Equipment-related advances in the fabrication of glass-ceramic/copper/polyimide substrates

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This paper pertains to the equipment used to produce the multilayer glass-ceramic/copper/polyimide substrates of the thermal conduction modules (TCMs) used in the IBM Enterprise System/9000™ water-cooled processors. Discussed are a flexible equipment concept applied to the punching, inspection, and testing of the glass-ceramic/copper portion of the substrates, and laser-based equipment for ablation and repair of their polyimide/copper thin-film portion.

Introduction

The TCMs of the IBM Enterprise System/9000™ water-cooled processors use newly developed multilayer glass-ceramic/copper/polyimide substrates [1, 2] that provide significant increases in electrical performance and wiring density [3–5]. Additionally, the new substrates are larger than their alumina/molybdenum predecessors, and contain increased numbers of chip sites and connector pins [1, 2, 6, 7]. These advances required the development of new fabrication equipment, and the following sections describe several aspects of that equipment.

Flexible glass-ceramic/copper thick-film equipment

The key process operations used to produce the glass-ceramic/copper portion of the substrate are casting, blanking, *punching*, screening, *inspection*, lamination, sintering, sizing, and *testing*. While the materials have changed significantly and the processing conditions have changed accordingly, the equipment required is generally the same as that used to produce the alumina/molybdenum substrates. That equipment, its operation, and the process have been described previously [5, 8]. Modifications to the equipment have been made primarily to adapt it to the new product design and size. However, in punching, inspection, and testing (italicized in the process operations list), the equipment modifications are more extensively linked to product design and require more time to implement. While traditional MLC (multilayer ceramic)

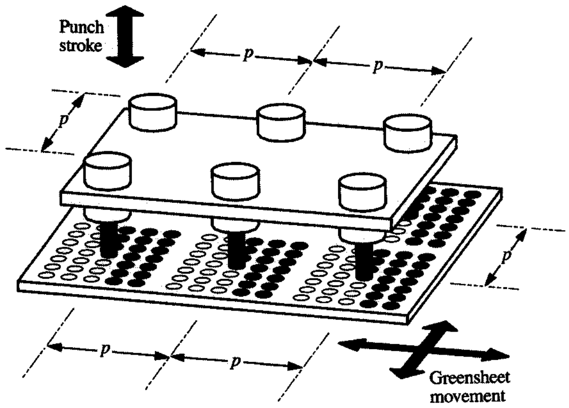


Figure 1

Schematic of traditional via-hole punching equipment. High productivity is achieved by using a multiple-punch head and matching punch spacings with repetitive hole pattern spacings.

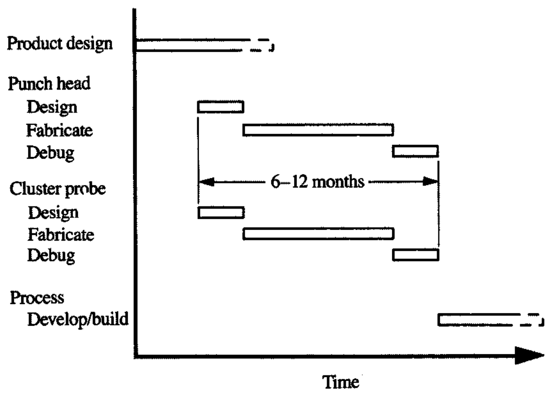


Figure 2

Flow chart illustrating the dominant tasks required to develop a new MLC substrate product.

equipment could have been used to meet the new product design and size requirements, the longer equipment modification time and the need to remodify the equipment for each design iteration would not have met reduced product development cycle time objectives. A "flexible" equipment approach, which minimizes equipment dependence on product design attributes, has provided a way to reduce this cycle time. In the MLC pilot line used to develop new products, replacing or augmenting the traditional equipment for punching, inspection, and testing with equipment based on this approach has reduced the new-product development cycle time by about 50%. Additional reductions are anticipated in the future with the extension of flexible equipment applications.

The terms *technology*, *product*, and *part number* have specific meanings in this paper. The first term pertains to a broad system of engineering knowledge with only the most general constraints. Accordingly, the glass-ceramic/copper/polyimide MLC packaging *technology* is limited only by the materials, multilayered structure, and generic processes with which its MLC substrates are fabricated. A particular set of additional constraints, generally called design rules, imposed on a *technology* is regarded as defining a *product*. The terms *product family*, *product type*, and *product line* are regarded as being synonymous with *product* in this context. In packaging, design rules specify attributes such as physical size, conductor widths and spacings, via-hole diameters, and allowable pattern shapes. New *product* development is regarded as being the creation of a new set of these fundamental design rules. While these rules set limits on design variability, they do not define any particular package design. Ultimately, the design rules are further constrained (by selecting the physical attributes and electrical interconnections required by a particular application) to produce an MLC substrate *part number*, which is composed of individual-layer *part numbers*. The substrate *part number* is common to all of the substrates of a particular design and is not to be confused with a serial number which, if used, is unique to each individual substrate.

- *Via-hole punching*

Traditional punching method

Mechanical punching [5] has been the traditional method used to create via-holes in unfired ceramic layers designated as greensheets. These holes are subsequently filled with a conductive material to create vertical wiring paths through the layers. With a greensheet layer suspended on an x-y table between a punch head and a die, a hole can be formed and the table moved at a rate of up to twenty holes a second. Productivity is achieved by using multiple punches in the same punch-head assembly with a corresponding set of dies. For example, if a punch head is populated with a number of punches equal to the number of chips on a substrate and spaced on dimensions equal to chip pitch p shown in **Figure 1**, each stroke of the punch head forms identical via-holes in each of the chip site locations. The x-y table is then stepped within the chip site pattern to complete a layer containing many thousands of vias in less than one minute.

Flexibility limitations in punching
Mechanical punching with multiple punches has proven to be a highly efficient process for mass production, but it has the following two major limitations.

As product designs change, the dimensions of the via-hole arrays change, and new punch heads must be fabricated before sheets can be punched. Since the multipunch head is a high-precision electromechanical assembly, substantial time is associated with its fabrication, as illustrated in **Figure 2**. Traditionally, that time has dominated the total time required to develop a new MLC substrate product.

As first-level packaging applications have evolved toward the use of mixed chip sets, additional components, and more random component placement, a more flexible via-hole placement capability has become necessary.

A flexible via-hole punching tool
A significant advance in via-hole punch flexibility was achieved with the development of a high-speed single-hole punch, with fine positioning controlled by software. This approach provides cycle time reduction by 1) replacing the relatively long time needed for conventional punch-head design, fabrication, and debugging with the simple loading of a data set; and 2) eliminating time-consuming and costly "false starts" due to product/process changes after conventional punch-head fabrication has begun. Furthermore, it allows relative freedom in via-hole pattern design and avoids the cost associated with all of the punch heads that would otherwise have to be fabricated.

