

High-performance glass-ceramic/copper multilayer substrate with thin-film redistribution

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IBM has pioneered the use of large-area alumina multilayer ceramic substrates using state-of-the-art greensheet, molybdenum paste, and tooling technologies for its mainframe computers since 1980. During this time, a new generation of substrate materials have been developed based on copper metallization and a unique glass that crystallizes to cordierite ($2\text{Al}_2\text{O}_3 \cdot 2\text{MgO} \cdot 5\text{SiO}_2$), which has a very low dielectric constant (5.0 compared to 9.4 in previous IBM systems). The glass-ceramic/copper system provides a factor of 3 improvement in electrical conductivity over alumina/molybdenum in previous IBM systems, and the number of metallized substrate layers has been increased from 45 to 63. The thermal expansion of the new substrate ($30 \times 10^{-7}^\circ\text{C}^{-1}$) is matched with that of the

silicon chips, thereby enhancing the reliability of the 78 500 solder-bonded chip-to-substrate connections in the System 390[®]-Enterprise System/9000[™] computers. Each substrate is 127.5 mm square and can support up to 121 complex logic and memory chips. The IBM advanced multichip module dissipates more than twice the heat flux of previous alumina/multichip modules—to 17 W/cm² at the package level and 50 W/cm² at the chip level.

Introduction

The alumina multilayer ceramic (MLC) packaging technology, an integral part of the thermal conduction module (TCM) introduced a decade ago by IBM for its 3081 mainframe computers, began an era of packaging

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Table 1 Electrical, thermal, and dimensional control properties of new substrate compared with alumina substrate.

	New substrate	Alumina substrate
Dielectric constant	5.0	9.4
Thermal expansion coefficient ($10^{-7}^{\circ}\text{C}^{-1}$)	30	66
Electrical conductivity of metals ($\mu\Omega\text{-cm}$)	3.5	12.0
Dimensional or shrinkage control tolerance (%)	± 0.1	± 0.2

Table 2 Glass-ceramic systems considered.

Crystal type	Thermal expansion	Dielectric constant	Sintering temperature
Cordierite $2\text{MgO} \cdot 2\text{Al}_2\text{O}_3 \cdot 5\text{SiO}_2$	Too low	Good	Too high
Beta-spodumene $\text{Li}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2$	Too low	Too high	Too high
Celsian $\text{BaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$	Good	Too high	Too high
Anorthite $\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$	Too high	Too high	Too high
Glass + alumina	High	High	950°C

which provided a revolutionary approach to mainframe chip packaging, with unprecedented performance and reliability [1]. The challenge met by the System/390®-Enterprise System/9000™ (ES/9000™) series of mainframe computers is to extend that novel TCM approach with a revolutionary set of materials having a combination of electrical, thermal, and dimensional control properties which would provide a leading-edge foundation for the 1990s. Because of the maturity of the generic co-fired technology at IBM, the cost per meter of wiring for the new advanced multichip module using the co-fired approach is expected to compete favorably at this time with other technologies such as polyimide-copper thin film.

This paper reviews the key technological developments in substrate materials and processes that have resulted in one of the most advanced multichip modules used in mainframe packaging.

The general requirements for a high-performance multichip package are discussed elsewhere [2]. These include low dielectric constant, high wiring density, metallization with high-conductive metal such as copper, matching of thermal expansion to that of silicon, and good mechanical and dimensional control properties. **Table 1**

highlights and compares the properties of the new substrate with those of the alumina substrate used in previous IBM systems.

The high-performance glass-ceramic substrate discussed in this paper meets all these requirements in an exceptional manner.

Glass-ceramic/copper materials and process technologies

The key technologies in developing the 63-layer glass-ceramic/copper substrate with thin-film redistribution are discussed in the following sections: glass-ceramic material, greensheet copper powder and paste, personalization, stacking and lamination, glass-ceramic/copper sintering, substrate machining and finishing, polyimide-copper thin-film redistribution.

• Glass-ceramic material

Table 2 lists various potential systems considered for forming glass-ceramic substrates in terms of their thermal and electrical properties as well as sintering temperature required to co-fire with highly conductive metal such as copper. None of the systems shown in **Table 2** met the requirements of a thermal expansion coefficient near that of silicon ($30 \times 10^{-7}^{\circ}\text{C}^{-1}$), a dielectric constant of 5.0, and sintering compatibility with copper. In addition to these glass-ceramic systems, glass and ceramic systems involving, for example, the addition of a greater amount of glass to alumina than in typical alumina substrates were also considered. In addition to these glass-ceramic systems, dielectric compositions consisting of a low-viscosity glass added to a ceramic such as alumina were also considered. For the glass-plus-ceramic compositions, binder removal was anticipated to be more difficult because of the need for a low-viscosity glass required to reach high density at about 950°C [2].

The glass developed to form the glass-ceramic has the following composition: SiO_2 : 50–55 wt%, Al_2O_3 : 18–23 wt%, MgO : 18–25 wt%; it contains P_2O_5 and B_2O_3 in 0–3 wt% [3]. The glass-ceramic technology has also been widely pursued in Japan, but most of these systems are based on the addition of glass to crystalline ceramic to form glass and ceramic systems. A number of these systems are discussed in a recent book [4].

Crystallizable cordierite glass offers process advantages for multilayer ceramic/Cu substrates. These advantages can be examined with the use of differential thermal analysis (DTA), as shown in **Figure 1**. To form the glass-ceramic substrate with copper, it is important that no sintering occur below 800°C, and that complete crystallization occur below the melting point of copper (1083°C). In **Figure 1**, both of these conditions are met, allowing adequate binder removal at temperatures below those at which sintering occurs, complete densification

prior to crystallization, and crystallization well below 1083°C. The crystallization peak occurs at approximately 1000°C in the dynamic DTA experiment and at lower temperatures for actual substrate formation.

When a stoichiometric cordierite glass is heated in a DTA experiment, the crystallization exotherm initiates at a lower temperature and proceeds at a higher rate. With the shift from stoichiometry and with small amounts of B₂O₃ and P₂O₅, the onset of crystallization is delayed to a higher temperature and the crystallization is reduced. This crystallization temperature increase and crystallization rate decrease help enable the glass to sinter to 100% of theoretical density [5]. Further studies on glass viscosity [6, 7], sintering [8], and crystallization [9, 10] show the effects of compositional modifications on final density.

