

LTCC - Multilayer Ceramic for Wireless and Sensor Applications

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Abstract

LTCC technology has large benefits in microwave applications. Ceramic substrates as well as the gold and silver pastes have excellent physical and electrical properties. Moreover, material and processing costs are competitive to other substrate systems like HTCC and printed circuit boards. A comparison between LTCC and PCB is followed by a listing of commercial LTCC materials and a selection of worldwide foundry services. On the basis of the prototyping line at IMST GmbH the manufacturing process of LTCC modules is described. Finally, with the example of a 25 GHz transceiver module a high integration and cost-effective application is demonstrated.

1 Introduction

LTCC (*low temperature co-fired ceramic*) stands for a ceramic substrate system, which is applied in electronic circuits as a cost-effective and competitive substrate technology with nearly arbitrary number of layers. Printed gold and silver conductors or alloys with platinum or palladium will be used in general. Copper conductors are available, too. The metallization pastes will be screen printed layer by layer upon the un-fired or “green” ceramic foil followed by stacking and lamination under pressure. The multilayer ceramic stack will be fired (sintered) in the final manufacturing step. The temperature of sintering is below 900°C for the LTCC glass-ceramic. This relative low temperature enables the co-firing of gold and silver conductors. The melting points of Au and Ag are at 960°C and 1100°C respectively.

The LTCC slurry is a mixture of recrystallized glass and ceramic powder in binders and organic solvents. It is cast under “doctor blades” to obtain a certain tape thickness. The dried tape is coiled on a carrier tape and ready for production. In contrast HTCC (*high temperature co-fired ceramic*) is an aluminium oxide substrate, also called Alumina or Al_2O_3 . The sintering temperature of Alumina is at 1600°C, which only allows co-firing of conductors with a higher melting point like tungsten (W, 3370°C) and molybdenum (Mo, 2623°C). The drawback of these conductors is the lower conductivity, which results in higher waveguide losses.

The low line losses as well as the competitive manufacturing costs are an advantage of LTCC for RF and microwave applications. In practice LTCC is rather in competition with PCB (*printed circuit boards*) like FR4 than with HTCC. FR4 is a sophisticated and well established substrate technology with low initial and production costs. However, FR4 is not suitable for high frequency applications. Other PCB substrates are made for the GHz-range. These boards are often made of PTFE (polytetrafluorethylene), fiberglass and ceramic and are more expensive than FR4. The following section compares LTCC and PCB/PTFE in more details.

2 Comparison of LTCC and PCB/PTFE

The authors consider the fields of applications of FR4 up to a few GHz. Typical examples can be given at the lower ISM-band frequencies (*industry science and medicine*): 433 MHz, 868 MHz, 915 MHz (American standard) and 2.45 GHz, as well as the frequencies for mobile communication at 900, 1800 or 1900 MHz. Beyond that range high frequency boards or ceramic substrates are recommended.

Among the costs it is also important to consider the physical and electrical properties, when the most suitable substrate system is chosen. Here an example: the main-board of today's mobile phones is typically a multilayer PCB for the digital and RF part (for good reasons). The power amplifier and also more often the diplexer is made of LTCC. The power amplifier exhibits the advantages that LTCC has a better thermal conductivity and that LTCC is suitable for high integration of passive components. Additionally the high volumes production costs for such small modules are very low. Each layer can be manufactured and inspected in parallel before the substrate stack is laminated.

Table 1: Comparison of a selection of RF-PCB/PTFE vs. LTCC

Supplier	Substrate	h μm	ϵ_r	ϵ_r tol. %	$\tan(\delta)^*$	TCE ppm/K	TC ** W/mK	relative Price ***	Material
Rogers	RO3003	760	3	1.3	0.13	17	0.5	1.2	PTFE / ceramic filled
	RO3006	635	6.15	2.4	0.25	17	0.61	2.2	
	RO3006	1270						3.7	
	RO3010	635	10.2	2.9	0.35	17	0.66	2.4	
	RO3010	1270						4.1	
Arlon	AR 600	635	6	2.5	0.35	12	0.43	6.1	PTFE / woven fiber-glass / ceramic
	AR 1000	635	10	5	0.35	14	0.65	4.8	
Taconic	RF-60	635	6.15	4.1	0.28	12	0.5	1.1	PTFE / woven fiber-glass / ceramic
	CER-10	635	10	5	0.35	14	0.3	1.8	
DuPont	951-AX, Au	210	7.8	1.3	0.5	5.8	3	1.5	glass / ceramic
	951-AX, Ag							1.0	
Ferro	A6M, Au	185	5.9	3.4	0.2	7	2	2.2	glass / ceramic
	A6S, Ag					8		0.6	

