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Related U.S. Application Data

(57) **ABSTRACT**

(60) Provisional application No. 62/469,906, filed on Mar. 10, 2017.

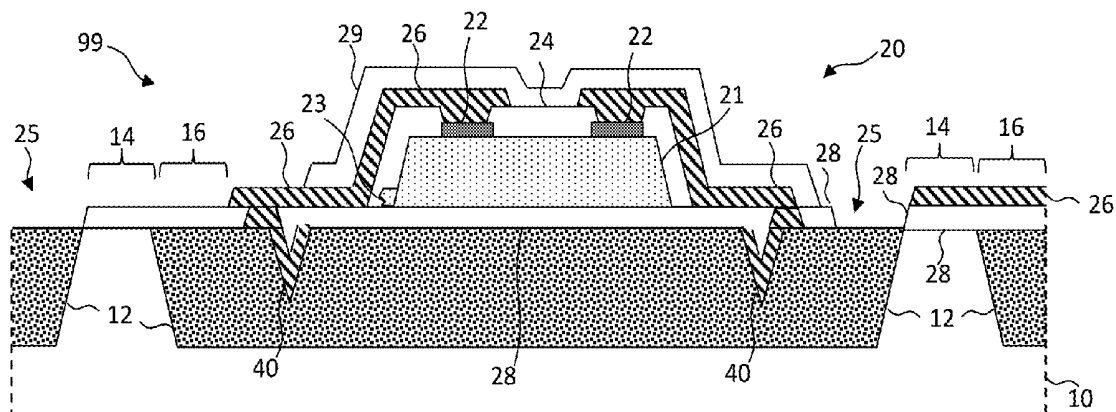
A method of making and testing transfer-printable micro-devices on a source wafer includes providing a source wafer comprising a plurality of sacrificial portions spatially separated by anchors, the source wafer comprising one or more test contact pads, providing a micro-device entirely over each of the plurality of sacrificial portions, each micro-device physically connected to at least one anchor with one or more tethers, providing one or more electrical test connections from each micro-device to a corresponding test contact pad, testing the micro-devices through the test connections to determine functional micro-devices and faulty micro-devices, and removing at least a portion of the one or more test connections.

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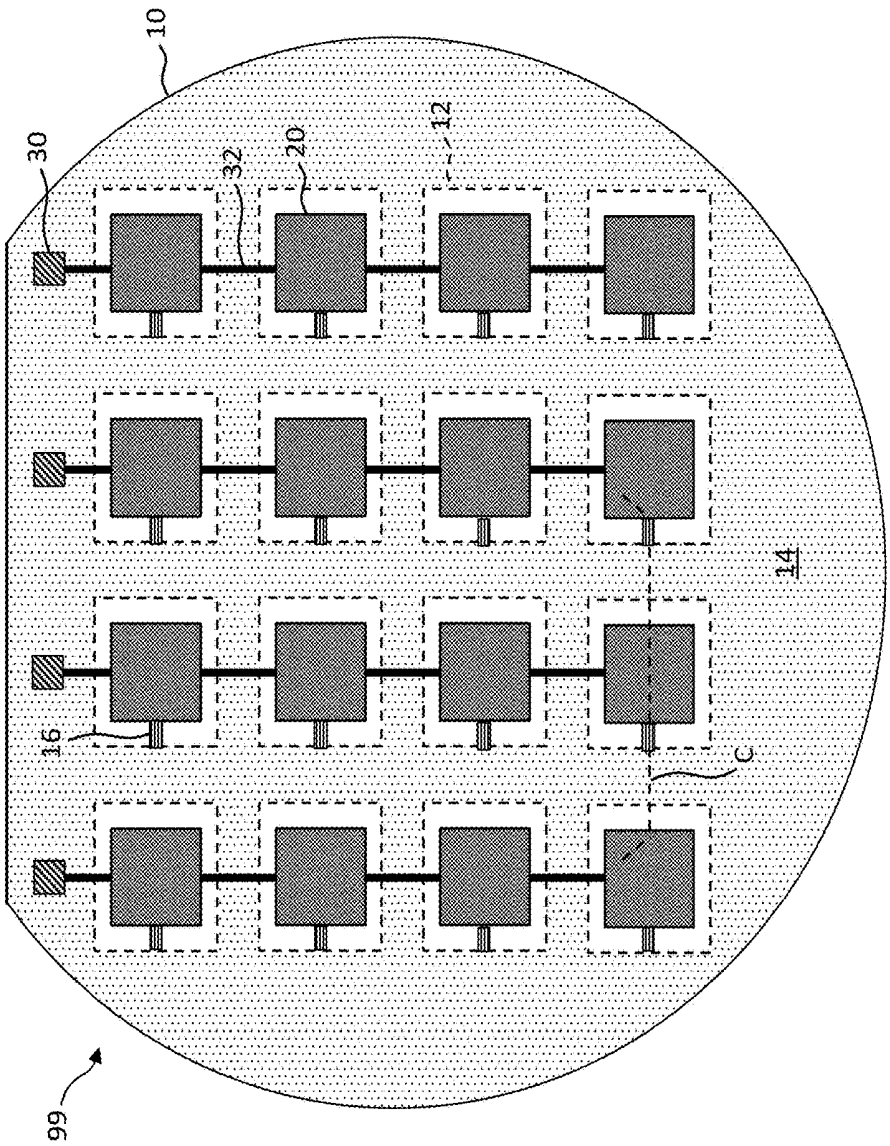


