US 20200258761A1

(19) United States
(12) Patent Application Publication
Pearson et al.
(10) Pub. No.: US 2020/0258761 A1
(43) Pub. Date: Aug. 13, 2020

(54) **PRINTING COMPONENT ARRAYS WITH DIFFERENT ORIENTATIONS**

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(21) Appl. No.: **16/274,969**

(22) Filed: **Feb. 13, 2019**

Publication Classification

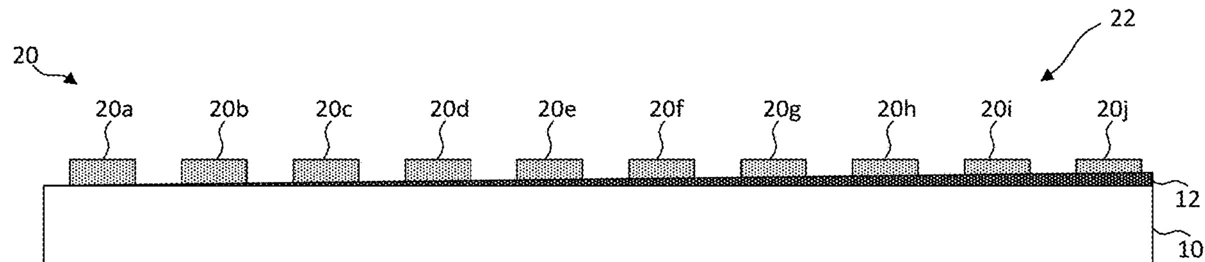
(51) **Int. Cl.**

H01L 21/67	(2006.01)
H01L 25/075	(2006.01)
H01L 33/62	(2006.01)
B65G 47/90	(2006.01)
B41F 16/00	(2006.01)

(52) **U.S. Cl.**
CPC ***H01L 21/67144*** (2013.01); ***H01L 25/0753*** (2013.01); *H01L 2933/0066* (2013.01); ***B65G 47/90*** (2013.01); ***B41F 16/006*** (2013.01); ***H01L 33/62*** (2013.01)

(57) **ABSTRACT**

A method of micro-transfer printing comprises providing a component source wafer and components disposed in, on, or over the component source wafer. A destination substrate and a stamp for transferring the components from the component source wafer to the destination substrate is provided. The component source wafer has an attribute or structure that varies across the component source wafer that affects the structure, operation, appearance, or performance of the components. A first array of components is transferred from the component source wafer to the destination substrate with a first orientation. A second array of components is transferred from the component source wafer to the destination substrate with a second orientation different from the first orientation. Components can be transferred by micro-transfer printing and different orientations can be a different rotation, overlap, interlacing, or offset.