* dissipation factor at 10 GHz

** thermal conductivity

*** relative prices for PCB substrates with Cu conductors;
for LTCC substrates with Au and Ag screen printed conductors with a coverage of 20%;
prices will vary from one distributor to another

The authors opposed PCB/PTFE and LTCC substrate materials for microwave applications in a topical investigation. The material costs and the physical properties, which were taken among other sources from data sheets and internet, have been compared and evaluated. The authors made the assumption, that a yearly production of medium volume (about 10,000 modules) should be launched. The application frequency is around 24 GHz with a required area of about 5 to 7 cm² for the RF part of the circuit. The authors found a number of qualified sub-

strate materials. Most of them have the capability for multilayer circuit design. For the comparison the authors have concentrated on boards from *Rogers*, *Arlon* and *Taconic* for the PCB/PTFE part and on *DuPont 951* and *Ferro A6* for the LTCC part. This selection has been made to keep the comparison in *table 1* clear and concise for the reader. The authors point out, that all figures of *table 1* represent the results of this specific investigation. Especially the price information, which are given as relative costs only, may differ under changed conditions. A length factor, which takes into account that the wavelength at a certain frequency is shorter in a waveguide with a higher permittivity, has no influence into this comparison. Example: The required area for an edge coupled line filter on a ceramic substrate with a dielectric constant of $\epsilon_r = 8$ is smaller than on PTFE with $\epsilon_r = 3$.

The following list summarizes the advantages of PCB/PTFE and LTCC substrate systems:

Advantages of PCB/PTFE substrates for microwave and RF applications:

- low tolerance in dielectric constant (*RO3003*)
- high TCE (close to Cu and Al)
- capable for multilayer modules with *prepreg* technology
- large circuit areas possible $>(20 \times 20)\text{inch}^2$
- low production price for low to high volume quantities
- low initial costs

Advantages of LTCC:

- low tolerance in dielectric constant (*DuPont 951*)
- better thermal conductivity
- low TCE (close to Si and GaAs)
- excellent for multilayer circuit design
- high degree of integration due to cavities and buried R-, L- and C-elements
- very robust against environmental stress (hermetical)
- low material costs for silver systems
- low production costs for medium and high quantities

3 Worldwide LTCC material suppliers and service foundries

This section deals with the LTCC technology sorted by materials, manufacturers and users. This should bring the fields of applications closer to the reader. There are 4 main LTCC material system suppliers available on the market. The authors define *systems* as set of unfired ceramic tape available in different thickness and with different permittivities. Each LTCC tape needs its own set of conductor pastes (this often includes resistor and capacitor pastes) for the screen printing process. The shrinkage properties of the pastes are matched to the ceramic tapes. Therefore conductors (resistors and capacitors respectively) are distinguished between inner and outer printing as well as filling via thru-holes. Special alloys are available for soldering and bonding contact pads. However, the main ingredients of conductor pastes is gold and silver.

Table 2: Examples of worldwide foundry services

Foundry	Country	LTCC-Tapes	Production
ACX	Taiwan	DuPont 951, Ferro A6, ACX	90,000 sq.-foot-facility
ATC	USA	ATC K30, DuPont 951, Ferro A6, Heraeus CT700	8"x8" wafers, medium and high quantities
C-MAC (SEI Scrantom)	Germany USA	DuPont 951, Heraeus CT-800, Ferro, ESL, Emca	5"x5", 8"x8" wafers; high volume
CoorsTek	USA	DuPont 951	high volume
CTS	USA	DuPont, Ferro, Heraeus	>100,000 sq.-foot-facility
EPCOS	Austria	NEG MKE-100, NEG MLS-41 DuPont conductor pastes	6"x6", 8"x8" wafers; high volume
IMST	Germany	DuPont 951, Ferro A6	3.5"x3.5" wafers; prototyp.
MSE	Germany	DuPont 951	medium quantities
National Semiconductors	USA	DuPont 951, 943, Ferro A6	6"x6" wafers; high volume
NIKKO	Japan	AG2, AG3	5"x5" wafers; 25k/month
Northrop Grumman	USA	Ferro A6, DuPont 951, NG low k tape ($\epsilon_r=3.9$, $\tan\delta=7\times 10^{-4}$)	6,000 sq.-foot-facility
Samsung, ThinkCera	Korea	TLC-4B, TLC-6A, TLC-7A, TLC-10H, TLC-20B	soon available
Selmic	Finland	DuPont 951	medium quant.; prototyping
TAHLES-Microelectronics	France	DuPont 951, Ferro A6	>10,000 sq.-foot-facility 6"x6" wafers; 10 mil./year
Via electronic	Germany	DuPont 951, Heraeus CT700	small quantities; prototyping
Vispro (Kyocera America)	USA	Ferro A6, DuPont 951	5"x5", 6"x6" wafers
VTT	Finland	DuPont 951, 943	small quantities; prototyping