FIG. 1A

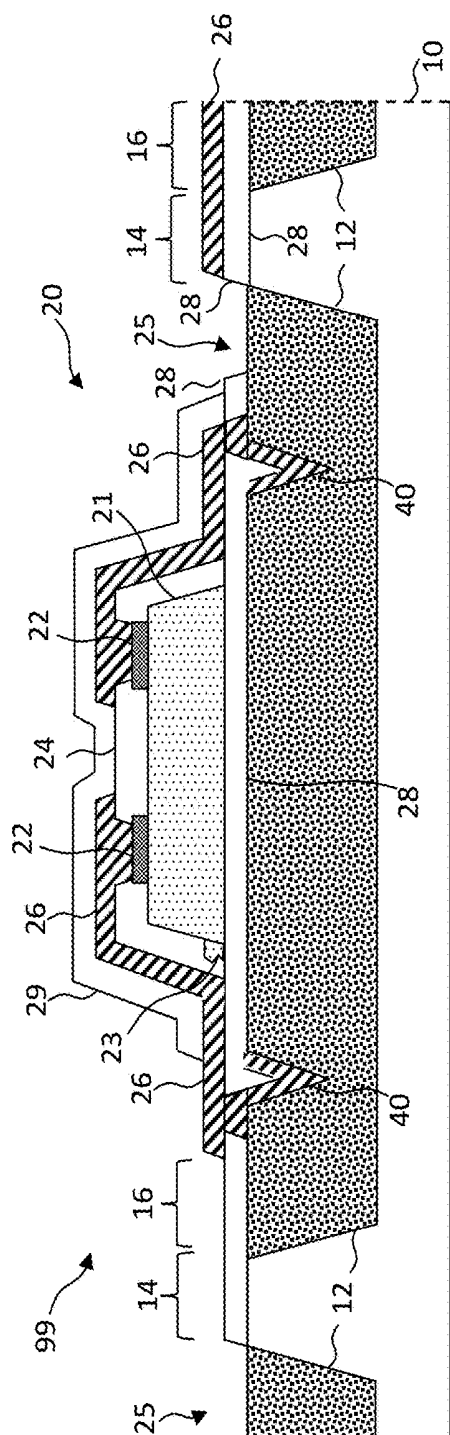


FIG. 1B

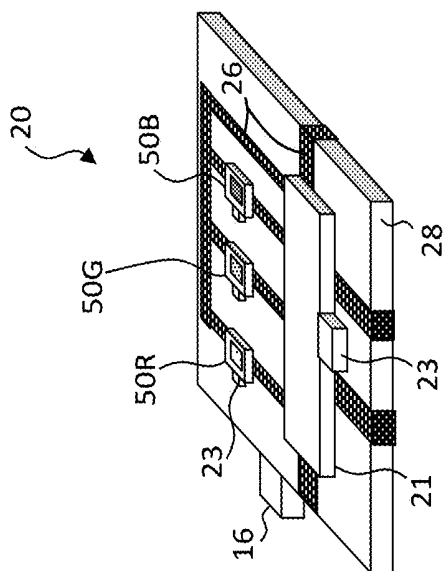


FIG. 2B

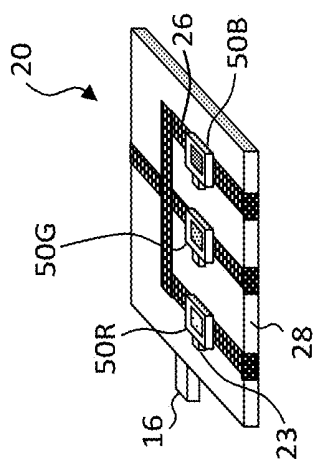
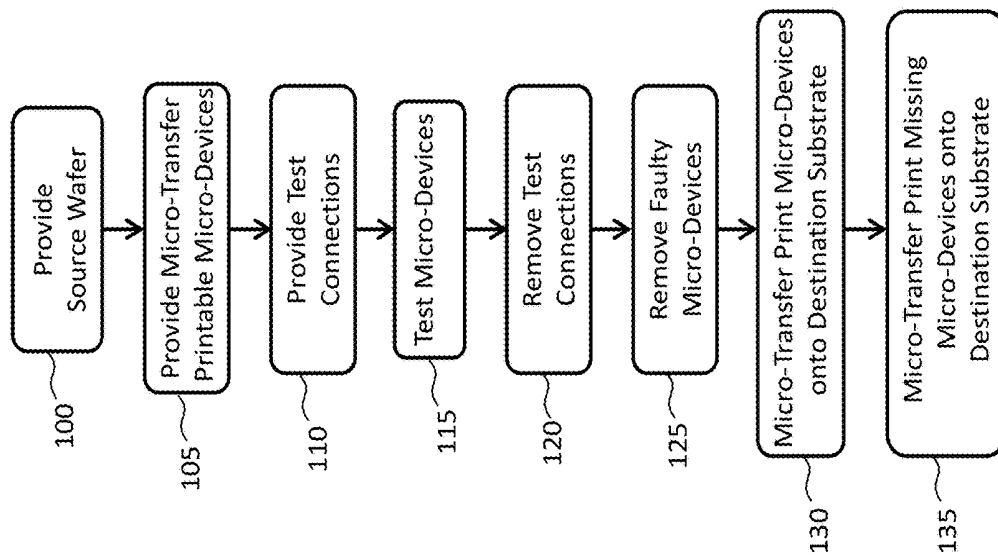


