

6

THICK FILM AND CERAMIC TECHNOLOGIES FOR HYBRID MULTICHIP MODULES

William A. Vitriol

6.1 INTRODUCTION

Ceramic based multichip modules (MCMs) have been used in the electronics industry for over 20 years; however, the term MCM-C has become popular only in the last few years. For the purpose of this chapter, ceramic MCMs are considered as sophisticated extensions of simple hybrid circuits in which bare chips are mounted on substrates and interconnected using screen printed conductor materials. Three ceramic based technologies are used to make the various microelectronic circuits that are considered MCM-C structures. They are thick film multilayer (TFM), high temperature cofired ceramic (HTCC), and low temperature cofired ceramic (LTCC) MCM-C technologies. In fact, standard TFM hybrid circuits may be the oldest type of MCM-C.

6.1.1 Definitions of MCM-C Technologies

Thick Film Technology

Thick film is a technology in which specially developed pastes (also referred to as inks) are deposited and patterned by screen printing onto a ceramic substrate. The paste can be formulated to produce any number of different passive electrical components such as conductors, resistors, inductors and capacitors.

D. A. Doane et al. (eds.), *Multichip Module Technologies and Alternatives: The Basics*
© Springer Science+Business Media New York 1993

215

The pastes are applied by a screen printing process. After printing, the pastes are dried at temperatures of 85°C - 150°C to remove low boiling point solvents and then fired at temperatures ranging from 400°C - 1000°C. The substrate in the thick film-based technology is a passive inorganic material used to provide a mechanical platform for the thick film circuit. Typically substrates are made from 96% alumina. For MCM applications multilayer circuits are generally used instead of single layer circuits because of greater density requirements. Figure 6-1 shows an exploded view of a fabrication sequence for a single layer of a TFM circuit. The first conductor layer is printed, dried and fired on the substrate. Next, the dielectric (or insulating) layers are printed, dried and fired. Depending on the materials and complexity of the circuit as many as four dielectric layers may be processed before the next conductor layer. After the dielectric is fired the vias (vertical conductors that provide electrical connection between dielectric layers) are filled, dried and fired. This sequence of operations is repeated until the complete multilayer circuit is produced.

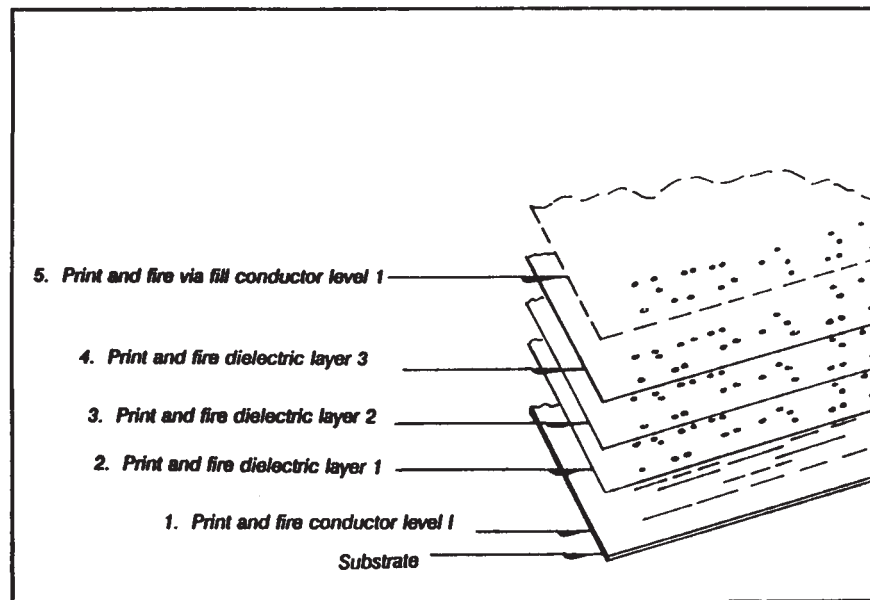


Figure 6-1 Exploded view of a fabrication sequence for single level of a thick film multilayer.

High Temperature Cofired Ceramic (HTCC) Technology

Cofired multilayer ceramic technologies have been developed to improve packaging densities by increasing circuit density, reducing the number of interconnects and by shortening conductor lengths. The building blocks for cofired ceramic structures are green (unfired) sheets of dielectric tape formed from a slurry of alumina powder, small amounts of glass and various organic components using a fabrication process called doctor blading. Doctor blading is a method of forming the slurry into a thin sheet by the use of a knife blade placed over a moving carrier to control slurry thickness. The dried, "green tapes" formed from the slurry, are usually 0.010" thick and have the consistency of fresh unchewed chewing gum!

Vias, or holes, then are formed in each individual sheet of tape. These vias are filled with a specially formulated conductive material to make electrical connection between metal layers. Each sheet then is patterned with a conductor material using screen printing techniques. After all the required sheets of alumina dielectric have been processed, they are stacked, aligned and laminated together using temperature and pressure. Figure 6-2 shows a drawing of the major steps involved in making a cofired part (both LTCC and HTCC). The finished product is formed by firing the laminated module at a high temperature, approximately 1600°C. At high temperatures only refractory metals such as tungsten (W) and molybdenum (Mo-Mn) can be used as conductors and they must be fired in a reducing (hydrogen) atmosphere to keep the conductors from oxidizing. The entire assembly shrinks approximately 17% in the x- and y-directions and 20% in the z-direction. Figure 6-3 shows an exploded view of the individual sheets of tape and is representative of either cofired technology.

Low Temperature Cofired Ceramic (LTCC) Technology

The conductor materials used to make high temperature cofired structures are limited by their low conductivity. Developments have sought to combine the advantages afforded by the cofired process (dielectric tape formation) with the advantages of standard thick film materials (use of metals with higher conductivity). For example, lowering the firing temperature of the dielectric tape to 850°C would make it possible to use thick film metals such as gold, silver and copper. These metals have a much higher conductivity than tungsten or molybdenum, allowing hybrid circuits to be made with faster processing speeds. The processing sequences using HTCC and LTCC technology are shown in Figures 6-4 and 6-5. The initial development in LTCC technology used a commercially available tape system from Dupont called Green Tape™.

Tape Transfer (TTRAN) is a variation of the LTCC process. It combines the serial processing of thick film technology with the use of dielectric tape. A single layer of cast tape replaces multiple screen printings of the thick film

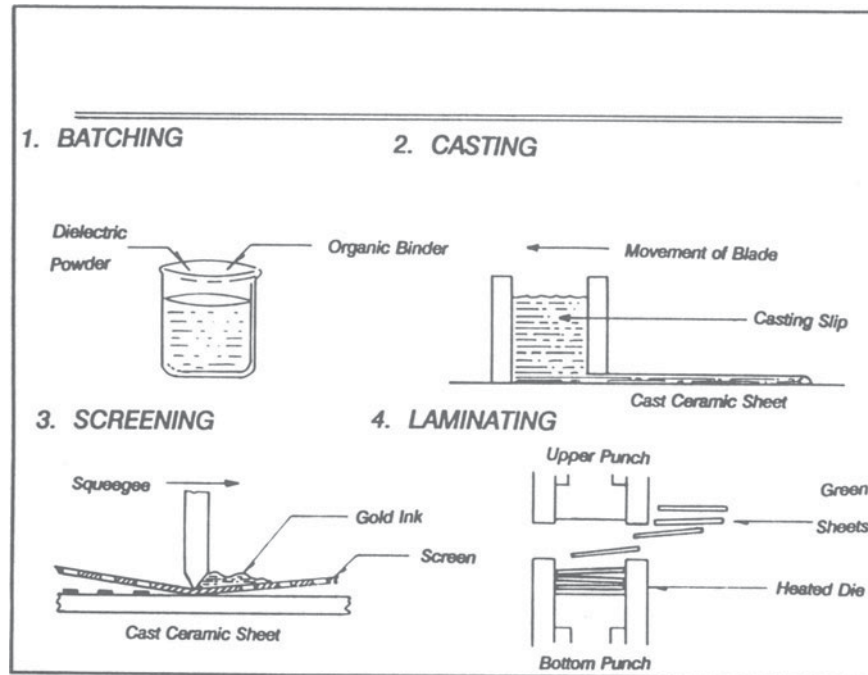


Figure 6-2 Cofired ceramic process steps.

dielectric layers in the TTRAN process [1]. Sheets of dielectric tape, with preformed vias, are registered and laminated to fired 96% alumina substrate at a fixed temperature and pressure. Since the tape adheres to the substrate it does not shrink in the x- or y- direction, but does shrink in the z-direction. Figure 6-6 compares the TTRAN process sequences to thick film processing for a single level of a multilayer circuit. Notice that fewer process steps are required when tape processing is used relative to thick film processing. It takes three or four individually printed and fired layers of thick film dielectric ($15\ \mu\text{m}$ - $25\ \mu\text{m}$ thick per layer) to replace a single sheet of 3 mil ($75\ \mu\text{m}$) thick tape laminated to a substrate and fired. The TTRAN process is lower cost and has higher yields relative to conventional TFM circuits [2]. Since it is fired on an alumina substrate, it exhibits superior mechanical and dimensional control compared to LTCC.

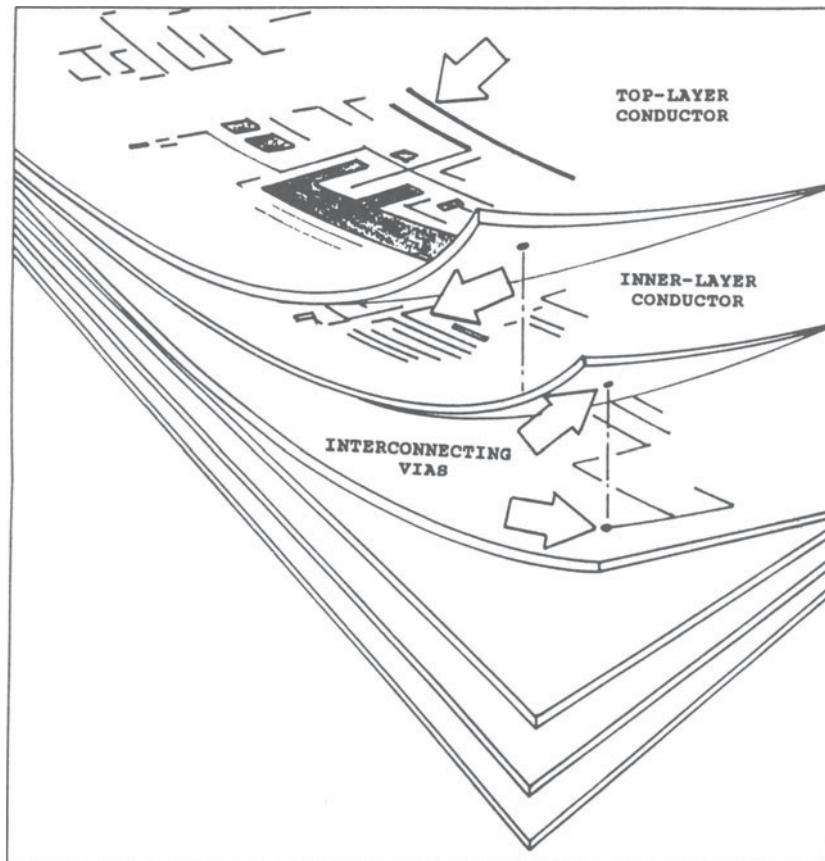


Figure 6-3 Exploded view of cofired ceramic structure.