Such LTCC material systems, which are qualified for RF applications, are offered by *DuPont* (951 and 943: low loss tape), *Ferro* (*A6M*: microwave tape, *A6S*: low cost microwave tape), *Heraeus* (*CT700*, *CT800* and *CT2000*) and *Electro-Science Laboratories (ESL)*. Other LTCC tapes are available on the market. Some of them have to be used with conductor pastes from one of the previous mentioned suppliers. This is for instance *CeramTec* and *Nippon Electrical Glass (NEG)*.

LTCC foundry services are spread all over the world. These foundries offer the production of modules and circuits made of standard LTCC from *DuPont*, *Ferro*, *Heraeus*, *ESL* or their own supplementary ceramic tape. The in-house LTCC solution could rise the problem, that a second source for the production is not available, which might be an important factor to launch a product on the market. Table 2 lists a selection of worldwide foundry services for LTCC modules and gives an impression about the applied tape materials and the production capabilities (as far as these information could be found out). Beyond these foundries a number of companies have its own LTCC production facilities, which are not available for customers.

Bosch, Hitachi and *Murata* are typical firms, who manufacture their own LTCC products for the automotive, mobile communication and consumer electronic markets.

4 LTCC manufacturing process

The manufacturing steps for multilayer LTCC starts with the preparation of the unfired ceramic tape and is finished with the inspection of the completed module. This process, which is similar at all facilities, is illustrated in *figure 1*. The following section describes the manufacturing steps with the example of IMST's sample and prototype production line. The process is organized to be compatible to most of those foundry services, which utilize the unconstrained sintering method.

The green or unfired LTCC foil is delivered on a roller or as coupons in pre-confected sizes. The foil from the roller will be cut to fit into the manufacturing equipment (3.5 inch by 3.5 inch for *IMST*). In the next step the tape will be processed under a YAG-laser, which is also used to trim resistors. The laser cuts 4 position holes in each corner and an additional one for the orientation of the coupon into the tape. A layout tool reads all cavities and vias from the layer's artwork and implements the position and shape coordinates into a software code, which controls the laser cutting. The dust from the laser burning is exhausted to keep the tape's surface clean of particles. In volume production punching of vias and cavities is preferred. Special punching machines with several tools in parallel *shoot* some ten thousand holes per minute into the tape. However, the laser cutting method is very flexible (arbitrary shapes of cavities and different diameters for via holes) and cheaper for prototyping, which results in the same quality.

In the next manufacturing step the vias will be filled with conductor paste. This is done with a screen printer: a stainless steel stencil with the same via holes like the tape is aligned above the ceramic. A doctor blade is squeezing down the paste thru the stencil into the via, while a vacuum pump below the porous nest helps to fill the via with the conductor ink. This technique enables the fabrication of solid filled via connections from one layer to an other. Typical diameters are 250 μm , 150 μm but also 100 μm are possible, which is a requirement for RF applications. In the next step the screen printer is used to print the conductor pastes and also the resistor or capacitor pastes onto the ceramic foil. In standard screen print technology a line resolution of 100 μm (line width and spacing) is achievable. It has been demonstrated that 30 μm is possible with a special screen printer and a standard conductor paste. Other techniques are available to enhance the line resolution: photoimageable pastes for inner and outer conductors (e.g. *Fodel* from *DuPont* or *TC2301PI* from *Heraeus*), etched conductors or thin-film on LTCC (post-fired, on top or button only).

