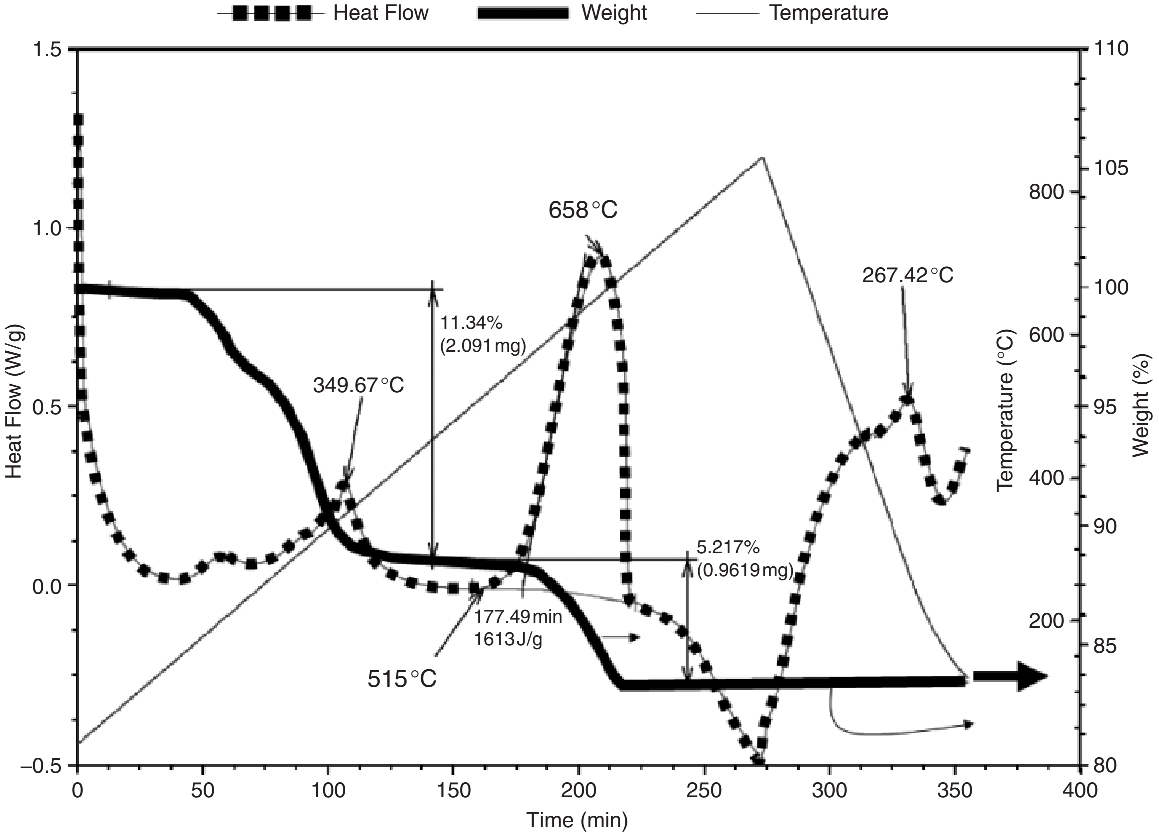

Fig. 7. Thermogravimetric/differential scanning calorimetry analysis shows weight loss and exotherms associated with burnout and firing.

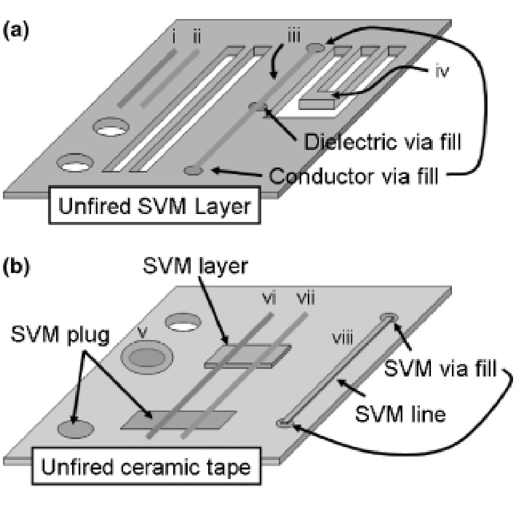

Fig. 8. (a) Sacrificial volume material (SVM) layer with thick-film lines on top. (b) Ceramic tape with thick film and SVM lines on top, and cutouts/vias filled with SVM.

ed into a tube wall. A related simple shape has been discussed in the literature and suggested for use as cooling channels.[32]

Feature v shows thick-film diaphragms supported over the tape openings by SVM plugs or via fill. Such diaphragms are shown in Fig. 10. The rings in Fig. 10a show a carbonaceous contamination associated with burnout and firing that has yet to be eliminated completely.

Features vi and vii in Fig. 8b show thick-film lines that can be raised above the substrate or suspended over an opening. Feature viii shows one way to create a microfluidic channel with inter-level access.

Microfluidic Channels

Microfluidic channels have been formed by the methods referenced above. Even in conventional board

Table I. Explanation of Features in Fig. 8

Feature	Description
i	Thick film dielectric line on SVM
ii	Thick film conductor line on SVM
iii	Conductor-on-conductor vias with center support that is dielectric
iv	Sacrificial volume area surrounded by open area for unfired tape bonding
v	Conductor bridging SVM plug on ceramic tape to form diaphragm on firing
vi	Thick film dielectric line crossing SVM layer to form bridge suspended above substrate and crossing SVM plug to form bridge across gap in tape layer
vii	Thick film conductor line crossing SVM layer to form bridge suspended above substrate and crossing SVM plug to form bridge across gap in tape layer
viii	SVM line on top of ceramic tape layer and on top of SVM via fill to form fluidic channel when laminated to another ceramic tape and fired

SVM, sacrificial volume material.

thicknesses, uses for both very large and very small channels are found (Fig. 11). Miniaturization is recognized as a key to future analytical chemistry and life sciences success. An excellent review of micromixers discusses miniature channels in silicon, polymers, glass, and metals.[43] Revolutionary results are now possible in laminated co-fired ceramics. Surface considerations will receive special attention, particularly with respect to texture[44] and inertness. The recent suggestion of low-level Pb contamination in electrolytes by LTCC and conductors in certain applications[45] reinforces the expectation that coatings such as parylene, particularly for some biological applications, may play an important role. Another possibility might be atomic layer deposition (ALD) of materials like aluminum oxide that can coat aspect ratios approaching 10^4 under some circumstances.[46]

Filling with an SVM has preserved vias and ports under a variety of lamination techniques. The device shown in Fig. 12a is an example of a larger scale manifold for a valve component, mounted using through holes. Ports were protected by SVM and fabrication was successful on the first try.

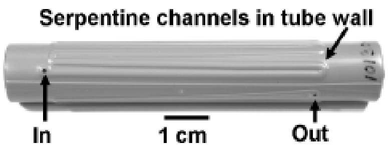

Fig. 9. Serpentine channel defined by sacrificial volume material with surface ports in the wall of a rolled tube.

We made no attempt to limit backside topography associated with the sacrificial channel formation because it was not a requirement for this device. The manifold was required to effect no more than a 3.5 Pa (0.5 psi) pressure rise at a flow of 0.2 L/min. Figure 12 shows the device ported to commercial fluid ports. Figure 12b shows the backside of the device with the topography evident. Figure 12c shows the design sketch including the component.

