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(54) HIGH THERMAL EFFICIENCY GLASS MICROFLUIDIC CHANNELS AND METHOD FOR FORMING THE SAME

(76) Inventors: **Philippe Caze**, Fontainebleau (FR); **Thierry Luc Alain Dannoux**, Avon (FR)

Correspondence Address:
CORNING INCORPORATED
SP-TI-3-1
CORNING, NY 14831

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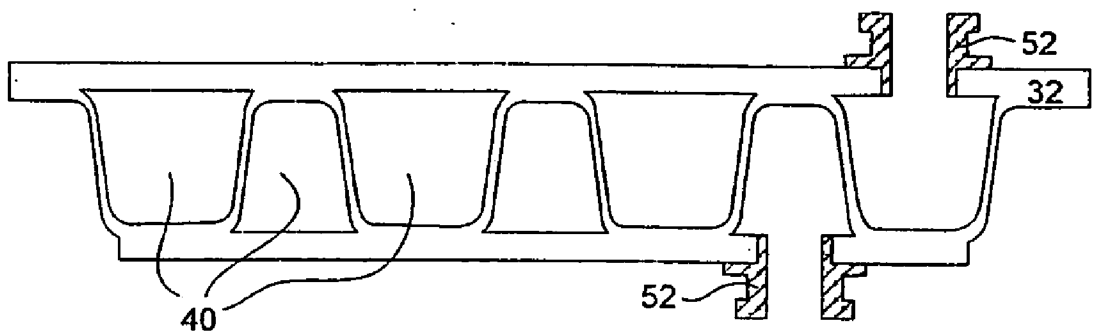
(57) **ABSTRACT**

A microfluidic device includes a formed sheet of glass or glass ceramic material formed to have one or more first micro channels on a first surface thereof and one or more second micro channels on a second surface opposite the first. The second channels are complementary to the first channels and the first channels are substantially closed by a first sheet of glass or glass ceramic material bonded to the first surface of the formed sheet. The second channels may be substantially closed by a second sheet of a glass or glass ceramic material bonded to the second surface. The first and second sheets may also be formed sheets. The device may be formed by vacuum-forming the formed sheet against a single surface mold, then bonding a plate to one or both sides of the formed sheet.