6.1.2 General Comparison of MCM-C Technologies

The major difference between TFM MCMs and HTCC or LTCC MCMs, other than the fact that a substrate support platform is required for TFM circuits, is that thick film parts are processed serially, layer by layer. Each conductor level of a multilayer circuit may require as many as six printing steps and firing operations per level. This consists of three (sometimes four) individually printed and fired layers of dielectric, two via fills and the conductor. A similar structure

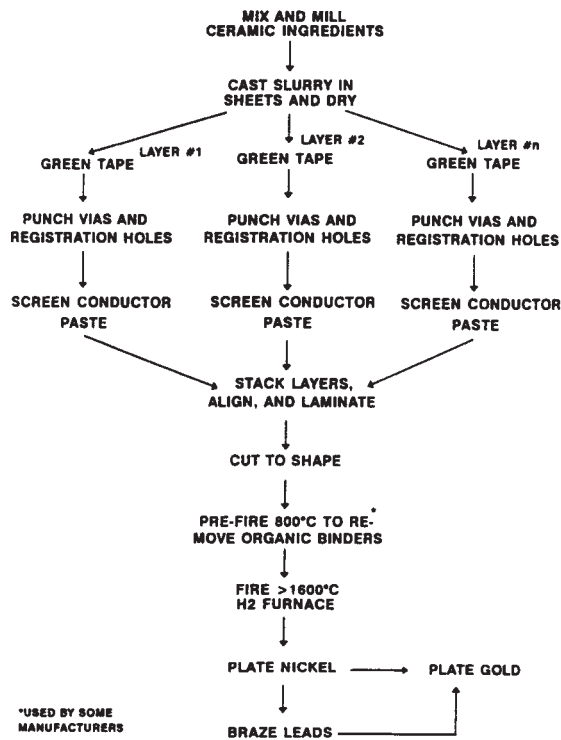


Figure 6-4 Process sequence for HTCCs.

using the cofired technology requires only a single step to fire all the laminated layers and then possibly three or four post firing process steps. The three technologies are described in Table 6-1.

In the cofired ceramic technologies, the substrate and the package form a single monolithic structure. The HTCC or LTCC package is usually sealed hermetically by attaching a metal lid to a metal seal ring which was previously soldered or brazed to the substrate. In contrast, surface mounted devices on TFM substrates are not hermetically sealed, so the substrate must be mounted into a package or the devices must be passivated in some other manner. Standard thick film sealing techniques can be used to attach the lid. Another possibility is to make an all ceramic package by forming a ceramic sidewall, integral to the package, during fabrication of the structure. Again, a metal lid can be attached to the ceramic sidewall to provide hermeticity. For high density applications, cavities can be manufactured in both the high and low temperature

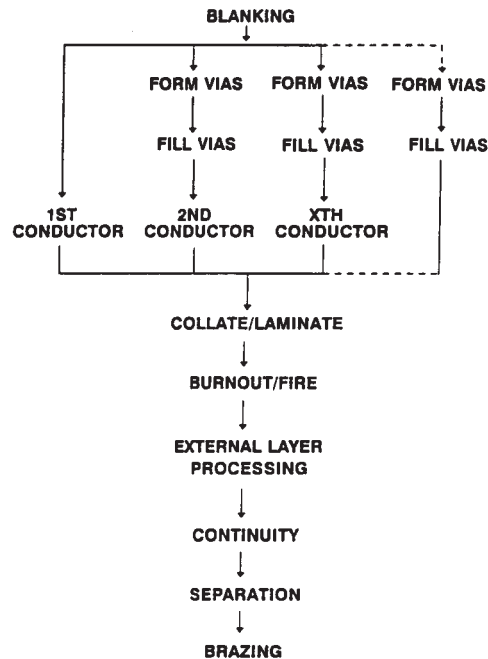


Figure 6-5 Process sequence for LTCCs.

ceramic structures to accommodate active and passive devices. When cavities are used, multiple bond shelves or ledges are used to fanout fine pitch bond fingers (pads) so that wire or tape automated bonds (TAB) can be made easily and reliably. Figure 6-7 shows a cofired package demonstrating multiple bond shelves. Tables 6-2a and 6-2b compare the three MCM-C technologies in terms of the technology options and the mechanical and electrical characteristics.

These tables show that LTCC MCM-Cs have a number of advantages over HTCC modules. One advantage is the use of high conductivity metals such as gold, silver or copper for the LTCC technology in place of the tungsten metal required for HTCC. Gold and silver do not oxidize to any great degree so they do not have to be plated to protect the metal. This is not the case when copper is used. Another big advantage of LTCC is that the basic ceramic substrate can be modified to provide any number of combinations of dielectric materials with different electrical and physical properties. For example, the dielectric constant can be varied between 4 and 400 and the coefficient of thermal expansion (CTE) can be designed to match silicon, gallium arsenide, or alumina. Finally, the same

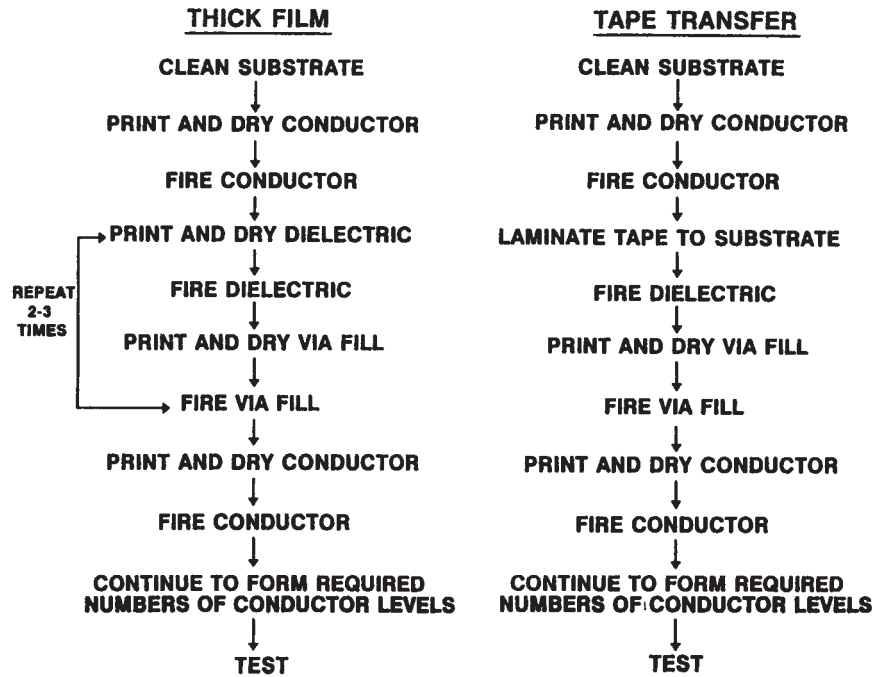


Figure 6-6 Fabrication process flow for thick film multilayer circuit: Comparison between thick film and tape transfer.

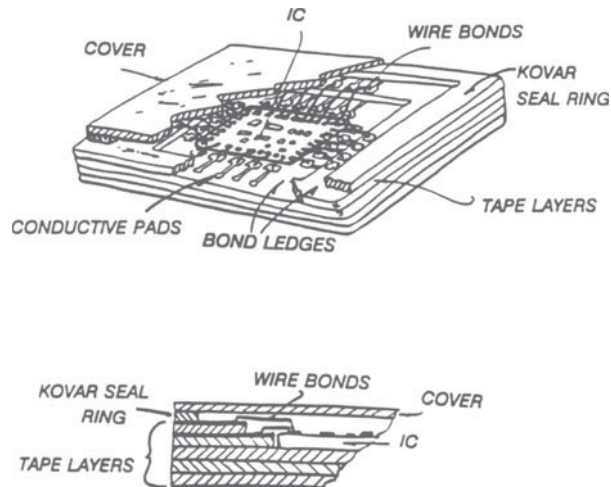


Figure 6-7 MCM-C package demonstrating the use of multiple bonding ledges.

Table 6-1 Comparison of Characteristic Differences of MCM-C Technologies.

MULTILAYER THICK FILM	LTCC	HTCC
• Requires a mechanical support base • Serial processing • 6 prints per layer (3 dielectric, 2 via fill, 1 conductor) • 60 sequential firing steps for up to 10 layers • Must protect devices	• Monolithic structure • Parallel processing • 2 prints per layer (1 via fill, 1 conductor) • 1 cofire step plus three postfire steps • Hermetic package	
	• Fires at 850°C • Uses standard thick film conductors—gold and silver • Fires in air • Standard thick film processing time • Tailorable dielectrics	• Fires at 1600°C • Requires refractory metals—tungsten and molybdenum • Fires in hydrogen • Long processing time to remove organics • Uses alumina dielectric

thick film resistor and capacitor materials developed for standard thick film circuits can be adapted to LTCC circuits. Both buried and surface resistors and capacitors have been designed into LTCC parts [3].

Tables 6-2a and 6-2b also show some advantages in the use of high temperature cofired MCMs. HTCC is a mature technology; its materials and processes are better understood. Also, alumina has a much higher mechanical strength than LTCC dielectric materials, making packages stronger and more durable. Finally, the thermal conductivity of alumina is almost 20 times higher than that of the basic LTCC dielectric materials.

Table 6-2a Feature Benefit Matrix for Multilayer Thick Film, HTCC and LTCC: Technology Characteristics. (Ranking order; 1 = best.)

