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Underfill cushion films for packaging substrates and methods of forming the same

Abstract

A semiconductor structure includes a fan-out package comprising at least one semiconductor die, a redistribution structure comprising fan-out bonding pads, and a first underfill material portion, a packaging substrate comprising chip-side bonding pads, solder material portions bonded to the chip-side bonding pads and the fan-out bonding pads, a second underfill material portion laterally surrounding the solder material portions, and at least one cushioning film located on the packaging substrate and contacting the second underfill material portion and having a Young's modulus that is lower than a Young's modulus of the second underfill material portion.

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Background/Summary

RELATED APPLICATIONS (1) This application claims priority from U.S. Provisional Application Ser. No. 63/224,879 titled “UF fillet cushion film for reliability improvement” and filed on Jul. 23, 2021, the entire contents of which are incorporated herein by reference.

BACKGROUND

(1) Interfaces between a fan-out wafer level package (FOWLP) and an underfill material portion are subjected to mechanical stress during subsequent handling of an assembly of the FOWLP, the underfill material portion, 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 FOWLP and an underfill material portion 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 material portions, redistribution structures, and/or various dielectric layers within a semiconductor die or within a packaging substrate. Thus, suppression of the formation of cracks in the underfill material is desired.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) 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.

(2) FIG. 1A is a vertical cross-sectional view of a region of an exemplary structure that includes a first carrier substrate and redistribution structures according to an embodiment of the present disclosure.

(3) FIG. 1B is a top-down view of the region of the exemplary structure of FIG. 1A.

(4) FIG. 2A is vertical cross-sectional view of a region of the exemplary structure after formation of redistribution-side bonding structures and first solder material portions according to an embodiment of the present disclosure.

(5) FIG. 2B is a top-down view of the region of the exemplary structure of FIG. 2A.

(6) FIG. 3A is a vertical cross-sectional view of a region the exemplary structure after attaching semiconductor dies according to an embodiment of the present disclosure.

(7) FIG. 3B is a top-down view of the region of the exemplary structure of FIG. 4A.

(8) FIG. 3C is a magnified vertical cross-sectional view of a high bandwidth memory die.

(9) FIG. 4 is a vertical cross-sectional view of a region of the exemplary structure after formation of first underfill material portions.

- (10) FIG. 5A is a vertical cross-sectional view of a region of the exemplary structure after formation of an epoxy molding compound (EMC) matrix according to an embodiment of the present disclosure.
- (11) FIG. 5B is a top-down view of the region of the exemplary structure of FIG. 5A.
- (12) FIG. 6 is a vertical cross-sectional view of a region of the exemplary structure after attaching a second carrier substrate and detaching the first carrier substrate according to an embodiment of the present disclosure.
- (13) FIG. 7 is a vertical cross-sectional view of a region of the exemplary structure after formation of fan-out bonding pads according to an embodiment of the present disclosure.
- (14) FIG. 8 is a vertical cross-sectional view of a region of the exemplary structure after detaching the second carrier substrate according to an embodiment of the present disclosure.
- (15) FIG. 9 is a vertical cross-sectional view of a region of the exemplary structure during dicing of a redistribution substrate and the EMC matrix according to an embodiment of the present disclosure.
- (16) FIG. 10A is a vertical cross-sectional view of a fan-out package according to an embodiment of the present disclosure.
- (17) FIG. 10B is a horizontal cross-sectional view of the fan-out package along the horizontal plane B-B' of FIG. 10A.
- (18) FIG. 11A is a vertical cross-sectional view of a packaging substrate according to an embodiment of the present disclosure.
- (19) FIG. 11B is a top-down view of the packaging substrate of FIG. 11A.
- (20) FIG. 12A is a vertical cross-sectional view of the packaging substrate after formation of a cushioning film according to an embodiment of the present disclosure.
- (21) FIG. 12B is a top-down view of the packaging substrate of FIG. 12A.
- (22) FIG. 13 is a vertical cross-sectional view of an exemplary structure after attaching the fan-out package to the packaging substrate according to an embodiment of the present disclosure.
- (23) FIG. 14A is a vertical cross-sectional view of the exemplary structure after formation of a second underfill material portion according to an embodiment of the present disclosure.
- (24) FIG. 14B is a horizontal cross-sectional view of the exemplary structure along the horizontal plane B-B' of FIG. 14A.
- (25) FIG. 15A is a horizontal cross-sectional view of a first alternative embodiment of the exemplary structure along a horizontal plane that corresponds to the horizontal plane B-B' of FIG. 14A.
- (26) FIG. 15B is a horizontal cross-sectional view of a second alternative embodiment of the exemplary structure along a horizontal plane that corresponds to the horizontal plane B-B' of FIG. 14A.
- (27) FIG. 15C is a horizontal cross-sectional view of a third alternative embodiment of the exemplary structure along a horizontal plane that corresponds to the horizontal plane B-B' of FIG. 14A.
- (28) FIG. 16 is a vertical cross-sectional view of the exemplary structure after the packaging substrate is attached to a printed circuit board (PCB) according to an embodiment of the present disclosure.
- (29) FIG. 17 is a flowchart illustrating steps for forming an exemplary structure according to an embodiment of the present disclosure.

DETAILED DESCRIPTION

(30) 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.

(31) 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.

(32) The present disclosure is directed to semiconductor devices, and particularly to uniform application of an underfill material in semiconductor die packaging. Generally, the methods and structures of the present disclosure may be used to provide a chip package structure 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 fan-out package configuration.

(33) Fan-out packages are subject to deformation under stress during subsequent assembly processes and/or during operation under mechanical stress and/or under heat. According to an aspect of the present disclosure, deformation of a fan-out package may be reduced by using at least one cushioning film that may be incorporated into a fan-out package. The at least one cushioning film may have a lower Young's modulus and/or a higher coefficient of thermal expansion than a molding compound material that laterally surrounds at least one semiconductor die in a fan-out package. The cushioning film may help to prevent or reduce deformation of a fan-out package under mechanical stress or under thermal stress.

(34) Typically, heterogeneous integration is used to integrate a large interposer (such as a CoWoS interposer or an organic interposer) and a high electrical performance substrate (such as a multi-layer core or a multilayer substrate which may include 12 or more layers) for a high performance chip. The effective coefficient of thermal expansion for such a structure may be more than four times the coefficient of thermal expansion for silicon. Such a large mismatch of coefficients of thermal expansion between a substrate and semiconductor dies on an interposer may often result in molding cracks at fan-out module corners. For these reasons, large fan-out modules formed by molding have high crack risk at the corners. According to an aspect of the present disclosure, an embedded cushioning film may be provided on an interposer such as a redistribution structure to effectively reduce the molding stress, thereby preventing formation of molding cracks in corner regions of an interposer, and providing enhanced reliability to the interposer. The various aspects and embodiments of the methods and structures of the present disclosure are described with reference to accompanying drawings herebelow.

(35) Referring to FIGS. 1A and 1B, an exemplary structure according to an embodiment of the present disclosure may include a first carrier substrate **300** and redistribution structures **920** formed on a front side surface of the first carrier substrate **300**. The first carrier substrate **300** may include an optically transparent substrate such as a glass substrate or a sapphire substrate. The diameter of the first carrier substrate **300** may be in a range from 150 mm to 290 mm, although lesser and greater diameters may be used. In addition, the thickness of the first carrier substrate **300** may be in a range from 500 microns to 2,000 microns, although lesser and greater thicknesses may also be used. Alternatively, the first carrier substrate **300** may be provided in a rectangular panel format.