The preferred powder particle size is about 3 μm in diameter, and because of surface nucleation, the final grain size is also typically less than 3 μm. The density of this material is more than 99% of theoretical value, and the pores generally measure less than 5 μm. The microstructure and X-ray diffraction data indicate the glass-ceramic to be approximately 95% alpha-cordierite, while the remainder is enstatite. The properties of this material are shown in Table 3.

• Greensheet technology

The greensheet, which resembles a sheet of paper, consists of glass powder in a matrix of organic binder. It serves as the basic building block for the fabrication of the 63-layer glass-ceramic TCM substrate, providing the strength and dimensional stability necessary to maintain precise dimensional control during the various MLC processing steps of via punching, metallurgical paste screening, and lamination. The positional accuracy that is maintained ensures the alignment of two million via connections in the sintered substrate.

To meet the stringent requirements of the glass-ceramic substrate, a modification of the binder system and the continuous casting process used previously for the alumina system was developed; it is capable of producing greensheets with the following characteristics:

- Stable dimensional properties after punching and handling.
- Microporosity levels which enable sufficient deformability to enclose screened lines and permeability to allow escape of gases during the sintering process.
- Wetting by copper paste solvents without dimensional change.
- Complete removal of organics in the sintering cycle.

Glass powder is formed by grinding the glass in a high-alumina ball mill to an average particle size of about 3.0 μm. The particle size, particle size distribution, and

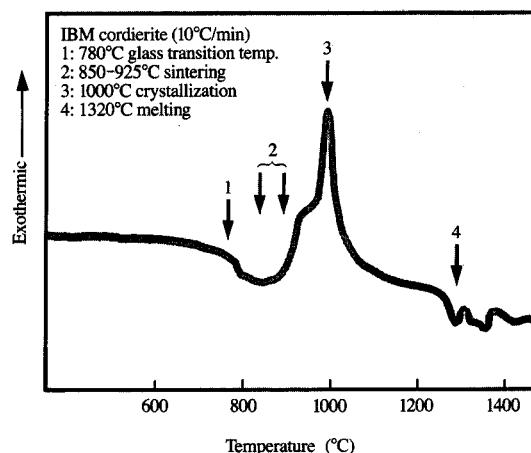


Figure 1

Differential thermal analysis of cordierite glass.

Table 3 Properties of cordierite glass-ceramic.

Dielectric constant: 5.0 at 1 MHz
Thermal expansion coefficient: $30 \times 10^{-7} \text{°C}^{-1}$ (25–200°C)
Mechanical strength: 210 MPa (30 KPSI)
Maximum process temperature: 950°C

surface area of the glass powder prior to incorporation into greensheets are critical control parameters in the fabrication of reproducible greensheets [11].

The greensheet obtains its stability, porosity, and chemical inertness from a binder system consisting of polyvinylbutyral (PVB), dipropylene glycol dibenzoate (DPGDB) plasticizer, and a binary solvent of methanol and methylisobutyl ketone [12]. This formulation provides a stable suspension of the glass particles in the slurry with a viscosity suitable for continuous casting of high-quality greensheets having the required mechanical strength and dimensional stability. The resulting greensheet has about 90% glass powder and 10% binder (PVB/DPGDB) by weight.

The polyvinyl butyral binder and solvent system provides excellent slurry properties. It has a viscosity of about 1500 centipoise and has a behavior which is pseudoplastic at low shear rates and Newtonian at the higher shear rates typically experienced in continuous casting. These properties permit precise control of the

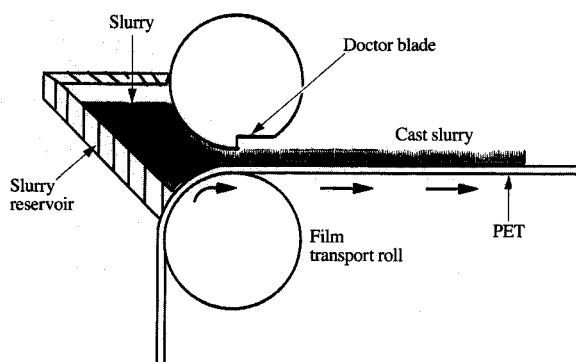


Figure 2

Doctor blade and casting assembly.

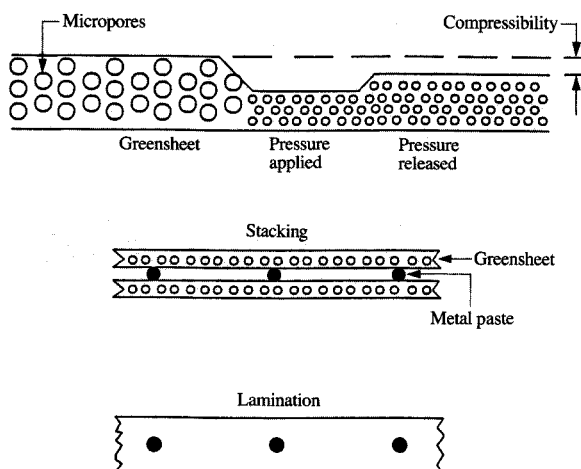


Figure 3

Greensheet compressibility and metal line enclosure at lamination.

slurry in the caster, resulting in a precise greensheet thickness necessary for the dimensional control of the sintered substrate.

During continuous casting, the slurry is filtered and then pumped to the doctor-blade assembly, where it is cast onto a polyethylene terephthalate (PET) carrier (**Figure 2**). The sheet is transported through a series of drying zones where air is blown onto its surface to remove solvents and eventually form a strong, porous, and dimensionally stable

greensheet. The slurry, which is doctor-blade cast as a 500- μm -thick liquid, is dried to a final thickness of 200 μm , separated from the PET carrier, and blanked to 185-mm-square sheets.

The sheet porosity is controlled with a novel rheological two-component solvent system. After the rapid removal of the lower-boiling-temperature solvent during greensheet drying, a rapid increase in the slurry viscosity sets up the sheet structure with a high proportion of the higher-boiling-temperature solvent. As the remaining solvents slowly evaporate, the integrity of the sheet is maintained, and since there is no further shrinkage of the sheet, the desired porosity is obtained.

The compressible nature of the greensheet during lamination is essential to enclosing the screened metal features (**Figure 3**). As the sheet conforms around the metal paste, intimate contact and bonding occur at the greensheet-to-greensheet interfaces, preventing delamination, lateral distortion, and voids from occurring in the sintered substrate.