Integration/Interposers for Silicon Microfluidics

MEMS is an area of intense activity with new designs coming out every day. Packaging has frequently been an afterthought, particularly in a research environ-

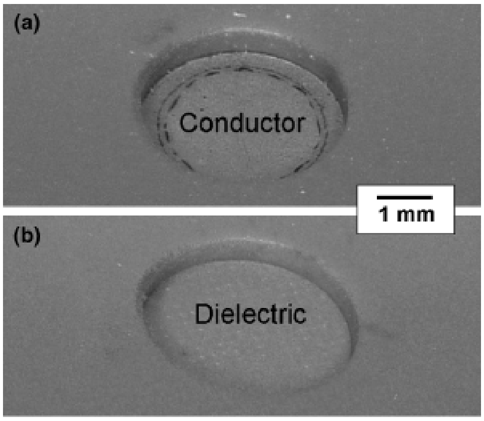

Fig. 10. Thick-film diaphragms have been fabricated using both conductor and dielectric.

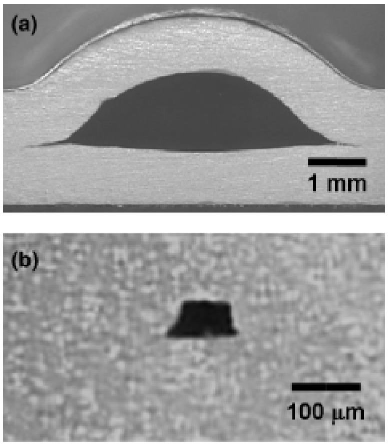

Fig. 11. (a) Fired large channel formed by deforming ceramic tape around sacrificial volume material during lamination. (b) Fired small channel punched through tape layer and laminated to top and bottom tape layers with protection over the channel.

ment. Unfortunately, simple tests on devices sometimes present challenges. Just as packages provide microelectronic fan out, we have previously used discrete electrical interposers to interconnect MEMS devices such as high-density mirror arrays. Now, electro-microfluidic interposers are also needed. In SMM silicon microfluidics, the most common microfluidic access is through the backside of the silicon using deep reactive ion etching (RIE) to define ports. Frequently, the features at the front of the chip dictate the minimum wall thickness between ports at the back of the chip.

The use of a disposable microfluidic/microelectronic interposer eases the fast acquisition of test data on new designs. One technique we have used was illustrated in Fig. 1. This is a ceramic version that builds on earlier work on an electro-microfluidic dual in-line package (EMDIP™).[47,48] It involves a standard package that can be easily connected to a commercial "zero insertion force" socket including provision for microfluidic connections—in this case a low-profile LTCC manifold with O-ring glands (far right). This results in leak-tight connections up to greater than 200 kPa (30 psi). These ports have not yet been tested to failure. Ports on the standard package are adapted to the customized ports on the silicon device by a microfluidic interposer (Fig. 13). Devices are attached to the front side with an appropriate method. Currently, depending on the application, epoxies, medical grade silicones, soft solders, Au/Si eutectic die attach, and field-assisted bonding are used. The interposer can be fabricated with electrical traces and, ultimately, replace the package altogether. The LTCC manifold can be thin to be placed atop the socket or thicker to replace the top layer of the socket. The outside world connections are large, so the end of the manifold is large. Leadless chip carriers, pin grid arrays, fluidic grid arrays (FGAs), and custom packages and sockets also lend themselves to this type of fixture. One stroke of a cam could connect the part mechanically, electrically, and fluidically for testing and that end of the manifold becomes much smaller. Also under consideration are miniature ports resembling ribbon cable for microfluidics.

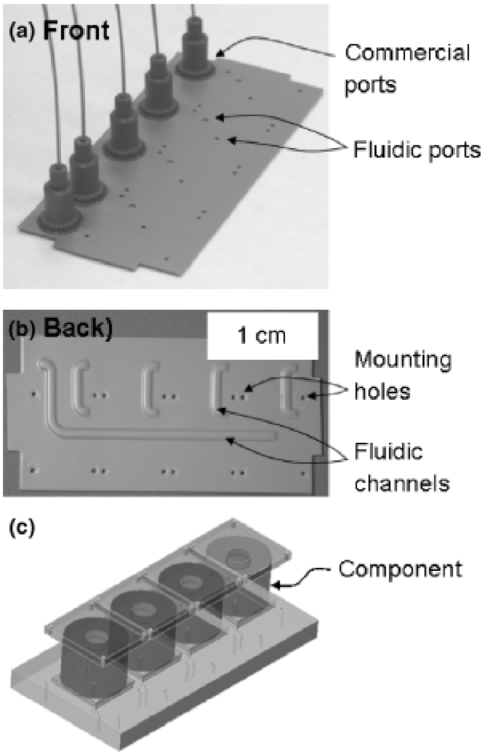

Fig. 12. (a) Front of meso-valve manifold with standard connectors. (b) Back of manifold showing contoured channels formed by sacrificial volume material lamination. (c) Mounted component sketch.

Figure 13a shows a standard footprint hole array on the back of an interposer. Figure 13b shows the deep RIE fluidic ports on two silicon parts just above their mating interposers. Figure 13c shows the magnified back of an interposer, laser scribed and ready to singulate, whereupon it will fit closely to the package floor

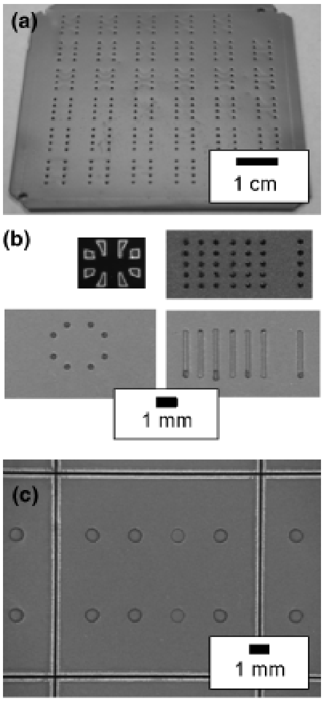

Fig. 13. (a) Interposer array; (b) silicon access holes (above) and mating interposer holes (below); (c) laser-scribed interposer.

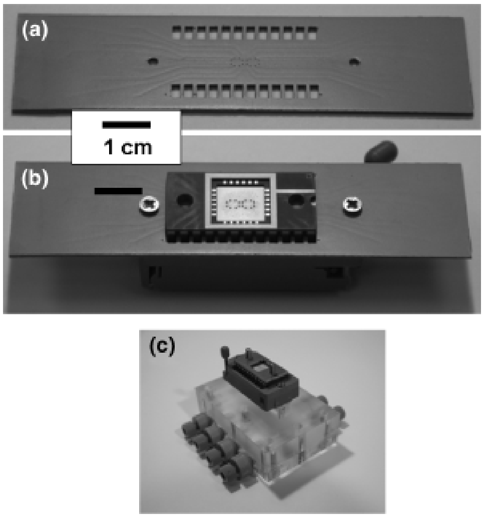

Fig. 14. Testing is facilitated by an low-temperature co-fired ceramic manifold that takes the place of a manifold block.

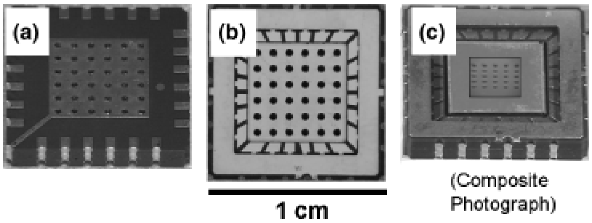

Fig. 15. Fluidic grid array precursor: (a) back; (b) front; (c) composite photograph with interposer.

without any special demand for alignment. The backside flatness is adequate for holes at this scale. The interposer array in Fig. 13a was specified, defined, cofired, and singulated within 24 h. Interposers as thick as 1.5 mm (0.060 in.) have been used, but interposers thinner than 300 mm (0.012 in.) would work with a lower profile for most applications. Figure 14a and b shows an earlier manifold for 16 fluidic ports. Manifolds demonstrated previously,[49] similar to that shown in Fig. 14c, may be replaced by LTCC.