The dimensions of the first carrier substrate **300** in such alternative embodiments may be substantially the same.

(36) A first adhesive layer **301** may be applied to the front-side surface of the first carrier substrate **300**. In one embodiment, the first adhesive layer **301** may be a light-to-heat conversion (LTHC) layer. The LTHC layer may be a solvent-based coating applied using a spin coating method. The LTHC layer may convert ultraviolet light to heat, which may cause the material of the LTHC layer to lose adhesion. Alternatively, the first adhesive layer **301** may include a thermally decomposing adhesive material. For example, the first adhesive layer **301** may include an acrylic pressure-sensitive adhesive that decomposes at an elevated temperature. The debonding temperature of the thermally decomposing adhesive material may be in a range from 150 degrees to 200 degrees Celsius.

(37) Redistribution structures **920** may be formed over the first adhesive layer **301**. Specifically, a redistribution structure **920** may be formed within each unit area UA, which is the area of a repetition unit that may be repeated in a two-dimensional array over the first carrier substrate **300**. Each redistribution structure **920** may include redistribution dielectric layers **922** and redistribution wiring interconnects **924**. The redistribution dielectric layers **922** include a respective dielectric polymer material such as polyimide (PI), benzocyclobutene (BCB), or polybenzobisoxazole (PBO). Other suitable materials may be within the contemplated scope of disclosure. Each redistribution dielectric layer **922** may be formed by spin coating and drying of the respective dielectric polymer material. The thickness of each redistribution dielectric layer **922** may be in a range from 2 microns to 40 microns, such as from 4 microns to 20 microns. Each redistribution dielectric layer **922** may be patterned, for example, by applying and patterning a respective photoresist layer thereabove, and by transferring the pattern in the photoresist layer into the redistribution dielectric layer **922** using an etch process such as an anisotropic etch process. The photoresist layer may be subsequently removed, for example, by ashing.

(38) Each of the redistribution wiring interconnects **924** may be formed by depositing a metallic seed layer by sputtering, by applying and patterning a photoresist layer over the metallic seed layer to form a pattern of openings through the photoresist layer, by electroplating a metallic fill material (such as copper, nickel, or a stack of copper and nickel), by removing the photoresist layer (for example, by ashing), and by etching portions of the metallic seed layer located between the electroplated metallic fill material portions. The metallic seed layer may include, for example, a stack of a titanium barrier layer and a copper seed layer. The titanium barrier layer may have thickness in a range from 50 nm to 400 nm, and the copper seed layer may have a thickness in a range from 100 nm to 500 nm. The metallic fill material for the redistribution wiring interconnects **924** may include copper, nickel, or copper and nickel. Other suitable metallic fill materials are within the contemplated scope of disclosure. The thickness of the metallic fill material that is deposited for each redistribution wiring interconnect **924** may be in a range from 2 microns to 40 microns, such as from 4 microns to 10 microns, although lesser or greater thicknesses may also be used. The total number of levels of wiring in each redistribution structure **920** (i.e., the levels of the redistribution wiring interconnects **924**) may be in a range from 1 to 10. A periodic two-dimensional array (such as a rectangular array) of redistribution structures **920** may be formed over the first carrier substrate **300**. Each redistribution structure **920** may be formed within a unit area UA. The layer including all redistribution structures **920** is herein referred to as a redistribution structure layer. The redistribution structure layer includes a two-dimensional array of redistribution structures **920**. In one embodiment, the two-dimensional array of redistribution structures **920** may be a rectangular periodic two-dimensional array of redistribution structures **920** having a first periodicity along a first horizontal direction **hd1** and having a second periodicity along a second horizontal direction **hd2** that is perpendicular to the first horizontal direction **hd1**.

(39) Referring to FIGS. 2A and 2B, at least one metallic material and a first solder material may be sequentially deposited over the front-side surface of the redistribution structures **920**. The at least

one metallic material comprises a material that may be used for metallic bumps, such as copper. The thickness of the at least one metallic material may be in a range from 5 microns to 60 microns, such as from 10 microns to 30 microns, although lesser and greater thicknesses may also be used. The first solder material may comprise a solder material suitable for C2 bonding, i.e., for microbump bonding. The thickness of the first solder material may be in a range from 2 microns to 30 microns, such as from 4 microns to 15 microns, although lesser and greater thicknesses may also be used.

(40) The first solder material and the at least one metallic material may be patterned into discrete arrays of first solder material portions **940** and arrays of metal bonding structures, which are herein referred to as arrays of redistribution-side bonding structures **938**. Each array of redistribution-side bonding structures **938** is formed within a respective unit area UA. Each array of first solder material portions **940** is formed within a respective unit area UA. Each first solder material portion **940** may have a same horizontal cross-sectional shape as an underlying redistribution-side bonding structures **938**.

(41) In one embodiment, the redistribution-side bonding structures **938** may include, and/or may consist essentially of, copper or a copper-containing alloy. Other suitable materials are within the contemplated scope of disclosure. The thickness of the redistribution-side bonding structures **938** may be in a range from 5 microns to 60 microns, although lesser or greater thicknesses may also be used. The redistribution-side bonding structures **938** may have horizontal cross-sectional shapes of rectangles, rounded rectangles, circles, regular polygons, irregular polygons, or any other two-dimensional curvilinear shape having a closed periphery. In one embodiment, redistribution-side bonding structures **938** may be configured for microbump bonding (i.e., C2 bonding), and may have a thickness in a range from 10 microns to 30 microns, although lesser or greater thicknesses may also be used. In this embodiment, each array of redistribution-side bonding structures **938** may be formed as an array of microbumps (such as copper pillars) having a lateral dimension in a range from 10 microns to 25 microns, and having a pitch in a range from 20 microns to 50 microns.

(42) Referring to FIGS. 3A and 3B, a set of at least one semiconductor die (**700, 800**) may be bonded to each redistribution structure **920**. In one embodiment, the redistribution structures **920** may be arranged as a two-dimensional periodic array, and multiple sets of at least one semiconductor die (**700, 800**) may be bonded to the redistribution structures **920** as a two-dimensional periodic rectangular array of sets of the at least one semiconductor die (**700, 800**). Each set of at least one semiconductor die (**700, 800**) includes at least one semiconductor die. Each set of at least one semiconductor die (**700, 800**) may include any set of at least one semiconductor die known in the art. In one embodiment, each set of at least one semiconductor die (**700, 800**) may comprise a plurality of semiconductor dies (**700, 800**). For example, each set of at least one semiconductor die (**700, 800**) may include at least one system-on-chip (SoC) die **700** and/or at least one memory die **800**. Each SoC die **700** may comprise an application processor die, a central processing unit die, or a graphic processing unit die. In one embodiment, the at least one memory die **800** may comprise a high bandwidth memory (HBM) die that includes a vertical stack of static random access memory dies. In one embodiment, the at least one semiconductor die (**700, 800**) may include at least one system-on-chip (SoC) die and a high bandwidth memory (HBM) die including a vertical stack of static random access memory (SRAM) dies that are interconnected to one another through microbumps and are laterally surrounded by an epoxy molding material enclosure frame.