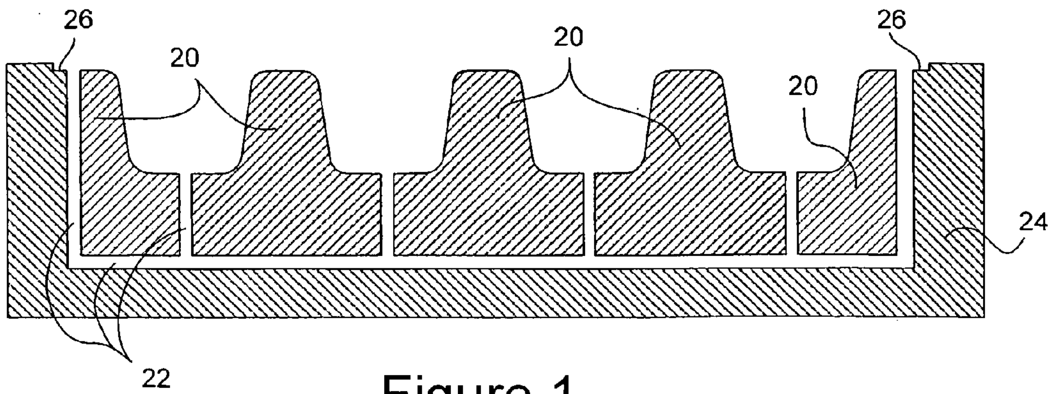


Figure 1

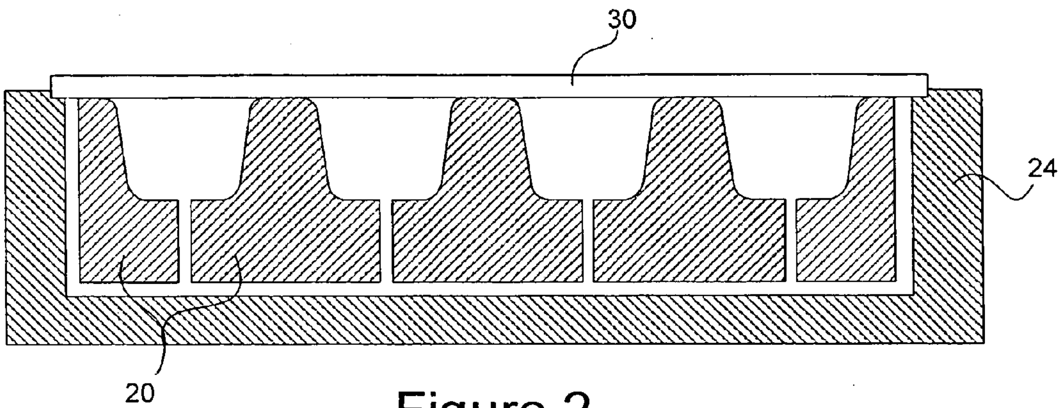


Figure 2

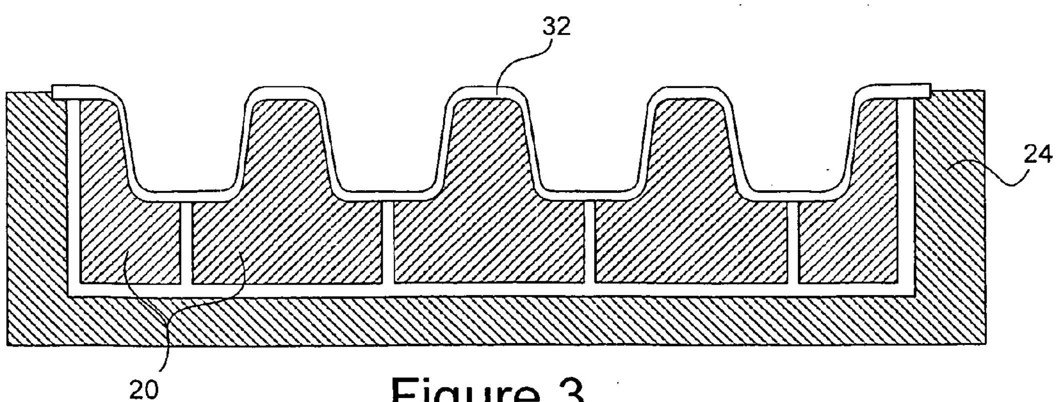


Figure 3

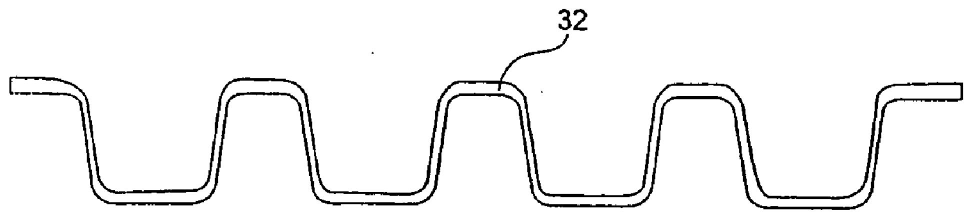


Figure 4

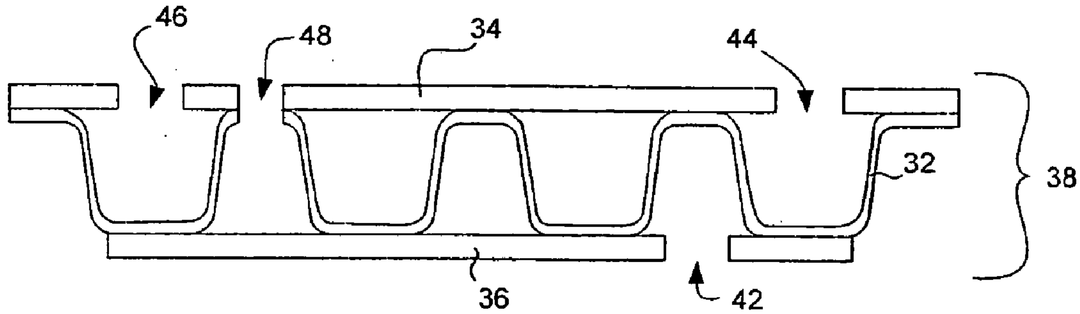


Figure 5

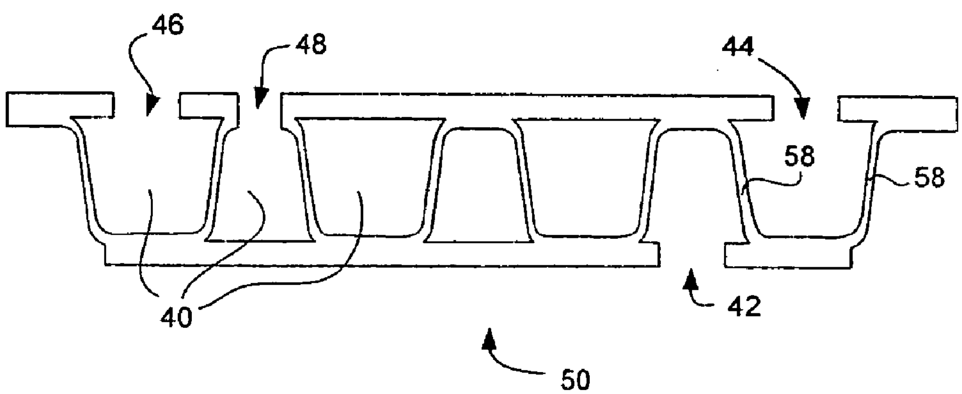


Figure 6

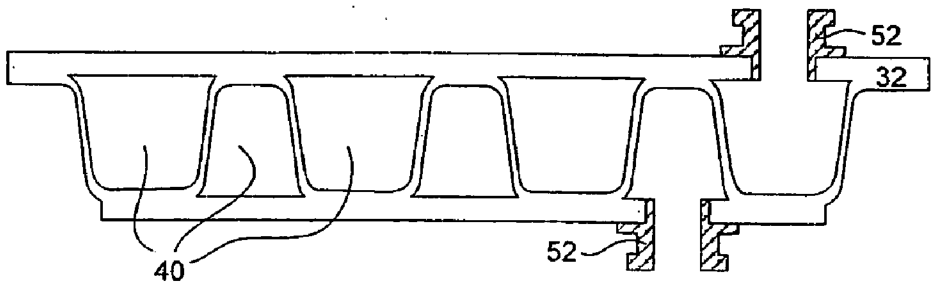


Figure 7

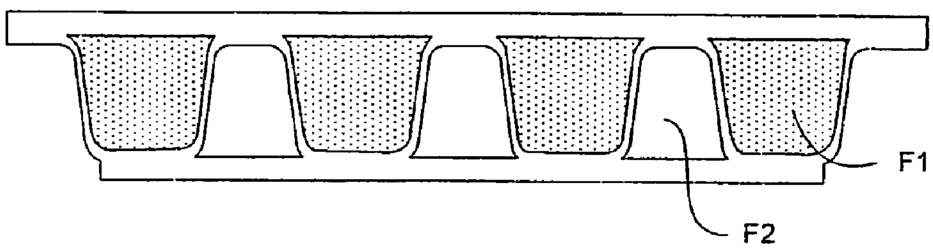


Figure 8

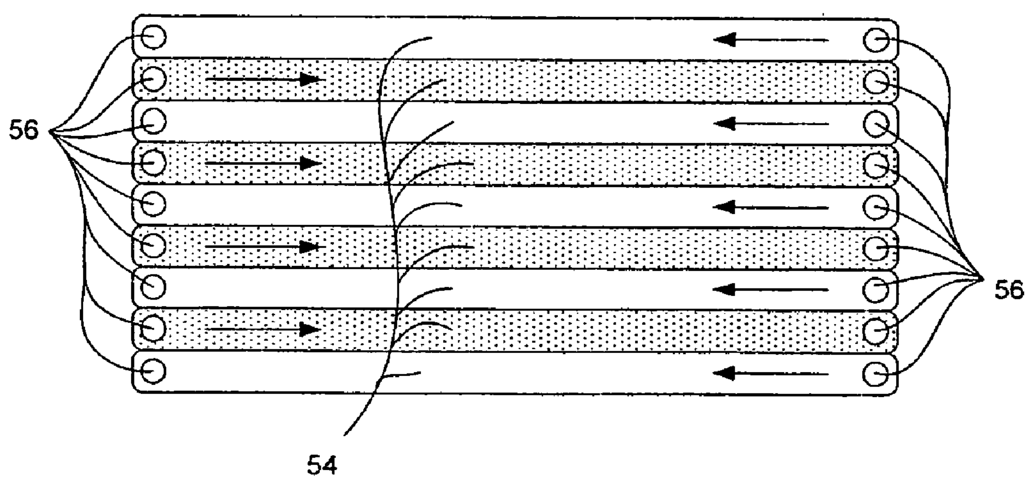


Figure 9

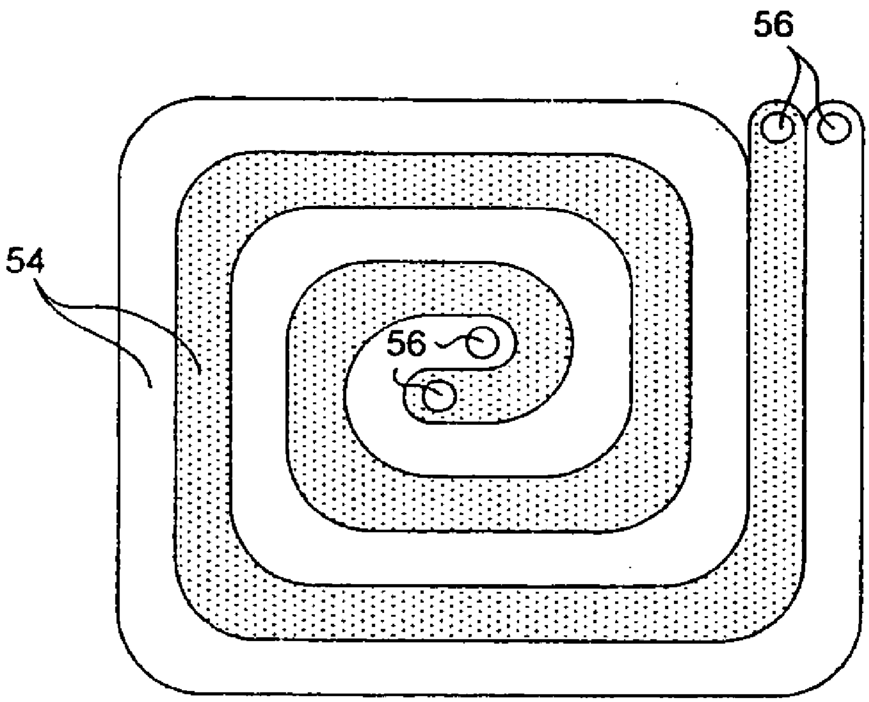


Figure 10

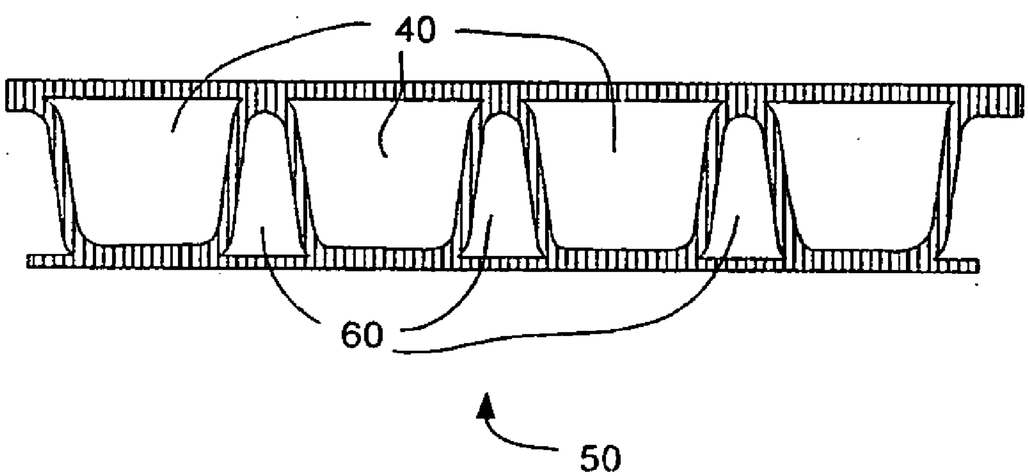


Figure 11

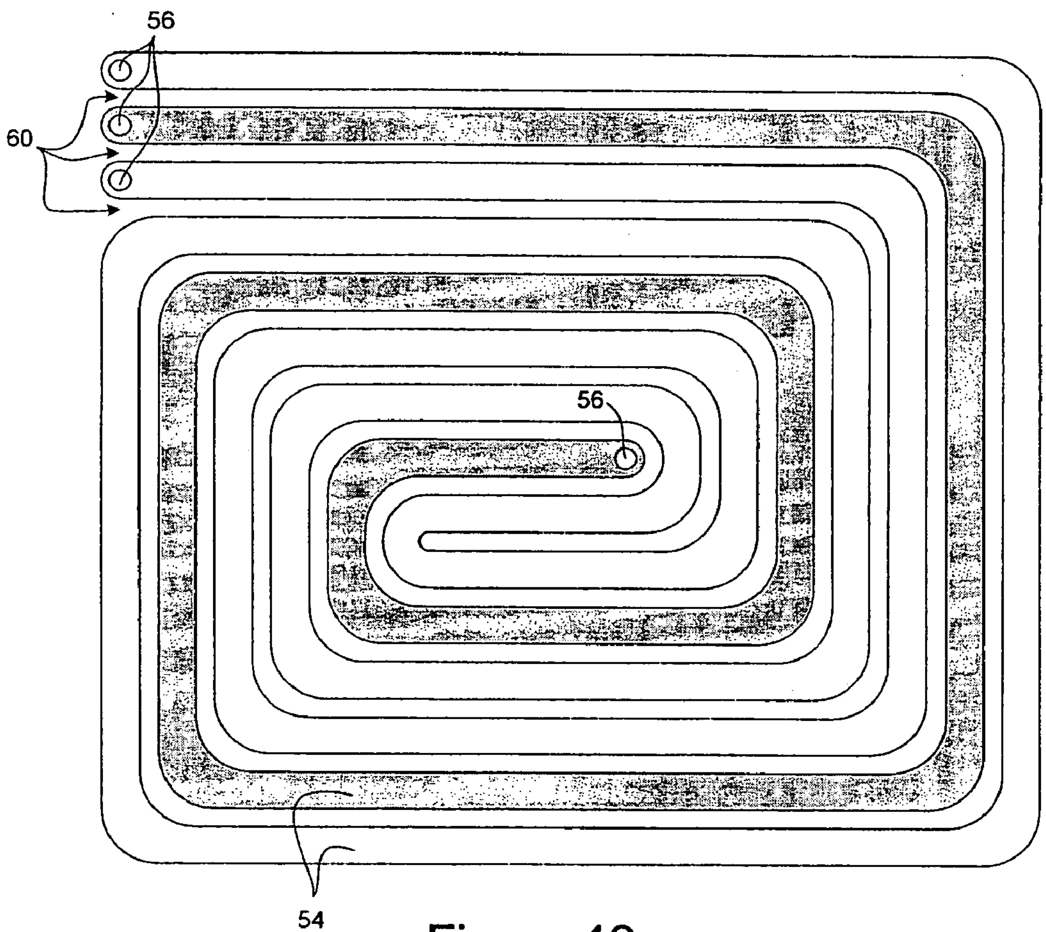


Figure 12

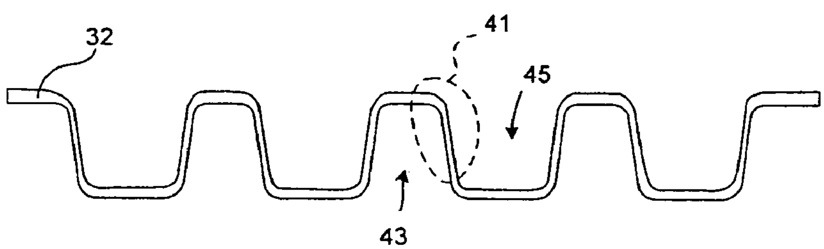


Figure 13

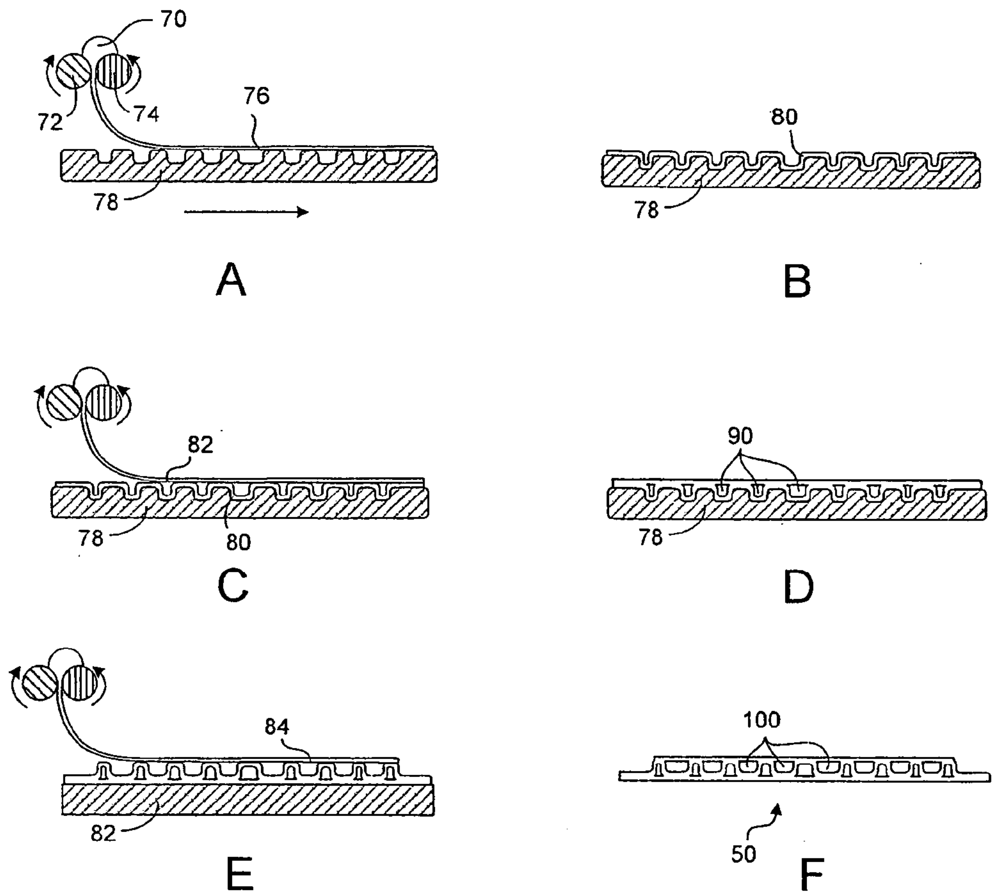


Figure 14

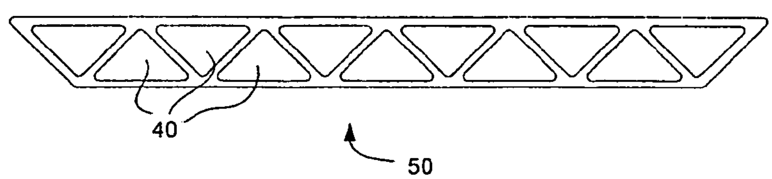


Figure 15

HIGH THERMAL EFFICIENCY GLASS MICROFLUIDIC CHANNELS AND METHOD FOR FORMING THE SAME

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of priority under 35 U.S.C. § 119 of European Patent Application Serial No. EP04291114.9 filed on Apr. 30, 2004.

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] The present invention relates generally to microfluidic devices and methods for producing such devices, and particularly to high-thermal-efficiency glass, glass-ceramic, or ceramic microchannel or microfludic devices and methods for producing such devices.

[0004] 2. Technical Background

[0005] Microchannel or microfluidic devices are generally understood as devices containing fluid passages having a characteristic dimension that generally lies in the range of 10 micrometers (μm) to 1000 μm in which fluids are directed and processed in various ways. Such devices