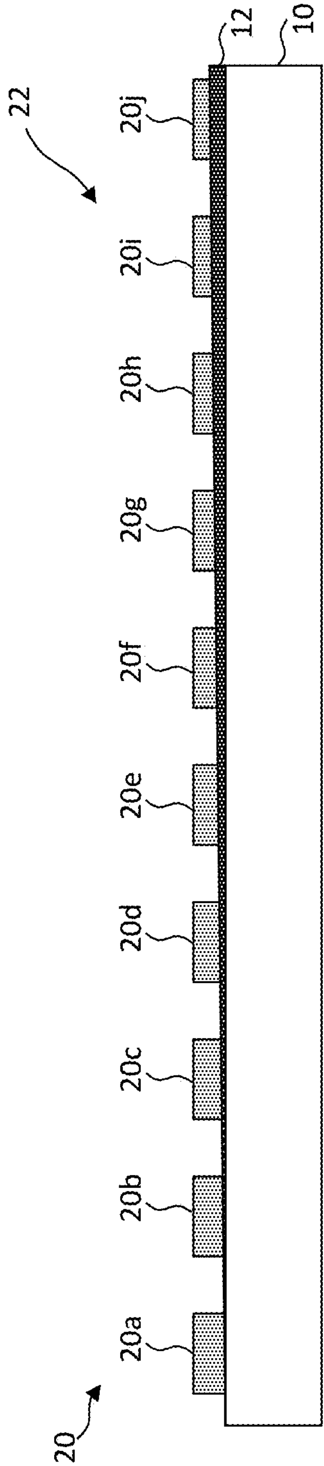


FIG. 1

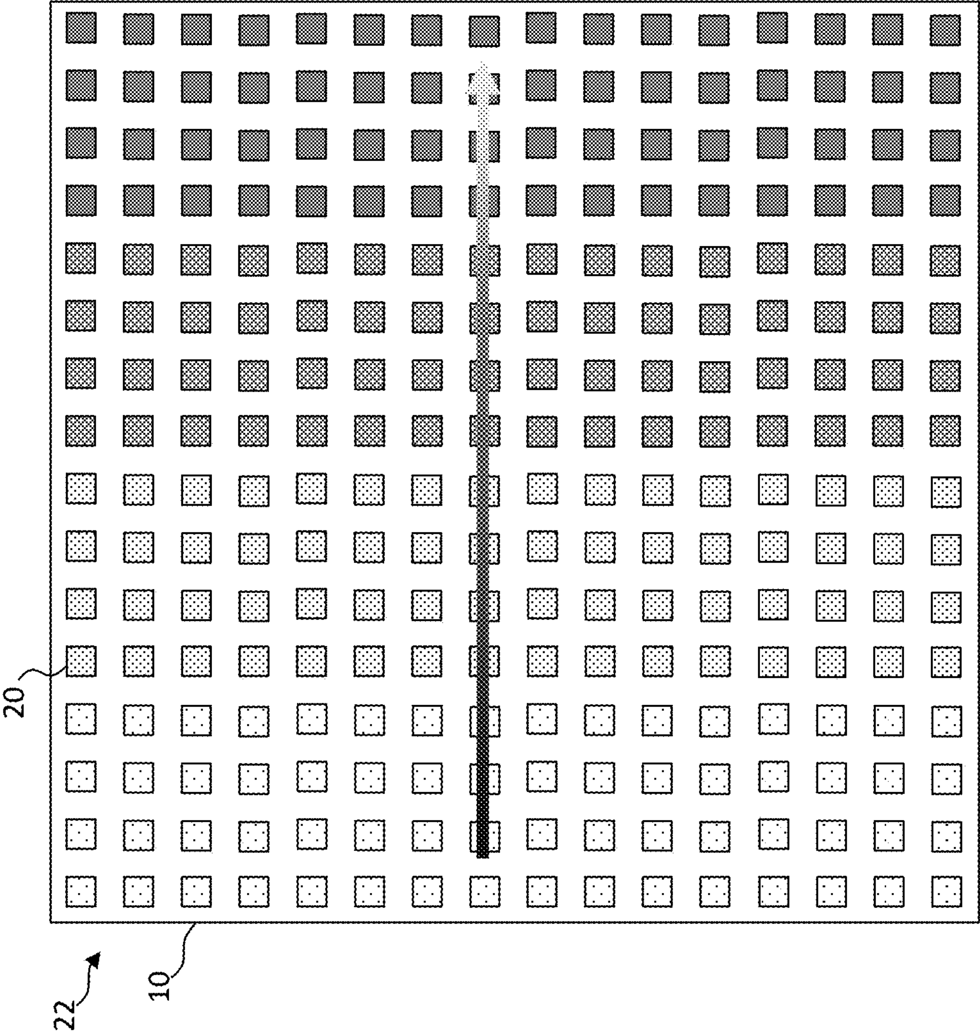


FIG. 2

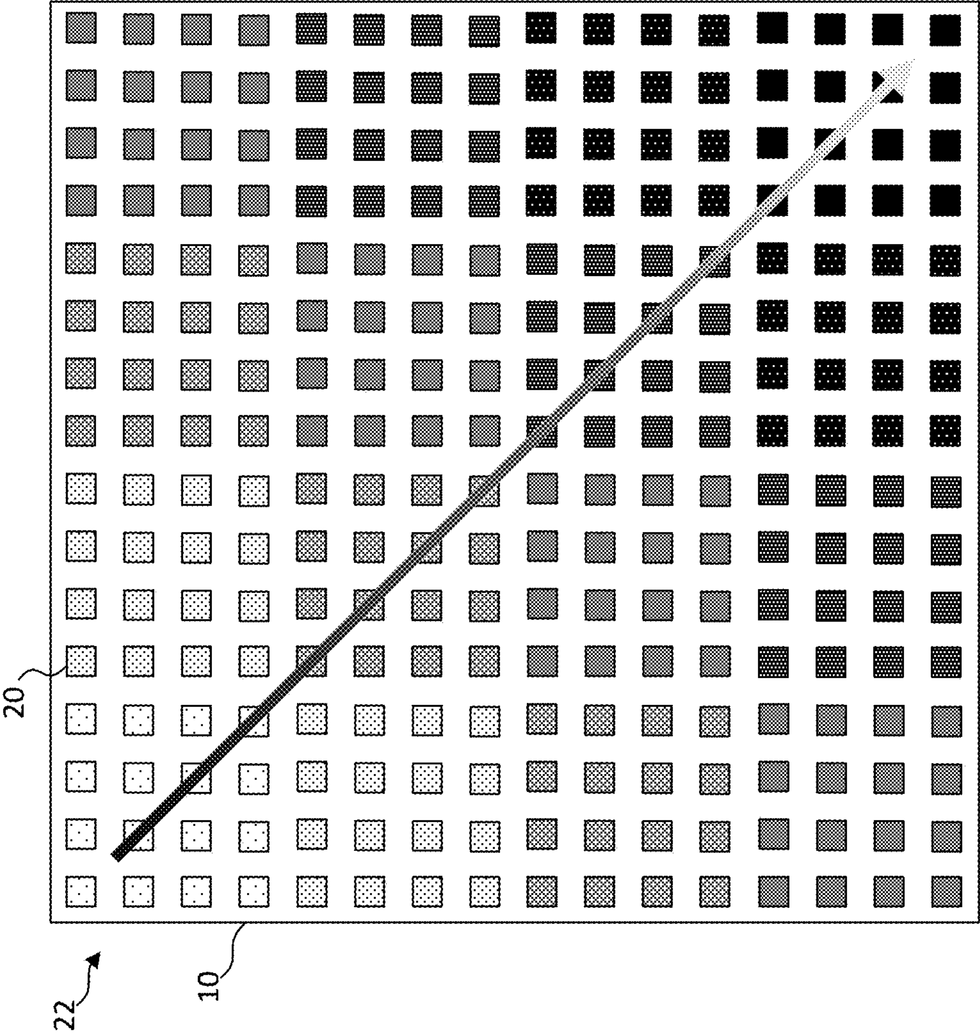


FIG. 3

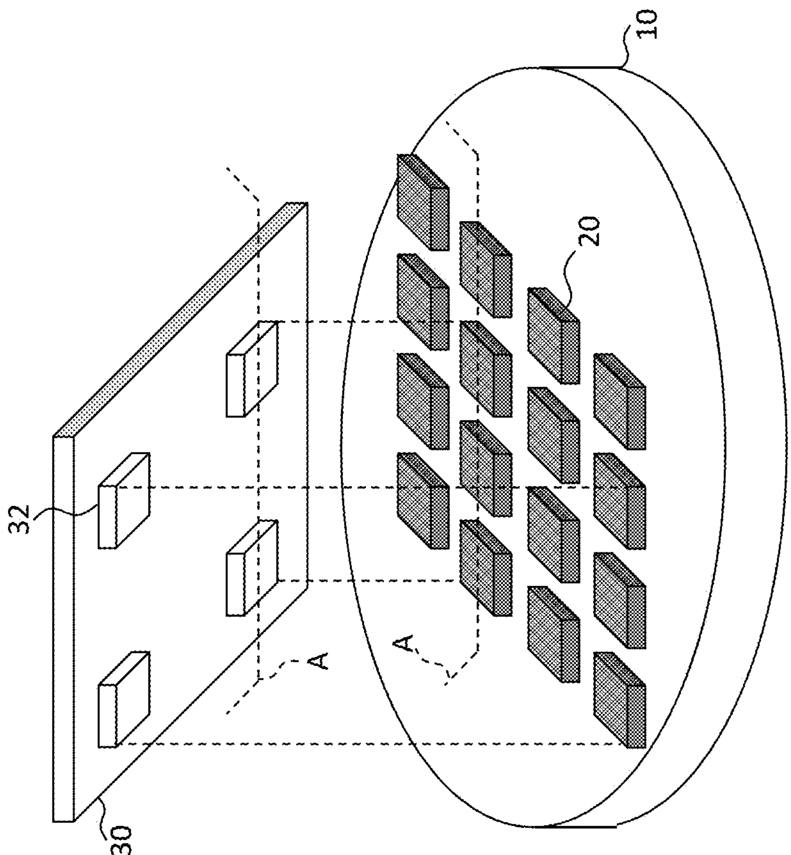


FIG. 4A

