RECENT DEVELOPMENT OF NON-ACTIVE INTEGRATED COMPONENTS IN MULTILAYER MODULES

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Abstract

The current and the future ceramic packaging technology as well as the various possibilities of multilayer modules and the user markets of HTCC (High Temperature Cofired Ceramic) and LTCC (Low Temperature Cofired Ceramics) are reviewed. The opportunities and the high potential of LTCC, especially for automotive applications, will be emphasized.

The material properties of the basic ceramic and the metal components , their ability for cofiring processes and the suitability for LTCC application are compared. Furthermore the requirements for the production of multilayer substrates are summarized and the actual LTCC production sequences are described.

The new LTCC technology offers for the first time the possibility to integrate non-active components, e.g. embedded resistors, capacitors and inductors into the multilayer module. Recent development activities and new results are discussed and reviewed critically. The selection criteria, advantages and disadvantages of potential future materials and their limitations are shown. Of special interest are the newly developed lead-base perovskite oxide powders as a replacement for barium titanate-based high K materials for use as internal capacitors.

Introduction

The continuously growing integration of semiconductor technology demands improved performance of the packaging. Increasing contact density, chip power and cycle time are enormous challenges for an advanced, highly sophisticated multilayer ceramic technology. Fast signals have to be fed through the interconnection wiring without losing the superior semiconductor performance.

Size reduction and integration of passive components are current trends in the microelectronic industry. Only the new LTCC (Low Temperature Cofired Ceramic) technology offers the unique ability to integrate components like resistors and capacitors into a multilayer electronic package.

In general, LTCC is a glass/ceramic composite in which both the ceramic and the metalization (e.g. Ag, AgPd, Au) are cofired at temperatures below the melting points of the metals. LTCC combines the features of high temperature cofired ceramic (HTCC) and thickfilm technology with the additional advantage of low sintering temperatures (< 980 °C) and low dielectric constants. There are two general types of LTCC systems. A mixture of glass and ceramic on one side and a real crystallizing glass-ceramic system on the other side

IBM Deutschland Produktion GmbH , a 100 % subsidiary of IBM Deutschland GmbH , is among other activities producing ceramic multilayer chip carriers on its Böblingen/Sindelfingen plant. This production started 1976 using HTCC technology. More than 3 million single and multichip modules were produced for the entire IBM computer product line since then. In 1986 a new product line for an IBM captive glass ceramic product was started and produced substrates for main frame processors. The production of these parts terminated in 1994 due to drastically decreasing demand numbers for high-end computers.

Since 1992 IBM Deutschland Produktion GmbH is offering its HTCC multilayer technology on the European market. Substrates for data processing and aerospace applications are delivered to French, Italian and German customers.

In 1993 a new technology, a commercial LTCC system, was phased in to extend the product portfolio **(1)**. The production of this technology is planned to be ramped up to high volume capacity in the coming years.

There is a large variety where HTCC- and LTCC-multilayer substrates are currently used and even wider fields for future applications. An always increasing number of electronic devices are brought into use in the automotive area. Especially in harsh environments and other applications, where high reliability and robustness are required, the use of ceramic electronic packaging solutions are superior to other technologies. LTCC development will take into account the progress in the automotive electronic industry like engine management, anti-lock brakes, gear control systems, fuel injections, airbag controls, sensors, etc. and the reliability requirements which can be enhanced by the use of LTCC. This is shown in **Fig. 1**.