• Copper powder and paste technology

Copper is the most desirable metal for co-firing with glass-ceramic because of its high electrical conductivity and low cost. This metal, however, presents major difficulties in forming suitable powders and pastes to fabricate 63-layer glass-ceramic/copper substrates, as discussed previously [2].

A powder suitable for screening 90- and 100- μm vias on 225- μm centers as well as fine lines (75 μm) must have a small particle size. This requires that the powder be deagglomerated so that it can be screened through a metal mask without clogging the holes in the mask. Unlike many other metal powders, copper is difficult to deagglomerate during paste manufacture. Copper particles tend to deform rather than deagglomerate. When copper thick-film technology originated, no known powder or paste met the requirements described above. A new powder technology was, therefore, developed to meet the challenging requirements of the glass-ceramic/copper substrate described earlier.

As expected, most fine, commercially available copper powders sinter between 600 and 780°C, whereas the glass begins to densify at about 800°C and completes at about 860°C. This mismatch presents major problems in the fabrication of multilayer glass-ceramic substrates, as discussed elsewhere [2].

As stated elsewhere [13], in fabricating the 63-layer glass-ceramic substrate, the copper powder utilized has been suitably modified [14, 15] and co-sintered with glass.

The interface between the copper and the glass-ceramic was studied by means of a number of material and process options. The bonding methods investigated were mechanical, chemical, and a combination of the two. Compatible glasses and glass-ceramics were used for

mechanical interfacial bonding, whereas chemical bonding was achieved by incorporation of suitable oxides in the paste. With both bonding methods, a controlled atmosphere was utilized during the sintering process to enhance the interfacial bonding. The details of these technologies are considered proprietary at this time.

- *Copper thick film*

The IBM molybdenum thick-film (paste) technology used to personalize the alumina TCM is well established [1]. The personalization of the glass-ceramic/copper package has a higher density with decreased grid spacings, requiring significant improvement in the paste technology. For example, via diameters are 90 and 100 μm on 225- μm spacing for glass-ceramic, compared to via diameters of 140 and 150 μm on approximately 300- μm spacing for alumina. In addition, more than 78 500 vias are screened simultaneously with lines on each greensheet. These vias extend through the greensheet and are filled simultaneously as the lines are screened.

To form these densely wired structures, paste interaction with the greensheet must be considered. The interaction between the solvent in the paste and the binder of the sheet must be small but not zero. Control of this interaction is essential for dimensional stability of the sheets after screening, thus ensuring proper alignment of the vias in as many as 63 discrete layers during lamination. Solid content, particle size distribution, rheology stability, and cross-sectional area are essential parameters for reproducible pastes.

A significant challenge in screening was to achieve good leveling of the screened features without spreading of the screened geometry. This is especially important for the glass-ceramic substrate, where the requirement for high electrical conductivity makes it necessary for the paste to have high solid content. The choice of paste solvent (or vehicle system) was critical, since its interaction with greensheets places a limit on the amount of leveling that can occur. A minimal amount of surfactant, combined with an appropriate amount of thixotrope, resulted in a paste that sets up adequately at the edges of the screened features while maintaining sufficient fluidity in the body of the paste to provide excellent leveling, thus producing copper features with desirable cross-sectional area.

Extensive experimentation was carried out in order to understand the trade-off among the various properties required. Vehicle systems containing various polar and nonpolar solvents such as acetates, oils, esters, and glycols were considered together with polymer systems containing compatible functional groups. Screening process optimization was carried out by means of statistical studies to simultaneously adjust three major parameters as a function of paste composition: line-height variation, line-width variation, and greensheet dimensional control.

Table 4 Comparison of feature parameters for alumina and glass-ceramic substrates.

<i>Technology</i>	<i>Alumina MLC</i>	<i>Glass-ceramic MLC</i>
Line width (μm)	116	75
Line spacing (μm)	300	225
Wiring length (m)	130	400
Smallest via diameter (μm)	140	90
Largest via diameter (μm)	150	100
Via spacing (μm)	300	225
Vias per layer	33,000	78,500
Vias per substrate	350,000	2,000,000

In-line controls such as grind gauge for the dispersion of particles, viscosity, and rheological measurements were instituted.

The resultant thick film is a balanced blend of pseudo plasticity, thixotropy, and yield strength. A typical thick-film composition includes 80 to 90 weight percent copper and 20 to 10 weight percent paste organics and solvents. This thick film is suitable for a wide variety of screened layers (for example, signal, redistribution, and vias-only, as shown in **Figure 4**), which in the past required many different formulations.

- *Personalization, stacking, and lamination technology*

After the greensheet is cast, dried, stripped from the carrier and blanked into squares, it is "personalized" in one screening operation. A specific wiring is deposited and a through-via pattern obtained by punching vias through the sheets and filling them. Subsequently, the appropriate individual layers are aligned one on top of another and then laminated together. For the alumina-based thermal conduction module, the vias were formed by means of mechanical punches, and the screening was done with various formulations of molybdenum metallurgical paste. Although in principle the same procedure was used for the glass-ceramic program, several factors presented major challenges with respect to the personalization of the latter system. These included the chemistry of new materials, and, most importantly, the dramatically increased density of features (both vias and lines). **Table 4** compares some feature parameters for the two systems.

- *Punching*

The change in materials from alumina to glass-ceramic presented interesting challenges with respect to the personalization of the greensheets. It is well known that the stresses induced in a greensheet during punching cause macroscopic deformations in the sheet [16, 17]. All other factors (organic binder, sheet thickness, and punching