Feature	Thick Film	HTCC	LTCC	Benefits
1. Mature materials and processes	1	1	3	Higher yields
2. Shorter proof of design cycles	3	3	1	Faster response to design changes
3. Lower nonrecurring expense (NRE)	1	3	1	Lower prototype costs
4. High print resolution	3	2	1	High frequency application
5. Unlimited number of layers	3	1	1	Highest possible circuit density
6. Postfiring process	1	3	1	Conventional thick film material
7. Wide processing options	2	3	1	Greatest design flexibility
8. Brazing	N/A	1	2**	Network and package processes
9. Tight process controls	2	3	1	Improved overall yield
10. Accommodates chip wire and surface mount assembly	1	1	1	Design flexibility
11. Cavities	3	1	1	Multiple bonding shelves

** Low temperature braze.

Table 6-2b Feature Benefit Matrix for Multilayer Thick Film, HTCC and LTCC: Mechanical and Electrical Characteristics. (Ranking order; 1 = best.)

Feature	Thick Film	HTCC	LTCC	Benefit
1. Camber	2	2	1	Improved wire bond assembly yield
2. Surface roughness	3	2	1	Better high frequency performance
3. Top layer dimensional stability	1	3	2	Improved wire bond, assembly yield stability
4. CTE matched to alumina or silicon	2**	3	1	Capability of assembly
5. Thermal conductivity	2	1	3***	Good thermal characteristics
6. Hermeticity	2	1	1	Development of packages
7. High conductivity metallization	1	3	1	Smaller line and space designs
8. Low K values	1	3	1	Improved high frequency performance
9. Excellent dielectric control	3	1	1	More consistent electrical performance
10. High mechanical strength	2	1	3	More rugged package

** Varies with substrate material.

*** Thermal via designs enhance thermal conductivity.

6.2 MATERIAL CONSIDERATIONS

6.2.1 Thick Film Technology

Substrates

A substrate is the base onto which all thick film circuits are printed. It provides mechanical support, electrical insulation and assists in dissipating heat. Substrates can be obtained in various shapes, sizes and thicknesses. The shape

Table 6-3 Common Substrate Materials by Application.

SUBSTRATE TYPE	APPLICATION
Alumina 99+%	Thick/thin film circuits Microwave integrated circuits
96% (glass)	Thick film single/multilayer circuits
85% - 94% (glass)	Refractory thick film/cofired circuits
40% - 60% (glass)	Thick film/LTCC
Beryllia	Thick/thin film power circuits
Aluminum Nitride	Thick/thin film power circuits Refractory thick film circuits

can be pressed and fired to meet a variety of configurations or laser scribed to size specification. Sizes may range from 1" × 0.33" up to 6" × 13" and from 0.010" - 0.060" thick. For special applications thicknesses as great as 0.125" can be made. Because of the variation in available sizes, circuits can be processed in a multiple-up format, scribed and singulated (separated) in subsequent operations to improve handling efficiencies. Substrates may be laser drilled to permit use of the other side of the substrate, with connections made using through-hole technology. Substrates and their applications typically are defined by the amount of glass contained in the ceramic body. For example, a 99+% alumina substrate is used for thin film circuits and for high frequency applications, while HTCC bodies range from 85 - 94% alumina, and LTCC formulations from 40 - 60% alumina. The majority of thick film circuits are printed on 96% alumina because it provides the best compromise of cost, strength, resistor stability and conductor adhesion. Table 6-3 summarizes commonly used substrate materials by their principal application. Table 6-4 lists the advantages and disadvantages of these same substrate types.

Most substrates used in the electronics industry are alumina; however several other ceramic materials have found limited application based on their specific material properties. Beryllia (BeO), one such material, has one of the highest thermal conductivities of any ceramic material and is used most widely for high power handling applications. A major consideration in using BeO is its toxicity. Special handling is required for its use in certain processing steps. Also, thick film materials specifically formulated to match the properties of the ceramic must be used, since adhesion promoters used with alumina do not work with BeO.

Table 6-4 Advantages and Disadvantages of Substrates for Thick Film Circuits.

SUBSTRATE TYPE	ADVANTAGES	DISADVANTAGES
99+% Alumina	Low microwave loss High strength Good stability for resistors Good thermal conductivity No alkali migration—low loss Good surface finish	High cost Low conductor adhesion
96% Alumina	Lower cost High strength Good stability for resistors Good conductor adhesion	Higher microwave loss
Beryllia	Highest thermal conductivity	High cost Requires special thick film materials Toxic
Aluminum Nitride	High thermal conductivity Low CTE	High cost Requires special thick film materials

More recently another ceramic material, aluminum nitride (AlN), has come into wide use. AlN has some very unique properties that make its use highly desirable [4]. AlN, like BeO, has a very high thermal conductivity. Since the thermal conductivity of AlN increases with temperature, unlike BeO which decreases with temperature, AlN is a better material for high power applications. Additionally, AlN has none of the toxicity problems associated with BeO. Another desirable property of AlN is its close coefficient of thermal expansion (CTE) match to silicon. This means that it is more compatible with the large silicon devices that are being designed into MCMs. A great deal of research and development time has been spent to attach AlN to both MCM-D (deposited) substrates and LTCC MCM-C structures thus taking advantage of the thermal benefits of AlN [5]. Table 6-5 shows some of the electrical and mechanical properties of substrate materials, including AlN, used in hybrid applications.

Conductors

Thick film conductors are made from mixtures of metal powders, small amounts of vitreous or oxide powders and an organic phase that determines the printing

Table 6-5 Properties of Commonly Used Ceramic Substrate Materials.

PROPERTIES	MATERIALS			
	AlN	BeO	Al ₂ O ₃	Al ₂ O ₃
Purity	98 - 99.8%	99.5%	96%	99.5%
Color	Dark gray to translucent	White	White	White
Density (g/cc)	3.255	3.01	3.70	3.87
Specific Heat (cal/g°K)	0.177			
Thermal Conductivity (W/m-k) at 25°C	80 - 260	250 - 260	20 - 35	20 - 35
CTE (10 ⁻⁶ /°C) (25°C - 400°C)	4.4	9.0	7.1	7.6
Dielectric Constant at 1 MHz	8.8 - 8.9	6.5	9.5	9.9
Dielectric Loss Tangent at 1 MHz	0.0007 - 0.0020	0.0004	0.0004	0.0001
Resistivity (Ω-cm)	> 10 ¹³	10 ¹⁵	10 ¹⁴	10 ¹⁴
Dielectric Strength (kV/mm)	10 - 14	9.5	26	24
Flexural Strength (N/mm ²)	280 - 320	170 - 240	250	400

Note: CTE (25°C-400°C) for Si = $3.35 \times 10^{-6}/^{\circ}\text{C}$, for GaAs = $5.73 \times 10^{-6}/^{\circ}\text{C}$.

characteristics of the ink or the paste. In most cases the conductor inks are designed to be fired between 850°C and 950°C. The glass or oxide constituents of the ink are developed so that they react with the substrate and form a glass or oxide bond. This reaction provides the adhesion mechanism critical to the performance and reliability of the electrical circuit. The main function of a thick film conductor is to provide the electrical connections between different points in the circuit. Conductors also are used as resistor terminations to provide low contact resistance, as capacitor electrodes, as attachment pads for active and passive devices and as low value resistors.

Most commonly used thick film conductors fall into two categories: noble metals that can be fired in air, and non-noble metals that must be fired in an inert or reducing atmosphere. The noble metals include platinum, palladium, silver and gold, as well as binary and ternary mixtures of these metals. The non-noble metals include copper, aluminum and nickel. Of the non-noble metals only copper plays a major role in thick film technology.

Critical parameters characterizing a conductor are its conductivity, solder wettability, solder leach resistance (the ability of a conductor to not dissolve in the solder), adhesion and wire bondability. Good adhesion to the substrate is the one property required of all thick film conductors. A great deal of time and effort has gone into improving adhesion.

There are three basic mechanisms of adhesion between the substrate and the metal: glass bonding (fritted), oxide bonding (fritless) and mixed bonding. Fritted conductor systems add small amounts of low melting point glass powder to the metal. The glass powder, typically a lead borosilicate, melts during the firing process and wets both the particles of metal and the substrate. If too much glass is added, excess glass can float to the surface and cause problems with soldering and wire bonding. If not enough glass is used, adhesion is reduced.

Fritless adhesion mechanisms were developed originally for use with air fired gold formulations but were quickly adapted for use in nitrogen atmospheres and with copper conductors. In fritless conductors the glass is replaced by small amounts of copper oxide. During firing the copper oxide reacts with the alumina substrate to form a spinel (copper aluminate) structure that creates a chemical bond between the substrate and the metal. Too much oxide in the formulation will result in an oxide layer on the surface of the copper, reducing solderability and wire bondability. Too little copper oxide reduces adhesion. In many cases manufacturers plate the top copper layer with gold to eliminate problems associated with oxide formation.

A mixed bonded system produces the best of both worlds. By using both oxide and glass, the amount of each can be reduced, minimizing the deleterious effect of too much of either additive. Typically, better adhesion and improved wire bond strength are obtained with mixed bonded conductors.

Table 6-6 Comparison of Key Conductor Metals for Thick Film Circuits.

PROPERTIES	SILVER	COPPER	GOLD
Conductivity	Excellent	Excellent	Excellent
Resistor Compatibility	Good	Good	Excellent
Print Definition	Good	Moderate	Excellent
Solder Leach Resistance	Poor	Excellent	Poor
Wire Bondability	Good*	Good*	Excellent
Processing	Very good	Moderate	Excellent
Cost	Very low	Low	High

* Aluminum wire

Three metals (gold, silver and copper) have found widespread use in thick film conductor inks used to make hybrid circuits. In addition, metals such as platinum and palladium have been added to the gold and silver, in either binary or ternary combinations, to enhance specific properties such as solderability and solder leach resistance. The properties of these materials are compared in Table 6-6.

Gold is useful because it is an inert metal and does not oxidize during subsequent processing steps. It is also highly conductive, and easily wire bondable. Active devices can be attached readily and reliably to gold pads on the substrate. The biggest drawback to the use of gold is its cost. Gold is approximately 10 to 20 times more expensive than silver or copper. Additionally, gold leaches (dissolves) readily with commonly used solder and is not typically used where soldering is required. If soldering is necessary, gold/tin solder can be used. Gold conductors find their greatest application where high reliability is an issue, particularly for military, medical and space related requirements. The addition of varying amounts of platinum and palladium to gold will improve the adhesion and the solder leach resistance at the expense of conductivity and wire bondability.