(43) Each semiconductor die (**700, 800**) may comprise a respective array of die-side bonding structures (**780, 880**). For example, each SoC die **700** may comprise an array of SoC metal bonding structures **780**, and each memory die **800** may comprise an array of memory-die metal bonding structures **880**. Each of the semiconductor dies (**700, 800**) may be positioned in a face-down position such that die-side bonding structures (**780, 880**) face the first solder material portions **940**. Each set of at least one semiconductor die (**700, 800**) may be placed within a respective unit area

UA. Placement of the semiconductor dies (700, 800) may be performed using a pick and place apparatus such that each of the die-side bonding structures (780, 880) may be placed on a top surface of a respective one of the first solder material portions 940.

(44) Generally, a redistribution structure 920 including redistribution-side bonding structures 938 thereupon may be provided, and at least one semiconductor die (700, 800) including a respective set of die-side bonding structures (780, 880) may be provided. The at least one semiconductor die (700, 800) may be bonded to the redistribution structure 920 using first solder material portions 940 that are bonded to a respective redistribution-side bonding structure 938 and to a respective one of the die-side bonding structures (780, 880).

(45) Each set of at least one semiconductor die (700, 800) may be attached to a respective redistribution structure 920 through a respective set of first solder material portions 940. Each of the at least one cushioning film within a unit area UA may be located outside an area including the at least one semiconductor die (700, 800) in the unit area UA in a plan view. The plan view is a view along a vertical direction, which is the direction that is perpendicular to the planar top surface of the redistribution structure layer.

(46) Referring to FIG. 3C, a high bandwidth memory (HBM) die 810 is illustrated, which may be used as a memory die 800 within the exemplary structures of FIGS. 3A and 3B. The HBM die 810 may include a vertical stack of static random access memory dies (811, 812, 813, 814, 815) that are interconnected to one another through microbumps 820 and are laterally surrounded by an epoxy molding material enclosure frame 816. The gaps between vertically neighboring pairs of the random access memory dies (811, 812, 813, 814, 815) may be filled with a HBM underfill material portion 822 that laterally surrounds a respective set of microbumps 820. The HBM die 810 may comprise an array of memory-die metal bonding structures 880 configured to be bonded to a subset of an array of redistribution-side bonding structures 938 within a unit area UA. The HBM die 810 may be configured to provide a high bandwidth as defined under JEDEC standards, i.e., standards defined by The JEDEC Solid State Technology Association.

(47) Referring to FIG. 4, a first underfill material may be applied into each gap between the redistribution structures 920 and sets of at least one semiconductor die (700, 800) that are bonded to the redistribution structures 920. The first underfill material may comprise any underfill material known in the art. A first underfill material portion 950 may be formed within each unit area UA between a redistribution structure 920 and an overlying set of at least one semiconductor die (700, 800). The first underfill material portions 950 may be formed by injecting the first underfill material around a respective array of first solder material portions 940 in a respective unit area UA. Any known underfill material application method may be used, which may be, for example, the capillary underfill method, the molded underfill method, or the printed underfill method.

(48) Within each unit area UA, a first underfill material portion 950 may laterally surround, and contact, each of the first solder material portions 940 within the unit area UA. The first underfill material portion 950 may be formed around, and contact, the first solder material portions 940, the redistribution-side bonding structures 938, and the die-side bonding structures (780, 880) in the unit area UA.

(49) Each redistribution structure 920 in a unit area UA comprises redistribution-side bonding structures 938. At least one semiconductor die (700, 800) comprising a respective set of die-side bonding structures (780, 880) is attached to the redistribution-side bonding structures 938 through a respective set of first solder material portions 940 within each unit area UA. Within each unit area UA, a first underfill material portion 950 laterally surrounds the redistribution-side bonding structures 938 and the die-side bonding structures (780, 880) of the at least one semiconductor die (700, 800).

(50) Referring to FIGS. 5A and 5B, an epoxy molding compound (EMC) may be applied to the gaps between contiguous assemblies of a respective set of semiconductor dies (700, 800) and a first underfill material portion 950.

(51) The EMC may include an epoxy-containing compound that may be hardened (i.e., cured) to provide a dielectric material portion having sufficient stiffness and mechanical strength. The EMC may include epoxy resin, hardener, silica (as a filler material), and other additives. The EMC may be provided in a liquid form or in a solid form depending on the viscosity and flowability. Liquid EMC provides better handling, good flowability, less voids, better fill, and less flow marks. Solid EMC provides less cure shrinkage, better stand-off, and less die drift. A high filler content (such as 85% in weight) within an EMC may shorten the time in mold, lower the mold shrinkage, and reduce the mold warpage. Uniform filler size distribution in the EMC may reduce flow marks, and may enhance flowability. The curing temperature of the EMC may be lower than the release (debonding) temperature of the first adhesive layer **301** in embodiments in which the adhesive layer includes a thermally debonding material. For example, the curing temperature of the EMC may be in a range from 125° C. to 150° C.

(52) The EMC may be cured at a curing temperature to form an EMC matrix **910M** that laterally surrounds and embeds each assembly of a set of semiconductor dies (**700, 800**) and a first underfill material portion **950**. The EMC matrix **910M** includes a plurality of epoxy molding compound (EMC) die frames that may be laterally adjoined to one another. Each EMC die frame is a portion of the EMC matrix **910M** that is located within a respective unit area UA. Thus, each EMC die frame laterally surrounds and embeds a respective a set of semiconductor dies (**700, 800**) and a respective first underfill material portion **950**. Young's modulus of pure epoxy is about 3.35 GPa, and Young's modulus of the EMC may be higher than Young's modulus of pure epoxy by adding additives. Young's modulus of EMC may be greater than 3.5 GPa.

(53) Portions of the EMC matrix **910M** that overlie the horizontal plane including the top surfaces of the semiconductor dies (**700, 800**) may be removed by a planarization process. For example, the portions of the EMC matrix **910M** that overlie the horizontal plane may be removed using a chemical mechanical planarization (CMP). The combination of the remaining portion of the EMC matrix **910M**, the semiconductor dies (**700, 800**), the first underfill material portions **950**, and the two-dimensional array of redistribution structures **920** comprises a reconstituted wafer **900W**. Each portion of the EMC matrix **910M** located within a unit area UA constitutes an EMC die frame.

(54) Referring to FIG. 6, a second adhesive layer **401** may be applied to the physically exposed planar surface of the reconstituted wafer **900W**, i.e., the physically exposed surfaces of the EMC matrix **910M**, the semiconductor dies (**700, 800**), and the first underfill material portions **950**. In one embodiment, the second adhesive layer **401** may comprise a same material as, or may comprise a different material from, the material of the first adhesive layer **301**. In embodiments in which the first adhesive layer **301** comprises a thermally decomposing adhesive material, the second adhesive layer **401** may comprise another thermally decomposing adhesive material that decomposes at a higher temperature, or may comprise a light-to-heat conversion material.

(55) A second carrier substrate **400** may be attached to the second adhesive layer **401**. The second carrier substrate **400** may be attached to the opposite side of the reconstituted wafer **900W** relative to the first carrier substrate **300**. Generally, the second carrier substrate **400** may comprise any material that may be used for the first carrier substrate **300**. The thickness of the second carrier substrate **400** may be in a range from 500 microns to 2,000 microns, although lesser and greater thicknesses may also be used.