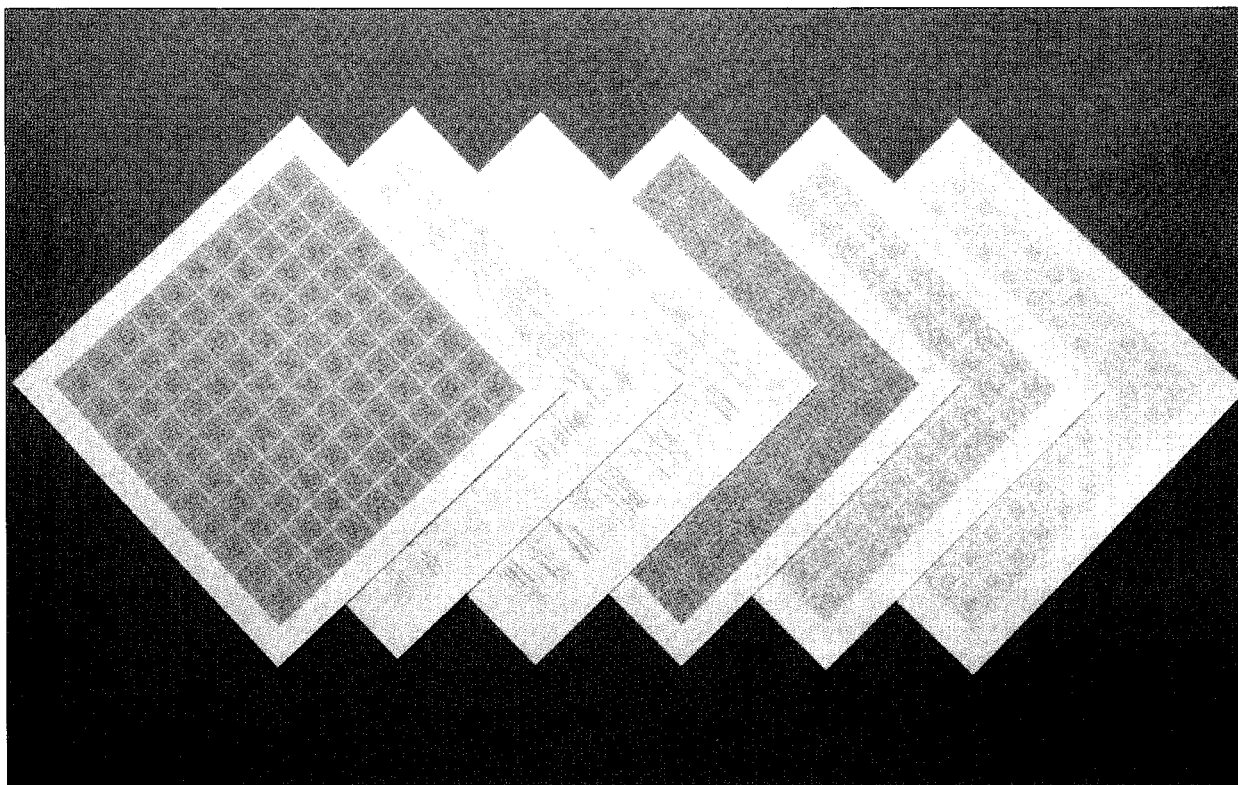


Figure 4

Variety of screened greensheets with copper thick-film paste.

parameters) remaining constant, this deformation differed significantly in glass-ceramic and alumina greensheets.

The magnitude and causes of distortion influenced by a number of materials and process parameters were investigated. In particular, a comprehensive study of both mechanical and chemical properties of the system were carried out.

One mechanical study involved the effect on via location error of the thickness of the greensheet being punched and the difference in diameter between the punch and its associated die bushing, illustrated in **Figure 5**. **Figure 6** shows a figure of merit for via location error as a function of one of the controllable parameters, the punch-to-die clearance. It can be seen that, if the sheet thickness is kept low enough, the sheet is relatively insensitive to other factors. Beyond a certain critical sheet thickness, relatively small changes in punch-to-die clearance have a large effect on the eventual distortion of the punched sheet. On the other hand, for any given set of materials and sheet thickness, an increase in the clearance between the punch and its associated die bushing results in a decrease in the distortion of the punched sheet.

The fundamental reason for the difference between the alumina and glass-ceramic sheets during punching was found to be the interfacial chemistry of the inorganic components of the greensheets (glass versus alumina) and the organic binder, as discussed in [18] and [19]. This effect was studied utilizing materials with a known degree of surface acidity/basicity (measured by their iso-electric point). There was a direct correlation between feature location accuracy and the known degree of acidity/basicity.

• Screening

A new screening process was developed for the copper paste because it was drastically different in composition and rheology from that used on alumina sheets. In the latter system, the pastes were customized with respect to their solvent and binder materials for individual patterns. For the glass-ceramic system, a single materials set for solvent and binder was used. This required the use of a system which was tailored for limited reaction with the greensheet. This provided sufficient adhesion of the screening paste to the greensheet without causing significant dimensional instability.

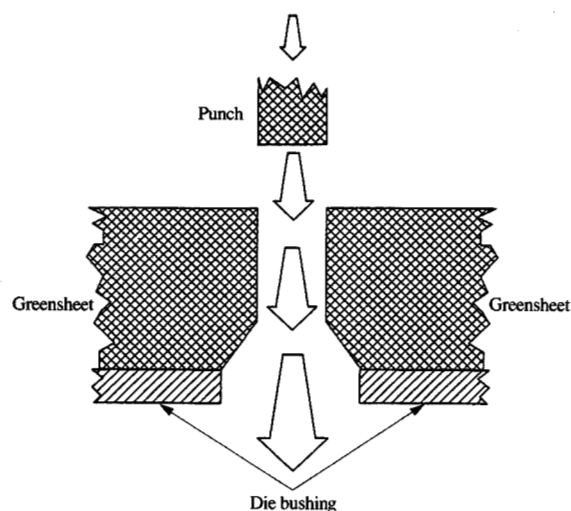


Figure 5

Schematic of greensheet punching.

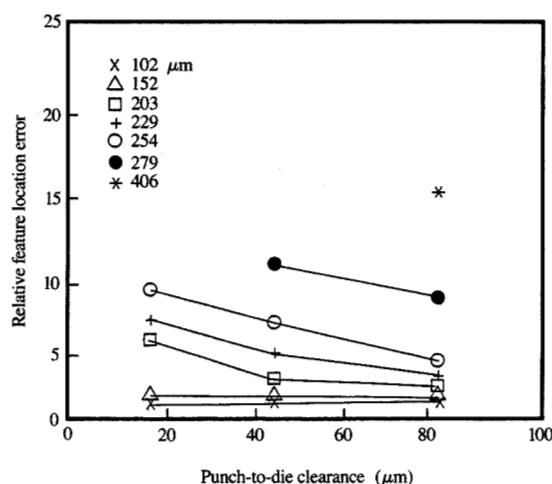


Figure 6

Relative greensheet feature location error as a function of punch-to-die clearance.

