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Semiconductor package including reinforcement structure and methods of forming the same

Abstract

A semiconductor package includes a package substrate a package substrate including: a substrate core; an upper redistribution layer disposed on a first side of the substrate core; and a lower redistribution layer disposed on an opposing second side of the substrate core; a semiconductor device vertically stacked on and electrically connected to the package substrate; and an upper reinforcement layer embedded in the upper redistribution layer between the semiconductor device and the substrate core, the upper reinforcement layer having a Young's modulus that is higher than a Young's modulus of the upper redistribution layer.

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Background/Summary

BACKGROUND

- (1) The semiconductor industry has continually grown due to continuous improvements in integration density of various electronic components, e.g., transistors, diodes, resistors, capacitors, etc. In large part, these improvements in integration density have come from successive reductions in minimum feature size, which allows more components to be integrated into a given area.
 - (2) In addition to smaller electronic components, improvements to the packaging of components seek to provide smaller packages that occupy less area than previous packages. Examples of the type of packages for semiconductors include quad flat pack (QFP), pin grid array (PGA), ball grid array (BGA), flip chips (FC), three-dimensional integrated circuits (3DICs), wafer level packages (WLPs), package on package (PoP), System on Chip (SoC) or System on Integrated Circuit (SoIC) devices. Some of these 3D devices (e.g., 3DIC, SoC, SoIC) are prepared by placing chips over chips on a semiconductor wafer level. These three-dimensional devices provide improved integration density and other advantages, such as faster speeds and higher bandwidth, because of the decreased length of interconnects between the stacked chips. However, there are many challenges related to three-dimensional devices.
 - (3) Interfaces between a fan-out wafer level package (FOWLP) and an underfill material are subjected to mechanical stress during subsequent handling of an assembly of the FOWLP, the underfill material, and a packaging substrate, such as the mechanical stress associated with attaching the packaging substrate to a printed circuit board (PCB). In addition, interfaces between a fan-out wafer level package (FOWLP) and an underfill material are subjected to mechanical stress during use within a computing device, such as when a mobile device is accidentally dropped to cause a mechanical shock during usage. Cracks may be formed in the underfill material, and may induce additional cracks in a semiconductor die, solder materials, interposer structures, and/or various dielectric layers within a semiconductor die or within a package substrate. Thus, formation of cracks in the underfill material should be suppressed.
 - (4) Aspects of the present disclosure are best understood from the following detailed description when read with the accompanying figures. It is noted that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.
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Description

BRIEF DESCRIPTION OF THE DRAWINGS

- (1) FIG. 1A is a top-down view of a semiconductor package, according to various embodiments of the present disclosure.
- (2) FIG. 1B is a vertical cross-sectional view taken along line B-B' of FIG. 1A.
- (3) FIG. 1C is an enlarged vertical cross-sectional view of a package substrate of FIG. 1A.
- (4) FIG. 2A is a vertical cross-sectional view of an alternative package substrate **150A** that may be included in the semiconductor package **100**, according to various embodiments of the present disclosure.

(5) FIG. 2B is a vertical cross-sectional view of another alternative package substrate **150B** that may be included in the semiconductor package **100**, according to various embodiments of the present disclosure.

(6) FIG. 3 is a flow diagram including operations of a method of forming a package substrate **300**, according to various embodiments of the present disclosure.

(7) FIGS. 4A-4O are vertical cross-sectional views illustrating intermediate structures formed during operations of the method of FIG. 3.

DETAILED DESCRIPTION

(8) The following disclosure provides many different embodiments, or examples, for implementing different features of the provided subject matter. Specific examples of components and arrangements are described below to simplify the present disclosure. These are, of course, merely examples and are not intended to be limiting. For example, the formation of a first feature over or on a second feature in the description that follows may include embodiments in which the first and second features are formed in direct contact, and may also include embodiments in which additional features may be formed between the first and second features, such that the first and second features may not be in direct contact. In addition, the present disclosure may repeat reference numerals and/or letters in the various examples. This repetition is for the purpose of simplicity and clarity and does not in itself dictate a relationship between the various embodiments and/or configurations discussed.

(9) Further, spatially relative terms, such as “beneath,” “below,” “lower,” “above,” “upper” and the like, may be used herein for ease of description to describe one element or feature's relationship to another element(s) or feature(s) as illustrated in the figures. The spatially relative terms are intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. The apparatus may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein may likewise be interpreted accordingly. Unless explicitly stated otherwise, each element having the same reference numeral is presumed to have the same material composition and to have a thickness within a same thickness range.

(10) Typically, in a semiconductor package a number of semiconductor integrated circuit (IC) dies (i.e., “chips”) may be mounted onto a common substrate, which may also be referred to as a “package substrate.” In some instances, electrical connections to the semiconductor package may be made by mounting the package substrate onto a support substrate containing electrical interconnects, such as a printed circuit board (PCB). In some semiconductor packages, such as in a fan out wafer level package (FOWLP) and/or fan-out panel level package (FOPLP), a plurality of semiconductor IC dies may be mounted to an interposer, such as an organic interposer or a semiconductor (e.g., silicon) interposer, that may include interconnect structures extending therethrough. The resulting semiconductor package structure, including the interposer and the semiconductor IC dies mounted thereon, may then be mounted onto a surface of a package substrate using solder connections. An underfill layer may be provided in the space between the interposer and the package substrate to encapsulate the solder connections and improve the structural coupling between the interposer and the package substrate. Generally, the methods and structures of the present disclosure may be used to provide a package substrate such as a FOWLP and fan-out panel level package (FOPLP). While the present disclosure is described using an FOWLP configuration, the methods and structures of the present disclosure may be implemented in an FOPLP configuration or any other package configuration.

(11) In related semiconductor packages, the coefficient of thermal expansion (CTE) differences among the various components contained in a semiconductor package may result in high amounts of thermal-mechanical stress. The different rates of thermal expansion and contraction may result in a warpage of the semiconductor package. Such warpage may result in the formation of cracks and/or dislocations among the various devices and layers in the semiconductor package.