The design incorporates a proprietary new high-speed punch actuator, conceptually shown in **Figure 3**, that provides a punching rate of 100 Hz using a special low-mass punch. The magnetic field B_1, produced by a high current impulse i_1 in the coil, induces a current i_2 in the conductive disk. The induced current i_2 produces an opposing magnetic field B_2 (Lenz's law). The opposing magnetic fields drive the disk away from the coil, thus driving the attached punch through the greensheet and into the punch die below the sheet (not shown). The materials of construction, design, and operating conditions are currently confidential and will be described at a later date, but the speed of the punch is briefly discussed. **Figure 4** shows a typical high-speed punch actuator displacement response curve. The actuator speed is sufficent to allow effective punching even while the table is in constant motion. Using the dimensional definitions in **Figure 5**, the following simple relationships apply for table speed v and punching frequency f:

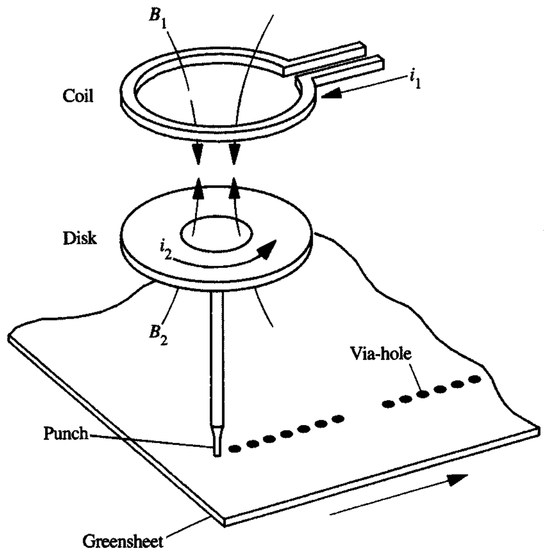


Figure 3

Schematic of high-speed punch actuator, illustrating principles of operation.

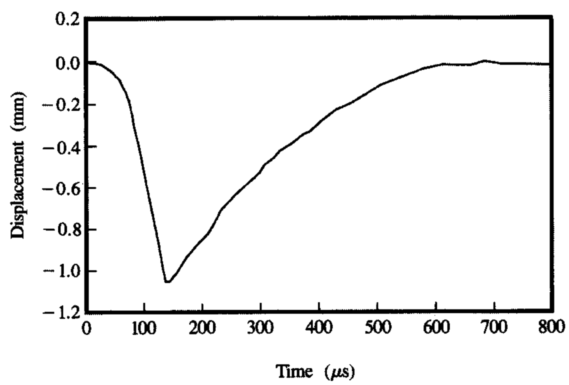


Figure 4

Typical plot of displacement in a high-speed punch actuator as a function of time.

$$v = \frac{d}{t}$$

and

$$f = \frac{v}{a},$$

where d is the allowed hole elongation, t is the time during which the punch is in contact with the sheet, and a is the

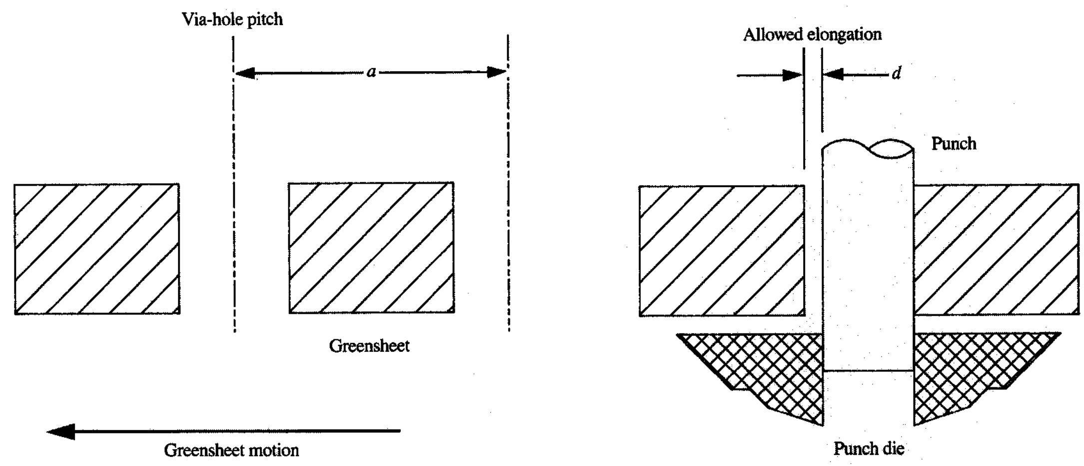


Figure 5

Schematic defining key punching variables.

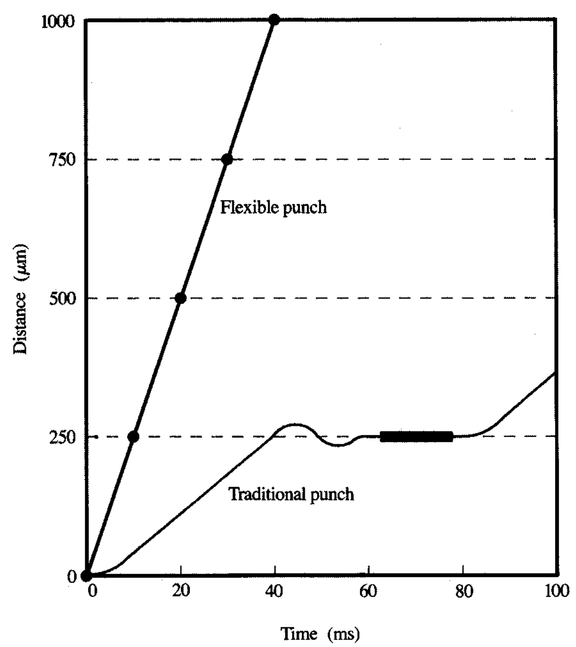


Figure 6

Illustrative timing diagram, showing the improved punching speed of the flexible punch. In traditional equipment the x-y table must accelerate, travel to a hole location (indicated by the dashed line), stop, settle, and then allow the relatively massive punch head to cycle through a punch stroke. The faster, lighter flexible punch can cycle through a punch stroke while its faster-moving table is in motion.

via-hole pitch. Evaluating these relationships using typical values ($d = 5.1\ \mu m$, $t = 0.2$ ms, and $a = 254\ \mu m$) indicates that a uniform table speed of up to 2.5 cm/s and a punch frequency of 100 Hz can be achieved with acceptable via-hole quality. Punching with the x-y table moving at a constant speed eliminates the time required to start and stop the table at each hole location and greatly increases punching throughput. **Figure 6** compares the travel and punching times required by the flexible and traditional methods to produce holes at the locations represented by the dashed horizontal lines. Software developed to drive the punching system accepts part number design information directly from the substrate design system used and converts it into a data file that controls the punch and the x-y table.

The impact of this new "flexible" concept was dramatic. Delay times from completion of substrate design to start of via-hole punching were reduced from several months to several days. As a consequence, via-hole punch-head fabrication was no longer a gating activity in new product development or in the initial production of new part numbers.

