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Yu et al.

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(54) **STACKED SEMICONDUCTOR DEVICES AND METHODS OF FORMING SAME**

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(2013.01); *H01L 2225/06596* (2013.01)

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(58) **Field of Classification Search**
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See application file for complete search history.

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Related U.S. Application Data

(60) Provisional application No. 62/011,987, filed on Jun. 13, 2014.

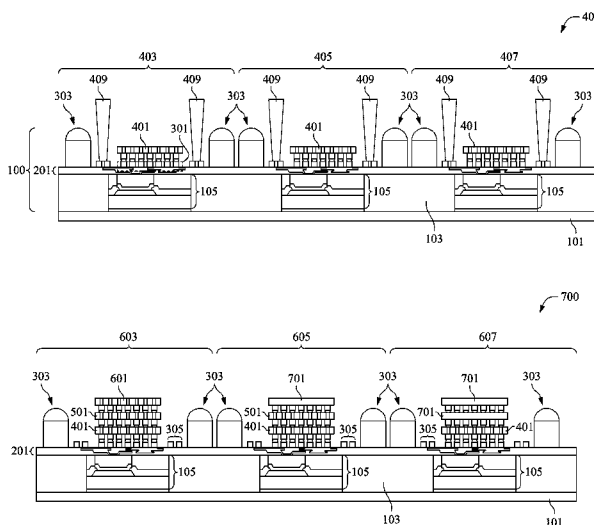
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H01L 21/66 (2006.01)
H01L 25/065 (2006.01)
H01L 25/00 (2006.01)
H01L 23/00 (2006.01)

(52) **U.S. Cl.**
CPC *H01L 22/20* (2013.01); *H01L 22/32*
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(57) **ABSTRACT**

Stacked semiconductor devices and methods of forming the same are disclosed. First tier workpieces are mounted on a top surface of a semiconductor device to form first tier stacks, the semiconductor device comprising one or more integrated circuit dies, the semiconductor device having one or more test pads per integrated circuit die on the top surface of the semiconductor device. Each of the first tier stacks is electrically tested to identify first known good stacks and first known bad stacks. Second tier workpieces are mounted atop the first known good stacks, thereby forming second tier stacks. Each of the second tier stacks is electrically tested to identify second known good stacks and second known bad stacks. Stacking process further comprises one or more workpiece mounting/testing cycles. The stacking process continues until the stacked semiconductor devices comprise desired number of workpieces.