Miniaturization is still lost, however, when a 0.3 cm square MEMS chip is packaged in a 1.5 cm × 3 cm (or larger) package. Packages shown in Fig. 15 are leading to the development of complete FGAs in multiple materials. We have successfully sealed FGAs with soldered annular seal rings that were prepared using flux, cleaned, and finally joined without flux. We have also investigated soldering in environments that obviate the need for flux—especially for high-temperature solder.

Applications in the near future will populate microfluidic system boards with a high silicon-to-board ratio, reminiscent of MCMs. Meanwhile, the first high-density applications may involve ‘‘parts farms’’ in order to generate large amounts of reliability information in a compact manner. This would expand on an approach used in the past for MEMS.[50] A candidate would be an interposer, used for mechanical/fluidic testing of silicon devices that are placed in a harsh environment (Fig. 16).

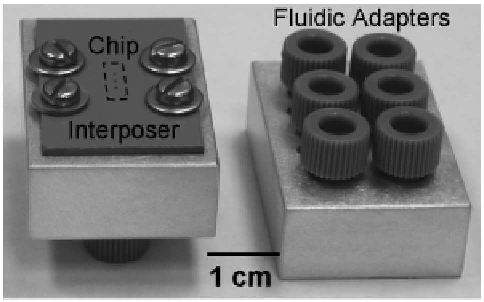

Fig. 16. Alternate interposer used in harsh environment test.

Ports

Many microfluidic prototypes have had a glass capillary tube glued into place for fluidic connection. We have developed structures that are compatible with commercial connectors and have used various types, including adhesively attached surface ports that mate to a range of fittings. We have also used O-ring glands in a top layer of a microfluidic board for connections which will be re-used frequently, such as the test fixture shown in Fig. 1.

It is further possible to active braze or direct braze metals with compatible thermal coefficients of expansion to LTCC devices. Test specimens using American Society for Testing and Materials F19 tensile buttons and LTCC interlayers with thin-film metals have been successfully joined at temperatures up to 750°C with strengths approaching 55 MPa (8000 psi). It is anticipated that reducing the brazed joint area to capillary tubing sizes will produce even greater joint strengths substantially reducing the surface area currently required for high-strength interconnections. Parts sealed with the newly developed process pass helium leak testing with leak rates less than 5.0×10^{-10} atm mL/min He. The direct incorporation of metals into LTCC structures during cofiring is also being evaluated by us and by others.[29] An environment that will properly co-fire the LTCC without irretrievably degrading the metal is of interest.

μ-HPLC

Channels in LTCC have been made on a scale with those used for typical glass devices that have been chemically wet etched (50 μm × 100 μm). The pumping hardware for such a system is shown in Fig. 17. Early experiments have been performed, where an electrode in the leading port is used to complete electrical connections for a capillary-based electrokinetic micropump. Two parallel channels are shown for introduction of two different solvents (water and acetonitrile). The center taps of each channel permit the pressure to be measured, followed by a fluid outlet port. Channels in μ-HPLC samples have been pressurized higher than 35 MPa (5000 psi) for electrokinetic pumping combined with μ-HPLC in an LTCC board for μ-TAS.

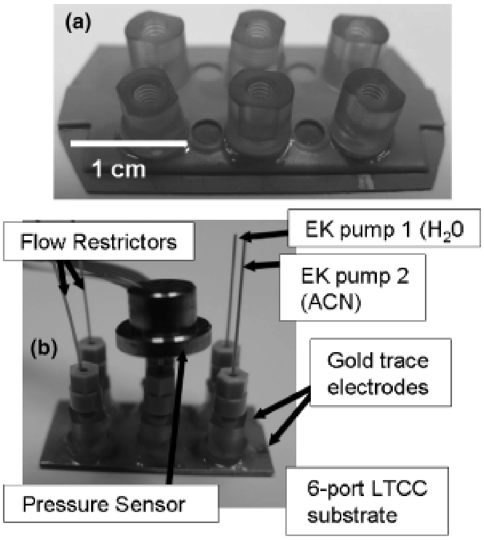

Fig. 17. Micro-high-performance liquid chromatography fluid pumping apparatus.

Cofired transparent windows have been incorporated with microfluidic channels for observation of fluid flow and mixing.[20] Early large windows (3 mm diameter) leaked at about 0.69 MPa (100 psi), but work continues to improve the integrity of the seal between the window and the substrate at high pressure, including design considerations. For example, we have succeeded with sealing viewing ports into LTCC as small as an optical fiber (125 μm diameter). These also passed helium leak testing with no detectible leak. We had previously sealed optical fibers into wall sections of LTCC structures for optical applications. Optical fibers have also been co-fired into zero-shrinkage LTCC in the literature.[51]

Cell Lyser

A new application to take advantage of LTCC properties for biological systems is a compact version of a rapid cell lyser and solubilizer. Channels were formed with LTCC features that readily accepted a glued-on surface port. The channel was surrounded by heaters on layers above and below. The ability to heat and apply pressure to the channel was used to successfully lyse robust spores of *Bacillus subtilius*. An example of one of the heater configurations is shown in Fig. 18a.

The vial tips shown in Fig. 18b have captured the output of the cell lyser operating at room temperature and at 180°C. The difference in turbidity suggests that the spores have been successfully lysed. The plot in Fig.

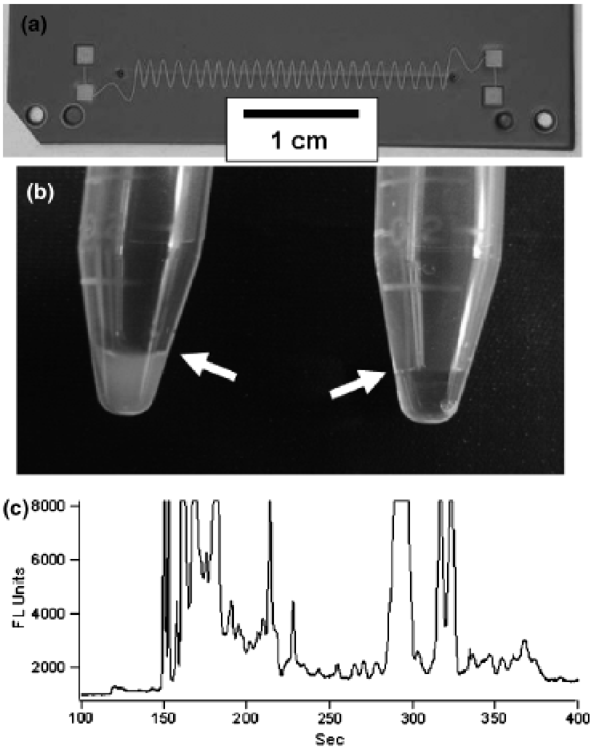

Fig. 18. (a) Low-temperature co-fired ceramic cell lyser with integrated heater traces. (b) Processed spores through the lyser at room temperature (left) and at 180°C (right). (c) Separation of solubilized proteins by molecular weight after lysing spores with the thermal lyser.

18c demonstrates that the spore contents have been successfully solubilized and the proteins, still intact, can be separated with conventional analytical techniques.[52,53]

Suspended Thick Films

The technique for making thick-film air bridges has previously been described to make structures like those shown in Fig. 19. Features like i and ii in Fig. 8a can be laminated transversely to a feature like the SVM layer in Fig. 8b to co-fire structures like the conductor in Fig. 19a or the dielectric in Fig. 19b. The usefulness of these suspended thick films can be enhanced in certain applications by making the bridge a cantilevered structure that would result in a lower mass as shown in Fig. 20.