- *Greensheet inspection*

Traditional inspection equipment

In the earlier days of the MLC technology, manual inspection with low-power magnification was used for greensheet inspection. It was expensive, slow, and insensitive to certain defects such as missing features. To overcome these limitations, a proprietary automatic

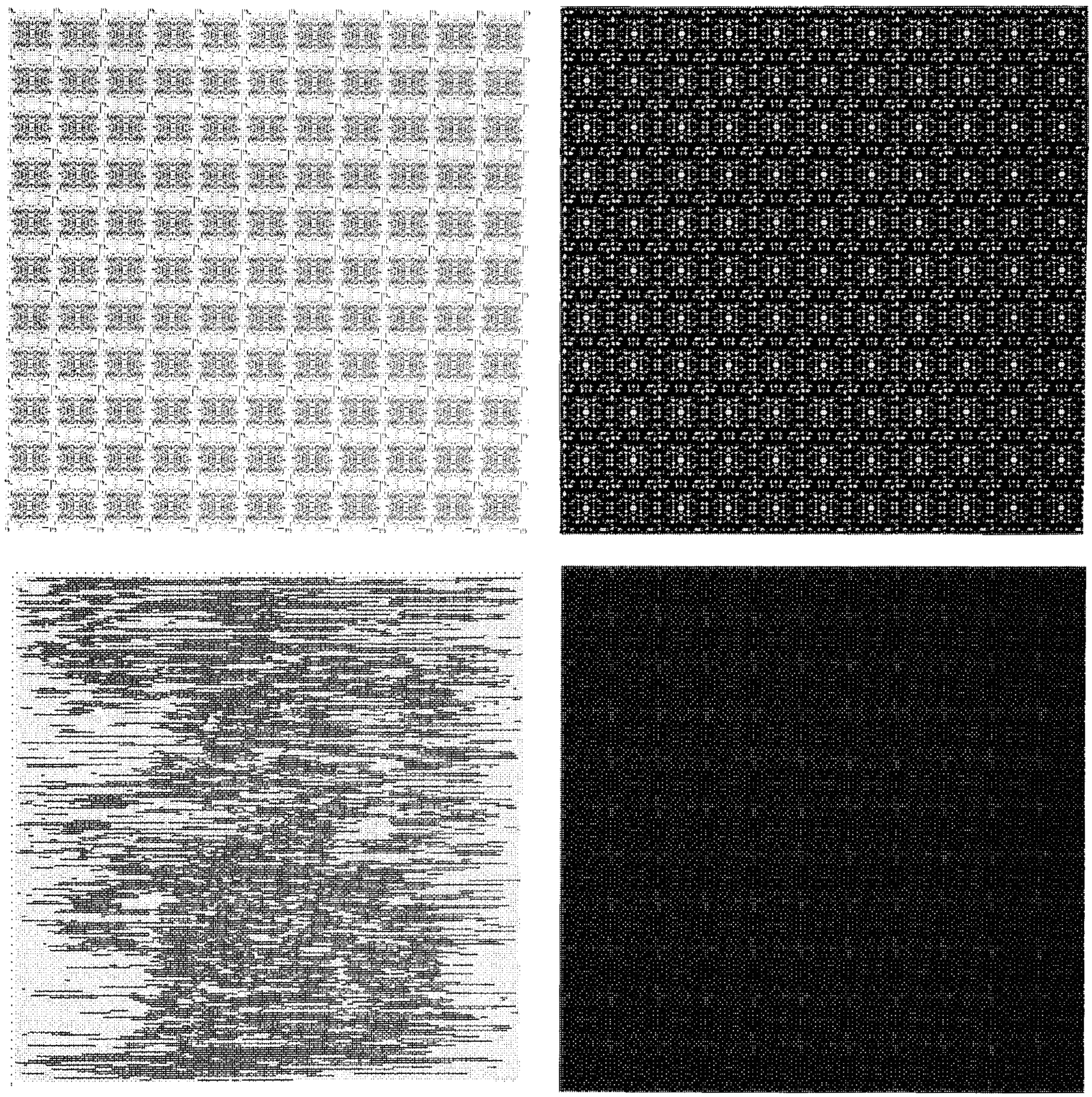


Figure 7

Typical screened greensheet layer patterns containing lines and filled via-holes.

inspection system was developed over a decade ago. Using laser scanning and a complex and highly parallel pattern processor, it could be used to inspect layers such as those in **Figure 7** in six seconds. Its pattern processor was able to compare part number information obtained electronically from the substrate design system with the actual patterns on a layer, thereby making it sensitive to missing or extraneous features.

This early inspection system placed two limitations on greensheet patterning. Features had to be on a single fixed grid, and the particular pattern shapes that were to be examined had to be hard-wired into the pattern processor. Hard-wiring necessitated redesigning and rebuilding a portion of the inspection system each time a new pattern shape was needed in the product design.

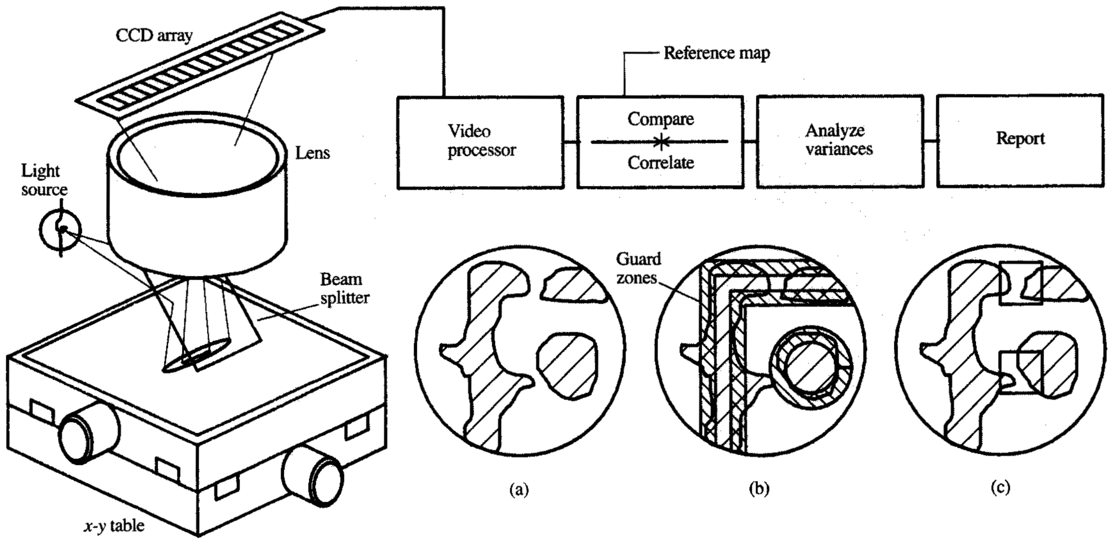


Figure 8

AGIS inspection sequence showing (a) a processed image, (b) typical variances detected by comparing the image and reference, and (c) defects identified after the variances have been analyzed.

A flexible inspection system

Attempts to develop an inspection system free of these limitations led to a new system designated as the Automatic Greensheet Inspection System (AGIS) [9], which uses layer part number information from the substrate design system to generate both a binary bit map of the original design and a binary bit map which contains guard zones on either side of its boundaries. Guard zones, illustrated in **Figure 8**, are used to disregard small variations that either exist in the greensheet pattern or are created during inspection by digitization edge-noise or misalignment. The guard zone width is defined on several levels ranging from global widths for all design features of a particular type down to the bit-by-bit adjustment of the shape and size of a zone around individual features. The mapping process places no restrictions on the size, shape, or placement of the design features. This provides significant flexibility and eliminates design-grid dependence. The individual greensheet pattern and guard zone maps are combined and compressed for storage efficiency to form a reference file containing all of the data needed to inspect greensheets of a particular design.

