LTCC TECHNOLOGY

WHERE WE ARE AND WHERE WE'RE GOING - IV

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Abstract

New electronic systems for automotive, industrial, medical, military and space applications have and will continue to challenge both packaging engineers and technology due to the increased performance requirements, higher densities, higher temperatures and limited space available. This challenge mandates the use of unique packaging techniques such as multi-chip modules (MCM) that must not only provide the increase circuit density but also the reliability, electrical, thermal and hermeticity performance.

Present interest in T/R & MCM technology has focused on different packaging technologies such as laminate, ceramic, and thin film technologies. One such ceramic technology, Low Temperature Co-fired Ceramic (LTCC), offers significant benefits over other packaging technologies for use in RF and high density fast digital applications that could require hermeticity with good thermal management.

This paper will address the current status of LTCC technology as well as new and promising developments that could make this the leading substrate and MCM ceramic packaging technology. Industry acceptance of LTCC will also be addressed. All market indicators are predicting tremendous growth in the MCM market. One forecasting company has projected that in North America alone the MCM market will have grown from $350 million in 1996 to about $10 billion by the year 2003. The military's share alone of the market will grow from about $36 million to $1.1 billion by the year 2003. So important is the MCM market, ARPA once awarded $40 million to one MCM consortium comprised of the key military electronics companies.

Today however, the huge monetary investments of major corporations like Hughes, Ericsson, Motorola, Microsoft, Nokia, Qualcom and Raytheon in the commercial LTCC wireless and space arena would make the military's portion of the MCM market pale in comparison. One major satellite program alone is expected to bring more than $50 million to the manufacturer's of LTCC product between 1999 and 2006.

INTRODUCTION TO LTCC

LTCC tape systems are composed of a glass/ceramic dielectric tape provided in rolls with shrinkage-matched metallization pastes. Unlike thick film technology where sequential printing, drying, and firing of each layer is required, LTCC technology like PWB technology, processes all the different layers in parallel (i.e. all layers are punched, printed, and dried in parallel). As a result, optimum yields and cost effectiveness are achieved since each process is not dependent on the previous process. Each layer can be inspected prior to stacking allowing for extremely high yields. Once all the layers are processed, they are stacked, laminated and then co-fired at temperatures between 800°C-900°C to form a high density, fully integrated substrate. Integral packages may be fabricated by simply adding leads or seal rings and in some cases thermal heat sinks, BGA (ball grid array) or PGA (pin grid array). LTCC integral packages are readily fabricated resulting in high cost savings over the more conventional integrated package using a separate ceramic or laminate insert that is mounted in a standard HTCC package. Additional wire bonding of the substrate to the package I/O's. is then required These conventional packages are also subject to frequent glass to metal seal failures of the I/O pins in the package wall resulting in a helium fine leak condition. LTCC packaging offers improved reliability because the wirebonds from the substrate to the package I/O's are eliminated and there are no glass to metal seals to fail therefore improving assembly yields with a resultant lower overall cost.

During the firing process, the LTCC tape will shrink between 12% - 16% + 0.2% in the X and Y-axis and 15%-25%+0.5% in the Z-axis (depending on manufacturer). Assuming balanced metal loading and good process control, the shrinkage is consistent; however, with certain systems, there maybe a narrow processing window in which the fabrication must take place.

MCM PACKAGING USING LTCC TECHNOLOGY

Besides cost effectiveness and integrated packaging, LTCC technology offers other features that are ideal for MCM packages.

- **Fine line and Spaces**
- **Low Resistance Metallization**
- **Excellent High Frequency Characteristics**
- **Allows for Unique Flexible Designs**
- **Small diameter vias**

Fine Lines and Spaces

While the definition of fine lines and spaces has changed with each improvement of technology, the thick film printing process in LTCC technology is easily capable of 0.004" lines and spaces, and 0.003" lines and spaces are do-able. Finer lines and spaces, using photo-imaging are available to provide line widths and spaces in the order of 0.0015"-0.002".