An optical inspection followed the processing of each single LTCC layer. This way faulty layers can be identified early and can be sorted out. All perfect coupons will be stacked next. The simplest way to proceed is to stack each tape on a tool with adjust pins for the position holes. In volume production special stacking machines carry out this job with an accuracy of a few micrometer. The LTCC layers have to be laminated in the next step. Two techniques are used in practice: the uniaxial pressing which is often used in production as well as the isostatic pressing. The first method is like coining money, where the LTCC stack is pressed between two parallel plates, which are heated up. A drawback here is, that larger tolerances in the substrate thickness will appear after firing, because the plates are never a hundred percent in parallel. Another difficulty is the uniaxial pressing with cavities in the LTCC stack. The cavity will be deformed due to the fact, that the strong pressure operates onto the edges only. The alternative method is the isostatic lamination. The tool uses water heated up to 80°C as a medium to uniformly distribute the force of the lamination. A pressure of 300 psi is recom-

mended. This process minimizes the de-lamination and gives more uniform shrinkage, which improves the yield of complex parts. Layers to be laminated are stacked on a backing plate before they are sealed in a flexible vacuum bag. Inserts may be used as an option to ensure accurate cavities. These are the reasons, why *IMST* decided to install an isostatic laminator for its prototyping process.

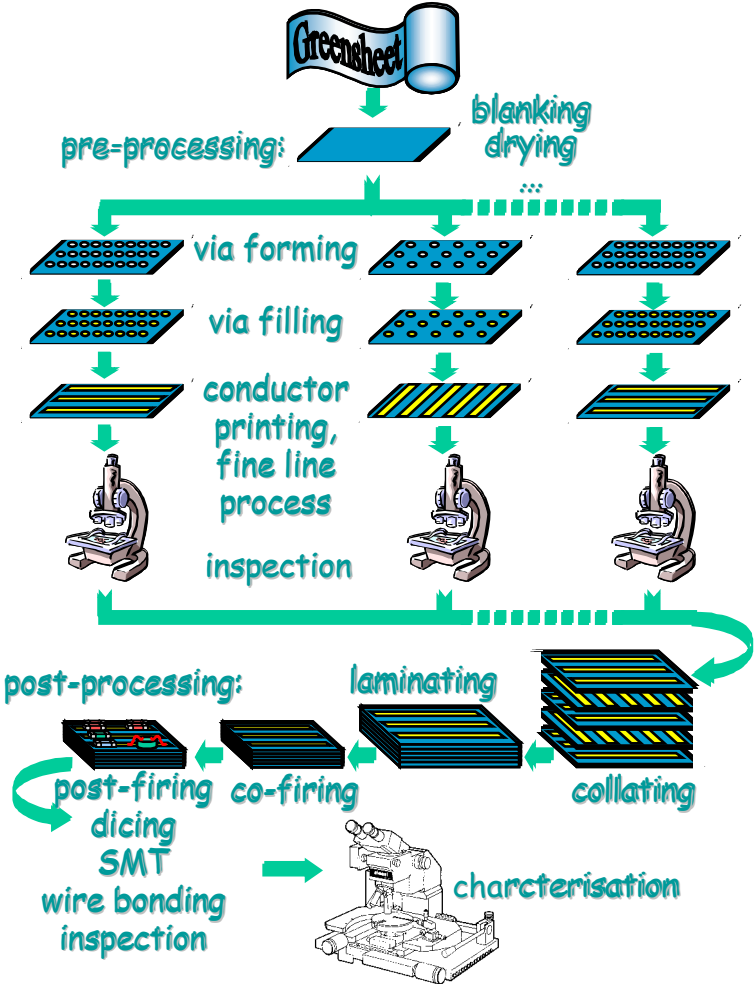


Fig. 1: Process steps for manufacturing and characterization of LTCC modules

The sintering of the stack in a process furnace follows the lamination procedure. A specific temperature-time profile, which depends on the glass-ceramic mixture, has to be observed during the firing process. LTCC suppliers deliver such profiles within their design rules. A typical practice is to heat up the oven to 450°C with a gradient of about 2-5°C per minute. The organic solvents have to escape completely during this period. In the next 30 minutes the temperature is raised to about 880°C, where the sintering process of the glass starts. This temperature remains constant for nearly 15 minutes to finish the sintering. A controlled cooling of the furnace to room-temperature is performed in the last phase of the firing process, which takes at least 3 hours. Two co-firing methods are used in practice:

- | | |
|--|--|
| 1. Unconstrained or Free Sintering: | 2. Constrained Sintering or Zero-Shrinkage: |
| X-, Y-shrinkage $\approx 13 \% \pm 0.3 \%$ | X-, Y-shrinkage $\approx 0.1 \% \pm 0.05 \%$ |
| Z-shrinkage $\approx 15 \% \pm 0.5 \%$ | Z-shrinkage $\approx 45 \% \pm 0.4 \%$ |

The zero-shrinkage process uses two additional tape layers which have to be co-laminated to the package of the unfired LTCC tapes. These two layers constrain the shrinking of the LTCC during the firing. The constraining tapes do not shrink or sinter itself, but maintain a uniformly high frictional contact to the surface of the LTCC. With the help of this method it is possible to reduce shrinking to about 0.05 % to 0.15 % with a tolerance of 0.05 % depending on the design. This process has its advantage in manufacturing large tiles (≥ 6 inch \times 6 inch). However, the volume production of modules with cavities is not yet established. That was the reason for IMST to decide for a free sintering process, where cavities for RF modules can easily be fabricated.