Silver is used in place of gold specifically where cost is an issue. Silver has a higher conductivity than gold and has lower losses at microwave frequencies. The biggest drawback to the use of pure silver in hybrid circuits is that it will

migrate in the presence of voltage, humidity and ionic contaminants if not passivated properly. This electromigration of silver has precluded its use in many military and high reliability applications. Silver over time will tarnish making for more difficult soldering and bonding. While pure silver conductors leach readily, they have a significantly higher leach resistance to commonly used solders such as 62 Sn/36 Pb/2 Ag than do gold conductors. Components can be solder attached reliably to silver conductors for many applications. The addition of platinum or palladium improves solder leach resistance and inhibits migration, but lowers conductivity and increases cost. Silver bearing thick film conductors are used mostly for commercial circuits and as capacitor and resistor terminations. If silver is buried within a hermetic material, so that moisture or ionic contaminants are not present, no migration can take place [6-7].

A copper thick film technology was developed because of the high cost of gold and the reliability related issues of silver. Even though copper will oxidize, it is migration resistant and, therefore, acceptable for military and high reliability applications. Some advantages of copper are its high electrical conductivity, its low loss at microwave frequencies and its low cost. Values for all of these properties fall between those of gold and silver. The overall fabrication cost of copper circuits includes the additional cost of nitrogen gas. As mentioned previously, copper will oxidize, so the surface needs to be protected, usually by plating with gold. The plating process also adds labor costs to the product.

Dielectrics

A dielectric material is a material that does not conduct electricity. In the strictest sense of the word, a dielectric refers to a material used in a capacitor. An insulator is a material that provides electrical isolation between conductive circuit elements. In the microelectronics industry the two terms have become synonymous. Thick film dielectric inks are mixtures of dielectric powders and an organic vehicle. The dielectric portion of the ink may be a low melting point glass, a mixture of glass and ceramic powders or a crystallizable material. As with thick film conductors, the organic portion of the ink defines the rheological characteristics and determines how well the ink prints. There are five major applications or uses for dielectric inks in a hybrid circuit: crossovers, insulating layers in multilayer circuits, capacitors, encapsulation, and hermetic seals. The critical properties that define whether a dielectric material can be used in a given application are the temperature and frequency and voltage response of its dielectric constant, dissipation factor, insulation resistance and dielectric breakdown voltage.

Crossover Dielectrics. The crossover dielectric is a low dielectric constant insulating material used in single layer thick film hybrid circuits to separate two conductor traces or lines. A crossover configuration allows the production of the

simplest type of three dimensional circuit. Crossover dielectrics are designed to separate conductors occupying the same location on the substrate, effectively increasing the available circuit area. The first crossover dielectrics were made from low melting point glasses such as lead aluminum borosilicates and were designed to be compatible with conductors fired around 850°C. Additionally these materials had to match the CTE of the substrate so that stresses were minimized during the processing of the hybrid circuit. It is important to be aware of some of the problems that can occur when using glass crossovers in a hybrid circuit. For example, depending on the number of times the glass is fired, reactions between the glass and the conductor can result in short circuits. Excessive flow of the glass can cause swimming (movement) of the conductor, possibly distorting the printed pattern.

Because of these problems, glass-ceramic formulations were developed to replace glass dielectrics. Glass-ceramic materials are made as a glass, printed and then crystallized during the firing process. The crystalline phase that forms is dispersed uniformly throughout the glassy matrix so that the resultant material has very uniform properties. The crystalline material has a higher softening point than the parent glass and is stable under multiple refirings as long as it is not fired higher than the original processing temperature. Another major advantage is that glass-ceramic crossovers have less tendency to form pinholes, minimizing short circuits. The glass-ceramic materials do not react with conductor materials to the same extent as their glassy counterparts. Other terms synonymous with glass-ceramics are crystallizable and devitrifying glasses.

Multilayer Dielectrics Once a hybrid circuit with crossovers has been designed and built there is no more area available on the substrate to increase the circuit density. Circuit density may be increased by increasing the size of the substrate, by printing on two sides of the substrate or by building a multilayer circuit. Since the latter has the fewest limitations, circuit designers have long been designing their hybrid circuits with multiple layers. By definition a TFM circuit is one containing multiple internal conductor traces separated by insulating dielectric layers.

Electrical connections between layers are made through vias in the dielectric filled with conductor. The same technical issues (of using glass-ceramic materials with the crossover dielectrics) presented even more serious challenges in making multilayer circuits. Material requirements for multilayer dielectrics are demanding due to the multiple firing steps required in processing. Glass-ceramics make the best multilayer dielectrics. As mentioned in the previous section, these stable materials limit problems such as blistering, conductor reactions and shorting. One common problem with devitrifying multilayer dielectrics is the incompleteness of the crystallization process during the first firing

step. Crystallization will continue through additional firings and the CTE of the layers may change making it difficult to control the CTE of the composite.

A glass-ceramic material developed for a multilayer circuit application must have certain properties that are not required when used as a crossover material. For example, because the overall thickness of the multilayer dielectric can be quite large and screen printed to cover the whole substrate, the dielectric material must have a CTE closely matched to the alumina substrate. Mismatch produces excessive substrate camber, making it difficult to print additional dielectric layers, to attach devices to the surface and to mount the substrate to a heatsink or to a package base. The via holes must remain open to allow electrical connections between the layers. Finally, the fired dielectric material should have a very good surface finish so that fine line patterning of the conductors is possible.

Capacitor Dielectrics As mentioned above, dielectrics also can be used as capacitors, but not so much in MCM applications. Typical materials are combinations of barium titanate (BaTiO_3) and glass to lower the firing temperature. Thick film capacitors for resistor capacitor (RC) networks or as blocking or bypass capacitors have dielectric constant values ranging from 20 - 2000. Typically they are porous and have poor mechanical integrity, but serve the purpose for which they were developed. Low firing (850°C - 1000°C) crystallizable capacitor formulations, called relaxor dielectrics, have been developed, which have very high dielectric constants ($> 20,000$).

Resistors Thick film resistors have been used in the microelectronics industry for over 40 years in applications ranging from simple resistor networks to printed resistors as part of very complex multilayer circuits. Most of the modern thick film resistor inks are combinations of heavy metal (lead or bismuth) ruthenate compositions or ruthenium dioxide dispersed in a glassy matrix. As with other thick film inks, these active ingredients are mixed with an organic vehicle that defines the printing characteristics of the ink. Resistor inks are usually formulated in a series of decade values ranging from $1\ \Omega/\square$ to $1\ \text{M}\Omega/\square$. The individual decade value inks, called end members, are blended in varying proportions to obtain resistivity values between those specified by the end members. The actual resistivity range is determined by the type of resistive element in the ink and by the ratio of this material to the glassy phase. When fired, (typically to 850°C) the glass softens and wets the resistive material and substrate. Typical electrical parameters of resistor inks are given in Table 6-7.

Resistor values, for design purposes, are determined by the equation shown in Figure 6-8. The key terms in the equation are sheet resistivity ($\Omega/\square$) and number of squares (defined as the resistor length divided by the resistor width). The resistance can be determined from this equation if the geometry of the resistor and the value of the ink are known. Thickness of the printed resistor is

Table 6-7 Typical Fired Resistor Properties¹.

Sheet Resistivity ² ($\Omega/\square$)	TCR ² (ppm/ $^{\circ}$ C)	Short Term Overload Voltage ³ (V/mm)	Standard Working Voltage ⁴ (V/mm)	Maximum Rated Power Dissipation ⁵ (mW/mm ²)	Blendable Series
10 $\pm$ 20%	0 $\pm$ 100	45	1.8	320	A
100 $\pm$ 20%	0 $\pm$ 100	22	9	810	A
1k $\pm$ 20%	0 $\pm$ 100	62	25	625	A
3k $\pm$ 20%	0 $\pm$ 100	77	30	300	A
3k $\pm$ 20%	0 $\pm$ 100	90	36	430	B
10k $\pm$ 20%	0 $\pm$ 100	145	58	340	B
100k $\pm$ 20%	0 $\pm$ 100	245	98	96	B
1M $\pm$ 20%	0 $\pm$ 100	310	124	15	B

¹ Typical resistor properties based on laboratory tests using recommended processing conditions; termination - DuPont Pd/Ag Conductor 8134 prefired over DuPont Dielectric 5704 at 850°C; substrate - 96% alumina; printing - 200 mesh stainless steel screen (8 μ m - 12 μ m; firing 30 minute cycle to peak temperature of 850°C for 10 minutes.

² Shipping specifications. Resistor geometry - 1.5 mm $\times$ 1.5 mm. Temperature coefficient of resistance - 55°C to +25°C to 125°C.

³ Short term overload voltage - tested under military specifications of MIL-R-83401D, Paragraph 3.15.

⁴ Standard working voltage - 0.4 $\times$ short term overload voltage.

⁵ Maximum rated power dissipation. $\frac{(\text{Standard Working Voltage})^2}{\text{Resistance}}$

another important factor affecting sheet resistivity. Values can be increased or decreased by varying the thickness of the printed resistor.

6.2.2 High Temperature Cofired Ceramic Technology

Dielectric Materials

The common dielectric material used to fabricate HTCC substrates or circuits is alumina with varying amounts of glass. Depending on the application, the percentage of alumina may vary from 88 - 96% but typically falls between 92 - 96%. Because of the maturity of this technology, the properties of both the raw materials and the fired ceramic have been well characterized. Table 6-8 shows

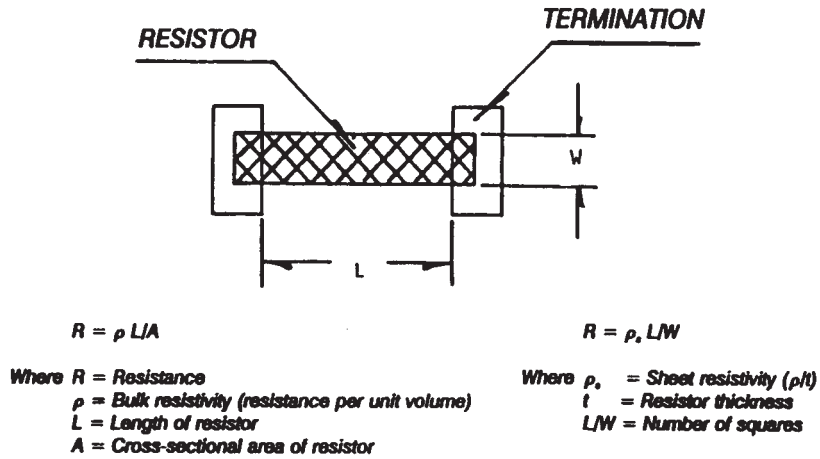


Figure 6-8 Equation to calculate resistance.

the key physical and electrical properties of fired alumina ceramic material. The critical parameters to note are flexural strength (which relates to the ability of the ceramic to withstand bending forces) and thermal conductivity. These properties differentiate HTCC dielectric materials from LTCC dielectric materials.