The inspection process and the system block diagram are illustrated in Figures 8 and 9, respectively. A line scan camera is used to create a binary bit map of the greensheet, which is dynamically correlated for best fit with the reference bit map. Once correlated, data in the guard zones are ignored. Any other variance between reference and greensheet triggers a snapshot of both reference and greensheet to be sent to the defect processor (**Figure 9**), which determines whether it is an actual defect, and if so classifies it into one of eight defect types.

The AGIS system provides more than pattern defect data. As inspection proceeds, information about the pattern location is monitored and used to measure pattern distortion. Line widths can also be measured simultaneously during inspection to produce a statistical compilation of line-width variations. Finally, snapshot bit maps (greensheet, reference, and guard zones) of the defects, which are important for off-line analysis, can be saved.

- *Electrical testing*

Traditional testing equipment

Traditionally, electrical testing of an MLC substrate has been carried out by probing the electrical contact sites (pads) on both the top and bottom of the substrate and electrically comparing all of its conductive paths with

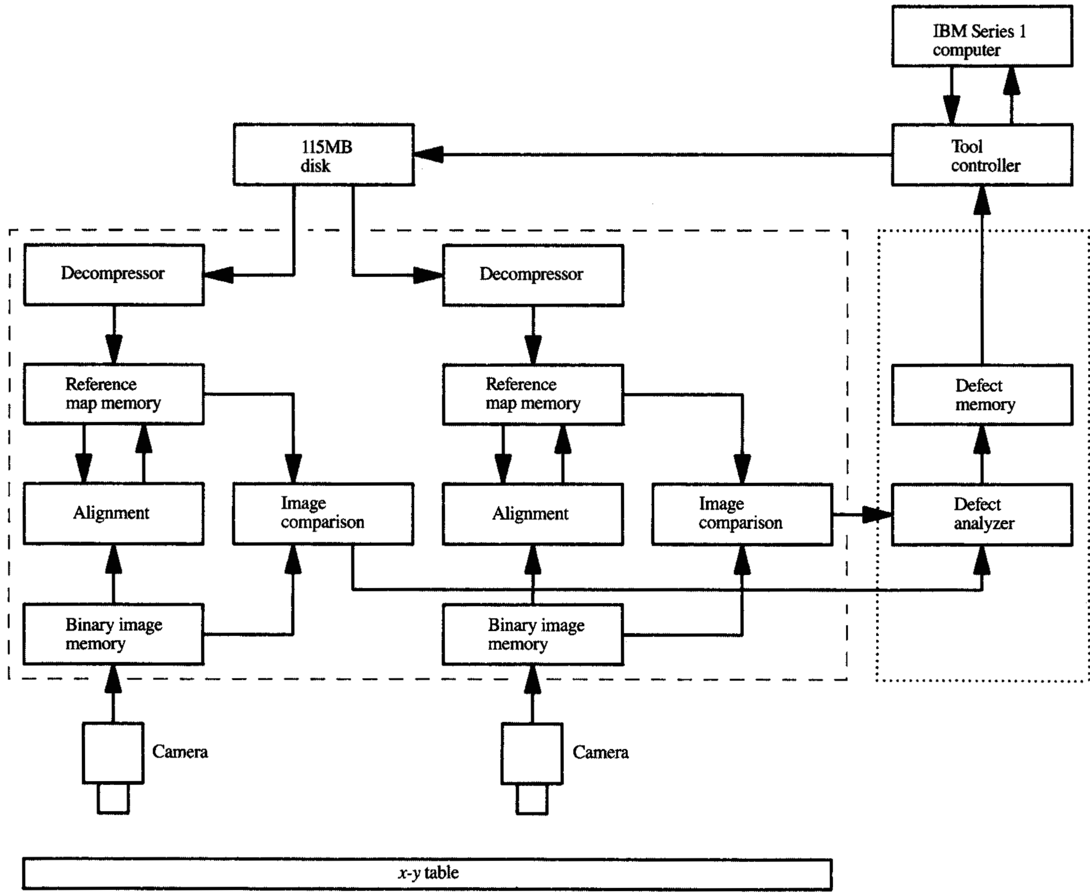


Figure 9

AGIS functional block diagram; image processor enclosed by dashed lines, defect processor by dotted lines.

intended paths (nets) in its design [5]. Missing nets thus represent opens and extended nets represent shorts. Efficiency is achieved by using clusters of probes which contact hundreds or thousands of pads simultaneously, and electronically selecting individual probes.

The efficiency of such cluster probe testing depends on the matching of probe and contact patterns. Contact pattern changes that occur for new designs or engineering changes require the design and fabrication of new probes. Cluster probe design, fabrication, and debugging consume a significant portion of the overall new-product development time, as illustrated in Figure 2.

A flexible testing tool

There has been a need for a testing method that is flexible enough to adapt to different pad layouts without requiring probe modifications, while retaining the speed and reliability of cluster probe contact testing. Electron-beam (E-beam) testing [10, 11] has been found in many cases to meet these requirements by using an electron beam to probe the substrate surface.

An electron beam with variable energy (potential) is produced and is accurately positioned on the substrate by utilizing a combination of x-y table movement and beam deflection. When the beam is used at a particular potential (material dependent), a charge can be placed on a particular pad and its net (the network of wiring and other pads connected to it). Reading (detecting) the presence or absence of a charge on a pad is accomplished with the same beam operating at a different potential. A flood beam located under the substrate is used to charge all of the pin pads on the bottom of the substrate.

