3D Ceramic Microfluidic Device Manufacturing

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Abstract. Today, semiconductor processing serves as the backbone for the bulk of micromachined devices. Precision lithography and etching technology used in the semiconductor industry are also leveraged by alternate techniques like electroforming and molding. The nature of such processing is complex, limited and expensive for any manufacturing foundry. This paper details the technology elements developed to manufacture cost effective and versatile microfluidic devices for applications ranging from medical diagnostics to characterization of bioassays. Two applications using multilayer ceramic technology to manufacture complex 3D microfluidic devices are discussed.

1. Introduction

A microfluidic device simply means an object often with microchannels where fluidic reactions, separations, and / or detections occur. These devices in general handle nanoliters of reaction volumes and often accomplish the specific task in milliseconds of reaction and diffusion times [1]. Silicon, glass and quartz have been the typical materials of choice for microfluidic devices over the years [2,3,4], but plastic and other materials are gaining acceptance [5,6]. Unlike microtiter plates where fluid is static, microfluidic devices engage fluid in motion at times. Therefore capillary effects, micro pumping and surface tension are to be managed along with design and fabrication of the micro-sized flow conduits precisely. Photolithographic techniques are commonly used to fabricate silicon and the like devices. But, they include the cost associated with the need for expensive clean room facilities, the use of large quantities of chemicals and associated expensive processing. An additional limitation, for example, in using lithography and etching of silicon is that only 2D structures can be fabricated. This impacts the quality of the data and is a hindrance to technology progress by the end user.

Microelectronics packaging technology, in particular, multilayer ceramic (MLC) technology offers very interesting and viable alternate solutions. Multilayer ceramic packaging technology used to build microelectronic modules is very mature and allows the fabrication of a 3D network by simply dividing the structure into multiple horizontal layers. The starting elements for these thin horizontal layers are called green sheets comprised of ceramic particulates dispersed in a polymeric binder system.

Fabrication of microchannels in such thin ceramic green sheets is very challenging. We in IBM have developed a high speed mechanical punch technique [7] that ensures rapid microchannel formation reliably and cost effectively. We also chose a glass ceramic material to improve the hydrodynamic properties and separation performance of the device. The formation of complex microfluidic networks for parallel processing of biological fluids is also possible due to the multilayer processing. The possibility of inclusion of conductors and special functionality elements in microfluidic chips is enhanced again due to the multilayer build. Since multilayer structures are sintered at elevated temperatures to form the resultant microfluidic devices, the need for special sealing between networks is eliminated.
In section 2 we present the channel formation technique in green sheets and the process flow required to build a multilayered microfluidic device. Section 3 describes the actual prototypes fabricated for custom applications. This is followed by a discussion in section 4.

**2. Microchannel Formation and Multilayer Ceramic (MLC) Technology**

2.1. Basic MLC Process

Many IBM computer systems, including the recently announced System z9, utilize one of the world’s most sophisticated packaging technologies, known internally as HPGC or high-performance glass-ceramic. These multichip modules or MCM substrates [8] are made from an IBM-invented cordierite glass-ceramic dielectric and copper-based internal thickfilm conductors. Table 1A outlines the MLC build process, starting with Al₂O₃–MgO–SiO₂ glass particles mixed with organic binders and solvents to form glass ceramic greensheets on casting. These thin cast greensheets, when dry and blanked are fragile, but relatively easy to handle. Green sheets are also flexible and machinable. Individual greensheets are then punched to form 50 to 100 microns circular holes, called vias. There may be a few hundred to over 250 thousand vias formed in approximately 30 seconds in a 175 mm square area of the greensheet. These vias become the vertical connectors in eventual circuits formed among layers. Copper metal powder mixed with organics, in the consistency of a paste, can then be screened on the greensheets using masks in the desired circuit pattern. In doing so, the vias are also filled simultaneously. After drying or the evaporation of solvents, multiples of such screened layers are stacked precisely, with a via-to-via alignment of better than 10 microns. The stack then is laminated using adequate heat and pressure for a given time. IBM uses a patented sinter process to remove the organics from the laminate and co-densify the glass particles and the metal powder with near zero distortion to form conductive circuits in a dielectric ceramic substrate. IBM’s unique sinter process further crystallizes the glass-copper composite into a cordierite based multilayered ceramic with dense co-fired copper interconnects. Subsequently, surface finishing and a plating process occur to yield electrically good modules capable of having semiconductor chips mounted on them for use in computer applications. Table 2A shows the typical groundrules for the features of a high-end substrate.
2.2. Extending the Technology to Microfluidics

In order to build 3D microfluidic structures based on the mature and reliable MLC processing, several new processes had to be developed. These processes included: formation of long channels, preservation of channel dimensions in the assembled green body, stability of open structures during sintering, surface finishing with integrity of channels (open) for flow and flow network (open) connectivity are major challenges. Additionally, the formation of a hydrophilic surface which is an essential feature for flow integrity in micro conduits had to be integrated into the processing. Table 1B outlines the microfluidic manufacturing process thus developed in IBM.

2.2.1. Channel Formation. Figure 1A and Figure 1B show cross-sectional details of a microelectronic substrate and a typical MLC based microfluidic device respectively. In a broader sense, one could conclude that the microfluidic flow network build is somewhat similar to that of a microelectronics interconnect circuit. But in contrast to an electronic circuit, the conduit cross-sections at various locations in a microfluidic network may widely vary. We have developed an overlap punching technique that allows formation of holes and channels of any dimensions and shape using a single size punch. Figure 2A details the overlap punching process for the formation of a 200 microns hole using a 100 microns punch. In this case the stepping of the punch is about one third the punch size. Similarly Figure 2B details the formation of a channel of any length using a circular punch size of 100 microns, for a given punch stepping size of 25, 50 and 10 microns respectively. The punch stepping sizes vary depending on the smoothness requirements for channel sidewall and outer boundary of the hole. Therefore, we could use the conventional MLC high throughput punch tools to make the microfluidic network holes and channels by designing overlap punch algorithms. Figure 3 shows optical photographs of large holes formed in a glass ceramic greensheet using 100 micron punches and 25 microns overlap. Figure 4 is an optical micrograph of sintered feed holes formed using 100 micron punches with near zero overlap punching (left) and 25 microns overlap punching (right) respectively.