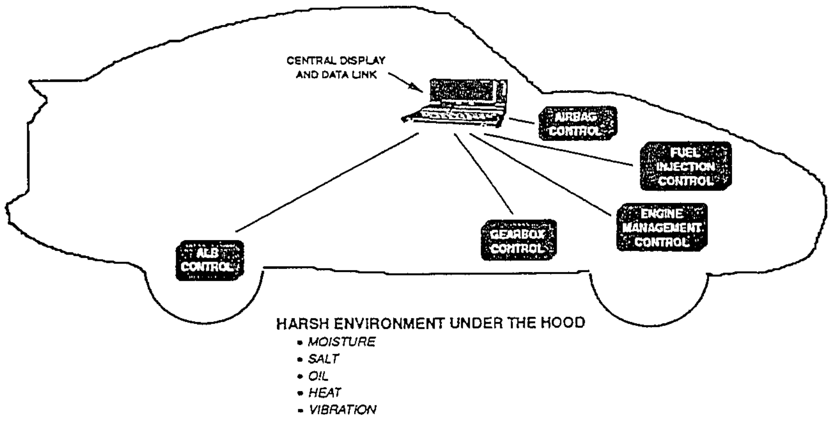

Fig. 1 : Trends in car electronics

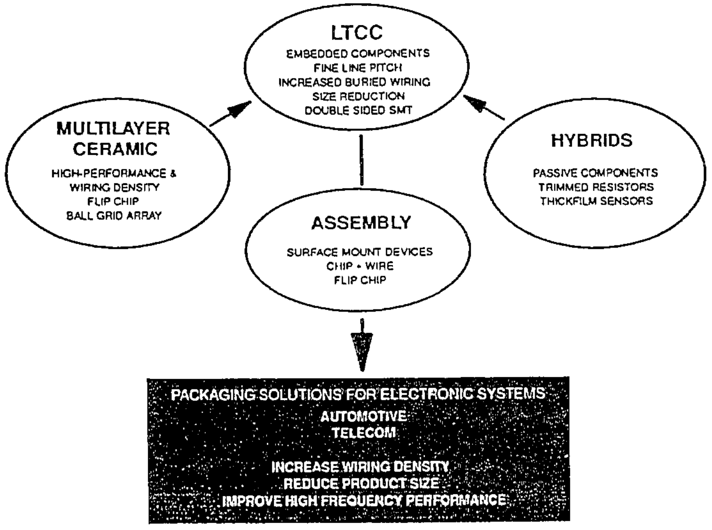

Fig. 2 : Packaging solutions for electronic systems

LTCC enables to produce multilayer/multichip modules with a very high integration. LTCC is either a modern stand alone packaging technology for different applications in telecommunication, data processing and in the automotive industry or can be used as an enhancement of hybrid circuits by transferring external wiring into the ceramic carrier. Furthermore, LTCC offers the advantage of embedding non-active components into the substrate and of improved high frequency behavior. This is summarized in **Fig. 2 and Fig. 3**.

The worldwide competition is putting an increasing pressure on the necessity of implementing cost effective solutions to stay in the market with competitive products. Especially packaging solutions in the automotive area with all safety and reliability requirements must provide the required high performance and cost effectiveness.

Beside this, by using ceramic instead of organic packaging the environmental aspects should be also taken into consideration. The development work is also oriented towards:

- Energy saving (i.e. low temperature firing)
- Process material saving (i.e. air firing vs. hydrogen)
- Economical use of noble metals
- Use of nontoxic pastes
- Consideration of recycling concepts

Current and future ceramic packaging

A comprehensive summary of the various possibilities of HTCC in microelectronic packaging is given by Tummala (2). The four major functions of a multilayer ceramic package are:

o **Power distribution**	o **Heat dissipation**
o **Signal distribution**	o **Package protection**

The overall trends in packaging since 1970 are an increase of power and line widths and a decrease of dielectric constant .

Hybrid multichip modules (MCM) are known as robust and reliable packaging solutions. In harsh environments they have clear advantage over printed circuit boards and will expand their market share for such applications.