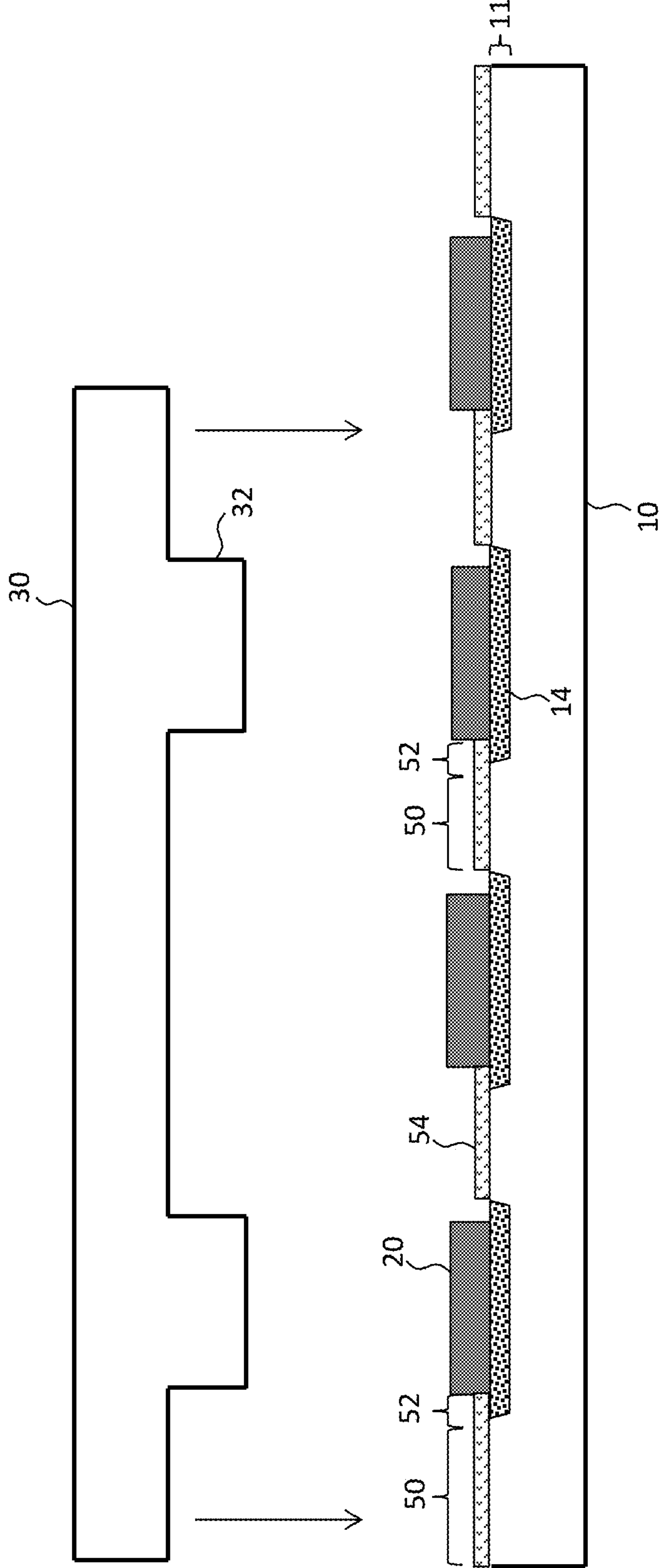


FIG. 4B

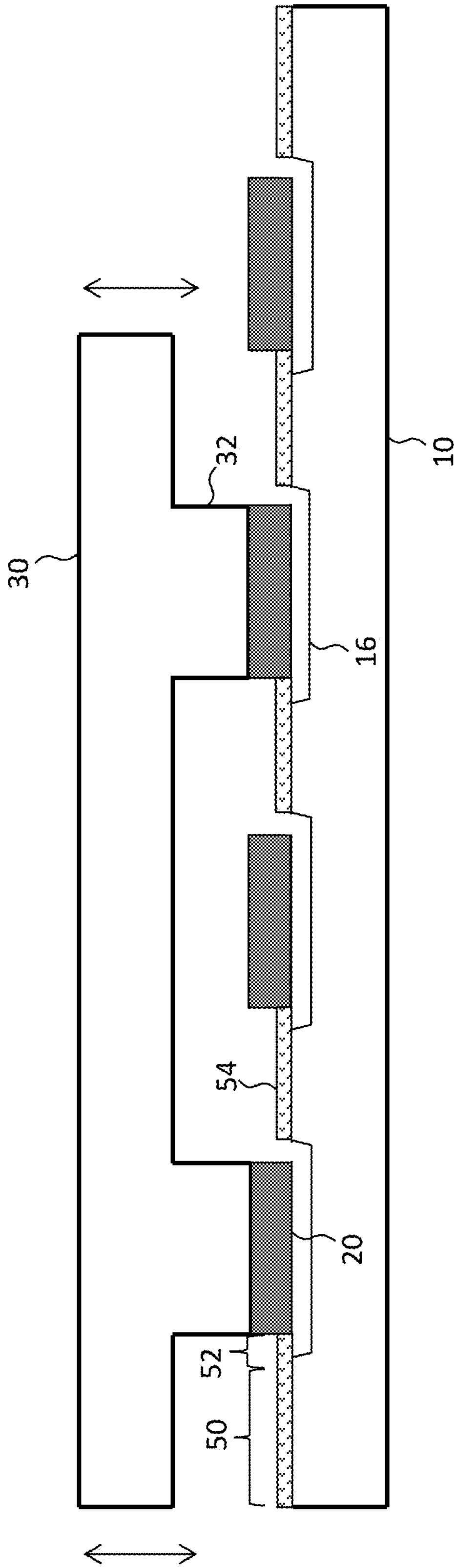


FIG. 5

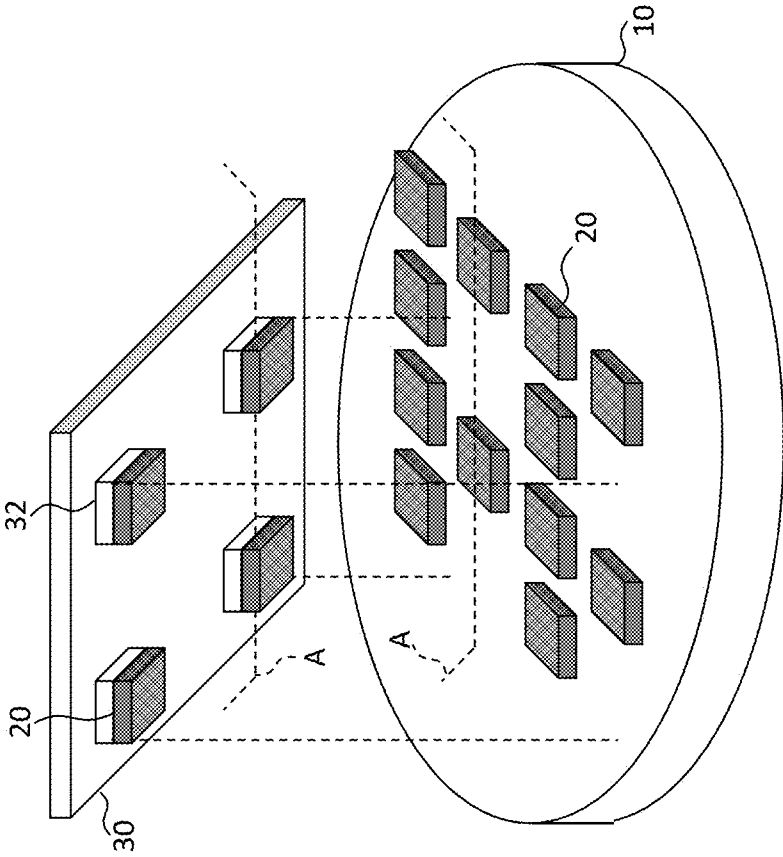


FIG. 6A

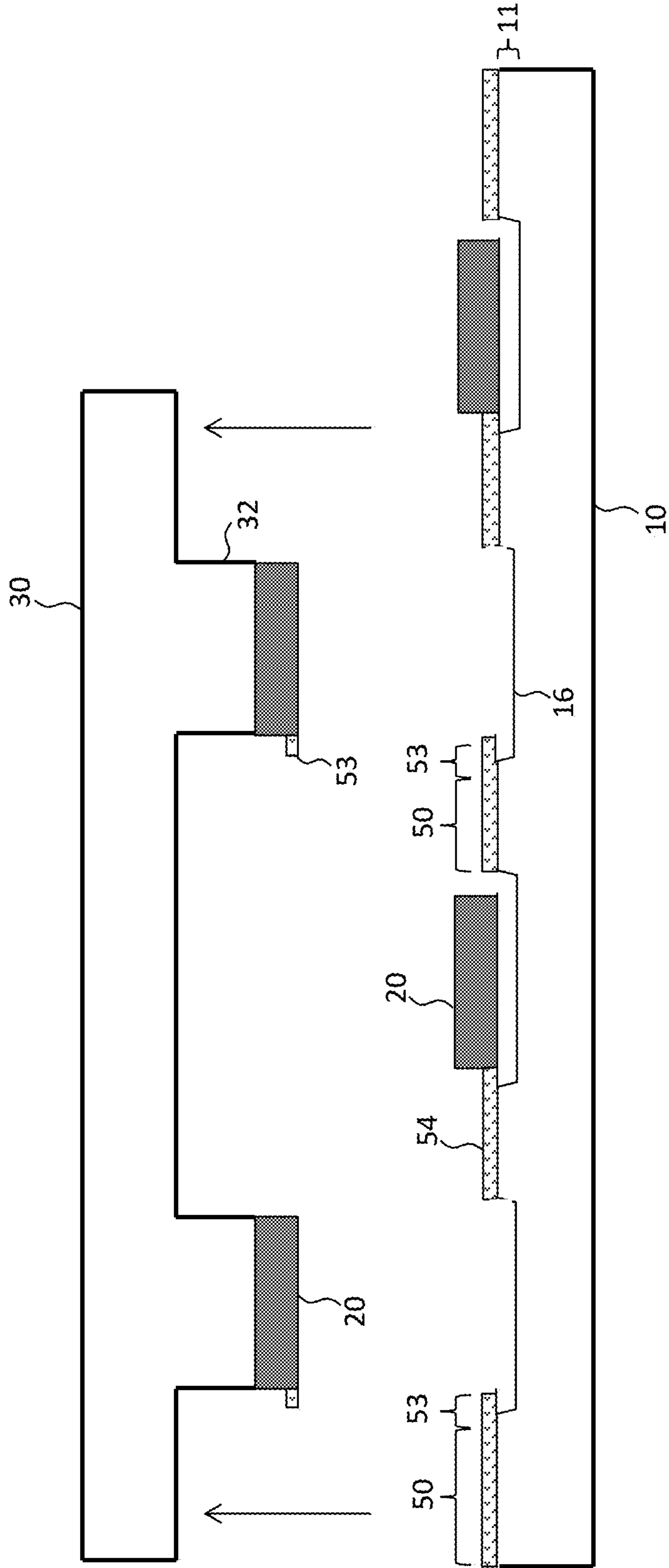


FIG. 6B

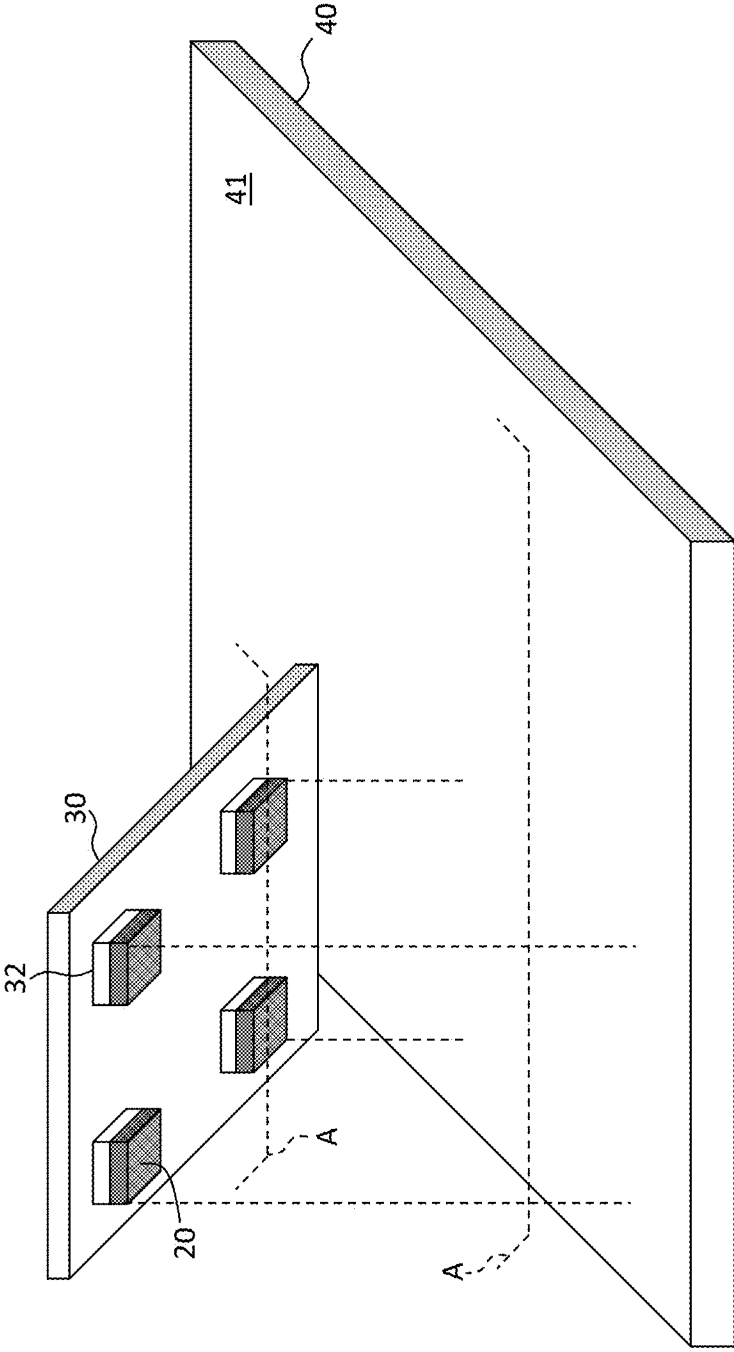


