Cost Effective Solutions for High Density Interconnect and RF Modules Using Low Temperature Cofired Ceramic Materials

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Abstract

Low Temperature Cofired Ceramic (LTCC) Materials were introduced commercially in the early 1980's and immediately presented designers with a unique option for the manufacture of high density interconnect circuits [1]. In consequence DuPont's Green Tape™ System became firmly established in a variety of high-performance, low and moderate volume, military, aerospace and medical applications.

During much of 1990's the growth of LTCC was fueled by high-volume, cost-performance applications such as those for automotive control modules and read/write amplifier modules for hard disk drives.

Now today, early in the year 2000, the third wave sees these materials being adopted for ultra high-volume, cost-sensitive portable wireless applications. Such applications are driven by the capability of LTCC materials to deliver user-friendly processing for large-format substrates, low-loss performance at frequencies above 900MHz, fine-line patterning and embedded component capability.

Constrained sintering [2,3] techniques enable the use of large-format substrates. New inorganic technologies extend the low loss behaviour to a proven operating range of 40GHz and beyond. Photopatterned thick film conductors that cofire with LTCC facilitate the formation of 50µm lines and spaces which add significantly to the high-density capability of LTCC. Use of planar resistor, capacitor and inductor materials which are incorporated within the structure give way to integrated packaging, and a new generation of miniature RF modules.

The evolutionary progress of Green Tape™ LTCC materials is reviewed in this paper with particular emphasis on new high-density interconnect and portable-wireless applications.

Introduction

Currently the most significant driver for packaging and high-density interconnects is wireless communications. **Figure 1** illustrates the projected regional growth of wireless subscribers through Y2003. Mobile phone development continues rapidly and already advanced handsets offering Internet and EMail access, as well as many of the features of a PDA, are becoming available. The progressive incorporation of new features into a smaller space while delivering increased battery life, lower cost, and higher levels of manufacturing robustness will continue to challenge the RF designers. Whereas the integration level of IC's continues to be important, module or substrate level integration is viewed

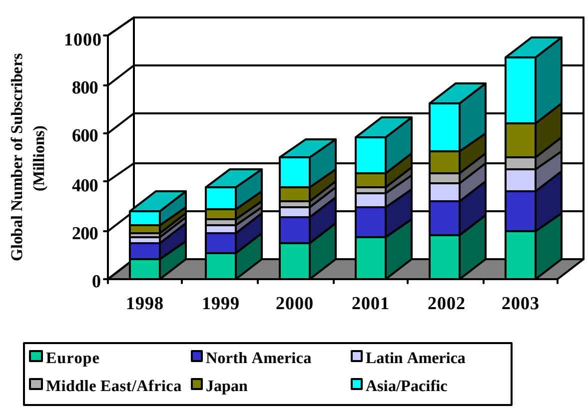

FIGURE 1 Forecast growth – wireless subscribers

increasingly as the key enabler. LTCC has demonstrated that it meets the density, performance and cost requirements for portable wireless and is well positioned to meet the high-density, interconnect requirements of signal processors with GHz clock rates.

The LTCC Process

With LTCC technology an unfired tape (Green Tape™) replaces the conventional screen printable paste dielectric. The tape is cast from a slurry of the same inorganic components used to formulate the thick film composition. A full discussion of the consequences of this is beyond the scope of this paper: however, three of the most important follow:

With conventional screen printing, paste transfer and via formation must occur simultaneously. With LTCC they are separate. This enables thicker, higher quality, more uniform, dense dielectric layers and smaller, finer pitch and perfectly formed vias to be achieved with LTCC versus thick film.

Screen printed multilayer circuits involve mainly sequential processes, thus yield and quality are only as good as the layer with the poorest yield and the poorest quality. With LTCC, each tape layer can be fully customized with conductor prints, via fills, embedded resistors capacitors and inductors and cavities and be fully inspected (and accepted or rejected) before they are all collated and fired. Thus the yield of LTCC circuits even with 40 to 50 layers (>50 demonstrated) can still be in the high 90th percentile.