Automotive electronic devices, where hybrid technology is currently dominating, are moving fast to higher complexity and wiring and component

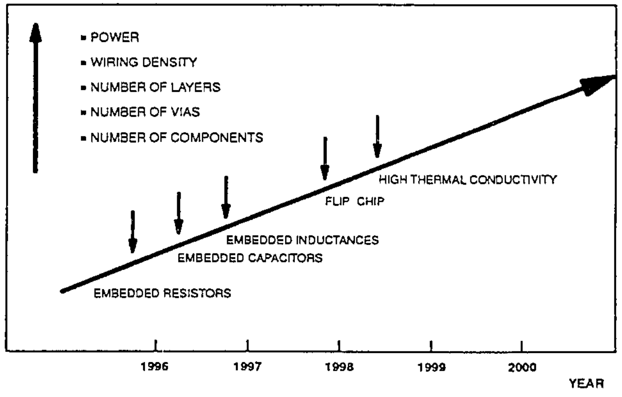

Fig. 3 : Trends in engine control units

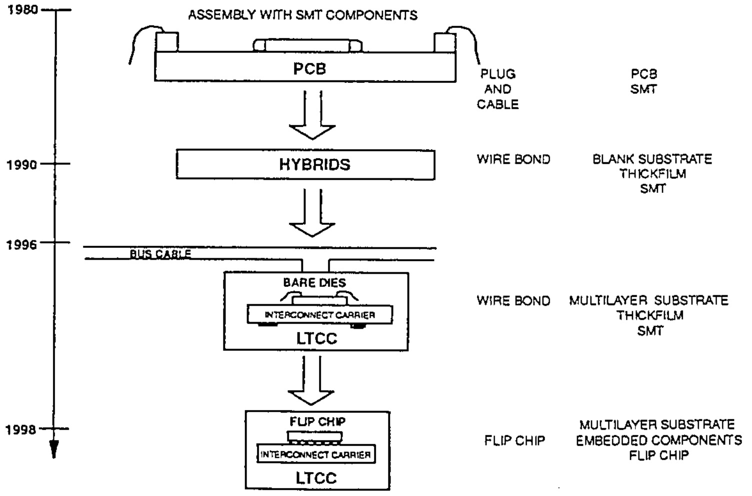

Fig. 4 : Integration road map

density. The strategy of leading car manufacturers is to bring these control units close to the point of use to save cable beams and thereby to reduce costs significantly. This means that these control units will be located under the hood in harsh environments (salt, moisture, oil, heat and vibration) where hybrid packaging on LTCC basis is the technology of first choice (see also **Fig. 1**).

Hybrid wiring pattern is built up in a subsequential series of printing, drying and firing processes (up to 30 sequences for a 4 thickfilm layer product). Because of the complicated manufacturing process in case of high wiring density hybrid manufacturing is coming to its limitation for the above mentioned applications. Whereas the regular hybrid technology is using only a non functional blank ceramic substrate, a very new innovative solution to that problem is to incorporate most of the wiring patterns into a LTCC carrier. This can be achieved by combining the advantages of state of the art multilayer technology with hybrid processes.

Mutilayer technology is used in VLSI (Very Large Scale Integration) packaging solutions for data processing applications by leading edge manufacturers. Very complex parts for main frame computers were built using HTCC and captive glass ceramic materials. Cofiring of up to 70 layers , with more than 1 million layer connections, 500 meters of wiring length embedded in the ceramic, 100 flip chip connections and 2700 I/O's was achieved and parts were manufactured in high volumes and process yield. Furthermore, a combination of thin film technology (sputtering, evaporation and plating processes) with multilayer ceramics was developed and successfully used for high end data processing applications.

These captive technologies are not suited for automotive need because of the incompatibility with hybrid processing. However, making use of this know how for "microhybrids" is opening up almost unlimited possibilities to move to very high integration as well. Furthermore non-active components (resistors, capacitors,inductors) can be used for SMD (surface mount devices) and printed resistors, doubling the area for component assembly (see **Fig. 4**).

This technology has started to prove its feasibility and manufactureability but further process and product development work has to be done.