FIG. 7A

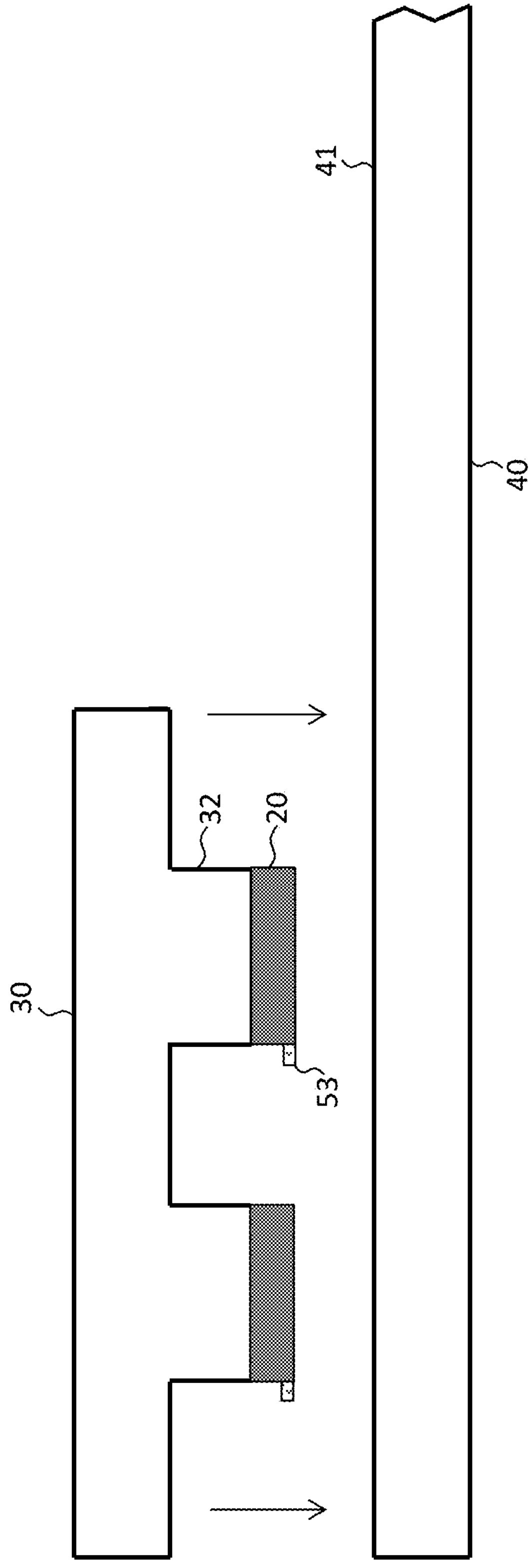


FIG. 7B

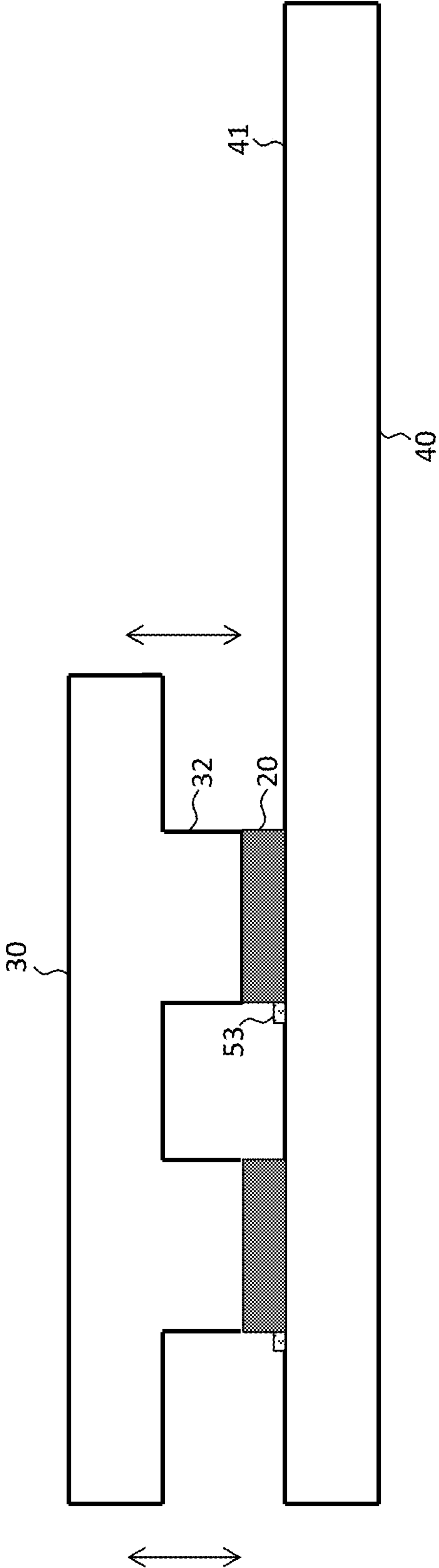


FIG. 8

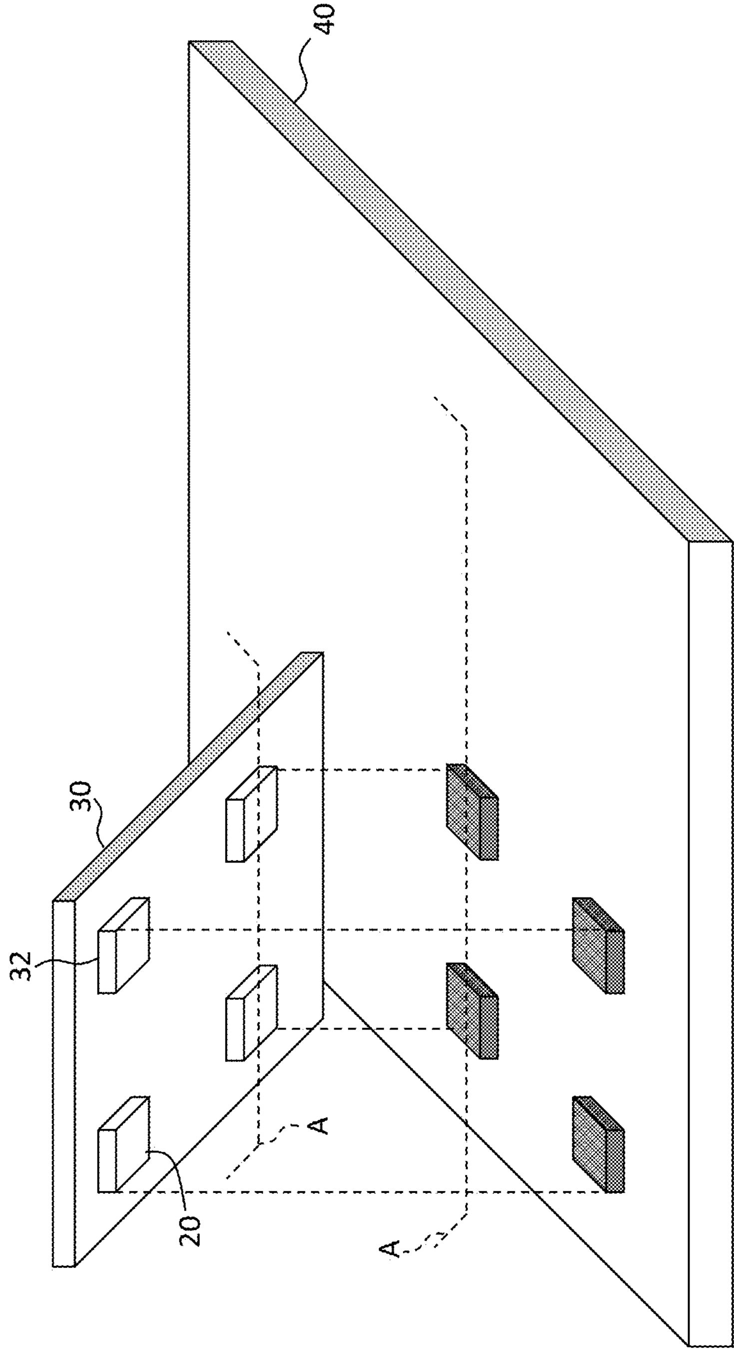


FIG. 9A

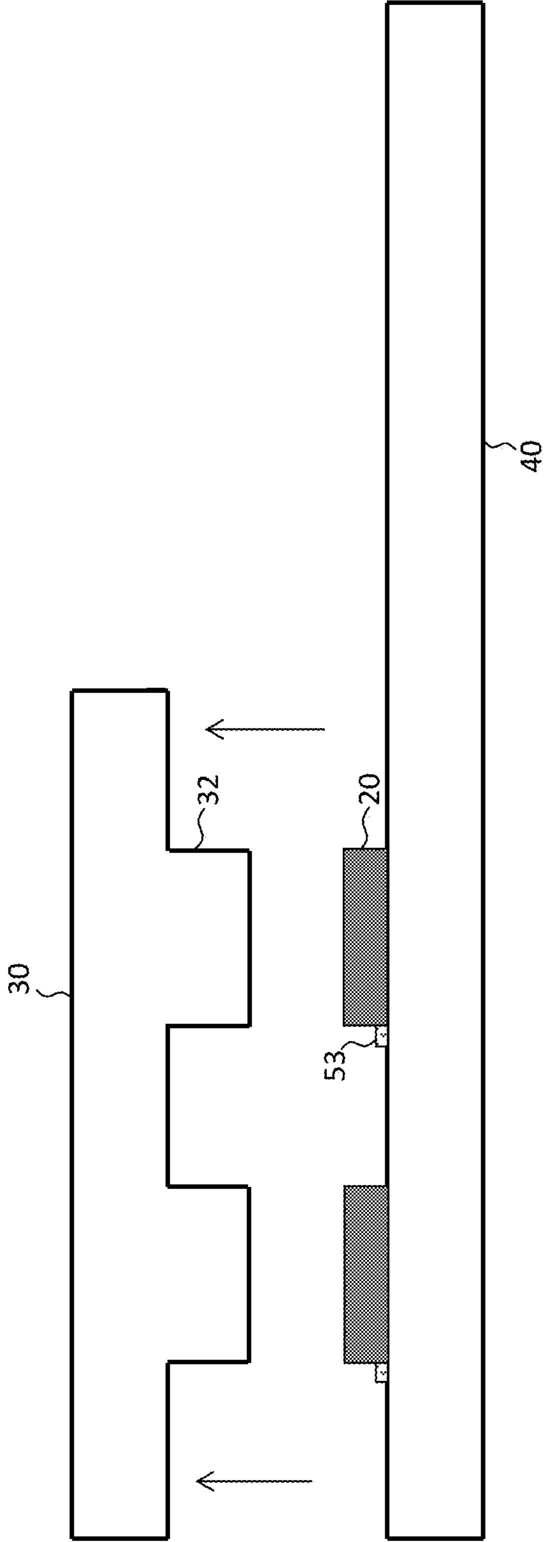


FIG. 9B