The firing temperature of high temp, co-fired ceramic (HTCC) is close to 1500°C, way above the melting temperatures of the high-conductivity conductors. HTCC conductors are therefore limited to refractory metals such as W or Mo - not noted for their high conductivities, a fundamental need for portable wireless applications. In contrast LTCC requires a firing temperature of 850 to 900°C This enables the use of higher conductivity conductors such as silver and gold – a significant advantage for LTCC. The process flow for Green Tape LTCC is shown in **Figure 2**. Each layer of tape is blanked to size, and registration holes punched. Vias are formed in

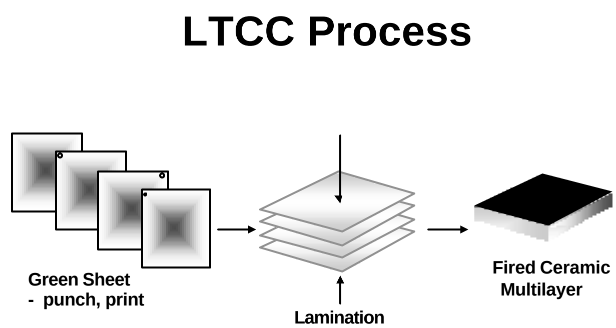

FIGURE 2 The LTCC Process Flow

the dielectric tape by punching or drilling. The conductor traces and via fills are screen-printed or photo-defined.

When all layers have been punched, printed, and inspected, the tape layers are registered, laminated and co-fired. The co-fire process (i.e., dielectric and conductor fired at the same time) involves much fewer firing steps than conventional thick film technology.

Selection of conductor metallurgy depends on the end use. Military and aerospace applications have generally tended to use Au (for inner layers, via fills and wire bonding) and Pt-Au alloy conductors (for solder assembly). Portable wireless applications more commonly use Ag (for inner layers and via fills) and Ag-Pd alloy conductors for solder assembly. For those applications where top Au conductors are combined with inner Ag conductors, transition via fill metallurgies are available.

Process enhancements

For substrates larger than 5” by 5” square manufacturers tend to prefer to use a variation of the basic LTCC process which incorporates the use of a constraining (release) tape and/or pressure. Either way the x-y planar shrinkage of the tape and the tolerance of this shrinkage is reduced from 12.7% ±0.3% to near zero.

The simplest of these is PLAS [2], pressure-less assisted sintering, which simply uses two constraining tape layers, co-laminated to the tape composite and requires no special tooling. The constraining layers do not sinter or shrink, but maintain a uniformly high frictional contact over the surface of the laminate during firing. Overall shrinkage for PLAS is 0.05 to 0.15% (depending on design) with a tolerance of <±0.05%.

The second variant PAS, pressure assisted sintering [3] is even more effective in reducing the shrinkage variance (tolerance <±0.008%). The same release tape coated laminates used with PLAS are stacked together with interleaved porous plates and the whole is placed between two constraining dies. The number of laminates that can be stacked depends on circuit design, furnace design etc. Up to 20 laminates has been demonstrated. Uniaxial pressure is applied to the constraining dies by use of a pressure ram. For fairly obvious reasons PAS firing is always carried out using a box furnace.

Regardless of which is used, customization of the release tape to prevent or minimize chemical interaction between it and the tape laminate is critical since the release tape needs to be cleanly removable at the end of the firing process.

In order to achieve fine-line features beyond 100µm, photo-patterned conductors have been developed [4]. For example, using a new cofireable Fodel™ Ag composition, it is now possible to pattern 50 µm lines and spaces on any layer of an LTCC interconnect structure (see **Figure 3** below). Demonstrated applications of this technology include high-density interconnects, spiral embedded inductors and inter-digitated capacitors.

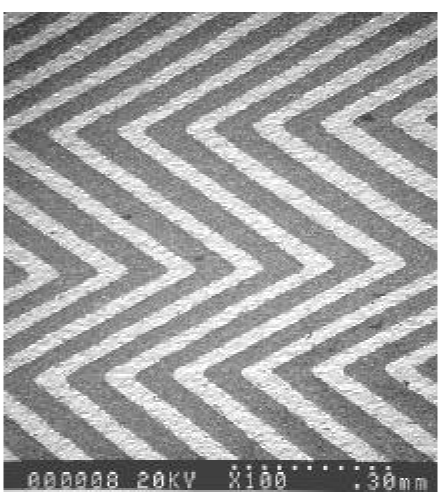

FIGURE 3 FODEL™ Ag on LTCC showing 50mm lines and spaces

The option of "designing in" embedded passive components in the form of resonators and filters is highly desirable to a designer.

