Integrated Microfluidic Devices Based on Low-Temperature Co-Fired Ceramic (LTCC) Technology

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ABSTRACT

This paper reviews recent developments in integrated fluidic mesosystems, based on low-temperature co-fired ceramic (LTCC) technology, in this laboratory and elsewhere. LTCC is shown to be an advantageous technique for integrated fluidic systems, due to its simplicity, low cost and ease of integration with other technologies and components (silicon, polymer, circuit boards. Also, the techniques utilized in making the structures are presented.

1. Introduction

Applications

Low-temperature co-fired ceramic (LTCC) is a relatively recent technology, derived from thick-film technology [1,2] and developed initially for packaging of multi-chip modules [3,4]. Use of LTCC has expanded to demanding applications such as high-frequency circuits [5] and automotive electronics (engine ignition) [6]. Recently, interest has been focused onto LTCC as a promising material for numerous kinds of sensors [7–9] and chemical systems [10,11]. Fig. 1 [12] gives an example of the various features available in an LTCC device.

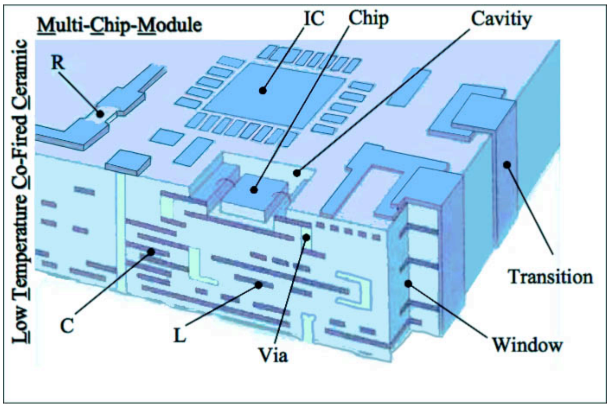

Fig. 1. A structure illustrating the possibilities of classical LTCC technology.

Standard processing

The attractivity of LTCC is due to its simple processing, whereby complex 3–D circuits can be obtained by stacking subsequent layers. The material comes as compliant sheets of "green" ceramic, e.g. ceramic powder dispersed in an organic binder and can be processed very easily in this state. The processing steps are outlinedas follows:

For each layer:

1) **Opening** of via holes, cavities ,channels, etc., in the LTCC sheet, with either laser cutting or mechanical punching.
2) **Filling** of electrical via holes with conductor paste (pastes are similar to those used in thick-film technology).
3) **Sceen-printing** and drying of conductors, optionally of resistors or other special-purpose compositions.

Then, for all the layers together:

4) **Aligning and stacking** of the sheets.
5) **Pressing** the sheets together.
6) **Co-firing** the whole, typically in air at 850–900°C.

Finally, for post-processing:

7) Optional **Screen-printing** and **post-firing** of layers not compatible with co-firing (especially resistors or layers on very thin membranes).
8) **Separation** of individual devices, by scoring and breaking or with a diamond saw.

After processing, the LTCC device has become a rigid structure with outstanding thermal, dimensional and – at least the ceramic – chemically stability.

The materials

The LTCC materials system is analogous to the classic thick-film on alumina one [2], except that alumina itself is not used as a massive material (although it enters as powder into the formulation of most LTCC compositions).

- **Substrate / dielectric** . The LTCC sheet essentially replaces both the alumina substrate and the multilayer dielectric. The composition of the LTCC is similar to that of the thick-film dielectrics, which gives it outstanding chemical stability. As will be shown later, the absence of a pre-fired alumina substrate entail very different properties for integrated devices.
- **Conductors** for LTCC are similar to thick-film ones – often, the latter can be used as is in LTCC. Dedicated LTCC materials do exist, presumably to optimise compatibility and processing. One feature of LTCC is the widespread use of pure Ag for inner conductor traces, which provide significant advantages in conductivity and cost.
- **Resistors** . Here also, thick-film compositions or similar ones may be used. However, their properties (value and temperature dependence, even reliability) are more difficult to control when

the resistors are co-fired with the LTCC, due to increased interdiffusion, especially when the resistor "buried" inside the LTCC structure.

2. Making fluidic structures in LTCC

Structure types

Fluidic structures, e.g. inner space intended to be filled with gases or liquids, will essentially consist of vias, channels, membranes and bridges, which may be created by several methods. These structures differ in the types of difficulties involved

Vias – stacking tolerance compensation

Vias allow vertical fluid passage. The main difficulty involved is the alignment of minute structures – mismatch tends to lead to a clogging of the passage.

Vias may be created explicitly, by cutting out a portion of an intermediate layer, or implicitly, by the superposition of two open portions of subsequent layers (Fig. 2).

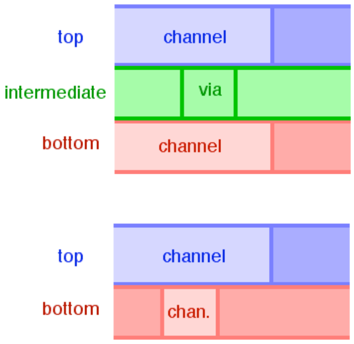

Fig. 2. Explicit (top) or implicit (bottom) vias.