FIG. 2A

FIG. 3

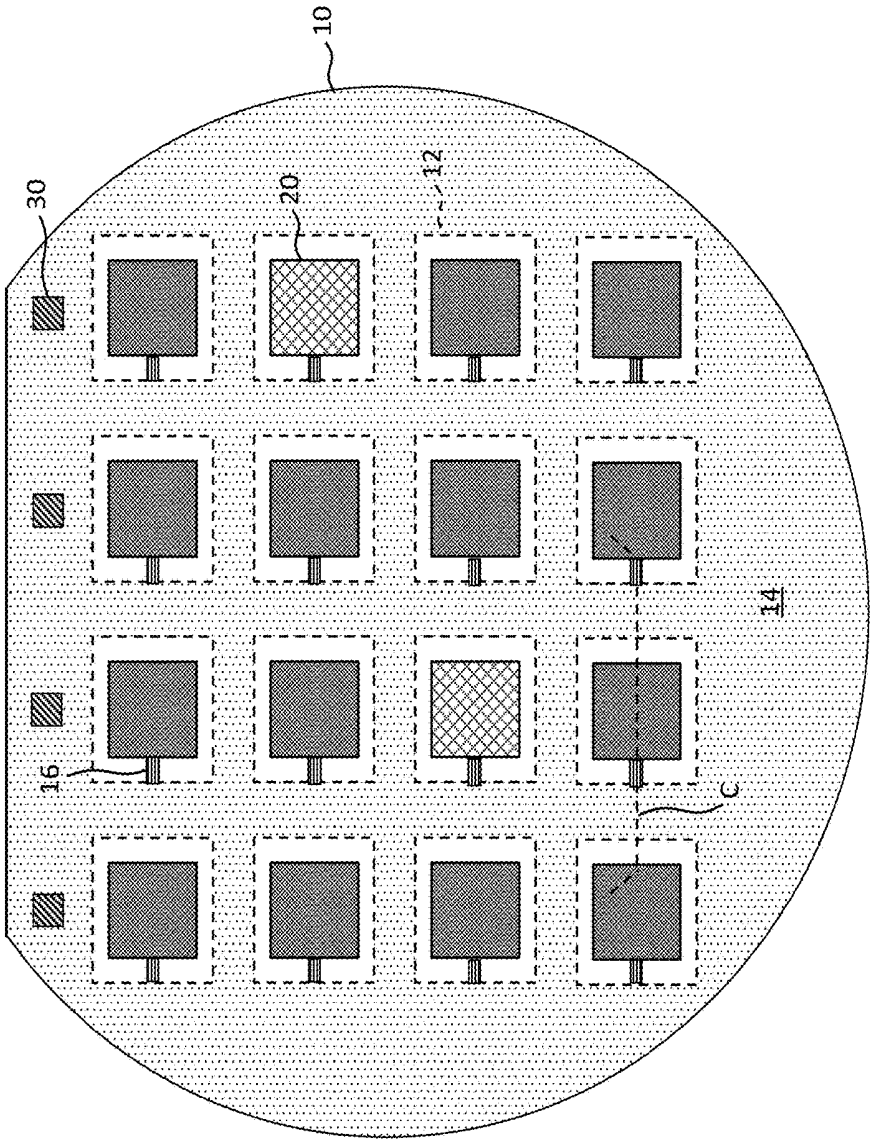


FIG. 4

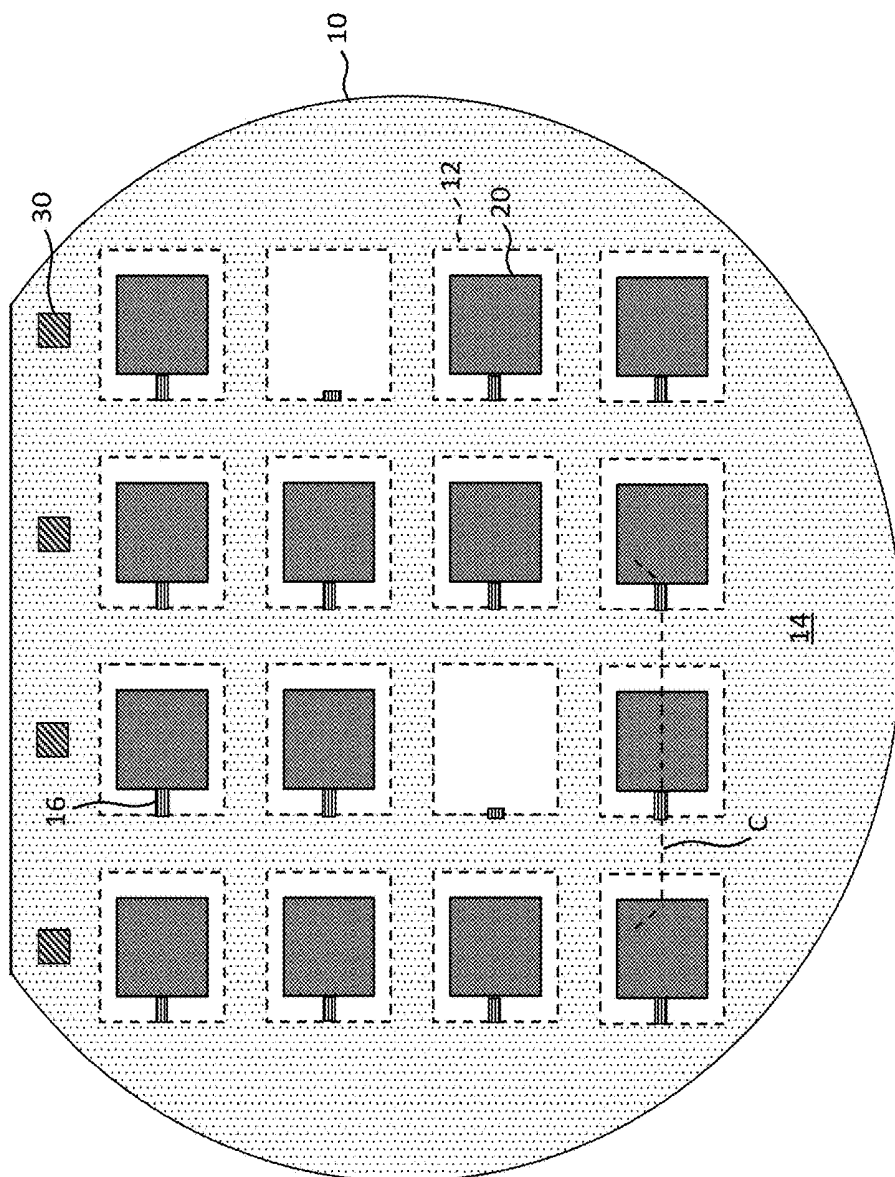


FIG. 5

TESTING TRANSFER-PRINT MICRO-DEVICES ON WAFER

PRIORITY APPLICATION

This application claims the benefit of U.S. Provisional Patent Application No. 62/469,906, filed on Mar. 10, 2017, entitled Testing Transfer-Print Micro-Devices on Wafer, the disclosure of which is hereby incorporated by reference herein in its entirety.

FIELD OF THE INVENTION

The present invention relates to structures and methods for testing transfer printable micro-scale devices on a source wafer.

BACKGROUND OF THE INVENTION

Substrates with electronically active components such as transistors or light-emitting diodes distributed over the extent of the substrate can be used in a variety of electronic systems, for example, flat-panel imaging devices such as flat-panel liquid crystal or organic light emitting diode (OLED) display devices and in flat-panel solar cells. A variety of methods may be used to distribute electronically active circuits over substrates, including forming the electronically active circuits on a substrate, for example thin-film transistor circuits, or forming the components on separate substrates and placing them on a substrate. In the latter case, a variety of assembly technologies for device packaging may be used.

One method for transferring active components from one substrate to another is described in "AMOLED Displays using Transfer-Printed Integrated Circuits" published in the Proceedings of the 2009 Society for Information Display International Symposium Jun. 2-5, 2009, in San Antonio Tex., US, vol. 40, Book 2, ISSN 0009-0966X, paper 63.2 p. 947. In this approach, small integrated circuits are formed over a buried oxide layer on the process side of a crystalline wafer. The small integrated circuits, or chiplets, are released from the wafer by etching the buried oxide layer formed beneath the circuits. A PDMS stamp is pressed against the wafer and the process side of the chiplets is adhered to the stamp. The chiplets are pressed against a destination substrate or backplane coated with an adhesive and thereby adhered to the destination substrate. The adhesive is subsequently cured. In another example, U.S. Pat. No. 8,722,458 entitled Optical Systems Fabricated by Printing-Based Assembly teaches transferring light-emitting, light-sensing, or light-collecting semiconductor elements from a wafer substrate to a destination substrate or backplane.

In such methods, it is important that pixels in the display are properly functional. The light-emitting semiconductor elements can be tested after they are transferred to the destination substrate and the display rejected if too many faulty light-emitters are found. Alternatively, as described in U.S. Pat. No. 9,142,468, the small integrated circuits on the wafer can be tested before transfer. In this approach, an integrated circuit test structure comprises a substrate and an anchor area comprising one or more electrical elements to conduct an electrical test signal. The anchor area is physically secured to a surface of the substrate. At least one printable electronic component comprises an active layer including one or more active element. The at least one printable electronic component is suspended over the surface of the substrate by electrically conductive breakable

tethers that physically secure and electrically connect the at least one printable electronic component to the anchor area to provide the electrical test signal to the one or more active elements. Each of the electrically conductive breakable tethers comprises an insulating layer and a conductive layer thereon that are configured to be preferentially fractured responsive to pressure applied thereto to release the at least one printable electronic component from the substrate. However, electrically conductive breakable tethers limit the materials and number of electrical connections that can be provided to an integrated circuit.

U.S. Pat. No. 9,165,989 discloses a method of assembling integrated circuit elements on a receiving substrate. If one of the integrated circuits is defective, it can be removed from the wafer before assembling. The method comprises providing a wafer having a plurality of chiplets thereon, determining that at least one of the chiplets on the wafer is defective, selectively removing the at least one of the chiplets that is defective from the wafer to define at least one empty chiplet location on the wafer between ones of the chiplets on the wafer prior to transferring the ones of the chiplets onto the receiving substrate, printing the ones of the chiplets from the wafer onto the receiving substrate in parallel, using a stamp that separates the ones of the chiplets from the wafer and adheres the ones of the chiplets thereto, to define the at least one empty chiplet location therebetween on the receiving substrate, and printing at least one additional chiplet onto the at least one empty chiplet location on the receiving substrate. Thus, as described in U.S. patent application Ser. No. 14/848,477, a wafer of chiplets can comprise a source substrate having an array of regularly-spaced chiplet locations thereon and a plurality of chiplets native to the source substrate. Each chiplet of the plurality of chiplets is disposed on the source substrate in one of the chiplet locations in the array, wherein one or more of the chiplet locations in the array is a removed-chiplet location that is devoid of a chiplet.

There is a need, therefore, for structures and methods that enable the testing and disposition of functional micro-devices on destination substrates (e.g., large-format destination substrates).

SUMMARY OF THE INVENTION

In accordance with an embodiment of the present invention, a method of making and testing transfer-printable micro-devices on a source wafer comprises providing the source wafer comprising a plurality of sacrificial portions spatially separated by anchors, the source wafer comprising one or more test contact pads; providing at least one micro-device disposed entirely over each of the plurality of sacrificial portions, each of the at least one micro-device physically connected to at least one of the anchors; providing one or more electrical test connections from each of the at least one micro-device to a corresponding test contact pad; testing the at least one micro-device disposed over each of the plurality of sacrificial portions through the one or more test connections to determine one or more functional micro-devices and one or more faulty micro-devices; and removing at least a portion of the one or more test connections.

In some embodiments, the sacrificial portions are etched to suspend at least a portion of each micro-device over a corresponding sacrificial portion by the corresponding tether. Etching the sacrificial portions can also remove at least a portion of the one or more test connections and removing at least a portion of the one or more test connections can at least partially define the tethers.

In some embodiments, faulty micro-devices are removed from the source wafer or from a destination substrate provided as a backplane onto which the micro-devices are micro-transfer printed. In some embodiments, only the functional micro-devices are micro-transfer printed to the destination substrate.

Test circuits can be provided on or in the source wafer connected to the test contacts and the test circuits operated to test the micro-devices.

In some embodiments, the micro-devices include light emitters. An optical device can receive light from the light emitters to determine functional micro-devices and faulty micro-devices and an external test controller electrically connected to the test contact pads can test the micro-devices.

In certain embodiments, a transfer-printable micro-device wafer system, comprising: a source wafer comprising a plurality of sacrificial portions spatially separated by anchors and one or more test contact pads; a micro-device disposed entirely over each of the plurality of sacrificial portions, the micro-device physically connected to at least one of the anchors by one or more tethers; and one or more electrical test connections electrically connecting the micro-device to a corresponding test contact pad, wherein the one or more test connections are formed on a part of the source wafer other than the one or more tethers.

In some embodiments, the micro-device includes a controller for controlling the one or more inorganic light-emitting diodes. The micro-device can include a device substrate separate from the source wafer and the controller can include a controller substrate separate from the source wafer and the device substrate.

The micro-device can include one or more inorganic light-emitting diodes and a device substrate separate from the source wafer. The one or more inorganic light-emitting diodes (iLEDs) can include an iLED substrate separate from the source wafer and the device substrate.