Accordingly, various embodiments are disclosed herein to provide semiconductor packages that include components configured to reduce the amount of thermal-mechanical stress applied to the semiconductor packages so as to mitigate the formation of cracks and/or dislocations.

Reinforcement structures may be provided that are embedded within a package substrate.

According to various embodiments the reinforcement structures may be configured to provide increased mechanical support to the package substrate to thereby reduce or eliminate mechanical distortions such as the warping of the package substrate. The reinforcement structure may therefore be chosen to have a mechanical strength (e.g., bulk modulus) that is greater than that of the package substrate. The reinforcement structures may be formed of a material having a higher Young's modulus than that of the dielectric structure **164**. For example, the reinforcement structure **180** may have a Young's modulus of greater than 13 GPa, such as a Young's modulus of at least 14 GPa, at least 15 GPa, or at least 20 GPa.

(12) FIG. **1A** is a top-down view of a semiconductor package **100**, according to various embodiments of the present disclosure. FIG. **1B** is a cross-sectional view taken along line B-B' of FIG. **1A**. FIG. **1C** is an enlarged view of a package substrate **150** of FIG. **1A**.

(13) Referring to FIGS. **1A-1C**, the semiconductor package **100** may be mounted on a support substrate **102**, such as a printed circuit board (PCB). The semiconductor package **100** in this example is a chip-on-wafer-on-substrate (CoWoS)[®] semiconductor package although it will be understood that a similar assembly and mounting process may be utilized for other types of semiconductor packages, such as integrated fan-out (InFO) semiconductor packages, flip-chip semiconductor packages, etc.

(14) The package **100** may include integrated circuit (IC) semiconductor devices, such as first IC semiconductor devices **104** and second IC semiconductor devices **106**. In various embodiments, the first IC semiconductor devices **104** may be three-dimensional devices, such as three-dimensional integrated circuits (3DICs), System on Chip (SOC) or System on Integrated Circuit (SoIC) devices. A three-dimensional IC semiconductor device **104** may be formed by placing chips over chips on a semiconductor wafer level. These three-dimensional devices may provide improved integration density and other advantages, such as faster speeds and higher bandwidths, due to a decreased length of interconnects between the stacked chips. In some embodiments, a first three-dimensional IC semiconductor device **104** may also be referred to as a "first die stack."

(15) The second IC semiconductor device(s) **106** may be different from the first IC semiconductor device(s) **104** in terms of their structure, design and/or functionality. The one or more second IC semiconductor devices **106** may be three-dimensional IC semiconductor devices, which may also be referred to as "second die stacks." In some embodiments, the one or more second IC semiconductor devices **106** may include a memory device, such as a high bandwidth memory (HBM) device. In the example shown in FIGS. **1A** and **1B**, the semiconductor package **100** may include a SOC die stack **104** and an HBM die stack **106**, although it will be understood that the semiconductor package **100** may include greater or fewer numbers of IC semiconductor devices.

(16) The first IC semiconductor device **104** and the second IC semiconductor device **106** may be mounted on an interposer **108**, and the interposer **108** may be mounted on a package substrate **150**. The package substrate **150** may be mounted on the support substrate **102** using an array of solder balls **112** between lower substrate side bonding pads **163** to device side bonding pads **132** of the support substrate **102**.

(17) In some embodiments, the interposer **108** may be an organic interposer including a polymer dielectric material (e.g., a polyimide material) having a plurality of metal interconnect structures extending therethrough. In other embodiments, the interposer **108** may be a semiconductor interposer, such as a silicon interposer, having a plurality of interconnect structures (e.g., through-silicon vias) extending therethrough. Other suitable configurations for the interposer **108** are within the contemplated scope of the disclosure. The interposer **108** may include a plurality of conductive bonding pads on upper and lower surfaces of the interposer and a plurality of conductive

interconnects extending through the interposer **108** between the upper and lower bonding pads of the interposer **108**. The conductive interconnects may distribute and route electrical signals between the first IC semiconductor devices **104**, the second IC semiconductor devices **106**, and the underlying package substrate **150**. Thus, the interposer **108** may also be referred to as a redistribution layer (RDL).

(18) Metal bumps **120**, such as microbumps, may electrically connect conductive bonding pads on the bottom surfaces of both the first IC semiconductor devices **104** and second IC semiconductor devices **106** to the conductive bonding pads on the upper surface of the interposer **108**. In one non-limiting embodiment, metal bumps **120** in the form of microbumps may include a plurality of first metal stacks, such as a plurality of Cu—Ni—Cu stacks, located on the bottom surfaces of the first IC semiconductor devices **104** and second IC semiconductor devices **106**, and a plurality of second metal stacks (e.g., Cu—Ni—Cu stacks) located on the upper surface of the interposer **108**. A solder material, such as tin (Sn), may be located between respective first and second metal stacks to electrically connect the first IC semiconductor devices **104** and the second IC semiconductor devices **106** to the interposer **108**. Other suitable materials for the metal bumps **120** are within the contemplated scope of disclosure.

(19) After the first IC semiconductor devices **104** and second IC semiconductor devices **106** are mounted to the interposer **108**, a first underfill material **122** may optionally be provided in the spaces surrounding the metal bumps **120** and between the bottom surfaces of the first IC semiconductor devices **104**, the second IC semiconductor devices **106**, and the upper surface of the interposer **108**. The first underfill material **122** may also be provided in the spaces laterally separating adjacent first IC semiconductor devices **104** and second IC semiconductor devices **106** of the semiconductor package **100**. In various embodiments, the first underfill material **122** may be include of an epoxy-based material, which may include a composite of resin and filler materials.

(20) The interposer **108** may be mounted on the package substrate **150** that may provide mechanical support for the interposer **108** and the first IC semiconductor devices **104** and second IC semiconductor devices **106** that are mounted on the interposer **108**. The package substrate **150** may include a suitable material, such as an organic material (e.g., a polymer and/or thermoplastic material), a semiconductor material (e.g., a semiconductor wafer, such as a silicon wafer), a ceramic material, a glass material, combinations thereof, or the like. Other suitable substrate materials are within the contemplated scope of present disclosure. In various embodiments, the package substrate **150** may include a plurality of conductive bonding pads (not shown) in an upper surface of the package substrate **150**. Metal bumps **124**, such as C4 solder bumps, may electrically connect conductive bonding pads (not shown) on the bottom surface of the interposer **108** to upper bonding pads **161** of the package substrate **150**. In various embodiments, the metal bumps **124** may include a suitable solder material, such as tin (Sn), although other suitable solder materials are within the contemplated scope of disclosure.