(56) The first adhesive layer **301** may be decomposed by ultraviolet radiation or by a thermal anneal at a debonding temperature. In embodiments in which the first carrier substrate **300** includes an optically transparent material and the first adhesive layer **301** includes an LTHC layer, the first adhesive layer **301** may be decomposed by irradiating ultraviolet light through the transparent carrier substrate. The LTHC layer may absorb the ultraviolet radiation and generate heat, which decomposes the material of the LTHC layer and causes the transparent first carrier substrate **300** to be detached from the reconstituted wafer **900W**. In embodiments in which the first adhesive layer **301** includes a thermally decomposing adhesive material, a thermal anneal process at a debonding

temperature may be performed to detach the first carrier substrate **300** from the reconstituted wafer **900W**.

(57) Referring to FIG. 7, fan-out bonding pads **928** and second solder material portions **290** may be formed by depositing and patterning a stack of at least one metallic material that may function as metallic bumps and a solder material layer. The metallic fill material for the fan-out bonding pads **928** may include copper. Other suitable materials are within the contemplated scope of disclosure. The thickness of the fan-out bonding pads **928** may be in a range from 5 microns to 100 microns, although lesser or greater thicknesses may also be used. The fan-out bonding pads **928** and the second solder material portions **290** may have horizontal cross-sectional shapes of rectangles, rounded rectangles, or circles. Other suitable shapes are within the contemplated scope of disclosure. In embodiments in which the fan-out bonding pads **928** are formed as C4 (controlled collapse chip connection) pads, the thickness of the fan-out bonding pads **928** may be in a range from 5 microns to 50 microns, although lesser or greater thicknesses may also be used. In some embodiments, the fan-out bonding pads **928** may be, or include, under bump metallurgy (UBM) structures. The configurations of the fan-out bonding pads **928** are not limited to be fan-out structures. Alternatively, the fan-out bonding pads **928** may be configured for microbump bonding (i.e., C2 bonding), and may have a thickness in a range from 30 microns to 100 microns, although lesser or greater thicknesses may also be used. In such an embodiment, the fan-out bonding pads **928** may be formed as an array of microbumps (such as copper pillars) having a lateral dimension in a range from 10 microns to 25 microns, and having a pitch in a range from 20 microns to 50 microns.

(58) The fan-out bonding pads **928** and the second solder material portions **290** may be formed on the opposite side of the EMC matrix **910M** and the two-dimensional array of sets of semiconductor dies (**700**, **800**) relative to the redistribution structure layer. The redistribution structure layer includes a three-dimensional array of redistribution structures **920**. Each redistribution structure **920** may be located within a respective unit area UA. Each redistribution structure **920** may include redistribution dielectric layers **922**, redistribution wiring interconnects **924** embedded in the redistribution dielectric layers **922**, and fan-out bonding pads **928**. The fan-out bonding pads **928** may be located on an opposite side of the redistribution-side bonding structures **938** relative to the redistribution dielectric layers **922**, and may be electrically connected to a respective one of the redistribution-side bonding structures **938**.

(59) Referring to FIG. 8, the second adhesive layer **401** may be decomposed by ultraviolet radiation or by a thermal anneal at a debonding temperature. In embodiments in which the second carrier substrate **400** includes an optically transparent material and the second adhesive layer **401** includes an LTHC layer, the second adhesive layer **401** may be decomposed by irradiating ultraviolet light through the transparent carrier substrate. In embodiments in which the second adhesive layer **401** includes a thermally decomposing adhesive material, a thermal anneal process at a debonding temperature may be performed to detach the second carrier substrate **400** from the reconstituted wafer **900W**.

(60) Referring to FIG. 9, the reconstituted wafer **900W** including the fan-out bonding pads **928** may be subsequently diced along dicing channels by performing a dicing process. The dicing channels correspond to the boundaries between neighboring pairs of unit area UA. Each diced unit from the reconstituted wafer **900W** may include a fan-out package **900**. In other words, each diced portion of the assembly of the two-dimensional array of sets of semiconductor dies (**700**, **800**), the two-dimensional array of first underfill material portions **950**, the EMC matrix **910M**, and the two-dimensional array of redistribution structures **920** constitutes a fan-out package **900**. Each diced portion of the EMC matrix **910M** constitutes a molding compound die frame **910**. Each diced portion of the redistribution structure layer (which includes the two-dimensional array of redistribution structures **920**) constitutes a redistribution structure **920**.

(61) Referring to FIGS. 10A and 10B, a fan-out package **900** obtained by dicing the exemplary

structure at the processing steps of FIG. 9 is illustrated. The fan-out package **900** comprises a redistribution structure **920** including redistribution-side bonding structures **938**, at least one semiconductor die (**700**, **800**) comprising a respective set of die-side bonding structures (**780**, **880**) that is attached to the redistribution-side bonding structures **938** through a respective set of first solder material portions **940**, a first underfill material portion **950** laterally surrounding the redistribution-side bonding structures **938** and the die-side bonding structures (**780**, **880**) of the at least one semiconductor die (**700**, **800**).

(62) The fan-out package **900** may comprise a molding compound die frame **910** laterally surrounding the at least one semiconductor die (**700**, **800**) and comprising a molding compound material. In one embodiment, the molding compound die frame **910** may include sidewalls that are vertically coincident with sidewalls of the redistribution structure **920**, i.e., located within same vertical planes as the sidewalls of the redistribution structure **920**. Generally, the molding compound die frame **910** may be formed around the at least one semiconductor die (**700**, **800**) after formation of the first underfill material portion **950** within each fan-out package **900**. The molding compound material contacts a peripheral portion of a planar surface of the redistribution structure **920**.

(63) Referring to FIGS. **11A** and **11B**, a packaging substrate **200** is provided. The packaging substrate **200** may be a cored packaging substrate including a core substrate **210**, or a coreless packaging substrate that does not include a package core. Alternatively, the packaging substrate **200** may include a system-on-integrated packaging substrate (SoIS) including redistribution layers and/or dielectric interlayers, at least one embedded interposer (such as a silicon interposer). Such a system-integrated packaging substrate may include layer-to-layer interconnections using solder material portions, microbumps, underfill material portions (such as molded underfill material portions), and/or an adhesion film. While the present disclosure is described using an exemplary substrate package, it is understood that the scope of the present disclosure is not limited by any particular type of substrate package and may include an SoIS. The core substrate **210** may include a glass epoxy plate including an array of through-plate holes. An array of through-core via structures **214** including a metallic material may be provided in the through-plate holes. Each through-core via structure **214** may, or may not, include a cylindrical hollow therein. Optionally, dielectric liners **212** may be used to electrically isolate the through-core via structures **214** from the core substrate **210**.

(64) The packaging substrate **200** may include board-side surface laminar circuit (SLC) **240** and a chip-side surface laminar circuit (SLC) **260**. The board-side SLC may include board-side insulating layers **242** embedding board-side wiring interconnects **244**. The chip-side SLC **260** may include chip-side insulating layers **262** embedding chip-side wiring interconnects **264**. The board-side insulating layers **242** and the chip-side insulating layers **262** may include a photosensitive epoxy material that may be lithographically patterned and subsequently cured. The board-side wiring interconnects **244** and the chip-side wiring interconnects **264** may include copper that may be deposited by electroplating within patterns in the board-side insulating layers **242** or the chip-side insulating layers **262**.