19 Claims, 10 Drawing Sheets



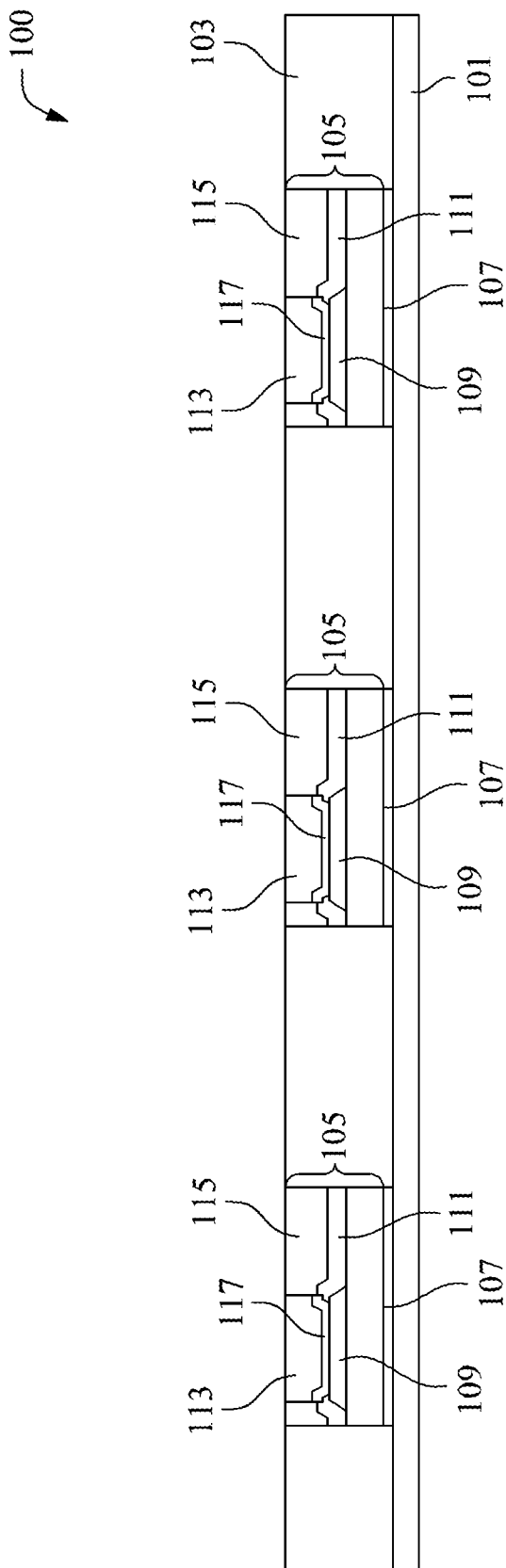


Fig. 1

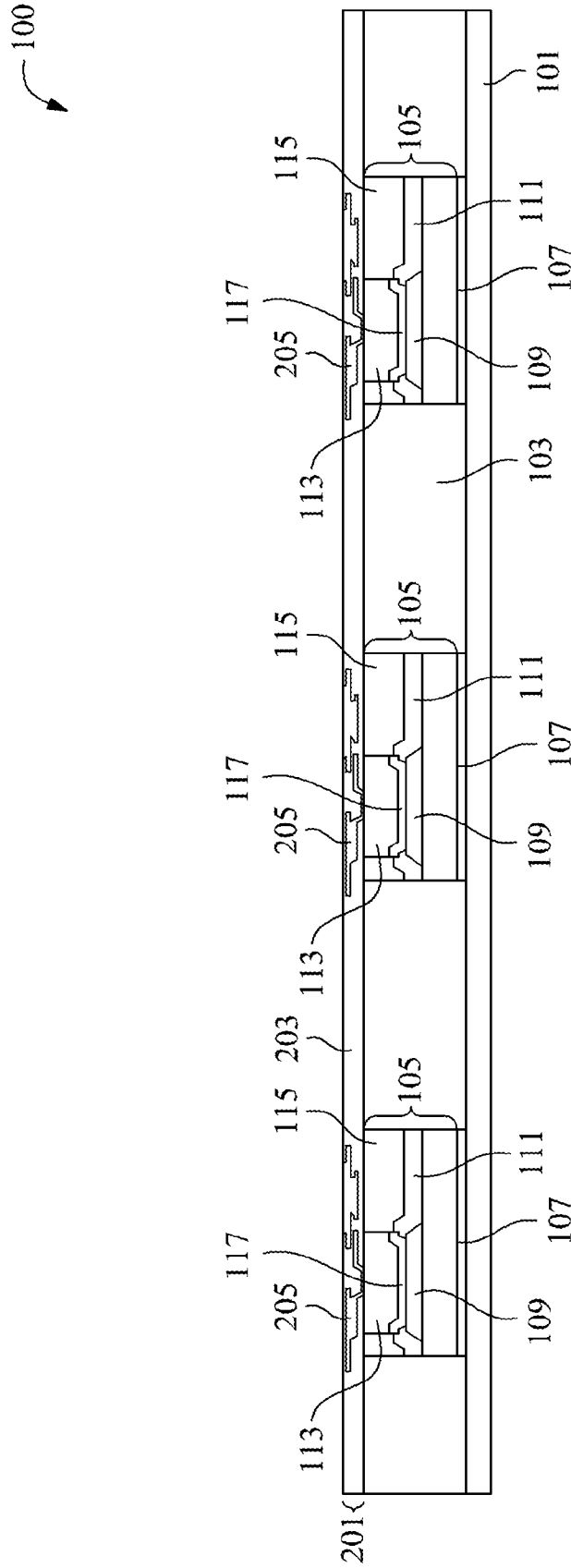


Fig. 2

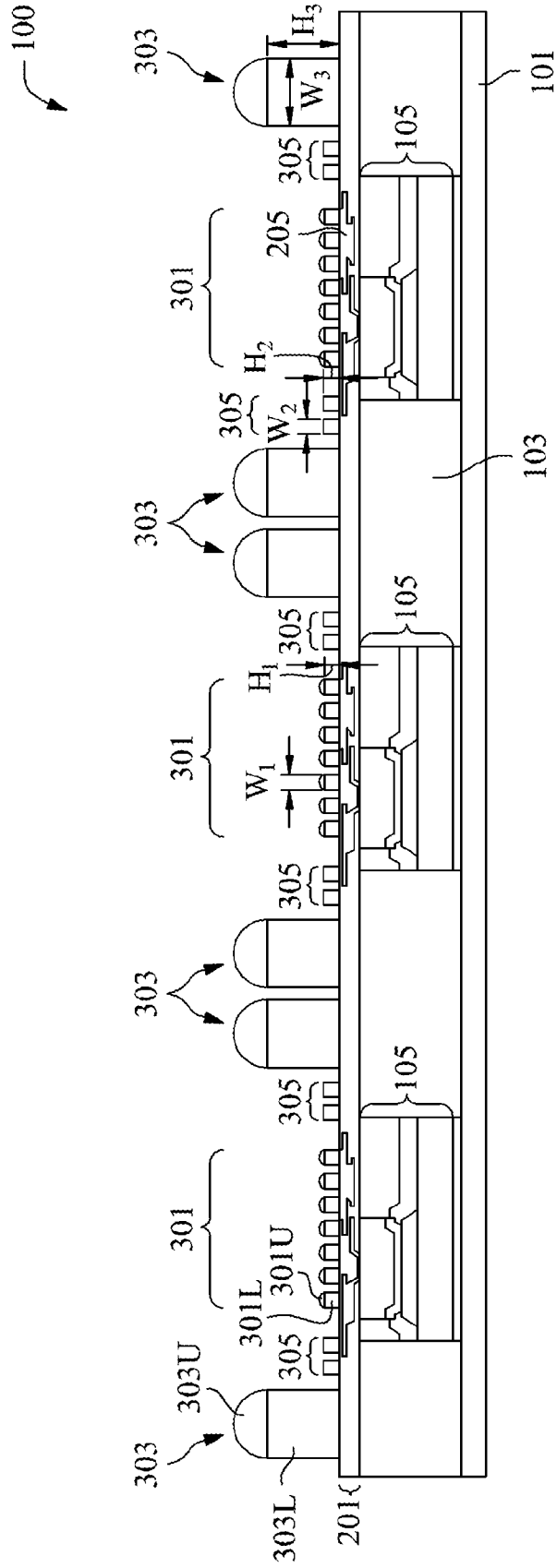


Fig. 3

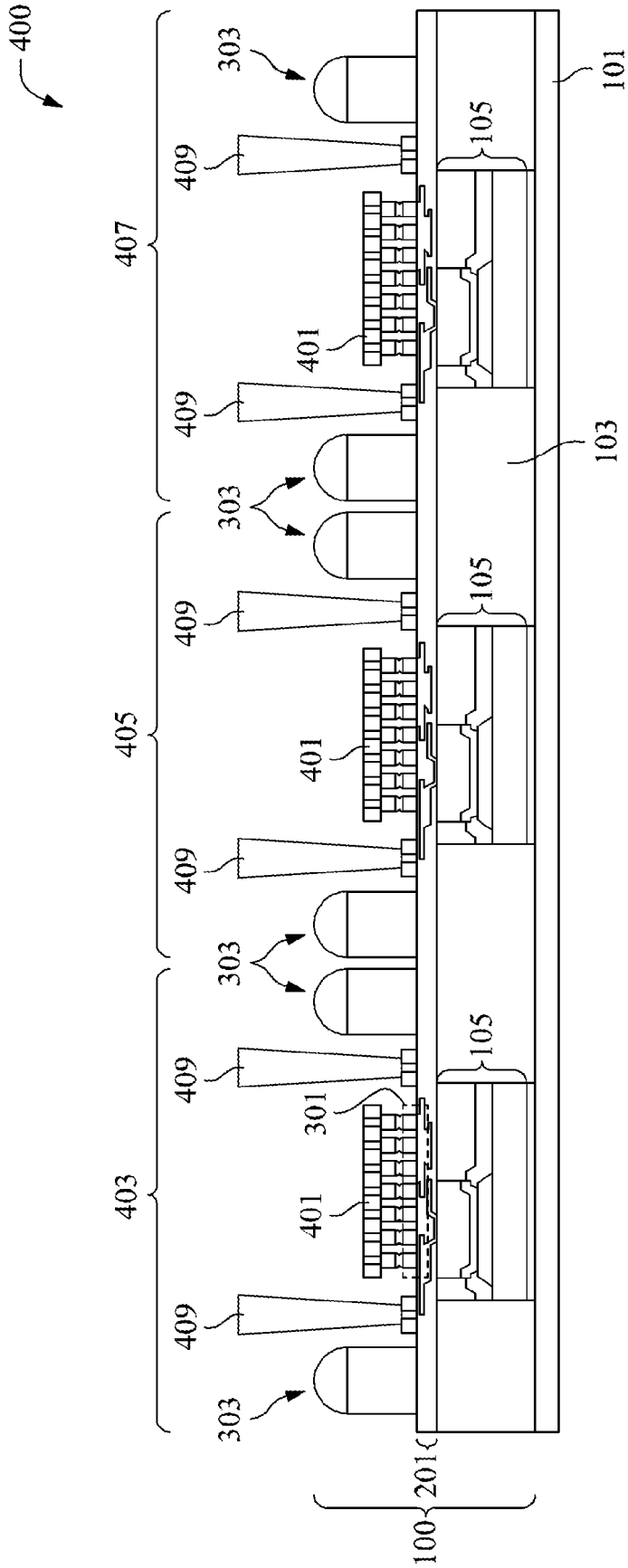


Fig. 4

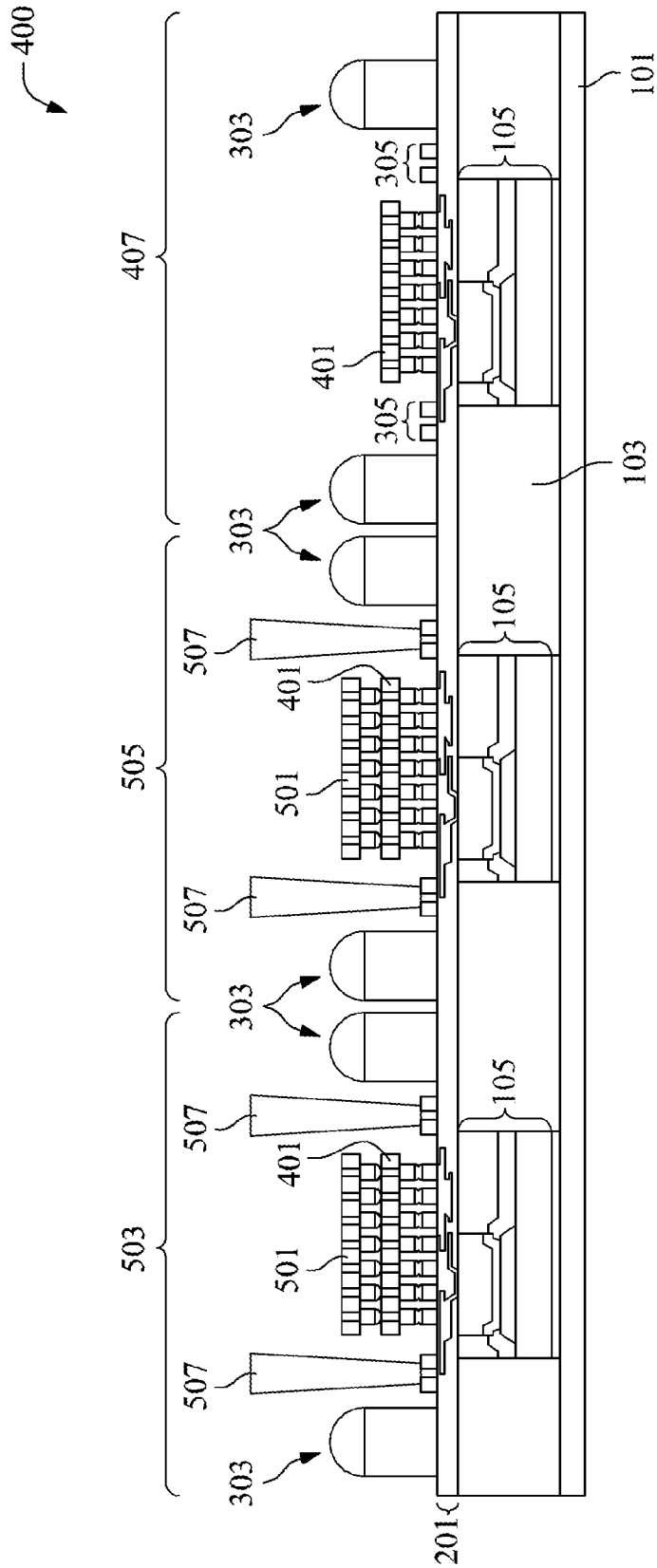


Fig. 5

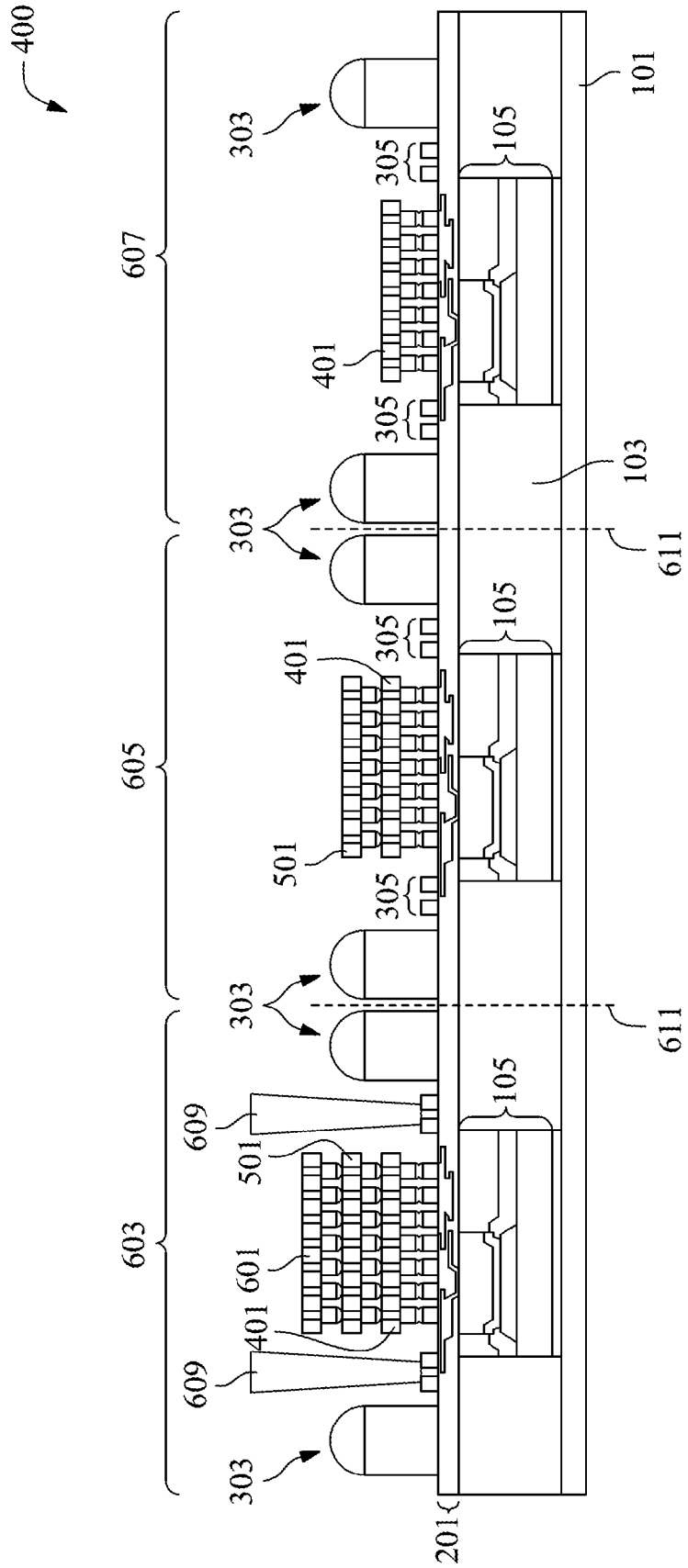


Fig. 6

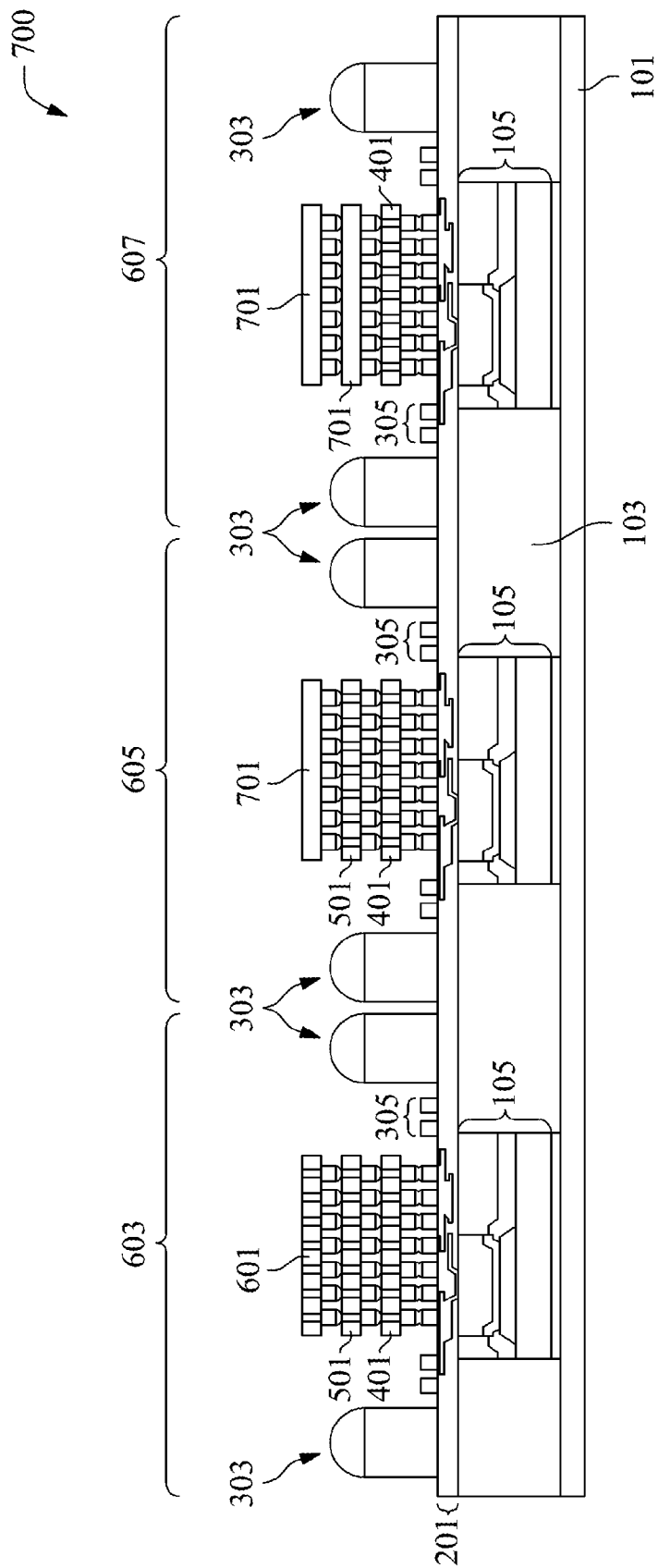


Fig. 7

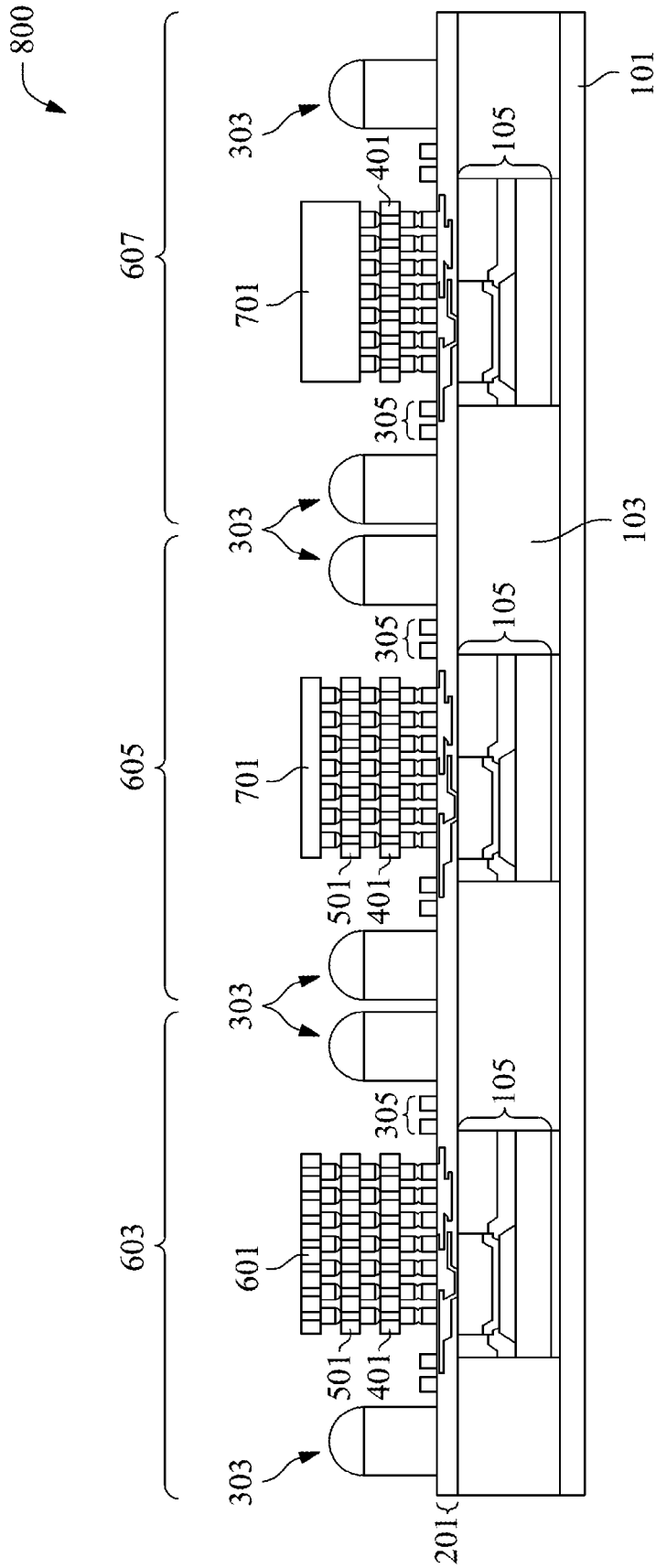


Fig. 8

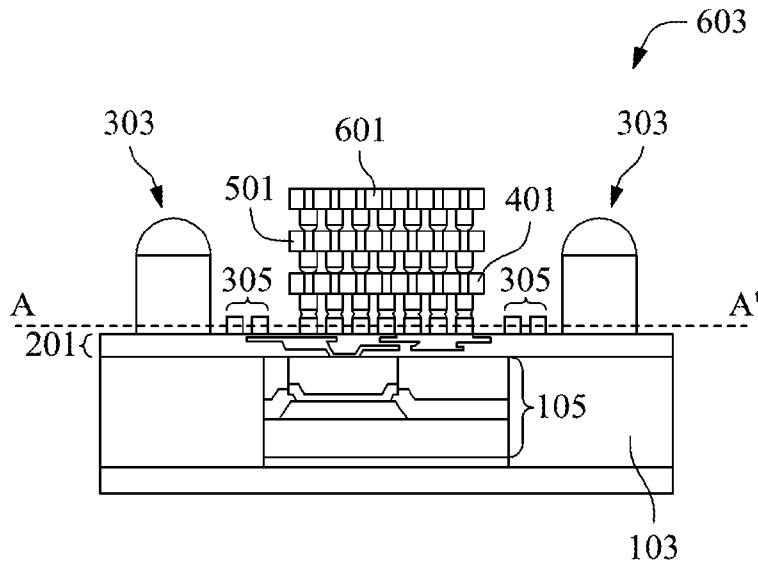


Fig. 9A

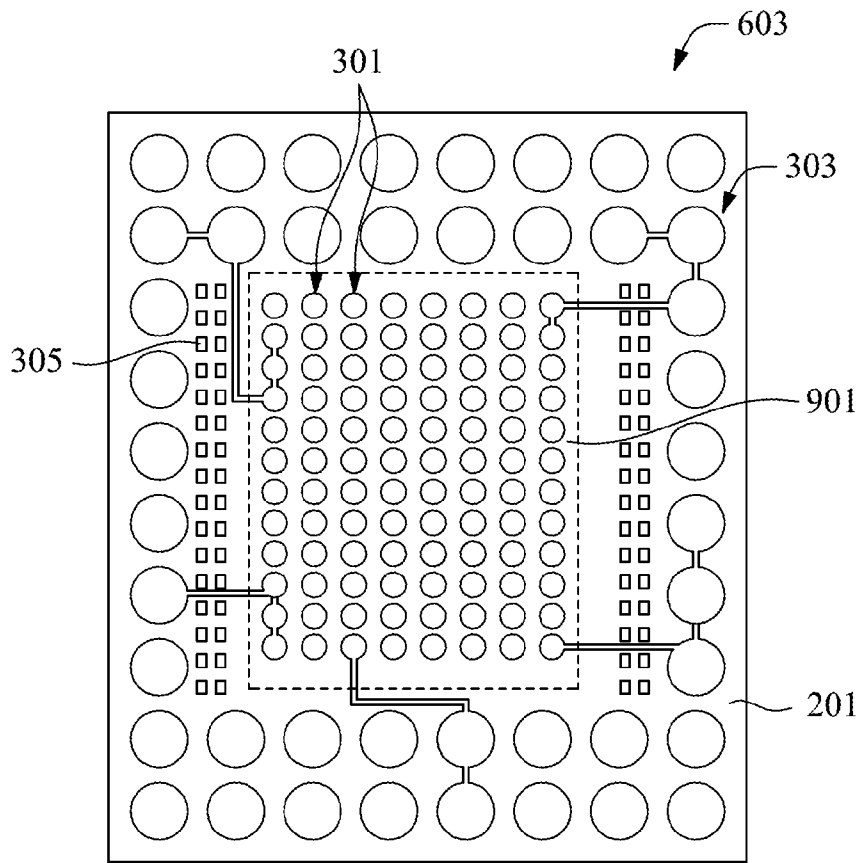


Fig. 9B

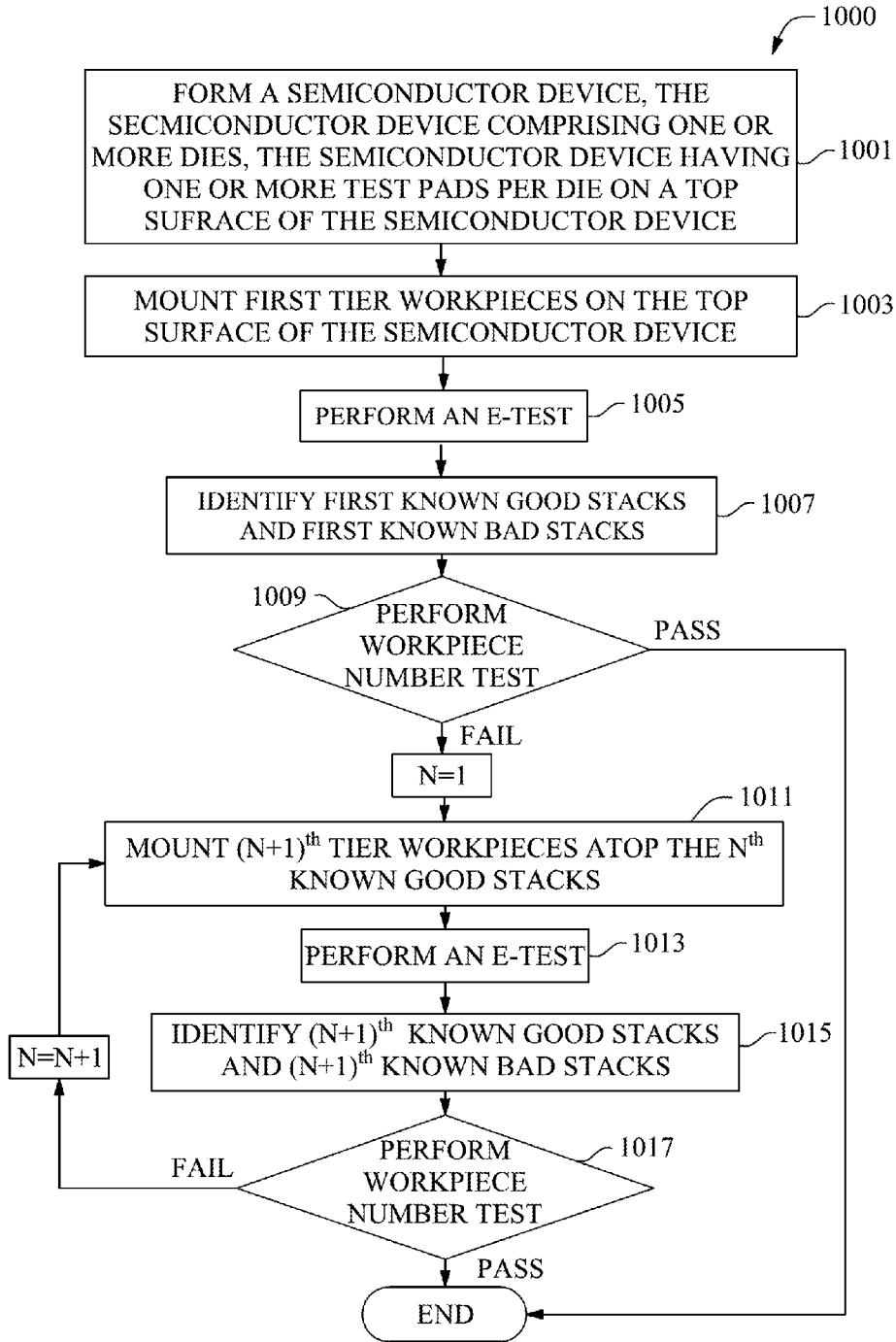


Fig. 10

STACKED SEMICONDUCTOR DEVICES AND METHODS OF FORMING SAME

PRIORITY CLAIM AND CROSS-REFERENCE

This application claims the benefit of U.S. Provisional Application Ser. No. 62/011,987, filed on Jun. 13, 2014, entitled "Testing Solution for Multiple Chip Stacking on InFO," which application is hereby incorporated herein by reference in its entirety.

BACKGROUND

The semiconductor industry has experienced rapid growth due to continuous improvements in the integration density of a variety of electronic components (e.g., transistors, diodes, resistors, capacitors, etc.). For