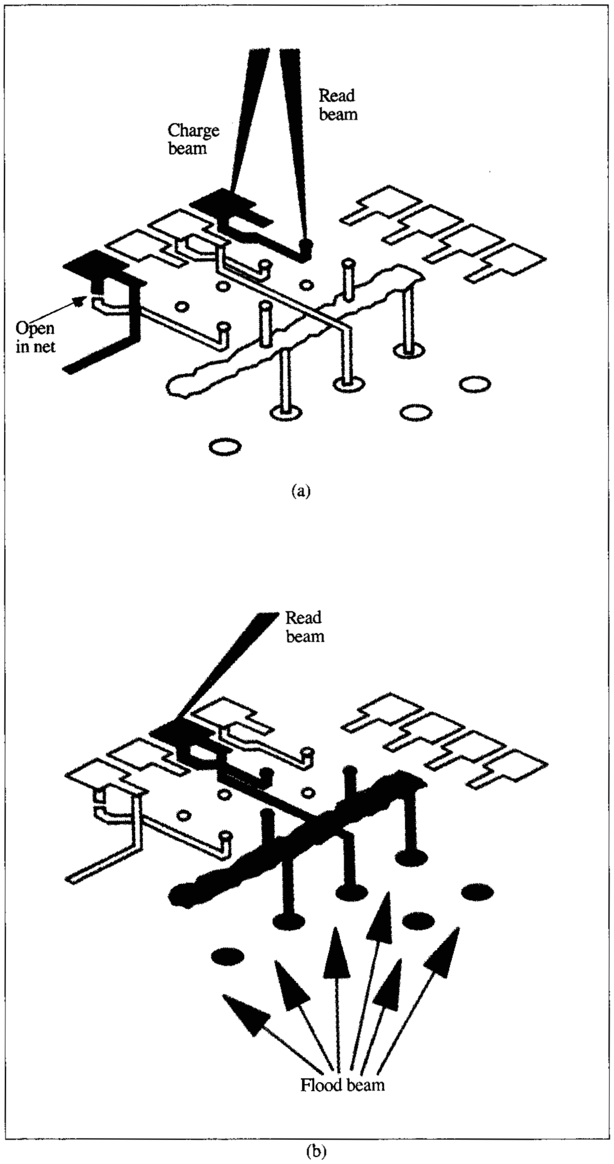


Figure 10

Illustration of E-beam testing process. Top-to-top testing (a) uses one beam potential to charge a net and a different beam potential to detect (read) all points connected to that net. Bottom-to-top testing (b) uses a flood beam to charge all of the lower pads and uses the read beam to detect charge on the upper pads.

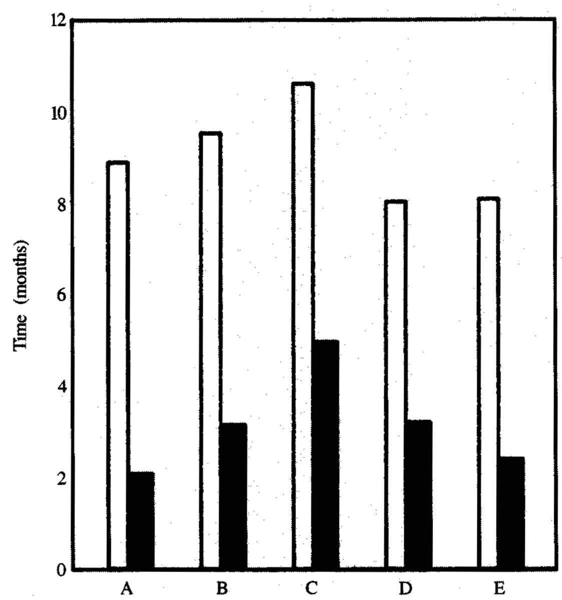


Figure 11

Comparative effect of the use of the flexible punching, inspection, and testing equipment for developing several new substrate products. Open bars: Estimated times without the use of the flexible equipment. Solid bars: Actual times with its use.

In a typical testing sequence, opens are detected by charging a net and reading all of the other pads on the net to ensure that they are also charged. Shorts are detected by leaving the previously tested nets charged and reading all of the pads of the next net to be tested before it is charged. The presence of charge indicates a short to a previously charged net. The specific identity of the previously charged net can be determined after the first scan has been completed (and the substrate discharged) by charging each of the shorted nets and reading to identify the connected net. Finally, connections to the pin pads on the bottom are tested by fully charging the bottom surface with the flood gun and checking the top for the correct charge pattern. **Figure 10** illustrates some of these operations. Only a knowledge of pad locations and the prescribed connections are needed to perform the test. This information is electronically transferred from the substrate design system and converted to a test file for each substrate part number.

The charging and reading beam potentials (0.6–12 kV) depend on the secondary emission yields (as a function of beam energy) for the materials involved and the particular testing regime being used. While the specific values are currently confidential, a general discussion of these material properties and different testing regimes can be found in [10] and [11].

Fast beam deflection, charging, and reading offer a high throughput potential. Examples of these parameters from a development system are a deflection time of 250 μs to cross the entire beam field; a charging time of 0.1–10 ms (dependent on net size and capacitance); and a reading time of 5 μs. A substrate containing 10 000 nets with 30 000 nodes requires a testing time of approximately 2 min (including loading/unloading time) using the values above (assuming a 5-ms charging time) and the slowest dual-potential testing regime.

The principal limitation of E-beam testing is its inability to discriminate between low- and high-resistance shorts. Any continuity of less than 10 megohms [12] is viewed as a connection. Packaging technologies without this magnitude of general isolation cannot be tested using E-beam methods. For technologies with this level of isolation, some shorts may be incorrectly identified if the product specification allows the isolation between adjacent conductors to be less than this value. Contact probe defect verification can compensate for this situation. Our experience is that false defects of this type are rare.

The use of E-beam testing in the MLC pilot line has demonstrated its flexibility by eliminating both the long cluster probe lead time and the need to fabricate several versions of cluster probes as product design rules evolve.

- *Flexible equipment benefits*

The preceding descriptions of flexible punching, inspection, and testing equipment illustrate the flexible approach and how equipment modification time and expense can be reduced. Although such reductions are important, individual tool applications do not usually produce the cycle-time-reduction benefits offered by flexible equipment. For example, in the MLC process, Figure 2 indicates that the use of flexible testing alone would not lead to much of a cycle time reduction because punching can be equally gating. For any given process there is usually a set of gating tools that must be made flexible to achieve meaningful reductions in cycle time. In the MLC substrate process, punching, inspection, and testing represent such a set.

Figure 11 contains a comparison of estimated and actual times required to modify equipment and fabricate substrates for several different products. The estimated times are projected from past experience with traditional tools, while the actual times reflect the use of the flexible equipment approach in punching, inspection, and testing. On average, these data represent an improvement of about 60%.

A similar comparison covering the total new-product development cycle time, which includes product design time, would also be of significant interest. Unfortunately, it cannot be quantified here for two reasons: First, design times are currently confidential; second, they are very sensitive to the style and complexity of specific product requirements and are therefore difficult to quantify in a general way. Nonetheless, we briefly discuss these improvements conceptually to illustrate both direct (obvious) and indirect sources of improvement. **Figure 12** illustrates the total development cycle diagramatically, showing both current and anticipated improvements. The direct improvements in equipment modification time are easily seen. The indirect improvements in development

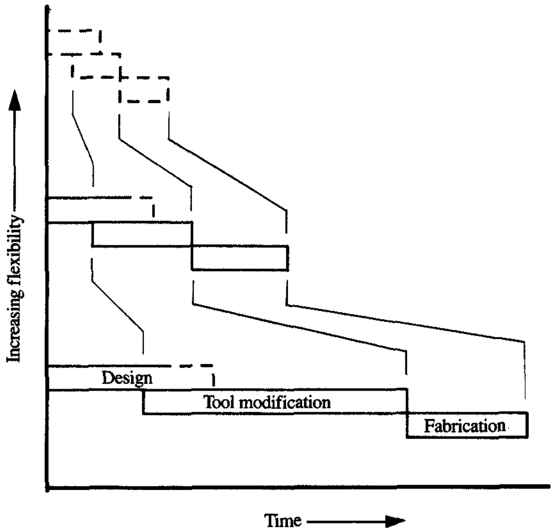


Figure 12

New-product development cycle time (lower bars) has been improved with the introduction of flexible punching, inspection, and testing equipment (middle bars). Additional improvements are anticipated with expanded application of the flexible equipment approach (upper bars).