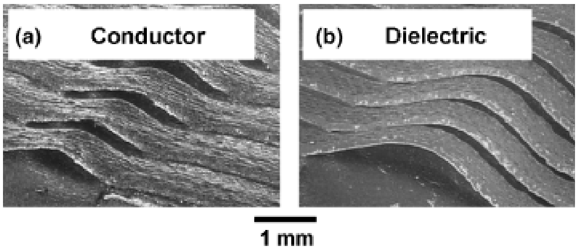

Fig. 19. Suspended thick-film bridges using (a) thick-film conductor (b) thick-film dielectric.

Inductors

The use of suspended thick films to realize inductors as shown in Fig. 21 may allow inductors with performance superior to planar spiral inductors. The technique will allow inductors with reduced inter-turn capacitance and series resistance, allowing higher Q and self-resonant frequencies. A similar approach was described using wirebonding,[54] but the high series resistance because of the small wire cross section limits the overall Q of the structure. Because the inductance of the structure is proportional to the cross-sectional area of the loops, maximizing the loop height above the substrates is critical. An example of fabricated inductors with "through" and "open" test structures is shown in Fig. 21b. However, the inductance of the structure was only about 1 nH (compared with the expected 4 nH) because of the small height of the loops above the substrate, which also increased the inter-turn parasitic capacitance. Increasing the bridge height to improve the loop cross section and lower the parasitic capacitance is expected to improve the overall inductor performance to the point where it is a viable alternative to lossy planar inductor structures. Simulation to determine the optimum dimensions for these types of structures is ongoing, but

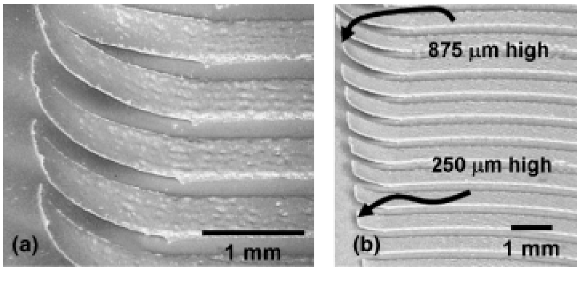

Fig. 20. Cantilevered dielectric thick films.

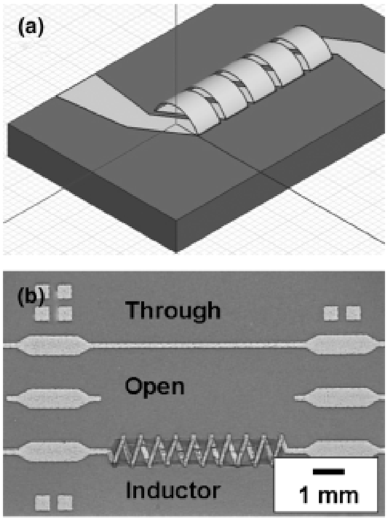

Fig. 21. Air core inductors fabricated using sacrificial volume materials with low-temperature co-fired ceramics.

preliminary simulations indicate that inductances of several nano-Henrys with *Q*s over 200 may be possible for these structures at frequencies up to a few Giga-Hertz. Additionally, these inductors may allow the insertion of a ferrite material into the core, increasing the inductance of the component and allowing for components such as integrated transformers.

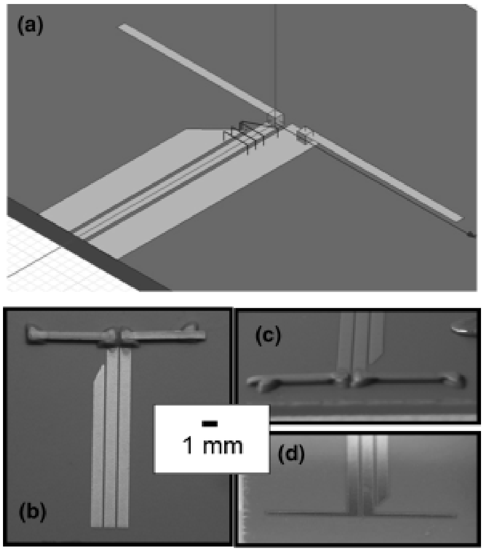

Fig. 22. Suspended thick-film antennae: (a) as-designed, (b) top view, (c) tilted view with thick film raised 250 µm from surface, (d) antenna fired on surface for comparison.

Because *Q* of an inductor generally increases with cross-sectional area, the approaches used to demonstrate LTCC tubes can also be used to realize high-inductance air-core inductors with thick-film conductors. One such example demonstrated inductance of 17 µH with a peak *Q* of 49 at 23 MHz and a self-resonant frequency over 40 MHz, which was the upper frequency limit of the test equipment. The hollow core of the tube will also allow the insertion of ferrite material, allowing extremely large inductors and transformers with better reproducibility than the typical wire-wound components.

Antennae

Suspended thick-film material may be used to realize integrated antennae on LTCC substrates. Generally, integrated antennae have poor performance because of the high dielectric constant and loss of the dielectric substrate, but the ability to suspend traces above the substrate should allow antenna designs with improved efficiency, directivity, and gain. A simple 3-D electromagnetic simulator model of one such antenna is shown in Fig. 22a. The antenna uses a coplanar launch and a simple balun to feed a 6 GHz dipole antenna suspended above the substrate. While initial simulations of this design only show slight improvement over antennae fabricated directly on the substrate, further optimization of this and other antenna designs should benefit from the ability to suspend the metal thick films above the substrate. Antennae have been fabricated using thick films raised above the surface of the substrate as shown in Fig. 22b–d. This prototype was assembled for the purpose of measurements and is not co-fired yet. Planar coils may also be improved by elevating them off the substrate. As with a planar coil, this structure may resort to having periodic dielectric supports made of LTCC.

Cavity Resonators

A potential application of internal sacrificial volumes is cavity resonators similar to those realized previously in silicon and other technologies.[55] These internal cavities may allow the realization of high-frequency filters and resonant structures with *Q* values previously unobtainable on LTCC materials. These cavities offer the potential for *Q*s of several hundred at frequencies of 10 GHz and higher. Additionally, these cavities will be inside the ceramic, leaving the ceramic surfaces for surface mount components and other large items. Process development for the realization of these structures is ongoing.

Thermistors

Prior work in the literature identified commercial thermistors that had very good properties.[9,10] The behavior of these thermistors was even found to be better on fired LTCC than on alumina, and evaluation of co-firing was recommended. We worked with the same thermistors, examining printing conditions and their effect on performance on fired LTCC. Because several of our applications involved immediate integration, such as anemometry in complex locations in proximity to heaters that would furthermore be air bridges, we co-fired these thermistor compositions with satisfactory results. As reported, the values were variable but the performance was quite good for prototypes and proof of concept. Other thermistor devices have been made for flow sensing, such as the device shown in Fig. 23, currently being tested. Here, the thermistors and heaters are located along a flow channel on the external surface.

Thermistor in Channels

It was mentioned that the use of channels and SVMs has expanded the number of compositions that can be considered for co-firing. Several materials will survive co-firing on a surface exposed to air during firing, but will not survive if buried and enclosed in the matrix of the body of a part. The use of a cavity permits nonburied thermistors to be considered for incorporation. A unique set of circumstances exists in a case like this. It can be desirable to have the fluid move through the channel without a great amount of heat being diverted. One would also like to have a thermal measurement without electrodes being directly exposed to the working fluid. Thick-film resistors are insulating on their surfaces. This makes an ideal situation for placing a thermistor in a channel. If, for instance, the thermistor crosses the channel, the amount of the buried resistor can be reduced to an insignificant amount. At the same time, the co-firable electrodes can be buried in the matrix. Channels have been made in this way and appear to work as desired. A schematic for the technique is shown in Fig. 24.

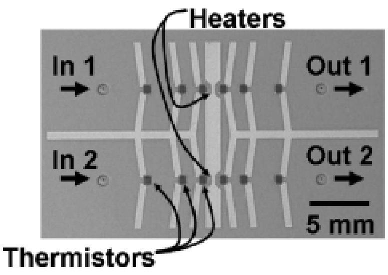

Fig. 23. Surface thermistors on a flow sensor.