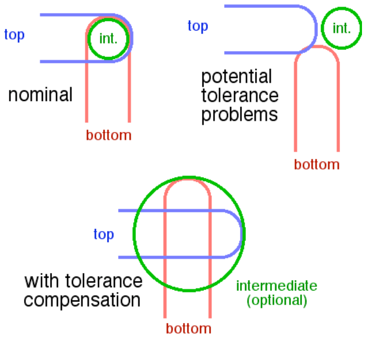

Fig. 3. Effect of stacking tolerances on via design.

The principal difficulty in via creation lies in mastering the tolerances for small vias: structure created with nominal dimensions can fail to superpose during stacking, resulting in increased flow resistance or even complete clogging of the fluidic paths (Fig. 3) .In this case, one must modify channels and vias accordingly, as shown at the bottom of Fig. 3. Of course, this will result in increased dead volume. Note that stacking tolerances will typically be of the order of 0.1 mm.

Channels (by cutting)

A simple example of cut channels in LTCC is the micromixer depicted in Fig. 4. This case is non-critical, because the most severely cut layer ("channels") has a large channel width of ca. 1 mm. Suppose now a narrow channel with a long, winding path. (Fig. 5). Cutting out such a channel from a single sheet is unpractical, because the sheet is now excessively weakened, especially if the sheet is very thin. For such a path, one must therefore use a two-sheet design, which only entails a series of slits in each sheet. An real example of such a structure, made in our laboratory, is the zig-zag micromixer given in Fig. 6, where the large number of angles can improve the mixing efficiency under suitable flow conditions [13,14].

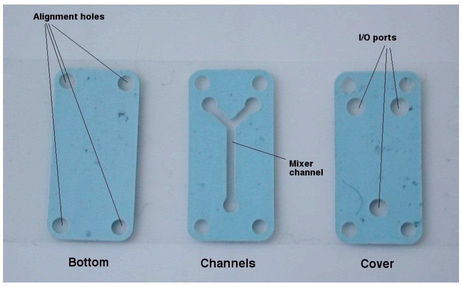

Fig. 4. Channels: simple micromixer example.

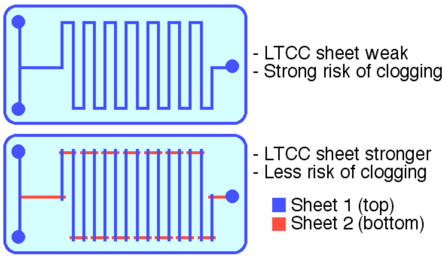

Fig. 5. Two-sheet design to stop avoid excessive sheet weakening & risk of clogging. See also Fig. 3!

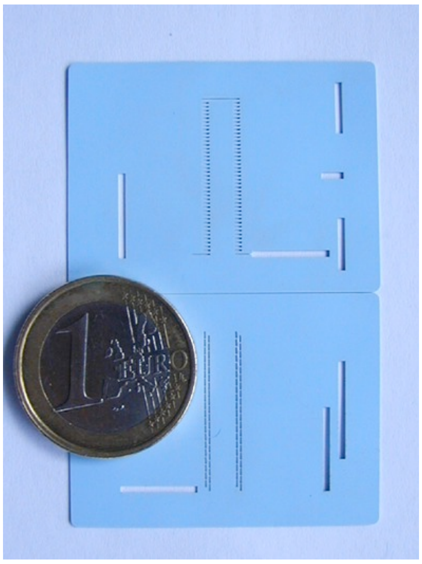

Fig. 6. Two-layer design of a zigzag micromixer .

Membranes

The main difficulty lies in achieving surfaces with low distortion for thin and large membranes. This requires careful control of the pressing conditions, and sufficiently slow temperature ramp up during firing to avoid thermal gradients within the structure. Nevertheless, it is possible to make thin (40 µm) and wide membranes (> 6 mm) with minimal distortion, as shown in Fig. 7.

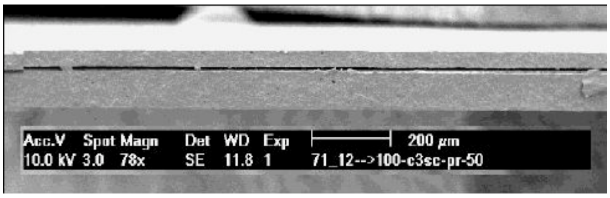

Fig. 7. Thin LTCC membrane.

Carbon sacrificial layer technique

For complex paths (e.g. Fig. 5, 6) or for thin gaps (Fig. 7), cutting is impractical. Rather, a carbon sacrificial layer is screen-printed instead (Fig. 8). This layer burns away during firing, leaving cavities behind. The shape of the resulting structure is no longer flat, however (see Fig. 8).