LTCC market perspectives

After a period of rapid and sustained growth in the early and mid 80's the hybrid circuit industry has been through a difficult period over the last 5 to 6 years. One of the major reasons for this was the erosion of traditional hybrid circuits markets by competitive technologies, particularly SMT PCBs.

Today there are strong signals that the market will increase significantly in the medium term since ceramic substrates still offer significant advantages over epoxy-based substrates in a range of niche markets. **Table 1** shows the forecast for the European market for hybrid circuits broken down per end-user sector.

End-User	**1994** (Million $)	**1996** (Million $)	**1998** (Million $)
Automotive	260,9	300,5	374,2
Computer and Office Equipment	19,1	20,3	21,6
Consumer	22,8	25,0	27,8
Medical	23,8	26,7	29,7
Military and Aerospace	245,3	240,9	249,8
Telecoms	218,0	253,9	310,9
Total	**971,8**	**1070,4**	**1240,6**

Note: All figures are rounded

Table 1 : European hybrid circuit market - revenues by end-user industry, selected years (source: Frost & Sullivan, Inc.)

The automotive sector is forecast to be one of the highest growth markets for hybrid circuits over the next few years. The major reason for this expected growth is that the average electronic content of a vehicle is expected to continue to rise significantly in the 90's.

LTCC is now penetrating the hybrid market in high end applications in all market segments, with the highest forecasts for automotive and telecom applications. Market volume in Europe is estimated up to 1 billion ECU.

Material properties and requirements

In **Table 2** the material parameters of currently applied HTCC- and LTCC-systems are compared. Note that in this table the properties of materials for embedded components are not listed.

A good overview of different available LTCC raw material combinations was compiled by Gupta **(3)**. A large variety of glass-ceramic systems and ceramic & glass mixtures could be used but only a few seem to have a good potential for industrial applications. The basic requirements for a suitable LTCC-system are :

- o Sintering temperature < 980 °C
- o Cofireability of ceramic/metal-system (shrinkage compatibility)
- o Resistance to Ag-migration/-diffusion
- o Low dielectric constant of ceramic
- o Good electrical parameters of conducting materials
- o Potential for embedded components
- o Acceptable mechanical properties
- o Compatible cofiring and postfiring metallization hierachies
- o Dimensional stability during postfiring processes (prerequisite for hybrid thickfilm technology)
- o Good long term reliablity (robust design)
- o Manufacturability in existing production lines
- o Cost competitiveness to other technologies

Taking into consideration all of the above mentioned parameters the number

	LTCC	**HTCC**
Dielectric material	Glass Ceramic	Alumina
Metal system	Ag, Ag Pd , Cu, Au	Mo, W
Sintering temperature	830 - 980 °C	1550 - 1620 °C
Density	2,5 - 3,1 g/ccm	3,3 - 4,0 g/ccm
TCE (x 10-6/K) 50 - 400 °C	3,5 - 7,5	6,5 - 7,6
Thermal conductivity	2,7 - 3,3 W/mK	13,2 - 13,9 W/mK
Bend strength (MPa)	230 - 280	480 - 520
Fract. toughness (MPa m1/2)	2,7 - 3,0	3,8 - 4,4
Young's modulus (GPa)	80 - 105	270 - 310
Poisson's ratio	0,23 - 0,28	0,22 - 0,25
X/Y-shrinkage (%)	12 - 15	15 - 18
Z-shrinkage (%)	12 - 20	13 - 20
Dielectric constant	5, 5 - 8,5	9,0 - 9,5
Dissip. factor (tan D) (x10-3)	1,1	0,7 - 2,0
Permittivity eps. R	8,0	10,0 - 10,3
Wave impedance (W)	50	50
Resistivity (W mm2/m)	0,032	0,150
Line resistance (W/cm)	0,11	0,44
Line capacitance (pF/cm)	2,90	3,50 - 3,80
Line propagation (ps/cm)	94	106
Line width (µm)	> 50	> 75
Via diameter (µm)	> 60	> 90

Table 2 : LTCC and HTCC material properties

of remaining LTCC-candidates with a good potential is only very limited.