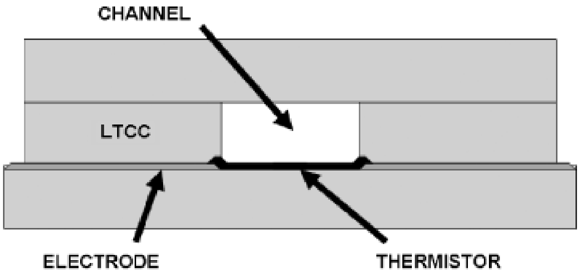

Fig. 24. Thermistor on interior surface of a microfluidic channel.

This device has been tested in conjunction with the heater shown in Fig. 4 to detect air flow as shown in Fig. 25. The resistance for both the thick-film heater and the thermistor is plotted. Both plots suggest useful applications as flow indicators.

Thermistors on Suspended Thick Films

Figure 26 shows an air bridge test part where 0.5 mm wide resistors were applied to co-fired dielectric bridges in geometries that varied from 1.5 squares to 8 squares. These parts showed remarkable results, such

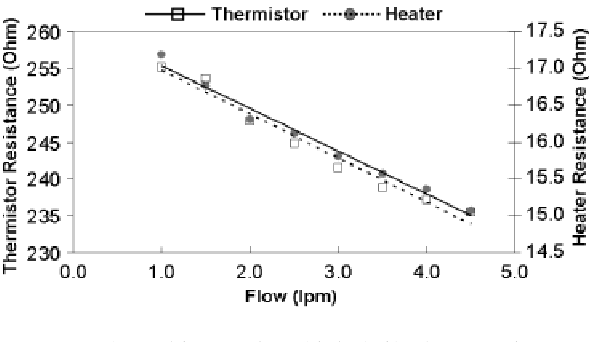

Fig. 25. Flow calibration for gold thick-film heater and thermistor.

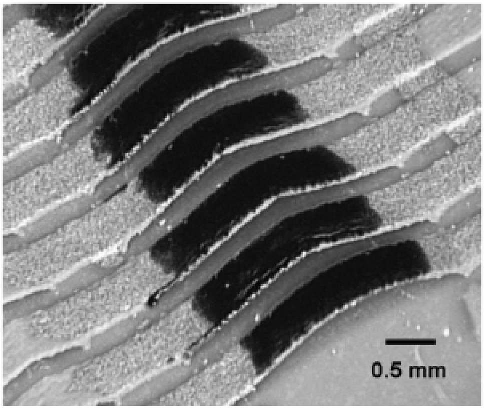

Fig. 26. Thermistors on suspended thick-film bridges.

as registering a 1°C temperature rise under illumination from a flashlight, and 0.1°C sensitivity. Using a rotating optical shutter, the time constant of these thermistor bridges was determined to be 0.5 s.

These materials have also been co-fired on thick-film bridges with good results. Our yields need to improve, but the performance of the devices is good. In order to succeed with co-fired thermistors, we need to support the glassy thermistor portion structurally. While they survive when printed directly onto the LTCC surface, they droop and become discontinuous in mid-air. We have supported the thermistor on a dielectric bridge, concentrating on having a small thermistor with electrical leads no more massive than they have to be. Because the conductor can support itself, we have also used suspended metal traces that overlap a small dielectric patch that serves as a platform for the thermistor and lets it overlap the conductor for proper electrical termination.

We have also co-fired structures in the *z*-axis by sandwiching a thick-film thermistor between the tips of thick-film metal lines. These devices result in very low resistances, but they are thermally responsive. They can also serve as heaters. When the heater is off it can be used to indicate a cooling rate proportional to flow rate in its surroundings. A similar structure has also been used in an application for an array of vertical load sensors, using the piezoresistive properties of the thick-film resistor.[56] Because anemometry may involve ther mistors in close proximity to heaters, we have considered the SVM technique for construction of heaters and thermistors in layers with a small gap between them.

Setter Tape as a Sacrificial Material

We previously alluded to a technique for preserving shapes that seemed impractical at the time. We have adopted a variant of that approach to further refine devices that can be made where sagging during firing would otherwise prevent them.

By treating a commercial setter tape from Harmonics Inc. as a sacrificial material, and copying from SMM MEMS manufacture geometrical techniques for achieving minimum spacing smaller than the stated minimum feature size, we have been able to create "functional-as-released" moving parts. "Functional-as-released" in this context means that aside from removing the sacrificial material, no additional assembly is required. Alignment of features is performed prior to lamination, just as alignment of mask layers would be performed on an SMM MEMS device. Release consists of blowing the setter particles out of the structure, either with compressed gas or some other particular working fluid for the device.

The technique we are using is to place a material in contact with the desired layers that prevents tape bonding, but then occupies the space during firing. An expansive thin layer that would sag upon firing is restrained from doing so. Deformation during lamination can be used to tighten the tolerance on a hub for a wheel. The concept for a simple wheel is shown in Fig. 27. The deformation of the unfired setter tape has repeatedly resisted perforation so that it does not fuse to the other layers of tape, say at a corner. A space is defined that permits the hub for the wheel to fuse to the substrate, but keeps the wheel from sticking to the hub or to the substrate. The top setter could also be an unfilled SVM in certain cases.

One factor to be considered is the large differential shrinkage between the setter layer (1%) and the LTCC layer (12–15%). Although it becomes a loose powder, trapping the material in certain ways can give rise to problems seen in laminated object manufacturing.[57] This problem can be mitigated by using the supporting material in a pattern, such as support posts or rings, or coated with carbon SVM.

Structures including the one shown in Fig. 2a were driven pneumatically in a manifold that directs jets of air at the structure perimeter—also constructed from LTCC. While these structures are just over 1 cm in diameter, they serve to prove the concept. A useful size range for such devices is likely 1–3 mm. Figure 28 shows a second attempt resulting in a freely spinning, "func-

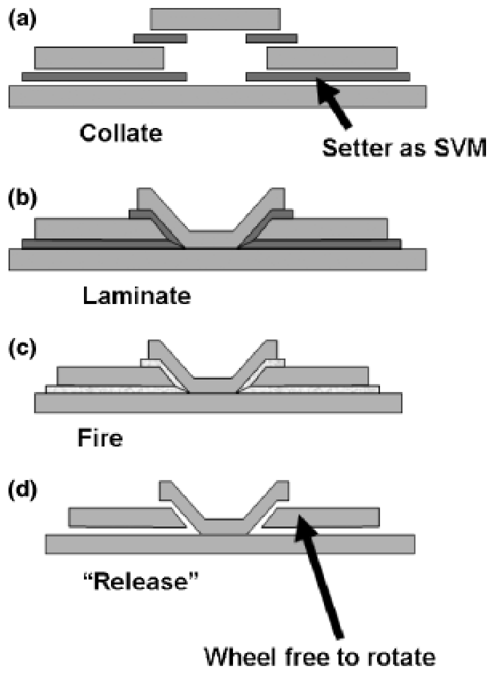

Fig. 27. Simplified illustration of "functional-as-released" low-temperature co-fired ceramic wheel.

tional-as-released" 3 mm diameter impeller. The tape setter materials suggest a use for inert filler materials such as pastes in order to reduce minimum spaces to micrometers where needed.