(21) A second underfill material **128** may be provided in the spaces surrounding the metal bumps **124** and between the bottom surface of the interposer **108** and the upper surface of the package substrate **150** as illustrated, for example, in FIG. **1B**. In various embodiments, the second underfill material **128** may include an epoxy-based material, which may include a composite of resin and filler materials. In some embodiments, a lid or cover (not shown in FIGS. **1A** and **1B**) may be mounted to the package substrate **150** and may provide an enclosure around the upper and side surfaces of the first IC semiconductor devices **104** and second IC semiconductor devices **106**.

(22) The package substrate **150** may be mounted to the support substrate **102**, such as a printed circuit board (PCB). Other suitable support substrates **102** are within the contemplated scope of disclosure.

(23) In various embodiments, the package substrate **150** may be a multi-layer structure including a substrate core **152**, substrate via structures **154**, a redistribution structure **160**, and at least one coating layer **158**. A reinforcement structure **180** may be embedded in the redistribution structure

160. The package substrate **150** may have a thickness **T1** that ranges from approximately 300 microns to approximately 2,000 microns. The substrate core **152** may have a core thickness **T2** that ranges from approximately 200 microns to 1,600 microns.

(24) In some embodiments, the redistribution structure **160** may include an upper redistribution layer **160A** disposed above the substrate core **152** and a lower redistribution layer **160B** disposed below the substrate core **152**. The coating layers **158** may be disposed on outer surfaces of the upper redistribution layer **160A** and the lower redistribution layer **160B**.

(25) The substrate core **152** may include an organic material (e.g., a polymer and/or thermoplastic material), a semiconductor material (e.g., a semiconductor wafer, such as a silicon wafer), a ceramic material, a glass material, combinations thereof, etc. For example, the substrate core **152** may include an epoxy-based material, which may include a composite of resin and filler materials. The substrate core **152** may be formed in a slab geometry. The via structures **154** may be disposed in through-holes formed in the substrate core **152**.

(26) The redistribution structure **160** may include metal features **162**, such as metal lines and via structures, embedded in a dielectric structure **164**. In some embodiments, the dielectric structure **164** may include multiple layers of a dielectric material, such as a photosensitive epoxy material. For example, the dielectric structure **164** may be a build-up film, such as a GL**102** build-up film available from Ajinomoto Group. Each layer of dielectric structure **164** may be lithographically patterned to form open regions (e.g., trenches and via openings) within the respective layers of dielectric structure **164**.

(27) A metallization process may be used to fill the open regions with a suitable conductive material, such as copper or a copper-alloy, within each layer of dielectric material to form the metal features **162** embedded within the dielectric structure **164**. The coating layers **158** may include a solder resist material formed over the respective upper redistribution layer **160A** and lower redistribution layer **160B**. Each of the coating layers **158** may provide a protective coating for the package substrate **150** and the underlying metal features **162**. The coating layers **158** formed of solder resist material may also be referred to as a “solder mask.”

(28) The solder balls (or bump structures) **112** may electrically connect the lower substrate side bonding pads **163** to device side bonding pads **132** of the support substrate **102**. In various embodiments, each of the upper bonding pads **161** and the lower bonding pads **163** in different regions of the package substrate **150** may have the same size and shape. The upper bonding pads **161** and the lower bonding pads **163** may be disposed the dielectric structure **164**. Alternatively, the upper bonding pads **161** and the lower bonding pads **163** may be embedded in the dielectric structure **164**.

(29) The solder balls **112** may be provided over the respective conductive bonding pads **132**. In one non-limiting example, the lower bonding pads **163** may have a width dimension that is between about 500 μm and about 550 μm (e.g., $\sim 530 \mu\text{m}$), and the solder balls **112** may have an outer diameter that may be between about 600 μm and about 650 μm (e.g., $\sim 630 \mu\text{m}$), although greater and lesser dimensions for the solder balls **112** and/or the lower bonding pads **163** are within the contemplated scope of disclosure.

(30) A first solder reflow process may include subjecting the package substrate **150** to an elevated temperature (e.g., at least about 250° C.) in order to melt the solder balls **112** and cause the solder balls **112** to adhere to the lower bonding pads **163**. Following the first reflow process, the package substrate **150** may be cooled causing the solder balls **112** to re-solidify. Each solder ball **112** may extend from the lower surface the package substrate **150** by a vertical height that may be less than the outer diameter of the solder ball **112** prior to the first reflow process. For example, where the outer diameter of the solder ball **112** is between about 600 μm and about 650 μm (e.g., $\sim 630 \mu\text{m}$), the vertical height of the solder ball **112** following the first reflow process may be between about 500 μm and about 550 μm (e.g., $\sim 520 \mu\text{m}$).

(31) In various embodiments, mounting of the package substrate **150** onto the support substrate

102, may include aligning the package substrate **150** over the support substrate **102**, such that the solder balls **112** contacting the lower bonding pads **163** of the package substrate **150** may be located over corresponding bonding pads (e.g., bonding pads **132**) on the support substrate **102**. A second solder reflow process may then be performed. The second solder reflow process may include subjecting the package substrate **150** to an elevated temperature (e.g., at least about 250° C.) to thereby melt the solder balls **112** and cause the solder balls **112** to adhere to the corresponding bonding pads **132** on the support substrate **102**. Surface tension may cause the semi-liquid solder to maintain the package substrate **150** in alignment with the support substrate **102** while the solder material cools and solidifies. Upon solidification of the solder balls **112**, the package substrate **150** may sit above the support substrate **102** by a stand-off height that may be between about 0.4 mm to about 0.5 mm, although greater or lesser stand-of heights are within the contemplated scope of disclosure.