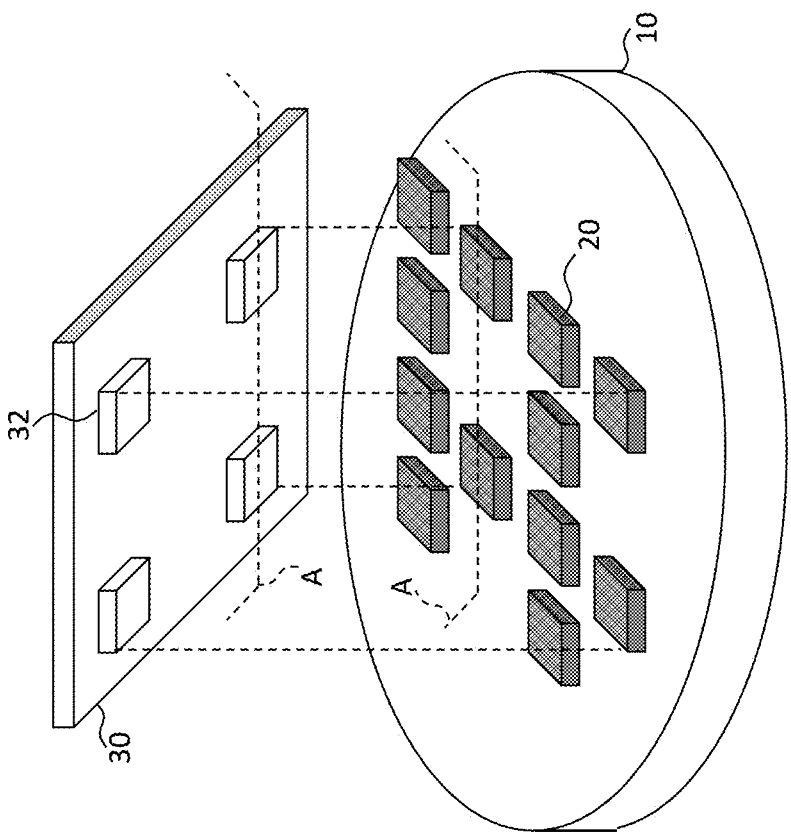


FIG. 10A

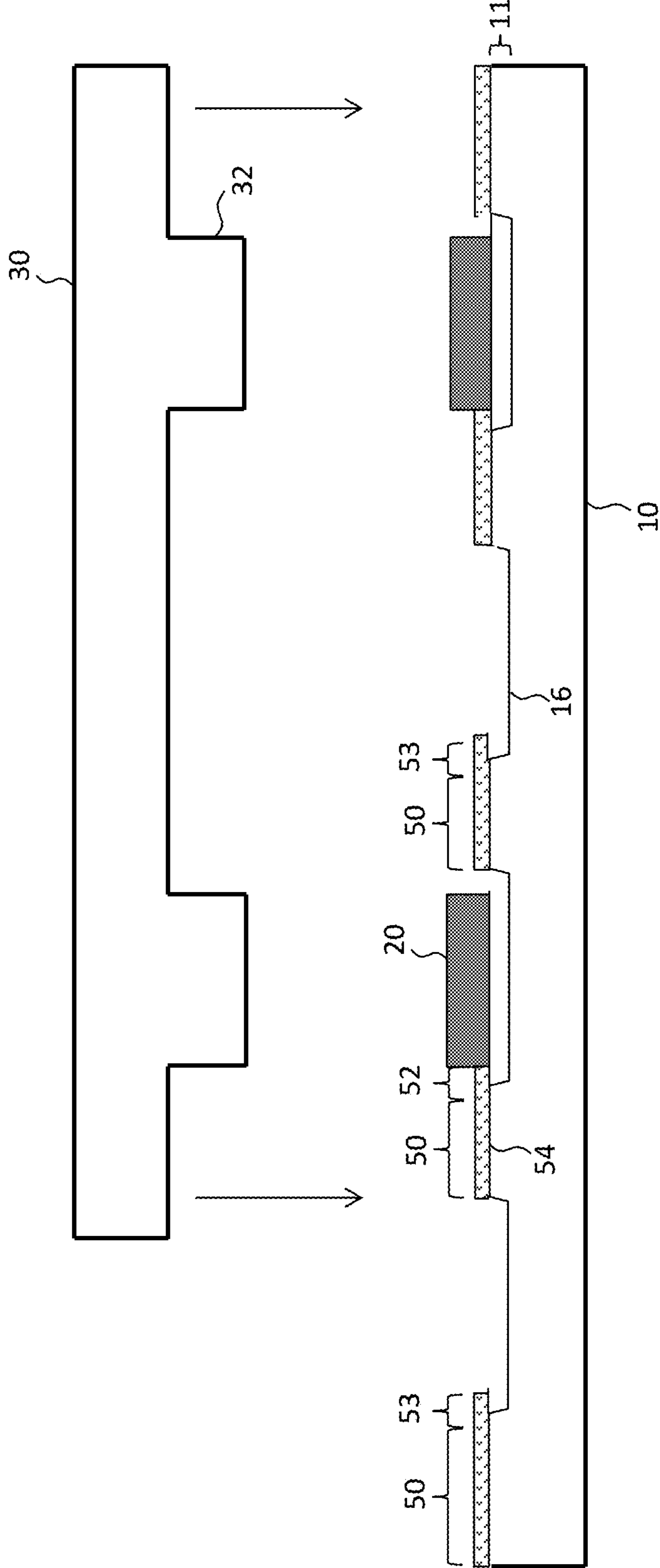


FIG. 10B

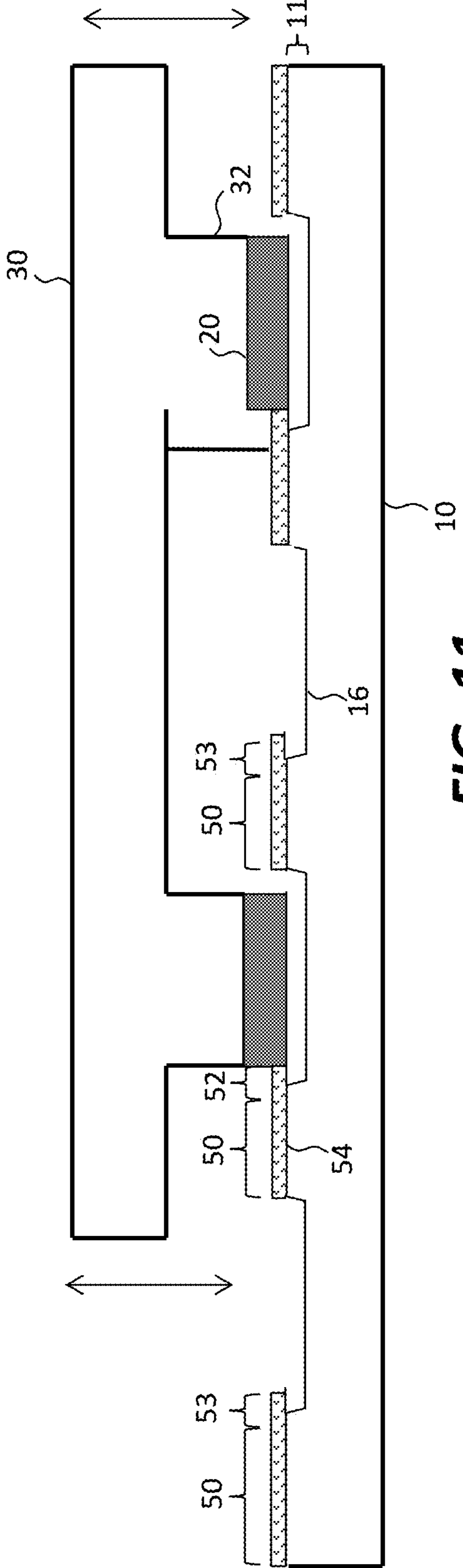


FIG. 11

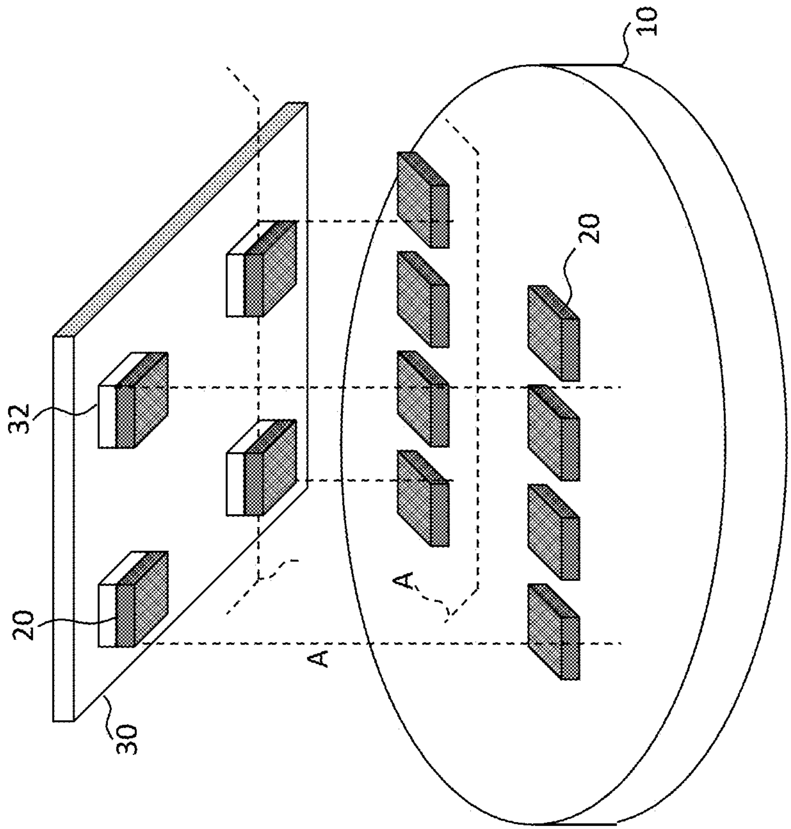


FIG. 12A