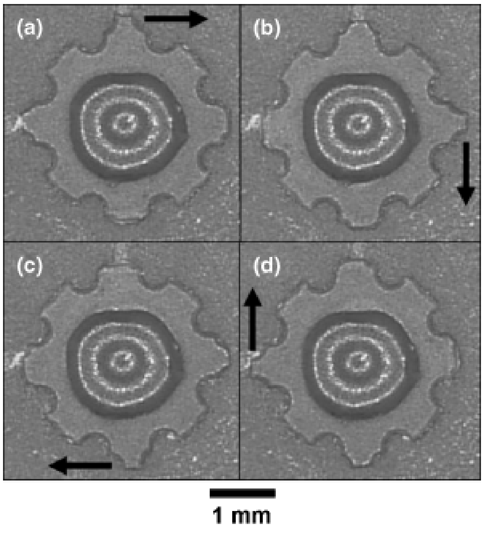

Fig. 28. A 3 mm "functional-as-released" freely rotating wheel is parked at four positions around one revolution.

Capacitance Sensing

Measurement of variable parallel plate capacitance as a mechanism for obtaining response is obvious in existing pressure sensors, accelerometers, and other devices. Several sensor types could be constructed in LTCC using this approach. A related example of such a product is the floating accelerometer plate shown in Fig. 2b. This plate is held to the surrounding frame by tethers, a technique copied from oscillators, comb drives, and other silicon SMM MEMS parts. Just as the wheels are free and can be rotated, the suspended plate in Fig. 2b is free and can be deflected up- or downward by probing. The device in Fig. 2b is a prototype without metallization.

A device was fabricated, consisting of a metallized co-fired parallel plate, 1 cm in diameter, suspended on an LTCC tether in proximity to its metallized base as shown in Fig. 29. Metallized "functional-as-released" parts have some technical issues. For parallel plate devices, to raise the capacitance one would like small separations and large metallized areas. These patterned metallized areas increase metal loading and may result in differential shrinkage and warpage. One would like thin conductive layers to avoid having to use a mesh pattern as have been used in ground planes. Techniques already mentioned that include putting a thin coating of the thick film or a dry transferred thin film would meet this need.

We looked at capacitance at various spacings on a cantilever/tether device as shown in Fig. 30. The parallel plate capacitance as calculated is shown in the solid line. Four data points were measured using shims, and that curve fit is also shown. The ability to both actuate and

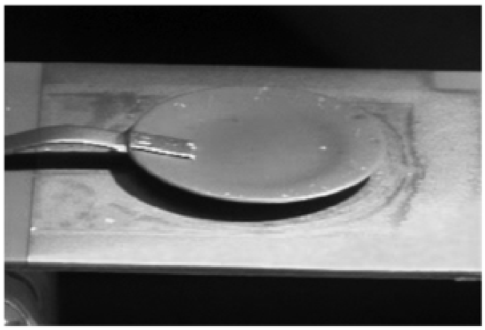

Fig. 29. Suspended structure: Cantilevered capacitor plate (12 mm diameter).

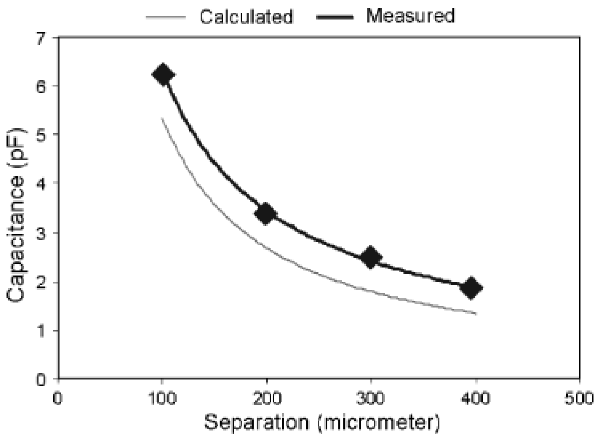

Fig. 30. Capacitance variation with gap spacing for metallized ceramic plates.

measure capacitive response suggests several devices that can be made.

Strain Gage Pressure Sensors

We have encountered applications with very different pressure requirements from 750 Pa (a few inches of water) to greater than 35 MPa (5000 psi). Pressure sensors are integral parts of many silicon microfluidic MEMS, and would be a key addition to LTCC boards. Pressure sensors have been fabricated using cavities and membranes with an SVM technique using the carbon and the setter material. Such a device is shown superimposed on a plot of the voltage output (Fig. 31). This pressure sensor is also a hybrid type, using a commercial foil diaphragm strain gage that comprises a Wheatstone bridge, with two elements in tension and two in compression. The 1 mm (0.040 in.) thick LTCC base serves as the diaphragm of this 12 mm diameter device. This device survived repeated excursions to 0.69 MPa (100 psi). We also tested a diaphragm of 100 µm (0.004 in.) thick LTCC and saw a comparable voltage span and stability, whereas maximum stress would be expected to be about 15 times higher, neglecting the glue and the gage. Quantitative calculations of membrane stress have not yet been performed. These sensors could be miniaturized by directly printing piezoresistive compositions in patterns appropriate to the device. Thick-film piezoresistors have been reported with gage factors almost an order of magnitude higher than can be obtained purely with geometrical effects.[11] Because these structures are not limited to planar geometries, we have also investigated curved channels that can change their shapes and sense pressure operating as miniature Bourdon tube devices. We continue to work with strain indicators to produce pressure sensors that work over wide ranges of pressure.

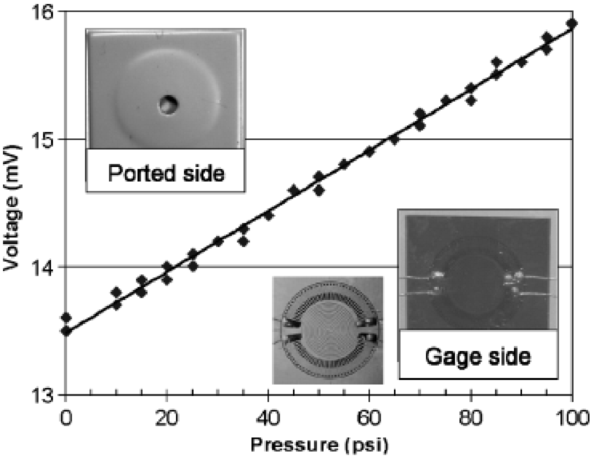

Fig. 31. Pressure readouts from an low-temperature co-fired ceramic diaphragm indicate a useful pressure sensor.

Electrostatic Actuation

Vertical actuation of cantilevered LTCC structures can be accomplished by electrostatic operation. We have electrostatically actuated fragile LTCC cantilevers normal to the plane of the substrate. We have yet to achieve anything as useful as a comb drive or other actuator (electrostatic, thermal, electromagnetic). The deformation of layers during firing and as affected by thick-film loading is more a factor here than in other applications, because of the small, uniform gaps required. All aspects leading to the net shape of the structures need additional work.

We have also deflected freestanding thick-film beams into contact with their activation pads as shown in Fig. 32. We have also deflected these structures into contact with a third line, but have not yet shown activation of a switch. This thick film was as-fired without any other surface preparation.

Conclusions

New techniques in LTCC technology continue to expand the integration of microsystems including connections to the outside world. These range from

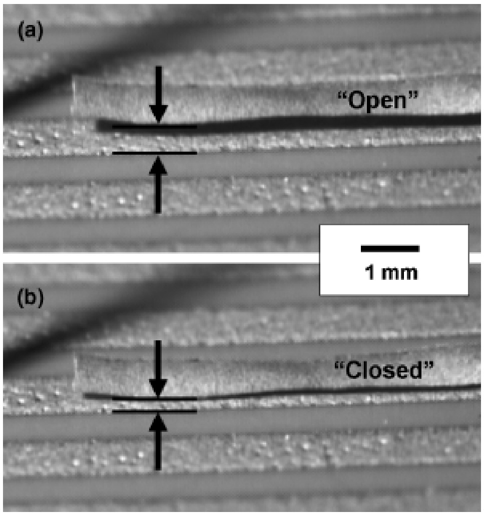

Fig. 32. Suspended thick-film conductors actuated vertically.

functionalizing existing silicon microfluidics to enabling meso-scale devices using new techniques. LTCC meso-scale devices bridge the size gap between the micro- and macro-worlds, and add real value in new functions. We fabricated smart channel prototypes using polymer chemiresistors that are responsive and offer promise for embedding these functions in smaller integral channels. Analytical functions such as μ-HPLC can be miniaturized using LTCC. Biological cell lysing using an LTCC device has been demonstrated. Large manifolds that need to be more inert than polymers are simple to fabricate in LTCC. RF components with improved performance such as inductors, antennae, and perhaps even switches are being developed. Raised bridges of low mass that are integral with the LTCC board provide several capabilities, including rapid thermal measurements for flow measurement. LTCC as a membrane has been used to obtain pressure measurements. Finally, "functional-as-released" moving mechanical structures have been demonstrated and continue to be developed.