Figure 2A Overlap Punch Technique to Form Larger Holes

Figure 2B Overlap Punch Technique to Form Channels

Figure 3 Optical Micrograph of Larger Microfluidic Hole in Glass Ceramic Greensheet
2.2.2. MLC Process for Microfluidic Device Manufacture: As with a conventional MLC substrate build, the microfluidic device manufacturing starts with mixing of glass powder with organics as shown in Table 1B. After the casting and blanking of the greensheets, the required channel and other features are formed as described in section 2.2.1. in appropriate greenlayers. Subsequently these layers are stacked and laminated at an elevated temperature and pressure. Such conditions help maintain an open and undistorted flow network. After singulation, the laminated devices are sintered and densified at much higher temperatures. Since the layers are bonded and fused on densification, the flow networks are inherently isolated from one another. If device surface flatness and smoothness is required for further testing and use, the surface holes may be plugged with molten wax prior to surface finish operations like grind and polish. The wax may be removed with warm organic solvents or thermal processing such as burn-off. Figure 5 gives schematics of one microfluidic network that was built using such a process. In Figure 5A, an example for the network with two greensheet layer build process is shown. In this case the top layer has feed holes and some long channels. The second or bottom layer has the fan-out channels that interconnect the feed hole and the channels respectively. In the middle picture of Figure 5A, the top layer is intentionally off-set slightly with respect to the bottom for understanding.
3. Ceramic Microfluidic Capillary Devices

3.1 Ceramic micromosaic Chip

IBM Researchers have developed 2-D microfluidic chips in silicon for miniaturizing surface immunoassays [9,10]. The surface-binding events in such assays are localized in the independent microchannels of the chip. These chips have loading ports, reaction channels, capillary valves and pumping mechanisms on the chip surfaces. The connecting pathways are located on the surfaces as well. These chips could displace a series of liquids under laminar flow conditions. Ridker, et al. [11] have demonstrated patterning fluorescently-labelled antibodies on a PDMS surface using a silicon microfluidic chip very accurately along with a surface fluorescence immunoassay for CRP, the 114kDa pentameric protein synthesized by the liver. The assay format is a micromosaic immunoassay and it was done using the two dimensional capillary systems. We in IBM Fishkill are developing customer specific 3-D microfluidic networks and manufacturing such devices using our MLC technology. Ceramic micromosaic chips are one such design. Figure 6 shows an optical micrograph of the fully sintered 21 channel multilayer 3-D ceramic chip. This cordierite based glass ceramic microfluidic network has surfaces ground and polished to a 0.01 micron finish. The surface is fully wettable with a water contact angle of ~43 degrees. The device material is chemically stable and is designed to be non-interfering for biological applications. The device in Figure 6 was built using 8 unique greensheet design layers and, if required by an application, one could build a device using even a hundred layers or more by using this technology.

![Figure 6 Ceramic Microfluidic Device](image)

The loading ports are machined to be tear drop shaped to enhance the ease of assay flow; the larger dimension of the port is around 3 mm and the depth is 7 layers deep. The microchannels are one layer deep upon sintering and then they are ground and polished down to ~25 microns deep. The 21 channels are 500 microns apart from one another. The multilayer technology enables the channels to be on the same side as the feed ports as shown in the Figure 6 or on the opposite side as shown in Figure 7. The fan-out and interconnects are internal (3D) to the device. The channels are then connected to the capillary pump to vent out fluids. The channels are about 75 microns wide and in general are made smaller in width than the capillary pump slots. A PDMS slab is used as the substrate when placed over the microchannels. Since the PDMS is very sticky, it seals to the chip surface, thereby isolating the channels from one another. Since the interconnects are internal to the device, fluid cross-over, mixing and creeping over the edges of the PDMS are eliminated. Therefore this device is used for testing 21 independent assays with no concern of cross-contamination.
3.2 Ceramic Tear Diagnostics Chip

Figures 8 and 9 illustrate, another example of an MLC microfluidic chip for a diagnostics application. Here, three greensheet layers were used to build a chip which measures the electrical resistance of tear fluid. It is known that the extent of the salt content in tears is proportional to the extent of Dry Eye Syndrome (DES) that one suffers. Since the volume of tear collected from a DES patient is very small (usually ~20nl of tear is used for the test) the chip should be capable of handling such a small volume with negligible drying during measurement to ensure the reliability of the test. We found that the subsurface channel feature as shown in Figures 8 and 9 accomplishes this. Cosintering of the ceramic with the conductor metal, needed to enable resistance measurements, by using MLC technology helps keep the production cost low. A tear drop when deposited in the feed port travels through the microchannel pushing the air out through the exit hole and in the process bridges the conductors. The electrical resistance of the fluid can be measured between any two of the conductors, and compared with a previously generated calibration chart for DES diagnosis.

4. Discussion

In the emerging field of miniaturization for biological and medical applications, such factors as reliability, design complexity, cost and convenience become very important. MLC which is a well established technology in microelectronics applications is gaining momentum to address many such needs effectively in microfluidics research, diagnostics and testing fields.

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