have been recognized as holding great promise for enabling revolutionary changes in chemical and biological process technology, in particular because heat and mass transfer rates in microfluidic devices may be increased by orders of magnitude over rates achievable in conventional chemical processing systems.

[0006] Fluidic microcircuits in glass or glass-ceramic have the advantage of generally superior chemical resistance. But glass and glass-ceramics are relatively poor conductors of heat, and thermal exchange is a key feature in most chemical synthesis. Accurate and safe local heat management generally allows chemical processing at relatively higher concentrations, pressures and temperatures, leading in most cases to better yields and higher efficiency.

SUMMARY OF THE INVENTION

[0007] The present invention provides a device having microfluidic channels formed of thin glass, glass-ceramic or ceramic sheet material possessing good surface characteristics and good strength, and provides a process for reliably and efficiently producing such devices and channels. The thin-walled microchannels allow efficient heat exchange while offering superior chemical durability and heat resistance. The inventive forming process provides a simplified and reliable manufacturing process while providing a resulting device that maximizes thermal exchange.

[0008] According to one embodiment of the present invention, a microfluidic device includes a formed sheet of glass or glass ceramic material. The formed sheet is formed to have one or more first micro channels on a first surface thereof and one or more second micro channels on a second surface opposite the first. The second channels are complementary to the first channels. The first channels are substantially closed by a first sheet of glass or glass ceramic material bonded to the first surface of the formed sheet, and the second channels may be substantially closed by a second sheet of a glass or glass ceramic material bonded to the second surface. The first or second sheet may also be a formed sheet if desired.

[0009] According to another embodiment of the present invention, a method is provided for forming a microfluidic device. The method includes providing a single-surface mold, positioning a sheet of glass or ceramicizable glass on the mold, heating the mold and the sheet, and applying a differential gas pressure to the sheet to conform the sheet to the mold. The result is the formation of micro channels on at least one surface of the sheet, generally on both surfaces. Microchannels are then substantially closed or enclosed by bonding a plate of glass or ceramicizable glass over at least one surface of the sheet that includes microchannels.

[0010] According to yet another embodiment of the present invention, a method is provided for forming a microfluidic device, the method including the step of rolling out a first soft glass sheet over a moving mold, the first sheet having a first surface opposite the mold and a second surface opposite the first surface and resting on said mold; the method further including vacuum forming said soft glass sheet to conform said sheet to said mold, forming thereby a conformed sheet having micro channels on both the first and second surfaces thereof; the method further including rolling out a second soft glass sheet onto said first surface of said conformed sheet, thereby bonding said second soft glass sheet to said conformed sheet and substantially closing said micro channels on said first surface; the method further including releasing said conformed sheet from said mold. The method may additionally include rolling out a third soft glass sheet onto said second surface of said conformed sheet, thereby bonding said second soft glass sheet to said conformed sheet and substantially closing said micro channels on said second surface.

[0011] It is to be understood that both the foregoing general description and the following detailed description present embodiments of the invention, and are intended to provide an overview or framework for understanding the nature and character of the invention as it is claimed. The accompanying drawings are included to provide a further understanding of the invention, and are incorporated into and constitute a part of this specification. The drawings illustrate various embodiments of the invention and, together with the description, serve to explain the principles and operations of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] **FIG. 1** is a cross-sectional view of a mold **20** and vacuum box **24** useful in connection with the present invention;

[0013] **FIG. 2** is the cross section of **FIG. 1** after a thin sheet **30** has been positioned on the mold.

[0014] **FIG. 3** is the cross section of **FIG. 2** after vacuum forming of the thin sheet **30** to form a formed sheet **32**.

[0015] **FIG. 4** is a cross section of the formed sheet **32** of **FIG. 3** after it has been released from the mold **20**.

