

US Patent & Trademark Office

Patent Public Search | Text View

United States Patent Application Publication

20250266340

Kind Code

A1

Publication Date

August 21, 2025

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MICROELECTRONIC ASSEMBLIES WITH SEALED LINERS FOR GLASS CORES

Abstract

A microelectronic assembly according to an embodiment of the present disclosure may include a glass core having a first face and a second face opposite the first face, and a TGV in the glass core, the TGV extending from the first face towards the second face and including a conductive material. The microelectronic assembly may further include an organic material in the TGV, between the conductive material and the glass core, wherein a modulus of the organic material is smaller than about 30 GPa, and an inorganic material over the organic material in the TGV, the inorganic material comprising silicon and nitrogen. In such a microelectronic assembly, the glass core, the conductive material, and the inorganic material may completely enclose the organic material to reduce or eliminate degradation (e.g., oxidation and/or crystallization) of the organic material.

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Appl. No.: 18/444431

Filed: February 16, 2024

Publication Classification

Int. Cl.: H01L23/498 (20060101); **H01L21/768** (20060101); **H01L23/10** (20060101)

U.S. Cl.:

CPC H01L23/49827 (20130101); **H01L21/76879** (20130101); **H01L23/10** (20130101);
H01L23/49883 (20130101);

Background/Summary

BACKGROUND

[0001] For the past several decades, scaling of features in integrated circuits (ICs) has been a driving force behind an ever-growing semiconductor industry and emerging applications in fields such as big data, artificial intelligence, mobile communications, and autonomous driving. Scaling to smaller and smaller features enables increased densities of functional units on the limited real estate of semiconductor chips. For example, shrinking transistor size allows incorporation of an increased number of memory or logic devices on a chip, lending to the fabrication of products with increased capacity. The drive for the ever-increasing capacity, however, is not without issue. The necessity to optimize fabrication and performance of each component (e.g., of each transistor) is becoming increasingly significant.

[0002] Parallel to optimizations at the transistor level, advanced IC packaging landscape is rapidly evolving to accommodate performance expectations and requirements of shrinking transistor size. Multiple IC dies are now commonly coupled together in a multi-die IC package to integrate features or functionality and to facilitate connections to other components, such as package substrates. For example, IC packages may include an embedded multi-die interconnect bridge (EMIB) for coupling two or more IC dies.

[0003] Integration of multiple dies in a single IC package has tremendous benefits but adds additional complexities due to placing materials with different material properties in close proximity to one another. When an IC package undergoes multiple processing steps involving various temperatures and pressure loads, individual materials within the package may behave differently from one another, resulting in out of plane deformation of various layers, known as “package warpage.” One way to address package warpage is to use stiffer cores to which different IC dies are attached. Recently, glass cores have been explored as alternatives to organic resin-based cores (e.g., cores based on using Ajinomoto Build-up Film (ABF)). Glass is considered more rigid than organic resin-based materials and has several advantages such as excellent thermal properties, low coefficient of thermal expansion (CTE), high electrical insulation, chemical resistance, optical transparency, and compatibility with advances semiconductor properties. However, a major challenge for widespread adoption of glass cores is the fact that glass is highly susceptible to damage due to mechanical and/or thermal stresses, e.g., damage due to stresses caused by through-glass vias (TGVs) filled with metals.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] Embodiments will be readily understood by the following detailed description in conjunction with the accompanying drawings. To facilitate this description, like reference numerals designate like structural elements. Embodiments are illustrated by way of example, not by way of limitation, in the figures of the accompanying drawings.

[0005] FIG. 1 is a schematic side, cross-sectional view of one example microelectronic assembly,

according to some embodiments of the present disclosure.

[0006] FIG. 2 is a schematic side, cross-sectional view of another example microelectronic assembly, according to some embodiments of the present disclosure.

[0007] FIG. 3 illustrates surfaces of a glass core from which TGV stress may initiate, according to some embodiments of the present disclosure.

[0008] FIGS. 4A-4C illustrate cross-sectional side views of example glass cores with sealed liners, according to some embodiments of the present disclosure.

[0009] FIG. 5 is a flow diagram of a first method of providing a glass core with a sealed liner, in accordance with some embodiments.

[0010] FIGS. 6A-6F provide cross-sectional side views at various stages in the fabrication of an example glass core with a sealed liner according to the method of FIG. 5, in accordance with some embodiments.

[0011] FIG. 7 is a flow diagram of a second method of providing a glass core with a sealed liner, in accordance with some embodiments.

[0012] FIGS. 8A-8C provide cross-sectional side views at various stages in the fabrication of an example glass core with a sealed liner according to the method of FIG. 7, in accordance with some embodiments.

[0013] FIG. 9 is a flow diagram of a third method of providing a glass core with a sealed liner, in accordance with some embodiments.

[0014] FIGS. 10A-10C provide cross-sectional side views at various stages in the fabrication of an example glass core with a sealed liner according to the method of FIG. 9, in accordance with some embodiments.

[0015] FIG. 11 is a top view of a wafer and dies that may be included in a microelectronic assembly with a glass core in accordance with any of the embodiments disclosed herein, according to some embodiments of the present disclosure.

[0016] FIG. 12 is a side, cross-sectional view of an IC device that may be included in a microelectronic assembly with a glass core in accordance with any of the embodiments disclosed herein, according to some embodiments of the present disclosure.

[0017] FIG. 13 is a side, cross-sectional view of an IC device assembly that may include a glass core in accordance with any of the embodiments disclosed herein, according to some embodiments of the present disclosure.

[0018] FIG. 14 is a block diagram of an example communication device that may include a microelectronic assembly with a glass core in accordance with any of the embodiments disclosed herein, according to some embodiments of the present disclosure.

DETAILED DESCRIPTION

[0019] As mentioned above, glass has properties that make it promising for integration in advanced IC packaging. When a glass core is included in a microelectronic assembly, it may be desirable to route electrical signals in and/or through the glass core. To that end, conductive vias may be provided in the glass core, such conductive vias commonly referred to as TGVs. TGVs may also support efficient thermal management by providing paths for heat dissipation from the active components to the package's external environment. In some implementations, TGVs may extend between the top and the bottom surfaces of a glass core, e.g., to provide electrical connectivity between electronic components such as dies and/or package substrates, coupled to the top and bottom surfaces of the glass core. In other implementations, TGVs may be blind vias that extend from the top/bottom surface of the glass core towards, but not reaching, the opposite surface, e.g., to provide electrical connectivity from a surface of the glass core to a conductive trace or an IC component embedded in the glass core.

[0020] Provision of TGVs in glass cores enables more compact and efficient designs for microelectronic assemblies. However, integration of TGVs in glass cores is not trivial.

Conventionally, fabrication of TGVs includes forming openings for future TGVs, lining the

openings with a seed material, and then depositing a conductive fill material into the lined openings. The seed material typically includes a low-resistivity metal such as copper that can be deposited in a thin layer on substantially non-conductive surfaces (e.g., sidewalls) of the openings in the glass core. The seed material is intended to provide conductive surfaces for uniform and controlled deposition of the conductive fill material in a subsequent deposition step, e.g., when the conductive fill material is deposited in the lined openings using a process such as electroplating. One challenge associated with integration of TGVs in glass cores arises from the differences in CTEs between materials that may be used for glass cores and metals of the seed material and of the conductive fill material deposited in the TGVs. CTE is a measure of how a material expands or contracts with changes in temperature and is typically defined as the fractional increase in length per unit rise in temperature, measured in, e.g., parts per million (ppm) per degrees Kelvin (K) or ppm/K. Glass materials that may be used for glass cores and metals have significantly different CTEs. Metals have relatively high CTEs, meaning that they may expand and contract significantly with changes in temperature. Glass materials, on the other hand, have much lower CTEs and are less responsive to temperature changes. For example, a CTE of glass is on the order of about 3.5 ppm/K, while a CTE of a metal such as copper is on the order of about 15 ppm/K. When a metal is in close contact with glass (e.g., a seed material or a conductive fill material within a TGV in the glass core), and the assembly is exposed to temperature variations such as heating or cooling, the metal will heat up or cool down much faster, and to a greater extent, than the glass. This leads to the generation of significant thermal stress at the interface between the two materials. The high thermal stress can exceed the strength of the glass, leading to the formation of cracks, which may then propagate and compromise the structural integrity of the glass. Even if cracks don't form immediately, the repeated thermal cycling can gradually weaken the glass surface, potentially leading to the development of surface flaws or micro-cracks. Prolonged exposure to CTE mismatch-induced stresses can cause gradual degradation of the glass, making it more prone to failure over time.

[0021] Embodiments of the present disclosure relate to various techniques, as well as to related devices and methods, for alleviating (e.g., mitigating or reducing) CTE mismatch-induced stresses caused by the proximity of conductive materials of TGVs to glass materials of the glass cores. As used herein, such stresses are referred to as “TGV stress.” Embodiments of the present disclosure are based on recognition that including a liner material on sidewalls of TGVs, as a buffer layer between the glass core and conductive material(s) in the TGVs, may help reduce TGV stress because the liner material separates the glass and metals of the seed material and the conductive fill material deposited in the TGVs. In particular, selecting a liner material as a material having a relatively low modulus, e.g., having Young's modulus below about 30 gigapascal (GPa), may be particularly advantageous for reducing TGV stress. Embodiments of the present disclosure are further based on recognition that such liner materials may be compromised/degraded due to, e.g., oxidation or crystallization that can occur during the processes involved in glass core substrate manufacturing. For example, one type of materials that have relatively low modulus but may be susceptible to degradation due to, e.g., oxidation and/or crystallization, is parylene, where, as used herein, the name “parylene” refers to a group of polymers known as poly-para-xylylenes. Inventors of the present disclosure established that decoupling the conductive materials of TGVs from the glass sidewalls through a low-modulus liner material such as parylene can reduce TGV stress significantly, but one other issue that may arise is that of a cohesive failure of the liner material that may be attributed to degradation of the liner material due to, e.g., oxidation (e.g., degradation of the parylene films during open air copper anneal) or crystallization. Therefore, microelectronic assemblies described herein further include a sealant that can seal the liner material, thus reducing or eliminating oxidation and/or crystallization of the liner material. In context of the present disclosure, a liner material that has been sealed with a sealant may be referred to as a “sealed liner.” In one aspect, a microelectronic assembly according to an embodiment of the present disclosure

may include a glass core having a first face and a second face opposite the first face, and a TGV in the glass core, the TGV extending from the first face towards the second face and including a conductive material. The microelectronic assembly may further include an organic liner material in the TGV, between the conductive material and the glass core, wherein a modulus of the organic material is smaller than about 30 GPa, and a sealant provided as an inorganic material over the organic material in the TGV, the inorganic material comprising silicon and nitrogen. In such a microelectronic assembly, the glass core, the conductive material, and the inorganic material may completely enclose the organic material to reduce or eliminate degradation (e.g., oxidation and/or crystallization) of the organic material.

[0022] Integration of layers of different materials (e.g., multiple dies, redistribution layers, package substrates) in a single IC package or a microelectronic assembly is challenging due to package warpage, among others. Providing IC packages or microelectronic assemblies with glass cores having TGVs with sealed liners as described herein may help. Various ones of the embodiments disclosed herein may help achieve reliable integration of multiple layers of different materials within a single microelectronic assembly at a lower cost and/or with greater design flexibility, relative to conventional approaches. Various ones of the microelectronic assemblies disclosed herein may exhibit reduced warpage, relative to microelectronic assemblies without glass cores. The microelectronic assemblies disclosed herein may be particularly advantageous for small and low-profile applications in computers, tablets, industrial robots, and consumer electronics (e.g., wearable devices).

[0023] In the following detailed description, reference is made to the accompanying drawings that form a part hereof wherein like numerals designate like parts throughout, and in which is shown, by way of illustration, embodiments that may be practiced. It is to be understood that other embodiments may be utilized, and structural or logical changes may be made, without departing from the scope of the present disclosure. Therefore, the following detailed description is not to be taken in a limiting sense.

[0024] Any of the features discussed with reference to any of accompanying drawings herein may be combined with any other features to form a microelectronic assembly **100**, a glass core **110**, an IC device **1600**, an IC device assembly **1700**, or a communication device **1800**, as appropriate. For convenience, the phrase “dies **114**” may be used to refer to a collection of dies **114-1**, **114-2**, and so on, etc. A number of elements of the drawings with same reference numerals may be shared between different drawings; for ease of discussion, a description of these elements provided with respect to one of the drawings is not repeated for the other drawings, and these elements may take the form of any of the embodiments disclosed herein. To not clutter the drawings, if multiple instances of certain elements are illustrated, only some of the elements may be labeled with a reference numeral (e.g., a plurality of conductive contacts **122** are shown in FIG. **1** but only one of the them is labeled with a reference numeral). Also to not clutter the drawings, not all reference numerals shown in one of the drawings are shown in other similar drawings.

[0025] The drawings are not necessarily to scale. Although many of the drawings illustrate rectilinear structures with flat walls and right-angle corners, this is simply for ease of illustration and may not reflect real-life process limitations which may cause various features to not look so “ideal” when any of the structures described herein are examined using e.g., scanning electron microscopy (SEM) images or transmission electron microscope (TEM) images. In such images of real structures, possible processing defects could also be visible, e.g., not-perfectly straight edges of materials, tapered vias or other openings, inadvertent rounding of corners or variations in thicknesses of different material layers. There may be other defects not listed here but that are common within the field of semiconductor device fabrication and packaging. Inspection of layout and mask data and reverse engineering of parts of a device to reconstruct the circuit using e.g., optical microscopy, TEM, or SEM, and/or inspection of a cross-section of a device to detect the shape and the location of various device elements described herein using, e.g., Physical Failure

Analysis (PFA) would allow determination of presence of a glass core with one or more sealed liners as described herein.

[0026] For the purposes of the present disclosure, the phrase “A and/or B” means (A), (B), or (A and B). For the purposes of the present disclosure, the phrase “A, B, and/or C” means (A), (B), (C), (A and B), (A and C), (B and C), or (A, B, and C). When used to describe a range of dimensions, the phrase “between X and Y” represents a range that includes X and Y. When used to describe a location of an element, the phrase “between X and Y” represents a region that is spatially between element X and element Y. The terms “substantially,” “close,” “approximately,” “near,” and “about,” generally refer to being within $\pm 20\%$, e.g., within $\pm 5\%$ or within $\pm 2\%$, of a target value based on the context of a particular value as described herein or as known in the art. Similarly, terms indicating orientation of various elements, e.g., “coplanar,” “perpendicular,” “orthogonal,” “parallel,” or any other angle between the elements, generally refer to being within $\pm 10\%$, e.g., within $\pm 5\%$ or within $\pm 2\%$, of the exact orientation.

[0027] The description uses the phrases “in an embodiment” or “in embodiments,” which may each refer to one or more of the same or different embodiments. Furthermore, the terms “comprising,” “including,” “having,” and the like, as used with respect to embodiments of the present disclosure, are synonymous. As used herein, the terms “package” and “IC package” are synonymous, as are the terms “die” and “IC die.” Furthermore, the terms “chip,” “chiplet,” “die,” and “IC die” may be used interchangeably herein.