Preliminary low-loss capacitor materials for wireless applications have been developed and are under evaluation. These materials exhibit K values of 20 to 80, X7R TCC behavior and Q factors between 180 and 300. To increase their utility the materials are available in paste or tape form. Work to increase the K value to 200 and to design in NPO TCC characteristics is in progress.

The first generation buried resistor materials have now been commercialized. They range from 10Ω to 10kΩ/square. A summary of their performance capability is provided in **TABLE 1** below. Since their 6σ tolerances are nominally ±20 to 30%, they are suitable for digital applications only. The reason is that their geometric variations cannot be smoothed by laser trimming (they are buried) to the tight tolerances of 0.5 to 1% required of analog circuitry – the great advantage of surface thick film resistors. Nonetheless, careful process control (primarily thickness) has enabled these materials to be used successfully in 5 to 10% tolerance applications.

	CF011	CF021	CF031	CF041
Value W / sq.	10	100	1000	10000
R Spec. (%)	±20	±20	±20	±20
DR 1 refire (range %)	-5, 10	0, -1	-4, -6	-8.-9
DR 3 refires (range %)	15, 20	0, -2	-4, -6	-25-30
TCR (ppm)	±200	±200	±200	±200
TCR 3 refires (range ppm)	±200	±200	±200	±200
ESD (1 X 5kV)	<0.2	-0.01	-0.01	-5, -7
Quantech noise (dB)	-40	-40	-25	-5
STOL V/mm	-	18	55	110

N.B. ppm indicates ΔR change in ppm/^{o}C from -55^{o}C to 25^{o}C (Cold TCR) and 25^{o}C to 125^{o}C (Hot TCR)

TABLE 1 CF Series Buried Resistors- basic data

Features and Benefits of LTCC

Table 2 summarizes the features of LTCC and the benefits to the OEM who is designing and manufacturing handsets. High Q, or low loss, is important since it influences the height of the frequency response peak resulting in higher common mode rejection and reduced phase noise. Another consequence is lower mean power consumption and extended battery life. Both factors are important to portable wireless applications.

The dense, hermetic ceramic structures that are characteristic of fired LTCC bodies eliminates concerns regarding moisture and moisture-related failure modes, including swelling, shrinking, delamination and metal migration. The environmental reliability of such structures has been repeatedly validated by applications in the aero-space, military and automotive areas.

The low thermal expansion of LTCC matches well with Si, GaAs and SiGe and facilitates bare chip attach without the need for an added epoxy under-fill process.

The ability to design in three dimensions (i.e., to incorporate interconnect and passive components and functions in a single integrated block, is an important feature of LTCC technology. Secondary benefits include (a) the elimination of large numbers of small components from the top or bottom layers of the circuit and a corresponding reduction in the total number of solder joints with their attendant processing and reliability issues and (b) potential for improved layout capability and x-y circuit size reduction. This latter feature, when combined with the larger format substrates that are possible with constrained sintering, represents a formidable approach to meeting the cost reduction initiatives that will continue to dominate and drive portable wireless growth.

Figure 4 shows 50Ω microstrip attenuation data (dB/in.) for two LTCC systems. This was generated using a T-pattern resonator [5]. Also included are data for 99% alumina substrates metallized with thin film Au and copper clad PTFE laminates [6]. The 951 LTCC system has attenuation below 0.5 dB/in. up to about 12 GHz, while the Low loss 943 system performs similarly to copper clad PTFE laminates. Its performance