Currently IBM is working with two independent systems from two different suppliers, a third one is under evaluation. The first is a glass/alumina mixture where the glass (lead-borosilicate) is only partially crystallizing during sintering. The two other systems are based on real crystallizing glass-ceramics (namely Al_2O_3 -BaO - SiO_2 and B_2O_3 - CaO - SiO_2). In all three cases noble metal pastes are used , e.g. Ag for inner metallization and AgPd or Au for outside connections.

The properties of both the tape cast ceramic material and the metal pastes must be adjusted to the individual production process steps and to the technological requirements.

LTCC production process

In **Fig. 5** a schematic process flow of the IBM-LTCC production is shown.

The ceramic raw materials are prepared by a ball milling process (RMP) and tape casting. The tapes are bought directly or are prepared in the own IBM tape casting line. Out of these tape rolls "green sheets" are blanked out and automatically and visually inspected.

After an aging and/or tempering process - which guarantees a good dimensional stability for the following process steps - the individual layers of a given product are punched. Via hole punching is a fully automated process which includes a 100 % verification of the punching results. The punched holes filled with paste are acting as connectors from the circuits of one layer to another.

On the contrary to the IBM-HTCC process where both via filling and pattern printing are simultaneous the screening of LTCC occurs in a two step mode. First the punched vias are filled by a mask screening process which is followed by pattern printing on a silk screener. Normally Ag-pastes are used for internal layers and Ag/AgPd-pastes for the outside metallization. All layers are automatically inspected for via filling and pattern defects and are sorted out or repaired accordingly.

After collating the different layers are stacked and laminated at temperatures > 70 °C. Then the laminates are sized if necessary.

Sintering at IBM is done in air in a batch furnace with defined temperature profiles for each individual LTCC-system. Automatic distortion and camber measurements are performed after sintering. Then the parts are tested electrically in a short/open mode using a capacitance test.

Depending on the application the parts can be selectively plated (electroless heavy gold) or they can be the base substrates for consecutive hybrid thickfilm processes (postfiring processes and final assembly of LTCC-hybrids).