In some embodiments, the test connections are electrically connected to the controller and the controller controls the iLEDs to emit light in response to test signals provided through the test connections.

Certain embodiments of the present invention enable, inter alia, a greater variety of test methods and structures for micro-transfer printable micro-devices. Improved tests reduce printing of faulty devices, improving yields and reducing costs.

In one aspect, the present invention is directed to a method of making and testing transfer-printable micro-devices on a source wafer, comprising: providing the source wafer comprising a plurality of sacrificial portions spatially separated by anchors, the source wafer comprising one or more test contact pads; providing at least one micro-device disposed entirely over each of the plurality of sacrificial portions, each of the at least one micro-device physically connected to at least one of the anchors; providing one or more electrical test connections from each of the at least one micro-device to a corresponding test contact pad; testing the at least one micro-device disposed over each of the plurality of sacrificial portions through the one or more test connections to determine one or more functional micro-devices and one or more faulty micro-devices; and removing at least a portion of the one or more test connections.

In certain embodiments, the method comprises etching the plurality of sacrificial portions thereby suspending each micro-device over a corresponding sacrificial portion by at least one corresponding tether. In certain embodiments, etching the plurality of sacrificial portions also removes at least a portion of the one or more test connections.

In certain embodiments, removing at least a portion of the one or more test connections at least partially defines the at least one corresponding tether for each micro-device.

In certain embodiments, the method comprises providing a destination substrate and micro-transfer printing the at least one micro-device disposed entirely over each of the plurality of sacrificial portions to the destination substrate.

In certain embodiments, the method comprises removing the one or more faulty micro-devices from the destination substrate. In certain embodiments, the method comprises removing the one or more faulty micro-devices from the source wafer.

In certain embodiments, the method comprises: providing a destination substrate; and micro-transfer printing only the one or more functional micro-devices to the destination substrate.

In certain embodiments, the method comprises: providing one or more test circuits disposed on or in the source wafer, wherein the test circuits are connected to the one or more test contact pads; and operating the one or more test circuits to test the micro-devices.

In certain embodiments, the micro-devices comprise light emitters. In certain embodiments, the method comprises providing an optical device (e.g., a camera or video camera) for receiving light from the light emitters; and determining the one or more functional micro-devices and the one or more faulty micro-devices using the optical device.

In certain embodiments, the method comprises: providing an external test controller; and electrically connecting the external test controller to the one or more test contact pads to test the at least one micro-device disposed over each of the plurality of sacrificial portions.

In another aspect, the present invention is directed to a transfer-printable micro-device wafer system, comprising: a source wafer comprising a plurality of sacrificial portions spatially separated by anchors and one or more test contact pads; a micro-device disposed entirely over each of the plurality of sacrificial portions, the micro-device physically connected to at least one of the anchors by one or more tethers; and one or more electrical test connections electrically connecting the micro-device to a corresponding test contact pad, wherein the one or more test connections are formed on a part of the source wafer other than the one or more tethers.

In certain embodiments, the micro-device comprises one or more inorganic light-emitting diodes.

In certain embodiments, the micro-device comprises a device substrate separate from the source wafer and each of the one or more inorganic light-emitting diodes (iLEDs) comprises an iLED substrate separate from the source wafer and the device substrate.

In certain embodiments, the micro-device comprises a controller for controlling the one or more inorganic light-emitting diodes. In certain embodiments, the controller comprises a controller substrate separate from the source wafer and the device substrate.

In certain embodiments, the one or more test connections are electrically connected to the controller and the controller controls the one or more iLEDs to emit light in response to test signals provided through the one or more test connections.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, aspects, features, and advantages of the present disclosure will become more

apparent and better understood by referring to the following description taken in conjunction with the accompanying drawings, in which:

FIG. 1A is a plan view illustrating an exemplary system according to illustrative embodiments of the present invention;

FIG. 1B is a cross section of the FIG. 1A plan view taken across line segment C according to illustrative embodiments of the present invention;

FIGS. 2A and 2B are perspectives of alternative structures of FIGS. 1A and 1B according to illustrative embodiments of the present invention;

FIG. 3 is a flow diagram illustrating an exemplary method according to illustrative embodiments of the present invention;

FIG. 4 is a plan view illustrating an exemplary system after test and removal of the test connections, according to illustrative embodiments of the present invention; and

FIG. 5 is a plan view illustrating an exemplary system after faulty micro-device removal, according to illustrative embodiments of the present invention.

The features and advantages of the present disclosure will become more apparent from the detailed description set forth below when taken in conjunction with the drawings, in which like reference characters identify corresponding elements throughout. In the drawings, like reference numbers generally indicate identical, functionally similar, and/or structurally similar elements. The figures are not drawn to scale since the variation in size of various elements in the Figures is too great to permit depiction to scale.

DETAILED DESCRIPTION OF THE INVENTION

The present invention provides, inter alia, structures and methods for efficiently and effectively testing transfer printable (e.g., micro-transfer printable) micro-devices on a source wafer. In certain embodiments, defective or faulty micro-devices are removed from the source wafer and the remaining micro-devices are transfer printed (e.g., micro-transfer printed) from the source wafer to a desired destination substrate.

Certain embodiments of the present invention are illustrated in the plan view of FIG. 1A, the corresponding cross section of FIG. 1B taken across line segment C of FIG. 1A, the alternative detail perspectives of FIGS. 2A and 2B, and the flow diagram of FIG. 3. As shown specifically in FIGS. 1A and 1B, a transfer-printable micro-device wafer system 99 comprises a source wafer 10 having a plurality of sacrificial portions 12 spatially separated by anchors 14. The source wafer 10 has one or more test contact pads 30 that can be electrically connected to external test devices or test controllers, for example through ribbon cables or electrical connectors or sockets. A micro-device 20 is disposed entirely over each of the sacrificial portions 12. In some embodiments, at least one micro-device 20 is disposed entirely over each of a plurality of sacrificial portions 12. Each micro-device 20 can be physically connected to at least one anchor 14 with one or more tethers 16. For example, in FIG. 1A, each micro-device 20 is attached to one anchor 14 with one tether 16. In some embodiments, micro-devices can be affixed in place with a tether 16 between each micro-device 20 and a source wafer 10 or held in place to an anchor 14 with a sacrificial portion 12. One or more electrical test connections 32 electrically connect each micro-device 20 to

a corresponding test contact pad 30. The test connections 32 are formed on a part of the source wafer 10 other than the tether 16.

As shown in FIG. 3, an exemplary method of making and testing transfer-printable micro-devices 20 on a source wafer 10 includes providing in step 100 a source wafer 10 having a plurality of sacrificial portions 12 spatially separated by anchors 14, the source wafer 10 having one or more test contact pads 30 formed, for example, by photolithographic and integrated circuit processes and materials. In step 105, a micro-device 20 is provided entirely over each of the sacrificial portions 12, where each micro-device 20 is physically connected to an anchor 14 with a lateral (as shown) or underlying (not shown) tether 16 or held in place to the anchor 14 with the sacrificial portion 12. The micro-device 20 can be a single integrated circuit or a plurality of integrated circuits, electronic circuit devices, or other electronic structures or structures having electronic attributes or capabilities. One or more of the micro-device 20 can be made in place, for example using integrated circuit processes and materials, or disposed on or over the sacrificial portions 12, for example using micro-transfer printing methods, and electrical connections or electrodes 26 provided to enable electrical connections to the one or more micro-devices 20. In step 110, one or more electrical test connections 32 are provided electrically connecting each micro-device 20 to a corresponding test contact pad 30.

In some embodiments, test contact pads 30, electrical test connections 32, and any electrodes 26 are made in a common step with common materials, for example metal wires such as aluminum, silver, tungsten, titanium, tin, or gold, for example, using photolithographic methods or printing-based methods such as inkjet printing. Test contact pads 30 can be designated portions of electrical test connections 32 or electrical test connections 32 can include test contact pads 30 or both. Test contact pads 30 and electrical test connections 32 can be made of common materials in a common step; they are not necessarily distinguished and can be part of a common electrically conductive structure. The resolution of an electrical conductor or connection is the size of the smallest element in a dimension over an area that can be reliably made or the minimum spacing between components that can be reliably achieved without electrical shorts. In various embodiments, electrodes 26 have a resolution of less than or equal to 10 microns, less than or equal to 5 microns, less than or equal to two microns or less than or equal to one micron.