FEATURES	BENEFITS
High Q / Low loss / Low T_f	Performance, talk time, Smaller IC's
Precisely defined properties	Cost, ease of design, time-to-market
Circuit density	Cost, size, functionality
Integral components	Cost, size, performance, design security, reliability
Functional trimming	Cost, performance
Environmental stability	Performance, reliability, lifetime
TCE match to Si, GaAs, SiGe	Cost, size, reliability, bare die/flip chips
Thermal Performance	Cost, size, reliability
Mixed analog / digital, RF	Cost, design flexibility, size, performance, reliability, modularity
Integral hermetic packaging	Cost, design flexibility, size, reliability
Volume manufacture	Cost, supply, known-good module

Table 2 Benefits of LTCC ceramic solutions

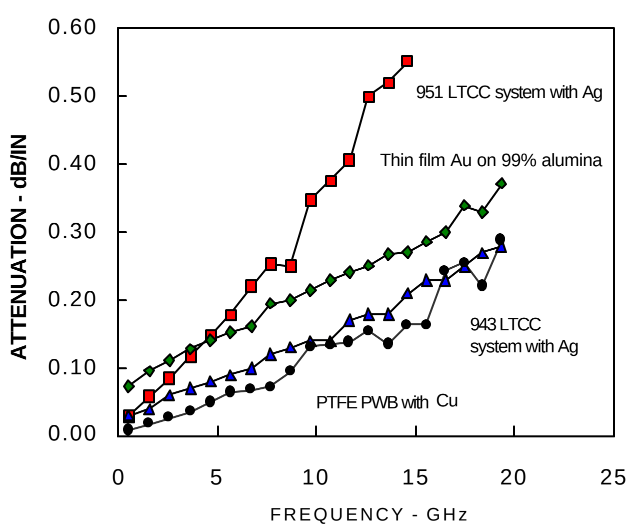

Figure 4 50 Ohm Microstrip Attenuation

is superior to that of thin film Au on 99% alumina. Cavity and open resonator studies have shown that the dielectric constant K and the loss tangent of 943 are insensitive to frequencies up to 40 GHz. The 943 LTCC system is a second generation system of materials developed spec-

	951 tape	943 Low loss tape
Electrical		
Dielectric constant @ 40 GHz	7.8	7.5
Loss tangent @ 40 GHz	.015	.002
Insulation resistance@100VDC	>10**12 ohms	>10**12 ohms
Breakdown voltage V/25 microns	>1000 Volts	>1000 Volts
Physical		
TCE (25-300^{o}C)	5.8 ppm/C	6.0 ppm/C
Density	3.1 g/cc	3.2 g/cc
Camber	<.001/inch	<.001/inch
Thermal conductivity	3.0 W/m-K	4.4 W/m-K
Flexural strength	320 MPa	230 MPa
Unfired Properties		
Thickness	951-AT 114 µm (4.5 mils) 951-A2 165 µm (6.5 mils) 951-AX 254µm (10 mils)	943 125µm (5.0 mils)
Shrinkage	x, y 12.7 ± 0.3% z 15 ±0.5%	x, y 9.5 ± 0.3% z 14.3 ± 0.3%

TABLE 3 Properties of Green Tape LTCC Materials

-ifically [7] to meet emerging needs for wireless applications above 12 GHz. As with the 951 system compatible conductors (inner, via fill, top layer) have been developed. **TABLE 3** above summarizes the properties of both tape materials.

Recent Wireless Applications

Figure 5 is a Bluetooth radio module. Bluetooth [8] is a global specification for short-range wireless

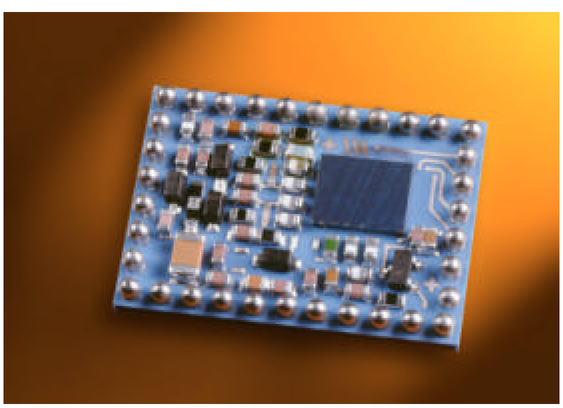

FIGURE 5 Bluetooth Radio Module (Ericsson)