The properties of the conductive metal within the paste were radically different. Molybdenum particles have high hardness and have a platelet shape, whereas copper particles are malleable and more nearly spherical. The change in density and surface area required extensive cooperation between the screening and the paste formulation development teams in order to fine-tune the rheology of different paste formulations and the screening parameters (pressure, wipe speed, etc.) for the individual layers. Major developments in the fabrication of screening masks were another key ingredient in the final success of the actual screening operation in the manufacture of glass-ceramic substrates.

• Inspection

Automated inspection of screened greensheets ensures that via fill and line dimensions meet specifications. Advances in this technology were required because of the reduction in feature size (Table 4) for glass-ceramic with copper thick film. This operation is critical to achieving high electrical test yields after sintering, because a single defective layer, if not rejected, can cause the loss of the 62 other defect-free layers which combined make up a substrate.

• Stacking and lamination

During stacking and lamination, the individual sheets must be stacked one on top of another; they must be aligned so

that any additional distortion is kept to a minimum during this process. The registration of all the sheets in the stack must be so precise that good electrical contact is made from vias in one layer to vias in the next layer for every one of the nearly two million vias in the laminate. Even after this is achieved, the stack must survive the lamination process, in which the stack is heated (under pressure) to a temperature just above the glass transition temperature of the binder in the sheet. Aside from the tooling challenge of building a press in which the platens have very tight tolerance placed on their flatness, parallelism, and temperature uniformity, a delicate balance had to be struck between conditions of temperature and pressure which would permit enough flow to allow for the consolidation of the individual sheets into a single unit, but were not so severe as to introduce additional distortion due to lateral flow.

Figure 4 gives examples of the major types of personalized, individual layers. The excellent via-to-via alignment achieved by careful control of the materials and process variables is shown later in the cross section of a sintered substrate (Figure 8).

• Glass-ceramic/copper sintering technology

Sintering a multilayer ceramic substrate requires co-firing a composite matrix of organics, metal powders, and ceramic and glass powders into a complex network of electrically conductive wiring embedded in a dense, insulating ceramic

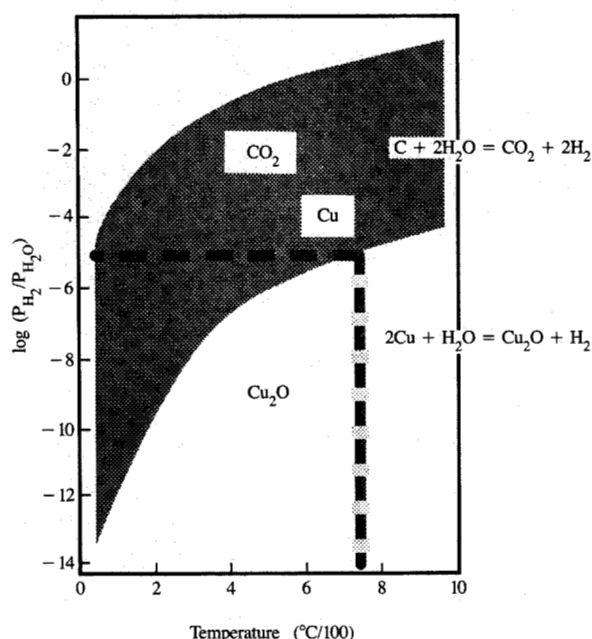


Figure 7

Thermodynamics of Cu-O-C system.

Table 5 Sintered glass-ceramic/copper substrate properties.

Fired ceramic density (g/cm ³) (99.5%)	2.66
Shrinkage tolerance (%)	±0.10
Camber or sintered flatness (μm/cm)	2.3
Ceramic flexural strength (MPa)	210
Copper resistivity (μΩ-cm)	3.5
Dielectric constant	5.0
Expansion coefficient (10 ⁻⁷ °C ⁻¹)	30

body. IBM pioneered MLC sintering technology in the '70s and introduced the first large alumina-molybdenum MLC substrate in 1978 [20].

The glass-ceramic/copper substrate technology developed for the System/390-ES/9000 computers presented the following new challenges to MLC sintering:

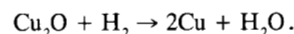
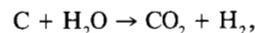
- Low-temperature organics removal (<800°C), without copper oxidation and low-temperature densification (<1000°C).
- Crystallization of glass to form a high-strength dielectric.
- Densification of copper powder to high-conductivity copper.

- Copper/ceramic interface integrity.
- Improved dimensional control to satisfy requirements for via alignment and for thin-film wiring.

• Binder removal and carbon oxidation

Various approaches were evaluated to reduce the residual carbon content to the desired low levels. These investigations included polymers that pyrolyze primarily into gaseous species ("unzip"), atmospheric firing cycles for oxidation of carbon and copper and subsequent reduction of copper oxide to copper, and catalysts to aid the binder burn-off. Differences in thermal degradation were noted for the free binder and the binder absorbed on a glassy surface. As discussed elsewhere [4], when the binder was mixed with powdered glass to simulate tape casting, all candidates left excessive residual carbon in the glass. This occurred because the surface of the glass was chemically active and bonded with the polymer.

The challenges in co-firing copper paste with glass greensheet to form a 63-layer structure of glass-ceramic/copper substrate can be overcome by the use of steam and hydrogen atmospheres [2]. **Figure 7** indicates the P_{H_2}/P_{H_2O} ratio necessary at 800°C to oxidize carbon and reduce copper oxide according to the following chemical reactions:



While the oxygen partial pressure required to drive the above reactions can be achieved by a number of ambients [21], the only kinetically acceptable process for forming the 63-layer structure in a few hours is the one based on the use of steam.

• Densification

Densification of the glass-ceramic/copper substrate depends on the composition of the glass-ceramic and the particle size distributions of the glass and metal powders. Greensheet laminate properties such as the ratio of organics to inorganics and laminate density play a role in the control of shrinkage.