Conductors

All of the processing parameters for HTCC circuits are established by the fact that the alumina dielectric is a refractory material and must be sintered at approximately 1600°C. This limits the selection of conductors to high temperature metals such as tungsten and molybdenum. The thick film inks used for conductor traces and as via fills have been modified to match the sintering temperature and shrinkage rate of the alumina body. Since tungsten and molybdenum both oxidize readily in air, any exposed metal must be plated to protect the conductor surface. Typically two different metals are plated sequentially to achieve the best results. Nickel is plated first for solderability and brazability. Gold is then applied to keep the nickel from oxidizing so that reliable gold wire bonds and soldered leads can be formed. Both electrolytic and electroless nickel plating is used, but gold is usually plated electrolessly. Plating is a process that is not required by the other two MCM-C technologies. Also, the relatively high resistivity of tungsten and molybdenum metals is a limitation on their use for high speed, high frequency applications.

6.2.3 Low Temperature Cofired Ceramic Technology

Dielectric Tape Materials

The driving force in developing a low temperature cofired process was the use

Table 6-8 Physical and Electrical Properties of Ceramic Material for HTCC Multichip Modules.

Composition	92% - 96% alumina
Color Available	White or black
Flexural Strength	55,000 psi (380 N/mm ²)
CTE 25°C - 200°C	$6.3 \times 10^{-6}/^{\circ}\text{C}$
Thermal Conductivity at 100°C	15 W/m-K
Volume Resistivity at 25°C	10^{14} ohm-cm
Dielectric Constant at 25°C	8.9
Hermeticity	1×10^{-8} cc/sec

of the high conductivity metals and thick film processing. The alumina dielectric used in the HTCC process was replaced with dielectric materials that fire below 1000°C, specifically around 850°C. Such materials were available from TFM circuit technologies. Standard thick film dielectric formulations in tape form became the basic building block for developing the LTCC technology. The low temperature dielectric allowed standard thick film materials and processes to be used when manufacturing LTCC MCMS.

Two basic types of dielectric materials are used in LTCC fabrication today. These are alumina filled glasses and crystallizable ceramics [8]. In the alumina-filled glass, glass softens and wets the alumina powder during firing, providing a dense hermetic structure. Most of the critical parameters of the fired composition, such as firing temperature, CTE, mechanical strength and thermal conductivity, are dictated by the nature and properties of the glass. Most typically the fired properties are designed to match the CTE of standard alumina ceramics. They are also designed to have dielectric constants from 6 to 9. Another benefit of using alumina filled glasses is that the glass softens during firing, allowing the dielectric to conform to the setter on which it is fired. The finished part can be extremely flat. Alumina filled glass dielectric tape, Green Tape®, is available from Dupont. Other thick film suppliers, such as ESL and EMCA, also manufacture and sell tapes.

Another dielectric formulation is a glass-ceramic or crystallizable material, a magnesium aluminum silicate, called cordierite [8]. As discussed in Section 6.1.2, glass-ceramic materials exhibit many of the same advantages over alumina

filled glass type formulations. For example, LTCC modules made from glass-ceramic materials are much less sensitive to the adverse effects of multiple firings. This is advantageous when parts are subject to additional postfiring steps. Also, the ceramic does not soften when fired as much as alumina filled glass parts soften. Glass-ceramic dielectric tapes are available from Ferro and Dupont. Different variations of commonly used LTCC dielectric materials and their electrical and physical properties are shown in Table 6-9.

The most significant feature of the cordierite glass-ceramic system is its stability when fired in nitrogen for use with copper conductors. Another process [9] is the firing of the LTCC/copper laminate in a steam-hydrogen gas mixture instead of in a nitrogen-oxygen gas mixture. The steam-hydrogen firing atmosphere ensures that a proper range of oxygen potentials exists, at the temperatures of interest, to remove completely carbon residue and to allow complete densification of the glass-ceramic without oxidizing the copper.

Conductors

The use of thick film dielectric formulations for the tape allows the use of the high conductivity conductors such as gold, silver and copper to make the LTCC MCMs. Most of the work has been with gold conductors.

Cofired top conductors, inner layer and via fill golds are available which eliminate registration problems associated with nonuniform fired shrinkage. Shrinkage variations are eliminated by printing the top conductor either on an un laminated sheet of tape or on the laminate prior to firing. The number of processing steps, the process time, and the cost of the finished part are all reduced by cofiring all of the top layer metallizations.

Gold conductors available from commercial suppliers exhibit physical properties that are comparable to their thick film counterparts. Gold materials have been tested and have been shown to exceed Mil Spec requirements for 1.0, 1.5 and 2.0 mil gold wire bond adhesion. These same conductors also have been tested and passed requirements for TAB applications. See the discussion in Section 9.4.

LTCC modules must also interface to other modules. A low temperature brazing capability (the joining of two metals together using a filler material with a lower melting temperature than either of the base metals) has recently been developed using either gold/tin solder or gold/indium solder [10]. Brazing allows reliable attachment of leads and seal rings giving the LTCC technology a packaging capability. Figure 6-9 shows an example of an LTCC module with brazed leads (25 mil pitch) and a brazed Kovar seal ring demonstrating the capability of manufacturing packages that can be sealed hermetically. The part is 2.8" × 2.8", made from 10 layers of 6.5 mil tape. There are over 10,000 6 mil electrical vias, 20 mil thermal vias, 5 mil lines and spaces and ground and power planes.

Table 6-9 Physical and Electrical Properties of Common LTCC Dielectric Materials.

Matrix	Fillers	Firing Temp. (°C)	Firing Atm	Dielectric Constant	Tan δ	TCE (ppm)	Shrinkage (%)	Shrinkage Tolerance (%)
BaO-Alumino-Borosilicate	Al ₂ O ₃ Forsterite	850-900	air	5.0-6.5	0.0008-0.002	3.8 - 6.8		
Alumino-Borosilicate	Proprietary	850	air	7.8	0.002	7.9	12	±0.2
Borosilicate	Al ₂ O ₃	900	reducing	5.6		4.0	16	
Pb-Alumino-Borosilicate	Al ₂ O ₃ CaZrO ₃	850	air	9 - 12	0.001 - 0.003		16	
Cordierite	None	925 - 1050	air/neutral	5.3 - 5.7		2.4 - 5.5		
Spodumene	None	850 - 990	air/neutral	5.0 - 6.5		2.0 - 8.3		
MgO-CaO-Alumino-Borosilicate	Al ₂ O ₃	1000	reducing	7.1	0.0025			
BaO, SiO ₂ , Al ₂ O ₃ , CaO, B ₂ O ₃	None	950 - 1000	reducing	6.1	0.0007	8	13.5	
CaO-Alumino-Borosilicate	Al ₂ O ₃	880	air	7.7	0.0003	5.5	16	
Pb-Borosilicate	1) Al ₂ O ₃ 2) Cordierite 3) SiO ₂	900 900 900	air air air	7.8 5.0 3.9	0.003 0.005 0.003	4.2 7.9 1.9	13 13.7 13.9	< 0.3 < 0.3 < 0.3

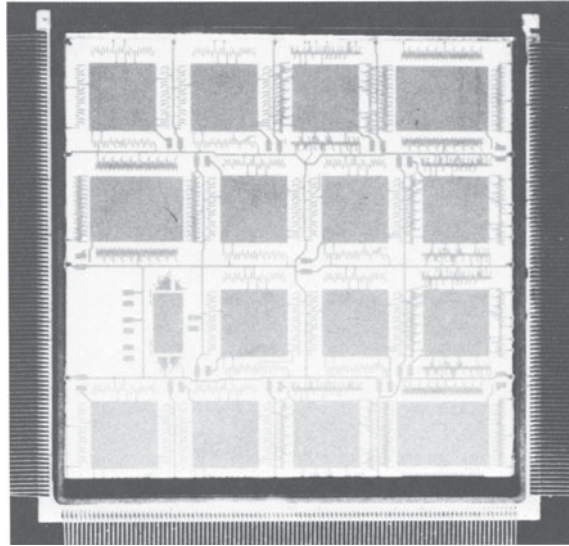


Figure 6-9 LTCC module demonstrating brazed leads and Kovar seal ring.

The full cost advantage of the LTCC technology requires that the expensive gold conductor be replaced with a reliable, lower cost metal. Both copper and silver conductor systems offer possibilities. The silver conductor system is easier to implement, since it can be fired in an air ambient. Formulations of silver and silver/palladium mixtures for inner layers, via fills and top layer conductor formulations compatible with commercially available dielectric tape formulations exist. These systems are used currently to build LTCC modules.

Silver and silver/palladium conductors also can be used on top of the LTCC structure to satisfy wire bonding and soldering needs for commercial applications where humidity is not a major issue. The metal system is not acceptable for military and commercial circuits requiring high reliability. Silver based conductors do not meet the environmental, wire bonding or soldering requirements demanded for those kinds of circuits. Gold conductor must be used where gold wire bonding is needed. For solderability requirements, the best results have been obtained using gold/platinum conductors. A low cost option to gold/platinum is a low firing ($< 600^{\circ}\text{C}$) copper conductor. This type of conductor will meet all of the soldering and adhesion requirements of high reliability circuits without degrading the properties of air fired conductors and dielectrics when fired in nitrogen [11].

Resistors

Resistors currently play a limited role in LTCC designs. The same standard thick film resistor inks developed to use on top of thick film dielectric can be used with the LTCC dielectric layers because the ceramic has already been fired. One problem is that the irregular fired surface makes it difficult to print the correct thickness of resistor. This problem is magnified when very small resistors ($< 0.030" \times 0.030"$) are needed. This nonflat or contoured surface occurs after firing because of differences in compressibility between the printed conductor and the dielectric tape.

A big advantage of the LTCC technology is that buried resistors can be printed and cofired with the rest of the part. This feature allows the MCM manufacturer to reserve more of the surface area of LTCC modules for active devices rather than for passive components. The major drawback to burying resistors is that resistor materials have not been developed fully for this purpose. Reaction with the dielectric tape can occur making it difficult to achieve correct design values. Buried resistors cannot be trimmed easily, so that resistor values must be designed with wide tolerances.