(32) A third underfill material **134** may be provided in the spaces surrounding the solder balls **112** and between the lower surface of the package substrate **150** and the upper surface of the support substrate **102**. In various embodiments, the third underfill material **134** may include an epoxy-based material, which may include a composite of resin and filler materials.

(33) The semiconductor package **100** may further include an epoxy molding compound (EMC) that may be applied to gaps formed between the interposer **108**, the first IC semiconductor device **104**, and the second IC semiconductor device **106**, to thereby form a multi-die EMC frame **202**. The EMC material may include an epoxy-containing compound that may be hardened (i.e., cured) to provide a dielectric material having sufficient stiffness and mechanical strength. The EMC material may include epoxy resin, hardener, silica (as a filler material), and other additives. The EMC material may be provided in a liquid form or in a solid form depending on the viscosity and flowability.

(34) Liquid EMC may provide better handling, good flowability, fewer voids, better fill, and fewer flow marks. Solid EMC may provide less cure shrinkage, better stand-off, and less die drift. A high filler content (such as 85% in weight) within an EMC material may shorten the time in mold, lower the mold shrinkage, and reduce the mold warpage. A uniform filler size distribution in the EMC material may reduce flow marks, and may enhance flowability. The curing temperature of the EMC material may be in a range from 125° C. to 150° C. The EMC frame **202** may be cured at a curing temperature to form an EMC matrix that laterally encloses each of the first IC semiconductor device **104** and the second IC semiconductor device **106**. Excess portions of the EMC frame **202** may be removed from above the horizontal plane including the top surfaces of the semiconductor devices (**104**, **106**) by a planarization process, such as CMP.

(35) The bonding pads **132**, **161**, **163** may be formed of a suitable conductive material, such as copper. Other suitable conductive materials are within the contemplated scope of disclosure. The solder balls **112** may include any suitable solder material, such as tin, lead, silver, indium, zinc, nickel, bismuth, antimony, cobalt, copper, germanium, alloys thereof, combinations thereof, or the like. Other suitable materials for the solder balls **112** are within the contemplated scope of disclosure.

(36) The solder balls **112** may form an array of solder balls **112**, such as a ball grid array (BGA) that may include an array pattern that corresponds to an array pattern of the bonding pads **132** on the upper surface of the support substrate **102**. In one non-limiting example, the array of solder balls **112** may include a grid pattern and may have a pitch (i.e., distance between the center of each solder ball **112** and the center of each adjacent solder ball **112**). In an example embodiment, the pitch may be between about 0.8 and 1.0 mm, although larger and smaller pitches may be used.

(37) Package Reinforcement Structures

(38) A parameter that may ensure proper interconnection between the package substrate **150** and the support substrate **102** is the degree of co-planarity between the surfaces of the solder balls **112** that may be brought into contact with the mounting surface (i.e., the upper surface of the support

substrate **102**). A low amount of co-planarity between the solder balls **112** may result in instances of solder cold joints (i.e., insufficient melting of the solder material, resulting in a poor bond that is susceptible to cracking and separation) and/or solder bridging issues (i.e., solder material from one solder ball **112** contacting material from a neighboring solder ball **112**, resulting in an unintended connection (i.e., electrical short)) during the reflow process.

(39) Deformation of the package substrate **150**, such as stress-induced warping of the package substrate **150**, may be a contributor to low co-planarity of the solder balls **112** during surface mounting of the package substrate **150** onto a support substrate **102**. Warpage of the package substrate **150** may result in variations of the distance between the lower surface of the package substrate **150** and the upper surface support substrate **102**. Such deformation of the package substrate **150** may increase the risk of defective solder connections with the underlying support substrate **102**. For example, deformation of the package substrate **150** may cause at least some of the solder joints between the package substrate **150** and the support substrate **102** to fail completely. The deformation of the package substrate **150** may have a bow-shape or cup-shape such that a separation between the lower surface of the package substrate **150** and the upper surface of the support substrate **102** may be smallest at the periphery of the package substrate **150** and may increase towards the center of the package substrate **150**.

(40) Deformation of a package substrate is not an uncommon occurrence, particularly in the case of semiconductor packages used in high-performance computing applications. High-performance semiconductor packages **100** tend to be relatively large and may include a number of IC semiconductor devices (e.g., **104**, **106**) mounted to the package substrate **150**, which may increase a likelihood that the package substrate **150** may be subject to warping or other deformations. Such deformations may present challenges to effective solder mounting of these types of semiconductor package substrates **150** onto a support substrate **102**.

(41) According to various embodiments the reinforcement structure **180** may be configured to provide increased mechanical support to the package substrate **150** to thereby reduce or eliminate mechanical distortions such as the warping of the package substrate **150**. The reinforcement structure **180** may therefore be chosen to have a mechanical strength (e.g., bulk modulus) that is greater than that of the package substrate **150**. For example, the reinforcement structure **180** may be configured to reduce and/or prevent deformation of the package substrate **150**, so that the co-planarity of the solder balls **112** and/or metal bumps **124** may be improved, thereby providing an improved solder connection between the package substrate **150** and the support substrate **102** and/or the interposer **108**.

(42) The package substrate **150** may include an organic material (e.g., a polymer and/or thermoplastic material), a semiconductor material (e.g., a semiconductor wafer, such as a silicon wafer), a ceramic material, a glass material, combinations thereof, etc. As such, the choice of material for the first reinforcement structure **180** may be chosen based on the mechanical properties of the package substrate **150**.

(43) For example, the reinforcement structure **180** may be formed of a material having a higher Young's modulus than that of the dielectric structure **164**. For example, the reinforcement structure **180** may have a Young's modulus of greater than 13 GPa, such as a Young's modulus of at least 14 GPa, at least 15 GPa, or at least 20 GPa. In some embodiments, the reinforcement structure **180** may have a Young's modulus ranging from 14 GPa to 100 GPa, such as from 15 GPa to 80 GPa, or from 20 GPa to 70 GPa. For example, the reinforcement structure **180** may be formed of silicon, silicon nitride, a ceramic material, a glass material, or the like, having a Young's modulus that exceeds a Young's modulus of the dielectric structure **164**, which may generally range from 4 GPa to 15 GPa when formed of conventional dielectric materials, such as polymer materials.