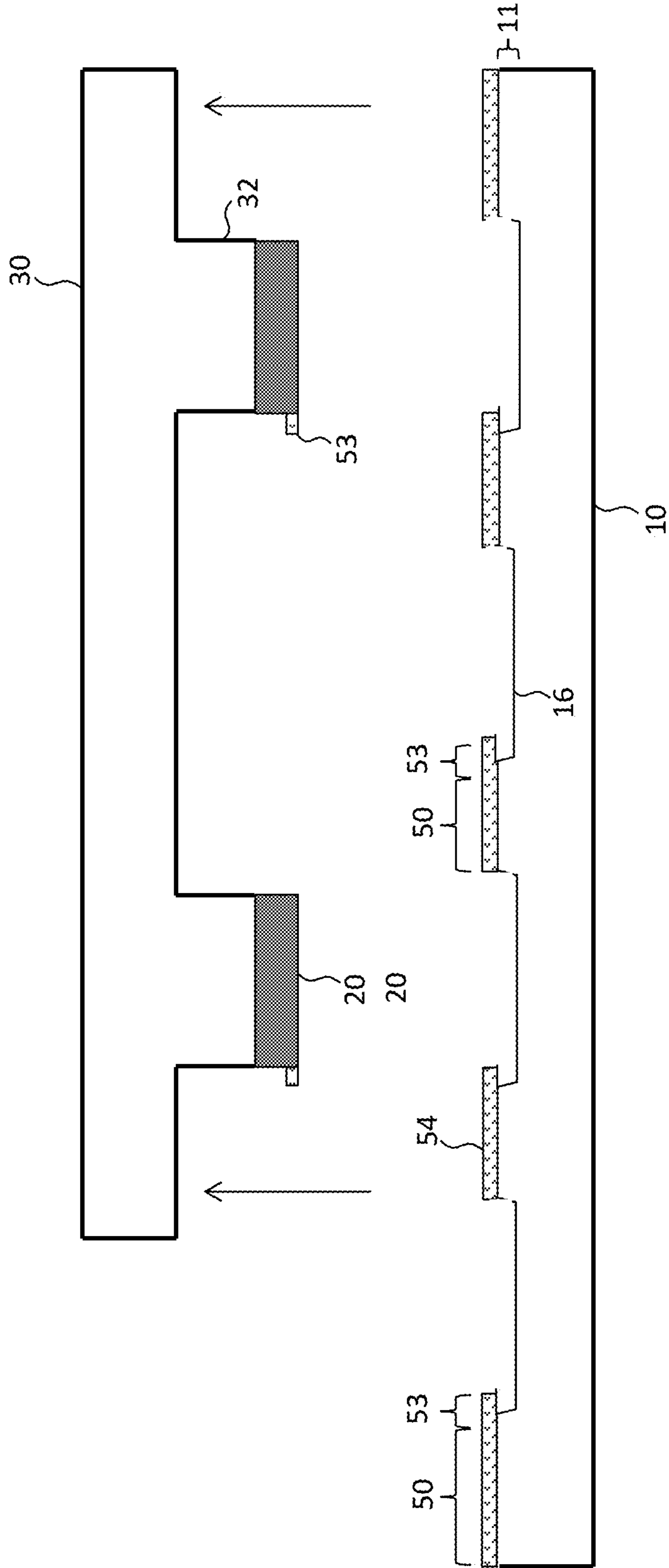


FIG. 12B

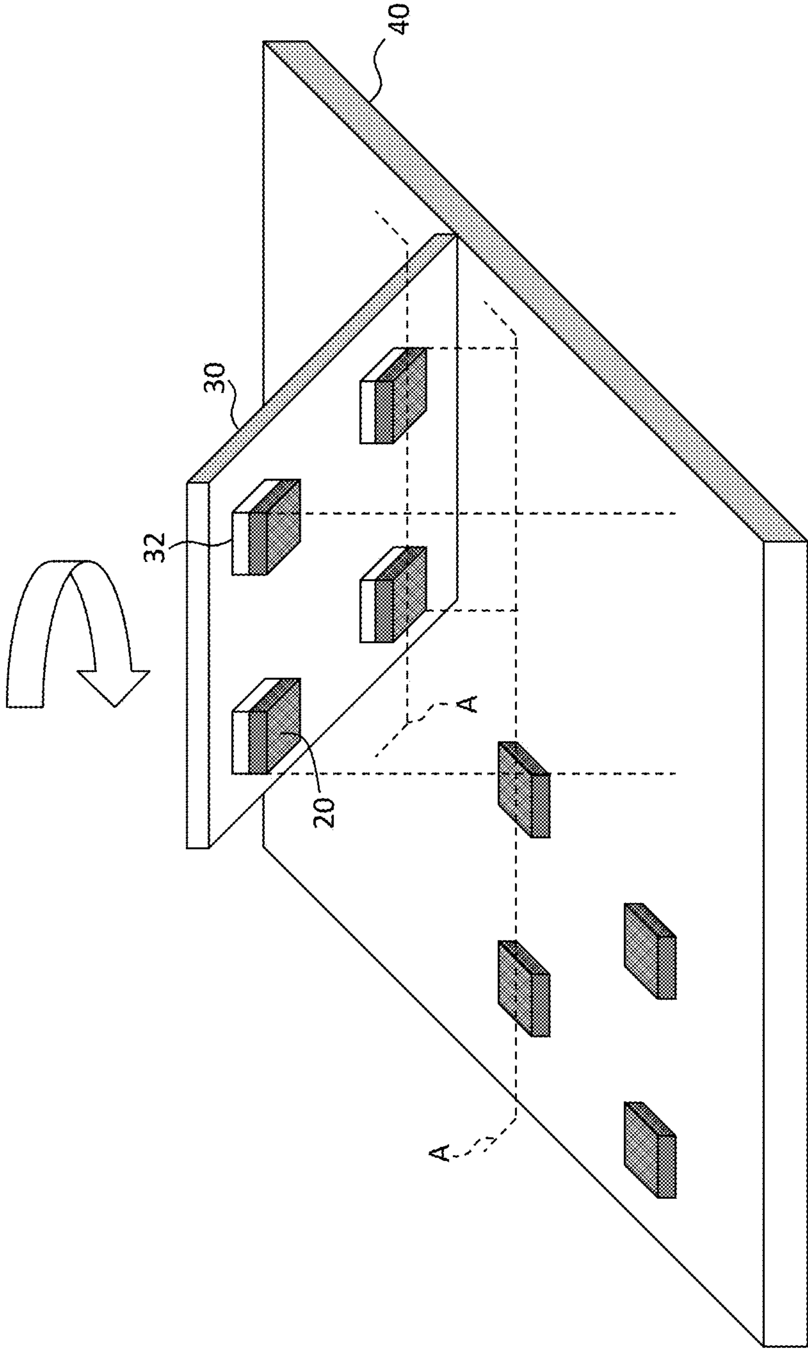


FIG. 13A

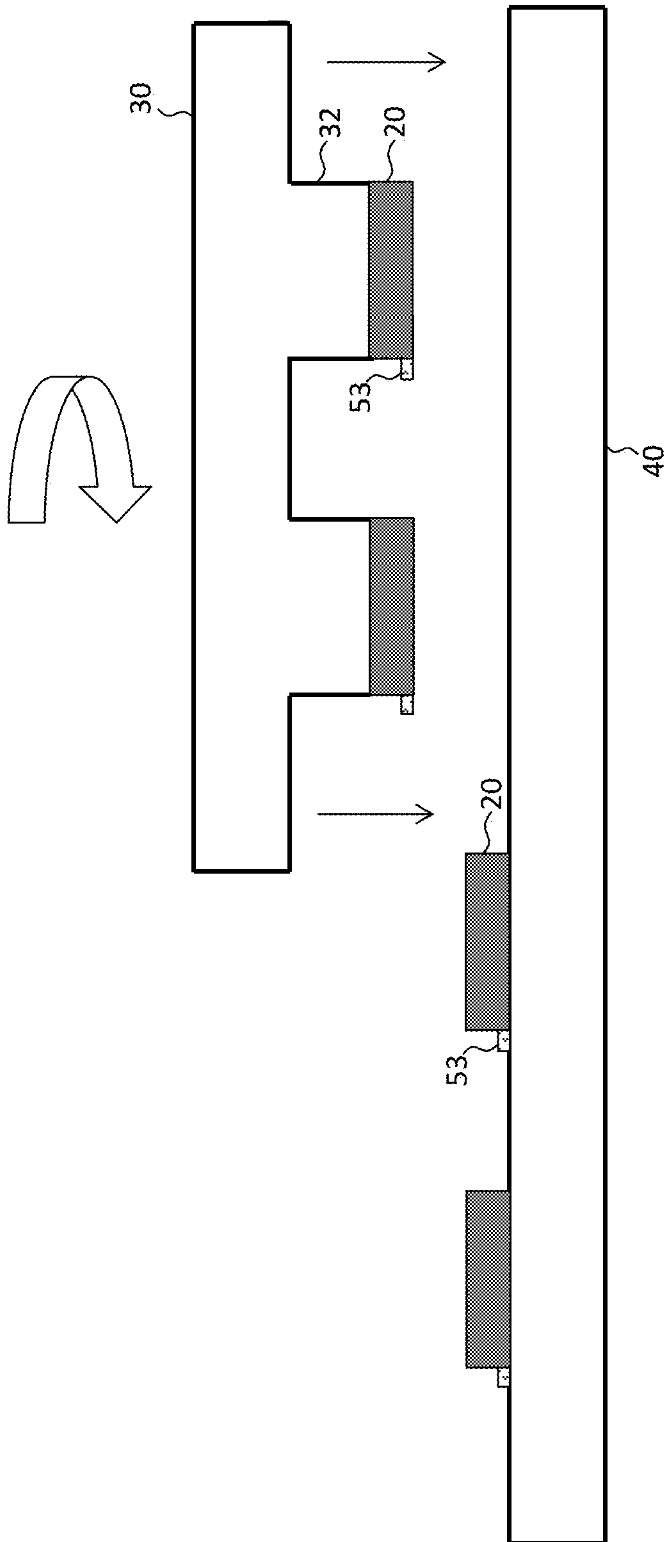


FIG. 13B

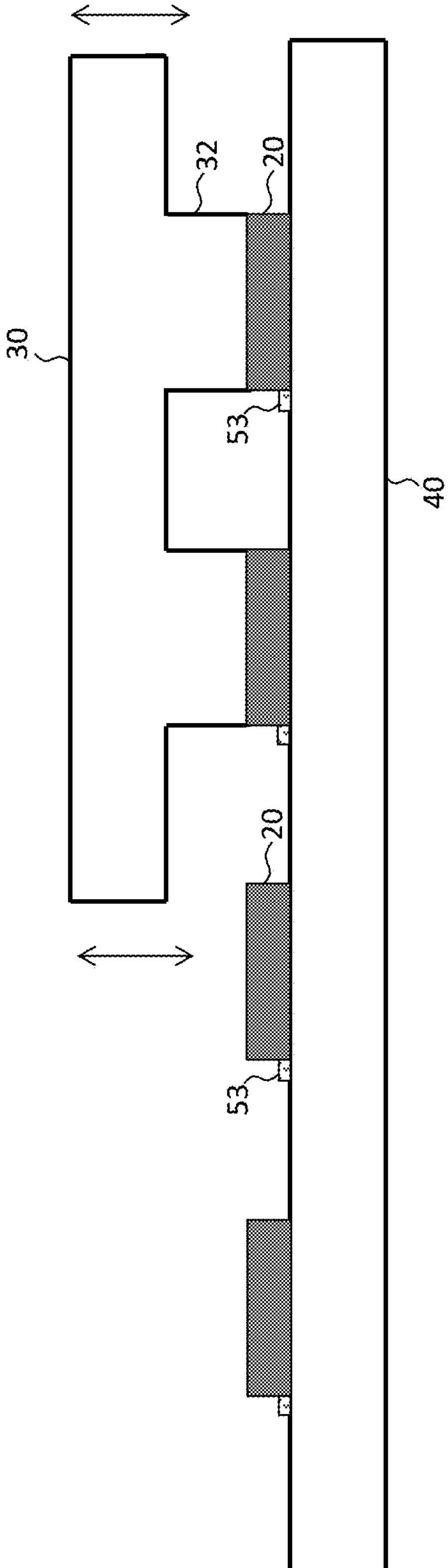


FIG. 14