Acknowledgments

The authors would like to thank Timothy Turner, Richard Sanchez, Dennis DeSmet, and Tom Massis of Sandia National Laboratories for contributions that made this work possible. The authors further wish to thank Luke Fergusson of Harmonics, Inc.

References

1. M. R. Gongora-Rubio, P. Espinoza-Vallejos, L. Sola-Laguna, and J. J. Santiago-Aviles, "Overview of Low Temp-Erature Co-Fired Ceramics Tape Technology for Meso-System Technology," *Sensor. Actuat. A*, 89 222–241 (2001).
2. W. K. Jones, Y. Liu, B. Larsen, P. Wang, and M. Zampino, "Chemical, Structural and Mechanical Properties of the LTCC Tapes," *Proceedings of the International Symposium on Microelectronics*, IMAPS, Boston, MA, 469–473, 2000.
3. K. G. Ewsuk, C. B. DiAntonio, F. Uribe, and S. L. Monroe, "Materials and Process Control Technology for LTCC Microelectronics Packaging," *Proceedings of the Ceramic Interconnect Technology Conference*, IMAPS, Denver, CO, 1–6, 2004.
4. P. Espinoza-Vallejos, J. Zhong, M. Gongora-Rubio, L. Sola-Laguna, and J. J. Santiago-Aviles, "Meso (Inter-Mediate)-Scale Electromechanical Systems for the Measurement and Control of Sagging in LTCC Struct-Ures," *Mat. Res. Soc. Symp. Proc.*, 518 73–79 (1998).
5. M. Wagner, A. Roosen, A. Stiegelschmitt, D. Schwanke, and F. Bechthold, "Optical Dilatometer for In-Situ Measurements of Warpage Effects During Firing of LTCC Multi Layer Structures," *Proceedings of International Symposium on Microelectronics*, IMAPS, Washington, 71–75, 2002.
6. H. Dannheim, U. Schmid, and A. Roosen, "Lifetime Pre-Diction for Mechanically Stressed Low Temperature Co-Fired Ceramics," *J. Eur. Ceram. Soc.*, 24 [8] 2187–2192 (2004).
7. L. J. Golonka, B. W. Licznerski, K. Nitsch, and H. Teterycz, "Thick-Film Humidity Sensors," *Meas. Sci. Technol.*, 8 92–98 (1997).
8. W. Qu, R. Green, and M. Austin, "Development of Multi-Functional Sensors in Thick-Film and Thin-Film Technology," *Meas. Sci. Technol.*, 11 1111–1118 (2000).
9. M. Hrovat, D. Belavic, and Z. Samardzija, "Temperature Sensors Made by Combinations of Some Standard Thick Film Materials," *J. Mat. Sci. Lett.*, 19 651–655 (2000).
10. H. Birol, T. Maeder, C. Jacq, and P. Ryser, "Effects of Firing Conditions on Thick-Film PTC Thermistor Characteristics in LTCC Technology," *Proceedings of the Ceramic Interconnect Technology Conference*, IMAPS, Denver, CO, 106–109, 2004.
11. M. Hrovat, D. Belavic, and S. Samardzija, "Characterisation of Thick Film Resistor Series for Strain Sensors," *J. Eur. Ceram. Soc.*, 21 2001–2004 (2001).
12. D. Belavic, M. Hrova, S. Bencan, W. Smetana, H. Homolka, R. Reicher, L. Golonka, A. Dziedzic, and J. Kita, "Investigations of Thick-Film Resistors on Different Substrates for Strain-Gage Applications," *Proceedings of the International Symposium on Microelectronics*, 441–446, 2002.
13. M. Hrovat, D. Belavic, A. Bencan, J. Bernard, J. Hole, J. Cilensek, W. Smetana, H. Homolka, R. Reicher, L. Golonka, A. Dziedzic, and J. Kita, "Thick-Film Resistors on Various Substrates as Sensing Elements for Strain Gauge Applications," *Sensor. Actuat. A*, 107 261–272 (2003).
14. M. Hrovat, J. Holc, S. Drnovsek, D. Belavic, J. Bernard, M. Kosed, L. Golonka, A. Dziedzic, and J. Kita, "Characterization of PZT Thick Films Fired on LTCC Substrates," *J. Mat. Sci. Lett.*, 22 1193–1195 (2003).
15. J. Juuti, A. Lozinski, and S. Leppavuori, "LTCC Com-Patible PLZT Thick-Films for Piezoelectric Devices," *Sensor. Actuat. A*, 110 361–364 (2004).
16. Harmonics, Inc. website: http://www.users.qwest.net/~hmnx/
17. M. Gongora-Rubio, L. M. Sola-Laguna, P. J. Moffett, and J. J. Santiago-Aviles, "The Utilization of Low Temper-Ature Co-Fired Ceramics (LTCC-ML) Technology for Meso-Scale EMS, a Simple Thermistor Based Flow Sensor," *Sensor. Actuat. A*, 73 [3] 215–221 (1999).
18. M. Gongora-Rubio, L. Sola-Laguna, J. J. Santiago-Aviles, and M. Smith, "Integrated LTCC Coils for Multiple Applications in Meso-Electromechanical Systems," *Proceedings of IMECE99:MEMS*, 189–194, 1999.
19. Y. C. Lee, K. C. Eun, and C. S. Park, "A New Low-Loss Microstrip Structure on LTCC Substrate," *IEICE Trans. Elect.*, E86-C [5] 867–869 (2003).
20. K. A. Peterson, S. B. Rohde, C. A. Walker, K. D. Patel, T. S. Turner, and C. D. Nordquist, "Microsystem Integration with New Techniques in LTCC," *Proceedings of the Ceramic Interconnect Technology Conference*, IMAPS, Denver, CO, 19–26, 2004.
21. C. B. Sippola and C. H. Ahn, "A Ceramic Sealed Cavity with Screen Printed Ceramic Diaphragm," *Proceedings of the Ceramic Interconnect Technology Conference*, IMAPS, Denver, CO, 179–182, 2004.