[0028] Although certain elements may be referred to in the singular herein, such elements may include multiple sub-elements. For example, “a dielectric material” may include one or more dielectric materials or “an insulator material” may include one or more insulator materials. The terms “oxide,” “carbide,” “nitride,” etc. refer to compounds containing, respectively, oxygen, carbon, nitrogen, etc. The term “high-k dielectric” refers to a material having a higher dielectric constant than silicon oxide, while the term “low-k dielectric” refers to a material having a lower dielectric constant than silicon oxide. The term “insulating” and variations thereof (e.g., “insulative” or “insulator”) means “electrically insulating,” the term “conducting” and variations thereof (e.g., “conductive” or “conductor”) means “electrically conducting,” unless otherwise specified. With reference to optical signals and/or devices, components and elements that operate on or using optical signals, the term “conducting” can also mean “optically conducting.” The term “insulating material” refers to solid materials (and/or liquid materials that solidify after processing as described herein) that are substantially electrically nonconducting. They may include, as examples and not as limitations, organic polymers and plastics, and inorganic materials such as ionic crystals, porcelain, glass, silicon and alumina or a combination thereof. They may include dielectric materials, high polarizability materials, and/or piezoelectric materials. They may be transparent or opaque without departing from the scope of the present disclosure. Further examples of insulating materials are underfills and molds or mold-like materials used in packaging applications, including for example, materials used in organic interposers, package supports and other such components.

[0029] FIG. 1 is a schematic side, cross-sectional view of one example microelectronic assembly **100** in which a glass core with one or more sealer liners as described herein may be implemented, according to some embodiments of the present disclosure. The microelectronic assembly **100** may include a substrate **107** with a double-sided bridge die **114-1** in a cavity **119** in the substrate **107**, the die **114-1** may be electrically coupled to a conductive pathway, e.g., a conductive trace **108A** or a conductive via **108B**, in a metal layer N-1 of the substrate **107** that is beneath a bottom of the cavity **119**. The substrate **107** may include a dielectric material **112** (e.g., a first dielectric material layer **112A** and a second dielectric material layer **112B**, as shown, together referred to as “one or more layers of the dielectric material **112**”) and a conductive material **108** arranged in the one or more layers of the dielectric material **112** to provide conductive pathways (e.g., conductive traces **108A** and conductive vias **108B**) through the substrate **107**, as well as to provide conductive pads

and contacts. The substrate **107** may include a first surface **120-1** and an opposing second surface **120-2**. The die **114-1** may be surrounded by the dielectric material **112** of the substrate **107**. The die **114-1** may include a bottom face (e.g., the surface facing towards the first surface **120-1**) with first conductive contacts **122**, an opposing top face (e.g., the surface facing towards the second surface **120-2**) with second conductive contacts **124**, and through-silicon vias (TSVs) **125** coupling respective first and second conductive contacts **122**, **124**. In some embodiments, a pitch of the first conductive contacts **122** on the first die **114-1** may be between 25 microns and 250 microns. As used herein, pitch is measured center-to-center (e.g., from a center of a conductive contact to a center of an adjacent conductive contact). In some embodiments, a pitch of the second conductive contacts **124** on the first die **114-1** may be between 25 microns and 100 microns. The dies **114-2**, **114-3** may include a set of conductive contacts **122** on the bottom face of the die (e.g., the surface facing towards the first surface **120-1**). The die **114** may include other conductive pathways (e.g., including lines and vias) and/or to other circuitry (not shown) coupled to the respective conductive contacts (e.g., conductive contacts **122**, **124**) on the surface of the die **114**. As used herein, the terms “die,” “microelectronic component,” and similar variations may be used interchangeably. As used herein, the terms “interconnect component,” “bridge die,” and similar variations may be used interchangeably. The bridge die **114-1** may be electrically coupled to dies **114-2**, **114-3** by die-to-die (DTD) interconnects **130** at a second surface **120-2**. In particular, conductive contacts **124** on a top face of the die **114-1** may be coupled to conductive contacts **122** on a bottom face of dies **114-2**, **114-3** by conductive vias **108B** through the second dielectric material layer **112B**.

[0030] As used herein, a “conductive contact” may refer to a portion of conductive material (e.g., metal) serving as an electrical interface between different components (e.g., part of a conductive interconnect); conductive contacts may be recessed in, flush with, or extending away (e.g., having a pillar shape) from a surface of a component, and may take any suitable form (e.g., a conductive pad or socket, or portion of a conductive line or via). In a general sense, an “interconnect” refers to any element that provides a physical connection between two other elements. For example, an electrical interconnect provides electrical connectivity between two electrical components, facilitating communication of electrical signals between them; an optical interconnect provides optical connectivity between two optical components, facilitating communication of optical signals between them. As used herein, both electrical interconnects and optical interconnects are comprised in the term “interconnect.” The nature of the interconnect being described is to be understood herein with reference to the signal medium associated therewith. Thus, when used with reference to an electronic device, such as an IC that operates using electrical signals, the term “interconnect” describes any element formed of a conductive material for providing electrical connectivity to one or more elements associated with the IC or/and between various such elements. In such cases, the term “interconnect” may refer to both conductive traces (also sometimes referred to as “metal traces,” “lines,” “metal lines,” “wires,” “metal wires,” “trenches,” or “metal trenches”) and conductive vias (also sometimes referred to as “vias” or “metal vias”). Sometimes, conductive traces and vias may be referred to as “metal traces” and “metal vias”, respectively, to highlight the fact that these elements include conductive materials such as metals. Likewise, when used with reference to a device that operates on optical signals as well, such as a photonic IC (PIC), “interconnect” may also describe any element formed of a material that is optically conductive for providing optical connectivity to one or more elements associated with the PIC. In such cases, the term “interconnect” may refer to optical waveguides (e.g., structures that guide and confine light waves), including optical fiber, optical splitters, optical combiners, optical couplers, and optical vias.

[0031] The die **114** disclosed herein may include an insulating material (e.g., a dielectric material formed in multiple layers, as known in the art) and multiple conductive pathways formed through the insulating material. In some embodiments, the insulating material of a die **114** may include a dielectric material, such as silicon dioxide, silicon nitride, oxynitride, polyimide materials, glass

reinforced epoxy matrix materials, or a low-k or ultra low-k dielectric (e.g., carbon-doped dielectrics, fluorine-doped dielectrics, porous dielectrics, organic polymeric dielectrics, photo-imageable dielectrics, and/or benzocyclobutene-based polymers). In some embodiments, the insulating material of a die **114** may include a semiconductor material, such as silicon, germanium, or a III-V material (e.g., gallium nitride), and one or more additional materials. For example, an insulating material may include silicon oxide or silicon nitride. The conductive pathways in a die **114** may include conductive traces and/or conductive vias, and may connect any of the conductive contacts in the die **114** in any suitable manner (e.g., connecting multiple conductive contacts on a same surface or on different surfaces of the die **114**). Example structures that may be included in the dies **114** disclosed herein are discussed below with reference to the IC device **1600**. The conductive pathways in the dies **114** may be bordered by liner materials, such as adhesion liners and/or barrier liners, as suitable. In some embodiments, the die **114** is a wafer. In some embodiments, the die **114** is a monolithic silicon, a fan-out or fan-in package die, or a die stack (e.g., wafer stacked, die stacked, or multi-layer die stacked).

[0032] In some embodiments, the die **114** may include conductive pathways to route power, ground, and/or signals to/from other dies **114** included in the microelectronic assembly **100**. For example, the die **114-1** may include TSVs **125**, including a conductive via, such as a metal via, isolated from the surrounding silicon or other semiconductor material by a barrier oxide), or other conductive pathways through which power, ground, and/or signals may be transmitted between the package substrate **102** and one or more dies **114** “on top” of the die **114-1** (e.g., in the embodiment of FIG. 1, the dies **114-2** and/or **114-3**). In some embodiments, the die **114-1** may not route power and/or ground to the dies **114-2** and **114-3**; instead, the dies **114-2**, **114-3** may couple directly to power and/or ground lines in the package substrate **102** by substrate-to-package substrate (STPS) interconnects **150**, conductive pathways provided by the conductive material **108** in the substrate **107**, and die-to-substrate (DTS) interconnects **140**. In some embodiments, the die **114-1** may be thicker than the dies **114-2**, **114-3**. In some embodiments, the die **114-1** may be a memory device or a high frequency serializer and deserializer (SerDes), such as a Peripheral Component Interconnect (PCI) express. In some embodiments, the die **114-1** may be a processing die, a radio frequency chip, a power converter, a network processor, a workload accelerator, a voltage regulator die, or a security encryptor. In some embodiments, the die **114-2** and/or the die **114-3** may be a processing die, a radio frequency chip, a power converter, a network processor, a workload accelerator, a voltage regulator die, or a security encryptor. In some embodiments, the die **114** may be as described below with reference to the die **1502** of FIG. 11.

[0033] The dielectric material **112** of the substrate **107** may be formed in layers (e.g., at least a first dielectric material layer **112A** and a second dielectric material layer **112B**). In some embodiments, the dielectric material **112** may include an organic material, such as an organic build-up film. In some embodiments, the dielectric material **112** may include a ceramic, an epoxy film having filler particles therein, glass, an inorganic material, or combinations of organic and inorganic materials, for example. In some embodiments, the conductive material **108** may include a metal (e.g., copper). In some embodiments, the substrate **107** may include layers of dielectric material **112**/conductive material **108**, with lines/traces/pads/contacts (e.g., conductive traces **108A**) of conductive material **108** in one layer electrically coupled to lines/traces/pads/contacts (e.g., conductive traces **108A**) of conductive material **108** in an adjacent layer by vias (e.g., **108B**) of the conductive material **108** extending through the dielectric material **112**. Conductive traces **108A** may be referred to herein as “conductive lines,” “conductive elements,” “conductive pads,” or “conductive contacts.” A substrate **107** including such layers may be formed using a printed circuit board (PCB) fabrication technique, for example.

[0034] An individual layer of dielectric material **112** (e.g., a first dielectric material layer **112A**) may include a cavity **119** and the bridge die **114-1** may be at least partially nested in the cavity **119**. The bridge die **114-1** may be surrounded by (e.g., embedded in) a next individual layer of dielectric

material **112** (e.g., a second dielectric material layer **112B**). In some embodiments, a cavity **119** is tapered, narrowing towards a bottom face of the cavity **119** (e.g., the surface towards the first surface **120-1** of the substrate **107**). A cavity **119** may be indicated by a seam between the dielectric material **112A** and the dielectric material **112B**. As shown in FIG. **1**, in cases where the bridge die **114-1** is partially nested in a cavity **119**, a top face of the bridge die **114-1** may extend above a top face of dielectric material **112A**. In cases where the bridge die **114-1** is fully nested in a cavity **119** (not shown), a top face of the bridge die **114-1** may be planar with or below a top face of dielectric material **112A**.

[0035] A substrate **107** may include N layers of conductive material **108**, where N is an integer greater than or equal to one. In FIG. **1**, the layers are labeled in descending order from the second surface **120-2** (e.g., the top face) of the substrate **107** (e.g., layer N, layer N-1, layer N-2, etc.). In particular, as shown in FIG. **1**, a substrate **107** may include four metal layers (e.g., N, N-1, N-2, and N-3). The N metal layer may include conductive contacts **121** at the second surface **120-2** of the substrate **107** that are coupled to conductive contacts **122** at bottom faces of the die **114-2**, **114-3** by DTS interconnects **140**. The N-2 metal layer may include conductive traces **108A** having a top face (e.g., the surface facing towards the second surface **120-2** of the substrate **107**), an opposing bottom face (e.g., the surface facing towards the first surface **120-1** of the substrate **107**), and lateral surfaces extending between the top and bottom faces of the conductive traces **108A**. A substrate **107** may further include an N-1 metal layer above the N-2 metal layer and below the N metal layer, where a portion of the N-1 metal layer includes a metal ring **118** exposed at a perimeter of the bottom of the cavity **119**. The metal ring **118** may be coplanar with the conductive traces **108A** of the N-1 metal layer and may be proximate to the edges of the cavity **119**, as shown.

[0036] Although a particular number and arrangement of layers of dielectric material **112**/conductive material **108** are shown in various ones of the accompanying figures, these particular numbers and arrangements are simply illustrative, and any desired number and arrangement of dielectric material **112**/conductive material **108** may be used. Further, although a particular number of layers are shown in the substrate **107** (e.g., four layers), these layers may represent only a portion of the substrate **107**, for example, further layers may be present (e.g., layers N-4, N-5, N-6, etc.).

[0037] As shown in FIG. **1**, the substrate **107** may further include a glass core **110** with TGVs **115** and further layers **111** may be present below the glass core **110** and coupled to a package substrate **102** by interconnects **150**. Any of the TGVs **115** may be a conductive via with a sealed liner as described herein. As used herein, the term “glass core” refers to a layer (e.g., a glass layer) or a structure (e.g., a portion of a glass layer) of any glass material such as quartz, silica, fused silica, silicate glass (e.g., borosilicate, aluminosilicate, alumino-borosilicate), soda-lime glass, soda-lime silica, borofloat glass, lead borate glass, photosensitive glass, non-photosensitive glass, or ceramic glass. In particular, the glass core **110** may be bulk glass or a solid volume/layer of glass, as opposed to, e.g., materials that may include particles of glass, such as glass fiber reinforced polymers (e.g., substrates/boards constructed of glass fibers and an epoxy binder). Such glass materials are typically non-crystalline, often transparent, amorphous solids. In some embodiments, the glass core **110** may be an amorphous solid glass layer. In some embodiments, the glass core **110** may include a material comprising silicon and oxygen, as well as any one or more of aluminum, boron, magnesium, calcium, barium, tin, sodium, potassium, strontium, phosphorus, zirconium, lithium, titanium, and zinc. In some embodiments, the glass core **110** may include a material, e.g., any of the materials described above, with a weight percentage of silicon being at least about 0.5%, e.g., between about 0.5% and 50%, between about 1% and 48%, or at least about 23%. For example, if the glass core **110** is fused silica, the weight percentage of silicon may be about 47%. In some embodiments, the glass core **110** may include a material having at least 23% silicon and/or at least 26% oxygen by weight, and, in some further embodiments, the glass core **110** may further include at least 5% aluminum by weight. In some embodiments, the glass core **110** may include

any of the materials described above and may further include one or more additives such as Al.sub.2O.sub.3, B.sub.2O.sub.3, MgO, CaO, SrO, BaO, SnO.sub.2, Na.sub.2O, K.sub.2O, SrO, P.sub.2O.sub.3, ZrO.sub.2, Li.sub.2O, Ti, and Zn. In some embodiments, the glass core **110** may be a layer of glass that does not include an organic adhesive or an organic material. The glass core **110** may be distinguished from, for example, the “prepreg” or “RF4” core of a PCB substrate which typically includes glass fibers embedded in a resinous organic material such as an epoxy. In such traditional cores/substrates including glass fibers and epoxy, the diameter of the glass fibers is generally in the range of 5 micron to 200 micron. In contrast, the glass core **110** may be a layer of glass that is about 10 millimeters on a side to about 250 millimeters on a side (e.g., 10 millimeters×10 millimeters to 250 millimeters×250 millimeters). In some embodiments, a cross-section of the glass core **110** in an x-z plane, a y-z plane, and/or an x-y plane of an example coordinate system **105**, shown in FIG. **1**, may be substantially rectangular (axes shown in subsequent drawings refer to the axes of the coordinate system **105**), although in some further embodiments the glass core **110** may have rounded or beveled edges/sides/sidewalls. In some embodiments, in the top-down view of the glass core **110** (e.g., the x-y plane of the coordinate system **105**), the glass core **110** may have a first length in a range of 10 millimeters to 250 millimeters, and a second length in a range of 10 millimeters to 250 millimeters, the first length perpendicular to the second length. A thickness of the glass core **110** (e.g., a dimension measured along the z-axis of the coordinate system **105**) may be in a range of about 50 micron to 1.4 millimeters. In some embodiments, the glass core **110** may be a glass core substrate, where the glass core substrate has a thickness in a range of about 50 microns to 1.4 millimeters. In some embodiments, the glass core **110** may be a layer of glass comprising a rectangular prism volume, possibly with rounded or beveled edges/sides/sidewalls. In some such embodiments, the rectangular prism volume may have a first side and a second side perpendicular to the first side, the first side having a length in a range of 10 millimeters to 250 millimeters and the second side having a length in a range of 10 millimeters to 250 millimeters. In some embodiments, the glass core **110** may be a rectangular prism volume with sections (e.g., vias) removed and filled with other materials (e.g., metal) e.g., the TGVs **115**. In some embodiments, the glass core **110** may be a layer of glass having a thickness in a range of 50 microns to 1.4 millimeters, a first length in a range of 10 millimeters to 250 millimeters, and a second length in a range of 10 millimeters to 250 millimeters, the first length perpendicular to the second length.