The objective of the sintering process is to define a temperature profile, atmospheric conditions, and fixtures to achieve a dense, high-strength ceramic and dense, highly conductive copper wiring. Copper/ceramic interface integrity also depends on materials properties and sintering atmosphere control. The glass-ceramic/copper sintering process development grew out of experience gained in developing the alumina-molybdenum sintering technology and required improvements in tools and processes. Steam furnaces were developed and designed to sinter glass-ceramic/copper substrates which are believed to be an industry first. The furnaces required significant

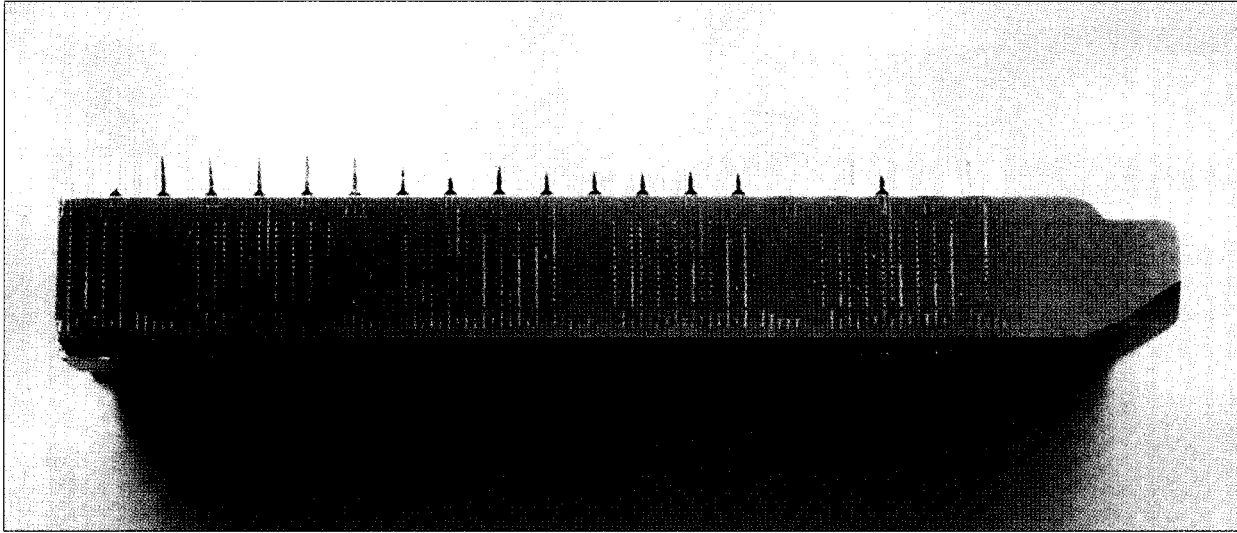


Figure 8

Cross section of a finished glass-ceramic/copper substrate with pins.

advances in mass flow control, atmosphere injection systems, and reaction chamber materials. Unique fixtures helped achieve the required mass transport for carbon oxidation and removal which affects materials densification and substrate characteristics. The results of this development effort are illustrated in **Figure 8**, which shows a cross section of a finished glass-ceramic/copper substrate with pins. This substrate sets new standards for multilayer ceramic packaging, as evidenced by the final properties presented in **Table 5** [2].

• Dimensional control

Dimensional control during the densification segment of the glass-ceramic/copper sintering profile is a function of processing before and during sintering [1, 22, 23]. Variations in greensheet properties, paste properties, paste loading, and lamination conditions have a significant impact on dimensional control and must be carefully controlled. Improved furnace materials, fixtures, and methods for temperature and atmosphere control have been developed for sintering glass-ceramic/copper substrates. These advances in sintering technology have resulted in significant improvements beyond state-of-the-art alumina-molybdenum sintering with respect to dimensional control.

With respect to requirements for dimensional control in a sintered substrate, the goal is to have all surface features located exactly within specifications relative to one another and the edges of the substrate. In a multilayer ceramic substrate, deviations from ideal locations are allowed

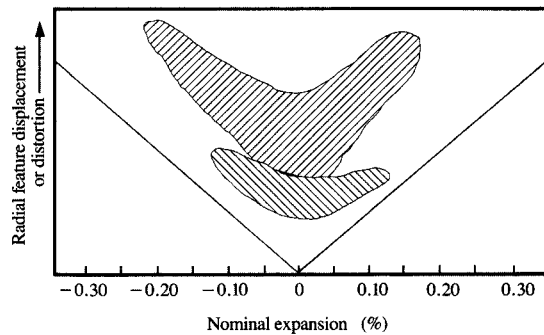


Figure 9

Dimensional control of alumina TCM compared to glass-ceramic TCM.

within specified limits. For example, a perfect substrate, where metal features have no deviations from ideal locations, is said to have 0% nominal movement. An MLC substrate tends to deviate from ideal locations by expansion or contraction around the desired value. On the other hand, if all the surface features expand or contract linearly, there is zero radial feature displacement or distortion. Radial feature displacement is measured in microns using an optical measurement system.

Figure 9 compares the dimensional control in two populations of sintered substrates. The larger area

Table 6 Details of substrate machining and finishing processes.

<i>Process</i>	<i>Process elements</i>	<i>Results</i>
Sizing	Diamond sawing	Size = 127.5 mm
Planarization	Abrasive slurry on lapping table	Flatness = 2.3 $\mu\text{m}/\text{cm}$ Vias above substrate surface
Flange grind	Abrasive wheel	Surface roughness = 4500 Å Thickness/parallelism = 50 μm
Ceramic polish	Submicron abrasive slurry with polishing pad	Surface roughness = 450 Å Vias coplanar with surface
Metal polish	Submicron abrasive slurry with polishing pad	Reflective vias

represents alumina-molybdenum substrates, and the smaller area represents glass-ceramic/copper substrates. Perfect dimensional control with ideal linearity (zero distortion) is represented by the two dark lines forming a "V." If, for example, a sintered substrate had a global expansion of +0.10% with ideal linearity, the radial feature displacement would be on top of the right-hand dark line just above the +0.10% mark. Therefore, the goal in dimensional control is twofold: a) it should be close to zero nominal expansion, and b) when deviations occur, the expansion should be linear.

As the data in Figure 9 illustrate, dimensional control in the glass-ceramic/copper population is significantly better than in the alumina-molybdenum population. Dimensional control in the glass-ceramic/copper population deviates less from the ideal dimensions and is closer to perfect linearity.

• *Substrate machining and finishing technology*

As described in the previous sections, the glass-ceramic/copper substrate is a culmination of extensive materials and process development. However, the sintered substrate, advanced as it is at this stage, is not yet complete. The thin-film redistribution wiring, top-surface terminal metallurgy, and back-side I/O pins must still be applied to the top and bottom surfaces and preparation made for mounting in the module hardware. The substrate machining and finishing processes prepare the substrate for these final operations.