22. H. Adluru, M. A. Zampino, Y. Liu, and W. K. Jones, "Em-Bedded Heat Exchanger in LTCC Substrate," *Proceedings of the Ceramic Interconnect Technology Conference*, IMAPS, Denver, CO, 205–210, 2003.
23. L. Rebenklau, K. J. Wolter, and S. Howitz, "Realization of Hybrid Microfluidic Systems Using Standard LTCC Process," *Proceedings of the Electrical Composites and Technology Conference*, 1696–1700, 2000.
24. M. Gongora-Rubio, L. Sola-Laguna, M. Smith, and J. J. Santiago-Aviles, "A Meso-Scale Electro-Magnetically Actuated Normally Closed Valve Realized on LTCC Tapes," *Proceedings of the SPIE, Conference on Microfluidic Devices and Systems II*, Santa Clara, CA, V3877, 230–239, 1999.
25. H. Lynch, J. Park, P. A. Espinoza-Vallejos, J. J. Santiago-Aviles, and L. Sola-Laguna, "Meso-Scale Pres-Sure Transducers Utilizing Low Temperature Co-Fired Ceramic Tapes," *Mat. Res. Soc. Symp. Proc.*, 54 177–182 (1999).
26. S. B. Rohde and K. A. Peterson, "Applying New LTCC/LIGA Construction Techniques in Realizing a Miniature Ion Mobility Spectrometer," Presented at the *IMAPS 35th Annual Symposium on Microelectronics*, Denver, CO, September 2002.
27. D. G. Plumlee, M. Tam, P. Dwivedi, H. Hill, J. A. Hartman, and A. J. Moll, "Ion Mobility Spectrometer (IMS) Fabricated in Low Temperature Cofire Ceramic (LTCC)," *Proceedings of the Ceramic Interconnect Technology Conference*, IMAPS, Denver, CO, 240–245, 2003.
28. W. K. Jones, Y. Liu, and M. Gao, "Micro Heat Pipes in Low Temperature Cofire Ceramic (LTCC) Substrates," *IEEE Trans. Comp. Pack. Tech.*, 26 [1] 110–115 (2003).
29. D. Plumlee, J. Steciak, and A. Moll, "Development of a Monopropellant Micro-Nozzle and Ion Mobility Spectrometer in LTCC," *Proceedings of the Ceramic Interconnect Technology Conference*, IMAPS, Denver, CO, 115–120, 2004.
30. B. B. Mathewson, W. S. Newman, A. H. Heuer, and J. D. Cawley, "Automated Fabrication of Ceramic Components from Tape-Cast Ceramic," *Proceedings of the Solid Freeform Fabrication Symposium*, Austin, TX, 253–260, 1995.
31. J. D. Cawley, A. H. Heuer, W. S. Newman, and B. B. Mathewson, "Computer-Aided Manufacturing of Laminated Engineering Materials," *Am. Cer. Soc. Bull.*, 75 [5] 75–79 (1996).
32. J. Li and G. K. Ananthasuresh, "Three-Dimensional Low-Temperature Co-Fired Ceramic Shells for Miniature Systems Applications," *J. Micromech. Microeng.*, 12 [3] 198–203 (2002).
33. K. A. Peterson, S. B. Rohde, K. B. Pfeifer, and T. S. Turner, "Novel LTCC Fabrication Techniques Applied to a Rolled Ion Mobility Spectrometer," *Electrochem. Soc. Ser.*, 2003 [27] 156–171.
34. J. G. Lee, H. W. Shin, E. D. Case, and P. Kwon, "The Fabrication of Smooth, Sub-Millimeter Open Channels and Internal Channels in Ceramics and Ceramic Composites Without Machining," *J. Mat. Sci. Lett.*, 20 [2] 107–109 (2001).
35. D. G. Plumlee, Y. Morales, B. Cheek, A. J. Paris, H. A. Ackler, W. B. Knowlton, and A. J. Moll, "Pressure Sensors Built in Low Temperature Co-Fired Ceramic Materials," Presented at *IMAPS ATW Packaging of MEMS and Releate Micro Integrated Nano Systems*, September 6–8, 2002, Denver, CO.
36. J. W. Burdon, R. F. Huang, D. Wilcox, and N. J. Naclerio, "Method for Fabricating a Multilayered Structure and the Structures Formed by the Method," U.S. Patent # 6,592,696, July 15, 2003.
37. A. Roosen, "Cold Low Pressure Lamination of LTCC's," *Proc. SPIE–Int. Soc. Optic. Eng.*, 4931 45–50 (2002).
38. D. J. Miehls, F. J. Martin, R. G. Pond, and P. S. Fleischner, "Method of Fabricating a Multilayer Electrical Circuit Structure," U.S. Patent #5,249,355, October 5, 1993.
39. E. A. Trickett and R. C. Assmus, "Ceramic Monolithic Structure Having an Internal Cavity Contained Therein and a Method of Preparing the Same," U.S. Patent # 4,806,295, February 21, 1989.
40. J. H. Alexander, "Method of Making Ceramic Article with Cavity Using LTCC Tape," U.S. Patent #5,601,673, February 11, 1997.
41. J. D. Cawley, A. H. Heuer, and W. S. Newman, "Method for Constructing Three Dimensional Bodies from Laminations," U.S. Patent # 5,779,833, July 14, 1998.
42. J. Van Tassel and C. A. Randall, "Potential for Integration of Electrophoretic Deposition into Electronic Device Manufacture; Demonstrations Using Silver/Palladium," *J. Mat. Sci.*, 39 867–879 (2004).
43. N. T. Nguyen, and Z. Wu, "Micromixers—A Review," *J. Micromech. Microeng.*, 15 R1–R6 (2005).
44. D. J. Draeger and E. D. Case, "Engineering the Surface Texture and Shape of Channels in Ceramic Substrates," *Mat. Sci. Eng.*, B97 94–105 (2003).
45. M. R. Gongora-Rubio, M. B. A. Fontes, Z. Mendes da Rocha, E. M. Richter, and L. Angnes, "LTCC Manifold for Heavy Metal Detection System in Biomedical and Environmental Fluids," *Sensor. Actuat. B*, 103 468–473 (2004).
46. J. W. Elam, D. Routkevitch, P. P. Mardilovich, and S. M. George, "Conformal Coating on Ultrahigh-Aspect-Ratio Nanopores of Anodic Alumina by Atomic Layer Deposition," *Chem. Mater.*, 15 3507–3517 (2003).
47. G. L. Benavides and P. C. Galambos, "Electro-Microfluidic Packaging," SAND2002-1941, unlimited release, June 2002, Sandia National Laboratories (http://www.ntis.gov/ordering.htm).
48. G. L. Benavides, P. C. Galambos, J. A. Emerson, K. A. Peterson, R. K. Giunta, D. L. Zamora, and R. D. Watson, "Packaging of Electro-Microfluidic Devices," U.S. Patent No. 6,548,895, April 15, 2003.
49. P. Galambos, G. Benavides, M. Okandan, and D. Hetherington, "Precision Alignment Packaging for Microsystems with Multiple Fluid Connections," *Proceedings of the ASME IMECE*, Nov. 11–16, 2001, New York, 1–8.
50. D. M. Tanner, N. F. Smith, D. J. Bowman, W. P. Eaton, and K. A. Peterson, "First Reliability Test of a Surface Micromachined Microengine Using SHIMMeR," *Proc. SPIE*, 14 3224 (1997).
51. E. Amaya, "Designing with Heralock™ 2000 Self-Constrained LTCC Tape," *Technical Presentations, IMAPS ATW: Ceramic Applications Microwave and Photonic Packaging*, Providence, RI, May 2–3, 2002.
52. Patent pending.
53. K. Patel, K. Hukari, and K. Peterson, "Low-Temperature Cofired Ceramic Substrate Technology for Microfluidic Systems: Development of a High-Temperature Ceram-Ic Lyser for Solubilizing Spores," *Conference on MicroScale BioSeparations*, February 13–17, 2005, New Orleans, LA.
54. S. J. Kim, Y. G. Lee, S. K. Yun, and H. Y. Lee, "Realization of High-Q Inductors Using Wirebonding Technology," *Proceedings of AP-ASIC*, 13–16, 1999.
55. L. Harle and L. P. B. Katehi, "A Horizontally Integrated Micromachined Filter," *IEEE MTT-S Dig.* 437–440 (2004).
56. D. Belavic, M. Hrovat, and M. Pavlin, "Vertical Thick-Film Resistors as Load Sensors," *J. Eur. Ceram. Soc.*, 21 1989–1992 (2001).
57. B. Y. Ang, C. K. Chua, and Z. H. Du, "Study of Trapped Material in Rapid Prototyping Parts," *Int. J. Adv. Manuf. Technol.*, 16 120–130 (2000).