[0038] In some implementations, together, the substrate **107**, including the glass core **110**, and the dies **114** may be referred to as a “a multi-layer die subassembly **104**.” The glass core **110** may provide mechanical stability to the multi-layer die subassembly **104**, the substrate **107**, and/or the microelectronic assembly **100**. The glass core **110** may reduce warpage and may provide a more robust surface for attachment of the multi-layer die subassembly **104** to a package substrate **102** or other substrate (e.g., an interposer or a circuit board).

[0039] In some implementations, together, the dielectric material **112** of the substrate **107** and the glass core **110** may be referred to as a “multi-layer glass substrate.” In some such embodiments, the multi-layer glass substrate may be a coreless substrate. In some such embodiments, the glass core **110** may be a glass layer having a thickness in a range of about 25 microns to 50 microns. In some embodiments, the further layers **111** may also be part of the multi-layer glass substrate.

[0040] The TGVs **115** may be vias extending between a first side and a second side of the glass core **110** (e.g., between the bottom face and the top face of the glass core **110**), the vias including any appropriate conductive material, e.g., a metal such as copper, silver, nickel, gold, aluminum, or other metals or alloys, for example. Openings for the TGVs **115** may be formed using any suitable process, including, for example, a direct laser drilling or laser-induced etching process (which may also be referred to as laser patterning or selective laser activation). For any of the TGVs **115**, via metallization may be performed using any of the fabrication methods utilizing sealed liners as described herein, e.g., any of the methods shown in FIG. **5**, FIG. **7**, or FIG. **9**. Therefore, although

not specifically shown in FIG. 1 or FIG. 2, any of the TGVs **115** shown in these drawings may be implemented as described with respect to the fabrication methods shown in FIG. 5, FIG. 7, or FIG. 9 (e.g., as conductive vias with sealed liners as shown in any of FIGS. 4A-4C). In some embodiments, the TGVs **115** disclosed herein may have a pitch between 50 microns and 500 microns, e.g., as measured from a center of one TGV **115** to a center of an adjacent TGV **115**. The TGVs **115** may have any suitable size and shape. In some embodiments, the TGVs **115** may have a circular, rectangular, or other shaped cross-section. In some embodiments, at least some of the TGVs **115** may have an hourglass shape, e.g., as shown in FIG. 2. In some embodiments, at least some of the TGVs **115** may taper down from one face of the glass core **110** to another, e.g., from the top face of the glass core **110** to the bottom face of the glass core **110**.

[0041] The substrate **107** (e.g., further layers **111**) may be coupled to a package substrate **102** by STPS interconnects **150**. In particular, the top face of the package substrate **102** may include a set of conductive contacts **146**. Conductive contacts **144** on the bottom face of the substrate **107** may be electrically and mechanically coupled to the conductive contacts **146** on the top face of the package substrate **102** by the STPS interconnects **150**. The package substrate **102** may include an insulating material (e.g., a dielectric material formed in multiple layers, as known in the art) and one or more conductive pathways to route power, ground, and signals through the dielectric material (e.g., including conductive traces and/or conductive vias, as shown). In some embodiments, the insulating material of the package substrate **102** may be a dielectric material, such as an organic dielectric material, a fire retardant grade 4 material (FR-4), bismaleimide triazine (BT) resin, polyimide materials, glass reinforced epoxy matrix materials, organic dielectrics with inorganic fillers or low-k and ultra low-k dielectric (e.g., carbon-doped dielectrics, fluorine-doped dielectrics, porous dielectrics, and organic polymeric dielectrics). In particular, when the package substrate **102** is formed using standard PCB processes, the package substrate **102** may include FR-4, and the conductive pathways in the package substrate **102** may be formed by patterned sheets of copper separated by build-up layers of the FR-4. The conductive pathways in the package substrate **102** may be bordered by liner materials, such as adhesion liners and/or barrier liners, as suitable. In some embodiments, the package substrate **102** may be formed using a lithographically defined via packaging process. In some embodiments, the package substrate **102** may be manufactured using standard organic package manufacturing processes, and thus the package substrate **102** may take the form of an organic package. In some embodiments, the package substrate **102** may be a set of redistribution layers formed on a panel carrier by laminating or spinning on a dielectric material, and creating conductive vias and lines by laser drilling and plating. In some embodiments, the package substrate **102** may be formed on a removable carrier using any suitable technique, such as a redistribution layer technique. Any method known in the art for fabrication of the package substrate **102** may be used, and for the sake of brevity, such methods will not be discussed in further detail herein.

[0042] In some embodiments, the package substrate **102** may be a lower density medium and the die **114** may be a higher density medium or have an area with a higher density medium. As used herein, the term “lower density” and “higher density” are relative terms indicating that the conductive pathways (e.g., including conductive interconnects, conductive lines, and conductive vias) in a lower density medium are larger and/or have a greater pitch than the conductive pathways in a higher density medium. In some embodiments, a higher density medium may be manufactured using a modified semi-additive process or a semi-additive build-up process with advanced lithography (with small vertical interconnect features formed by advanced laser or lithography processes), while a lower density medium may be a PCB manufactured using a standard PCB process (e.g., a standard subtractive process using etch chemistry to remove areas of unwanted copper, and with coarse vertical interconnect features formed by a standard laser process). In other embodiments, the higher density medium may be manufactured using semiconductor fabrication process, such as a single damascene process or a dual-damascene process. In some embodiments,

additional dies may be disposed on the top face of the dies **114-2**, **114-3**. In some embodiments, additional components may be disposed on the top face of the dies **114-2**, **114-3**. Additional passive components, such as surface-mount resistors, capacitors, and/or inductors, may be disposed on the top face or the bottom face of the package substrate **102**, or embedded in the package substrate **102**. [0043] The microelectronic assembly **100** of FIG. **1** may also include an underfill material **127**. In some embodiments, the underfill material **127** may extend between the substrate **107** and the package substrate **102** around the associated STPS interconnects **150**. In some embodiments, the underfill material **127** may extend between different ones of the top level dies **114-2**, **114-3** and the top face of the substrate **107** around the associated DTS interconnects **140** and between the bridge die **114-1** and the top level dies **114-2**, **114-3** around the DTD interconnects **130**. The underfill material **127** may be an insulating material, such as an appropriate epoxy material. In some embodiments, the underfill material **127** may include a capillary underfill, non-conductive film (NCF), or molded underfill. In some embodiments, the underfill material **127** may include an epoxy flux that assists with soldering the multi-layer die subassembly **104** to the package substrate **102** when forming the STPS interconnects **150**, and then polymerizes and encapsulates the STPS interconnects **150**. The underfill material **127** may be selected to have a CTE that may mitigate or minimize the stress between the substrate **107** and the package substrate **102** arising from uneven thermal expansion in the microelectronic assembly **100**. In some embodiments, the CTE of the underfill material **127** may have a value that is intermediate to the CTE of the package substrate **102** (e.g., the CTE of the dielectric material of the package substrate **102**) and a CTE of the dies **114** and/or dielectric material **112** of the substrate **107**.

[0044] The STPS interconnects **150** disclosed herein may take any suitable form. In some embodiments, a set of STPS interconnects **150** may include solder (e.g., solder bumps or balls that are subject to a thermal reflow to form the STPS interconnects **150**), for example, as shown in FIG. **1**, the STPS interconnects **150** may include solder between a conductive contacts **144** on a bottom face of the substrate **107** and a conductive contact **146** on a top face of the package substrate **102**. In some embodiments, a set of STPS interconnects **150** may include an anisotropic conductive material, such as an anisotropic conductive film or an anisotropic conductive paste. An anisotropic conductive material may include conductive materials dispersed in a non-conductive material.

[0045] The DTD interconnects **130** disclosed herein may take any suitable form. The DTD interconnects **130** may have a finer pitch than the STPS interconnects **150** in a microelectronic assembly. In some embodiments, the dies **114** on either side of a set of DTD interconnects **130** may be unpackaged dies, and/or the DTD interconnects **130** may include small conductive bumps (e.g., copper bumps). The DTD interconnects **130** may have too fine a pitch to couple to the package substrate **102** directly (e.g., too fine to serve as DTS interconnects **140** or STPS interconnects **150**). In some embodiments, a set of DTD interconnects **130** may include solder. In some embodiments, a set of DTD interconnects **130** may include an anisotropic conductive material, such as any of the materials discussed above. In some embodiments, the DTD interconnects **130** may be used as data transfer lanes, while the STPS interconnects **150** may be used for power and ground lines, among others. In some embodiments, some or all of the DTD interconnects **130** in a microelectronic assembly **100** may be metal-to-metal interconnects (e.g., copper-to-copper interconnects, or plated interconnects). In such embodiments, the DTD interconnect **130** may be bonded together (e.g., under elevated pressure and/or temperature) without the use of intervening solder or an anisotropic conductive material. Any of the conductive contacts disclosed herein (e.g., the conductive contacts **122**, **124**, **144**, and/or **146**) may include bond pads, solder bumps, conductive posts, or any other suitable conductive contact, for example. In some embodiments, some or all of the DTD interconnects **130** and/or the DTS interconnects **140** in a microelectronic assembly **100** may be solder interconnects that include a solder with a higher melting point than a solder included in some or all of the STPS interconnects **150**. For example, when the DTD interconnects **130** and the DTS interconnects **140** in a microelectronic assembly **100** are formed before the STPS interconnects **150**

are formed, solder-based DTD interconnects **130** and DTS interconnects **140** may use a higher-temperature solder (e.g., with a melting point above 200 degrees Celsius), while the STPS interconnects **150** may use a lower-temperature solder (e.g., with a melting point below 200 degrees Celsius). In some embodiments, a higher-temperature solder may include tin; tin and gold; or tin, silver, and copper (e.g., 96.5% tin, 3% silver, and 0.5% copper). In some embodiments, a lower-temperature solder may include tin and bismuth (e.g., eutectic tin bismuth) or tin, silver, and bismuth. In some embodiments, a lower-temperature solder may include indium, indium and tin, or gallium.

[0046] In the microelectronic assemblies **100** disclosed herein, some or all of the DTS interconnects **140** and the STPS interconnects **150** may have a larger pitch than some or all of the DTD interconnects **130**. DTD interconnects **130** may have a smaller pitch than STPS interconnects **150** due to the greater similarity of materials in the different dies **114** on either side of a set of DTD interconnects **130** than between the substrate **107** and the top level dies **114-2**, **114-3** on either side of a set of DTS interconnects **140**, and between the substrate **107** and the package substrate **102** on either side of a set of STPS interconnects **150**. In particular, the differences in the material composition of a substrate **107** and a die **114** or a package substrate **102** may result in differential expansion and contraction due to heat generated during operation (as well as the heat applied during various manufacturing operations). To mitigate damage caused by this differential expansion and contraction (e.g., cracking, solder bridging, etc.), the DTS interconnects **140** and the STPS interconnects **150** may be formed larger and farther apart than DTD interconnects **130**, which may experience less thermal stress due to the greater material similarity of the pair of dies **114** on either side of the DTD interconnects. In some embodiments, the DTS interconnects **140** disclosed herein may have a pitch between 25 microns and 250 microns. In some embodiments, the STPS interconnects **150** disclosed herein may have a pitch between 55 microns and 1000 microns, while the DTD interconnects **130** disclosed herein may have a pitch between 25 microns and 100 microns.

[0047] The microelectronic assembly **100** of FIG. **1** may also include a circuit board (not shown). The package substrate **102** may be coupled to the circuit board by second-level interconnects at the bottom face of the package substrate **102**. The second-level interconnects may be any suitable second-level interconnects, including solder balls for a ball grid array arrangement, pins in a pin grid array arrangement or lands in a land grid array arrangement. The circuit board may be a motherboard, for example, and may have other components attached to it. The circuit board may include conductive pathways and other conductive contacts for routing power, ground, and signals through the circuit board, as known in the art. In some embodiments, the second-level interconnects may not couple the package substrate **102** to a circuit board, but may instead couple the package substrate **102** to another IC package, an interposer, or any other suitable component. In some embodiments, the substrate **107** may not be coupled to a package substrate **102**, but may instead be coupled to a circuit board, such as a PCB.

[0048] Although FIG. **1** depicts a microelectronic assembly **100** having a substrate with a particular number of dies **114** and conductive pathways provided by the conductive material **108** coupled to other dies **114**, this number and arrangement are simply illustrative, and a microelectronic assembly **100** may include any desired number and arrangement of dies **114**. Although FIG. **1** shows the die **114-1** as a double-sided die and the dies **114-2**, **114-3** as single-sided dies, the dies **114-2**, **114-3** may be double-sided dies and the dies **114** may be a single-pitch die or a mixed-pitch die. In some embodiments, additional components may be disposed on the top face of the dies **114-2** and/or **114-3**. In this context, a double-sided die refers to a die that has connections on both surfaces. In some embodiments, a double-sided die may include through TSVs to form connections on both surfaces. The active surface of a double-sided die, which is the surface containing one or more active devices and a majority of interconnects, may face either direction depending on the design and electrical requirements.

[0049] Many of the elements of the microelectronic assembly **100** of FIG. **1** are included in other ones of the accompanying drawings; the discussion of these elements is not repeated when discussing these drawings, and any of these elements may take any of the forms disclosed herein. Further, various elements are illustrated in FIG. **1** as included in the microelectronic assembly **100**, but, in various embodiments, some of these elements may not be included. For example, in various embodiments, the further layers **111**, the underfill material **127**, and the package substrate **102** may not be present in the microelectronic assembly **100**. In some embodiments, individual ones of the microelectronic assemblies **100** disclosed herein may serve as a system-in-package (SiP) in which multiple dies **114** having different functionality are included. In such embodiments, the microelectronic assembly **100** may be referred to as an SiP.

[0050] FIG. **2** is a schematic cross-sectional view of another example microelectronic assembly **100** according to some embodiments of the present disclosure. The configuration of the embodiment shown in the figure is like that of FIG. **1**, except for differences as described further. Instead of including the glass core **110** as a part of the substrate **107**, as was shown in FIG. **1**, the microelectronic assembly **100** of FIG. **2** includes a glass core **110** on its own, where one or more dies **114** may be coupled to the glass core **110**. In FIG. **2**, the multi-layer die subassembly **104** includes the glass core **110** and the plurality of dies **114** as described above. The multi-layer die subassembly **104** may have a first surface **160-1** (e.g., the bottom face) and an opposing second surface **160-2** (e.g., the top face). The glass core **110** may provide mechanical stability to the multi-layer die subassembly **104** and/or the microelectronic assembly **100** of FIG. **2**, may reduce warpage, and may provide a more robust surface for attachment of the multi-layer die subassembly **104** to a package substrate **102** or other substrate (e.g., an interposer or a circuit board).