The application of thin films onto the glass-ceramic substrate generates new requirements not encountered in the fabrication of earlier substrates. Specific requirements pertain to the substrate dimensions, flatness, surface roughness, and the condition of the metal vias exiting the surface. Additionally, a flange must be ground into the periphery of the substrate for module encapsulation. These requirements are met using a series of operations summarized in the process flow given in Table 6.

• *Postsinter sizing*

Precision diamond-saw sizing is the first machining operation for the sintered substrate. This operation precisely sizes the substrate to 127.5 mm. In this operation the substrate is cut square, the corners are truncated, and a 45° bevel is machined on all edges. The truncating of the corners and beveling of the edges help to minimize chipping and damage to edges during subsequent operations.

The sizing process uses resin-bonded diamond blades on a double arbor wet saw. A specially formulated coolant is used to minimize the buildup of heat and prevent mechanical damage to the substrate. The saw sizing operation is completely automatic, first cutting the sides of the substrate and then truncating the corners. Precise dimensional control as well as pattern centrality are important for subsequent processing. This is achieved by the use of an integrated optical alignment technique that targets pattern alignment fiducials on the substrate and transfers these alignment data to the saw. After the cutting operations are complete, the newly formed edges are beveled on a deburring machine.

• *Planarization*

The accurate application of thin films to the substrate requires that it be planarized to produce flat surfaces. Further, since the substrate is electrically tested after planarization, the process must leave the copper vias in the surface protruding above the glass-ceramic surface in order to ensure probe contact during electrical test.

A free-abrasive lapping process is used to planarize the substrate. The process utilizes an abrasive slurry and a lapping table to planarize both the top and bottom surfaces of the substrate. Slurry consistency and its distribution to the part, as well as lapping table speed and the pressure applied to the part, are important in achieving the desired flatness. The machining mechanics of a free abrasive

lapping operation result in the enhanced removal of the ceramic over the more ductile copper [24]. Thus, after planarization, the copper vias protrude above the ceramic surface, as required for electrical test.

Measurement of the planarized surface is critical to the assessment of process integrity. An automated laser scanning interferometer not only measures the overall flatness of the part, but also gives a contour map of the surface, showing the location and the degree of deviation from ideal flatness.

- *Seal flange grind*

Once a substrate has been planarized and electrically tested, those parts passing electrical test have a seal flange ground into their periphery. The flange is used to mount and seal the top surface of the substrate into the module hardware.

Key elements of the flange are its surface finish and its parallelism. The top surface of the flange must be smooth enough to permit a hermetic seal to the module. The flange surfaces must be parallel, so that even distribution of pressure to the module seal is obtained without bending moments on the ceramic.

A ground seal flange is not new to ceramic technology; alumina TCM substrates have had this feature for several years [25]. However, machining such a flange into the glass-ceramic/copper substrate required the development of a new process, largely because of the differences in the physical properties between alumina and the crystallized glass-ceramic.

The seal flange is machined into the substrate by means of a cam grinder using a specially shaped, abrasive wheel that grinds both the top and bottom flange surfaces simultaneously. A combination coolant/lubricant is used in conjunction with the process. This coolant, along with the speed of the grinding wheel and the feed rate of the substrate, is critical in preventing damage to the ceramic during processing. Considerable effort has also gone into designing the fixturing used to hold the substrate during grinding. The fixtures must be able to resist the bending and vibrational modes placed on the substrate during grinding, while maintaining the dimensional accuracy of the resultant flange. After the flange has been machined, the same abrasive wheel is used to bevel the flange edges to prevent chipping of the ceramic. By means of this process, the flange thickness and parallelism are controlled to within 50 μm , and the surface roughness is maintained at 4500 Å. **Figure 10** shows substrates with ground flanges.

- *Polishing*

The complete surface finishing of a glass-ceramic/copper substrate requires two polishing operations. The first operation, the ceramic polish, produces a smooth surface

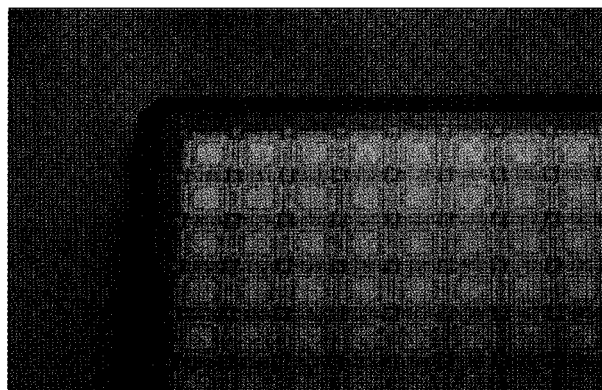


Figure 10

Substrate with ground flange.

suitable for the application of thin-film metallization. The second operation, the metal polish, brightens the surface of the copper vias to enable them to be seen by the automatic mapping tools used in thin-film processing. These polishing operations are used on both the top and bottom surfaces of the substrate.

The ceramic polishing operation was developed to provide a smooth surface, maximize surface flatness, and achieve copper vias which are coplanar with the ceramic surface. The ceramic polish uses a submicron abrasive slurry and polishing pad to achieve these goals. Process parameters such as applied pressure, table speed, substrate rotation speed, slurry concentration, and slurry delivery rate are also critical to the quality of the polish. Their relative importance in the process was determined using a robust experimental design methodology [26]. Considerable effort has also gone into developing fixturing for the substrate that ensures a nearly uniform polishing rate across the entire substrate surface. The ceramic polish routinely yields substrates with a surface roughness of 450 Å, minimal change to the surface flatness achieved during the lapping process, and copper vias coplanar with the ceramic surface.

The metal polish operation also uses not only a pad but also a still finer submicron abrasive slurry. The improved reflectivity of the copper achieved by this polish allows for precise optical mapping of via locations for subsequent thin-film processing.

- *The finished ceramic substrate*

Upon completion of the metal polish, the substrate is rigorously cleaned, dried, and inspected before being introduced into thin-film processing. **Figure 11** shows a substrate at this stage.