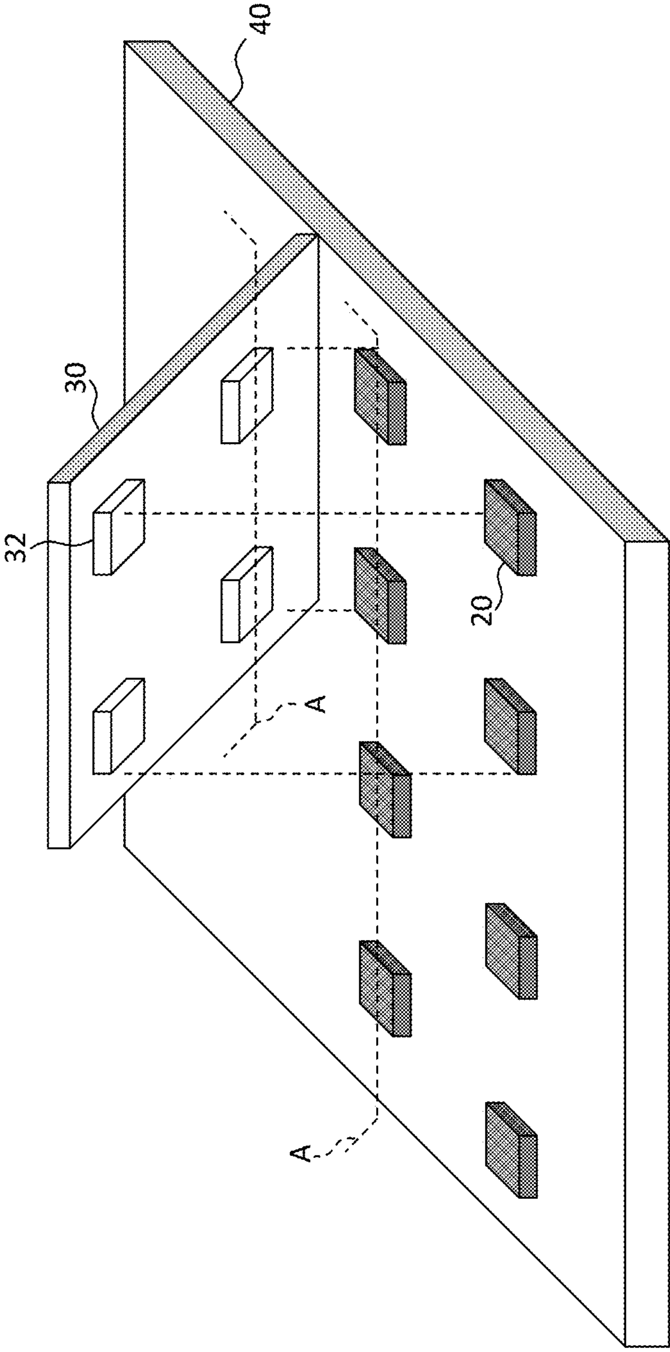


FIG. 15A

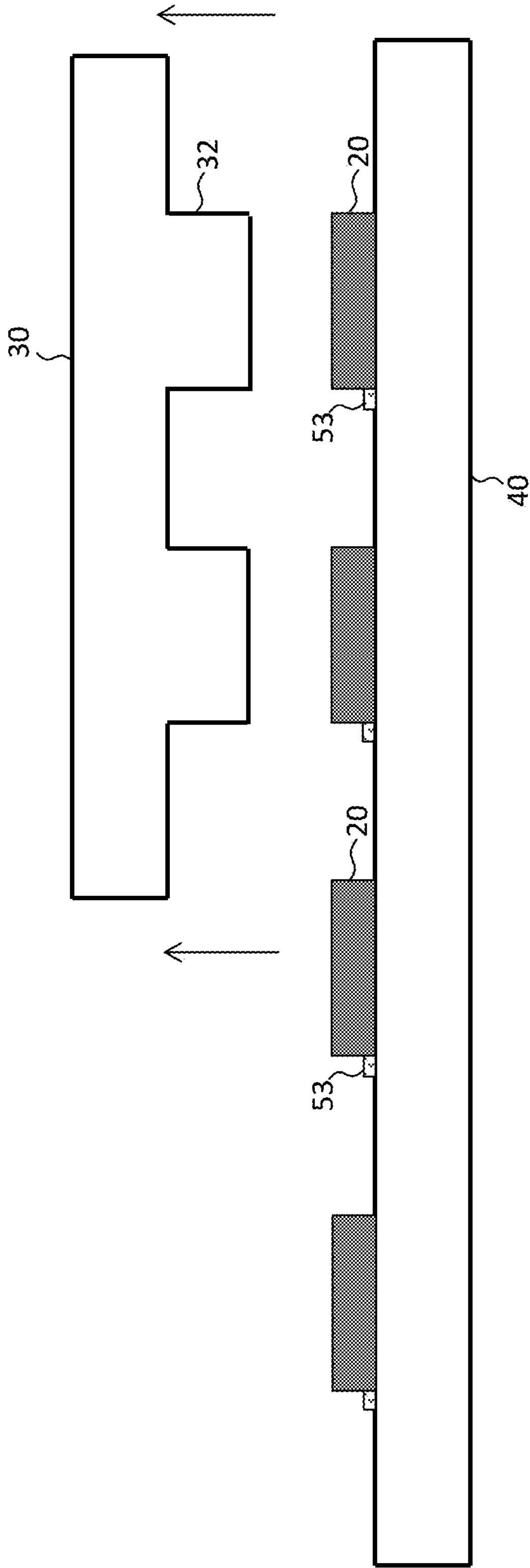


FIG. 15B

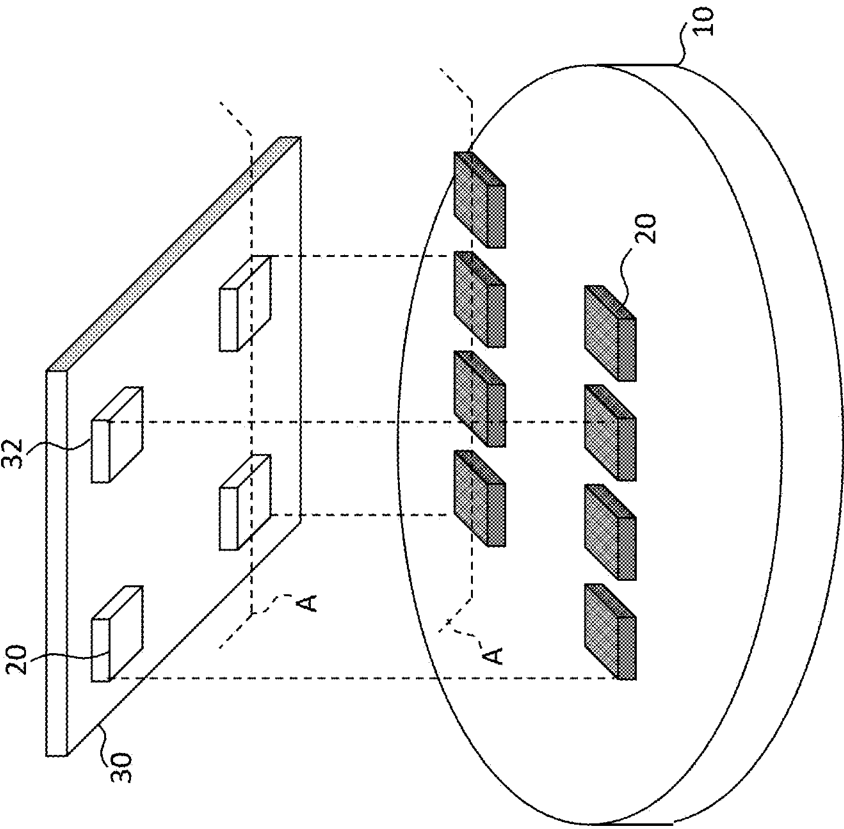


FIG. 16

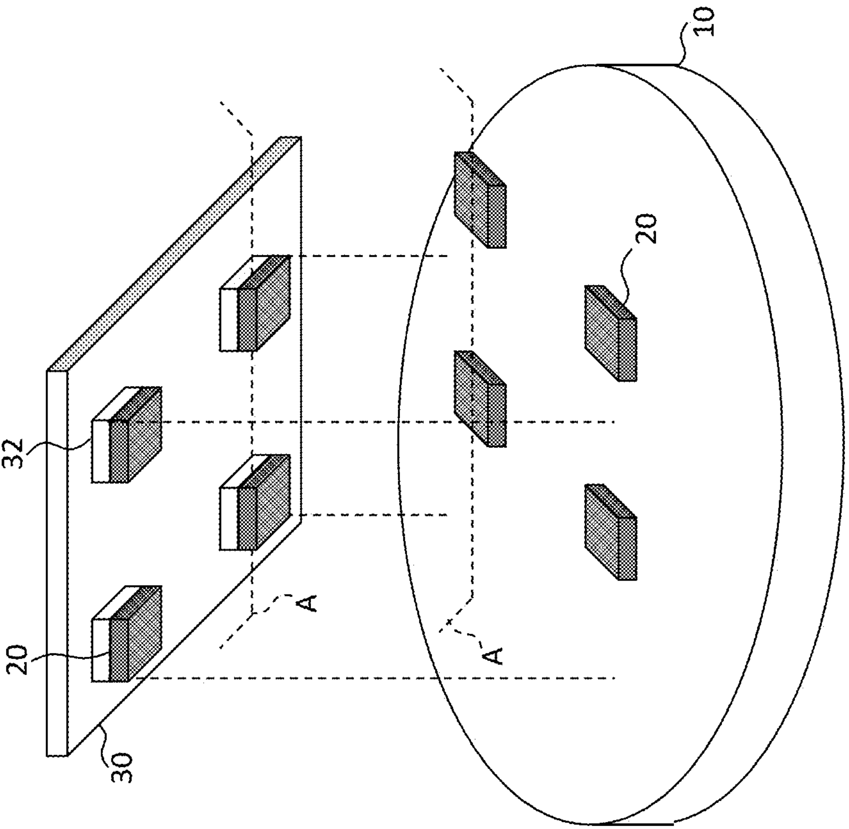
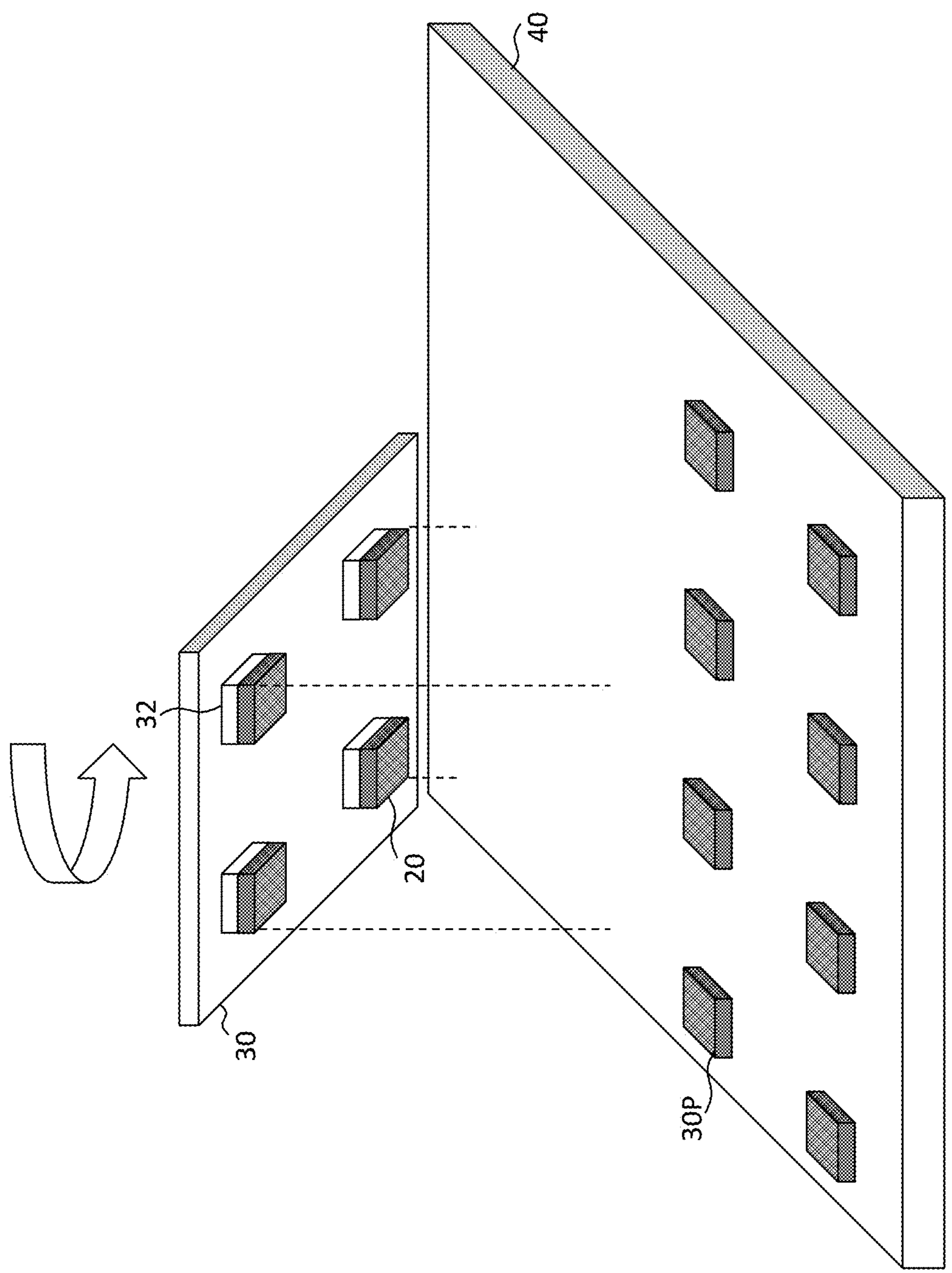