[0051] The glass core **110** may include a cavity **129** with an opening facing the second surface **160-2** and the die **114-1** may be nested, fully or at least partially, in the cavity **129**. As shown in FIG. **2**, in cases where the die **114-1** is fully nested in a cavity **129**, a top face of the die **114-1** may be planar with or below a top face of the glass core **110**. In cases where the die **114-1** is partially nested in a cavity **129**, a top face of the die **114-1** may extend above a top face of the glass core **110**. The cavity **129** may be at least partially filled with a dielectric material **112A** or **112B**, described above. The die **114-1** may be attached to a bottom face of the cavity **129** by a die-attach film (DAF) **132**. A DAF **132** may be any suitable material, including a non-conductive adhesive, die-attach film, a B-stage underfill, or a polymer film with adhesive property. A DAF **132** may have any suitable dimensions, for example, in some embodiments, a DAF **132** may have a thickness (e.g., height or z-height) between 5 microns and 10 microns.

[0052] The die **114-1** may be coupled to the dies **114-2**, **114-3** in a layer above the die **114-1** through the DTD interconnects **130**. The DTD interconnects **130** may be disposed between some of the conductive contacts **122** at the bottom of the dies **114-2**, **114-3** and some of the conductive contacts **124** at the top of the die **114-1**. Some other conductive contacts **122** at the bottom of the dies **114-2** and/or **114-3** may further couple one or more of the dies **114-2**, **114-3** to the glass core **110** by glass core-to-die (GCTD) interconnects **142**. The GCTD interconnects **142** may be disposed between some of the conductive contacts **122** at the bottom of the dies **114-2**, **114-3** and some of the conductive contacts **128** at the top of the glass core **110**. The GCTD interconnects **142** may be similar to the DTS interconnects **140**, described above. In some embodiments, the underfill material **127** may extend between different ones of the dies **114** around the associated DTD interconnects **130** and/or GCTD interconnects **142**. In some embodiments, a die **114-2** and/or a die **114-3** may be embedded in an insulating material **133**. In some embodiments, an overall thickness (e.g., a z-height) of the insulating material **133** may be between 200 microns and 800 microns (e.g., substantially equal to a thickness of die **114-2** or **114-3** and the underfill material **127**). In some embodiments, the insulating material **133** may form multiple layers (e.g., a dielectric material formed in multiple layers, as known in the art) and may embed one or more dies **114** in a layer. In some embodiments, the insulating material **133** may be a dielectric material, such as an organic

dielectric material, a fire retardant grade **4** material (FR-4), BT resin, polyimide materials, glass reinforced epoxy matrix materials, or low-k and ultra low-k dielectric (e.g., carbon-doped dielectrics, fluorine-doped dielectrics, porous dielectrics, and organic polymeric dielectrics). In some embodiments, the insulating material **133** may be a mold material, such as an organic polymer with inorganic silica particles.

[0053] As shown in FIG. **2**, the glass core **110** may further include conductive contacts **126** at the bottom of the glass core **110**, and TGVs **115** may extend between and electrically couple conductive contacts **126** at the bottom of the glass core **110** and conductive contacts **128** at the top of the glass core **110**. The conductive contacts **126**, **128** may be similar to other conductive contacts disclosed herein (e.g., the conductive contacts **122**, **124**, **144**, and/or **146**), and may include bond pads, solder bumps, conductive posts, or any other suitable conductive contact, for example. As shown in FIG. **2**, in some embodiments, at least some of the TGVs **115** may have an hourglass shape. For example, at least some of the TGVs **115** may have a first width at the first face of the glass core **110** (e.g., at the bottom face of the glass core **110**), a second width at the second face of the glass core **110** (e.g., at the top face of the glass core **110**), and a third width between the first face and the second face of the glass core **110**, where the third width is smaller than the first width and the second width.

[0054] The dies **114-2**, **114-3** may be electrically coupled to the package substrate **102** through the TGVs **115** and glass core-to-package substrate (GCTPS) interconnects **152**, which may be power delivery interconnects or high-speed signal interconnects. The GCTPS interconnects **152** may be similar to the STPS interconnects **150**, described above. The top face of the package substrate **102** may include a set of conductive contacts **146**, the multi-layer die subassembly **104** may include a set of conductive contacts **126** on the first surface **160-1**, and the GCTPS interconnects **152** may be between, and couple the conductive contacts **146** with corresponding ones of the conductive contacts **126**. In some embodiments, the underfill material **127** may extend between the glass core **110** and the package substrate **102** around the associated GCTPS interconnects **152**.

[0055] The glass core **110** included in a microelectronic assembly **100** as described with reference to FIG. **1** or FIG. **2** or included in any other microelectronic assembly or device, may be subject to TGV stress prior to inclusion in the microelectronic assembly **100**. For example, FIG. **3** illustrates surfaces of a glass core **110** from which TGV stress may initiate, according to some embodiments of the present disclosure. As shown in FIG. **3**, a glass core **110** may have a first face **190-1** and an opposing second face **190-2**, e.g., be bottom and top faces when the glass core **110** is included in a microelectronic assembly **100** (where, together, the first and second faces **190-1**, **190-2** may be referred to as “faces **190**”). The glass core **110** may also include a side **190-3**, which is a surface of the glass core **110** that may be referred to as an edge or a sidewall of the glass core **110**, i.e., a surface that extends between the first face **190-1** and the second face **190-2**. As further shown in FIG. **3**, TGV openings **192** may be formed in the glass core **110**, extending between the first face **190-1** and the second face **190-2**. A sidewall **190-4** may then refer to one or more sidewalls of the TGV openings **192**. When a conductive material is deposited in the TGV openings **192**, TGV stress may initiate from the sidewall **190-4** due to CTE mismatch between the glass material of the glass core **110** and the conductive material in the TGV openings **192**.

[0056] One or more techniques for TGV stress alleviation as described herein may be applied to reduce TGV stress at the sidewalls **190-4**, before including the glass core **110** in a microelectronic assembly **100**. In particular, various techniques for TGV stress alleviation are based on implementing conductive vias (e.g., TGVs **115**) in glass cores as conductive vias with sealed liners. To that end, three different fabrication methods for providing conductive vias with sealed liners are described herein, as shown in FIGS. **5**, **7**, and **9**. As a result of carrying out the methods of FIGS. **5**, **7**, and **9**, microelectronic assemblies **400A**, **400B**, and **400C** with different arrangements of sealed liners may be realized, as shown in FIGS. **4A**, **4B**, and **4C**, respectively. Each of the microelectronic assemblies **400A-400C** may be an example of a portion of any of the

microelectronic assemblies **100** described herein. FIG. 4A, FIG. 4B, and FIG. 4C illustrate cross-sectional side views (e.g., views of a y-z plane of the example coordinate system **105**, described herein) of a portion of a glass core **110** in which three conductive vias with sealed liners are fabricated using metallization processes of the methods **500**, **700**, and **900**, respectively.

[0057] Each of FIGS. 4A-4C illustrates a glass core **110** with three TGVs **415** extending between the first and second faces **190-1**, **190-2**, where an individual TGV **415** includes a TGV opening **420**, a liner material **422** on sidewall(s) of the TGV opening **420**, a seed material **424** over the liner material **422**, and a conductive fill material **426** filling the remaining space of the TGV opening **420**, with conductive contacts **428** provided at the opposite ends of the TGV **415**. Each of FIGS. 4A-4C further illustrates a sealant **430**, configured to seal the liner material **422** in the TGVs **415**, e.g., the glass core **110**, the conductive materials in the TGV openings (e.g., the seed material **424** and the conductive fill material **426**), and the sealant **430** may completely enclose the liner material **422** as to reduce or eliminate oxidation of the liner material **422**. Thus, because of the presence of the sealant **430** as described herein, the liner material **422** may be referred to as a “sealed liner” of the TGVs **415**. FIGS. 4A-4C further illustrate further layers **432** on the opposite faces **190** of the glass core **110**.

[0058] Although the TGVs **415** are shown in the present drawings as extending all the way through the thickness of the glass cores **110**, in other embodiments, any of the TGVs **415** may be a blind via, in which case the sealant **430** would only be provided over one face **190** of the glass core **110**, the face from which the blind via starts. Furthermore, although further layers **432** are shown in FIGS. 4A-4C on both faces **190-1** and **190-2** of the glass cores **110**, in some embodiments, further layers **432** may be absent on the first face **190-1**, the second face **190-2**, or both faces **190-1** and **190-2**. Still further, although three TGVs **415** are shown in the present drawings, in other embodiments, the microelectronic assemblies **400-400C** may include any number of one or more TGVs **415**.

[0059] FIGS. 4A-4C differ in how the sealant **430** is implemented with respect to the glass core **110**. In particular, in the microelectronic assembly **400A** shown in FIG. 4A, the sealant **430** may be in contact with one or more portions of the first face **190-1** and/or one or more portions of the second face **190-2** of the glass core **110**. As used herein, unless specified otherwise, description of element A being “in contact” with element B includes element A being in direct physical contact with element B. In contrast to FIG. 4A, in the microelectronic assembly **400B** shown in FIG. 4B, the sealant **430** is not in contact with any portions of the first face **190-1** or the second face **190-2** of the glass core **110** because a buffer layer **434** is provided over these faces so that, e.g., for the first face **190-1**, the buffer layer **434** is between the first face **190-1** and the sealant **430**, e.g., between the liner material **422** over the first face **190-1** and the sealant **430**. In the microelectronic assembly **400C** shown in FIG. 4C, two of layers of the sealant **430** may be provided, with one layer being as shown in FIG. 4B, and another layer of the sealant **430** being between the buffer layer **434** and the first face **190-1**, e.g., between the buffer layer **434** and the liner material **422** over the first face **190-1**.

[0060] Turning to the details of how the TGVs **415** with sealed liners of FIGS. 4A-4C may be fabricated, FIG. 5, FIG. 7, and FIG. 9 are flow diagrams of, respectively, a method **500**, a method **700**, and a method **900** of providing a glass core with a sealed liner, in accordance with various embodiments. FIGS. 6A-6F provide cross-sectional side views at various stages in the fabrication of an example glass core with a sealed liner according to the method **500** of FIG. 5, in accordance with some embodiments. FIGS. 8A-8C provide cross-sectional side views at various stages in the fabrication of an example glass core with a sealed liner according to the method **700** of FIG. 7, in accordance with some embodiments. FIGS. 10A-10C provide cross-sectional side views at various stages in the fabrication of an example glass core with a sealed liner according to the method **900** of FIG. 9, in accordance with some embodiments. Similar to FIGS. 4A-4C, each of FIGS. 6A-6F, FIGS. 8A-8C, and FIGS. 10A-10C illustrates a cross-sectional side view (e.g., a view of a y-z

plane of the example coordinate system **105**, described herein) of a portion of a glass core **110** in which three conductive vias with sealed liners are fabricated using metallization processes of the methods **500**, **700**, and **900**.

[0061] Although the operations of the methods **500**, **700**, and **900** are illustrated once each and in a particular order, the operations may be performed in any suitable order and repeated as desired. For example, one or more operations may be performed in parallel to fabricate multiple conductive vias with sealed liners substantially simultaneously. In another example, one or more operations may be performed in parallel to fabricate conductive vias with sealed liners in multiple glass cores substantially simultaneously.

[0062] In addition, the example fabricating methods **500**, **700**, and **900** may include other operations not specifically shown in FIGS. **5**, **7**, and **9**, such as various cleaning or planarization operations as known in the art. For example, in some embodiments, a glass core **110**, as well as layers of various other materials subsequently deposited thereon, may be cleaned prior to, after, or during any of the processes of the methods **500**, **700**, and **900** described herein, e.g., to remove oxides, surface-bound organic and metallic contaminants, as well as subsurface contamination. In some embodiments, cleaning may be carried out using e.g., a chemical solutions (such as peroxide), and/or with ultraviolet (UV) radiation combined with ozone, and/or oxidizing the surface (e.g., using thermal oxidation) then removing the oxide (e.g., using hydrofluoric acid (HF)).

[0063] The method **500** may begin with a process **502** that includes providing a glass core with one or more TGV openings therein. FIG. **6A** illustrates an assembly **602** that may be an example result of the process **502**, showing a glass core **110** with TGV openings **420** therein. Again, FIG. **6A** as well as FIGS. **6B-6F**, FIGS. **8A-8C**, and FIGS. **10A-10C** illustrate TGV openings **420** in the glass core **110** to be extending between the first face **190-1** and the second face **190-2** of the glass core **110**, although descriptions provided herein are applicable to openings that are blind openings, e.g., openings that start at one of the faces **190** and extend towards, but do not reach, the other one of the faces **190**. In some embodiments, the TGV openings **420** may be formed in the glass core **110** using any suitable subtractive technique such as direct laser drilling or laser-induced etching process, possibly in combination with any suitable patterning technique such as photolithographic or electron-beam (e-beam) patterning. In other embodiments, the TGV openings **420** may be formed during fabrication of the glass core **110** itself, e.g., when molten glass is filled into a mold that has space for the future TGV openings **420**.

[0064] Next, the method **500** may include a process **504**, in which the TGV openings **420** of the process **502** may be lined with a liner material. To that end, a layer of a liner material may be deposited on sidewalls of the TGV openings **420** of the process **502** and, possibly, also on the bottoms of the TGV openings **420** for those TGV openings **420** that may be implemented as blind openings. FIG. **6B** illustrates an assembly **604** that may be an example result of the process **504**, showing a glass core **110** in which the TGV openings **420** are lined with a layer of a liner material **422**, thus creating lined TGV openings. In various embodiments, the liner material **422** may be deposited using any suitable deposition technique such as chemical vapor deposition (CVD), atomic layer deposition (ALD), or physical vapor deposition (PVD). In some embodiments, besides being deposited as a liner in the TGV openings **420**, the liner material **422** may also be deposited over the first face **190-1**, the second face **190-2**, or both faces **190**, depending on how the liner material **422** is deposited. In such embodiments, the liner material **422** deposited over the first face **190-1** and/or the second face **190-2** may be materially continuous with the liner material **422** on the sidewalls of the TGV openings **420**. In some embodiments, portions of the liner material **422** on the sidewalls of the TGV openings **420** may be in contact with the sidewalls of the TGV openings **420** (e.g., in contact with the glass core **110** at the sidewalls of the TGV openings **420**). In some embodiments, a thickness of the liner material **422** may be between about 200 nanometers and about 10 microns, e.g., between about 200 nanometers and about 5 microns, or between about 500 nanometers and about 1 micron. In some embodiments, the liner material **422** may be deposited as

a conformal layer, i.e., it may be conformal to the shapes of the underlying surfaces over which the liner material **422** is deposited.

[0065] The liner material **422** may include any suitable material that may separate the glass materials of the glass core **110** at the sidewalls of the TGV openings **420** and the conductive materials that will later be deposited in the TGV openings **420**. In some embodiments, the liner material **422** may include a material having a relatively low modulus, e.g., having Young's modulus below about 30 GPa, e.g., below about 10 GPa, e.g., between about 3 GPa and 30 GPa or between about 1 GPa and 30 GPa, where the Young's modulus may be defined as the ratio of stress to strain in a material undergoing deformation. In some embodiments, the liner material **422** may include a material having a modulus (e.g., Young's modulus) smaller than that of the glass core **110** and/or having a modulus (e.g., Young's modulus) smaller than that of the conductive fill material **426** deposited in a later process. In some embodiments, a CTE of the liner material **422** may be smaller than a CTE of the conductive fill material **426**, e.g., smaller than about 17 ppm/K or smaller than about 15 ppm/K or 10 ppm/K.