(65) In one embodiment, the packaging substrate **200** includes a chip-side surface laminar circuit **260** comprising chip-side wiring interconnects **264** connected to an array of chip-side bonding pads **268** that may be bonded to the array of second solder material portions **290**, and a board-side surface laminar circuit **240** including board-side wiring interconnects **244** connected to an array of board-side bonding pads **248**. The array of board-side bonding pads **248** is configured to allow bonding through solder balls. The array of chip-side bonding pads **268** may be configured to allow bonding through C4 solder balls. Generally, any type of packaging substrate **200** may be used. While the present disclosure is described using an embodiment in which the packaging substrate **200** includes a chip-side surface laminar circuit **260** and a board-side surface laminar circuit **240**, embodiments are expressly contemplated herein in which one of the chip-side surface laminar

circuit **260** and the board-side surface laminar circuit **240** is omitted, or is replaced with an array of bonding structures such as microbumps. In an illustrative example, the chip-side surface laminar circuit **260** may be replaced with an array of microbumps or any other array of bonding structures. (66) Referring to FIGS. **12A** and **12B** and according to an aspect of the present disclosure, at least one cushioning film **270** may be formed on a top surface of a packaging substrate **200**, which may be a physically exposed horizontal planar surface of the chip-side insulating layers **262**. The at least one cushioning film **270** may comprise a single cushioning film **270**, or may comprise a plurality of cushioning films **270**. The at least one cushioning film **270** comprises, and/or consists essentially of, a cushioning material. The at least one cushioning film **270** may be formed by depositing a continuous cushioning material layer on the top surface of the packaging substrate **200**, and by patterning the continuous cushioning material layer into the at least one cushioning film **270**. The continuous cushioning material layer may be formed by spin-coating or chemical vapor deposition, and may be patterned by applying and patterning a photoresist thereabove, and by transferring the pattern in the photoresist layer through the continuous cushioning material layer by etching unmasked portions of the continuous cushioning material layer. Alternatively, the continuous cushioning material layer may be photosensitive, and may be directly patterned by lithographic exposure and development.

(67) The cushioning material of the at least one cushioning film **270** may include a material that absorbs mechanical stress that is subsequently applied to the fan-out package **900**, and especially to corner regions of the fan-out package **900**. The cushioning material may include a material that may absorb mechanical stress better than a second underfill material to be subsequently applied between the packaging substrate **200** and the fan-out package **900** that is subsequently bonded to the packaging substrate **200**. For example, the cushioning material may have a first Young's modulus, and the second underfill material to be subsequently used may have a second Young's modulus that is higher than the first Young's modulus. Thus, the cushioning material deforms more easily than the second underfill material to be subsequently used.

(68) Further, the cushioning material may include a material providing more thermal expansion than the second underfill material to be subsequently used. In one embodiment, the cushioning material of the at least one cushioning film **270** may comprise, and/or may consist essentially of, a material having a first coefficient of thermal expansion at room temperature (i.e., at 20 degrees Celsius), and the second underfill material to be subsequently used may comprise, and/or may consist essentially of, a material having a second coefficient of thermal expansion at room temperature that is lower than the first coefficient of thermal expansion at room temperature.

(69) The at least one cushioning film **270** may include, and/or may consist essentially of, a material having a Young's modulus that is lower than a Young's modulus of a second underfill material to be subsequently applied between the packaging substrate **200** and the fan-out package **900** as provided at the processing steps of FIGS. **10A** and **10B**. In an illustrative example, the at least one cushioning film **270** may comprise a polymer material or an epoxy-based material. In one embodiment, the at least one cushioning film **270** may comprise, and/or may consist essentially of, a material having a Young's modulus less than 4.0 GPa, and/or less than 2.0 GPa. In one embodiment, the at least one cushioning film **270** may comprise, and/or may consist essentially of, a material selected from polyimide (PI), polybenzoxazole (PBO), benzocyclobutene (BCB), and silicone. In one embodiment, the at least one cushioning film **270** may comprise, and/or may consist essentially of, a material having a Young's modulus less than 200 MPa.

(70) In one embodiment, the at least one cushioning film **270** may have a uniform thickness throughout. In one embodiment, the uniform thickness is less than a maximum height of an array of solder material portions to be subsequently used to attach the fan-out package **900** to the packaging substrate **200**. In one embodiment, the thickness of the at least one cushioning film **270** may be in a range from 10% to 50% of the height of solder material portions to be subsequently used to attach the fan-out package **900** to the packaging substrate **200**. In an illustrative example, the thickness of

the at least one cushioning film **270** may be in a range from 3 microns to 50 microns, such as from 6 microns to 25 microns and/or from 9 microns to 20 microns, although lesser and greater thicknesses may also be used.

(71) In one embodiment, the at least one cushioning film **270** within each unit area UA may comprise a single rectangular frame-shaped cushioning film **270** having a rectangular outer periphery and a rectangular inner periphery. In this embodiment, an opening within the cushioning film **270** may have a rectangular shape such that a pair of lengthwise sidewalls is parallel to the first horizontal direction **hd1**, and a pair of widthwise sidewalls is parallel to the second horizontal direction **hd2**.

(72) Referring to FIG. **13**, the fan-out package **900** may be disposed over the packaging substrate **200** with an array of the second solder material portions **290** therebetween. In embodiments in which the second solder material portions **290** are formed on the fan-out bonding pads **928** of the fan-out package **900**, the second solder material portions **290** may be disposed on the chip-side bonding pads **268** of the packaging substrate **200**. A reflow process may be performed to reflow the second solder material portions **290**, thereby inducing bonding between the fan-out package **900** and the packaging substrate **200**. Each second solder material portion **290** may be bonded to a respective one of the fan-out bonding pads **928** and to a respective one of the chip-side bonding pads **268**. In one embodiment, the second solder material portions **290** may include C4 solder balls, and the fan-out package **900** may be attached to the packaging substrate **200** through an array of C4 solder balls. Generally, the fan-out package **900** may be bonded to the packaging substrate **200** such that the redistribution structure **920** is bonded to the packaging substrate **200** by an array of solder material portions (such as the second solder material portions **290**).

(73) Referring to FIGS. **14A** and **14B**, a second underfill material portion **292** may be formed around the second solder material portions **290** by applying and shaping a second underfill material. The second underfill material portion **292** may be formed by injecting the second underfill material around the array of second solder material portions **290** after the second solder material portions **290** are reflowed. Any known underfill material application method may be used, which may be, for example, the capillary underfill method, the molded underfill method, or the printed underfill method.

(74) The second underfill material portion **292** may be formed between the redistribution structure **920** and the packaging substrate **200**. According to an aspect of the present disclosure, the second underfill material portion **292** may be formed directly on each sidewall of the molding compound die frame **910** and directly on segments of a top surface and at least one sidewall of one, and/or each, of the at least one cushioning film **270**. The second underfill material portion **292** may contact each of the second solder material portions **290** (which may be C4 solder balls or C2 solder caps), and may contact vertical sidewalls of the fan-out package **900**. The second underfill material portion laterally surrounds, and contacts, the array of second solder material portions **290** and the fan-out package **900**.

(75) Optionally, a stabilization structure **294**, such as a cap structure or a ring structure, may be attached to the assembly of the fan-out package **900** and the packaging substrate **200** to reduce deformation of the assembly during subsequent processing steps and/or during usage of the assembly.

(76) In one embodiment, the fan-out package **900** comprises a molding compound die frame **910** that laterally surrounds the at least one semiconductor die (**700**, **800**) and contacting a peripheral portion of a top surface of the redistribution structure **920**. The second underfill material portion **292** may be formed directly on sidewalls of the molding compound die frame **910**. In one embodiment, the second underfill material portion **292** covers a first portion of each of the at least one cushioning film **270**, and does not cover a second portion of each of the at least one cushioning film **270** that is located outside the first portion of each of the at least one cushioning film **270**.