6.3 PROCESSING**6.3.1 Thick Films*****Screen Printing***

Thick film circuits are manufactured with a series of screen printing passes. A flow diagram for processing a TFM circuit is shown in Figure 6-6. The process starts with the development of a thick film layout from the circuit schematic. Layouts are generated typically on a computer aided design (CAD) system. Each print must have its own artwork. From a CAD system, a photoplotter is used to generate the mylar film or glass mask necessary for each screen, even in multiple-up configurations. The artwork positive (the pattern to be printed is dark) is placed against a photosensitive emulsion coating on the proper mesh size screen and exposed, defining the desired pattern. Once the screen is made, it is placed in a screen printing machine and covered with ink. The pattern is aligned to the substrate or to a previous pattern. A squeegee forces the thick film material through the open areas of the screen onto the substrate. The part is then dried and fired. This printing cycle is repeated for each print pass required.

The printing process requires control of a number of key parameters: print head speed, durometer (hardness) of the squeegee, sharpness of the squeegee, angle of attack and snapoff distance. Other parameters needing control are the screen mesh type, the wire diameter, the number of openings per inch, the

emulsion buildup, the emulsion type and the ink viscosity. Screen printing machines may be fed automatically or by hand. Automatic systems may include the use of vision systems to reduce set up time and to optimize printer throughput.

Drying and Firing

After each pattern is printed the ink must be dried to remove organic solvents that give the ink its desired rheological properties. A typical drying temperature is 85°C - 150°C for five to ten minutes. Drying can be done in either a box oven or a continuous belt dryer. The drying process plays a critical role in obtaining the fine line definition required for the circuit. After each printed layer of the multilayer is dried, the part must be fired. Firing is a well defined process and can be accomplished using conventional furnace equipment. A typical thick film furnace profile is shown in Figure 6-10. Most materials are fired to 850°C with a 10 minute dwell time at peak temperature in clean, dry air. Other critical parts of the firing profile are the heating and cooling rates. As the part is heated, the organic binder portion of the ink is burned off, usually by 500°C. From

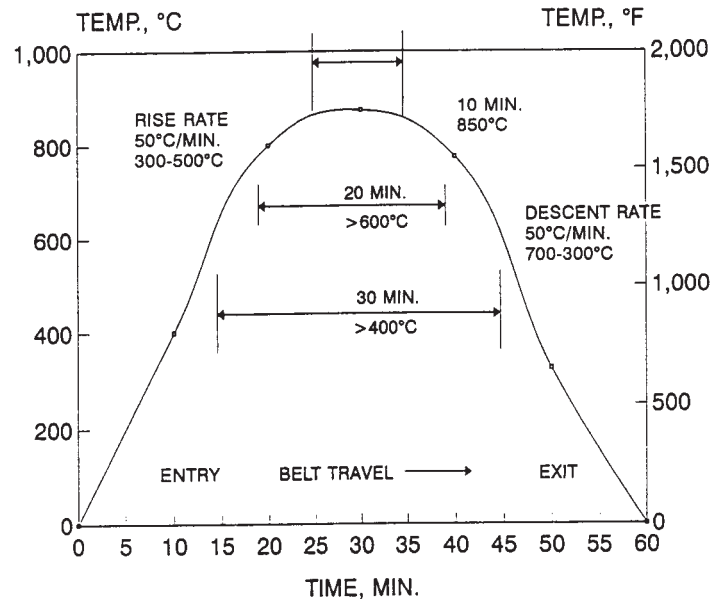


Figure 6-10 Typical thick film furnace profile.

500°C - 850°C any glass or oxide in the paste will soften and react with other elements of the ink or the material on which it is printed (the alumina substrate or a dielectric layer). It is during this part of the profile that sintering and densification occur. The rate of heating is important because it controls how rapidly and how completely the organics are removed. The cooling rate is critical because thermal stresses are set up during cooling. If parts are very large, if the substrate has been laser machined or if there are laser drilled holes, cracking may occur during cooling.

6.3.2 High Temperature Cofired Ceramics

Process Flow

The process sequence for a typical HTCC process is given in Figure 6-4. It begins with the dielectric tape. Initially, each lot of cast tape is inspected for defects such as pits, thin spots and contamination and is characterized prior to use. Tape is cast in thicknesses from 0.004" - 0.025" depending on the electrical and mechanical requirements of the parts being fabricated.

Once the tape is accepted it is blanked (cut into individual sheets) to a standard size using either a blanking die or a computer controlled cutting machine. Each sheet of the tape is punched to form vias, cavities and/or castellations (grooves formed in the edges of the ceramic to aid in solder attach and subsequent inspection). These features can be made using either hard tool punching dies or with computer aided punching machines. After all of the tape machining steps have been completed, the vias are filled with conductor ink and the conductor is printed, both usually with tungsten metal. Typical conductor thicknesses vary from 0.0003" - 0.0005". As with thick film processing each conductor print must be dried prior to performing any additional processing. Next the individual sheets are stacked onto each other and laminated for fixed times, temperatures, and pressures. Laminating pressures can vary from 2000 psi to 4000 psi; laminating temperature varies from room temperature to 100°C depending upon the tape formulation used by each manufacturer. In most cases the completed laminate is scribed and/or cut into individual parts or to the final shape of an individual part.

The individual laminated parts are fired to approximately 1600°C in a reducing atmosphere to sinter the structure and to prevent oxidation of the refractory metals. Firing can be done either in an automatically controlled high temperature box furnace or in large continuous pusher type furnaces. The overall burnout and firing cycle is quite long, 24 to 48 hours. Typical HTCC parts when fired shrink approximately 16% $\pm$ 0.5 in the x- and y-directions and 20% $\pm$ 2 in the z-direction.

6.3.3 Low Temperature Cofired Ceramics

Process Flow

Extensive hands-on labor is required for making LTCC circuits, because of the newness of the technology and the lack of high volume applications. Most manufacturers of LTCC products buy the tape formulated and cast by materials suppliers, which shifts the burden of defining good material to the user. Tape is cast on mylar and stored in this fashion. The first step in the manufacturing process is to inspect the tape for defects, such as pits, holes and contamination. Areas that are not usable are marked and removed from the roll. Then the tape is stripped from the mylar and blanked using steel ruled dies or some type of cutter to a specific standard size such as 5" × 5". Because of problems associated with tape relaxation (shrinkage) after removal of the mylar, the tape goes through a low temperature preconditioning bake to stabilize it. Preconditioning allows the tape to be stored without further shrinkage.

The process sequence for LTCC parts is shown in Figure 6-5. It is very similar to the process flow for HTCC parts. Each sheet is rotated 90° to eliminate any possibility of nonuniform firing shrinkage resulting from tape casting direction. Registration holes and vias are formed in the individual sheets of tape. The vias are filled using specially formulated via fill conductor inks designed to shrink at the same rate as the dielectric material when fired. Conductors are printed using standard screen printing equipment and processes. After printing all conductors, any cavities in the tape are cut or nibbled using an automatic punch. Finished sheets are stacked on a laminating plate over tooling pins. The laminating fixture is placed in a conventional uniaxial laminator or in an isostatic laminator. The typical laminating cycle is 3000 psi at 70°C for ten minutes, but pressures can vary from 2000 - 4000 psi and temperatures from 60°C - 80°C. Isostatic lamination is more advantageous than uniaxial lamination because the same uniform pressure is applied to the whole part, and because parts of varying sizes can be laminated simultaneously.

The part can be fired after lamination using either of two slightly different procedures. The first procedure requires a separate furnace to burnout the organics. After burn out the part is fired in a conventional thick film belt furnace using a profile similar to the one shown in Figure 6-10. The second firing process uses a modified thick film furnace so that burnout and firing can be done as a single step. For this firing process there are two separate temperature holds. The first, typically at 500°C, is the binder burnout step. The hold, typically at 850°C, allows the ceramic material to densify. The single step furnace profile is faster than the two step furnace process, but may not be as desirable for large complex modules. Fired parts typically shrink 12% ±0.2 in the x- and y-directions and 17% ±2 in the z-direction. The tighter shrinkage

Table 6-10 Thick Film Multilayer Design Guidelines.

PARAMETERS	STANDARD	CUSTOM
Substrate Size	< 7" × 7"	> 7" × 7"
Substrate Thickness	> 0.025"	< 0.025"; 0.050"
Maximum Number of Layers	< 8	> 8
Dielectric Thickness	> 0.045 μm	> 0.045 μm
Minimum Line Width	0.008"	0.005"
Minimum line Spacing	0.008"	0.005"
Minimum Via Diameter	0.008"	0.005"

tolerance is a major advantage over HTCC technology. The fired dielectric material, whether an alumina filled glass or a glass-ceramic, is very dense and has proven to be hermetic. Hermeticity is the key material property necessary for developing a low cost silver LTCC process. Moisture will not penetrate the package and buried silver will not migrate since the dielectric is hermetic.

6.4 DESIGN RULES

Well defined design rules exist for both TFM and HTCC technologies since these are both mature technologies. Typical design guidelines for these two technologies are given in Tables 6-10 and 6-11. LTCC is a relatively new technology and is evolving so that design rules are still changing. A typical set of LTCC design rules for circuits being built today is listed in Table 6-12.

When comparing the design rules for LTCC circuits with thick film and HTCC, the number of dielectric layers and the pitch of the printed conductors are the areas of difference. Typically the number of layers is greater and the pitch is lower with LTCC designs. LTCC circuits generally require some additional means to handle thermal dissipation. Since the thermal conductivity of the LTCC dielectric material is much lower than the alumina used for thick film and HTCC, thermal vias or slots are designed into these circuits for power management. The addition of thermal vias increases the thermal conductivity of the LTCC module so that it becomes a thermal equivalent to 96% alumina. An example of a part with thermal arrays is shown in Figure 6-11. This module is

Table 6-11 HTCC Design Guidelines.

PARAMETERS	STANDARD	CUSTOM
Size (max.area)	6"× 6"	6" × 6"
Number of Layers	≤ 15	≥ 15
Layer Thickness	0.010" - 0.025"	0.005" - 0.010"
Tolerances Length and Width Thickness Camber	±0.8%, NLT ±0.004 ±10%, NLT ±0.003 0.003"/", NLT ±0.002	±0.5%, NLT ±0.002 ±5%, NLT ±0.001 0.002"/", NLT ±0.001
Conductor Width	0.007" minimum	0.004" minimum
Conductor Spacing	0.007 minimum	0.004" minimum
Via Diameter	0.007 nom.	0.005" nom.
Via Cover Pad	0.014"8	0.006"
Via Center to Center	0.024"	0.010"
Via Center to Center (with one conductor)	0.034"	0.020"
Sheet Resistivity	0.012 Ω/□	0.008 Ω/□
Via Hole Resistance	0.010 Ω/□	0.005 Ω/□

a MIL STD 883 Group D test coupon, built by CTS Microelectronics Division. It is made from nine layers of 6.5 mil tape and has arrays of 20 mil thermal vias stacked from top to bottom beneath the two large die pads for thermal management. When fully assembled there is 60% silicon coverage of the top surface. This test coupon also demonstrates the ability to print 3 mil lines and spaces.