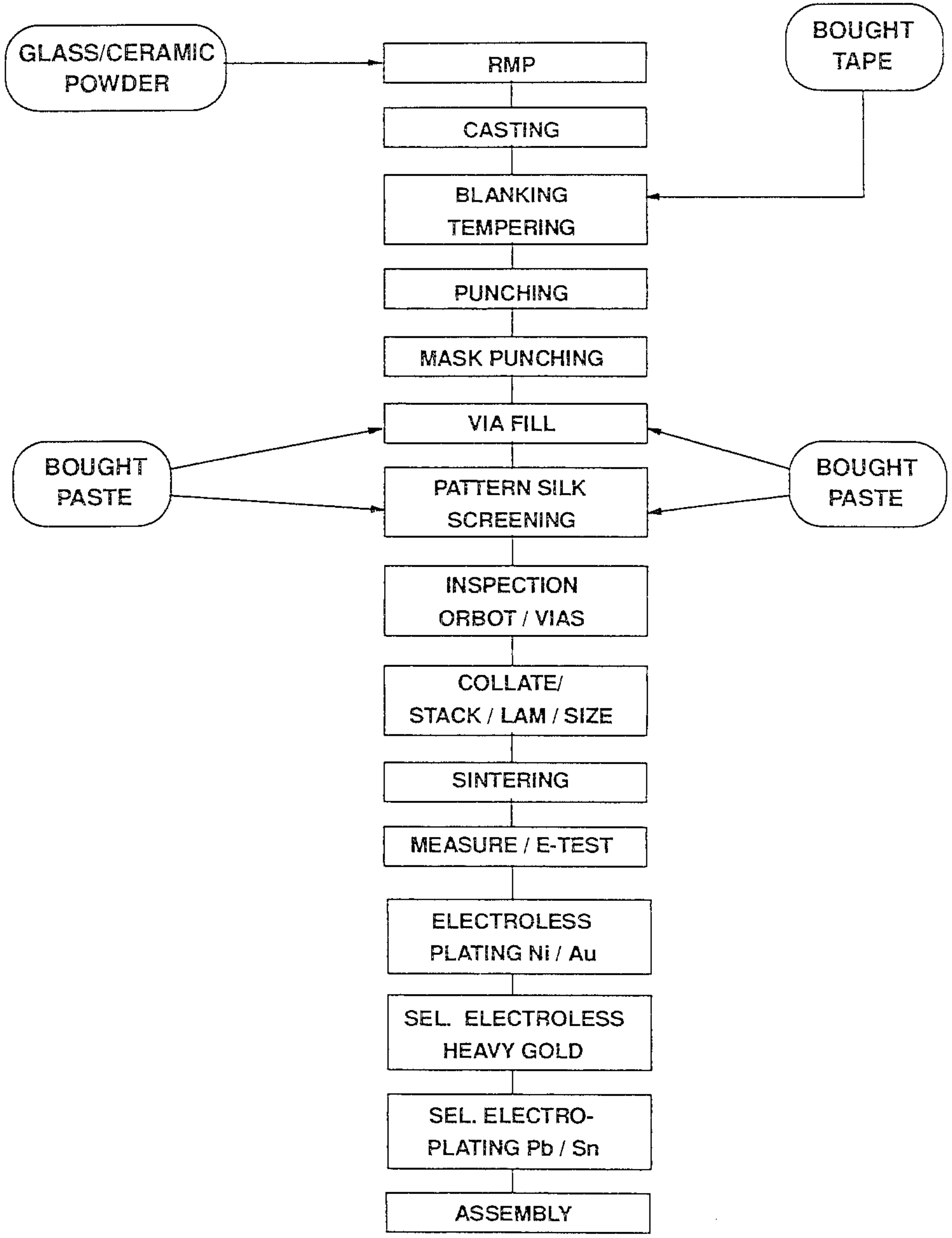

Fig. 5 : Schematic LTCC production process flow

Recent development on embedded components

LTCC development started about 10 years ago. The application was limited to small circuits, few layers and low volume production for a long time. The basic idea was to deliver a ceramic substrate to the hybrid manufacturers which can be sintered at about 850 °C in the existing furnaces. This offered the possibility to bury part of the wiring into the multilayer package of the microhybrid.

Since then only a few companies took this opportunity. However, the demand for LTCC has increased dramatically during the last year. This was basically driven by the automotive industry. For the adaption of LTCC to a mass production major modifications dependent on the customer had to be made. For example the tape stiffness had to be improved to achieve better handling conditions, the paste rheology had to be adjusted to increase the screenability and also dimensional instability had to be minimized to assure a proper stack alignment and electrical integrity.

The outer metallization of the top and bottom side is silver-palladium to avoid critical corrosion and silver migration effects. Currently this is done in a postfiring step but a change to cofiring will happen soon. Major focus is the interface connection between the inner Ag- and the outer AgPd-metallization. Diffusion voiding (Kirkendall effect) and geometric reasons can lead to interface separations. Some development effort was needed to solve this basic problem.

Within IBM the LTCC technology is at the moment in a qualification stage. First qualification test circuits with different material systems have been built and prototypes are already tested by the automotive customers. In **Fig. 6** typical qualification test designs are shown.

For the first electronic circuits for automotive applications a lot of the outside wiring on the former hybrid was integrated into the LTCC package which reduced size enormously. The discrete components are still on top of the multilayer ceramic as SMDs.