connectivity and data transmission originally proposed by Ericsson. This low-cost microwave radio technology is intended to replace cables simplify person-to-person and machine-to-machine interaction. Bluetooth will allow creation of personal-area networks in which any electronic device within a radius of 3 meters can seamlessly share data. It will be used in a broad range of electronic devices for voice and data communication, including mobile phones, modems, laptop and desk computers, fax machines, printers, wireless headsets and digital cameras. The prerequisites for the design of Ericsson's initial Bluetooth hardware module were small size, low cost, reliability, low power, and the ability to function in many applications. Ericsson selected flip chip assembly for the IC, and LTCC based on its flip chip compatibility, small size and robust high frequency and mechanical properties. With LTCC Ericsson was able to integrate microwave structures for the antenna filter and transmit / receive baluns into the Bluetooth transceiver substrate.

Figure 6 shows an innovative IC package for a wireless application manufactured by National Semiconductor. This high density interconnect includes embedded decoupling capacitors and other RF passive structures, including the VCO resonator. It facilitated the removal of many e xternal components. It has a μ-BGA footprint and it is cost-competitive with standard packages.

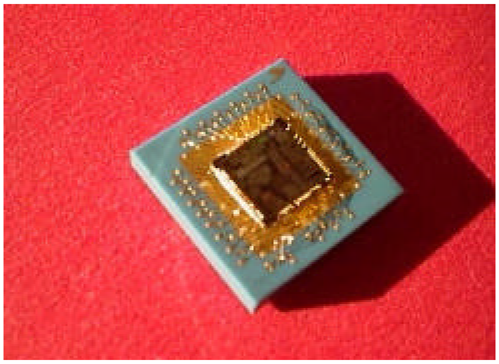

FIGURE 6 BGA package for wireless

Roadmap for the future

LTCC is a key technology for integrated packaging in high volume, cost sensitive, applications in wireless, automotive and high-speed digital interconnect markets. The tradeoff between system cost and performance is mission critical, and time-to-market is the driver. **Figure 7** shows the strategic directions for future LTCC developments. First the number and variety of tape platforms will be expanded. An example is a tape with a temperature coefficient of expansion (TCE) between that of alumina and a glass reinforced FR-4 printed wiring board (PWB). This high TCE tape will facilitate reliable LTCC module attachment to PWB's.

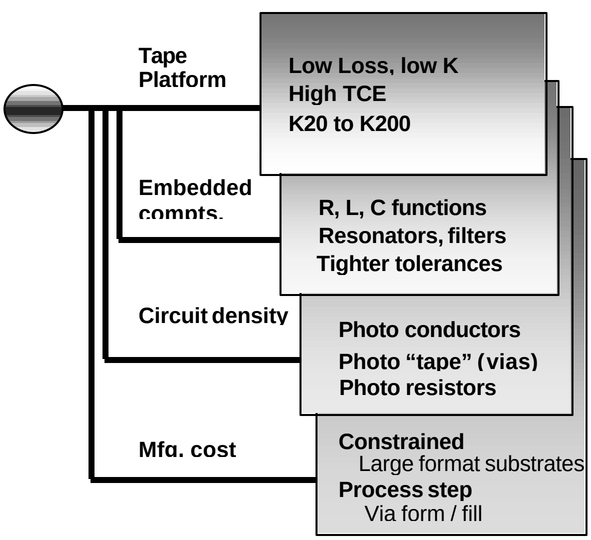

FIGURE 7 Technology Roadmap for LTCC

Second, although the performance of today's embedded passives is acceptable for many applications, the range of applications will be extended by innovations in materials and process to allow tighter tolerances. The paradigm will shift from embedded passives to embedded functions and integrated packaging will become pervasive.

Precise feature definition (line, space, edge, line shape) is key to performance in high frequency and high speed digital applications. Combining photo patterning and LTCC technology can deliver increased performance as well as increased circuit density. Photo-chemical technology has the potential to drive new process developments which can decrease equipment investment, and shorten the development cycle time.

Finally, larger panel size and more efficient process sequences will be required to meet the need for continuous improvement throughout the manufacturing cycle.

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