6.5 APPLICATIONS

Current and future applications for MCM-C can be divided into three major categories: military/aerospace, medical, and commercial.

Table 6-12 LTCC Design and Producibility Guidelines.

Parameters	Preferred Manufacturing	Prototype Manufacturing	Future Development
Maximum Substrate Size (fired)	1.5" × 1.5"	3.5" × 3.5"	12" × 12"
Minimum Line Width (cofired)	10 mil	5 mil	2 mil
Minimum Line Space 8(cofired)	10 mil	5 mil	2 mil
Minimum Line Width (postfired)	10 mil	5 mil	2 mil
Minimum Line Space (postfired)	10 mil	5 mil	2 mil
Minimum Via Diameter	8	6	4
Maximum Layers of Stacked Vias	3	4	6
Maximum Thermal Via Diameter: 4.5 mil thick tape ≥4.5 mil thick tape	15 mil 20 mil	20 mil 25 mil	25 mil/slots 25 mil/slots
Maximum Number of Metal Layers	10	15	25+

The initial development of LTCC MCMs, using commercially available material, was a result of government funded programs. This development is discussed further in Chapter 15 of this book as a case study. The first applications were for memory circuits. LTCC modules were fabricated with over 1 megabyte of memory packaged in a ceramic block less than an inch square.

There is still interest in using MCM-C technology in military electronics, particularly in the areas of microwave and millimeter wave packages. The technology driver here is improved performance and lower cost. LTCC could become the dominant military packaging technology as dielectric materials are modified to perform better at higher frequencies and as the less expensive metals become acceptable.

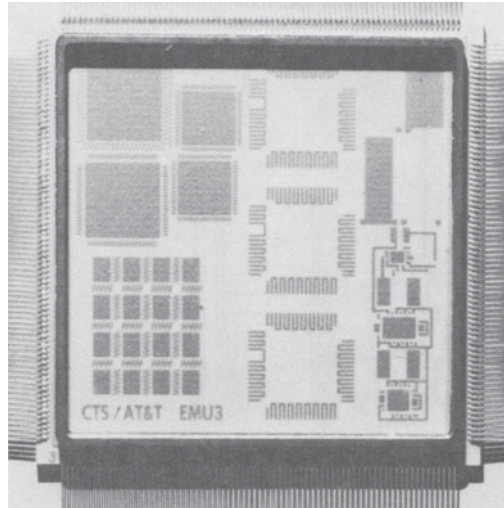


Figure 6-11 LTCC module with thermal arrays. (Courtesy CTS Corporation.)

The medical industry is another industry that has adopted the use of MCM-Cs, in particular, LTCC circuits. These applications require high reliability, reduced weight and smaller packages at lower cost. Large numbers of medical pacemakers, hearing aids and defibrillators are being manufactured using LTCC technology. Figure 6-12 shows a heart pacemaker manufactured for a supplier of medical hybrids. It uses seven layers of 6.5 mil tape and has 900 8 mil electrical vias, 5 mil lines and spaces and is double sided. The hearing aid in Figure 6-13 is manufactured with five layers of 7.5 mil tape and has 10 MΩ, 20% resistors postfired on the surface. This part also is double sided and has a hole punched in it after lamination.

The overall growth in MCM-C usage will be determined by high volume commercial applications, such as occur in the computer, transportation and telecommunications industries. The need for high performance CPUs, microprocessors and memory circuits, combined with the growing popularity of workstations, personal and laptop computers makes the computer industry a critical area of focus. The drive to reduce the size and weight of packages combined with the need for increased electrical performance makes MCM-C packaging technologies ideal for these applications. The electronics requirements of the transportation industry continue to grow becoming a major component in

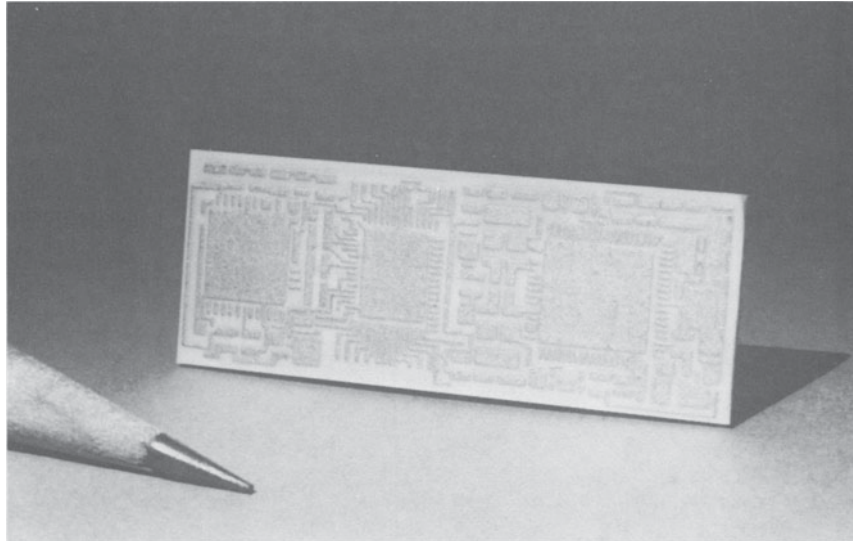


Figure 6-12 LTCC heart pacemaker. (Courtesy Pacesetter Systems Inc.)

the cost of new cars. Some applications include on board computers and collision avoidance radar, as well as electronic sensors to determine brake wear and fuel levels. The part shown in Figure 6-14 is an aircraft antilock brake hybrid circuit made with eight layers of 6.5 mil tape, 8 mil vias and a stepped through cavity. It contains three decade value 1% postfired resistors. All these applications require low cost, small, rugged electronic packages. MCM-C hybrid circuits meet these requirements. MCM-Cs will play a major role in telecommunications, particularly home satellite receivers and their related electrical circuitry, where the requirements are also for low cost, light weight hybrid circuits such as MCM-Cs.

6.6 FUTURE TRENDS

At a recent conference on MCM technology [12] a great deal of discussion took place on the merits and future of each individual MCM technology (MCM-L, MCM-D and MCM-C). Manufacturers of MCM-L made it quite clear that they have the low cost alternative. They claimed that MCM-L would be the technology leader within the next ten years, if advances are made in fine line processing techniques and in methods to handle the thermal dissipation.

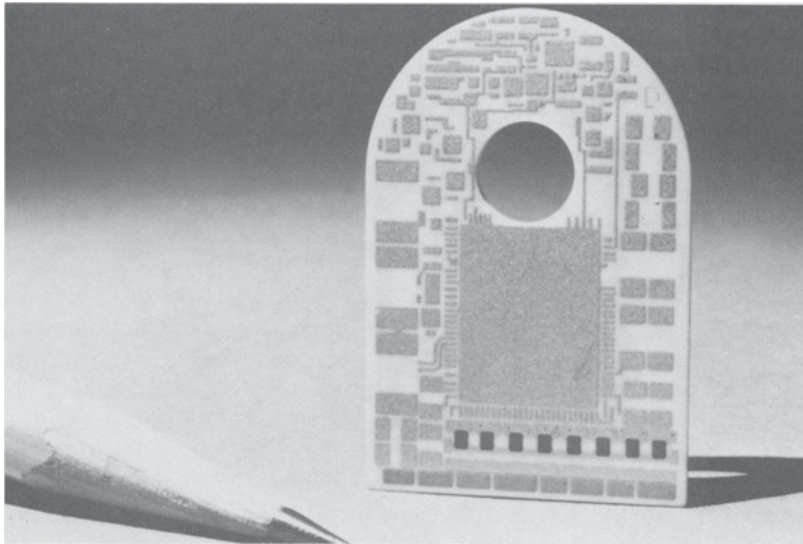


Figure 6-13 LTCC hearing aid. (Courtesy MiniMed Technologies.)

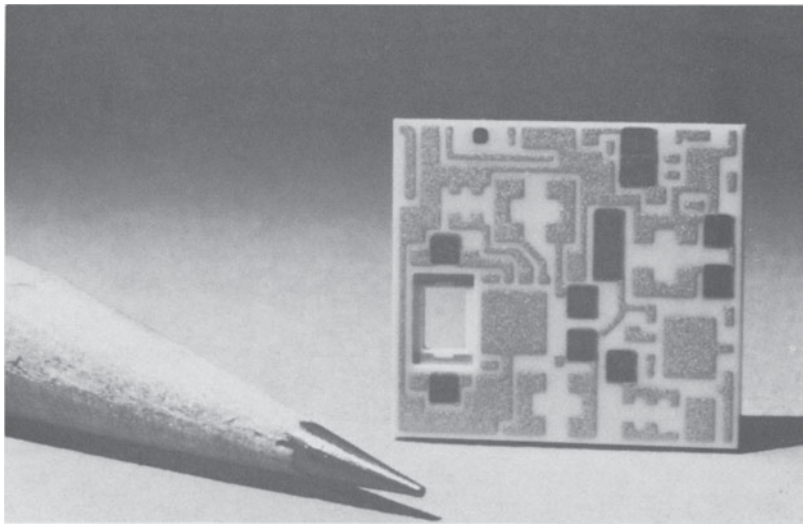


Figure 6-14 LTCC antilock brake substrate. (Courtesy Allied Signal Bendix Engine Controls.)

Engineers and scientists involved with MCM-D argued their case with equal fervor. They pointed to future requirements for high speed, high density circuits and indicated that no other technology could do what MCM-D could do.

Surprisingly no one vouched for the future of MCM-Cs. The consensus, however, was that it is the technology of the present! Specifically, we now consider high frequency applications, new ceramic materials, buried passive components, fine pitch interconnections and thermal management techniques as areas for future development.

Input from military systems' houses and newly funded government programs indicate that MCMs will need to be capable of performing at very high frequencies (in the 40 - 60 GHz range) in future years. LTCC materials are expected to meet this capability. Some new low firing ceramic dielectric formulations already operate at these frequencies with low transmission loss. Silver will be used as an interconnect metal for MCMs. The combined benefits of reduced transmission loss and the lower cost of silver conductor will encourage the replacement of gold. Using lower dielectric constant tape materials will produce a positive benefit for high frequency and high speed requirements. Dielectric materials with dielectric constants as low as 4, and developmental materials having dielectric constants as low as 2.5, will be available for both thick film and LTCC MCMs. Similarly, new high temperature materials for HTCC MCMs, such as mullite, with a CTE similar to silicon and a dielectric constant lower than alumina (6.8), will open application areas for HTCC [13].