The main technological improvements for future LTCC applications are enhancement of system integration, elimination of solder joints, reliability in harsh environments and EMC (electro magnetic compatibility) effectiveness. In order to achieve these challenges and to realize further cost reductions there is a strong demand by the automotive industry to bury more than 50 % of the resistors and capacitors, which are currently on the surface of the hybrids, into the LTCC package. The resistors should be in the range from 10 Ω to 100 kΩ / sq. with an accuracy of at least +/- 30 %. Capacitors should have K-values from 100 to 1,000 (or even up to 10,000) with a +/- 20 % tolerance and a X7R temperature coefficient of capacity. The overall substrate flatness should be less than 10 µm.

The first meaningful step will be the integration of capacitors due to their large space consumption. In parallel the resistors can be placed at the back of the substrate. This has the additional advantage that these outside resistors can be laser trimmed. Thus, an accuracy < 5 % can be achieved. In a further step resistors with lower accuracy requirements, e.g.

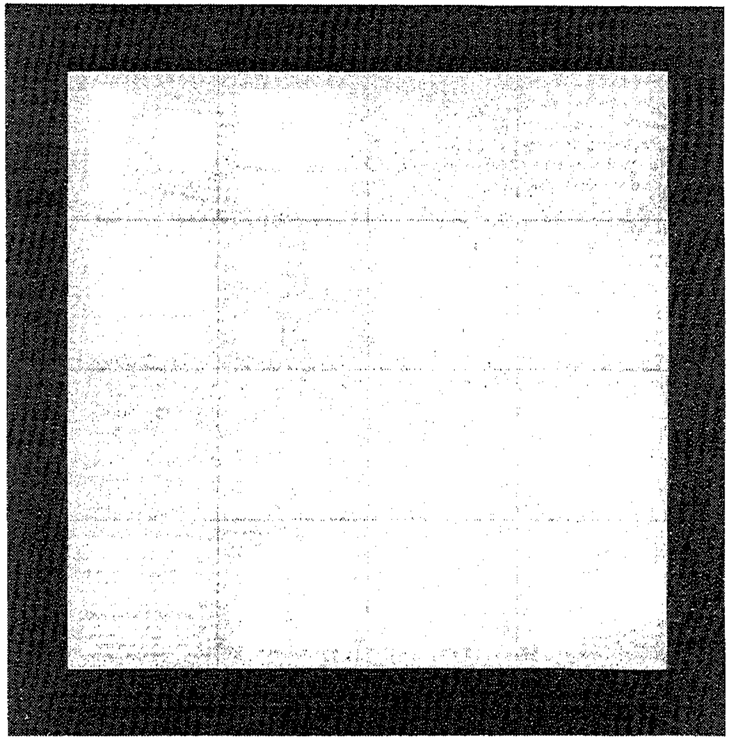

Fig. 6 : LTCC qualification test circuits

for RC devices especially in EMC improved circuits, can be also buried and thus long distant wiring can be saved.

The major technical problem for the development of embedded, cofireable components is to minimize the shrinkage mismatch of the individual ingredients and the glass-ceramic matrix and the compatibility of the different chemistries to allow a simultaneous sintering.

Most hybrid thick film resistors that are made today for postfiring applications are designed to be fired in air at around 850 °C. For all resistors the general approach is to have a two component material, a conductive phase and an adhesion material.

Resistor pastes normally contain a minimum of electrically conducting phase, an insulating glass frit and organic binders. Typical conductive phases are Ag/Pd for low value resistors and RuO_2, IrO_2 and ruthenates of lead and bismuth for high value resistors. For conventional thick film hybrids (built on fired alumina substrates) the typical frit for high value resistors is a lead borosilicate glass and a non-lead frit for low value resistors. The resistance is varied by changing the amount of conductive and insulating phases. The glass plays a major role in sintering and formation of required resistor microstructure. Therefore the selection of the glass chemistry is a crucial factor in the development of any resistor. The electrical properties are also dependent on the size of the conducting particles.