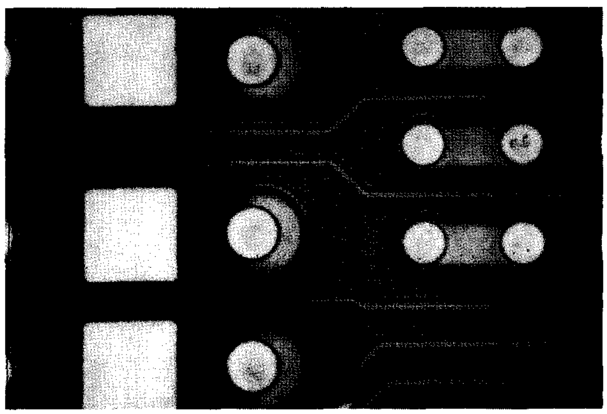


Figure 13

Photograph of typical contact openings in a polyimide layer overlying a patterned copper layer. The openings were produced using laser ablation.

Table 1 Operating parameters for laser-related sytems.

Application	Ablation	Micromachining	Chemical vapor deposition
Laser	Excimer	Excimer	Argon ion
Wavelength (nm)	308	308	514
Power (W)	150	15	2
Pulse rate (Hz)	300	100	(Continuous wave)
Pulse (ns)	50–55	20–40	(Continuous wave)
Spot size (μm)	50–300	5–100	5–20
Fluence (mJ/cm^2)	140–200	10–20	Not applicable
Ambient	Air	Air	Reactive gas
Pressure (torr)	760	760	1×10^{-4}–760
Alignment	Auto	Auto (coarse) Manual (fine)	Auto (coarse) Manual (fine)

lead time and fabrication time produced by flexible equipment are less obvious. Since flexible equipment is less dependent on design attributes, tool modifications can begin much earlier in the design phase, thus reducing design lead time. Design time is also shortened through the design flexibility gained, for example, by the reduced dependence on fixed design grids, pattern shapes, and contact placements. Changes can still occur during design, but they will have a minimal impact on the total development schedule. During substrate fabrication, less down time is required for equipment modification because fewer modifications are needed. Setup changes are reduced to data set replacements, thus significantly reducing both setup time and associated product movement queuing delays. Setup improvements are particularly beneficial where small job sizes and many different products usually drive many changes. Indirect improvements such as these, along with direct flexible equipment improvements, can be significant.

On average, the MLC pilot line has experienced a 50% improvement in its overall new-product development cycle time.

Laser-based polyimide/copper thin-film equipment

In contrast to the thick-film equipment described in [2], which evolved from our existing tool base, the introduction of thin-film processing [13] to substrate fabrication involved the development of new equipment. The implementation of processes for ablation and micropattern fabrication required a new family of laser-based systems for use in both pilot and manufacturing lines.

The following process sequence outlines the thin-film operations and highlights (in italics) their laser-related aspects: capture pad formation, polyimide dielectric application, *formation of via-holes by laser ablation*, blanket metallization, polishing, blanket metallization, lift-off stencil fabrication, wiring and terminal metallization, redundant pattern etching, inspection, testing, *laser-based repair*, polyimide passivation layer application, and *formation of contact openings by laser ablation*.

General descriptions of the types of thin-film equipment used, such as lithographic exposure systems, evaporation and sputtering systems, reactive ion etching (RIE) systems, and polymer preparation tools, can be found in [14] and [15]. Such commonly available systems were modified, where feasible, to accommodate the physical attributes of the glass-ceramic/copper substrates (dimensions = 127 × 127 mm, and up to 11 mm thick; weight = 0.3–0.7 kg; feature size = 25 μm).

The following sections describe the laser-based equipment and several engineering problems that had to be overcome to successfully incorporate it into substrate production. A summary of key laser-related parameters is shown in **Table 1**.

• *Laser-ablation system*

A laser-ablation system [16–20] was developed for producing via-holes for vertical wiring connections and creating contact openings through the polyimide insulating layers of the substrate. The system can be used to drill more than 78 000 holes in a polyimide thin-film layer. A photograph of contact openings produced by this method is shown in **Figure 13**.

Use has been made of the process for the formation of openings having different characteristics (sidewall profile, alignment accuracy, etc.) by varying parameters such as fluence level (to achieve ablation), laser energy level and beam profile (for proper wall angle control), uniformity of the illumination (to ensure via-hole opening), alignment between mask and substrate, and extent of debris removal. For example, a via-hole having a diameter of 80 μm at the upper surface of a 15-μm-thick polyimide layer and a sidewall angle of approximately 60° can be formed using a fluence level of 170 mJ/cm^2.

The laser-ablation system, illustrated in **Figure 14**, is essentially a lithographic step-and-repeat projection system containing a 150-W excimer laser as a light source. The laser is operated at a wavelength of 308 nm, and the optic elements are specially designed for use at high energy densities.