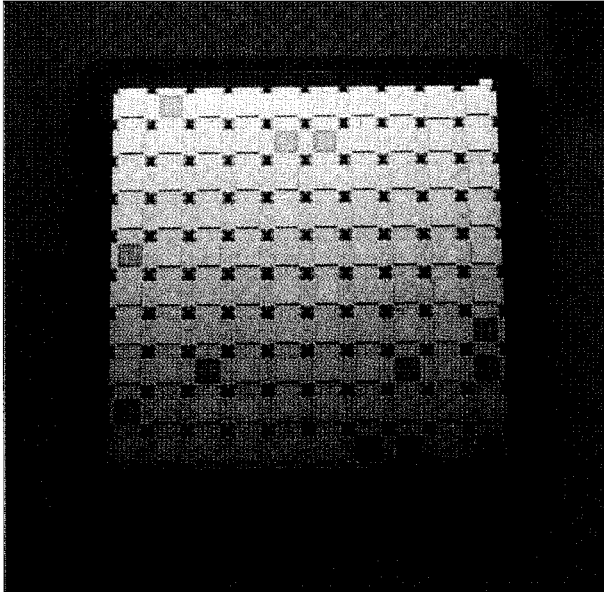


Figure 11

Finished glass-ceramic/copper substrate ready for thin-film processing.

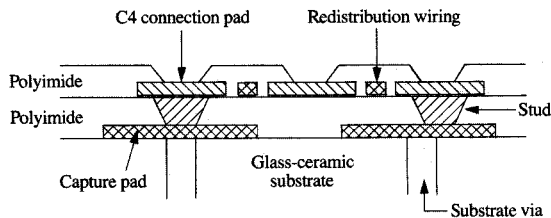


Figure 12

Thin-film structure.

Polyimide-copper thin-film redistribution

The use of thin-film wiring for signal redistribution on this substrate takes maximum advantage of the electrical properties of solid copper wiring and a polyimide dielectric. In addition to providing low-capacitance fanout lines, thin-film redistribution eliminates five to six layers of ceramic redistribution. This shortens the distance between the engineering-change wiring in the ceramic [27] and the engineering-change pads, reducing coupled noise and providing better control of characteristic impedance.

In addition to redistribution wiring, the thin-film structure also incorporates the interconnection metallurgy required to solder-join chips and ultrasonically bond engineering-change wires. The overall thin-film structure is shown in **Figure 12**. It includes a capture pad layer, a polymer dielectric layer with interconnection studs, a combination wiring and interconnection metallurgy layer, and finally an encapsulation layer. A detailed description of the thin-film technology has been published elsewhere [28]. The process technology is outlined briefly below.

The process flow developed to build the thin-film structure is presented in **Table 7**. These processes represent the extension of some semiconductor process technologies as well as new processes unique to thin-film packaging.

• Capture pad layer

Because the position of the vias in a sintered ceramic substrate is not fixed to photolithographic tolerances either within a substrate or from substrate to substrate, the first operation in thin-film processing is the measurement of the location of groups of vias relative to sintered copper fiducials located outside the active substrate area. This map of via locations is then used for photolithographic definition of capture pads.

The capture pads are formed by sputtering a layer of 20 nm chromium, 2 μ m copper, and 20 nm chromium onto the substrate; applying, exposing, and developing a photoresist; and subtractively etching the pad [29]. The locations of the capture pads are determined from the map data and adjusted to transform the nonuniform via location of the sintered substrate vias into a regular grid. This allows subsequent thin-film processing to be carried out without the need for feature location mapping.

• Dielectric layer/stud/interconnections

A polyimide layer is deposited on top of the capture pad layer using standard spin-coat techniques. The polyimide is cured in a stepwise fashion to 400°C in a nitrogen environment.

Laser ablation is then used through a projection mask to generate via holes in the polyimide [30, 31]. This process represents the first use of projection ablation in production. Because of limitations in laser power, it is not possible to ablate all 78 500 vias simultaneously. A step-and-repeat laser ablation pattern is used in which each chip site is ablated separately. This approach is made possible by the fact that each site is identical, requiring only one mask for the entire substrate.

To fill the vias, the thin layer of chromium followed by a thick layer of copper is sputtered onto the substrate. The structure is then planarized [32] to give a solid copper stud which connects the capture pad to the redistribution wiring layer.

• Wiring layer

To maximize yield, a redundant wiring layer is designed and built, using both lift-off technology and subtractive etching technology. The wiring layer is also designed to include both the conductor metallurgy and the joining metallurgy.

A blanket layer of 20 nm chromium, 2 μ m copper, 20 nm chromium is first sputtered onto the surface of the substrate. A lift-off stencil is then built using standard techniques, with the blanket metal film acting as a reactive ion etch barrier. A chromium, copper, nickel, gold metallurgy is then deposited through the lift-off stencil, providing a wiring structure and a surface metallurgy suitable for solder chip joining and ultrasonic wire bonding. The lift-off stencil is then removed.

The blanket sputtered layer is now subtractively etched using standard photoresist and wet-etching techniques. This dual set of processes using separate masks produces a very high yield in the more than 30 meters of wire length incorporated in the redistributed wiring layers.

The wiring layer is then coated with another polyimide film using standard spin-on techniques. After the polyimide is cured, openings are made in the film using projection laser ablation to provide areas for solder joining of chips and ultrasonic bonding of wires.

The substrate with thin-film redistribution is now complete and ready for assembly operations.

Summary

A new multilayer substrate technology has been described which incorporates all the key features required for a high-performance multichip package in the 1990s. This new generation of substrate consists of a unique glass and copper greensheet laminate which is processed to form a cordierite glass-ceramic dielectric with low dielectric constant, matched expansion to silicon, high strength, high density, and high-conductivity copper wiring in its 63 layers. The glass-ceramic substrate is further enhanced by high-density polyimide-copper thin-film redistribution utilizing a number of unique processes. This glass-ceramic/thin-film substrate development has extended the application of multichip technology by overcoming a unique set of challenges posed by a new set of materials. This revolutionary package extends the reliability of multilayer ceramic substrates into the System/390-ES/9000 family of computers.

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Table 7 Thin-film process outline.

Thin-film structure	Thin-film process
Capture pads	Subtractive etching of chromium, copper, chromium
Dielectric layer	Spin application of polyimide
Interconnection stud	Laser ablation Sputtering of chrome copper Planarization
Wiring pattern/ interconnector metallurgy	Subtractive etching of chromium, copper, chromium Metal deposition through lift-off stencil of chromium, copper, nickel, gold
Passivation layer	Spin application of polyimide Laser ablation

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System/390 is a registered trademark, and Enterprise System/9000 and ES/9000 are trademarks, of International Business Machines Corporation.

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