The sintered LTCC substrates are now ready for inspection and post-processing. Typical steps are further screen prints of conductors or resistors, which is also called post-firing, the dicing of circuits from the wafer and the assembly processes like wire bonding or SMD technology. IMST has accredited measurement laboratories to characterize circuits up to 110 GHz and antennas up to 60 GHz as well as an EMC-qualification center to perform relevant tests for the CE sign.

5 LMDS-Module as an Application Example

LMDS stands for local multipoint distribution services, where digital radio networks are applied to local regions like urban and company areas or others. Central multipoint base stations (relay stations) supply terminals with data in a wireless network. Services like local computer networks, digital voice and video as well as others are offered. There are several frequency bands allocated from European organizations like CEPT (European Conference of Postal and Telecommunications Administrations) or ERO (European Radio Communication Office). Recommendations regulate the use and specifications of these band. The one for the 24.5 GHz to 26.5 GHz band is called "T/R 13-02". Corresponding to this standard a transceiver module has been designed, fabricated, assembled and evaluated. Figure 2 shows a photo of the circuit.

Ferro's A6M LTCC tape with gold conductors on the top and silver conductors for inner layers have been used. 5 substrate layers are required for microstrip and stripline waveguides within the module. Monolithic integrated GaAs-circuits (MMICs) are mounted into simple and stepped cavities to obtain optimal transitions from the chips to the LTCC environment. In figure 2 the position of the MMICs is illustrated: attenuator (Att), amplifier (Amp), mixer, low noise amplifier (LNA) and power amplifier (PA). Bandpass filters (BP), Wilkinson power divider and tripler are realized in LTCC to keep the module's costs low. DC supply lines are crossing over the bandpass filters, which are completely buried as L-shaped stripline segments. The module consists of three branches: the transmit, receive and local oscillator path. Double rows of via chains are shielding the branches within the LTCC substrates. Metal walls in the cap are connected with these via fences for an optimal shielding. SMA connectors are utilized for the IF and LO ports, while GPO connectors from Gilbert are used for the RF ports. All this results in a very compact and cost effective transceiver module for LMDS applications. The size of the LTCC substrate within the Aluminium housing is 30 x 55 mm.

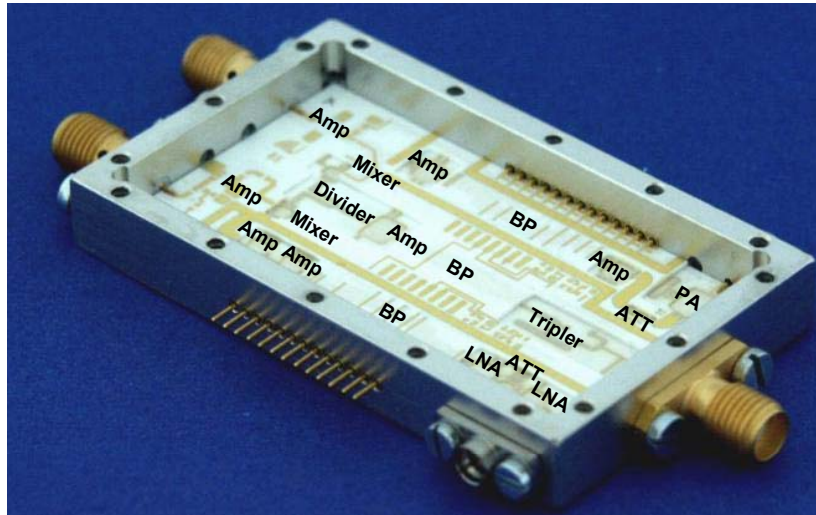


Fig. 2: LMDS transceiver module for 24.5 to 26.5 GHz (LTCC substrate: Ferro A6M, 5 layers)

6 Further Information

Booklet: "LTCC – An Introduction and Overview", IMST GmbH, December 2001

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