(44) In some embodiments, the reinforcement structure **180** may be disposed in the package substrate **150** and may be disposed between the interposer **108** and the support substrate **102**. In some embodiments, the reinforcement structure **180** may be generally rectangular. However, the

reinforcement structure **180** may have any suitable peripheral shape. The perimeter of the reinforcement structure **180** may be disposed outside of the perimeter of the interposer **108**, when viewed in a vertical direction perpendicular to a plane of the reinforcement structure **180**. In other words, the area of the reinforcement structure **180** may be greater than the area of the interposer **108**. The perimeter of the reinforcement structure **180** may be disposed inside of the perimeter of the package substrate **150**. In other words, the area of the reinforcement structure **180** in the vertical direction may be less than the area of the package substrate **150** taken in the vertical direction.

(45) The reinforcement structure **180** may include one or more reinforcement layers embedded in the package substrate **150**. For example, as shown in FIGS. **1B** and **1C**, the reinforcement structure **180** may include an upper reinforcement layer **180A** embedded in the upper redistribution layer **160A** and a lower reinforcement layer **180B** embedded in the lower redistribution layer **160B**. In some embodiments, the upper reinforcement layer **180A** and the lower reinforcement layer **180B** may have substantially the same size and/or shape. However, on other embodiments, dimensions of the upper reinforcement layer **180A** and the lower reinforcement layer **180B** may vary in shape and size from one another.

(46) In some embodiments, the upper reinforcement layer **180A** may be disposed between the upper bonding pads **161** and uppermost conductive lines of the metal features **162**. The uppermost metal features **162** of the upper redistribution layer **160A** may extend through the upper reinforcement layer **180A**. The lower reinforcement layer **180B** may be disposed between the lower bonding pads **163** and lowermost conductive lines of the metal features **162** of the lower redistribution layer **160B**. The lowermost via structures of the metal features **162** of the lower redistribution layer **160B** may extend through the lower reinforcement layer **180B**.

(47) A total thickness of the reinforcement structure **180**, taken in a vertical direction perpendicular to a plane of the package substrate **150** (i.e., a total thickness of all reinforcement layers included in the reinforcement structure **180**) may be less than or equal to a total thickness of the upper redistribution layer **160A** and the lower redistribution layer **160B** the redistribution structure **160** (i.e., a combined thickness of the upper redistribution layer **160A** and the lower redistribution layer **160B**) taken in the vertical direction. For example, the total thickness of the reinforcement structure **180** may range from 10 μm to 164 μm , such as from 10 μm to 100 μm , from 10 μm to 50 μm , or from 10 μm to 20 μm . Accordingly, a thickness **T3** of the upper reinforcement layer **180A** and/or a thickness **T3** of the lower reinforcement layer **180B** may be less than or equal to the thickness of the corresponding upper redistribution layer **160A** and lower redistribution layer **160B**. For example, the thickness of the upper reinforcement layer **180A** and/or a thickness of the lower reinforcement layer **180B** may range from 5 μm to 82 μm , such as from 10 μm to 50 μm , from 10 μm to 30 μm , from 10 μm to 20 μm , or about 15 μm .

(48) FIG. **2A** is a vertical cross-sectional view of an alternative package substrate **150A** that may be included in the semiconductor package **100**, according to various embodiments of the present disclosure. The package substrate **150A** may be similar to the package substrate **150** of FIG. **1C**. As such, only the differences therebetween will be discussed in detail.

(49) Referring to FIG. **2A**, the package substrate **150B** may include a reinforcement structure that includes only an upper reinforcement layer **180A** embedded in the upper redistribution layer **160A**. In other words, the lower reinforcement layer **180B** of FIG. **1C** may be omitted. The upper reinforcement layer **180A** may be disposed between the upper bonding pads **161** and adjacent metal lines of the conductive features **162** of the upper redistribution layer **160A**. However, the upper reinforcement layer **180A** is not limited to being disposed at any particular depth within the upper redistribution layer **160A**.

(50) FIG. **2B** is a vertical cross-sectional view of another alternative package substrate **150B** that may be included in the semiconductor package **100**, according to various embodiments of the present disclosure. The package substrate **150B** may be similar to the package substrate **150** of FIG. **1C**. As such, only the differences therebetween will be discussed in detail.

(51) Referring to FIG. 2B, the package substrate **150B** may include a reinforcement structure that comprises only a lower reinforcement layer **180B** embedded in the lower redistribution layer **160B**. In other words, the upper reinforcement layer **180A** of FIG. 1C may be omitted. The lower reinforcement layer **180B** may be disposed between the lower contact pads **163** and adjacent metal lines of the conductive features **162** of the lower redistribution layer **160B**. However, the lower reinforcement layer **180B** is not limited to being disposed at any particular depth within the lower redistribution layer **160B**.

(52) Accordingly, as shown in FIGS. 1C-2B, the reinforcement structure **180** may include a single reinforcement layer disposed in either the upper redistribution layer **160A** or the lower redistribution layer **160B**, or may include two or more reinforcement layers. Alternatively, the upper reinforcement layer **180A** and/or the lower reinforcement layer **180B** may be continuous layers, or may be discontinuous layers including several disconnected portions (not shown). Further, the reinforcement structure **180** may be located below semiconductor devices connected to a package substrate in which the reinforcement structure **180** is embedded. However, in other embodiments, the reinforcement structure **180** may be disposed in any region of a package substrate **150** that may be subject to mechanical distortions such as warping.

(53) FIG. 3 is a process flow diagram including operations of a method of forming a package substrate **100**, according to various embodiments of the present disclosure. FIGS. 4A-4O are vertical cross-sectional views illustrating intermediate structures formed during operations of the method of FIG. 3.