The micro-devices 20 are tested in step 115 through the test connections 32 to determine functional micro-devices 20 and faulty micro-devices 20. At least a portion of the one or more test connections 32 are removed in step 120, for example the portion of the one or more test connections 32 that are attached to the micro-devices 20 over the sacrificial portions 12 (e.g., as shown in FIG. 4). In some embodiments, only portions of a test connection 32 over sacrificial portions 12 are removed, while the portion(s) of the test connection 32 that are not over any sacrificial portion 12 remain. For example, referring to FIG. 1A, the portions of test connections 32 over sacrificial portions 12 can be removed while leaving behind the portions not over sacrificial portions 12. In step 125, the faulty micro-devices 20 (e.g., as illustrated in FIG. 4 with cross hatching) are removed from the source wafer 10 (e.g., as shown in FIG. 5). Removing the faulty micro-devices 20 can include etching the sacrificial portions 12 to at least partially suspend each micro-device 20 over a corresponding sacrificial portion 12 by the corresponding tether 16 followed by micro-transfer

printing the faulty micro-devices **20** to an unused or disposal substrate. Etching the sacrificial portions **12** can also remove at least a portion of the one or more test connections **32**. Furthermore, removing at least a portion of the one or more test connections **32** can at least partially define the tethers **16**.

In step **130**, the remaining functional micro-devices **20** are micro-transfer printed to a desired destination substrate. The destination substrate can be provided with substrate contact pads to make electrical connections to the micro-devices **20** or the destination substrate electrical connections can be made after the destination substrate is provided. In step **135**, other functional micro-devices **20** are micro-transfer printed from a source wafer **10** to the desired destination substrate in the locations where no functional micro-devices **20** were micro-transfer printed because the faulty micro-devices **20** were removed from the source wafer **10**. The system of micro-devices **20** on the destination substrate can then be put into service and operated.

In some embodiments, faulty micro-devices **20** are not removed from a source wafer **10** (e.g., as in step **125**) but are removed from the destination substrate after the micro-devices **20** have been transfer printed (e.g., micro-transfer printed). In some such embodiments, all of a plurality of micro-devices **20**, including both one or more functional and one or more faulty micro-devices **20** are transfer printed (e.g., micro-transfer printed) to a destination substrate. The one or more faulty micro-devices **20** are then removed or electrically isolated from the destination substrate and replaced with corresponding functional micro-devices **20** or additional functional micro-devices **20** are added in the faulty micro-device **20** locations.

By providing test connections **32** on a part of a source wafer **10** other than a tether **16**, a greater variety of materials and a greater number of test connections **32** can be formed and used to facilitate testing micro-devices **20**. Tethers **16** are typically quite small, for example a few microns in width and depth, and there is, therefore, limited space for electrically conductive test connections **32** on a typical tether **16**. Moreover, materials that make up tethers **16** are carefully chosen and structured to fracture in a desired manner under carefully controlled pressure and conditions found in micro-transfer printing with a stamp. In certain embodiments, forming effective test connections **32** can interfere with the tether **16** fracturing process, inhibiting successful transfer printing (e.g., successful micro-transfer printing). In some embodiments, in which tethers **16** are not present, test connections **32** are the only way to electrically test micro-devices **20** prior to transfer printing. Thus, certain embodiments of the present invention can enable effective testing and transfer printing of micro-devices **20** on and from a source wafer **10**.

A source wafer **10** can be any wafer suitable for lithographic or integrated circuit processing, for example, glass, plastic, quartz, metal, ceramic, or a semiconductor substrate such as silicon (e.g., silicon {**111**} or silicon {**100**}, where the indices refer, as is convention, to the orientation of silicon relative to the processing surface of the substrate). A source wafer **10** can be circular with a flat edge (e.g., as shown in FIG. **1A**) or circular or rectangular or any shape (e.g., polygonal shape) that is readily processed in a fabrication facility.

Sacrificial portions **12** can be designated portions of a source wafer **10**, for example when the source wafer **10** comprises anisotropically etchable semiconductor materials that enables etching in one direction in preference to another. In some embodiments, sacrificial portions **12** include a

material that is differentially etchable from a source wafer **10** material or a layer of a micro-device **20**, for example a layer of the micro-device **20** that is adjacent to the source wafer **10**. Sacrificial portions **12** can be rectangular, as shown, and can include patterned oxides or nitrides such as silicon dioxide or silicon nitride. Thus, in an exemplary method according to certain embodiments of the present invention, a patterned sacrificial portion **12** is a patterned layer of material different from a source wafer **10** material that can be etched to form at least a gap that extends at least partially between at least a portion of a micro-device **20** and a source wafer **10**. In an exemplary method according to certain embodiments of the present invention, a patterned sacrificial portion **12** is a defined portion of a source wafer **10** that can be anisotropically etched to form a gap that extends at least partially between at least a portion of a micro-device **20** and a source wafer **10**. In some embodiments, sacrificial portions **12** define gaps or are filled with an etchable material. An etched sacrificial portion results in one or more tethers **16** that physically connects a micro-device **20** to at least one anchor **14**. In certain embodiments, a stamp post of a micro-transfer stamp can contact a micro-device **20**, fracture one or more tethers **16** to separate the micro-device **20** from its source wafer **10**, and adhere the micro-device **20** to the stamp post and thereby enable the micro-device **20** to be micro-transferred to a destination substrate.

An anchor or anchors **14** can be one or more areas of a source wafer **10** surface that are not covered with sacrificial portions **12** or micro-devices **20**. A device substrate **28** of each micro-device **30** can be surrounded in a lateral, horizontal direction parallel to the surface of a source wafer **10** by one or more sacrificial portions **12** and sacrificial portions **12** can be surrounded by anchors **14** in the lateral, horizontal direction parallel to the surface of a source wafer **10**. Test contact pads **30** and test connections **32** can be patterned metal structures such as rectangular areas, lines, traces, or wires, and can be formed on a source wafer **10**, for example using photolithographic processes and materials or by inkjet printing conductive inks.

As shown in the cross section of FIG. **1B**, a micro-device **20** can be disposed on a source wafer **10** and can include a device substrate **28**, for example a patterned layer of dielectric material such as silicon dioxide or silicon nitride. A device substrate **28** can include an adhesive layer (or have an adhesive layer disposed thereon), for example a curable or cured adhesive such as SUB. In certain embodiments, a micro-device **20** is located entirely over a corresponding sacrificial portion **12** and can include one or more integrated circuits **21** (ICs) that can each have a broken (e.g., fractured) or separated IC tether **23** and that each can be transfer printed (e.g., micro-transfer printed) onto a device substrate **28** from respective IC source wafers. Integrated circuits **21** can be semiconductor (such as silicon) devices such as CMOS logic circuits or compound semiconductor devices such as inorganic light-emitting diodes (iLEDs) **50** (for example, as shown in FIGS. **2A**, **2B**), any one or all of which can comprise an IC tether **23**. In some embodiments, referring to the FIG. **2A** perspective, a micro-device **20** includes one or more red iLEDs **50R** that emit red light, one or more green iLEDs **50G** that emit green light, and one or more blue iLEDs **50B** that emit blue light, collectively iLEDs, that can form a passive-matrix display pixel module. In certain embodiments, iLEDs can be transfer printed (e.g., micro-transfer printed) to a device substrate **28** and can, in consequence, have a broken (e.g., fractured) or separated IC tether **23**. In some embodiments, referring to the perspective of FIG. **2B**, a micro-device **20** further includes an IC **21** pixel

controller that can control the light output by the red, green, and blue iLEDs 50R, 50G, 50B to form an active-matrix display pixel module (e.g., an RGB pixel module). In some embodiments, an IC 21 pixel controller can also be transfer printed (e.g., micro-transfer printed) to a device substrate 28 and can, in consequence, comprise a broken (e.g., fractured) or separated IC tether 23.