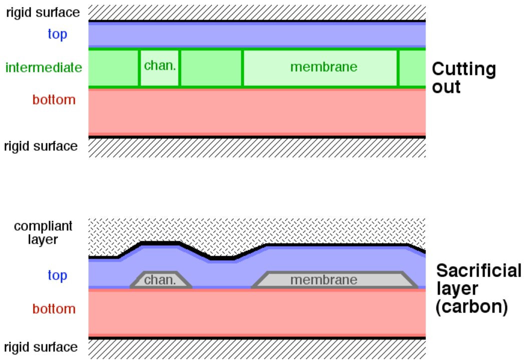

Fig. 8. The two techniques for creating LTCC fluidics. Note the different required pressing surfaces indicated.

3. Integrating sensor functions - examples

Comparison of LTCC and alumina

There is considerable difference in physical properties and available thickness ranges between LTCC [15] and alumina [16], as shown in Table I. The calculated values of thermal resistance, rupture strain and flexural sensitivity are discussed in the following sections.

The achievable sheet thermal resistance R_{th} for LTCC & alumina is given as a function of min. sheet thickness h_{min} and thermal conductivity λ by:

$$R_{th} = (\lambda \cdot h_{\min})^{-1} \qquad (1)$$

The rupture strain $\varepsilon_{\max}$ is simply given as a function of strength $\sigma_{\max}$ and Young's modulus E by:

$$\varepsilon_{\max} = \sigma_{\max} / E \qquad (2)$$

Finally, we define the flexural sensitivity S as a function of E and h_{min}:

$$S = E^{-1} \cdot h_{\min}^{-3} \qquad (3)$$

Table I. Comparison of LTCC and alumina for sensors.

Material	**LTCC**	**Al_2O_3**
Available thichnesses [mm]	0.04…	0.17…1.5
Strength [MPa]	320	600
Young's modulus [GPa]	150	320
Thermal conductivity [W/m/K]	3	25
Thermal resistance [K/W]	8300	240
Rupture strain [ppm]	2100	1900
Flexural sensitivity [$N^{-1} \cdot m^{-1}$]	100	0.6

Thermal flow sensors

LTCC is an ideal material for thermal sensors, due to its low heat conductivity and thin available sheets – the achievable R_{th} values are >30x above those of alumina. Of course, this advantage is compounded by the ease of structuring, allowing easy fabrication of flow sensors as in Fig. 9 [17].

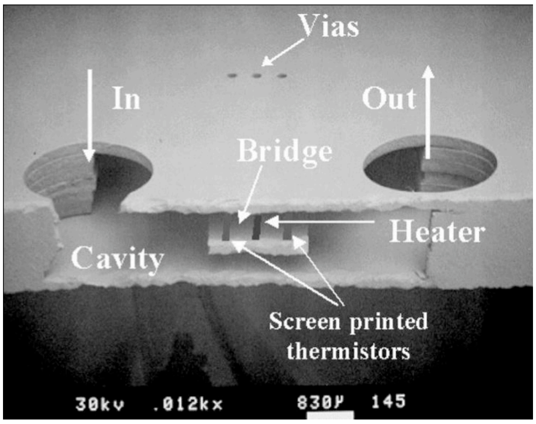

Fig. 9. Cross-section of anemometric flow sensor.

Gas sensors

A low thermal conductivity is also advantageous for applications that involve local heating, such as the gas sensor depicted in Fig. 10 [18], as it cuts losses due to thermal conductivity in the substrate.

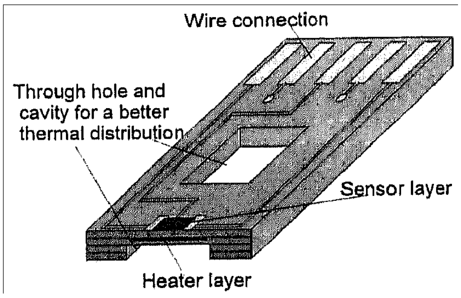

Fig. 10. LTCC low-power gas sensor.

Pressure sensors utilising substrate bending

The values ε_{max} and S define the suitability of LTCC for pressure sensing:

- Values of ε_{max} are similar for LTCC and alumina: in general, LTCC *is not* superior to alumina for strain-based pressure (and force) sensing. Of course, ease of integration more than offsets this disadvantage in the low to medium pressure range.
- However, due to the low elastic modulus but especially to the very thin available sheets, LTCC allows, for a given membrane size, a more than 100-fold increase in sensitivity S, which makes it ideal for low-pressure sensing.

As a closing note, one must be careful with indicated shrort-term strength values. Ceramic and glassy materials are known to suffer from a phenomenon called *static fatigue* where specimens loaded below the short-term strength fail after some time. This effect depends on the substrate material and on its coverage by films [19]. However, LTCC has yet been insufficiently characterized in this respect. Tests in our laboratory are under way to clarify this issue.

4. Conclusion

LTCC is shown to be a superior materials platform for fluidics, allowing simultaneous integration of sensors, and electronics. The properties of LTCC make it especially suitable for applications involving local heating (flow meters, microreactors, gas sensors, etc.) and for measuring pressures with very high sensitivity.

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