the most part, this improvement in integration density has come from repeated reductions in minimum feature size (e.g., shrinking the semiconductor process node towards the sub-20 nm node), which allows more components to be integrated into a given area. As the demand for miniaturization, higher speed and greater bandwidth, as well as lower power consumption and latency has grown recently, there has grown a need for smaller and more creative packaging techniques of semiconductor dies.

As semiconductor technologies further advance, stacked semiconductor devices, e.g., 3D integrated circuits (3DICs), have emerged as an effective alternative to further reduce the physical size of a semiconductor device. In a stacked semiconductor device, wafers/dies are stacked on top of one another and are interconnected using through connections such as through vias (TVs). Some of the benefits of 3DICs, for example, include exhibiting a smaller footprint, reducing power consumption by reducing the lengths of signal interconnects, and improving yield and fabrication cost if individual dies are tested separately prior to assembly.

BRIEF DESCRIPTION OF THE DRAWINGS

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.

FIGS. 1-6 are cross-sectional views of various processing steps during fabrication of stacked semiconductor devices in accordance with some embodiments.

FIG. 7 is a cross-sectional view of stacked semiconductor devices in accordance with some embodiments.

FIG. 8 is a cross-sectional view of stacked semiconductor devices in accordance with some embodiments.

FIGS. 9A and 9B illustrate cross-sectional and top views, respectively, of a stacked semiconductor device in accordance with some embodiments.

FIG. 10 is a flow diagram illustrating a method of forming stacked semiconductor devices in accordance with some embodiments.

DETAILED DESCRIPTION

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.

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.

Structures of stacked semiconductor devices and methods of forming the same are provided. In particular, stacked semiconductor devices with embedded test pads are described in greater detail below. In addition, methods of forming stacked semiconductor devices that are utilizing embedded test pads are also provided below.