(54) Referring to FIGS. 3 and 4A-4I, in operation 30, through holes **152H** may be formed in a substrate core **152**. The substrate core **152** may include an organic material (e.g., a polymer and/or thermoplastic material), a semiconductor material (e.g., a semiconductor wafer, such as a silicon wafer), a ceramic material, a glass material, combinations thereof, etc. For example, the substrate core **152** may include an epoxy-based material, which may include a composite of resin and filler materials. The substrate core **152** may be formed in a slab geometry, as described above. The through holes **152H** may be drilled or etched or otherwise formed in the substrate core **152**.

(55) As shown in FIG. 4B, a copper seed layer **12** may be deposited on the substrate core **152**. Patterned photoresist layers **14** may then be formed on opposing sides of the substrate core **152**. For example, the photoresist layers **14** may be formed by depositing a photoresist material using a dry film lamination process. The photoresist material may be patterned by a photolithography process to form the patterned photoresist layers **14**.

(56) As shown in FIG. 4C, an electroplating process may be performed to form a copper layer **16** on the substrate core **152**. As shown in FIG. 4D, the photoresist layer **14** may be removed, and a thin copper etching process may then be performed to form through-substrate via (TSV) structures **154** in the through holes **152H** and conductive lines **162L** on opposing sides of the substrate core **152**.

(57) As shown in FIG. 4E, polymer layers **164L** may be deposited on opposing sides of the substrate core **152**. The polymer layers **164L** may include polyethylene terephthalate (PET), polyimide (PI), an epoxy resin, etc. The polymer layers **164L** may be formed by vacuum laminating a thin film polymer material on both sides of the substrate core **152**. A heat treatment may then be applied to pre-cure the polymer layers **164L**. For example, the polymer layers **164L** may be subjected to a heat treatment at 100° C. for less than thirty minutes. The heat treatment may cause the polymer layers **164L** to soften without appreciably initiating cross-linking reactions. The softened polymer layers **164L** may flow and cover underlying gaps.

(58) As shown in FIG. 4F, the polymer layers **164L** may then be laser patterned to form through holes **164H**. The through holes **164H** may expose the conductive lines **162L**. A copper seed layer **12** may then be formed on the polymer layers **164L** and in the through holes **164H**, by any suitable deposition process.

(59) As shown in FIG. 4G, photoresist layers **14** may be formed on the polymer layers **164L**. A

copper electroplating process may be performed to form a copper plating layer **18** on the polymer layers **164L**. As shown in FIG. **4H**, the photoresist layer **14** may be removed, and a thin copper etching process may then be performed to form through via structures **162V** and conductive lines **162L** on opposing sides of the substrate core **152**. As shown in FIG. **4I**, the operations of FIGS. **4E** through **4H** may be repeated to form a partial upper redistribution layer **160A'** and a partial lower redistribution layer **160B'**.

(60) Referring to FIG. **4J**, in operation **32**, outer polymer layers **164O** may be formed on the partial upper redistribution layer **160A'** and the partial lower redistribution layer **160B'**. A full-curing process may be performed, where the structure of FIG. **4J** may be subject to a heat treatment at temperatures between 180° C. to 190° C., for times between 60 and 90 minutes. This full-curing process may cause polymer cross-linking reactions to occur that increase the mechanical strength (i.e., cause hardening) of the polymer layers **164L** and outer polymer layers **164O**.

(61) Photoresist layers **20** may be formed on the outer polymer layers **164O**. The photoresist layers **20** may be provided in the form of a dry polymer film that may be laminated the outer polymer layers **164O**. The photoresist layer **20** may be formed by laser patterning a deposited photoresist material.

(62) As shown in FIG. **4K**, in operation **34** the outer polymer layers **164O** may be etched to form trenches **180T** in the outer polymer layers **164O**. The dry film photoresist layer **20** may then be removed by dissolution with a solvent (e.g., sodium hydroxide, potassium hydroxide, acetone, etc.).

(63) As shown in FIG. **4L**, in operation **36**, a reinforcement material **180M** may be deposited on the outer polymer layers **164O** and in the trenches **180T**, using any suitable method. As described above, the reinforcement material **180M** may be any suitable dielectric material having a Young's modulus of greater than about 14 GPa. As shown in FIG. **4M**, in operation **38** and thinning process may be performed on the reinforcement material **180M** to form an upper reinforcement layer **180A** and a lower reinforcement layer **180B**. In some embodiments, the reinforcement material **180M** may be thinned using an etch back process. In alternative embodiments, a chemical mechanical polishing (CMP) process may be performed to on the reinforcement material **180M** to form an upper reinforcement layer **180A** and a lower reinforcement layer **180B** to thin the reinforcement material **180M** to create a co-planer surface with the outer polymer layers **164O**.

(64) As shown in FIG. **4N**, in operation **40** upper bonding pads **161** may be formed on the upper reinforcement layer **180A**, and lower bonding pads **163** may be formed on the lower reinforcement layer **180B**. In particular, operation **40** may include etching the upper reinforcement layer **180A** and the lower reinforcement layer **180B** to form vias, a copper seed layer may be deposited, and then a copper layer may be electroplated. An etching process may be performed, to form via structures **162V** and the upper and lower bonding pads **161**, **163**. As a result, an upper redistribution layer **160A** and a lower reinforcement layer **160B** may be completed. Protective layers **158** and solder balls **112**, may be formed on the structure of FIG. **4N**, to complete a package substrate **150**, as shown in FIG. **1C**.

(65) In operation **42**, as shown in FIG. **4O**, a semiconductor package **100** may be assembled. For example, operation **42** may include attaching, and electrically connecting, semiconductor devices (**104**, **106**) to the package substrate **150**. In this regard, the semiconductor devices (**104**, **106**) may be directly connected to the package substrate **150** or may be connected to an interposer **108** which is connected to the package substrate **150**. The package substrate **150** may be electrically connected to the support substrate. Operation **42** may also include dispensing a first underfill material **122**, a second underfill material **128**, and a third underfill material **134**, as shown in FIG. **1B**, after bonding the semiconductor dies (**104**, **106**), the interposer **108**, the package substrate **150**, and the support substrate **102**.