Integrated circuits 21 can be bare die adhered to a device substrate 28. Protective dielectric structures 24 can insulate integrated circuits 21 and expose device contacts 22 that provide electrical connections to electrodes 26. Dielectric structures 24 can be patterned oxide or nitride materials such as silicon dioxide or silicon nitride. Device contacts 22 can be designated portions of an IC 21, for example a designated portion of a doped or undoped semiconductor layer or semiconductor structure. In some embodiments, device contacts 22 are metallized portions of an IC 21. Electrodes 26 can be patterned metal traces, such as aluminum, gold, silver, tungsten, tantalum, titanium or other metals or metal alloys. These elements can be deposited (e.g., by evaporation or coating) and patterned (e.g., with photo-sensitive material and exposure masks) using photolithographic methods, materials, and tools.

A micro-device 20 can also include a protective encapsulation layer 29, if desired, that can extend over or be part of a tether 16 (not shown), or not (e.g., as shown in FIG. 1B). An encapsulation layer 29 can be made of a dielectric material such as silicon dioxide or nitride. In certain embodiments, a conductive material (e.g., a contact pad or electrode 26) extends beyond an edge of an encapsulation layer 29 (as shown in FIG. 1B), or no encapsulation layer 29 is present (not shown), such that an electrical connection can be made between a micro-device 20 and a test connection 32. In certain embodiments, a via through an encapsulation layer 29 exists such that a test connection 32 can be electrically connected to a micro-device 20. A tether 16 can be in a common layer with or made in a common step with common materials as a device substrate 28 but the device substrate 28 refers only to that portion of the layer over or on the sacrificial portion 12 and not attached to an anchor 14. In some embodiments, a tether 16 includes portions of layers made in common steps with both a device substrate 28 and an encapsulation layer 29. Protective dielectric structures 24, device contacts 22, electrodes 26, and an encapsulation layer 29 can all be made using photolithographic methods and materials. In some embodiments, a device substrate 28, an optional encapsulation layer 29, a tether 16, and patterned dielectric structures 24 can all be or comprise the same material.

Thus, in some embodiments of the present invention, micro-devices 20 include a device substrate 28, an integrated circuit pixel controller 21 with a controller substrate, and one or more iLEDs (e.g., one or a combination of red iLED 50R, green iLED 50G, and blue iLED 50B), all of which are distinct, independent, and separate from each other and from a source wafer 10 and destination substrate and have a substrate that is separate, independent, and distinct. A substrate that is separate, independent, and distinct from another substrate can be made separately at a different time or at a different location using different materials or methods than the other substrate. Each separate, independent, and distinct substrate can exist and be processed, transported, or manipulated independently of any other separate, independent, and distinct substrate. In some embodiments, each iLED (e.g., one or a combination of a red iLED 50R, a green iLED 50G, and a blue iLED 50B), pixel controller 21, and device

substrate 28 can be independently micro-transfer printed from respective source wafers (e.g., iLED or pixel controller source wafers).

In some embodiments of the present invention, a micro-device 20 includes electrically conductive connection posts 40 that are electrically connected to electrodes 26 and thence to device contacts 22 to enable power, ground, and control signals to operate one or more ICs 21 disposed on or in the micro-device 20. Connection posts 40 enable electrical connections to be made to a micro-device 20 by transfer printing (e.g., micro-transfer printing). Connection posts 40 can be made by pattern-wise etching forms into sacrificial portions 12 before a device substrate 28 or IC(s) 21 are disposed or formed over sacrificial portions 12. The forms are then pattern-wise coated with an electrical conductor such as metal. The device substrate 28 is deposited and patterned to form vias and openings 25. Connection posts 40 are discussed in more detail, in U.S. Pat. No. 8,889,485, entitled *Methods for Surface Attachment of Flipped Active Components* by Christopher Bower, and in U.S. patent application Ser. No. 14/822,864, filed Aug. 10, 2015, entitled *Chiplets with Connection Posts* by Prevatte et al., the disclosures of each of which are incorporated herein by reference in their entirety.

ICs 21 can be disposed on a source wafer 10, for example by micro-transfer printing, or formed in situ using integrated circuit processes and materials, or both, and any device contacts 22 formed. In an exemplary method according to certain embodiments, a patterned epitaxial growth layer is provided upon sacrificial portions 12 and structures are formed on the epitaxial growth layer. Electrodes 26 are then deposited and patterned, as is an encapsulation layer 29. IC(s) 21 can be protected by patterning dielectric structures 24 and electrically connected to connection posts 40 by patterning electrical conductors (e.g., electrodes 26) that fill vias and form wires over the dielectric structures 24 connected to device contacts 22. Sacrificial portions 12 can be etched through an opening 25 between micro-devices 20 (e.g., adjacent to a device substrate 28) and one or more anchors 14.

Micro-devices 20 can be tested by providing a test circuit on a source wafer 10 or electrically connecting an external test controller (not shown) to test contact pads 30, for example through a ribbon cable. A test controller provides electrical test signals that propagate through test contact pads 30, test connections 32, connection posts 40 (if present), electrodes 26, and device contacts 22 to electrically stimulate a micro-device 20. An electrical response from the micro-device 20 can be returned to the controller through the electrical connections for analysis and determination of a functional or faulty micro-device 20. In some embodiments in which a micro-device 20 is a light emitter, for example an iLED, an optical device such as a camera can be located to receive light emitted from the micro-device 20, for example take a picture (e.g., still or video picture) of the operating device. In some such embodiments, it can be useful to control all of a plurality of micro-devices 20 to emit light at the same time so that a single image captures the output of the plurality of micro-devices 20 on a source wafer 10 at a single moment. The image can then be downloaded from the camera to the test controller and analyzed to determine functional and faulty micro-devices 20. Faulty micro-devices 20 can, for example, emit too little, too much, or the wrong color of light, or require too much electrical current.

Once faulty micro-devices 20 have been determined, they can be removed from a source wafer 10, for example using a micro-transfer printing stamp with a single post that

sequentially contacts and prints the faulty micro-devices **20** from the source wafer **10** to a waste substrate, such as a piece of disposable adhesive tape. Remaining micro-devices **20** can then be micro-transfer printed with a stamp having a post for each location of micro-devices **20**, whether the location of a functional micro-device **20** or the location of a removed faulty micro-device **20**. The stamp posts located at the positions of removed faulty micro-devices **20** will perform no function. In certain embodiments, after the remaining functional micro-devices **20** are micro-transfer printed to a desired destination substrate, the destination substrate will have locations where a micro-device **20** is desired but no micro-device **20** is present. A single post micro-transfer stamp can then print one functional micro-device **20** at a time from the same or another source wafer **10** to the desired locations on the destination substrate to complete the printing process. In some embodiments of the present invention, it can be easier, faster, or cheaper to remove faulty micro-devices **20** from a source wafer **10** than a destination wafer.

Micro-devices **20** can be active components, for example including one or more active elements such as integrated circuits, electronic transistors, or diodes or light-emitting diodes and photodiodes that produce an electrical current in response to ambient light as well as passive components such as resistors, capacitors, or conductors. Micro-devices **20** can be semiconductor devices having one or more semiconductor layers, such as an integrated circuit **21**. Micro-devices **20** can be or include unpackaged die. In some embodiments, micro-devices **20** are compound elements having a plurality of active and/or passive elements, such as multiple semiconductor devices with separate substrates, each with one or more active elements or one or more passive elements, or both.

Micro-devices **20** made by methods in accordance with certain embodiments of the present invention can include or be a variety of chiplets (micro-ICs **21**) having semiconductor structures, including a diode, a light-emitting diode (LED) (such as a micro-LED that can be an inorganic LED), a transistor, or a laser. Micro-devices **20** can include inorganic materials such as silicon or gallium arsenide, or inorganic materials having various structures, including crystalline, microcrystalline, polycrystalline, or amorphous structures. Micro-devices **20** can also include insulating layers and structures such as silicon dioxide, nitride, and passivation layers and conductive layers or structures such as wires made of aluminum, titanium, silver, or gold that form an electronic circuit.