[0066] In some embodiments, the liner material **422** may include a polymer material, e.g., an organic polymer. In other embodiments, the liner material **422** may include an organic material other than a polymer, e.g., monomers or oligomers. In some embodiments, the liner material **422** may include a homopolymer, which is a polymer composed of repeating units of a single type of monomer. Simple signal chemical system organic liners such as homopolymers may be particularly advantageous for use as the liner material **422** because they may be relatively easy to manufacture and because they can be adapted readily for use as the liner material **422**. In some embodiments, the liner material **422** may include poly-para-xylylene (which is also commonly referred to as "parylene"), such as parylene N, parylene C, parylene D, or parafree (halogen free). In other embodiments, the liner material **422** may include a heteropolymer, which is a polymer composed of repeating units of two or more types of monomers or oligomers. For example, the liner material **422** may include heteropolymers such as polyester (PET), polyurethane (PU), polycarbonate (PC), or polyvinyl chloride (PVC).

[0067] In other embodiments, the liner material **422** may include a material that is not a polymer, e.g., an inorganic non-polymer material. In some such embodiments, the liner material **422** may include inorganic materials such as carbon-doped oxide (CDO), low modulus SiO_x, silicon oxycarbide (SiOC), or other low-k dielectrics.

[0068] The method **500** may then proceed with a process **506**, in which TGV metallization may be performed on the assembly **604** with the TGV openings **420** lined with the liner material **422**. FIG. 6C illustrates an assembly **606** that may be an example result of the process **506**, showing that TGV metallization may include depositing a layer of a seed material **424** to line the TGV openings **420** lined with the liner material **422**, and then at least partially fill the remaining space in the TGV openings **420** with a conductive fill material **426**, thus creating conductive vias in the form of TGVs **415**. The TGVs **415** are one example of any of the TGVs **115**, described herein. The seed material **424** may include any suitable conductive material, e.g., a metal, a metal alloy, or a combination of metals, e.g., a low-resistivity metal such as copper, that can be deposited in a thin layer on substantially non-conductive surfaces (e.g., sidewalls) of the TGV openings **420** lined with the liner material **422**. The seed material **424** provides a conductive surface for uniform and controlled deposition of a conductive fill material in a subsequent step of the TGV metallization of the process **506**. For example, the seed material **424** may serve as a foundation or base for the subsequent electroplating of a thicker layer of metal. In some embodiments, the seed material **424** may include one or more metals such as copper, ruthenium, nickel, gold, palladium, platinum, or silver. In various embodiments, a thickness of the layer of the seed material **424**, e.g., as measured in a direction perpendicular to the sidewalls of the TGV openings **420**, may be between about 5 nanometer and 20 micron, e.g., between about 10 nanometers and 15 micron, or between about 10 nanometers and 1 micron. In various embodiments, the seed material **424** may be deposited using

any suitable deposition technique such as CVD, ALD, or PVD. In some embodiments, the seed material **424** may be deposited as a conformal layer. In some embodiments, the seed material **424** may include two or more layers of different conductive materials, deposited on the liner material **422** sequentially. For example, the seed material **424** may include a layer of a first material deposited on the liner material **422**, and then a layer of a second material deposited on the first material. The first material may be a conductive material that has good adhesive properties in terms of adhesion between the first material and the liner material **422**, and, possibly, in terms of adhesion between the first material and the second material. The second material may be a conductive material that may protect the first material from oxidation before and/or during deposition of the conductive filler material in a subsequent process. For example, the first layer of the seed material **424** may include titanium, while the second layer of the seed material **424** may include copper. In other embodiments, the seed material **424** may include a single layer of a conductive material, e.g., a layer of copper or a layer of ruthenium. The conductive fill material **426** may include any suitable conductive material, e.g., any of the materials described with reference to the seed material **424**. In some embodiments, material compositions of the seed material **424** and the conductive fill material **426** may be substantially the same, e.g., both may be, or may include, copper. In other embodiments, material compositions of the seed material **424** and the conductive fill material **426** may be different. The conductive fill material **426** may be deposited using any suitable deposition technique such as electroplating, ALD, CVD, or PVD.

[0069] Next, the method **500** may include a process **508**, in which conductive contacts are formed at the ends of the TGV openings **420** of the assembly **606**. FIG. **6D** illustrates an assembly **608** that may be an example result of the process **508**, showing a glass core **110** with conductive contacts **428** at the opposite ends of the TGV openings **420**. In some embodiments, the conductive contacts **428** may be fabricated by removing remainder of the overburden of the conductive fill material **426** that may be deposited over the faces **190** in the process **506**, e.g., using any suitable etching process, possibly in combination with any suitable patterning technique such as photolithographic or e-beam patterning.

[0070] The method **500** may further include a process **510**, in which the seed material **424** and the liner material **422** exposed by the removal of the conductive fill material **426** to form the conductive contacts **428** in the process **508** may be removed as well. FIG. **6E** illustrates an assembly **610** that may be an example result of the process **510**, showing that the seed material **424** and the liner material **422** on portions of the faces **190** that are outside the footprint of the conductive contacts **428** may be removed, exposing the surfaces of the glass core **110**. In some embodiments, the process **510** may include any suitable etching process, e.g., a two-step etching process in which a first set of one or more etchants is used to remove the seed material **424**, thus exposing the liner material **422**, and then a second set of one or more etchants is used to remove the liner material **422**. In other embodiments, the conductive contacts **428** may be provided using any other suitable techniques, e.g., using additive techniques to add the conductive contacts **428**, as long as the conductive fill material **426** of the TGVs **415** may be brought in conductive contact with conductive materials of the conductive contacts **428**. Descriptions provided with respect to conductive contacts of the microelectronic assemblies **100** shown in FIGS. **1-2** (e.g., the conductive contacts **122**) are applicable to the conductive contacts **428** and, therefore, for the sake of brevity, are not repeated.

[0071] Next, the method **500** may include a process **512**, in which a sealant is deposited to seal the liner material **422**. FIG. **6F** illustrates an assembly **612** that may be an example result of the process **512**, showing a layer of a sealant **430** deposited over the top and bottom surfaces of the assembly **610**, enclosing the liner material **422** in the TGVs **415**. The sealant **430** may be deposited using any suitable deposition technique such as electroplating, ALD, CVD, or PVD. In some embodiments, a thickness of the sealant **430** may be between about 100 nanometers and about 10 microns, e.g., between about 200 nanometers and about 5 microns, or between about 250 nanometers and about 1

microns. In some embodiments, the sealant **430** may be deposited as a conformal layer.

[0072] In some embodiments, the sealant **430** may include any suitable material that may reduce or eliminate oxidation of the liner material **422**. For example, in some such embodiments, the sealant **430** may include an inorganic material, e.g., silicon nitride. In other such embodiments, the sealant **430** may include other nitrides, or other materials that do not oxidize easily and that may withstand subsequent processes that may be applied to the assembly **612**. In other embodiments, the sealant **430** may include any suitable material that may reduce or eliminate crystallization of the liner material **422**. For example, in some such embodiments, the sealant **430** may include an inorganic material, e.g., silicon oxide. In other such embodiments, the sealant **430** may include other oxides, or other materials that may reduce or eliminate crystallization of the liner material **422** and that may withstand subsequent processes that may be applied to the assembly **612**. The choice of the material(s) used as the sealant **430** may depend on the specific application, environmental conditions, and the choice of the liner material **422** being sealed. In various embodiments, the sealant **430** may include one or more of silicone, polyurethane, an acrylic material, fluorosilicone, butyl rubber, epoxy, neoprene, or polyvinyl chloride.

[0073] The method **500** may further include a process **514** in which further layers are provided over the first face **190-1** and/or over the second face **190-2** of the glass core **110** of the assembly **612**. FIG. **4A**, described above, illustrates an example result of the process **514**, showing further layers **432** provided over the first face **190-1** and over the second face **190-2** of the glass core **110**. In some embodiments, the further layers **432** may include build-up layers, e.g., build-up layers described with reference to FIGS. **1-2**. In some embodiments, the further layers **432** may include ABF. In some embodiments, the sealant **430** may be a material that can promote adhesion of the further layers **432** to the top and/or bottom surfaces of the assembly **612**.

[0074] Performing the method **500** may result in several features characteristic of the use of the method **500**. One such feature may be that, in some embodiments, a portion of the sealant **430** may be in contact with a portion of the first face **190-1** of the glass core **110** and/or a portion of the sealant **430** may be in contact with a portion of the second face **190-2** of the glass core **110**, e.g., portions of the sealant **430** that are not on the conductive contacts **428**. An example of that may be seen within a dashed contour **620**, shown in FIG. **6F**. Another feature characteristic of the use of the method **500** may be that a portion of the liner material **422** over a given face **190** of the glass core **110** may be in contact with a portion of the sealant **430**. An example of that may be seen within a dashed contour **622**, shown in FIG. **6F**. Similarly, a portion of the seed material **424** over a given face **190** of the glass core **110** may be in contact with a portion of the sealant **430**, as can also be seen within the dashed contour **622** of FIG. **6F**. Yet another feature characteristic of the use of the method **500** may be that a portion of the liner material over a given face **190** of the glass core **110** may be in contact with a portion of that face **190** of the glass core **110**. An example of that may be seen within a dashed contour **624**, shown in FIG. **6F**. Because in the method **500** the sealant **430** is deposited after formation of the conductive contacts **428**, in some embodiments, a portion of the sealant **430** may be on a sidewall of a conductive contact **428**, e.g., as shown within a dashed contour **626**, shown in FIG. **6F**, while another portion of the sealant **430** may be on the top surface of a conductive contact **428**, e.g., as shown within a dashed contour **628**, shown in FIG. **6F**.

[0075] Turning to the second method of providing a glass core with sealed liners, the method **700**, shown in FIG. **7**, may include processes **702**, **704**, and **706**, which may be substantially the same as the processes **502**, **504**, and **506**, respectively, described with reference to the method **500**. For the sake of brevity, descriptions of these processes are not repeated and their illustrations are not shown in FIGS. **8A-8C**. After the process **706**, the method **700** may include a process **708**, in which TGV metals deposited over the faces **190** during the TGV metallization of the process **706** may be planarized and a buffer layer may be provided over the first face **190-1** and/or the second face **190-2**. FIG. **8A** illustrates an assembly **808** that may be an example result of the process **708**, showing a buffer layer **434** provided over the first face **190-1** and another buffer layer **434** provided over the

second face **190-2**. Using the buffer layers **434** over one or more of the faces **190** of the glass core **110** may be advantageous in terms of providing a separation between the conductive contacts **428** and the glass core **110** in an attempt to minimize CTE mismatch issues. In some embodiments, the buffer layer **434** may include an insulator material such as ABF, polyimide, or any other suitable dielectric material that can reduce the stress generated from the CTE mismatch between glass core and conductive contacts that are usually made of copper. These materials have a much lower modulus than copper and typically less than 60 GPa. In some embodiments, a thickness of the buffer layer **434** may be between about 5 microns and about 50 microns, e.g., between about 5 microns and about 35 microns, or between about 15 microns and about 35 microns.

[0076] Next, the method **700** may include a process **710**, in which one or more openings may be formed in the buffer layer **434** to expose the conductive fill material **426** in the one or more TGVs **415** of the assembly **808**. FIG. **8B** illustrates an assembly **810** that may be an example result of the process **710**, showing openings **438** in the buffer layer **434** at the opposite ends of the TGV openings **420**. In some embodiments, the openings **438** may be formed using any suitable etching process, possibly in combination with any suitable patterning technique such as photolithographic or e-beam patterning.

[0077] The method **700** may further include a process **712**, in which conductive contacts are formed at the ends of the openings **438** of the assembly **808** and a sealant is deposited to seal the liner material **422**. FIG. **8C** illustrates an assembly **812** that may be an example result of the process **712**, showing a glass core **110** with conductive contacts **428** at the opposite ends of the openings **438** in the buffer layer **434**, and further showing a layer of the sealant **430** deposited over the top and bottom surfaces of the assembly **812** after the conductive contacts **428** have been formed, enclosing the liner material **422** in the TGVs **415**. The conductive contacts **428** may be formed in the process **712** using any suitable techniques as known in the art, as long as the conductive material(s) of the conductive contacts **428** is in conductive contact with the conductive fill material **426** of the TGVs **415**, e.g., by virtue of filling the openings **438** with a conductive material. Descriptions of the sealant **430** provided with reference to the method **500** are applicable to the sealant **430** deposited in the process **712** and, therefore, for the sake of brevity, are not repeated.

[0078] The method **700** may further include a process **714** in which further layers are provided over the first face **190-1** and/or over the second face **190-2** of the glass core **110** of the assembly **812**. FIG. **4B**, described above, illustrates an example result of the process **714**, showing further layers **432** provided over the first face **190-1** and over the second face **190-2** of the glass core **110**. Descriptions of the further layers **432** provided with reference to the method **500** are applicable to the further layers **432** provided in the process **714** and, therefore, for the sake of brevity, are not repeated.

[0079] Similar to the method **500**, performing the method **700** may result in several features characteristic of the use of the method **700**. One such feature may be that, in some embodiments, a portion of the buffer layer **434** may be between the liner material **422** over a given face **190** of the glass core **110** and the sealant **430**. An example of that may be seen within a dashed contour **820**, shown in FIG. **8C**. Another feature characteristic of the use of the method **700** may be that a portion of the buffer layer **434** may be in contact with a portion of the conductive contact **428**. An example of that may be seen within a dashed contour **822**, shown in FIG. **8C**. Yet another feature characteristic of the use of the method **700** may be that a portion of the sealant **430** may be in contact with a portion of the buffer layer **434**. An example of that may be seen within a dashed contour **824**, shown in FIG. **8C**. Because in the method **700** the sealant **430** is deposited after formation of the conductive contacts **428**, similar to the method **500**, in some embodiments, a portion of the sealant **430** may be on a sidewall of a conductive contact **428**, e.g., as shown within a dashed contour **826**, shown in FIG. **8C**, while another portion of the sealant **430** may be on the top surface of a conductive contact **428**, e.g., as shown within a dashed contour **828**, shown in FIG. **8C**.

[0080] Turning to the third method of providing a glass core with sealed liners, the method **900**, shown in FIG. **9**, may include processes **902**, **904**, and **906**, which may be substantially the same as the processes **502**, **504**, and **506**, respectively, described with reference to the method **500**. For the sake of brevity, descriptions of these processes are not repeated and their illustrations are not shown in FIGS. **10A-10C**. After the process **906**, the method **900** may include a process **908**, in which TGV metals deposited over the faces **190** during the TGV metallization of the process **906** may be planarized, and a first layer of a sealant may be provided over the first face **190-1** and/or the second face **190-2**, followed by provision of a buffer layer over the first sealant. FIG. **10A** illustrates an assembly **1008** that may be an example result of the process **908**, showing a sealant **430** deposited over the first face **190-1** and the second face **190-2**, and then providing a buffer layer **434** over the sealant **430**. Descriptions of the buffer layers **434** provided with reference to the method **700** are applicable to the buffer layers **434** provided in the process **912** and, therefore, for the sake of brevity, are not repeated.

[0081] Next, the method **900** may include a process **910**, in which one or more openings may be formed in the buffer layer **434** and the first layer of the sealant **430** to expose the conductive fill material **426** in the one or more TGVs **415** of the assembly **1008**. FIG. **10B** illustrates an assembly **1010** that may be an example result of the process **910**, showing openings **440** in the buffer layer **434** and the first layer of the sealant **430** at the opposite ends of the TGV openings **420**. In some embodiments, the openings **440** may be formed using any suitable etching process, possibly in combination with any suitable patterning technique such as photolithographic or e-beam patterning.