Since the matrix material interacts with the glass phase of the resistor it is very challenging to develop a stable buried resistor system for LTCC. Resistors made with various Pb, Ca and Ba based glasses were studied for chemical compatibility and shrinkage match with the matrix. Flow properties of the glass, such as softening point and viscosity, and particle size of the conductive phase were optimized. The sheet resistance of the buried resistors is varied by changing the ratio of the amount of RuO_2 to glass.

The pastes consist of submicron size conductive particles of RuO_2 and glass particles of a few microns. The glass allows a liquid phase sintering where the RuO_2-particles rearrange and form continuous conducting chains in an insulating matrix. The complete sintering of the thick film resistor before the crystallization of the matrix material is essential to achieve consistent electrical properties.

Vasudevan et al. (**4**) could realize embedded, cofired resistors with sheet resistances of 10 Ω, 100 Ω, 1 kΩ, 10 kΩ, and 100 k Ω/sq. in the B_2O_3 - CaO - SiO_2 - system. Cofireable surface resistors have been developed with almost the same glass chemistry as the buried resistors but with somewhat different glass/RuO_2 quantities in the same system (**5**).

Furthermore, a compatible capacitor with a dielectric constant of 130 which is based on perovskite phases has been developed (**6**). In addition the production of both planar and three-dimensional inductor coils of values in the 150 - 400 nH range has been demonstrated.

For producing embedded components usually the standard printing process is favorized by the LTCC suppliers. However, another approach to bury capacitors into a LTCC package is reported by Drozdyk (**7**). The barium

titanate-based high K capacitor was realized by a tape inserts array method. Compatible high K tape is tranferred into punched holes which are placed in a square array in the matrix LTCC tape. An effective K of 380 (at 1 kHz) could be demonstrated prototypes. Nevertheless, this process seems to be inappropriate for a high volume production.

An alternative process, the insertion of a complete layer of high K material, which would lead to K-values from 1,300 to 10,000 was unsuccessful because of major sintering problems, e.g. high porosity, cracks and delamination.

Wahlers et al. (**8**) developed low firing cofire tape products with K values from 7,300 up to about 12,000 which can be fired at temperatures from 850 to 930 °C. The tapes consisted of specially prepared high K perovskite powders and could be sintered to a 98 % theoretical density at > 900 °C. Standard high K titanate materials require firing temperatures > 1200 °C. However, a compatibility prove to a standard LTCC system could not be given.

In the field of powder development for electroceramics (mainly for multilayer ceramic capacitors) strong efforts are currently made to offer new high K materials with relatively low sintering temperatures (**9, 10**) . These materials are also of special interest for a potential future application in embedded capacitive components. Typical examples are lead-base perovskite oxides, especially lead magnesium niobates (PMN) which can be sintered at temperatures as low as 825 °C.

Conclusion

LTCC has a very high potential to be the future packaging technology for high performance applications in the automotive industry. The basic requirements for the next interconnector generations e.g. high integration and reliability in harsh environments can be fulfilled. Furthermore, the technical possibility of embedding non-active components is a very attractive and promising feature.

First LTCC prototypes with buried components have been successfully demonstrated. Currently major development and qualification efforts have been started by both the material suppliers and the LTCC manufacturers to realize a controlled and reliable high volume production.

It is believed that by the implementation of new, low sintering powder materials, e.g. lead magnesium niobates (PMN) in form of compatible paste systems, the achievable dielectric range for embedded capacitors can be extended much further. This would offer the opportunity for larger varieties of applications.

LTCC allows to combine the advantages of a sophisticated ceramic multilayer packaging with standard hybrid manufacturing technologies. This will lead to a definite enhancement of the overall technical performance, higher integration and a significant size reduction.

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The Use of Tantalum/Niobium-Compounds in the Electronic Industry

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This presentation will give an overview of present and future use of tantalum and niobium compounds in the electronic industry.