Before addressing illustrated embodiments specifically, advantageous features and certain aspects of the exemplary embodiments are discussed generally. General aspects of embodiments described herein include test pads designed on a front side of an integrated fan-out (InFO) device upon which workpieces are mounted to form stacked semiconductor devices, simply referred as stacked devices below. As described below in greater detail, the workpieces may be integrated circuit dies, interposers, or the like. Another general aspect is that electronic functional testing, so-called E-test, can be applied during a stacking process, such as after each stacking step for stacking multiple workpieces, an E-test can be performed. In this way, known bad stacks (KBSs) can be identified and re-worked, replaced, flagged or otherwise accounted for during the stacking process. Another general aspect of the following embodiments is that further processing/stacking of additional workpieces can be limited to only known good stacks (KGSs), thus reducing manufacturing cost and improving overall yield. In addition, dummy workpieces (such as, for example, workpieces free from active and/or passive devices) may be stacked atop KBSs to maintain uniform form factors (such as, for example, thickness) for all stacked devices.

Turning now to the illustrated embodiments, FIGS. 1-6 illustrate cross-sectional views of various processing steps during fabrication of stacked semiconductor devices in accordance with some embodiments. In particular, FIGS. 1-3 illustrate cross-sectional views of various processing steps during fabrication of a semiconductor device 100 such as an InFO device in accordance with some embodiments. FIGS. 4-6 illustrate cross-sectional views of various processing steps during fabrication a semiconductor device 400, which is formed by stacking workpieces atop the semiconductor device 100 in accordance with some embodiments.

FIG. 1 illustrates dies 105 mounted on a carrier 101 and encapsulated by an encapsulant 103. The carrier 101 may be formed of quartz, glass, or the like, and provides mechanical support for subsequent operations. In some embodiments,

the dies **105** are attached to the carrier **101** using, for example, a pick and place apparatus. In other embodiments, the dies **105** may be attached to the carrier **101** manually, or using any other suitable method. The dies **105** may be attached to the carrier **101** using one or more adhesive layers **107** formed on back sides of the dies **105**. The one or more adhesive layers **107** may comprise a die attach film, any suitable adhesive, epoxy, wax, ultraviolet (UV) glue (which loses its adhesive property when exposed to UV radiation), or the like, and may be formed using a deposition process, a spin coating, a printing process, a lamination process, or the like.

In some embodiments, the dies **105** may be logic dies, memory dies, sensor dies, analog dies, or the like. The dies **105** may be formed using a complementary metal-oxide-semiconductor (CMOS) process, a micro-electro-mechanical systems (MEMS) process, a nano-electro-mechanical systems (NEMS) process, the like, or a combination thereof. In some embodiments, the dies **105** may be formed as part of a wafer. The wafer is singulated by sawing, laser ablation, or the like, to form individual dies **105**. Subsequently, functional testing may be performed on the dies **105**. Thus, the dies **105** in FIG. **1** may include only known good dies (KGDs), which have passed one or more functional quality tests.

As shown in FIG. **1**, in some embodiments, each of the dies **105** includes a passivation layer **111**, a contact pad **109** embedded in the passivation layer **111**, a protective layer **115** over the passivation layer **111**, a conductive via **113** embedded in the protective layers **115**, and seed layer **117** interposed between the contact pad **109** and the conductive via **113** on a front side of each of the dies **105**.

The dies **105** may comprise a substrate, various active and passive devices on the substrate, and various metallization layers over the substrate, which are not explicitly illustrated in FIG. **1** as their inclusion is not necessary for understanding various embodiments described below. The substrate may be formed of silicon, although it may also be formed of other group III, group IV, and/or group V elements, such as silicon, germanium, gallium, arsenic, and combinations thereof. The substrate may also be in the form of silicon-on-insulator (SOI). The SOI substrate may comprise a layer of a semiconductor material (e.g., silicon, germanium and/or the like) formed over an insulator layer (e.g., buried oxide and/or the like), which is formed on a silicon substrate. In addition, other substrates that may be used include multi-layered substrates, gradient substrates, hybrid orientation substrates, any combinations thereof and/or the like.

In some embodiments, the variety of active and passive devices may include various n-type metal-oxide semiconductor (NMOS) and/or p-type metal-oxide semiconductor (PMOS) devices such as transistors, capacitors, resistors, diodes, photo-diodes, fuses and/or the like.

The metallization layers may include an inter-layer dielectric (ILD)/inter-metal dielectric layers (IMDs) formed over the substrate. The ILD/IMDs may be formed, for example, of a low-K dielectric material, such as phosphosilicate glass (PSG), borophosphosilicate glass (BPSG), FSG, SiO_xC_y , Spin-On-Glass, Spin-On-Polymers, silicon carbon material, compounds thereof, composites thereof, combinations thereof, or the like, by any suitable method known in the art, such as spinning, chemical vapor deposition (CVD), and plasma enhanced CVD (PECVD).

In some embodiments, interconnect structures may be formed in the ILD/IMDs using, for example, a damascene process, a dual damascene process, or the like. The ILD/IMDs may be patterned using photolithography techniques

to form trenches and vias. The interconnect structures are formed by depositing a suitable conductive material in the trenches and the vias of the ILD/IMDs using various deposition and plating methods, or the like. In addition, the interconnect structures may include one or more barrier/adhesion layers (not shown) to protect the ILD/IMDs from diffusion and metallic poisoning. The one or more barrier/adhesion layers may comprise titanium, titanium nitride, tantalum, tantalum nitride, or other alternatives. The barrier layer may be formed using physical vapor deposition (PVD), atomic layer deposition (ALD), sputtering, or the like. The conductive material of the interconnect structures may comprise copper, a copper alloy, silver, gold, tungsten, tantalum, aluminum, and the like. In an embodiment, the steps for forming the interconnect structures may include blanket forming the one or more barrier/adhesion layers, depositing a thin seed layer of a conductive material, and filling the trenches and the vias in the ILD/IMDs with the conductive material, for example, by plating. A chemical-mechanical polishing (CMP) is then performed to remove excess portions of the interconnect structures. In some embodiments, the interconnect structures may provide electrical connections between the various passive and active devices formed on the substrate.

Referring further to FIG. **1**, the contact pad **109** is formed over the metallization layers and may be electrically coupled to the active devices through various interconnect structures of the metallization layers. In the illustrated embodiment, the contact pad **109** comprises aluminum, although other conductive materials such as copper, tungsten, silver, gold, the like, or a combination thereof may also be used. In the illustrated embodiment, the conductive material of the contact pad **109**, such as aluminum, is deposited over the metallization layers and patterned to form the contact pad **109** as illustrated in FIG. **1**. The contact pad **109** may be patterned using photolithography techniques. Generally, photolithography techniques involve depositing a photoresist material, which is subsequently irradiated (exposed) and developed to remove a portion of the photoresist material. The remaining photoresist material protects the underlying material, such as the conductive material of the contact pad **109**, from subsequent processing steps, such as etching. A suitable etching process, such as a reactive ion etch (RIE) or other dry etch, an isotropic or anisotropic wet etch, or any other suitable etch or patterning process may be applied to the conductive material of the contact pad **109** to remove the exposed portion of the conductive material and form the contact pad **109**. For example, exposed portions of the conductive material such as aluminum may be etched using a mixture of 80% phosphoric acid, 5% nitric acid, 5% acetic acid, and 10% de-ionized (DI) water. In other embodiments, the contact pad **109** comprising copper may be formed using, for example, a damascene process.

In some embodiments, the passivation layer **111** is formed over the metallization layers and the contact pad **109**. In some embodiments, the passivation layer **111** may comprise dielectric materials such as polyimide, benzocyclobutene (BCB), polybenzoxazole (PBO), silicon nitride, silicon carbide, silicon oxide, silicon oxynitride, low-k dielectrics such as carbon doped oxides, extremely low-k dielectrics such as porous carbon doped silicon dioxide, the like, or a combination thereof. The passivation layer **111** may be deposited by chemical vapor deposition (CVD), physical vapor deposition (PVD), atomic layer deposition (ALD), a spin-on-dielectric process, the like, or a combination thereof.

Referring further to FIG. **1**, an opening is formed in the passivation layer **111** to expose the contact pad **109**. In some

embodiments, a photoresist material (not shown) is formed over the passivation layer **111**. The photoresist material is subsequently irradiated (exposed) and developed to remove a portion of the photoresist material. Subsequently, exposed portions of the passivation layer **111** are removed using, for example, a suitable etching process to form the openings. In an embodiment with the passivation layer **111** formed of silicon oxide, the passivation layer **111** is etched using, for example, buffered hydrofluoric acid (HF). In another embodiment with the passivation layer **111** formed of silicon nitride, the passivation layer **111** is etched using, for example, hot phosphoric acid (H₃PO₄).

The seed layer **117** and the conductive via **113** are formed on the exposed contact pad **109** as illustrated in FIG. 1. In some embodiments, the seed layer **117** may comprise a conductive material such as titanium, titanium nitride, tantalum, tantalum nitride, or other alternative, and may be formed using ALD, PVD, the like, or a combination thereof. The seed layer is formed on the passivation layer **111** and the contact pad **109** and a patterned mask having an opening (not shown) exposing a portion of the seed layer **117** on the contact pad **109** is formed on the seed layer **117**. The opening is filled with a conductive material to form the conductive via **113**. The conductive material may comprise copper, tungsten, aluminum, silver, gold, the like, or a combination thereof, and may be formed using an electrochemical plating process, an electroless plating process, ALD, PVD, the like, or a combination thereof.