Micro-devices **20** can include or be one or more small integrated circuits **21** (chiplets) that can be unpackaged dies transferred from respective IC source wafers, such as a semiconductor or compound semiconductor source wafer, and, in some embodiments, can be micro transfer printed. Chiplets can have at least one of a width from 2 to no more than 5 μm , 5 to no more than 10 μm , 10 to no more than 20 μm , or 20 to no more than 50 μm , a length from 2 to no more than 5 μm , 5 to no more than 10 μm , 10 to no more than 20 μm , or 20 to no more than 50 μm , and a height from 2 to no more than 5 μm , 5 to no more than 10 μm , 10 to no more than 20 μm , or 20 to no more than 50 μm . Chiplets can have a doped or undoped semiconductor substrate thickness of 2 to no more than 5 μm , 5 to no more than 10 μm , 10 to no more than 20 μm , or 20 to no more than 50 μm . Chiplets can be micro-light-emitting diodes with a length greater than width, for example having a length to width aspect ratio greater than or equal to 2, 4, 8, 10, 20, or 50 and device contacts **22** that are adjacent to the ends of the printable semiconductor chiplets along the length of the printable semiconductor

chiplets. This structure enables low-precision manufacturing processes to electrically connect wires to the device contacts **22** without creating registration problems and possible unwanted electrical shorts or opens.

Methods of forming micro-transfer printable structures are described, for example, in the paper "AMOLED Displays using Transfer-Printed Integrated Circuits" and U.S. Pat. No. 8,889,485. Lithographic processes for forming chiplets, for example transistors, wires, and capacitors, can be found in the integrated circuit art. U.S. patent application Ser. No. 14/743,981, filed Jun. 18, 2015, entitled Micro Assembled LED Displays and Lighting Elements, incorporated by reference herein, describes micro-transfer printing structures and processes useful in structures and methods according to certain embodiments of the present invention. For a discussion of micro-transfer printing techniques see also U.S. Pat. Nos. 8,722,458, 7,622,367 and 8,506,867, the disclosure of each of which is hereby incorporated by reference in its entirety. Micro-transfer printing using compound micro assembly structures and methods can also be used in structures and methods according to certain embodiments of the present invention, for example, as described in U.S. patent application Ser. No. 14/822,868, filed Aug. 10, 2015, entitled Compound Micro-Assembly Strategies and Devices, which is hereby incorporated by reference in its entirety. A micro-device **20** can be a compound micro-system.

According to various embodiments of the present invention, a native source wafer **10** can be provided with micro-devices **20**, sacrificial portions **12**, tethers **16**, anchors **14**, and source connection posts **40** already formed, or they can be constructed as part of a method in accordance with certain embodiments of the present invention. In certain embodiments, device contacts **22** are planar electrical connections formed on a process side of micro-devices **20** and source wafer **10**. Such device contacts **22** are typically formed from metals such as aluminum or polysilicon using masking and deposition processes.

Connection posts **40** are electrical connections that extend generally perpendicular to the surface of a micro-device **20**. Such connection posts **40** can be formed from metals such as aluminum, titanium, tungsten, copper, silver, gold, or other conductive metals. Connection posts **40** can be formed by repeated masking and deposition processes that build up three-dimensional structures or by using a form. In some embodiments, connection posts **40** are made of one or more high elastic modulus metals, such as tungsten. As used herein, a high elastic modulus is an elastic modulus sufficient to maintain the function and structure of the connection post **40** when pressed into an electrical contact pad. Connection posts **40** can have a variety of aspect ratios and typically have a peak area smaller than a base area. Connection posts **40** can have a sharp point for embedding in or piercing electrical contact pads. Structures with protruding connection posts **40** are generally discussed in U.S. Pat. No. 8,889,485, referenced above, whose contents are incorporated by reference herein in their entirety.

In an exemplary micro-transfer printing process, a stamp includes a plurality of stamp posts (also referred to as pillars) that are pressed against corresponding released micro-devices **20** to adhere the components to the stamp posts to transfer the pressed components from the source wafer **10** to the stamp posts. A released micro-device **20** is one whose underlying sacrificial portion **12** has been etched to form a gap between the micro-device **20** and its source wafer **10**, wherein the etching has defined one or more tethers **16** physically connecting the released micro-device **20** to one or

more anchors **14** of the source wafer **10**. By pressing the stamp against the micro-devices **20**, the tethers **16** are broken or separated and the micro-devices **20** are adhered to the stamp posts, for example by van der Waal's forces. The stamp is removed from the source wafer **10**, leaving the micro-devices **20** adhered to the stamp posts. An adhesive layer can be provided on a destination substrate. The stamp is then placed adjacent to the destination substrate. The micro-devices **20** on the stamp posts of the transfer stamp are brought into alignment with electrical conductors on a destination substrate and pressed onto or into them by micro-transfer printing with sufficient mechanical pressure against the electrical conductors to drive the connection posts **40** into or through a surface of the electrical conductors to form a robust electrical contact between the connection posts **40** of the micro-devices **20** and the destination substrate electrical conductors. A sufficient mechanical pressure can be an amount of force needed to cause the substrate electrical conductors or connection post **40** to plastically deform as the connection post **40** is pressed into the substrate electrical conductors. Thus, in this exemplary embodiment, the connection posts **40** on the components may have sharp points and/or a high elastic modulus, for example, by incorporating tungsten. A connection post **40** can have a sharp point, for example, if the top of the post has an area less than 10 microns square, less than 5 microns square, or less than one micron square. The substrate electrical conductors can also provide adhesion to help adhere the components to the substrate. In some embodiments, components (e.g., micro-devices **20**) do not have connection posts **40** but are adhered to a substrate with an adhesive and photolithographic methods are used to form electrical connections.

The adhesion between the micro-devices **20** and the receiving side of the substrate should be greater than the adhesion between the micro-devices **20** and the stamp posts of the transfer stamp. Thus, when the transfer stamp is removed from the receiving side of the substrate, the micro-devices **20** adhere more strongly to the destination substrate than to the transfer stamp, thereby transferring the micro-devices **20** from the transfer stamp to the receiving side of the destination substrate.

The transfer stamp is then removed leaving the micro-devices **20** adhered to the destination substrate. An optional heat treatment can solder or weld connection posts **40** (if present) of micro-devices **20** to destination substrate electrical contacts. Thus, in a method in accordance with certain embodiments of the present invention, destination substrate electrical contacts (or connection posts **40**) are heated, causing a substrate electrical contact metal to reflow and improve adhesion between components (e.g., micro-devices **20**) and the substrate and improve the electrical connection to the connection posts **40**.

Connection posts **40** can be made by pattern-wise etching a forming layer. For example, a silicon **100** wafer can be etched by a combination of dielectric hard masks, photolithography, mask etching, and anisotropic silicon wet etching with, for example KOH or TMAH, or dry etching. A layer of conductive material is deposited, for example with evaporation, e-beam deposition, sputtering, or CVD, and patterned by etching through a patterned photo-resist mask, to form connection posts **40** at least in the form. Soft metals can be used, such as gold, silver, tin, solders, or hard materials such as Ti, W, Mo, Ta, Al, or Cu.

A destination substrate for receiving transfer-printed printable components can include a surface on or in which a plurality of non-planar contact pads or electrical conductors are formed and exposed on the surface so that electrical

connections can be made to the electrical conductors, such as electrical contact pads. The electrical contact pads can be multi-layer contact pads and can include a layer of solder. In some embodiments, electrical contact pads can be coated with a non-conductive layer or formed on a compliant non-conductive layer, to facilitate electrical connection and adhesion. The non-conductive layer can be a polymer or an adhesive or the compliant non-conductive layer can be a polymer.