[0016] **FIG. 5** is a cross section of an assembly **38** including the formed sheet **32** of **FIG. 4** and top plate **34** and bottom plate **36**.

[0017] **FIG. 6** is a cross section of a microfluidic device **50** according to an embodiment of the present invention, the device **50** having been formed by bonding together the assembly of **FIG. 5**.

[0018] **FIG. 7** is a cross section of the microfluidic device **50** of **FIG. 6** including fluid connectors **52**.

[0019] **FIG. 8** is a cross section of the microfluidic device of **FIG. 6** showing the alternating channels in which a first fluid F1 and a second fluid F2 may be disposed.

[0020] **FIG. 9** is a plan view of a microfluidic circuit design potentially useful with devices of the present invention, the design having parallel channels **54** each with two access holes **56**.

[0021] **FIG. 10** is a plan view of another microfluidic circuit design potentially useful with devices of the present invention, the design having two concentric spiraling alternate channels each with an access hole at the edge of the spiral and at the center.

[0022] **FIG. 11** is a cross section of a microfluidic device **50** including minimized channels **60**.

[0023] **FIG. 12** is a plan view of another microfluidic circuit design potentially useful with devices of the present invention, the design including minimized channels **60**.

[0024] **FIG. 13** is a cross-sectional view of the formed sheet **32** of **FIG. 4**, indicating (within the dashed perimeter **41**) a location at which material may be removed to establish fluid communication between neighboring alternate channels **43** and **45**.

[0025] **FIGS. 14A-14F** are cross sections illustrating certain of the steps of a presently preferred inventive method of forming devices of the present invention.

[0026] **FIG. 15** is a cross-section of another embodiment of a microfluidic device **50**, having triangular-shaped channels **40**.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0027] The present invention provides a device having microfluidic channels formed of thin glass, glass-ceramic or ceramic sheet material possessing good surface characteristics and good strength, and provides a process for reliably and efficiently producing such devices and channels. The method of the present invention employs forming by means of differential gas pressure to achieve the desired thin-walled, high-surface quality microchannels of glass, glass-ceramic, or ceramic. The resulting thin-walled microchannels allow efficient heat exchange while offering superior chemical durability and heat resistance. The inventive forming process provides a simplified and reliable manufacturing process while providing a resulting device that maximizes thermal exchange.

[0028] According to the present invention, micro channels are created by a process that includes closing a three dimensional glass, glass ceramic or ceramic shape, and not solely by stacking micro-structured plates. An exemplary process constituting one aspect of the present invention will be described below with reference to **FIGS. 1-7**.

[0029] **FIG. 1** shows a cross-section of an apparatus **10** useful in connection with one aspect of the present invention. The apparatus **10** includes a fluid-circuit mold **20** that has been previously machined or otherwise formed from a suitable material, such as a refractory steel plate NS 30/ASI 310, available from Thyssen-France, 78 Maurepas, France. The mold **20** includes micro-passages **22** for vacuum distribution. The mold **20** is placed in a vacuum-sealing structure such as a vacuum box **24** having a surface or ledge **26** for vacuum sealing surrounding the mold **20**. The interior volume of the vacuum box **24** is connected to a vacuum source such as a vacuum pump not shown in the figure.

[0030] Prior to use, the mold **20** is coated with a suitable release agent, such as calcium hydroxide (Alcohol+Disperbick 190 at 0.5% suspension, for example). Disperbick 190 is readily available from BYK-Chemie Gmbh, Abelstr. 14 D-46483 Wesel, Gemany.) The relief agent is desirably sprayed uniformly over the entire surface of the mold **20**.

[0031] As shown in **FIG. 2 a** thin sheet **30**, composed of a suitable glass material and having a surface area sized to cover the surface or ledge **26**, is then applied to the mold **20**. The glass may be Corning 1737® for example, available from Corning Incorporated, Corning N.Y., USA.

[0032] The sheet **30** and the mold **20** are then heated together to a point above the annealing point of the glass material, and desirably near but below the softening point thereof. In the case of Corning 1737® which has an annealing point of about 721° C. and a softening point of about 925° C., for example, the mold and sheet may be heated to about 870° C. over a period of about 20 minutes.

[0033] Vacuum is then applied to the vacuum box **24** for a sufficient time to cause the sheet **30** to conform to the profile of the mold **20**, resulting in formed sheet **32** as represented in **FIG. 3**. As an alternative, gas pressure could be applied to the surface of the thin sheet **30** opposite the mold **20**, and the micro-passages **22** could be used solely to relieve back pressure. As an additional alternative, positive pressure from outside the mold and vacuum within the mold could be used at the same time.

[0034] The vacuum forming, in addition to reshaping the thin sheet **30** into a formed sheet **32**, also has the effect of redrawing ("vacuum redrawing") the sheet **30**, resulting a formed sheet **32** that is generally thinner than the originally thin sheet **30**, particularly in the areas where material was drawn into the mold. This vacuum forming process thus allows reliable, repeatable formation of wall structures as thin as 0.3 mm or less, desirably in the range of about 0.2 mm to about 0.7 mm or less. On the other hand, using suitably thick starting sheets, wall structures of greater thicknesses may also be formed using this process, including thicknesses in the range of about 0.7 mm to about 3 mm, which thicknesses may be useful in for use in high pressure or very high pressure applications.

[0035] After vacuum forming, the mold **20** and formed sheet **32** are cooled to a temperature sufficiently low to allow the formed sheet **32** to retain its formed shape, but desirably sufficiently high to allow easy removal from the mold **20**. For Corning 1737®, for example, the sheet **30** may be cooled to about 750° C. over a 2 minute period. A light air pressure is then applied to the vacuum channels **22** to remove the formed sheet **32** from the mold **20**. The release agent significantly facilitates this step. The resulting formed sheet **32** is depicted in cross section in **FIG. 4**.