After the conductive via **113** is formed, the patterned mask and portions of the seed layer **117** not interposed between the contact pad **109** and the conductive via **113** are removed. In some embodiments, the patterned mask formed of a photoresist material is removed using, for example, an ashing process followed by a wet clean process. The portions of the seed layer **117** may be removed using, for example, a suitable etch process and portions of the passivation layer **111** are exposed. The protective layer **115** is subsequently formed over the passivation layer **111** and conductive via **113**. The protective layer **115** may comprise a dielectric material such as polyimide, benzocyclobutene (BCB), polybenzoxazole (PBO), the like, or a combination thereof, and may be formed using a spin-on coating process, or the like.

Referring further to FIG. 1, the encapsulant **103** is formed over the carrier **101** and between neighboring dies **105**. In some embodiments, the encapsulant **103** may comprise a molding compound such as an epoxy, a resin, a moldable polymer, or the like. The molding compound may be applied while substantially liquid, and then may be cured through a chemical reaction, such as in an epoxy or resin. In other embodiments, the molding compound may be an ultraviolet (UV) or thermally cured polymer applied as a gel or malleable solid capable of being disposed around and between the dies **105**.

In some embodiments, portions of the protective layers **115** and the encapsulant **103** extending over top surfaces of the conductive vias **113** may be removed to expose the conductive vias **113**. The portions of the protective layers **115** and the encapsulant **103** may be removed using a CMP, a grinding process, an etch process, or another suitable thinning process. In some embodiment, the above process is performed until the top surfaces of the conductive vias **113** are substantially coplanar with top surfaces of the protective layers **115** and a top surface of the encapsulant **103** as illustrated in FIG. 1.

As shown in FIG. 1, each of the dies **105** comprises a single passivation layer (such as the passivation layer **111**),

a single contact pad (such as the contact pad **109**), a single conductive via (such as the conductive via **113**), and a single protective layer (such as the protective layer **115**). One skilled in the art will recognize that numbers of passivation layers, contact pads, conductive vias, and the protective layers are provided for illustrative purpose only and are not limiting the scope of the present disclosure. In other embodiments, each of the dies **105** may comprise appropriate number of passivation layers, contact pads, conductive vias, and the protective layers depending on design requirements for the dies **105**.

Referring to FIG. 2, one or more redistribution layers (RDLs) **201** are formed over the dies **105** and the encapsulant **103**. In some embodiments, the RDLs **201** comprise one or more dielectric layers **203** and one or more conductive features **205** disposed within the one or more dielectric layers **203**. In the illustrated embodiment, the one or more dielectric layers **203** are formed using materials and methods similar those of the protective layer **115** and the description is not repeated herein. In some embodiments, each of the one or more dielectric layers **203** may be patterned to expose underlying conductive features. For example, a bottommost dielectric layer of the one or more dielectric layers **203** is patterned to expose the underlying conductive vias **113**. In some embodiment, the one or more dielectric layers **203** comprising photo-patternable materials may be patterned using an acceptable photolithography technique. For example, the bottommost dielectric layer of the one or more dielectric layers **203** is exposed to light and subsequently developed and/or cured.

Referring further to FIG. 2, a first conductive feature (not individually shown) of the one or more conductive features **205** is formed over the bottommost dielectric layer of the one or more dielectric layers **203**. The first conductive feature may comprise various lines/traces (running “horizontally” across a top surface of the bottommost dielectric layer) and/or vias (extending “vertically” through the bottommost dielectric layer, and contacting the underlying conductive vias **113**). In some embodiments, a seed layer (not shown) is deposited over the bottommost dielectric layer. The seed layer may comprise copper, titanium, nickel, gold, manganese, the like, or a combination thereof, and may be formed by ALD, PVD, sputtering, the like, or a combination thereof. Subsequently, a photoresist material (not shown) is deposited over the seed layer and patterned to define the desired pattern for the first conductive feature. A conductive material, such as copper, tungsten, aluminum, silver, gold, the like, or a combination thereof, and is formed on the seed layer by an electro-chemical plating process, an electroless plating process, ALD, PVD, the like, or a combination thereof. The photoresist material is removed using appropriate photoresist stripping process, such as ashing followed by a wet clean process. Exposed portions of the seed layer over the bottommost dielectric layer are removed using, for example, a wet or dry etch. Referring further to FIG. 2, the process described above is applied to other dielectric layers of the one or more dielectric layers **203** until formation of the RDLs **201** is completed.

Referring to FIG. 3, first connectors **301**, second connectors **303**, and test pads **305** are formed on a top surface of the RDLs **201**. The first connectors **301** and the second connectors **303** provide electrical connections between external devices and the active and passive devices of the dies **105** (via the RDLs **201**, the conductive vias **113**, the contact pads **109**, and the metallization layers of the dies **105**). In some embodiments, the first connectors **301** may have first upper portions **301U** and first lower portions **301L**, and the second

connectors **303** may have second upper portions **303U** and second lower portions **303L**. In some embodiments, the first lower portions **301L**, the second lower portions **303L**, and the test pads **305** may comprise conductive materials such as copper, tungsten, aluminum, silver, gold, the like, or a combination thereof, and may be formed using, an electrochemical plating process, an electroless plating process, ALD, PVD, the like, or a combination thereof. The first upper portions **301U** and the second upper portions **303U** may comprise solder materials such as lead-based solders such as PbSn compositions, lead-free solders including InSb, tin, silver, and copper ("SAC") compositions, and other eutectic materials that have a common melting point and form conductive solder connections in electrical applications. For lead-free solder, SAC solders of varying compositions may be used, such as SAC **105** (Sn 98.5%, Ag 1.0%, Cu 0.5%), SAC **305**, and SAC **405**, as examples. Lead-free solders also include SnCu compounds, without the use of silver (Ag), and SnAg compounds, without the use of copper (Cu).

In some embodiments, the first connectors **301** and the test pads **305** may be formed at the same time using a same formation method. In the illustrated embodiment, a topmost dielectric layer of the RDLs **201** is patterned to expose first portions and the second portions of the one or more conductive features **205**. A first patterned mask (not shown) is formed over the topmost dielectric layer of the RDLs **201**. In some embodiments, the first patterned mask comprises a photoresist material, or any photo-patternable material. A material of the first patterned mask is deposited, irradiated (exposed) and developed to remove portions of the material and form openings. The first patterned mask masks the second portions of the one or more conductive features **205** while exposes the first portions of the one or more conductive features **205** through the openings in the first patterned mask.

The openings in the first patterned mask are subsequently filled by a conductive material, thereby forming the first lower portion **301L** of the first connectors **301** and the test pads **305**. In some embodiments, the openings containing the first lower portions **301L** of the first connectors **301** are further filled by solder material to form the first upper portion **301U** of the first connectors **301** and complete formation of the first connectors **301**. After the first connectors **301** and the test pads **305** are formed, the first patterned mask is removed. In an embodiment with the first patterned mask comprising a photoresist material, the first patterned mask may be removed using, for example, ashing followed by a wet clean process. In the illustrated embodiment, the test pads **305** and the first lower portions **301L** of the first connectors **301** have the same height.

In other embodiments, the first connectors **301** and the test pads **305** may be formed sequentially using methods similar to that described in the previous paragraph. In such an embodiment, the test pads **305** and the first lower portions **301L** of the first connectors **301** may have different heights. In some embodiments, the first lower portions **301L** of the first connectors **301** have a first height H_1 between about 3 μm and about 50 μm , and a first width W_1 between about 10 μm and about 50 μm . In some embodiments, the test pads **305** have a second height H_2 between about 3 μm and about 50 μm , and a second width W_2 between about 30 μm and about 80 μm .

After the first connectors **301** and the test pads **305** are formed, a second patterned mask (not shown) is formed over the topmost dielectric layer of the RDLs **201**. In some embodiments, the second patterned mask comprises a photoresist material, or any photo-patternable material. A material of the second patterned mask is deposited, irradiated (exposed) and developed to remove portions of the material and form openings. The second patterned mask masks the first connectors **301** and the test pads **305** while exposes the second portions of the one or more conductive features **205** through the openings in the second patterned mask.

The openings are subsequently filled with a conductive material, thereby forming the second lower portions **303L** of the second connectors **303**. In some embodiments, the openings are further filled by solder material to form the second upper portions **303U** of the second connectors **303** and complete formation of the second connectors **303**. After the second connectors **303** are formed, the second patterned mask is removed. In an embodiment with the second patterned mask comprising a photoresist material, the second patterned mask may be removed using, for example, ashing followed by a wet clean process. In some embodiments, the second lower portions **303L** of the second connectors **303** have a third height H_3 between about 5 μm and about 600 μm , and a third width W_3 between about 40 μm and about 600 μm .

In some embodiments, the formation of the first connectors **301** and the second connectors **303** may include the formation of under bump metallurgies (UBMs) (not shown) interposed between the first connectors **301** and the first portions of the one or more conductive features **205**, and between the second connectors **303** and the second portions of the one or more conductive features **205**. In some embodiment, the UBMs may comprise one or more layers of a suitable conductive material.