[0082] The method **900** may further include a process **912**, in which conductive contacts are formed at the ends of the openings **440** of the assembly **1008** and a second layer of a sealant is deposited to seal the liner material **422**. FIG. **10C** illustrates an assembly **1012** that may be an example result of the process **912**, showing a glass core **110** with conductive contacts **428** at the opposite ends of the openings **440** in the buffer layer **434**, and further showing a second layer of the sealant **430** deposited over the top and bottom surfaces of the assembly **1012** after the conductive contacts **428** have been formed, enclosing the liner material **422** in the TGVs **415**. The conductive contacts **428** may be formed in the process **912** using any suitable techniques as known in the art, as long as the conductive material(s) of the conductive contacts **428** is in conductive contact with the conductive fill material **426** of the TGVs **415**, e.g., by virtue of filling the openings **440** with a conductive material. Descriptions of the sealant **430** provided with reference to the method **500** are applicable to the first layer of the sealant **430** deposited in the process **910** and the second layer of the sealant **430** deposited in the process **912** and, therefore, for the sake of brevity, are not repeated. In some embodiments, a material composition of the sealant **430** of the first layer (i.e., the one deposited in the process **910**) may be different from a material composition of the sealant **430** of the second layer (i.e., the one deposited in the process **912**). In other embodiments, these material compositions may be substantially the same.

[0083] The method **900** may further include a process **914** in which further layers are provided over the first face **190-1** and/or over the second face **190-2** of the glass core **110** of the assembly **1012**. FIG. **4C**, described above, illustrates an example result of the process **914**, showing further layers **432** provided over the first face **190-1** and over the second face **190-2** of the glass core **110**. Descriptions of the further layers **432** provided with reference to the method **500** are applicable to the further layers **432** provided in the process **914** and, therefore, for the sake of brevity, are not repeated.

[0084] Similar to the methods **500** and **700**, performing the method **900** may result in several features characteristic of the use of the method **900**. Some such features are the same as those shown within dashed contours **822**, **824**, **826**, and **828**, as explained with reference to FIG. **8C**. Therefore, the dashed contours **822**, **824**, **826**, and **828** are also shown in FIG. **10C**. Another feature that was not present in FIG. **8C** is that a sealant **430** (the sealant **430** of the first layer deposited in the process **910**) is present between the buffer layer **434** and the liner material **422** over a given

face **190** of the glass core **110**. An example of that may be seen within a dashed contour **1020**, shown in FIG. **10C**. Similarly, one other feature is that a portion of the buffer layer **434** may be in contact with a portion of the first layer of the sealant **430**, as is also seen within the dashed contour **1020**, shown in FIG. **10C**. A related feature characteristic of the use of the method **900** may be that a portion of the buffer layer **434** may be between the sealant **430** of the first layer and the sealant **430** of the second layer. An example of that may be seen within a dashed contour **1022**, shown in FIG. **10C**.

[0085] Various embodiments of conductive vias with sealed liners, described above may, advantageously, be easily fabricated in parallel with conventional manufacturing techniques for glass core substrates. Various arrangements of the microelectronic assemblies **100** and glass cores **110** as shown in FIGS. **1-10** do not represent an exhaustive set of microelectronic assemblies and glass cores in which one or more conductive vias with sealed liners as described herein may be implemented, but merely provide some illustrative examples. In particular, the number and positions of various elements shown in FIGS. **1-10** is purely illustrative and, in various other embodiments, other numbers of these elements, provided in other locations relative to one another may be used in accordance with the general architecture considerations described herein. For example, although not specifically shown in the present drawings, in some embodiments, a microelectronic assembly **100** may include a redistribution layer (RDL) between any pair of layers shown in FIG. **1** and FIG. **2**, the RDL including a plurality of interconnect structures (e.g., conductive lines and conductive vias) to assist routing of signals and/or power between components. In another example, although also not specifically shown in the present drawings, in some embodiments, a package substrate **102** of a microelectronic assembly **100** may include one or more recesses. In such embodiments, a bottom face of a recess in the package substrate **102** may be provided by the solid material of the package substrate **102**. A recess may be formed in a package substrate **102** in any suitable manner (e.g., via three-dimensional printing, laser cutting or drilling the recess into an existing package substrate, etc.). At least a portion of the substrate **107** or the glass core **110** may be positioned over or at least partially in such a recess. In yet another example, features of any one of FIGS. **1-10** may be combined with features of any other one of FIGS. **1-10**. For example, in some embodiments, some portions of a glass core **110** may include one or more conductive vias with sealed liners fabricated using the method **500**, while other portions of a glass core **110** may include one or more conductive vias with sealed liners fabricated using the method **700** and/or using the method **900**.

[0086] The microelectronic assemblies **100** and/or the glass cores **110** disclosed herein, in particular the glass cores **110** with one or more conductive vias with sealed liners as described herein, may be included in any suitable electronic component. FIGS. **11-14** illustrate various examples of apparatuses that may include, or be included in, any of the microelectronic assemblies **100** and/or the glass cores **110** disclosed herein.

[0087] FIG. **11** is a top view of a wafer **1500** and dies **1502** that may be included in any of the microelectronic assemblies **100** as described herein. For example, a die **1502** may be any of the dies **114** described herein. The wafer **1500** may be composed of semiconductor material and may include one or more dies **1502** having IC structures formed on a surface of the wafer **1500**. Each of the dies **1502** may be a repeating unit of a semiconductor product that includes any suitable IC. After the fabrication of the semiconductor product is complete, the wafer **1500** may undergo a singulation process in which the dies **1502** are separated from one another to provide discrete “chips” of the semiconductor product. The die **1502** may include one or more transistors (e.g., some of the transistors **1640** of FIG. **12**, discussed below) and/or supporting circuitry to route electrical signals to the transistors, as well as any other IC components. In some embodiments, the wafer **1500** or the die **1502** may include a memory device (e.g., a random-access memory (RAM) device, such as a static RAM (SRAM) device, a magnetic RAM (MRAM) device, a resistive RAM (RRAM) device, a conductive-bridging RAM (CBRAM) device, etc.), a logic device (e.g., an

AND, OR, NAND, or NOR gate), or any other suitable circuit element. Multiple ones of these devices may be combined on a single die **1502**. For example, a memory array formed by multiple memory devices may be formed on a same die **1502** as a processing device (e.g., the processing device **1802** of FIG. **14**) or other logic that is configured to store information in the memory devices or execute instructions stored in the memory array.

[0088] FIG. **12** is a side, cross-sectional view of an IC device **1600** that may be included in any of the microelectronic assemblies **100** as described herein. For example, an IC device **1600** may be provided on/in any of the dies **114** described herein. The IC device **1600** may be formed on a substrate **1602** (e.g., the wafer **1500** of FIG. **11**) and may be included in a die (e.g., the die **1502** of FIG. **11**). The substrate **1602** may be a semiconductor substrate composed of semiconductor material systems including, for example, n-type or p-type materials systems (or a combination of both). The substrate **1602** may include, for example, a crystalline substrate formed using a bulk silicon or a silicon-on-insulator (SOI) substructure. In some embodiments, the substrate **1602** may be formed using alternative materials, which may or may not be combined with silicon, that include but are not limited to germanium, indium antimonide, lead telluride, indium arsenide, indium phosphide, gallium arsenide, or gallium antimonide. Further materials classified as group III-V materials (i.e., materials from groups III and V of the periodic system of elements), group II-VI (i.e., materials from groups II and IV of the periodic system of elements), or group IV materials (i.e., materials from group IV of the periodic system of elements) may also be used to form the substrate **1602**. Although a few examples of materials from which the substrate **1602** may be formed are described here, any material that may serve as a foundation for an IC device **1600** may be used. The substrate **1602** may be part of a singulated die (e.g., the dies **1502** of FIG. **11**) or a wafer (e.g., the wafer **1500** of FIG. **11**).

[0089] The IC device **1600** may include one or more device layers **1604** disposed on the substrate **1602**. The device layer **1604** may include features of one or more transistors **1640** (e.g., metal oxide semiconductor field-effect transistors (MOSFETs)) formed on the substrate **1602**. The device layer **1604** may include, for example, one or more source and/or drain (S/D) regions **1620**, a gate **1622** to control current flow in the transistors **1640** between the S/D regions **1620**, and one or more S/D contacts **1624** to route electrical signals to/from the S/D regions **1620**. The transistors **1640** may include additional features not depicted for the sake of clarity, such as device isolation regions, gate contacts, and the like. The transistors **1640** are not limited to the type and configuration depicted in FIG. **12** and may include a wide variety of other types and configurations such as, for example, planar transistors, non-planar transistors, or a combination of both. Planar transistors may include bipolar junction transistors (BJT), heterojunction bipolar transistors (HBT), or high-electron-mobility transistors (HEMT). Non-planar transistors may include FinFET transistors, such as double-gate transistors or tri-gate transistors, and wrap-around or all-around gate transistors, such as nanoribbon and nanowire transistors.

[0090] Each transistor **1640** may include a gate **1622** formed of at least two layers, a gate dielectric and a gate electrode. The gate dielectric may include one layer or a stack of layers. The one or more layers may include silicon oxide, silicon dioxide, silicon carbide, and/or a high-k dielectric material. The high-k dielectric material may include elements such as hafnium, silicon, oxygen, titanium, tantalum, lanthanum, aluminum, zirconium, barium, strontium, yttrium, lead, scandium, niobium, and zinc. Examples of high-k materials that may be used in the gate dielectric include, but are not limited to, hafnium oxide, hafnium silicon oxide, lanthanum oxide, lanthanum aluminum oxide, zirconium oxide, zirconium silicon oxide, tantalum oxide, titanium oxide, barium strontium titanium oxide, barium titanium oxide, strontium titanium oxide, yttrium oxide, aluminum oxide, lead scandium tantalum oxide, and lead zinc niobate. In some embodiments, an annealing process may be carried out on the gate dielectric to improve its quality when a high-k material is used.

[0091] The gate electrode may be formed on the gate dielectric and may include at least one p-type work function metal or n-type work function metal, depending on whether the transistor **1640** is to

be a p-type metal oxide semiconductor (PMOS) or an n-type metal oxide semiconductor (NMOS) transistor. In some implementations, the gate electrode may consist of a stack of two or more metal layers, where one or more metal layers are work function metal layers and at least one metal layer is a fill metal layer. Further metal layers may be included for other purposes, such as a barrier layer. For a PMOS transistor, metals that may be used for the gate electrode include, but are not limited to, ruthenium, palladium, platinum, cobalt, nickel, conductive metal oxides (e.g., ruthenium oxide), and any of the metals discussed below with reference to an NMOS transistor (e.g., for work function tuning). For an NMOS transistor, metals that may be used for the gate electrode include, but are not limited to, hafnium, zirconium, titanium, tantalum, aluminum, alloys of these metals, carbides of these metals (e.g., hafnium carbide, zirconium carbide, titanium carbide, tantalum carbide, and aluminum carbide), and any of the metals discussed above with reference to a PMOS transistor (e.g., for work function tuning).

[0092] In some embodiments, when viewed as a cross-section of the transistor **1640** along the source-channel-drain direction, the gate electrode may consist of a U-shaped structure that includes a bottom portion substantially parallel to the surface of the substrate and two sidewall portions that are substantially perpendicular to the top face of the substrate. In other embodiments, at least one of the metal layers that form the gate electrode may simply be a planar layer that is substantially parallel to the top face of the substrate and does not include sidewall portions substantially perpendicular to the top face of the substrate. In other embodiments, the gate electrode may consist of a combination of U-shaped structures and planar, non-U-shaped structures. For example, the gate electrode may consist of one or more U-shaped metal layers formed atop one or more planar, non-U-shaped layers.

[0093] In some embodiments, a pair of sidewall spacers may be formed on opposing sides of the gate stack to bracket the gate stack. The sidewall spacers may be formed from materials such as silicon nitride, silicon oxide, silicon carbide, silicon nitride doped with carbon, and silicon oxynitride. Processes for forming sidewall spacers are well known in the art and generally include deposition and etching process steps. In some embodiments, a plurality of spacer pairs may be used; for instance, two pairs, three pairs, or four pairs of sidewall spacers may be formed on opposing sides of the gate stack.

[0094] The S/D regions **1620** may be formed within the substrate **1602** adjacent to the gate **1622** of each transistor **1640**. The S/D regions **1620** may be formed using an implantation/diffusion process or an etching/deposition process, for example. In the former process, dopants such as boron, aluminum, antimony, phosphorous, or arsenic may be ion-implanted into the substrate **1602** to form the S/D regions **1620**. An annealing process that activates the dopants and causes them to diffuse farther into the substrate **1602** may follow the ion-implantation process. In the latter process, the substrate **1602** may first be etched to form recesses at the locations of the S/D regions **1620**. An epitaxial deposition process may then be carried out to fill the recesses with material that is used to fabricate the S/D regions **1620**. In some implementations, the S/D regions **1620** may be fabricated using a silicon alloy such as silicon germanium or silicon carbide. In some embodiments, the epitaxially deposited silicon alloy may be doped in situ with dopants such as boron, arsenic, or phosphorous. In some embodiments, the S/D regions **1620** may be formed using one or more alternate semiconductor materials such as germanium or a group III-V material or alloy. In further embodiments, one or more layers of metal and/or metal alloys may be used to form the S/D regions **1620**.

[0095] Electrical signals, such as power and/or input/output (I/O) signals, may be routed to and/or from the devices (e.g., the transistors **1640**) of the device layer **1604** through one or more interconnect layers disposed on the device layer **1604** (illustrated in FIG. **12** as interconnect layers **1606**, **1608**, and **1610**). For example, electrically conductive features of the device layer **1604** (e.g., the gate **1622** and the S/D contacts **1624**) may be electrically coupled with the interconnect structures **1628** of the interconnect layers **1606**, **1608**, and **1610**. The one or more interconnect

layers **1606**, **1608**, and **1610** may form a metallization stack (also referred to as an “ILD stack”) **1619** of the IC device **1600**.

[0096] The interconnect structures **1628** may be arranged within the interconnect layers **1606-1610** to route electrical signals according to a wide variety of designs (in particular, the arrangement is not limited to the particular configuration of interconnect structures **1628** depicted in FIG. 12). Although a particular number of interconnect layers **1606**, **1608**, and **1610** is depicted in FIG. 12, embodiments of the present disclosure include IC devices having more or fewer interconnect layers than depicted.

[0097] In some embodiments, the interconnect structures **1628** may include lines **1628a** and/or vias **1628b** filled with an electrically conductive material such as a metal. The lines **1628a** may be arranged to route electrical signals in a direction of a plane that is substantially parallel with a surface of the substrate **1602** upon which the device layer **1604** is formed. For example, the lines **1628a** may route electrical signals in a direction in and out of the page from the perspective of FIG. 12. The vias **1628b** may be arranged to route electrical signals in a direction of a plane that is substantially perpendicular to the surface of the substrate **1602** upon which the device layer **1604** is formed. In some embodiments, the vias **1628b** may electrically couple lines **1628a** of different interconnect layers **1606**, **1608**, and **1610** together.

[0098] The interconnect layers **1606**, **1608**, and **1610** may include a dielectric material **1626** disposed between the interconnect structures **1628**, as shown in FIG. 12. In some embodiments, the dielectric material **1626** disposed between the interconnect structures **1628** in different ones of the interconnect layers **1606**, **1608**, and **1610** may have different compositions; in other embodiments, the composition of the dielectric material **1626** between different interconnect layers **1606**, **1608**, and **1610** may be the same.