[**0036**] Next, top and bottom plates **34** and **36** are positioned against the formed sheet **32** as shown in the cross section of **FIG. 5**, forming an assembly **38**. Desirably, any desired input and output holes are formed through the top plate **34** and/or the bottom plate **36**, (and through the formed sheet **32** also, if desired) by drilling, grinding, or other suitable process, before the assembly **38** is bonded together. As shown in **FIG. 5**, the access holes may be formed in opposite plates as in the case of holes **42** and **44** (on the right side in the Figure) or, if desired, in the same plate, as in the case of holes **46** and **48**. Access holes may extend, as in the case of hole **48**, through both the top plate **34** and the formed sheet **32**.

[**0037**] The assembly **38** is then bonded to form a microfluidic device **50** having closed or enclosed microchannels or passages **40**, as shown in **FIG. 6**, with sample access holes **42**, **44**, **46**, and **48**. The bonding of the assembly **38** may desirably be accomplished by glass-to-glass thermal bonding of Corning 1737® glass plates to a Corning 1737® formed sheet, by maintaining the assembly **38** at about 870° C. for about 90 minutes. By drilling or otherwise forming the access holes prior to bonding, micro cracks and surface damage from the hole forming process, if any, can be annealed.

[**0038**] The above-described example of the inventive process is capable of forming, in the same process step, twin circuits separated by a thin glass layer. Starting from a 0.5 mm thick sheet, for example, the thickness of the sidewalls **58** may range from 0.4 to 0.3 mm, offering little barrier to heat exchange. The sidewalls may be thicker if desired, by starting with a 0.7 mm or a 1 mm thick sheet.

[**0039**] Standard fluid connectors **52**, shown in **FIG. 7**, can be affixed by polymeric bonding or other compatible glass-bonding means.

[**0040**] Since the forming process described above easily produces twin complementary channel patterns on the upper and lower surfaces of the formed sheet **32**, one natural application for microfluidic devices formed in this manner is heat exchange. Channels one side of the formed sheet **32** may contain a first fluid **F1**, while channels on the other side of the formed sheet **32** may contain a second fluid **F2**, as shown in **FIG. 8**. Because the alternate channels are separated by a minimally thick sheet of glass, quick and efficient heat transfer is possible.

[**0041**] **FIG. 9** shows a plan view of one possible orientation of alternate channels as in **FIG. 8** in a microfluidic circuit. The channels **54** may be positioned in a straight, parallel arrangement, with access holes **56** provided at each end of each channel. Such channels can be used for two fluids in alternate channels in contrary flow, as suggested by the arrows and shading in the Figure, or in other configurations, such as in parallel flow if desired, for high-throughput heat exchange.

[**0042**] **FIG. 10** shows a plan view of another possible orientation of alternate channels such as in **FIG. 8**. In **FIG. 10**, two alternate channels **54** are arranged together in a concentric spiral with access holes **56** at the outer edge and at the center of the spiral.

[**0043**] Microchannel arrangements created by the processes described herein need not be limited to alternating, non-communicating channel arrangements such as those shown in **FIGS. 9 and 10**.

[**0044**] For example, if desired, the mold on which the formed sheet **32** is formed may be designed to minimize the channel size of some or all channels on one side of the formed sheet **32**, resulting, in minimized channels **60** interspersed with regular channels **40**, such as shown in the microfluidic device **50** of **FIG. 11**. The resulting minimized channels may then be omitted from the fluid circuit design altogether. If desired, the minimized channels **60** may alternatively be filled with air, helium or other gas, or even a partial vacuum to aid in thermally insulating adjacent fluid circuit channels. Conversely, the minimized channels may also be filled with water or other fluid if high thermal mass and relatively high thermal conductivity and temperature uniformity is desired.

[**0045**] An embodiment of a device according to the present invention having minimized channel size on one side of the formed sheet is shown in plan view in **FIG. 12**. In this embodiment, minimized channels **60** are not included in the microfluidic circuit, and the non-minimized channels **54** are provided with access holes **56**. In embodiments such as the one shown in **FIG. 12**, it is possible to close the non-minimized channels with a single plate.

[**0046**] In another alternative embodiment of microfluidic devices of the present invention, openings for fluid communication may be established, as desired, between the fluid channels on one side of the formed sheet **32** and the complementary fluid channels on the other side, by removing selected portions of the channel walls within the formed sheet **32**. For example, removal (by grinding, drilling, or other suitable process) from the formed sheet **32** of the material within the dashed perimeter **41** shown in **FIG. 13** will establish a fluid connection or through-hole between the neighboring alternate channels **43** and **45**. The removed material need not extend to any great length along the channels (in the direction in and out of the Figure), so the formed sheet **32** can substantially retain its structural integrity.

[**0047**] Microfluidic devices of the present invention have been successfully produced using various glass compositions, including Corning 0211, Corning 7059, Corning 1737, available from Corning Incorporated, Corning, N.Y., USA, and Glaverbel D 263, available from Glaverbel Group, 1170 Brussels, Belgium. Of these, Corning 1737 offers the smallest coefficient of thermal expansion of about 37.6×10^{-7} C. A microfluidic device formed of Corning 1737 is suitable for use with fluid temperatures of up to 650° C. Alumino-boro-silicate glasses, such as Kerablack, (available from Keraglass, 77 Bagneau sur Loing, France) may also be used. After the microfluidic device is formed as above, then Kerablack would by ceramicized into vitroceram, providing an ultra-low coefficient of thermal expansion of about to -2.10^{-7}.