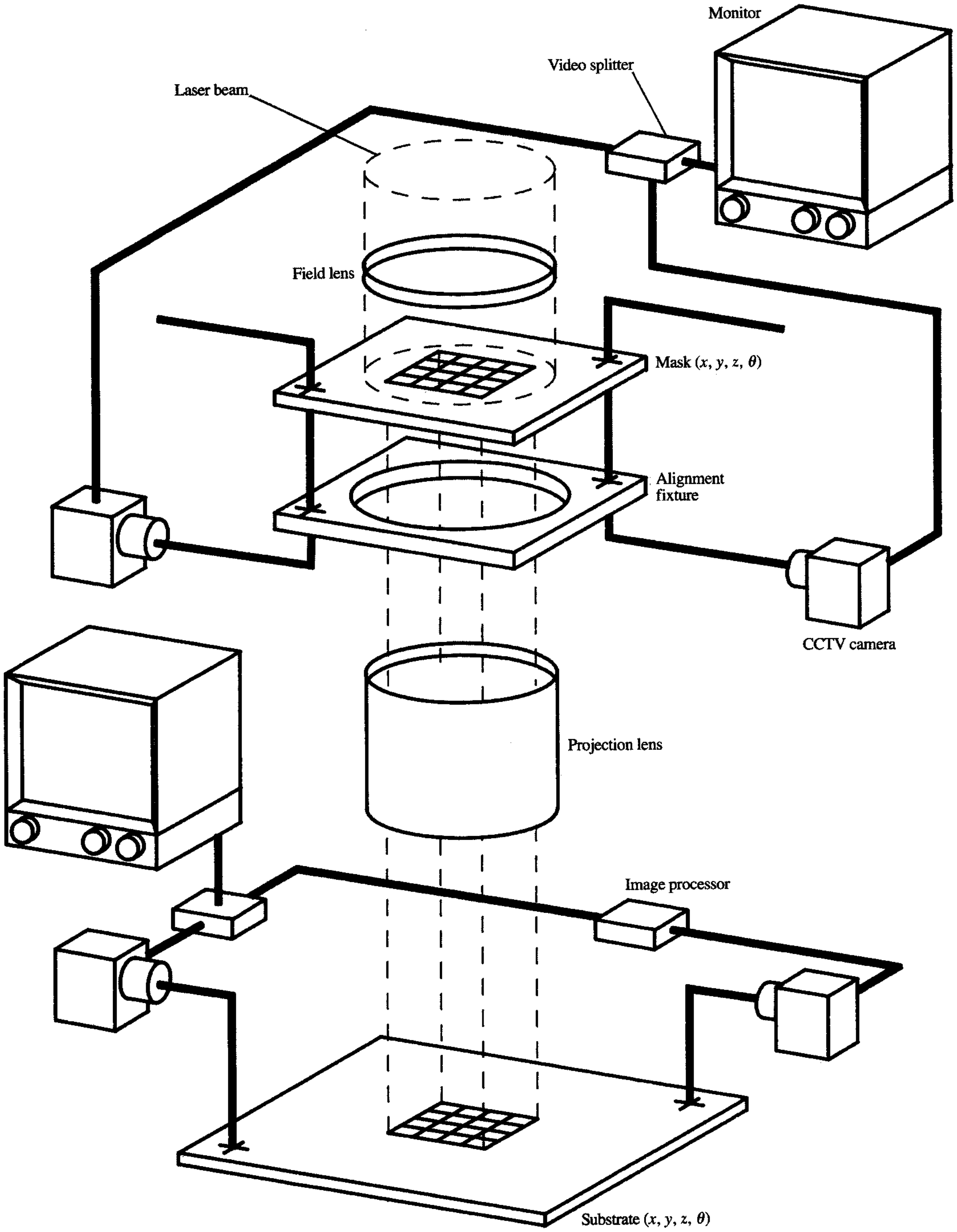
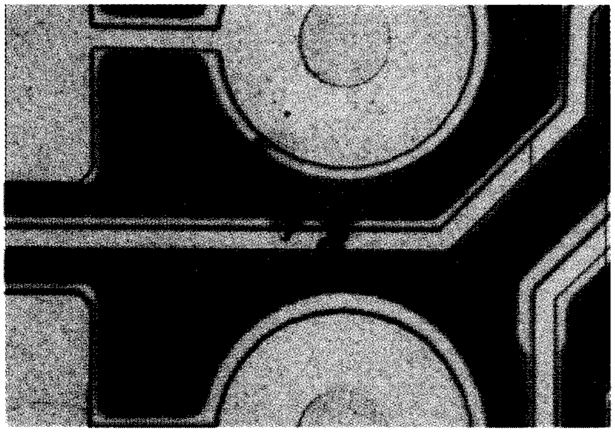
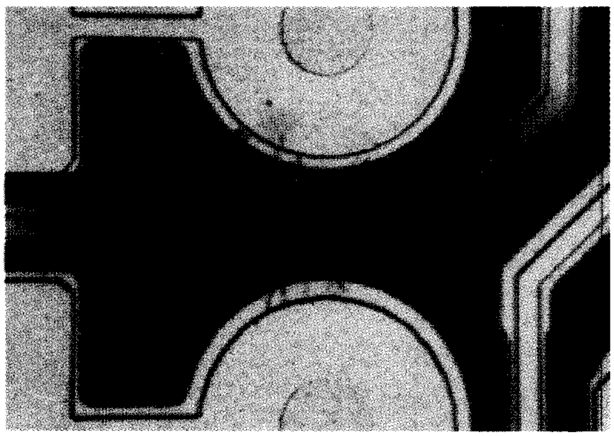


Figure 14

Laser-ablation system, highlighting alignment features and optical paths.



(a)



(b)

Figure 15

Electrical open in a copper conductor, (a) before and (b) after repair by laser-assisted chemical vapor deposition.

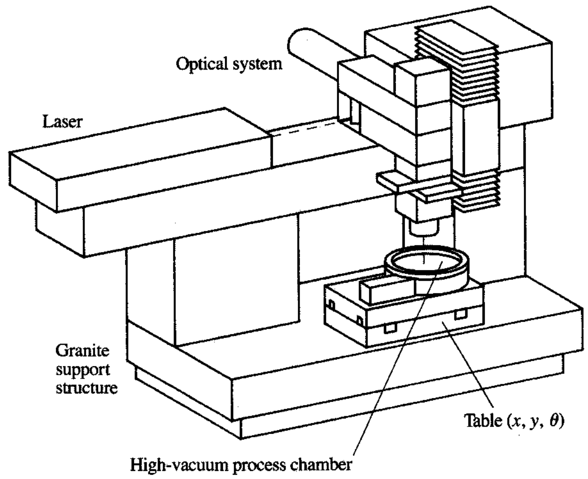


Figure 16

Schematic of laser-assisted chemical vapor deposition system, illustrating its major components.

An alignment fixture is first precisely positioned relative to the optic axis of the system. Each mask is then auto-aligned to the alignment fixture by means of a video imaging and processing system. Substrate-to-mask alignment is achieved by measuring the relative displacement between substrate alignment marks at the four corners of a substrate and the optical axis, using the two video cameras and the image processing system. An alignment algorithm is used to calculate the difference in x, y, and θ coordinates between the substrate and the mask. The differences are then used to compensate automatically for displacement errors.

A large amount of debris is generated during the ablation process. Most of it is removed *in situ* by means of a stream of pressurized nitrogen and a vacuum hose that is used to capture the debris removed by the gas stream. After the ablation process, an additional plasma cleaning process is used to complete the removal of any remaining debris.

The laser used in this application required extensive development to meet power and pulse rate requirements. Recent work to improve pulse rate, power stability, and laser efficiency, and to extend gas lifetime, is described in [21] and [22]. Excimer laser reliability, maintenance, and safety issues in a manufacturing environment have been addressed by Lankard [23].

- *Laser microfabrication systems*

An important aspect of the first-level packaging approach that has been used in IBM is the capability to detect and repair conductor shorts and opens. A laser-assisted chemical vapor deposition (LCVD) system and a micromachining system were developed to make this possible in the copper/polyimide layers of the new glass-ceramic/copper/polyimide substrate.

Laser-assisted chemical vapor deposition

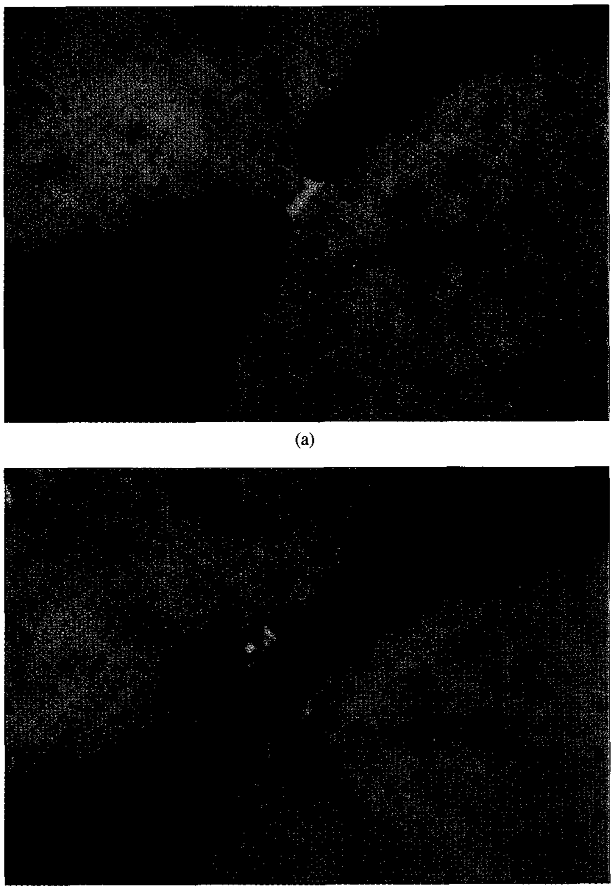
The laser-assisted chemical vapor deposition process was developed by Baum [24] and Wassick [25] and has been used, for example, to selectively add a gold segment to the copper conductor line shown in **Figure 15**, thereby overcoming the electrical open in that conductor. The system, shown schematically in **Figure 16**, contains an argon ion laser operating at a wavelength of 514 nm. The focused laser beam is directed toward the substrate surface in a reaction chamber mounted on an x-y table. A closed-circuit television system permits direct substrate viewing. A conductive gold thin-film pattern can be formed on the substrate by scanning the laser beam relative to the substrate at a predetermined laser power and scanning speed. Servo control of the laser power is provided by a motorized, variable attenuator/beamsplitter system. The spot size is adjusted through a beam-expanding telescope, and computerized shutters control beam access to the work surface.