(66) Referring to all drawings and according to various embodiments of the present disclosure, a semiconductor package **100** is provided. The semiconductor package **100** may comprise a package

substrate **150** comprising: a substrate core **152**, an upper redistribution layer **160A** disposed on a first side of the substrate core **152**; and a lower redistribution layer **160B** disposed on an opposing second side of the substrate core **152**; a semiconductor device **104** vertically stacked on and electrically connected to the backage substrate **150**; and an upper reinforcement layer **180A** embedded in the upper redistribution layer **160A** between the semiconductor device **104** and the substrate core **152**, the upper reinforcement layer **180A** having a Young's modulus that is higher than a Young's modulus of the upper redistribution layer **160A**. In some embodiments, the semiconductor package **100** comprises an interposer **108** electrically connecting the upper redistribution layer **160A** and the semiconductor device **104**.

(67) In one embodiment, a perimeter of the upper reinforcement layer **180A** may be disposed outside of a perimeter of the semiconductor device **104**. In one embodiment, the Young's modulus of the upper reinforcement layer **180A** ranges from 14 GPa to 100 GPa. In one embodiment, the upper reinforcement layer **180A** may have a thickness that is less than or equal to a thickness of the upper redistribution layer **160A**. In one embodiment, the thickness of the upper reinforcement layer **180A** ranges from 10 μm to 164 μm . In one embodiment, the upper reinforcement layer **180A** comprises a dielectric material selected from a silicon, silicon nitride, a ceramic material, or a glass material. In one embodiment, the upper redistribution layer **160A** may include metal features embedded in a dielectric structure **164**. In one embodiment, the dielectric structure **164** may include a build-up film of polymer layers. In one embodiment, the substrate core **152** may include a dielectric material selected from a silicon, silicon nitride, a ceramic material, or a glass material. In one embodiment, the semiconductor package **100** may further include a lower reinforcement layer **180B** embedded in the lower redistribution layer **160B**, the lower reinforcement layer **180B** having a Young's modulus that is higher than a Young's modulus of the upper redistribution layer **180A**. In one embodiment, the upper reinforcement layer **180A** may include a dielectric material selected from a silicon, silicon nitride, a ceramic material, or a glass material. In one embodiment, the lower reinforcement layer **180B** may have a thickness that is less than or equal to a thickness of the lower redistribution layer **160B**. In one embodiment, the thickness of the lower reinforcement layer **180B** ranges from 10 μm to 164 μm ; and a thickness of the upper reinforcement layer **180A** ranges from 10 μm to 164 μm . In one embodiment, the semiconductor package **100** may also include an interposer **108** electrically connecting the upper redistribution layer **160A** and the semiconductor device **104**, **106**; a perimeter of the upper reinforcement layer **180A** is disposed outside of a perimeter of the semiconductor device **104**, **106**; and a perimeter of the lower reinforcement layer **180B** is disposed outside of the perimeter of the semiconductor device **104**, **106**.

(68) According to various embodiments, provided is a semiconductor package **100** may comprise a package substrate **150** comprising: a substrate core **152**, an upper redistribution layer **160A** disposed on a first side of the substrate core **152**; and a lower redistribution layer **160B** disposed on an opposing second side of the substrate core **152**; a semiconductor device **104** vertically stacked on and electrically connected to the interposer; and a lower reinforcement layer **180B** embedded in the lower redistribution layer **160B** facing the semiconductor device **104**, the upper reinforcement layer **180A** having a Young's modulus that is higher than a Young's modulus of the upper redistribution layer **160A**.

(69) In one embodiment, a perimeter of the upper reinforcement layer **180A** may be disposed outside of a perimeter of the semiconductor device **104**. In one embodiment, the Young's modulus of the upper reinforcement layer **180A** ranges from 14 GPa to 100 GPa. In some embodiments, the upper reinforcement layer may have a thickness that is less than or equal to a thickness of the upper redistribution layer. In some embodiments, the thickness of the upper reinforcement layer **180A** may range from 10 μm to 164 μm . In various embodiments, the upper reinforcement layer **180A** comprises a dielectric material selected from a silicon, silicon nitride, a ceramic material, or a glass material. In various embodiments, the package substrate **150** may also include a lower reinforcement layer **180B** embedded in the lower redistribution layer **160B**, the lower

reinforcement layer **180B** having a Young's modulus that is higher than a Young's modulus of the lower redistribution layer **160B**. In some embodiments, the semiconductor package **100** comprises an interposer **108** electrically connecting the upper redistribution layer **160A** and the semiconductor device **104**.

(70) In one embodiment, the semiconductor package may include an interposer **108** electrically connecting the upper redistribution layer **160A** and the semiconductor device **104**, **106**; and a perimeter of the lower reinforcement layer **180B** may be disposed outside of the perimeter of the semiconductor device **104**, **106**. In one embodiment, the lower reinforcement layer **180B** may include a dielectric material selected from a silicon, silicon nitride, a ceramic material, or a glass material; and the substrate core **152** may include a dielectric material selected from a silicon, silicon nitride, a ceramic material, or a glass material. In one embodiment, the Young's modulus of the lower reinforcement layer **180B** ranges from 14 GPa to 100 GPa; and a thickness of the lower reinforcement layer **180B** ranges from 10 μm to 164 μm .

(71) According to various embodiments, provided is a method of manufacturing a semiconductor package **100**, comprising: forming package substrate **150** comprising a substrate core **152**, an upper redistribution layer **160A** disposed on a first side of the substrate core **152**, and a lower redistribution layer **160B** disposed on an opposing second side of the substrate core **152**; etching the upper redistribution layer **160A** to form a first trench **T1**; depositing a reinforcement material **180M** on the upper redistribution layer **160A** and in the first trench **T1**; thinning the reinforcement material **180M** to form an upper reinforcement layer **180A** in the first trench; forming via structures **162V** in the upper reinforcement layer **180A**; forming upper bonding pads **161** on the via structures **162V**; and bonding a semiconductor device **104** to the package substrate **150**, such that a perimeter of the semiconductor device **104** is disposed inside of a perimeter of the upper reinforcement layer **180A**; wherein the upper reinforcement layer **180A** has a Young's modulus that is greater than a Young's modulus of the upper redistribution layer **160A**.