[**0048**] As yet another embodiment of the present invention, two glass materials having reasonably close coefficients of thermal expansion may be used to form a single microfluidic device. For example, the formed sheet **32** may be formed of Corning 1737 while the top and bottom sheets **34** and **36** used to close the passages in the device **50** may be formed of Pyrex 7740 (see **FIGS. 5 and 6**). The difference in softening point of these two glass materials of about 100° C. allows thermal sealing at about 780° C. This lower thermal sealing temperature can potentially help prevent post-vacuum-forming deformation of formed sheet **32**.

[**0049**] Preferred Manufacturing Process

[**0050**] The isothermal process described above has been demonstrated for prototype building and may be suitable for very small-scale manufacture. One embodiment of a more cost-effective and efficient industrial process is described below with reference to **FIGS. 13A-13F**.

[**0051**] As shown in **FIG. 14A**, glass gob **70** is delivered from a tank feeder (not shown) onto two heated rotating rollers **72** and **74**. A soft glass sheet **76** is then rolled out over a moving mold **78** and vacuum formed immediately, forming a formed sheet **80** as shown in **FIG. 14B**, with its thickness reduced relative to the soft glass sheet **76** by the vacuum redraw. In a second and immediately following pass, a second soft glass sheet **82** is put over the formed sheet **80**, as shown in **FIG. 14C**. The second soft glass sheet immediately closes the upper surface of the formed sheet **80**, as shown in **FIG. 14D**, forming closed upper channels **90**. The upper channels **90** are thus created and closed quickly, in as short as about 5 to 10 seconds. The formed sheet with its closed upper channels **90** is then removed from the mold and placed in inverted position on a support **82**. The previously unclosed complementary fluid circuit is then covered with a third soft glass sheet **84**, as shown in **FIG. 14E**, forming closed lower channels **100** and resulting in the microfluidic device **50** of **FIG. 14F**.

[**0052**] For forming 7740 Pyrex, for example, desirable thermal conditions are 1350° C. glass delivery onto 650° C. heated rollers and mold. The release agent is desirably carbon black from acetylene cracking. The thinner the glass sheet, the higher the roller temperature should be. 0.8 mm rolled and vacuum formed sheets have been demonstrated, offering less than 0.2 mm thick glass at the bottom of the formed shape.

[**0053**] Microfluidic devices of the present invention and produced by the process of the present invention need not be limited to designs with near-vertical channel walls. **FIG. 15** shows a cross-sectional view of microfluidic device **50** having triangular channels **40** therein. This and other configurations are easily achievable according to the present invention. For example, as a further extension of the present invention, one formed sheet may be bonded to another formed sheet to form even higher-aspect-ratio channels, or to form complex passages between the two sheets.

[**0054**] The process and method of the present invention allow repeatable and reliable formation of very thin-walled glass microchannels. The resulting microfluidic devices of the present invention are particularly suited to high-throughput microfluidic heat exchange.

[**0055**] In comparison with other methods of forming microfluidic devices, the current invention also allows for the provision of increased wall surface area between adjacent channels relative to the cross-sectional area of the channels. The large wall surface area is mainly attributable to the relatively high channel aspect ratios (ratios of channel height to channel width) achievable with the disclosed method, as high as 2:1 or more.

What is claimed is:

1. A microfluidic device comprising a molded sheet of a glass or glass ceramic material bonded to at least one sheet of a glass or glass ceramic material so as to form micro channels.

2. The microfluidic device as recited in claim 1 wherein the molded sheet of a glass or glass ceramic material is bonded between two sheets, each of a glass or glass ceramic material, so as to form complementary micro channels.

3. The microfluidic device of claim 2 wherein the molded sheet comprises a first glass material and the two sheets each comprise a second glass material, the first glass material having a higher softening temperature than the second glass material.

4. The microfluidic device of claim 1 wherein the molded sheet comprises a first glass material and the two sheets each comprise a second glass material, the first glass material having a higher softening temperature than the second glass material.

5. The microfluidic device of claim 2 further comprising at least one through-hole through the molded sheet, said through-hole establishing fluid communication between an adjacent pair of said micro channels.

6. The microfluidic device of claim 1 further comprising at least one through-hole through the molded sheet, said through-hole establishing fluid communication between an adjacent pair of said micro channels.

7. The microfluidic device of claim 1 wherein the molded sheet, between adjacent micro channels separated by said molded sheet, has a thickness in the range of about 0.2 mm to about 0.7 mm.

8. The microfluidic device of claim 1 wherein the molded sheet, between adjacent micro channels separated by said molded sheet, has a thickness in the range of about 0.7 mm to about 3 mm.

9. The microfluidic device of any one of claims **1** wherein said at least one sheet comprises a second molded sheet.

10. A method of forming a microfluidic device, the method comprising:

providing a mold;

positioning a softened sheet of glass or ceramicizable glass over said mold;

applying a differential gas pressure to said sheet to conform said sheet to said mold, thereby forming micro channels on at least one surface of said sheet;

substantially closing said micro channels on said at least one surface of said sheet by bonding a sheet of glass or ceramicizable glass over said mold.

11. The method of claim 10 further comprising the step of ceramicizing said plate and said sheet.

12. The method of claim 10 wherein the step of applying a differential gas pressure to said sheet to conform said sheet to said mold comprises applying a vacuum to said sheet between said sheet and said mold.

13. The method of claim 10 wherein the step of positioning a softened sheet of glass or ceramicizable glass over said mold comprises rolling out a first soft glass sheet over said mold.

14. The method claim 10 wherein the step of positioning a softened sheet of glass or ceramicizable glass over said mold comprises positioning a sheet of glass or ceramicizable glass over said mold then heating said sheet of glass or ceramicizable glass.

15. The method of claim 10 wherein the step of substantially closing said micro channels on said at least one surface of said sheet by bonding a sheet of glass or ceramicizable glass over said mold comprises rolling out a soft glass sheet onto said conformed sheet, thereby bonding said soft glass sheet to said conformed sheet.

* * * * *