Fine line technology is another future trend that will influence the use of MCM-Cs. A great deal of time and money is being spent to reduce the pitch of conductor traces on thick film and cofired ceramic modules. While 5 mil lines and spaces are common now, future goals include 2 mil lines and spaces. One approach is the use of standard screen printing techniques with new fine print conductor pastes and advanced wire materials and emulsions for making the screens. Wires are now available as fine as 0.7 mils in 325 and 400 mesh screens. Screen mesh open areas greater than 50% allow denser lines to be printed. These advanced wires also are much stronger and do not stretch as easily and quickly as standard wire materials. Finally, new emulsion materials allow much sharper line definition than is possible with the older emulsions.

New techniques for attaining top layer fine lines are being investigated and, in some cases, are being implemented into advanced designs. Technologies such as photolithography, sputtering, laser delineation of solid ground planes and ink writing are all techniques for reducing the conductor pitch. The ultimate goal may be to couple thin film MCM-D technology with multilayer thick film and cofired MCM-C technology (MCM-C/D). See the discussion in Chapter 7.

Power management is becoming more important and more difficult to accomplish. It is not high power circuits alone where heat management is

critical. As more and more low power devices are packed onto ceramic modules, the overall heat dissipation requirement of these packages becomes an issue. Several future trends in this area are becoming apparent. AlN is an important substrate material for TFM circuits and HTCCs. Development of compatible thick film materials (gold, silver and tungsten) is continuing. The increased availability and increasingly lower cost of AlN has renewed interest in its use. The tape transfer process can be used on AlN substrates. Tapes compatible with AlN material also have been developed. Combining the use of AlN substrate/package base with the ability to make cavities in the tape, so that high power devices can be mounted directly on the substrate, makes this future combination of new technologies quite interesting. AlN can also be coupled to LTCC structures using pressure assisted sintering techniques. The same benefits as with TTRAN on AlN are realized. A more standard approach to power management for LTCC modules has been the use of arrays of thermal vias beneath the high power devices. Such configurations are limited in capability. A better approach is to attach heatsinks (such as AlN, W/Cu and any number of the new thermally conductive composite materials) to the fired module. The heatsink can be soldered or brazed to the bottom of the package and the devices mounted directly on them.

Another possible trend is the use of buried components within the LTCC body. Buried resistors are examples here, but there may be an even greater demand for buried capacitors and inductors.

6.7 ENGINEERING CHOICES

The first decision a circuit designer makes is which of the three major MCM technologies should be chosen (MCM-L, MCM-D or MCM-C). This decision is based generally on three specific areas: familiarity with the technology, technology innovations or drivers and cost.

In many cases the selection is based on familiarity with and availability of a specific technology. For example, people comfortable with or already using organic printed wiring boards (PWBs) would tend towards MCM-L technology since this is what they understand best. Similarly circuit designers working with and knowledgeable about thin film or semiconductor technology would most likely pick MCM-D technology as their first choice. Finally, it is apparent also that practitioners of thick film technology look upon MCM-C technology as being the closest, in materials and processing, to what they do best.

Looking at technology drivers and cost as critical decision makers the choice becomes much more complex. Suppliers of MCM-L claim that their product is less costly to manufacture and is therefore more attractive to use [14].

Unfortunately there are a number of applications where MCM-Ls cannot be used until technological issues such as high density, power management and hermeticity are fully resolved.

The choice between using MCM-D or MCM-C technology is not clear cut since both technologies require different uses of ceramic materials, either as a platform or as the package itself. The determination of the selection is made usually because of circuit density and cost requirements.

Most manufacturers of MCM-D circuits point to three specific advantages of their technology. The first advantage is the ability to achieve finer conductor geometries with thin film processing. The second advantage is the lower dielectric constant of the polyimide dielectric. The final advantage is the higher thermal conductivity of the silicon, alumina or AlN substrate on which the multilayer thin film circuit is processed. The major shortcoming of this process is that it is essentially a serial, batch process; therefore, process times and manufacturing costs are quite high. Unfortunately MCM-D technology does not readily lend itself to high volume production. This may limit the area of potential applications.

Manufacturers of MCM-C circuits will highlight their ability to process larger parts with many more layers than can be made with MCM-D technology. While line density and spacing may not be as fine as that attainable with thin film technology, there are other technology tradeoffs: lower cost, higher volume manufacturing, faster prototype turn around time, tailorable ceramic dielectric properties, the capability to add integral passive components and to seal the package hermetically.

The technology innovations and process changes being made in both the materials and manufacturing processes for MCM-Cs (specifically thick film and LTCC) and MCM-Ds will make it more difficult in the future to determine which of these technologies to choose. Manufacturers of MCM-Ds could build circuits that have tighter pitches (approaching 2 mil lines and spaces rather than micron size). The defect density of the substrate would become less of an issue. Yields go up and costs come down. Manufacturers of thick film and LTCC circuits are reducing the print geometry of their conductor traces. New technology in the area of screen emulsions and wires and the development of fine print conductors allow lines and spaces approaching 2 mils, albeit not yet for high volume manufacturing. Finally, new dielectric materials have been developed with dielectric constants as low as 3.5, making inorganic systems equivalent to their organic counterparts. What this all means is, as the performance gap between MCM-D and thick film and LTCC MCM-C technologies continues to diminish, the deciding factor in choosing one over the other will come down to cost, yield and volume throughput.

What is not so well defined is where LTCC technology should be used instead of the other two MCM-C technologies. Simple, low layer count circuits will be less expensive to build with thick film than with either of the other ceramic technologies. However, the industry appears to be moving away from this concept toward denser MCMs with increasing silicon area demands. As this happens, LTCC circuits with their potentially lower cost and quicker manufacturing turnaround time should dominate, especially as this technology moves up the learning curve.

LTCC circuits, since they use higher conductivity metals, also have a major advantage over HTCC MCMs. There is an increasing interest in MCMs that operate at millimeter wave frequencies (20 - 40 GHz) and higher. HTCC circuits using tungsten metal cannot be used for this application. LTCC technology also has the advantage of being much more flexible than HTCC technology. The potential for dielectric materials with varying dielectric constants and CTE makes it even more attractive.

In general the decision on which one of the three MCM-C technologies to use is still an open issue. Both TFM and HTCC circuits, because of their maturity, appear to be the technology of today. However, the future may belong to LTCC technology. As materials improve, processes become better controlled and the technology matures, the natural advantages of LTCC could predominate and make it the MCM-C of choice. Most likely all of the technologies will continue to be used depending on the particular application required.

Acknowledgments

The author wishes to thank his many colleagues at CTS Microelectronics and CTS Corporate Headquarters for their assistance with figures and tables and Jon Krause (Zenith Microcircuits Corporation) for his many helpful suggestions during a review of this chapter.

References

- 1 W. A. Vitriol, *et al.*, "Development of a New Tape Dielectric Technology for Thick Film Multilayer Applications," *Proc. Internat. Symp. on Microelect.*, (Dallas TX), pp. 487-495, Oct. 1986.
- 2 P. Danner, "High Density Ceramic Modules," *Proc. Internat. Conf. on Multichip Modules*, (Denver, CO), pp. 325-328, April 1992.
- 3 R. G. Pond, *et al.*, "Processing and Reliability of Resistors Incorporated within Low Temperature Cofired Ceramic Structures," *Proc. Internat. Symp. on Microelect.*, (Dallas TX), pp. 461-472, Oct. 1986.
- 4 D. D. Marchant, T. E. Nemecek, "Aluminum Nitride: Preparation, Processing, and Properties," *Ceramic Substrates and Packages for Electronic Applications, Advances*

- in *Ceramics*, vol. 26, M. F. Yan, *et al.*, eds., American Ceramic Society Publication, pp. 52-81, 1989.
- 5 K. R. Mikeska, R. H. Jensen, "Pressure Assisted Sintering of Multilayer Packages," *Ceramic Transactions, Materials and Processes for Microelectronic Systems*, vol. 15, K. M. Nair, *et al.*, eds., American Ceramic Society Publication, pp. 29-35, 1990.
 - 6 R. R. Sutherland, I. D. E. Videlo, "A Comparison of the Reliability of Copper and Palladium-silver Thick Film Crossovers," *IEEE Trans. on Components, Hybrids, and Manuf. Tech.*, vol. CHMT-12, no. 4, pp. 676-682, Dec. 1987.
 - 7 S. N. Mesher, "A Comparison of the Reliability of Silver Compatible Multilayer Dielectric Materials," *Proc. Internat. Symp. on Microelect.*, (Minneapolis MN), pp. 1-7, Sept. 1987.
 - 8 J. H. Alexander, *et al.*, "A Low Temperature Cofiring Tape System Based on a Crystallizing Glass," *Proc. Internat. Symp. on Microelect.*, (Orlando FL), pp. 414-425, Oct. 1991.
 - 9 A. H. Kumar, R. R. Tummala, "State-of-the-art, Glass-ceramic/copper, Multilayer Substrate for High Performance Computers", *Internat. J. for Hybrid Microelect.*, vol. 14, no. 4, pp. 137-150, Dec. 1991.
 - 10 T. R. Bloom, "Parameters for Au/In Brazing to Thick Film Au on Green Tape," *Proc. Internat. Symp. on Microelect.*, (Orlando FL), pp. 513-516, Oct. 1991.
 - 11 S. Nishigaki, *et al.*, "LFC-III: A New Low Temperature Multilayered Ceramic Substrate with Au(top)-Ag(internal)-Ti/Mo/Cu(bottom) Conductor System," *Proc. Internat. Symp. on Microelect.*, (Minneapolis MN), pp. 400-407, Sept. 1987.
 - 12 *Proc. Internat. Conf. on Multichip Modules*, (Denver CO), pp. 37, April 1-3, 1992.
 - 13 R. E. Sigliano, K. Gaughan, "Ceramic Material Options for MCMs," *Proc. Internat. Conf. on Multichip Modules*, (Denver CO), pp. 291-299, April 1992.
 - 14 B. Freyman, B. Miles, "A DSP-based MCM Employing Advanced Multilayer Printed Circuit Board Technology," *Proc. Internat. Conf. on Multichip Modules*, (Denver, CO), pp. 490-498, April 1992.