(77) In one embodiment, the fan-out package **900** may have a rectangular horizontal cross-sectional

shape having a first length L1 along a first horizontal direction and having a first width W1 along a second horizontal direction that is perpendicular to the first horizontal direction. In one embodiment, the outer periphery **2922** of the second underfill material portion **292** that defines the outermost extent of the second underfill material portion **292** may be equidistant, or may be substantially equidistant, from the sidewalls of the fan-out package **900**. The lateral distance (i.e., the horizontal distance) between the outer periphery **2922** of the second underfill material portion **292** and the most proximal one of the sidewall of the fan-out package **900** is herein referred to as a fillet width FW, which may be in a range from 3 microns to 30 microns, such as from 5 microns to 20 microns and/or from 8 microns to 15 microns, although lesser and greater lateral dimensions may also be used.

(78) In one embodiment, the at least one cushioning film **270** comprises a single rectangular frame-shaped cushioning film **270** having a rectangular outer periphery and a rectangular inner periphery, the lateral distance between the rectangular outer periphery of the cushioning film **270** and a most proximal sidewall of the fan-out package **900** is herein referred to as a first lateral offset distance D1. The first lateral offset distance D1 may be greater than the fillet width FW. For example, the first lateral offset distance D1 may be in a range from 4 microns to 60 microns, such as from 6 microns to 40 microns and/or from 10 microns to 30 microns, although lesser and greater lateral dimensions may also be used.

(79) The lateral distance between the rectangular inner periphery of the cushioning film **270** and a most proximal sidewall of the fan-out package **900** is herein referred to as a second lateral offset distance D2. The second lateral offset distance D2 may be less than the fillet width FW. For example, the second lateral offset distance D2 may be in a range from 0.01 micron to 20 microns, such as from 1 microns to 15 microns and/or from 2 microns to 10 microns, although lesser and greater lateral dimensions may also be used. In one embodiment, the entirety of the outer periphery **2922** of the second underfill material portion **292** may be located on a top surface of the cushioning film **270**. In one embodiment, the entirety of the outer periphery **2922** of the second underfill material portion **292** may be laterally offset inward from the outer sidewalls of the cushioning film **270**, and may be laterally offset outward from the inner sidewalls of the cushioning film **270**.

(80) Referring to FIG. 15A, a first alternative embodiment of the exemplary structure is illustrated. An entirety of the at least one cushioning film **270** (which may be a rectangular frame-shaped cushioning film **270**) may be located outside a periphery of an area of the fan-out package **900** (i.e., outside the area defined by the outer sidewalls of the molding compound die frame **910**) in a plan view along a vertical direction. The vertical direction is the direction that is perpendicular to horizontal surfaces of the packaging substrate **200**, such as the direction that is perpendicular to a horizontal plane including bonding surfaces of the chip-side bonding pads **268**.

(81) Referring to FIG. 15B, a second alternative embodiment of the exemplary structure is illustrated. The at least one cushioning film **270** may comprises a plurality of L-shaped cushioning films **270** located outside corner regions of the fan-out package **900** and not having an areal overlap with the fan-out package **900** in a plan view along the vertical direction. Each L-shaped cushioning film **270** may have a maximum length along a lengthwise direction, which is herein referred to as a second length L2. The ratio of the second length L2 to the first length L1 may be in a range from 0.001 to 0.5, such as from 0.05 to 0.3, although lesser and greater ratios may also be used. Each L-shaped cushioning film **270** may have a maximum width along a widthwise direction, which is herein referred to as a second width W2. The ratio of the second width W2 to the first width W1 may be in a range from 0.001 to 0.5, such as from 0.05 to 0.3, although lesser and greater ratios may also be used.

(82) Referring to FIG. 15C, a third alternative embodiment of the exemplary structure is illustrated. The at least one cushioning film **270** may comprise a plurality of rectangular cushioning films **270** located about corner regions of the fan-out package **900** and having a respective areal overlap with the fan-out package **900** in a plan view along a vertical direction. Each rectangular-shaped

cushioning film **270** may have a maximum length along a lengthwise direction, which is herein referred to as a second length **L2**. The ratio of the second length **L2** to the first length **L1** may be in a range from 0.001 to 0.5, such as from 0.05 to 0.3, although lesser and greater ratios may also be used. Each L-shaped cushioning film **270** may have a maximum width along a widthwise direction, which is herein referred to as a second width **W2**. The ratio of the second width **W2** to the first width **W1** may be in a range from 0.001 to 0.5, such as from 0.05 to 0.3, although lesser and greater ratios may also be used.

(83) Referring collectively to FIGS. **14A**, **14B**, **15A**, **15B**, and **15C** and according to various embodiments of the present disclosure, the second underfill material portion **292** may contact a first portion of a top surface of one, or each, of the at least one cushioning film **270**, and a second portion of the top surface of one, or each, of the at least one cushioning film **270** is not contacted by the second underfill material portion **292**.

(84) In some embodiments, the entirety of each bottom surface of the at least one cushioning film **270** may be in contact with a horizontal top surface of the packaging substrate **200**, and each of the at least one cushioning film **270** may include a respective first sidewall that contacts the second underfill material portion **292** and a respective second sidewall that does not contact the second underfill material portion **292** and is physically exposed to an ambient gas, such as atmosphere.

(85) In one embodiment, a first portion of the at least one cushioning film **270** has an areal overlap with the fan-out package **900** in a plan view along a vertical direction that is perpendicular to a horizontal plane including bonding surfaces of the chip-side bonding pads **268**; and a second portion of the at least one cushioning film **270** is located outside a periphery of an area of the fan-out package in the plan view as illustrated in FIG. **15A**.

(86) The at least one cushioning film **270** comprises a frame-shaped cushioning film **270** comprising an inner periphery and an outer periphery that laterally surrounds the inner periphery and is laterally spaced from the inner periphery; and the inner periphery laterally surrounds the array of second solder material portions **290**.

(87) In one embodiment, the second underfill material portion **292** contacts sidewalls of the redistribution structure **920** and sidewalls of the molding compound die frame **910**.

(88) In one embodiment, the at least one cushioning film **270** has a uniform thickness; and each of the at least one cushioning film **270** comprises a portion that is located outside a periphery of an area of the fan-out package **900** in a plan view along a vertical direction that is perpendicular to a horizontal plane including a horizontal surface of the packaging substrate **200** that is proximal to the fan-out package **900**.

(89) Referring to FIG. **16**, a printed circuit board (PCB) **100** including a PCB substrate **110** and PCB bonding pads **180** may be provided. The PCB **100** includes a printed circuitry (not shown) at least on one side of the PCB substrate **110**. An array of solder joints **190** may be formed to bond the array of board-side bonding pads **248** to the array of PCB bonding pads **180**. The solder joints **190** may be formed by disposing an array of solder balls between the array of board-side bonding pads **248** and the array of PCB bonding pads **180**, and by reflowing the array of solder balls. An underfill material portion **192** may be formed around the solder joints **190** by applying and shaping an underfill material. The packaging substrate **200** is attached to the PCB **100** through the array of solder joints **190**.