Furthermore, the first connectors **301** and the second connectors **303** may have different sizes as illustrated in FIG. 3. In some embodiments, the first connectors **301** may be micro-bumps, while the second connectors may be controlled collapse chip connection (C4) bumps. Different sizes of the first connectors **301** and the second connectors **303** allow different devices to be bonded to the dies **105**. For example, the first connectors **301** may be used to electrically connect the dies **105** to other dies, and the second connectors **303** may be used to electrically connect the dies **105** to a package substrate, a printed circuit board, an interposer, another die, wafer, or the like. In addition, in some embodiments, the first connectors **301**, the second connectors **303**, and the test pads **305** are electrically coupled via the RDLs **201**.

Referring to FIGS. 4-6, as described below in greater detail, a semiconductor device **400** is formed by stacking multiple tiers of workpieces on the semiconductor device **100**. After each tier of workpieces is mounted on the semiconductor device **100**, an E-test is performed to identify KGSs and KBSs. In some embodiments, subsequent stacking is performed atop only the KGSs and, therefore, after completing all stacking steps, number of the workpieces in each of the stacked devices as well as thicknesses of the stacked devices may vary. In what follows, in the illustrated embodiments, three tiers of workpieces are attached to the semiconductor device **100**. In other embodiments, number of the tiers may vary according to design specifications for the stacked devices.

Turning first to FIG. 4, first tier workpieces **401** are mounted on the semiconductor device **100** atop the dies **105** using the first connectors **301** to form first tier stacks **403**, **405** and **407**. In some embodiments, the first tier workpieces **401** and other subsequently stacked workpieces comprise one or more system-on-chips (SoCs), memory chips,

memory cubes, processor chips, logic chips, analog chips, the like, or combinations thereof.

Referring further to FIG. 4, after the first tier workpieces 401 are mounted on the semiconductor device 100 as described above, electrical and/or functional testing (E-test) 5 is performed to ensure proper functioning of the first tier stacks 403, 405 and 407. In some embodiments, a first E-test 409 is performed resulting in, for example, a “pass” indication for the first tier stacks 403 and 405, and a “fail” indication for the first tier stack 407. Based on the results of the first E-test 409, the first tier stacks 403 and 405 are identified as KGSs, while the first tier stack 407 is identified as a KBS. In some embodiments, E-tests (such as the first E-test 409) may comprise an open/short test, a circuit probe test, a KGS test, a leakage test, the like, or a combination thereof. 15

Referring to FIG. 5, subsequently second tier workpieces 501 are mounted atop some of the first tier stacks to form second tier stacks 503 and 505. Because the first tier stack 407 is identified as a KBS, no subsequent stacking processes are performed on the first tier stack 407. By identifying the first tier stack 407 as a KBS at an intermediate stage, manufacturing costs can be substantially reduced by not mounting additional workpieces atop the first tier stack 407. In addition, no subsequent E-tests are performed on the first tier stack 407. In the illustrated embodiment, the second tier workpieces 501 are mounted atop the first tier stacks 403 and 405 (identified as KGSs). The second tier workpieces 501 may be mounted atop the first tier stacks 403 and 405 using connectors such as, for example, micro-bumps, copper pillars, and the like, which provide electrical connections between the second tier workpieces 501 and the first tier stacks 403 and 405. 20

Referring further to FIG. 5, after the second tier workpieces 501 are mounted atop the first tier stacks 403 and 405, a second E-test 507 is performed to test the second tier stacks 503 and 505. The second E-test 507 is performed to ensure proper functioning of intermediate stacks, such as the second tier stacks 503 and 505, as a whole. In the illustrated embodiment, only two stacked devices (e.g., the second tier stacks 503 and 505) need to be tested, since the first tier stack 407 has already been flagged as a KBS. For example, the second E-test 507 results in a “fail” indication for the second tier stack 505, and a “pass” indication for the second tier stack 503. Accordingly, the second tier stack 505 is identified as a KBS, and the second tier stack 503 is identified as a KGS, because the second tier stack 503 passed both rounds of E-testing, such as the first E-test 409 and the second E-test 507. 40

Referring to FIG. 6, third tier workpieces 601 are mounted atop some of the second tier stacks formed during the previous step. The third tier workpieces 601 are mounted atop only KGSs such as the second tier stack 503, which completes formation of stacked devices such as stacked devices 603, 605 and 607 as shown in FIG. 6. In the illustrated embodiment, the stacked device 603 is a complete stack comprising three workpieces, while the stacked devices 605 and 607 are incomplete stacks comprising two workpieces and a single workpiece, respectively. Moreover, the stacked devices 605 and 607 are identical to the second tier stack 505 and the first tier stack 407, respectively, since no additional workpiece are mounted atop the second tier stack 505 and the first tier stack 407 as described above with reference to FIGS. 4-6. Subsequently, a final E-test 609 is performed on the stacked device 603 to ensure proper functioning of the stacked device 603. In the illustrated embodiment, the final E-test 609 results in a “pass” indica- 50

tion for the stacked devices 603. Accordingly, the stacked device 603 is identified as a KGS. In other embodiments, the final E-test 609 performed on some of the stacked devices (similar to the stacked device 603) may result in a “fail” indication and those stacked devices are identified as KBSs. 5

After all the stacking steps are completed, the semiconductor device 400 is debonded from the carrier 101 and singulated to form individual stacked devices (such as the stacked devices 603, 605 and 607), for example, by sawing the semiconductor device 400 along the scribe lines 611. In some embodiments, the stacked devices 605 and 607 with incomplete stacks may be functional devices albeit not meeting design requirements for the stacked devices with complete stacks such as the stacked device 603. The stacked devices 605 and 607 could be re-worked if commercially viable, or could be singulated and sold as non-fully-stacked devices. Subsequently, the singulated stacked devices may be packaged to form integrated circuit packages. 10

As described in greater detail above, in the illustrated embodiments, stacked devices (such as the stacked devices 603, 605 and 607) comprise at most three workpieces. However, in other embodiments, the stacked devices may comprise any number of workpieces according to design specifications for the stacked devices. Furthermore, numerous variations of the above discussed embodiments will be apparent to those skilled in the art once informed by the present disclosure. 15

FIG. 6 illustrates an embodiment, wherein the stacked devices (such as the stacked devices 603, 605 and 607) have varying thicknesses. In other embodiments, all the stacked devices may have the same thicknesses. For example, FIG. 7 illustrates a cross-sectional view of a semiconductor device 700 formed using a method similar to that described above with reference to FIGS. 1-6. In the illustrated embodiment, the semiconductor device 700 has a uniform thickness. Referring to FIG. 7, dummy workpieces 701 are mounted atop KBSs (such as the first tier stack 407 and the second tier stack 505 illustrated in FIG. 5) such that all stacked devices (such as the stacked devices 603, 605 and 607) have the same number of workpieces (including functional as well as dummy workpieces). In the illustrated embodiment, all workpieces (functional as well as dummy workpieces) have the same height and, therefore, the stacked devices 603, 605 and 607 have the same thicknesses as illustrated in FIG. 7. In some embodiments, the dummy workpieces 701 are dies and/or interposers that are free of active and/or passive devices and do not provide additional functionalities to the stacked devices. In other embodiments, the dummy workpieces 701 may be known bad dies (KBDs). 20

Referring further to FIG. 7, in some embodiments, the dummy workpieces 701 are mounted atop the KBSs (such as the first tier stack 407 and the second tier stack 505 illustrated in FIG. 5) after all functional workpieces are mounted atop the semiconductor device 700. In other embodiments, the dummy workpieces 701 are mounted atop the KBSs while mounting the functional workpieces atop the semiconductor device 700. Subsequently, the stacked devices 603, 605, and 607 may be singulated for packaging in integrated circuit packages. 25

FIG. 8 illustrates a cross-sectional view of a semiconductor device 800 (similar to the semiconductor device 700) having a uniform thickness in accordance with some embodiments. In the illustrated embodiment, the dummy workpieces 701 have various thicknesses. Therefore an appropriate number of the dummy workpieces 701 are mounted atop KBSs (such as the first tier stack 407 and the second tier stack 505 illustrated in FIG. 5) such that thick- 30

nesses of all the stacked devices (such as the stacked devices **603**, **605** and **607**) are the same. In the illustrated embodiments, the stacked devices **603**, **605**, **607** have different number of workpieces (functional as well as dummy workpieces) but have the same thicknesses.

Referring further to FIG. **8**, in some embodiments, the dummy workpieces **701** are mounted atop the KBSs (such as the first tier stack **407** and the second tier stack **505** illustrated in FIG. **5**) after all functional workpieces are mounted atop the semiconductor device **800**. In other embodiments, the dummy workpieces **701** are mounted atop the KBSs while mounting the functional workpieces atop the semiconductor device **800**. Subsequently, the stacked devices **603**, **605**, and **607** may be singulated for packaging in integrated circuit packages.

FIGS. **9A** and **9B** illustrate cross-sectional and top views (along a line AA' in FIG. **9A**), respectively, of the stacked device **603** (see FIG. **6**) formed according to the method described above with reference to FIGS. **1-6**. Referring to FIG. **9A**, in the illustrated embodiment, a height of stacked workpieces (such as a stack of the first tier workpiece **401**, the second tier workpiece **501** and the third tier workpiece **601**) is larger than a height of the second connectors **303**. In other embodiments, the height of the stacked workpiece may equal to or may be less than the height of the second connectors **303** depending on design specifications of the stacked device **603**. Referring to FIG. **9B**, a chip area **901** (indicated by the dashed line) represents projection of the stacked workpieces on a top surface of the RDLs **201**. In the illustrated embodiment, the test pads **305** have rectangular shapes as illustrated in FIG. **9B**. One skilled in the art will recognize that the particular shape of the test pads **305** is provided for illustrative purpose only and is not limiting the scope of the present disclosure. In other embodiments, the test pads **305** may have variety of shapes such as circular, square, oval, polygonal, or the like.