A thin film deposition process can be used on the outer layers to produce finer lines and spaces: However, it's very expensive, and the surface of the fired tape must be extremely smooth for good adhesion. Polishing will help, but very small pits may remain and cause adhesion problems. Another method to achieve finer lines and spaces on the top layer is a photo-imagable thick film post-fire process. This is less expensive than thin film and two paste manufacturers (Hereaus and Dupont) offering this approach enables one to resolve 0.001/0.002" lines and spaces, respectively. These material systems require printing a gold area where the fine resolution is required. After drying, the fine line pattern is exposed onto the gold area by a high intensity ultraviolet light source. The pattern is developed using a sodium carbonate spray process followed by a water rinse and drying. The resulting pattern is then fired through a belt furnace at 850°C like a standard thick film print. Other thick film attachable gold processes are available, but the sodium carbonate developer used in this method does not attack the glass in the LTCC, and so no additional masking and stripping is required. A recent development by another paste (thick film) company allows fine lines and spaces on every conductive layer of the circuit by using a method called TOSS (Tape On Substrate). While fine lines and spaces are available with LTCC technology, it comes with some potential cost increases. One must weigh the option of adding layers and using wider lines/spaces or using the more expensive thin film or photo-printable thick film processes. In many cases where higher processing speeds or high frequencies are used, there is justification for fine lines and spaces: However, in the majority of applications, additional layers and wider lines and spaces can be used and significant cost savings can be realized.

Low Resistance Metallization

What makes LTCC technology desirable today for many applications is the use of high conductivity metals such as gold and silver. MCM applications requiring high speed digital and/or low level, high frequency analog processing cannot tolerate the IR losses associated with the metallizations used in High Temperature Co-fired Ceramic (HTCC) technology. But the metallizations in HTCC do offer many cost advantages and in some high impedance applications they have more than adequate conductivity.

Without sacrificing the electrical performance, LTCC tape manufacturers have addressed the cost issue by offering mixed metallization and copper systems. Mixed metallization systems use lower cost silver in the buried layers and gold is used on the top or bonding layers. A barrier via fill connects the outer and inner layers, eliminating a potential Kirkendal void electrical open. Lower cost copper systems are also available with LTCC. While the copper metallization is lower cost, the fabrication process requires a nitrogen process which can be costly to install and maintain if not supported by significant production. The manufacturers of LTCC tape systems have continued to work with their metallizations to reduce costs, however, they will always be subject to the cost fluctuations of the world commodity market. As a result, future emphasis will be placed on mixed metallization systems of gold/silver, copper or a mix of copper/silver/gold that is solderable and wire bondable.

Excellent High Frequency Characteristics

LTCC tape systems (such as Ferro A6 or Dupont 943) exhibit excellent high frequency characteristics making it ideal for RF applications. Motorola has recently announced a low temperature tape system that exhibits extremely high dielectric k stability with temperature change. These materials have a low dielectric constant (see table 1), low insertion loss, and good loss tangent characteristics. In addition, the tapes are cast in consistent 0.005"- 0.010" thickness, so dielectric thickness' are predictable to within a fired ± 0.0002". While a low dielectric k tape is desired for impedance control, some tape manufacturers are combining the low k dielectric with a very high k tape. This capability enables designers to design high value capacitors on the inner layers of the substrate as well as resistors and inductors allowing many GaAs MMIC devices to be smaller. Efforts continue in these tape systems for both military and commercial applications.

LTCC technology is being used in many GaAs MMIC packaging applications because of its closely matching CTE to that of GaAs (7.0 Vs. 6.5).

WHERE WE ARE AND WHERE WE'RE GOING - IV

Unique MCM Package Designs

Being able to process each layer allows the designer to create unique package designs without high tooling costs. Custom pin grid arrays (PGA), ball grid arrays (BGA's), and quad flat packs (QFP's) are easily manufactured using LTCC technology. These packages can be made with cavities, bonding steps, printed resistors, inductors, filters, couplers and capacitors internal to the body of the substrate. Because of the extremely flat printed surface, mounting pads, seal rings, lead frames and pins can be added.