(72) In one embodiment, the method may also include: etching a lower redistribution layer **160B** to form a second trench; depositing a reinforcement layer material on the lower redistribution layer **180B** and in the second trench; etching back the reinforcement layer material to form a lower reinforcement layer **180B** in the second trench; forming via structures **162V** in the lower reinforcement layer **180B**; and forming lower bonding pads **163** on the via structures **162V** of the lower reinforcement layer **180B**, wherein the lower reinforcement layer **180B** has a Young's modulus that is greater than a Young's modulus of the lower redistribution layer **160B**.

(73) The foregoing outlines features of several embodiments so that those skilled in the art may better understand the aspects of the present disclosure. Those skilled in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same purposes and/or achieving the same advantages of the embodiments introduced herein. Those skilled in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the present disclosure, and that they may make various changes, substitutions, and alterations herein without departing from the spirit and scope of the present disclosure.

Claims

1. A semiconductor package comprising: a package substrate comprising: a substrate core; an upper redistribution layer disposed on a first side of the substrate core and comprising a dielectric structure and metal features that extend through the dielectric structure; and a lower redistribution layer disposed on an opposing second side of the substrate core; an interposer vertically stacked on the upper redistribution layer and connected to the metal features; a semiconductor device vertically stacked on and connected to the interposer; and an upper reinforcement layer embedded in the upper redistribution layer between the semiconductor device and the substrate core, the upper

- reinforcement layer having a Young's modulus that is higher than a Young's modulus of the upper redistribution layer, wherein the metal features extend through the upper reinforcement layer.
2. The semiconductor device of claim 1, wherein a horizontal perimeter of the upper reinforcement layer is disposed outside of a perimeter of the semiconductor device.
 3. The semiconductor device of claim 1, wherein the Young's modulus of the upper reinforcement layer ranges from 14 GPa to 100 GPa.
 4. The semiconductor device of claim 1, wherein the upper reinforcement layer has a thickness that is less than or equal to a thickness of the upper redistribution layer.
 5. The semiconductor device of claim 4, wherein the thickness of the upper reinforcement layer ranges from 10 μm to 164 μm .
 6. The semiconductor device of claim 1, wherein the upper reinforcement layer comprises a dielectric material selected from a silicon, silicon nitride, a ceramic material, or a glass material.
 7. The semiconductor device of claim 6, wherein the metal features comprise bonding pads formed on an upper surface of the reinforcement layer.
 8. The semiconductor device of claim 7, wherein the dielectric structure comprises a build-up film of polymer layers.
 9. The semiconductor device of claim 6, wherein the substrate core comprises a dielectric material selected from a silicon, silicon nitride, a ceramic material, or a glass material.
 10. The semiconductor device of claim 1, further comprising a lower reinforcement layer embedded in the lower redistribution layer, the lower reinforcement layer having a Young's modulus that is higher than a Young's modulus of the upper redistribution layer.
 11. The semiconductor device of claim 10, wherein the upper reinforcement layer comprises a dielectric material selected from a silicon, silicon nitride, a ceramic material, or a glass material.
 12. The semiconductor device of claim 10, wherein the lower reinforcement layer has a thickness that is less than or equal to a thickness of the lower redistribution layer.
 13. The semiconductor device of claim 12, wherein: the thickness of the lower reinforcement layer ranges from 10 μm to 164 μm ; and a thickness of the upper reinforcement layer ranges from 10 μm to 164 μm .
 14. The semiconductor device of claim 10, wherein: a horizontal perimeter of the upper reinforcement layer is disposed outside of a perimeter of the semiconductor device; and a horizontal perimeter of the lower reinforcement layer is disposed outside of the perimeter of the semiconductor device.
 15. A semiconductor package comprising: a package substrate comprising: a substrate core; an upper redistribution layer disposed on a first side of the substrate core; and a lower redistribution layer disposed on an opposing second side of the substrate core and comprising a dielectric structure and metal features that extend through the dielectric structure; an interposer vertically stacked on and connected to the upper redistribution layer; a semiconductor device vertically stacked on and connected to the interposer; and a lower reinforcement layer embedded in the lower redistribution layer facing the semiconductor device, the lower reinforcement layer having a Young's modulus that is higher than a Young's modulus of the lower redistribution layer, wherein the metal features extend through the lower reinforcement layer.
 16. The semiconductor device of claim 15, wherein a horizontal perimeter of the lower reinforcement layer is disposed outside of the perimeter of the semiconductor device.
 17. The semiconductor device of claim 15, wherein: the lower reinforcement layer comprises a dielectric material selected from a silicon, silicon nitride, a ceramic material, or a glass material; and the substrate core comprises a dielectric material selected from a silicon, silicon nitride, a ceramic material, or a glass material.
 18. The semiconductor device of claim 15, wherein: the Young's modulus of the lower reinforcement layer ranges from 14 GPa to 100 GPa; and a thickness of the lower reinforcement layer ranges from 10 μm to 164 μm .

19. A method of manufacturing a semiconductor package, comprising: forming package substrate comprising a substrate core, an upper redistribution layer disposed on a first side of the substrate core, and a lower redistribution layer disposed on an opposing second side of the substrate core; etching the upper redistribution layer to form a first trench; depositing a reinforcement layer material on the upper redistribution layer and in the first trench; thinning the reinforcement layer material to form an upper reinforcement layer in the first trench; forming via structures in the upper reinforcement layer; forming upper bonding pads on the via structures; and bonding a semiconductor device to the package substrate, such that a perimeter of the semiconductor device is disposed inside of a perimeter of the first reinforcement layer, wherein the upper reinforcement layer has a Young's modulus that is greater than a Young's modulus of the upper redistribution layer.

20. The method of claim 19, further comprising: etching the lower redistribution layer to form a second trench; depositing a reinforcement layer material on the lower redistribution layer and in the second trench; etching back the reinforcement layer material to form a lower reinforcement layer in the second trench; forming via structures in the lower reinforcement layer; and forming lower bonding pads on the via structures of the lower reinforcement layer, wherein the lower reinforcement layer has a Young's modulus that is greater than a Young's modulus of the lower redistribution layer.