(90) Referring to FIG. **17**, a flowchart illustrates steps for forming an exemplary structure according to an embodiment of the present disclosure.

(91) Referring to step **1710** and FIGS. **1A-10B**, a fan-out package **900** comprising at least one semiconductor die (**700**, **800**) and a redistribution structure **920** is provided.

(92) Referring to step **1720** and FIGS. **11A-12B**, at least one cushioning film **270** may be formed on a top surface of a packaging substrate **200**.

(93) Referring to step **1730** and FIG. **13**, the fan-out package **900** may be bonded to the packaging substrate **200** such that the redistribution structure **920** is bonded to the packaging substrate **200** by

solder material portions (such as the second solder material portions **290**).

(94) Referring to step **1740** and FIGS. **14A**, **14B**, **15A-15C**, and **16**, an underfill material portion (such as the second underfill material portion **292**) may be applied around the solder material portions on segments of a top surface of the at least one cushioning film **270**.

(95) In one embodiment, the fan-out package **900** may include a molding compound die frame **910** that laterally surrounds the at least one semiconductor die (**700**, **800**) and may contact a peripheral portion of a top surface of the redistribution structure **920**; and the underfill material portion **292** may be formed directly on sidewalls of the molding compound die frame **910**. In one embodiment, the underfill material portion **292** may cover a first portion of each of the at least one cushioning film **270** and does not cover a second portion of each of the at least one cushioning film **270** that is located outside the first portion of each of the at least one cushioning film **270**. In one embodiment, the at least one cushioning film **270** may have a Young's modulus that is lower than a Young's modulus of the underfill material portion **292**. In one embodiment, the at least one cushioning film **270** may be formed by depositing a continuous cushioning material layer on the top surface of the packaging substrate **200** and patterning the continuous cushioning material layer into the at least one cushioning film **270**.

(96) Referring to all drawings and according to various embodiments of the present disclosure, a semiconductor structure is provided, which may include: a fan-out package **900** that may include at least one semiconductor die (**700**, **800**), a redistribution structure **920** that may include fan-out bonding pads **928**, and a first underfill material portion **950** located between the at least one semiconductor die (**700**, **800**) and the redistribution structure **920**; a packaging substrate **200** that may include chip-side bonding pads **268**; solder material portions (such as the second solder material portions **290**) bonded to the chip-side bonding pads **268** and the fan-out bonding pads **928**; a second underfill material portion **292** laterally surrounding the solder material portions; and at least one cushioning film **270** located on the packaging substrate **200** and contacting the second underfill material portion **292** and having a Young's modulus that is lower than a Young's modulus of the second underfill material portion.

(97) In one embodiment, the at least one cushioning film **270** has a uniform thickness. In one embodiment, the uniform thickness is less than a maximum height of the solder material portions (such as the second solder material portions **290**) along a vertical direction that is perpendicular to a horizontal plane including bonding surfaces of the chip-side bonding pads **268**. In one embodiment, the at least one cushioning film **270** may include a material selected from polyimide (PI), polybenzoxazole (PBO), benzocyclobutene (BCB), and silicone. In one embodiment, the second underfill material portion **292** may contact a first portion of a top surface of the at least one cushioning film **270**, and a second portion of the top surface of the at least one cushioning film **270** is not contacted by the second underfill material portion **292**. In one embodiment, an entirety of the at least one cushioning film **270** may be located outside a periphery of an area of the fan-out package **900** in a plan view along a vertical direction that is perpendicular to a horizontal plane including bonding surfaces of the chip-side bonding pads **268**. In one embodiment, an entirety of each bottom surface of the at least one cushioning film **270** may be in contact with a top surface of the packaging substrate **200**; and each of the at least one cushioning film **270** may include a respective first sidewall that contacts the second underfill material portion **292** and a respective second sidewall that does not contact the second underfill material portion **292** and may be physically exposed to an ambient gas. In one embodiment, a first portion of the at least one cushioning film **270** has an areal overlap with the fan-out package **900** in a plan view along a vertical direction that is perpendicular to a horizontal plane including bonding surfaces of the chip-side bonding pads **268**; and a second portion of the at least one cushioning film **270** is located outside a periphery of an area of the fan-out package **900** in the plan view. In one embodiment, the at least one cushioning film **270** may include a frame-shaped cushioning film that includes an inner periphery and an outer periphery that laterally surrounds the inner periphery and is laterally spaced

from the inner periphery; and the inner periphery laterally surrounds the solder material portions (such as the second solder material portions **290**). In one embodiment, the at least one cushioning film **270** may include a plurality of L-shaped cushioning films located outside corner regions of the fan-out package and not having an areal overlap with the fan-out package in a plan view along a vertical direction that is perpendicular to a horizontal plane including bonding surfaces of the chip-side bonding pads.

(98) Referring to all drawings and according to various embodiments of the present disclosure, a semiconductor structure is provided, which may include: a fan-out package **900** that may include at least one semiconductor die (**700,800**), a molding compound die frame **910** that laterally surrounds the at least one semiconductor die (**700, 800**), a redistribution structure **920** that may include fan-out bonding pads **928**, and a first underfill material portion **950** located on the redistribution structure **920** and contacting sidewalls of the at least one semiconductor die (**700, 800**); a packaging substrate **200** attached to the redistribution structure **920** by solder material portions (such as the second solder material portions **290**); a second underfill material portion **292** laterally surrounding the solder material portions (such as the second solder material portions **290**); and at least one cushioning film **270** located on the packaging substrate **200** and contacting a horizontal surface of the packaging substrate **200** that is proximal to the fan-out package **900**. In one embodiment, the at least one cushioning film **270** may have a Young's modulus that is lower than a Young's modulus of the second underfill material portion **292**. In one embodiment, the second underfill material portion **292** may contact sidewalls of the redistribution structure **920** and sidewalls of the molding compound die frame **910**. In one embodiment, the at least one cushioning film **270** may have a uniform thickness; and each of the at least one cushioning film **270** may include a portion that is located outside a periphery of an area of the fan-out package **900** in a plan view along a vertical direction that is perpendicular to a horizontal plane including the horizontal surface of the packaging substrate **200**.

(99) According to another aspect of the present disclosure, a semiconductor structure is provided, which comprises: a fan-out package **900** comprising at least one semiconductor die (**700, 800**), a molding compound die frame **910** that laterally surrounds the at least one semiconductor die (**700, 800**), a redistribution structure **920** comprising fan-out bonding pads **928**, and a first underfill material portion **950** located on the redistribution structure **920** and contacting sidewalls of the at least one semiconductor die (**700, 800**); a packaging substrate **200** attached to the redistribution structure **920** by solder material portions (such as the second solder material portions **290**); a second underfill material portion **292** laterally surrounding the solder material portions; and at least one cushioning film **270** located on the packaging substrate **200** and contacting a horizontal surface of the packaging substrate **200** that is proximal to the fan-out package **900**.

(100) The various structures and methods of the present disclosure may be used to provide a chip package structure including a fan-out package **900**, a packaging substrate **200**, and at least one cushioning film **270** located on the packaging substrate **200**. The at least one cushioning film **270** deforms more than the molding compound material of the molding compound die frame **910** and absorbs mechanical and/or thermal stress. The various methods and structures of the present disclosure may be used to reduce deformation of a fan-out package **900** and to increase the reliability of the fan-out package **900**.