A stainless steel vacuum cell is initially evacuated with roughing and turbomolecular pumps to less than one millitorr and sealed. An appropriate organometallic precursor is introduced to the chamber, and the vapor pressure monitored by a vacuum gauge. Heat generated by adsorption of the laser light by the substrate promotes a chemical reaction in the gas, resulting in the localized deposition of the conductive film.

Laser micromachining system
Removal of copper, as illustrated in **Figure 17**, is achieved using a laser-based micromachining system. The system, shown in **Figure 18**, consists of a low-power excimer laser operating at a wavelength of 308 nm, computer-controlled stages for coarse positioning, beam delivery, and viewing optics, and a closed-circuit television system to provide an image of the area being processed.

The excimer laser is under microprocessor control and uses predetermined numbers of pulses and pulse rates to achieve desired material removal (to a given depth, etc.). A beam-attenuator system is used to change the fluence without changing other beam characteristics. The system is capable of producing a fluence of up to 20 J/cm^2 with a variation in uniformity of less than 15% at the workpiece, permitting precise and reproducible control of the machining [26]. A computer-controlled rectangular aperture system is used to create beam sizes from 5 to 100 μm in the x and y directions. The aperture can also be rotated 45°. A jog control on the stages allows manual fine-positioning of the beam.

A polyimide layer is applied to the substrate after the laser-based repair and patterned with contact holes that are used during subsequent chip-joining operations.



(a) (b)

Figure 17

Electrical short in a patterned copper layer, (a) before and (b) after removal using laser micromachining system.

Summary
Several equipment-related advances associated with the development and manufacture of the multilayer glass-ceramic/copper/polyimide substrates used in the TCMs of the IBM Enterprise System/9000 water-cooled processors have been discussed.

Tools for processing and testing the glass-ceramic/copper portions of the substrates have been developed that function in a "flexible" manner. By minimizing the dependence of tool design on product attributes, the use of flexible equipment has approximately halved the time required to develop new substrate configurations. Flexible tooling applications have been described for via-hole punching, greensheet pattern inspection, and electrical testing.

Additionally, laser-based tools have been developed for use in the fabrication and repair of the polyimide/copper portions of the substrates. The laser-based tools that have been discussed are 1) a laser-ablation system—for producing up to 78 000 via-holes in a polyimide layer; and 2) a micromachining system and a laser-assisted chemical vapor deposition system—for repairing electrical shorts and opens in a copper layer.

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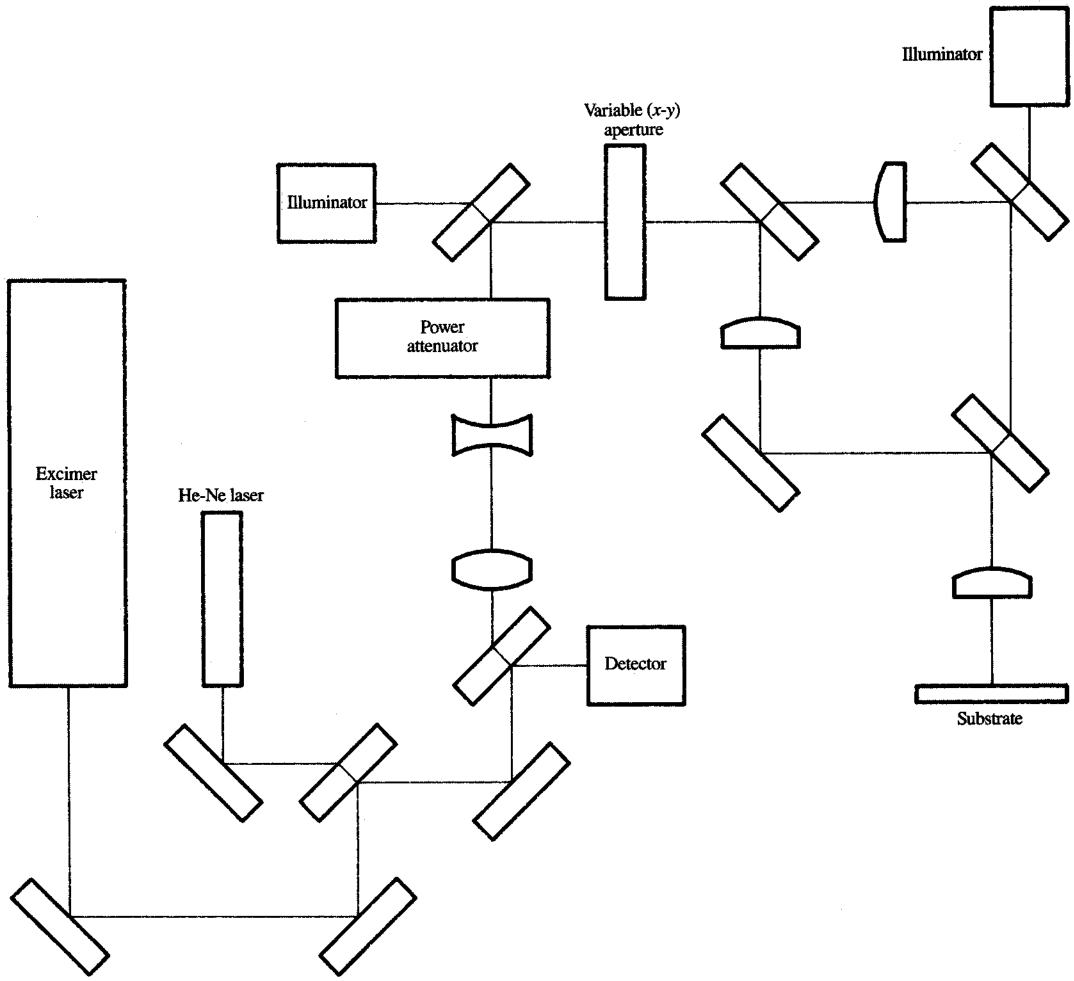

Figure 18

Optical block diagram of laser-based micromachining system.

Enterprise System/9000 is a trademark of International Business Machines Corporation.

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