[0099] A first interconnect layer **1606** may be formed above the device layer **1604**. In some embodiments, the first interconnect layer **1606** may include lines **1628a** and/or vias **1628b**, as shown. The lines **1628a** of the first interconnect layer **1606** may be coupled with contacts (e.g., the S/D contacts **1624**) of the device layer **1604**.

[0100] A second interconnect layer **1608** may be formed above the first interconnect layer **1606**. In some embodiments, the second interconnect layer **1608** may include vias **1628b** to couple the lines **1628a** of the second interconnect layer **1608** with the lines **1628a** of the first interconnect layer **1606**. Although the lines **1628a** and the vias **1628b** are structurally delineated with a line within each interconnect layer (e.g., within the second interconnect layer **1608**) for the sake of clarity, the lines **1628a** and the vias **1628b** may be structurally and/or materially contiguous (e.g., simultaneously filled during a dual-damascene process) in some embodiments.

[0101] A third interconnect layer **1610** (and additional interconnect layers, as desired) may be formed in succession on the second interconnect layer **1608** according to similar techniques and configurations described in connection with the second interconnect layer **1608** or the first interconnect layer **1606**. In some embodiments, the interconnect layers that are “higher up” in the metallization stack **1619** in the IC device **1600** (i.e., farther away from the device layer **1604**) may be thicker.

[0102] The IC device **1600** may include a solder resist material **1634** (e.g., polyimide or similar material) and one or more conductive contacts **1636** formed on the interconnect layers **1606**, **1608**, and **1610**. In FIG. 12, the conductive contacts **1636** are illustrated as taking the form of bond pads. The conductive contacts **1636** may be electrically coupled with the interconnect structures **1628** and configured to route the electrical signals of the transistor(s) **1640** to other external devices. For example, solder bonds may be formed on the one or more conductive contacts **1636** to mechanically and/or electrically couple a chip including the IC device **1600** with another component (e.g., a circuit board). The IC device **1600** may include additional or alternate structures to route the electrical signals from the interconnect layers **1606**, **1608**, and **1610**; for example, the conductive contacts **1636** may include other analogous features (e.g., posts) that route the electrical

signals to external components.

[0103] FIG. **13** is a side, cross-sectional view of an IC device assembly **1700** that may include a glass core with one or more sealer liners in accordance with any of the embodiments disclosed herein. The IC device assembly **1700** includes a number of components disposed on a circuit board **1702** (which may be, e.g., a motherboard). The IC device assembly **1700** includes components disposed on a first face **1740** of the circuit board **1702** and an opposing second face **1742** of the circuit board **1702**; generally, components may be disposed on one or both faces **1740** and **1742**. Any of the IC packages discussed below with reference to the IC device assembly **1700** may take the form of any of the embodiments of the microelectronic assemblies **100** discussed above, e.g., may include one or more microelectronic assemblies **100** as discussed with reference to FIG. **1** and FIG. **2**, and/or may include one or more glass cores as discussed with reference to FIGS. **3-10**.

[0104] In some embodiments, the circuit board **1702** may be a PCB including multiple metal layers separated from one another by layers of dielectric material and interconnected by electrically conductive vias. Any one or more of the metal layers may be formed in a desired circuit pattern to route electrical signals (optionally in conjunction with other metal layers) between the components coupled to the circuit board **1702**. In other embodiments, the circuit board **1702** may be a non-PCB substrate.

[0105] The IC device assembly **1700** illustrated in FIG. **13** includes a package-on-interposer structure **1736** coupled to the first face **1740** of the circuit board **1702** by coupling components **1716**. The coupling components **1716** may electrically and mechanically couple the package-on-interposer structure **1736** to the circuit board **1702**, and may include solder balls (as shown in FIG. **13**), male and female portions of a socket, an adhesive, an underfill material, and/or any other suitable electrical and/or mechanical coupling structure.

[0106] The package-on-interposer structure **1736** may include an IC package **1720** coupled to a package interposer **1704** by coupling components **1718**. The coupling components **1718** may take any suitable form for the application, such as the forms discussed above with reference to the coupling components **1716**. Although a single IC package **1720** is shown in FIG. **13**, multiple IC packages may be coupled to the package interposer **1704**; indeed, additional interposers may be coupled to the package interposer **1704**. The package interposer **1704** may provide an intervening substrate used to bridge the circuit board **1702** and the IC package **1720**. The IC package **1720** may be or include, for example, a die (the die **1502** of FIG. **5**), an IC device (e.g., any of the IC devices described herein, or any combination of such IC devices), or any other suitable component.

Generally, the package interposer **1704** may spread a connection to a wider pitch or reroute a connection to a different connection. For example, the package interposer **1704** may couple the IC package **1720** (e.g., a die) to a set of ball grid array (BGA) conductive contacts of the coupling components **1716** for coupling to the circuit board **1702**. In the embodiment illustrated in FIG. **13**, the IC package **1720** and the circuit board **1702** are attached to opposing sides of the package interposer **1704**; in other embodiments, the IC package **1720** and the circuit board **1702** may be attached to a same side of the package interposer **1704**. In some embodiments, three or more components may be interconnected by way of the package interposer **1704**.

[0107] In some embodiments, the package interposer **1704** may be formed as a glass core with one or more sealer liners as described herein, e.g., as any embodiment of the glass core **110**, described herein. In some embodiments, the package interposer **1704** may be formed as a PCB. In some embodiments, the package interposer **1704** may be formed of an epoxy resin, a fiberglass-reinforced epoxy resin, an epoxy resin with inorganic fillers, a ceramic material, or a polymer material such as polyimide. In some embodiments, the package interposer **1704** may be formed of alternate rigid or flexible materials that may include the same materials described above for use in a semiconductor substrate, such as silicon, germanium, and other group III-V and group IV materials. In any of these embodiments, the package interposer **1704** may include multiple metal layers separated from one another by layers of dielectric material and interconnected by electrically

conductive vias. The package interposer **1704** may include metal lines **1710** and vias **1708**, including but not limited to conductive vias **1706**. If the package interposer **1704** is a glass core, e.g., the glass core **110** as described herein, then the conductive vias **1706** may be TGVs **115** as described herein, e.g., conductive vias with sealed liners as described herein. The package interposer **1704** may further include embedded devices **1714**, including both passive and active devices. Such devices may include, but are not limited to, capacitors, decoupling capacitors, resistors, inductors, fuses, diodes, transformers, sensors, electrostatic discharge (ESD) devices, and memory devices. More complex devices such as radio frequency (RF) devices, power amplifiers, power management devices, antennas, arrays, sensors, and microelectromechanical systems (MEMS) devices may also be formed on the package interposer **1704**. The package-on-interposer structure **1736** may take the form of any of the package-on-interposer structures known in the art. [0108] The IC device assembly **1700** may include an IC package **1724** coupled to the first face **1740** of the circuit board **1702** by coupling components **1722**. The coupling components **1722** may take the form of any of the embodiments discussed above with reference to the coupling components **1716**, and the IC package **1724** may take the form of any of the embodiments discussed above with reference to the IC package **1720**.

[0109] The IC device assembly **1700** illustrated in FIG. **13** includes a package-on-package structure **1734** coupled to the second face **1742** of the circuit board **1702** by coupling components **1728**. The package-on-package structure **1734** may include an IC package **1726** and an IC package **1732** coupled together by coupling components **1730** such that the IC package **1726** is disposed between the circuit board **1702** and the IC package **1732**. The coupling components **1728** and **1730** may take the form of any of the embodiments of the coupling components **1716** discussed above, and the IC packages **1726** and **1732** may take the form of any of the embodiments of the IC package **1720** discussed above. The package-on-package structure **1734** may be configured in accordance with any of the package-on-package structures known in the art.

[0110] FIG. **14** is a block diagram of an example communication device **1800** that may include one or more microelectronic assemblies **100** and/or one or more glass cores **110** in accordance with any of the embodiments disclosed herein. A handheld communication device or a laptop communication device may be examples of the communication device **1800**. Any suitable ones of the components of the communication device **1800** may include one or more of the microelectronic assemblies **100**, IC packages **1720**, **1724**, IC device assemblies **1700**, IC devices **1600**, or dies **1502** disclosed herein. In particular, any suitable ones of the components of the communication device **1800** may include one or more glass cores **110** as described herein, e.g., as a part of a microelectronic assembly **100** as described herein. A number of components are illustrated in FIG. **14** as included in the communication device **1800**, but any one or more of these components may be omitted or duplicated, as suitable for the application. In some embodiments, some or all of the components included in the communication device **1800** may be attached to one or more motherboards. In some embodiments, some or all of these components are fabricated onto a single system-on-a-chip (SoC) die.

[0111] Additionally, in various embodiments, the communication device **1800** may not include one or more of the components illustrated in FIG. **14**, but the communication device **1800** may include interface circuitry for coupling to the one or more components. For example, the communication device **1800** may not include a display device **1806**, but may include display device interface circuitry (e.g., a connector and driver circuitry) to which a display device **1806** may be coupled. In another set of examples, the communication device **1800** may not include an audio input device **1824** or an audio output device **1808**, but may include audio input or output device interface circuitry (e.g., connectors and supporting circuitry) to which an audio input device **1824** or audio output device **1808** may be coupled.

[0112] The communication device **1800** may include a processing device **1802** (e.g., one or more processing devices). As used herein, the term “processing device” or “processor” may refer to any

device or portion of a device that processes electronic data from registers and/or memory to transform that electronic data into other electronic data that may be stored in registers and/or memory. The processing device **1802** may include one or more digital signal processors (DSPs), application-specific integrated circuits (ASICs), central processing units (CPUs), graphics processing units (GPUs), cryptoprocessors (specialized processors that execute cryptographic algorithms within hardware), server processors, or any other suitable processing devices. The communication device **1800** may include a memory **1804**, which may itself include one or more memory devices such as volatile memory (e.g., dynamic RAM (DRAM)), nonvolatile memory (e.g., read-only memory (ROM)), flash memory, solid state memory, and/or a hard drive. In some embodiments, the memory **1804** may include memory that shares a die with the processing device **1802**. This memory may be used as cache memory and may include embedded DRAM (eDRAM) or spin transfer torque magnetic RAM (STT-MRAM).

[0113] In some embodiments, the communication device **1800** may include a communication module **1812** (e.g., one or more communication modules). For example, the communication module **1812** may be configured for managing wireless communications for the transfer of data to and from the communication device **1800**. The term “wireless” and its derivatives may be used to describe circuits, devices, systems, methods, techniques, communications channels, etc., that may communicate data through the use of modulated electromagnetic radiation through a nonsolid medium. The term does not imply that the associated devices do not contain any wires, although in some embodiments they might not. The communication module **1812** may be, or may include, any of the microelectronic assemblies **100** disclosed herein.

[0114] The communication module **1812** may implement any of a number of wireless standards or protocols, including but not limited to Institute for Electrical and Electronic Engineers (IEEE) standards including Wi-Fi (IEEE 802.11 family), IEEE 802.16 standards (e.g., IEEE 802.16-2005 Amendment), Long-Term Evolution (LTE) project along with any amendments, updates, and/or revisions (e.g., advanced LTE project, ultra mobile broadband (UMB) project (also referred to as “3GPP2”), etc.). IEEE 802.16 compatible Broadband Wireless Access (BWA) networks are generally referred to as WiMAX networks, an acronym that stands for Worldwide Interoperability for Microwave Access, which is a certification mark for products that pass conformity and interoperability tests for the IEEE 802.16 standards. The communication module **1812** may operate in accordance with a Global System for Mobile Communication (GSM), General Packet Radio Service (GPRS), Universal Mobile Telecommunications System (UMTS), High-Speed Packet Access (HSPA), Evolved HSPA (E-HSPA), or LTE network. The communication module **1812** may operate in accordance with Enhanced Data for GSM Evolution (EDGE), GSM EDGE Radio Access Network (GERAN), Universal Terrestrial Radio Access Network (UTRAN), or Evolved UTRAN (E-UTRAN). The communication module **1812** may operate in accordance with Code Division Multiple Access (CDMA), Time Division Multiple Access (TDMA), Digital Enhanced Cordless Telecommunications (DECT), Evolution-Data Optimized (EV-DO), and derivatives thereof, as well as any other wireless protocols that are designated as 3G, 4G, 5G, and beyond. The communication module **1812** may operate in accordance with other wireless protocols in other embodiments. The communication device **1800** may include an antenna **1822** to facilitate wireless communications and/or to receive other wireless communications (such as AM or FM radio transmissions). The antenna **1822** may include one or more microelectronic assemblies **100** and/or one or more glass cores **110** as described herein, e.g., as a part of a microelectronic assembly **100** as described herein.

[0115] In some embodiments, the communication module **1812** may manage wired communications, such as electrical, optical, or any other suitable communication protocols (e.g., the Ethernet). As noted above, the communication module **1812** may include multiple communication modules. For instance, a first communication module **1812** may be dedicated to shorter-range wireless communications such as Wi-Fi or Bluetooth, and a second communication module **1812** may be dedicated to longer-range wireless communications such as global positioning

system (GPS), EDGE, GPRS, CDMA, WiMAX, LTE, EV-DO, or others. In some embodiments, a first communication module **1812** may be dedicated to wireless communications, and a second communication module **1812** may be dedicated to wired communications. In some embodiments, the communication module **1812** may support millimeter wave communication.

[0116] The communication device **1800** may include battery/power circuitry **1814**. The battery/power circuitry **1814** may include one or more energy storage devices (e.g., batteries or capacitors) and/or circuitry for coupling components of the communication device **1800** to an energy source separate from the communication device **1800** (e.g., AC line power).

[0117] The communication device **1800** may include a display device **1806** (or corresponding interface circuitry, as discussed above). The display device **1806** may include any visual indicators, such as a heads-up display, a computer monitor, a projector, a touchscreen display, a liquid crystal display (LCD), a light-emitting diode display, or a flat panel display.

[0118] The communication device **1800** may include an audio output device **1808** (or corresponding interface circuitry, as discussed above). The audio output device **1808** may include any device that generates an audible indicator, such as speakers, headsets, or earbuds.

[0119] The communication device **1800** may include an audio input device **1824** (or corresponding interface circuitry, as discussed above). The audio input device **1824** may include any device that generates a signal representative of a sound, such as microphones, microphone arrays, or digital instruments (e.g., instruments having a musical instrument digital interface (MIDI) output).

[0120] The communication device **1800** may include a GPS device **1818** (or corresponding interface circuitry, as discussed above). The GPS device **1818** may be in communication with a satellite-based system and may receive a location of the communication device **1800**, as known in the art.

[0121] The communication device **1800** may include an other output device **1810** (or corresponding interface circuitry, as discussed above). Examples of the other output device **1810** may include an audio codec, a video codec, a printer, a wired or wireless transmitter for providing information to other devices, or an additional storage device.

[0122] The communication device **1800** may include an other input device **1820** (or corresponding interface circuitry, as discussed above). Examples of the other input device **1820** may include an accelerometer, a gyroscope, a compass, an image capture device, a keyboard, a cursor control device such as a mouse, a stylus, a touchpad, a bar code reader, a Quick Response (QR) code reader, any sensor, or a radio frequency identification (RFID) reader.