According to some embodiments of the present invention, a source wafer **10** can be provided with electronic elements, electrodes **26**, and connection posts **40** already formed on the source wafer **10**. In some embodiments, an unprocessed source wafer **10** can be provided and electronic elements (e.g., micro-devices **20** or portions thereof), electrodes **26**, and connection posts **40** formed on the source wafer **10**. An unprocessed source wafer **10** is a substrate that does not yet include the electronic elements, electrodes **26**, and connection posts **40**. The unprocessed source wafer **10** can have other processing steps completed, for example, cleaning, deposition of material layers, or heat or chemical treatments. In certain embodiments, integrated circuits **21** are formed, for example using photo-lithographic processes including forming masks over a source wafer **10**, etching materials, removing masks, and depositing materials. Using such processes, integrated circuits **21** can be formed on or in a source wafer **10**.

In some embodiments, micro-devices **20** include small integrated circuits **21** (chipselets) formed in a semiconductor wafer, for example silicon or compound semiconductors such as gallium arsenide, which can have a crystalline structure. Processing technologies for these materials typically employ high heat and reactive chemicals. However, by employing transfer technologies that do not stress the chipselets or substrate materials, more benign environmental conditions can be used compared to thin-film manufacturing processes. Thus, certain embodiments of the present invention have an advantage in that flexible substrates, such as polymeric substrates, that are intolerant of extreme processing conditions (e.g. heat, chemical, or mechanical processes) can be employed for a destination substrates. Furthermore, it has been demonstrated that crystalline silicon substrates have strong mechanical properties and, in small sizes, can be relatively flexible and tolerant of mechanical stress. This is particularly true for substrates having 5-micron, 10-micron, 20-micron, 50-micron, or even 100-micron thicknesses.

Micro-devices **20** or chipselets disposed thereon or therein can be constructed using foundry fabrication processes. Layers of materials can be used, including materials such as metals, oxides, nitrides and other materials. Each chipselet can be a complete semiconductor integrated circuit **21** and can include, for example, transistors. Micro-devices **20** or chipselets can have different sizes, for example, 1000 square microns or 10,000 square microns, 100,000 square microns, or 1 square mm, or larger, and can have variable aspect ratios, for example 1:1, 2:1, 5:1, or 10:1. Micro-devices **20** or chipselets can be rectangular or can have other shapes.

Certain embodiments of the present invention provide advantages over other methods described in the prior art. By employing connection posts **40** on micro-devices **20** and a printing method that provides connection posts **40** adjacent to electrical contact pads on a destination substrate, a low-cost method for printing chipselets in large quantities over a destination substrate is enabled. Furthermore, in certain embodiments, additional process steps for electrically connecting micro-devices **20** to a destination substrate are

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obviated and faulty micro-devices may have already been removed prior to electrical connection.

As is understood by those skilled in the art, the terms “over” and “under” are relative terms and can be inter-
changed in reference to different orientations of the layers,
elements, and substrates included in the present invention.
For example, a first layer on a second layer, in some
implementations means a first layer directly on and in
contact with a second layer. In other implementations, a first
layer on a second layer includes a first layer and a second
layer with another layer therebetween.

Having described certain implementations of embodiments,
it will now become apparent to one of skill in the art
that other implementations incorporating the concepts of the
disclosure may be used. Therefore, the disclosure should not
be limited to certain implementations, but rather should be
limited only by the spirit and scope of the following claims.

Throughout the description, where apparatus and systems
are described as having, including, or comprising specific
components, or where processes and methods are described
as having, including, or comprising specific steps, it is
contemplated that, additionally, there are apparatus, and
systems of the disclosed technology that consist essentially
of, or consist of, the recited components, and that there are
processes and methods according to the disclosed technology
that consist essentially of, or consist of, the recited
processing steps.

It should be understood that the order of steps or order for
performing certain action is immaterial so long as the
disclosed technology remains operable. Moreover, two or
more steps or actions in some circumstances can be con-
ducted simultaneously. The invention has been described in
detail with particular reference to certain embodiments
thereof, but it will be understood that variations and modi-
fications can be effected within the spirit and scope of the
invention.

PARTS LIST

C cross section line segment
10 source wafer
12 sacrificial portion
14 anchor
16 tether
20 micro-device
21 integrated circuit (IC)/pixel controller
22 device contacts
23 IC tether/pixel controller tether
24 dielectric structure
25 opening
26 electrode
28 device substrate
29 encapsulation layer
30 test contact pads
32 test connections
40 connection post
50R red iLED
50G green iLED
50B blue iLED
99 transfer-printable micro-device wafer system
100 provide source wafer step
105 provide micro-transfer printable micro-devices step
110 provide test connections step
115 test micro-devices step
120 remove test connections step
125 remove faulty micro-devices step

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130 micro-transfer print micro-devices onto destination sub-
strate step

135 micro-transfer print missing micro-devices onto desti-
nation substrate step

The invention claimed is:

1. A method of making and testing transfer-printable
micro-devices on a source wafer, comprising:

providing the source wafer comprising a plurality of
sacrificial portions spatially separated by anchors, the
source wafer comprising one or more test contact pads;
providing at least one micro-device disposed entirely over
each of the plurality of sacrificial portions, each of the
at least one micro-device physically connected to at
least one of the anchors;

providing one or more electrical test connections from
each of the at least one micro-device to a corresponding
test contact pad;

testing the at least one micro-device disposed over each of
the plurality of sacrificial portions through the one or
more test connections to determine one or more func-
tional micro-devices and one or more faulty micro-
devices; and

removing at least a portion of the one or more test
connections.

2. The method of claim 1, comprising etching the plurality
of sacrificial portions thereby suspending each micro-device
over a corresponding sacrificial portion by at least one
corresponding tether.

3. The method of claim 2, wherein etching the plurality of
sacrificial portions also removes at least a portion of the one
or more test connections.

4. The method of claim 2, wherein removing at least a
portion of the one or more test connections at least partially
defines the at least one corresponding tether for each micro-
device.

5. The method of claim 2, comprising providing a desti-
nation substrate and micro-transfer printing the at least one
micro-device disposed entirely over each of the plurality of
sacrificial portions to the destination substrate.

6. The method of claim 5, comprising removing the one
or more faulty micro-devices from the destination substrate.

7. The method of claim 1, comprising removing the one
or more faulty micro-devices from the source wafer.

8. The method of claim 7, comprising:
providing a destination substrate; and
micro-transfer printing only the one or more functional
micro-devices to the destination substrate.

9. The method of claim 1, comprising:
providing one or more test circuits disposed on or in the
source wafer, wherein the test circuits are connected to
the one or more test contact pads; and
operating the one or more test circuits to test the micro-
devices.

10. The method of claim 1, wherein the micro-devices
comprise light emitters.

11. The method of claim 10, comprising:
providing an optical device for receiving light from the
light emitters; and determining the one or more func-
tional micro-devices and the one or more faulty micro-
devices using the optical device.

12. The method of claim 1, comprising:
providing an external test controller; and
electrically connecting the external test controller to the
one or more test contact pads to test the at least one
micro-device disposed over each of the plurality of
sacrificial portions.

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13. A transfer-printable micro-device wafer system, comprising:

a source wafer comprising a plurality of sacrificial portions spatially separated by anchors, the source wafer further comprising one or more test contact pads;

a micro-device disposed entirely over each of the plurality of sacrificial portions, the micro-device physically connected to at least one of the anchors by one or more tethers; and

one or more electrical test connections electrically connecting the micro-device to a corresponding test contact pad,

wherein the one or more test connections are formed on a part of the source wafer other than the one or more tethers.

14. The transfer-print micro-device wafer system of claim 13, wherein the micro-device comprises one or more inorganic light-emitting diodes.

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15. The transfer-print micro-device wafer system of claim 14, wherein the micro-device comprises a device substrate separate from the source wafer and each of the one or more inorganic light-emitting diodes (iLEDs) comprises an iLED substrate separate from the source wafer and the device substrate.

16. The transfer-print micro-device wafer system of claim 14, wherein the micro-device comprises a controller for controlling the one or more inorganic light-emitting diodes.

17. The transfer-print micro-device wafer system of claim 16, wherein the controller comprises a controller substrate separate from the source wafer and the device substrate.

18. The transfer-print micro-device wafer system of claim 16, wherein the one or more test connections are electrically connected to the controller and the controller controls the one or more iLEDs to emit light in response to test signals provided through the one or more test connections.

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