Since each LTCC tape layer is individually fabricated, cavities and steps are formed by simply punching the cavity on the applicable tape layers and then stacking the layers to the required cavity depth. In addition, bonding steps for close pitch wire bonds can be incorporated just by changing the cavity dimensions. LTCC lends itself to many value added post fire processed which adds to the uniqueness of the MCM package. Thick film resistors can be printed on the top and bottom layers and then trimmed to within 1%-2%. Surface capacitors and inductors may also be printed on the top and bottom layers and then trimmed to specific values. It is desirable in many applications to bury precision passive components in the inner layers. The technology is presently to a point where resistors can be printed and co-fired to an accuracy of ± 15%-30%, capacitors to an accuracy of ± 10%-20% and inductors ± 5%-10% in a production environment. However, engineering prototypes have been built recently that incorporated 48 tape layers and conductors with eight Wilkinson power divider resistor tape layers, with all resistors within ± 20%! Concentrated efforts by LTCC material and components manufacturers to improve material availability and ease of manufacturing is proving successful. Where the values of resistors or capacitors exceed the limits of thick film printing processes, surface mount components can be added to the top or bottom surfaces. Solderable surface mount pads that interconnect to the inner layers can be printed as a co-fired or post fire process and the surface mount chip components can then be added during a final process.

Tape manufacturers have also developed low temperature solder/braze systems for LTCC which enable seal rings, lead frames, pins and connectors to be attached to the LTCC package. Hermetic packages (MCM's, T/R Modules, PGA, QFP, BGA) are manufactured by routing the I/O's to surface pads. In the case of PGA's, pins are attached to the pads/vias on the bottom layer, and lead frames are attached to pads along the top or bottom perimeter of the package on QFP/MCM's. Integrated LTCC packages allow for routing the I/O's through the inner layers of the package to pads outside the hermetic seal rings, therefore no glass to metal seals are required. As a result, all leaks caused by stressing the glass to metal seal during the lead form and assembly process are eliminated as there is no glass to metal seals used.

Typical solder/braze systems for LTCC utilize a gold tin, gold germanium, or gold-indium eutectic that reflows between temperatures from 325°C to 580°C. These solder/braze systems also include adhesion and barrier materials to facilitate the attachment process. While the braze systems provide for hermetic packages with lead frames or pins, the gold content can drive the price of the package quite high. Manufacturers are looking at alternative materials to attach seal rings and lead frames/pins that would be more cost effective. Lead/Tin solders have been used successfully and have passed hermetic and salt spray environmental testing.

Perceived LTCC Limitations And New Developments

This paper has presented LTCC as a versatile high density packaging technology that is ideal for many applications. While there is no doubt that LTCC technology offers many benefits over other packaging technologies, there are three characteristics that are perceived as limitation of this technology; shrinkage control, strength and thermal conductivity. While these are valid concerns, it should be noted that industry has addressed these issues by improved materials, fabrication processes and thermal via/heat sink technology.

Shrinkage Control

Fabricating large multi-layer structures > 6" X 8" that incorporate fine lines and spaces (<0.006") can result in alignment problems in the X and Y axis due to the shrinkage tolerance of $\pm$ 0.2%. This poses a particular problem with fine pitch connector pads that traverse across the width of the substrate. The cumulative tolerance of 0.2% could result in the connector leads not aligning with the substrate. Tape manufacturers have addressed the shrinkage issue by improving their tape casting processes and refining processing windows. Manufacturers of LTCC substrates and packages are fabricating 5" X 5.5" SEMS having a 20+ layer substrate with consistent and repeatable results.

To eliminate shrinkage altogether, some manufacturers have promoted a Tape-On Substrate technology (TOS). Shrinkage is virtually eliminated by laminating and firing each layer of tape on a substrate made of $A1_20_3$, BeO or ALN. While this eliminates any component assembly alignment problems associated with shrinkage, tape on substrate is a serial process resulting in higher costs, and the number of layers in the TOS stack up is limited. Other manufacturers such as CMAC- Thomson and Ragan have developed a zero shrink (ZST) LTCC tape system. This system requires no base substrate and has shrinkage of less than 1% with tolerance of +0.02%. Preliminary test result on the tapes physical and electrical properties appear promising, and the metallization system is close to being released. Work is still needed to bring this promising zero shrink tape to market.