(101) 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 structure comprising: a fan-out package comprising at least one semiconductor die, a redistribution structure comprising fan-out bonding pads, and a first underfill material portion located between the at least one semiconductor die and the redistribution structure; a packaging substrate comprising chip-side bonding pads; solder material portions bonded to the chip-side bonding pads and the fan-out bonding pads; a second underfill material portion laterally surrounding the solder material portions; and at least one cushioning film located on the packaging substrate and contacting the second underfill material portion and having a Young's modulus lower than a Young's modulus of the second underfill material portion, wherein each of the at least one cushioning film comprises a respective top surface and a respective set of sidewalls adjoined to a periphery of the respective top surface and extending vertically to a top surface of the packaging substrate, a first region of the respective top surface is located within an area of the fan-out package in a plan view along a vertical direction that is perpendicular to a horizontal plane including bonding surfaces of the chip-side bonding pads, a second region of the respective top surface is located outside of the area of the fan-out package in the plan view, all sidewall segments among the respective set of sidewalls which are located within the area of the fan-out package in the plan view are in direct contact with the second underfill material portion, and at least one sidewall segment among the respective set of sidewalls which is located outside the area of the fan-out package is not in direct contact with the second underfill material portion and is physically exposed to an ambient gas.
2. The semiconductor structure of claim 1, wherein the at least one cushioning film has a uniform thickness.
3. The semiconductor structure of claim 2, wherein the uniform thickness is less than a maximum height of the solder material portions along a vertical direction that is perpendicular to a horizontal plane including bonding surfaces of the chip-side bonding pads.
4. The semiconductor structure of claim 1, wherein the at least one cushioning film comprises a material selected from polyimide (PI), polybenzoxazole (PBO), benzocyclobutene (BCB), and silicone.
5. The semiconductor structure of claim 1, wherein: the second underfill material portion contacts the first region of the respective top surface of each of the at least one cushioning film and contacts a first segment of the second region of the respective top surface of each the at least one cushioning film; and a second segment of the second region of the respective top surface of each of the at least one cushioning film is not contacted by the second underfill material portion.
6. The semiconductor structure of claim 1, wherein: an entirety of each bottom surface of the at least one cushioning film is in contact with a top surface of the packaging substrate; and an additional sidewall segment among the respective set of sidewalls which is located outside the area of the fan-out package is in direct contact with the second underfill material portion.
7. The semiconductor structure of claim 1, wherein: a first portion of the at least one cushioning film has an areal overlap with the fan-out package in a plan view along a vertical direction that is perpendicular to a horizontal plane including bonding surfaces of the chip-side bonding pads; and a second portion of the at least one cushioning film is located outside a periphery of an area of the fan-out package in the plan view.
8. The semiconductor structure of claim 1, wherein: the at least one cushioning film comprises a frame-shaped cushioning film comprising an inner periphery and an outer periphery that laterally surrounds the inner periphery and is laterally spaced from the inner periphery; and the inner periphery laterally surrounds the solder material portions.
9. The semiconductor structure of claim 1, wherein the at least one cushioning film comprises a plurality of rectangular cushioning films located about corner regions of the fan-out package and

having a respective areal overlap with the fan-out package in the plan view.

10. A semiconductor structure comprising: a fan-out package comprising at least one semiconductor die, a molding compound die frame that laterally surrounds the at least one semiconductor die, a redistribution structure comprising fan-out bonding pads, and a first underfill material portion located on the redistribution structure and contacting sidewalls of the at least one semiconductor die; a packaging substrate attached to the redistribution structure by solder material portions; a second underfill material portion laterally surrounding the solder material portions; and at least one cushioning film located on the packaging substrate and contacting a horizontal surface of the packaging substrate that is proximal to the fan-out package, wherein each of the at least one cushioning film comprises a respective top surface and a respective set of sidewalls adjoined to a periphery of the respective top surface and extending vertically to the horizontal surface of the packaging substrate, a first region of the respective top surface is located within an area of the fan-out package in a plan view along a vertical direction that is perpendicular to a horizontal plane including bonding surfaces of the chip-side bonding pads, a second region of the respective top surface is located outside of the area of the fan-out package in the plan view, all sidewall segments among the respective set of sidewalls which are located within the area of the fan-out package in the plan view are in direct contact with the second underfill material portion, and at least one sidewall segment among the respective set of sidewalls which is located outside the area of the fan-out package is not in direct contact with the second underfill material portion and is physically exposed to an ambient gas.

11. The semiconductor structure of claim 10, wherein the at least one cushioning film has a Young's modulus that is lower than a Young's modulus of the second underfill material portion.

12. The semiconductor structure of claim 10, wherein the second underfill material portion contacts sidewalls of the redistribution structure and sidewalls of the molding compound die frame.

13. The semiconductor structure of claim 10, wherein: the at least one cushioning film has a uniform thickness; and each of at least one cushioning film comprises a portion that is located outside a periphery of an area of the fan-out package in a plan view along a vertical direction that is perpendicular to a horizontal plane including the horizontal surface of the packaging substrate.

14. A semiconductor structure comprising: a fan-out package comprising at least one semiconductor die, a redistribution structure comprising fan-out bonding pads, and a first underfill material portion located between the at least one semiconductor die and the redistribution structure; a packaging substrate comprising chip-side bonding pads; solder material portions bonded to the chip-side bonding pads and the fan-out bonding pads; a second underfill material portion laterally surrounding the solder material portions; and at least one cushioning film having a uniform thickness throughout and located on the packaging substrate and contacting the second underfill material portion, wherein an entirety of the at least one cushioning film is located outside a periphery of an entire area of the fan-out package in a plan view along a vertical direction that is perpendicular to a horizontal plane including bonding surfaces of the chip-side bonding pads, wherein each of the at least one cushioning film comprises a respective planar top surface and a respective set of sidewalls adjoined to a periphery of the respective planar top surface and extending vertically to a top surface of the packaging substrate, a first portion of the respective planar top surface is in direct contact with the second underfill material portion, a second portion of the respective planar top surface is not in direct contact with the second underfill material portion, first sidewall segments among the respective set of sidewalls are in direct contact with the second underfill material portion, and second sidewall segment among the respective set of sidewalls are not in direct contact with the second underfill material portion.

15. The semiconductor structure of claim 14, wherein the uniform thickness is less than a maximum height of the solder material portions along the vertical direction.

16. The semiconductor structure of claim 14, wherein: an entirety of each bottom surface of the at least one cushioning film is in contact with a top surface of the packaging substrate; and each of the

at least one cushioning film comprises a respective first sidewall that contacts the second underfill material portion and a respective second sidewall that does not contact the second underfill material portion and is physically exposed to an ambient gas.

17. The semiconductor structure of claim 14, wherein the at least one cushioning film comprises a plurality of L-shaped cushioning films located outside corner regions of the fan-out package and not having any areal overlap with the fan-out package in the plan view.

18. The semiconductor structure of claim 14, wherein each of the at least one cushioning film is laterally offset inward relative to sidewalls of the packaging substrate by a respective lateral offset distance.

19. The semiconductor structure of claim 14, wherein: the at least one cushioning film is a frame-shaped film having an inner periphery and an outer periphery and laterally encloses the entire area of the fan-out package in the plan view; and the inner periphery of the frame-shaped film is laterally offset outward from the periphery of the entire area of the fan-out package in the plan view.

20. The semiconductor structure of claim 14, wherein the at least one cushioning film has a Young's modulus that is lower than a Young's modulus of the second underfill material portion.