[0123] The communication device **1800** may have any desired form factor, such as a handheld or mobile communication device (e.g., a cell phone, a smart phone, a mobile internet device, a music player, a tablet computer, a laptop computer, a netbook computer, an ultrabook computer, a personal digital assistant (PDA), an ultra mobile personal computer, etc.), a desktop communication device, a server or other networked computing component, a printer, a scanner, a monitor, a set-top box, an entertainment control unit, a vehicle control unit, a digital camera, a digital video recorder, or a wearable communication device. In some embodiments, the communication device **1800** may be any other electronic device that processes data.

[0124] The following paragraphs provide examples of various ones of the embodiments disclosed herein.

[0125] Example 1 provides a microelectronic assembly, including a glass core (e.g., a layer of glass, e.g., a layer of glass including a substantially rectangular prism volume, possibly with rounded or beveled edges) having a first face and a second face opposite the first face; a TGV in the glass core, the TGV extending from the first face towards the second face (the TGV may at least partially extend through the glass core, i.e., in some embodiments, the TGV may extend all the way to the second face, while, in other embodiments, the TGV may be a blind via that does not reach the second face) and including a conductive material; a liner material (or, more generally, an organic material) in the TGV, between the conductive material and the glass core, where a modulus

(e.g., a Young's modulus) of the liner material is smaller than about 30 GPa, e.g., between about 1 GPa and 30 GPa; and a sealant (or, more generally, an inorganic material) over the liner material in the TGV, the sealant including silicon and nitrogen, where the glass core, the conductive material, and the sealant completely enclose the liner material as to reduce or eliminate degradation (oxidation and/or crystallization) of the liner material.

[0126] Example 2 provides the microelectronic assembly according to example 1, where the liner material includes/is a polymer material.

[0127] Example 3 provides the microelectronic assembly according to examples 1 or 2, where the liner material includes/is a homopolymer.

[0128] Example 4 provides the microelectronic assembly according to any one of the preceding examples, where the liner material includes/is poly-para-xylylene.

[0129] Example 5 provides the microelectronic assembly according to any one of the preceding examples, where a thickness of the liner material is between about 200 nanometers and about 10 microns, e.g., between about 200 nanometers and about 5 microns, or between about 500 nanometers and about 1 micron.

[0130] Example 6 provides the microelectronic assembly according to any one of the preceding examples, where a portion of the liner material is in contact (e.g., in direct physical contact) with a sidewall of the TGV (e.g., in contact with the glass core at the sidewall of the TGV).

[0131] Example 7 provides the microelectronic assembly according to any one of the preceding examples, further including the liner material over the first face of the glass core, where the liner material over the first face of the glass core is materially continuous with the liner material in the TGV.

[0132] Example 8 provides the microelectronic assembly according to example 7, where a portion of the sealant is in contact (e.g., in direct physical contact) with a portion of the first face of the glass core.

[0133] Example 9 provides the microelectronic assembly according to example 7, where a portion of the liner material over the first face of the glass core is in contact (e.g., in direct physical contact) with a portion of the sealant.

[0134] Example 10 provides the microelectronic assembly according to examples 7 or 9, where a portion of the liner material over the first face of the glass core is in contact (e.g., in direct physical contact) with a portion of the first face of the glass core.

[0135] Example 11 provides the microelectronic assembly according to any one of examples 7-10, further including a conductive contact over the first face, where the conductive material of the TGV is in conductive contact with a conductive material of the conductive contact, and where a portion of the sealant is on a sidewall of the conductive contact.

[0136] Example 12 provides the microelectronic assembly according to example 11, where a further portion of the sealant is on a surface of the conductive contact that is farthest away from the first face.

[0137] Example 13 provides the microelectronic assembly according to example 7, further including a buffer layer over the first face of the glass core, where the buffer layer is between the liner material over the first face of the glass core and the sealant.

[0138] Example 14 provides the microelectronic assembly according to example 13, further including a conductive contact over the buffer layer, where the conductive material of the TGV is in conductive contact with a conductive material of the conductive contact, and where a portion of the sealant is on a sidewall of the conductive contact.

[0139] Example 15 provides the microelectronic assembly according to example 14, where a further portion of the sealant is on a surface of the conductive contact that is farthest away from the first face.

[0140] Example 16 provides the microelectronic assembly according to examples 14 or 15, where a portion of the buffer layer is in contact (e.g., in direct physical contact) with a portion of the

conductive contact.

[0141] Example 17 provides the microelectronic assembly according to any one of examples 13-16, where a portion of the sealant is in contact (e.g., in direct physical contact) with a portion of the buffer layer.

[0142] Example 18 provides the microelectronic assembly according to any one of examples 7-17, where: the sealant is a first sealant, the microelectronic assembly further includes a second sealant, the second sealant includes silicon and nitrogen, and the second sealant is between the buffer layer and the liner material over the first face of the glass core.

[0143] Example 19 provides the microelectronic assembly according to example 18, where a portion of the buffer layer is in contact (e.g., in direct physical contact) with a portion of the second sealant.

[0144] Example 20 provides the microelectronic assembly according to examples 18 or 19, where the buffer layer is between the first sealant and the second sealant.

[0145] Example 21 provides a microelectronic assembly, including a glass core having a first face and a second face opposite the first face, and including a conductive via extending from the first face towards the second face (the via may at least partially extend through the glass core, i.e., in some embodiments, the via may extend all the way to the second face, while, in other embodiments, the via may be a blind via that does not reach the second face); an organic material in the conductive via, where the organic material is on a sidewall of the conductive via, between a conductive material of the conductive via and the glass core, and; and an inorganic material enclosing the organic material in the conductive via.

[0146] Example 22 provides the microelectronic assembly according to example 21, where a modulus (e.g., a Young's modulus) of the organic material is smaller than a modulus (e.g., a Young's modulus) of the glass core.

[0147] Example 23 provides the microelectronic assembly according to examples 21 or 22, where a modulus (e.g., a Young's modulus) of the organic material is smaller than a modulus (e.g., a Young's modulus) of the conductive material of the conductive via.

[0148] Example 24 provides the microelectronic assembly according to any one of examples 21-23, where the organic material includes/is an organic polymer, e.g., an organic homopolymer.

[0149] Example 25 provides the microelectronic assembly according to any one of examples 21-24, where the organic material includes/is poly-para-xylylene (which is also commonly referred to as "parylene").

[0150] Example 26 provides the microelectronic assembly according to any one of examples 21-25, where the organic material includes/is parylene N, parylene C, parylene D, or parafree.

[0151] Example 27 provides the microelectronic assembly according to any one of examples 21-26, where a thickness of the organic material is between about 200 nanometers and about 10 microns, e.g., between about 200 nanometers and about 5 microns, or between about 500 nanometers and about 1 micron.

[0152] Example 28 provides the microelectronic assembly according to any one of examples 21-27, where the inorganic material includes silicon and nitrogen.

[0153] Example 29 provides the microelectronic assembly according to any one of examples 21-28, where the inorganic material includes a material to reduce or eliminate oxidation of the organic material.

[0154] Example 30 provides the microelectronic assembly according to any one of examples 21-29, where the inorganic material includes a material to reduce or eliminate crystallization of the organic material. **31.** The microelectronic assembly according to any one of claims **21-30**, where the organic material is the liner material and the inorganic material is the sealant according to any one of claims **7-20**.

[0155] Example 32 provides the microelectronic assembly according to any one of the preceding examples, where a cross-section of the glass core in a plane perpendicular to a surface of the

component is substantially rectangular.

[0156] Example 33 provides the microelectronic assembly according to any one of the preceding examples, where a cross-section of the glass core in a plane parallel to a surface of the component is substantially rectangular.

[0157] Example 34 provides the microelectronic assembly according to any one of the preceding examples, where the glass core is a layer of glass including at least 23% silicon by weight.

[0158] Example 35 provides the microelectronic assembly according to any one of the preceding examples, where the glass core is a layer of glass including at least 26% oxygen by weight.

[0159] Example 36 provides the microelectronic assembly according to any one of the preceding examples, where the glass core is a layer of glass including at least 23% silicon by weight and at least 26% oxygen by weight.

[0160] Example 37 provides the microelectronic assembly according to any one of the preceding examples, where the glass core is a layer of glass including at least 5% aluminum by weight.

[0161] Example 38 provides the microelectronic assembly according to any one of the preceding examples, where the glass core is a layer of glass that does not include an organic adhesive or an organic material.

[0162] Example 39 provides the microelectronic assembly according to any one of the preceding examples, where the glass core is a layer of glass having a thickness in a range of 50 micron (μm) to 1.4 millimeters (mm), a first length in a range of 10 mm to 250 mm, and a second length in a range of 10 mm to 250 mm, the first length perpendicular to the second length.

[0163] Example 40 provides the microelectronic assembly according to any one of the preceding examples, where the glass core is a layer of glass having a thickness in a range of 50 μm to 1.4 mm.

[0164] Example 41 provides the microelectronic assembly according to any one of the preceding examples, where the glass core is a layer of glass having a first length in a range of 10 mm to 250 mm, and a second length in a range of 10 mm to 250 mm, the first length perpendicular to the second length.

[0165] Example 42 provides the microelectronic assembly according to any one of the preceding examples, where the glass core is a layer of glass including a rectangular prism volume.

[0166] Example 43 provides the microelectronic assembly according to any one of the preceding examples, where the glass core is a layer of glass including a rectangular prism volume having a first side and a second side perpendicular to the first side, the first side having a length in a range of 10 mm to 250 mm and the second side having a length in a range of 10 mm to 250 mm.

[0167] Example 44 provides the microelectronic assembly according to any one of the preceding examples, where the glass core is a layer of glass including a rectangular prism volume and a via extending from a first side of the rectangular prism volume to a second side of the rectangular prism volume, the via including a metal.

[0168] Example 45 provides the microelectronic assembly according to any one of the preceding examples, where the glass core is a solid layer of glass. **46.** The microelectronic assembly according to any one of the preceding claims, where the conductive material is a metal or a metal alloy. **47.** The microelectronic assembly according to any one of the preceding claims, where the conductive material includes one or more of copper, silver, nickel, gold, or aluminum.

[0169] Example 48 provides a method of fabricating a microelectronic assembly, the method including depositing an organic material on a sidewall of a via opening in a glass core, where the glass core has a first face and a second face opposite the first face, and where the via opening extends from the first face towards the second face; depositing a seed material over the organic material on the sidewall of the via opening, where the organic material is between the sidewall of the via opening and the seed material; depositing a conductive fill material in the via opening, where the seed material is between the organic material and the conductive fill material; forming a conductive contact at the first face of the glass core, over the via opening, where the conductive contact is electrically continuous with the conductive fill material in the via opening; and

depositing a sealant over the conductive contact and over the first face of the glass core.

[0170] Example 49 provides the method according to example 48, where depositing the organic material includes depositing the organic material using CVD.

[0171] Example 50 provides the method according to examples 48 or 49, where the organic material as deposited as a liner that is conformal to the sidewall of the via opening.

[0172] Example 51 provides the method according to any one of examples 48-50, where depositing the conductive fill material includes depositing the conductive fill material using electroplating.

[0173] Example 52 provides the method according to any one of examples 48-51, further including providing one or more build-up layers over the sealant.

[0174] Example 53 provides the method according to any one of examples 48-52, where the microelectronic assembly is a microelectronic assembly according to any one of claims 1-47.

[0175] The above description of illustrated implementations of the disclosure, including what is described in the Abstract, is not intended to be exhaustive or to limit the disclosure to the precise forms disclosed. While specific implementations of, and examples for, the disclosure are described herein for illustrative purposes, various equivalent modifications are possible within the scope of the disclosure, as those skilled in the relevant art will recognize. These modifications may be made to the disclosure in light of the above detailed description.

Claims

1. A microelectronic assembly, comprising: a layer of glass having a first face and a second face opposite the first face; a through-glass via (TGV) in the layer of glass, the TGV extending from the first face towards the second face and comprising a conductive material; an organic material in the TGV, between the conductive material and the layer of glass, wherein a modulus of the organic material is smaller than about 30 gigopascal; and an inorganic material over the organic material in the TGV, the inorganic material comprising silicon and nitrogen.
2. The microelectronic assembly according to claim 1, wherein the organic material includes a homopolymer.
3. The microelectronic assembly according to claim 1, wherein the organic material includes poly-para-xylylene.
4. The microelectronic assembly according to claim 1, further comprising the organic material over the first face of the layer of glass, wherein the organic material over the first face of the layer of glass is materially continuous with the organic material in the TGV.
5. The microelectronic assembly according to claim 4, wherein a portion of the inorganic material is in contact with a portion of the first face of the layer of glass or a portion of the organic material over the first face of the layer of glass is in contact with a portion of the inorganic material.
6. The microelectronic assembly according to claim 4, wherein a portion of the organic material over the first face of the layer of glass is in contact with a portion of the first face of the layer of glass.
7. The microelectronic assembly according to claim 4, further comprising a conductive contact over the first face, wherein the conductive material of the TGV is in conductive contact with a conductive material of the conductive contact, and wherein a portion of the inorganic material is on a sidewall of the conductive contact.
8. The microelectronic assembly according to claim 7, wherein a further portion of the inorganic material is on a surface of the conductive contact that is farthest away from the first face.
9. The microelectronic assembly according to claim 4, further comprising a buffer layer over the first face of the layer of glass, wherein the buffer layer is between the organic material over the first face of the layer of glass and the inorganic material.
10. The microelectronic assembly according to claim 9, further comprising a conductive contact over the buffer layer, wherein the conductive material of the TGV is in conductive contact with a

conductive material of the conductive contact, and wherein a portion of the inorganic material is on a sidewall of the conductive contact.

11. The microelectronic assembly according to claim 10, wherein a further portion of the inorganic material is on a surface of the conductive contact that is farthest away from the first face.

12. The microelectronic assembly according to claim 10, wherein a portion of the buffer layer is in contact with a portion of the conductive contact.

13. The microelectronic assembly according to claim 9, wherein a portion of the inorganic material is in contact with a portion of the buffer layer.

14. The microelectronic assembly according to claim 9, wherein: the inorganic material is a first inorganic material, the microelectronic assembly further includes a second inorganic material, the second inorganic material includes silicon and nitrogen, and the second inorganic material is between the buffer layer and the organic material over the first face of the layer of glass.

15. The microelectronic assembly according to claim 14, wherein a portion of the buffer layer is in contact with a portion of the second inorganic material.

16. The microelectronic assembly according to claim 14, wherein the buffer layer is between the first inorganic material and the second inorganic material.

17. A microelectronic assembly, comprising: a glass core having a first face and a second face opposite the first face, and comprising a conductive via extending from the first face towards the second face; a liner material in the conductive via, wherein the liner material is on a sidewall of the conductive via, between a conductive material of the conductive via and the glass core, and wherein a thickness of the liner material is between about 200 nanometers and about 10 microns; and a sealant enclosing the liner material in the conductive via.

18. The microelectronic assembly according to claim 17, wherein a modulus of the liner material is smaller than a modulus of the glass core, the liner material includes an organic polymer, and the sealant includes silicon and nitrogen.

19. A method of fabricating a microelectronic assembly, the method comprising: depositing an organic material on a sidewall of a via opening in a glass core, wherein the glass core has a first face and a second face opposite the first face, and wherein the via opening extends from the first face towards the second face; depositing a seed material over the organic material on the sidewall of the via opening, wherein the organic material is between the sidewall of the via opening and the seed material; depositing a conductive fill material in the via opening, wherein the seed material is between the organic material and the conductive fill material; forming a conductive contact at the first face of the glass core, over the via opening, wherein the conductive contact is electrically continuous with the conductive fill material in the via opening; and depositing a sealant over the conductive contact and over the first face of the glass core.

20. The method according to claim 19, wherein the organic material as deposited as a liner that is conformal to the sidewall of the via opening.