WHERE WE ARE AND WHERE WE’RE GOING - IV

Strength

While LTCC is known for its good electrical properties, mechanical strength has been identified as one of its main weaknesses (17,000 psi - 26,000 psi flexural strength), as compared to that of Al_2O_3 (40,000 - 50,000 psi). Recent developments with the EMCA T8800 tape system has shown that LTCC may now compete mechanically on an equal level with Al_2O_3. This materials flexural strength has been tested in excess of 40,000 psi! While strong, this material also offers excellent electrical properties and complete compatibility with existing metal systems.

Thermal

As the power density of MCMs continue to increase, the thermal conductivity of the package must be able to conduct and spread the heat to maintain the product reliability. Although offering a thermal conductivity significantly higher than that of organic laminate material, LTCCs thermal conductivity of 2.0-2.5 W/m° K is a limitation to MCM designs dissipating many watts of power.

Many thermal management techniques are being utilized to improve the thermal conductivity through the substrate (Z-axis) as well as spreading the heat across the area of the substrate (X-and Y-axis). Probably the most common method of conducting the heat through the Z-axis is through thermal vias. Thermal vias are through holes that are filled with gold of silver metallization and are strategically placed beneath the die pads of hot components. The high thermal conductivity of the metals in the vias reduces the thermal impedance in the Z-axis and can improve the thermal conductivity to better than 70 W/m° K.

Once the heat is transferred through the thermal vias it is necessary to spread the heat uniformly across the X and Y axis. The most common method of spreading the heat is by applying a thick layer of gold or silver on the back side. For applications requiring better heat spreading, some manufacturers are looking at applying a higher conductivity thin internal layer or mounting the substrate on higher conductive materials such as copper tungsten (CuW) or copper-moly-copper (CuMoCu). What makes CuW and CuMoCu ideal for many high power applications is their thermal conductivity of 160-190 W/m-°K. The one disadvantage of using these materials as heat spreaders is the additional weight they add to the modules. In some applications where weight and thermal conductivity are critical, different packaging options are available. One such option is a metal matrix composite material is Aluminum Silicon Carbide (AlSiC). Other light weight materials are offered from Brush Wellman, HiRel and Balo. These materials have excellent thermal conductivity’s and CTE characteristics. A second option that was mentioned earlier to achieve shrinkage control, Tape On Substrate, will also provide improved thermal conductivity since the base substrate can be $A1_20_3$ (17 W/m°K) or ALN (200W/m°K-(250W/m°K).

Packages fabricated totally from ALN are also an alternative. Besides its excellent thermal conductivity, AlN's CTE matches closely with silicon ($4.2x10^{-6}$ ppm/°C). However, a possible limitation to its high frequency applications is its 8.5 dielectric constant.

Like LTCC, ALN can be cast as a green tape: However, instead of co-firing the mulitlayer packages in air at 850°C, ALN packages are formed using a hot press at 2000°C in a dry reducing atmosphere to prevent oxidation. Because of the higher temperatures required to process this material, refractory metals such as W and Mo/Mn must be used which have higher electrical resistance with a resultant loss in in transmission characteristics. While certainly demonstrating excellent thermal conductivity characteristics, ALN is still a very expensive alternative.

Efforts to reduce LTCC cost, and development of a high thermal conductivitiy low temperature co-fire ceramic tapes that can utilize thick film precious metallization continues.

In typical MCM applications, there are only a handful of components that dissipate large amounts of power. In most cases the thermal management can be handled through thermal vias and a heat spreader, but in instances where thermal vias cannot meet the thermal management requirements components may be mounted "chip down" directly onto the heat spreader for highly improved thermal performance. This is easily implemented by the use of cavities in the LTCC structure allowing access to the underlying heat spreader. This technique not only will solve the most severe thermal management issues, but it is also very cost effective.

LTCC Acceptance

In the past four years LTCC product has proven itself to be cost effective, compatible and up to the most stringent tests of todays applications. Today's LTCC product may be found in air and ground based radar systems, medical, wireless, high frequency communication, digital/analog circuitry, computer hardware, satellite, and various military armament applications. LTCC has also been selected for use by JPL in the Deep Space II impact mission to the planet Mars. Deep Space II was launched in early 1999 and is designed to impact and penetrate the Martian crust and then gather scientific data for transmittance back to earth. LTCC is presently being designed into a future space mission to Europa, a moon of Jupiter.