Referring further to FIGS. **9A** and **9B**, in the illustrated embodiment, the test pads **305** are formed outside the chip area **901**, between the first connectors **301** and the second connectors **303**. In some embodiments, the test pads **305** may be formed near the scribe lines **611** (see FIG. **6**), and thus may be located near edges of the stacked device **603**. In other embodiments, the test pads **305** may be formed in any available area outside of the chip area **901**. One skilled in the art will recognize that number of the test pads **305** illustrated in FIG. **9B** is provided for illustrative purpose only and is not limiting the scope of the present disclosure. In other embodiments, the number of the test pads **305** may vary according to design requirements for the stacked device **603**.

FIG. **10** is a flowchart illustrating a method for forming stacked devices in accordance with some embodiments. The method starts with step **1001**, wherein a semiconductor device (such as the semiconductor device **100** illustrated in FIG. **3**) is formed as described above with reference to FIGS. **1-3**. The semiconductor device may comprise one or more integrated circuit dies (such the dies **105**) and having one or more test pads (such as the test pads **305**) per integrated circuit die on a top surface of the semiconductor device as described above with reference to FIG. **3**. The method continues to step **1003**, wherein first tier workpieces are mounted on the top surface of the semiconductor device and atop the integrated circuit dies to form first tier stacks (such as the first tier stacks **403**, **405** and **407**) as described above with reference to FIG. **4**. In step **1005**, an E-test is performed on each of the first tier stacks. Depending on results of the E-test, in step **1007**, known bad stacks (such as the first tier stack **407**) are identified, which comprise first tier stacks that

failed the E-test as described above with reference to FIG. **4**. In addition, known good stacks (such as the first tier stacks **403** and **405**) are identified, which comprise first tier stacks that passed the E-test as described above with reference to FIG. **4**. Subsequently, in step **1009**, a workpiece number test is performed on each of the known good stacks. If a number of workpieces in each of the known good stacks is equal to the desired number (e.g., one set by design specifications) the method ends at this step.

Otherwise, the method continues to step **1011**, wherein second tier workpieces are mounted on the known good stacks to form second tier stacks (such as the second tier stacks **503** and **505**) as described above with reference to FIG. **5**. In step **1013**, an E-test is performed on each of the second tier stacks as discussed above with reference to FIG. **5**. Depending on results of the E-test, in step **1015**, known bad stacks (such as the second tier stack **505**) are identified, which comprise second tier stacks that failed the E-test as discussed above with reference to FIG. **5**. In addition, known good stacks (such as the second tier stack **503**) are identified, which comprise second tier stacks that passed the E-test as discussed above with reference to FIG. **5**. Subsequently, in step **1017**, a workpiece number test is performed on each of the known good stacks. If a number of workpieces in each of the known good stacks is equal to the desired number (e.g., one set by design specifications) the method ends at this step. Otherwise, steps **1011-1017** are repeated one or more times until known good stacks comprise the desired number of workpieces.

According to an embodiment, a method comprises forming a semiconductor device. The semiconductor device comprises integrated circuit dies and has at least one test pad per integrated circuit die on a first side of the semiconductor device. The method further comprises mounting first tier workpieces on the first side of the semiconductor device, thereby forming first tier stacks, wherein the first tier workpieces are electrically coupled to corresponding integrated circuit dies, and testing each of the first tier stacks and identifying first known good stacks and first known bad stacks.

According to another embodiment, a method comprises forming a semiconductor device. The semiconductor device comprises integrated circuit dies, at least one first connector and at least one second connector per integrated circuit die on a first side of the semiconductor device, the at least one first connector and the at least one second connector being electrically coupled to a corresponding integrated circuit die. The semiconductor device further comprises at least one test pad per integrated circuit die on the first side of the semiconductor device, the at least one test pad being electrically coupled to the corresponding integrated circuit die. The method further comprises mounting first tier workpieces on the first side of the semiconductor device using the at least one first connector, thereby forming first tier stacks, and testing each of the first tier stacks using the at least one test pad to identify first known good stacks and first known bad stacks.

According to yet another embodiment, a stacked semiconductor device comprises a semiconductor device. The semiconductor device comprises one or more integrated circuit dies, and first connectors and second connectors on a first side of the semiconductor device, the first connectors and the second connectors being electrically coupled to the one or more integrated circuit dies. The semiconductor device further comprises one or more test pads on the first side of the semiconductor device, the one or more test pads being electrically coupled to the first connectors, the one or

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more test pads being interposed between the first connectors and the second connectors. The tacked semiconductor device further comprises a stack of one or more workpieces on the first side of the semiconductor device, the stack of one or more workpieces being mounted to the semiconductor device using the first connectors.

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.

What is claimed is:

1. A method comprising:
forming a semiconductor device, the semiconductor device comprising integrated circuit dies, the semiconductor device having at least one test pad per integrated circuit die on a first side of the semiconductor device and having at least one external connector per integrated circuit die disposed on the first side of the semiconductor device;

mounting first tier workpieces on the first side of the semiconductor device, thereby forming first tier stacks, wherein the first tier workpieces are electrically coupled to corresponding integrated circuit dies, wherein the at least one test pad per integrated circuit die is interposed between a respective first tier workpiece on the integrated circuit die and the respective at least one external connector on the integrated circuit die; and

testing each of the first tier stacks and identifying first known good stacks and first known bad stacks.

2. The method of claim **1**, wherein at least one of the first tier workpieces comprises an integrated circuit die.

3. The method of claim **1**, wherein at least one of the first tier workpieces comprises an interposer.

4. The method of claim **1**, further comprising mounting dummy workpieces atop the first known bad stacks.

5. The method of claim **1**, wherein testing each of the first tier stacks comprises using the at least one test pad to test functionality of each of the first tier stacks.

6. The method of claim **1**, further comprising:
mounting second tier workpieces atop the first known good stacks, thereby forming second tier stacks; and testing each of the second tier stacks and identifying second known good stacks and second known bad stacks.

7. The method of claim **6**, further comprising mounting dummy workpieces atop the second known bad stacks.

8. A method comprising:
forming a semiconductor device, the semiconductor device comprising:
integrated circuit dies;

at least one first connector and at least one second connector per integrated circuit die on a first side of the semiconductor device, the at least one first connector and the at least one second connector being electrically coupled to a corresponding integrated circuit die; and

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at least one test pad per integrated circuit die on the first side of the semiconductor device, the at least one test pad being electrically coupled to the corresponding integrated circuit die;

mounting first tier workpieces on the first side of the semiconductor device using the at least one first connector, thereby forming first tier stacks;

testing each of the first tier stacks using the at least one test pad to identify first known good stacks and first known bad stacks; and

mounting dummy workpieces atop the first known bad stacks.

9. The method of claim **8**, wherein at least one of the first tier workpieces comprises an integrated circuit die.

10. The method of claim **8**, wherein at least one of the first tier workpieces comprises an interposer.

11. The method of claim **8**, wherein the at least one test pad is interposed between the at least one first connector and the at least one second connector.

12. The method of claim **8**, wherein the at least one test pad and the at least one first connector are formed by a same process.

13. The method of claim **8**, further comprising:
mounting second tier workpieces atop the first known good stacks, thereby forming second tier stacks; and testing each of the second tier stacks using the at least one test pad to identify second known good stacks and second known bad stacks.

14. A method comprising:
attaching a plurality of integrated circuit dies to a carrier; forming a molding compound over the carrier and around each of the plurality of integrated circuit dies;

forming one or more redistribution layers (RDLs) over the molding compound and the plurality of integrated circuit dies;

forming a plurality of first connectors over the one or more RDLs;

forming a plurality of second connectors over the one or more RDLs, wherein a size of the plurality of first connectors is different from a size of the plurality of second connectors;

forming a plurality of test pads over the one or more RDLs, wherein the one or more RDLs electrically couple the plurality of first connectors, the plurality of second connectors and the plurality of test pads to the plurality of integrated circuit dies;

bonding first tier workpieces to the one or more RDLs using the plurality of first connectors, thereby forming first tier stacks, wherein each of the first tier stacks comprises one of the plurality of integrated circuit dies and one of the first tier workpieces; and

testing the first tier stacks using the plurality of testing pads to identify first known good stacks and first known bad stacks.

15. The method of claim **14**, further comprising mounting dummy workpieces atop the first known bad stacks.

16. The method of claim **14**, further comprising:
mounting second tier workpieces atop the first known good stacks, thereby forming second tier stacks; and testing the second tier stacks using the plurality of testing pads to identify second known good stacks and second known bad stacks.

17. The method of claim **16**, further comprising mounting dummy workpieces atop the first known bad stacks and the second known bad stacks.

18. The method of claim 14, wherein the plurality of first connectors and the plurality of test pads are formed using a same method.

19. The method of claim 14, wherein testing the first tier stacks comprises performing electronic functional testing on the first tier stacks.

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