WHERE WE ARE AND WHERE WE'RE GOING - IV

Summary

The market for LTCC product has grown tremendously in the last several years and this type of packaging technology is playing and will continue to play an important part in the maximum density, and electrical and mechanical performance requirements of the MCM. LTCC technology offers many features that are beneficial for high reliability MCM applications at cost effective prices.

Development of new tape systems and buried passive components has brought the cost down while improving performance. Better thermal management techniques; and low loss, high/low k dielectric tapes for high frequency applications has allowed LTCC technology to expand into many commercial and industrial applications.

The authors believe that LTCC is today's technology and will be tomorrow's electronic packaging cornerstone.

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TABLE 1A

TYPICAL LTCC PROPERTIES

PROPERTY	DUPONT 951	FERRO A6M	FERRO A6-B	EMCA T8800	HERATAPE CT700
Color	Blue	White	Black	Blue	Blue
Available Fired Thickness (Mils)	3.7, 5.2, 8.2	3.7, 7.4	3.3, 6.7	3.5-15	3.6, 5.7, 7.9
Dielectric Constant (K)	7.8	5.9	6.5	7.2	7.9
Loss Tangent	.15%	<.2%	<.5%	<.2%	<.2%
Mwave Insertion Loss (dB/in) @ 10Ghz		.18	<.35	<.5	-
Insulation Resistance	$>10^{12}$ Ohms	$>10^{12}$ Ohms	$>10^{12}$ Ohms	$>10^{12}$ Ohms	$>10^{12}$ Ohms
Breakdown Voltage	>1000 V/Mil	>900 V/Mil	>1000 V/Mil	>1000 V/Mil	>1000 V/Mil
Electrolytic Leak Current		<1 µ-amp/cm^2	<1 µ-amp/cm^2	-	-
Flexural Strength (kpsi)	28.3	17.1	17.1	40.6	-
(3 point test method)					
		-	-	-	-
Youngs Modulus (kpsi)	15	12	12	27	-
Poisson Ratio	.17				
Fired Density (gm/cc)	3.1	2.5	2.5	3.06	3.1
TCE (ppm/°C)	5.9	7.5	9-10	6.0	6.7
Surface Roughness	<10 µ in	<15 µ in	<15 µ in	<15 µ in	<22 µ in
Camber	Conforms to setter	Conforms to setter	Conforms to setter	Conforms to setter	Conforms to setter
Shrinkage					
X,Y	13%±.2%	15%±.2%	14.5%±.2%	12%±.2%	15%±.2%
Z	15%±.5%	25%±.5%	35%±.5%	14%±.5%	25%±.5%
Metallizations	Au/Ag - Ag - Au	Au/Ag - Ag - Au	Au/Ag - Ag - Au	Au/Ag - Ag - Au	Au/Ag - Ag - Au

TABLE 1B

TYPICAL LTCC PROPERTIES

PROPERTY	Motorola T2000	Dupont 943			
Color	White	Blue			
Available Fired Thickness (Mils)	3.8	4.5			
Dielectric Constant (K)	9.1	7.5			
Loss Tangent	<.3%	<.1%			
Mwave Insertion Loss (dB/in) @ 10Ghz	-	.12			
Insulation Resistance	-	>2x10^{12} Ohms			
Breakdown Voltage	-	>1100 V/Mil			
Electrolytic Leak Current	-	-			
Flexural Strength (kpsi)	36	33.4			
(3 point test method)					
Youngs Modulus (kpsi)	-	-			
Poisson Ratio	-	-			
Fired Density (gm/cc)	3.13	3.2			
TCE (ppm/°C)	5.6	6.0			
Surface Roughness	-	-			
Camber	Conforms to setter	Conforms to setter			
Shrinkage					
X,Y	10.9%	9.5%±.3%			
Z	14.7%	10.3%±.5%			
Metallizations	Au/Ag - Ag - Au	Au/Ag - Ag - Au			