FIG. 17



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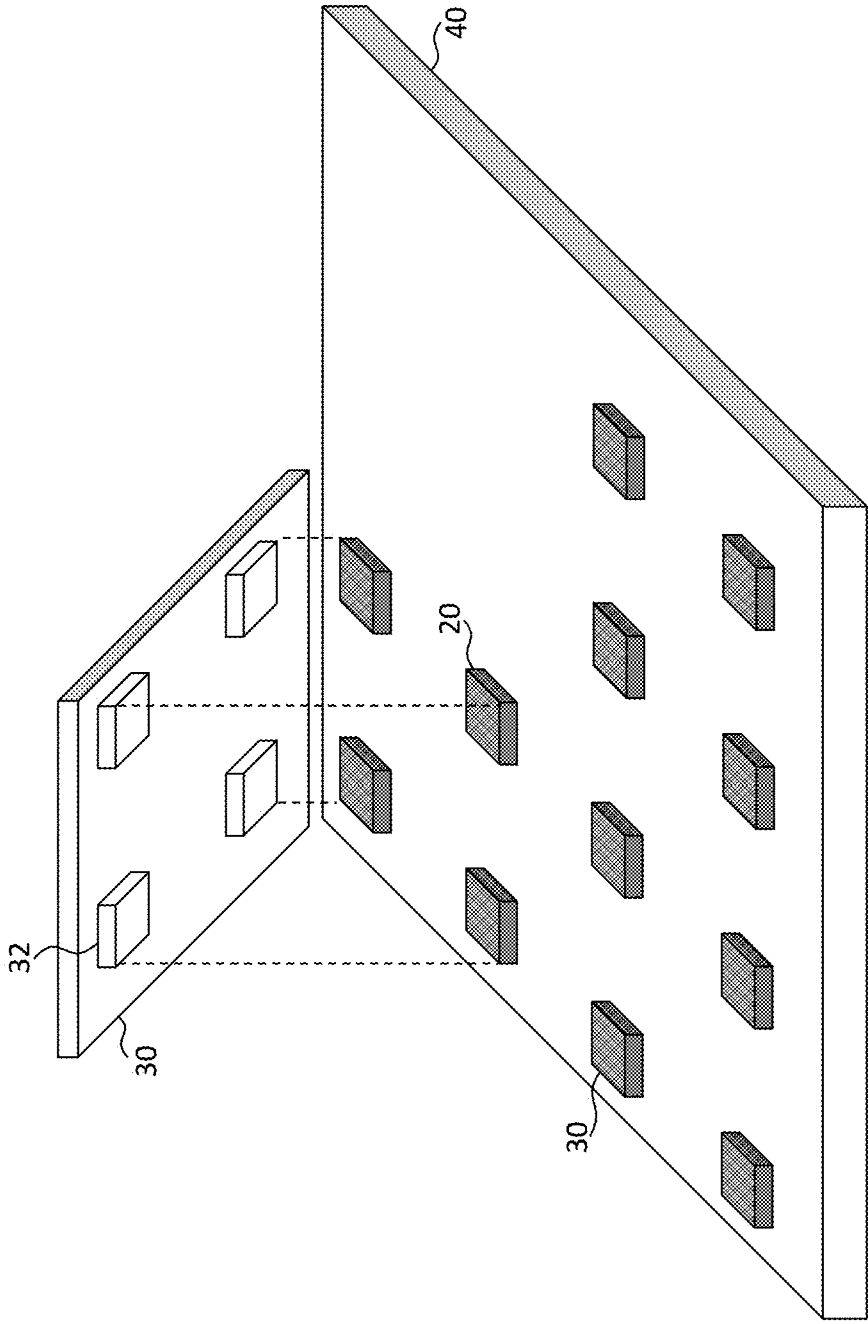

FIG. 19

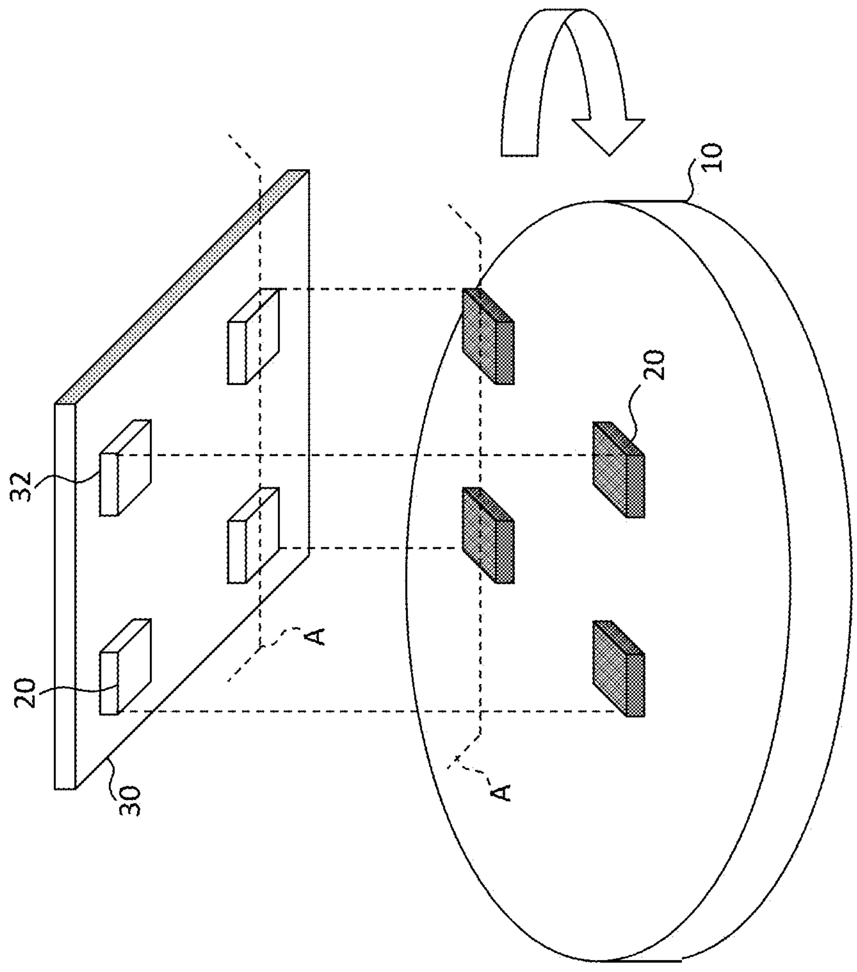

FIG. 20

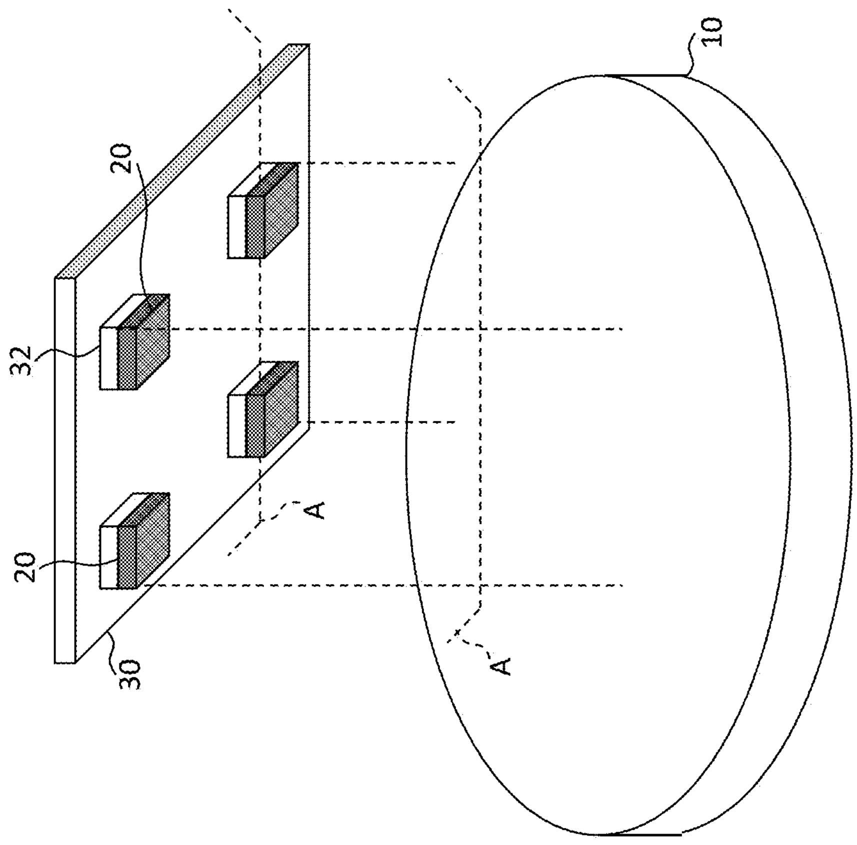

FIG. 21

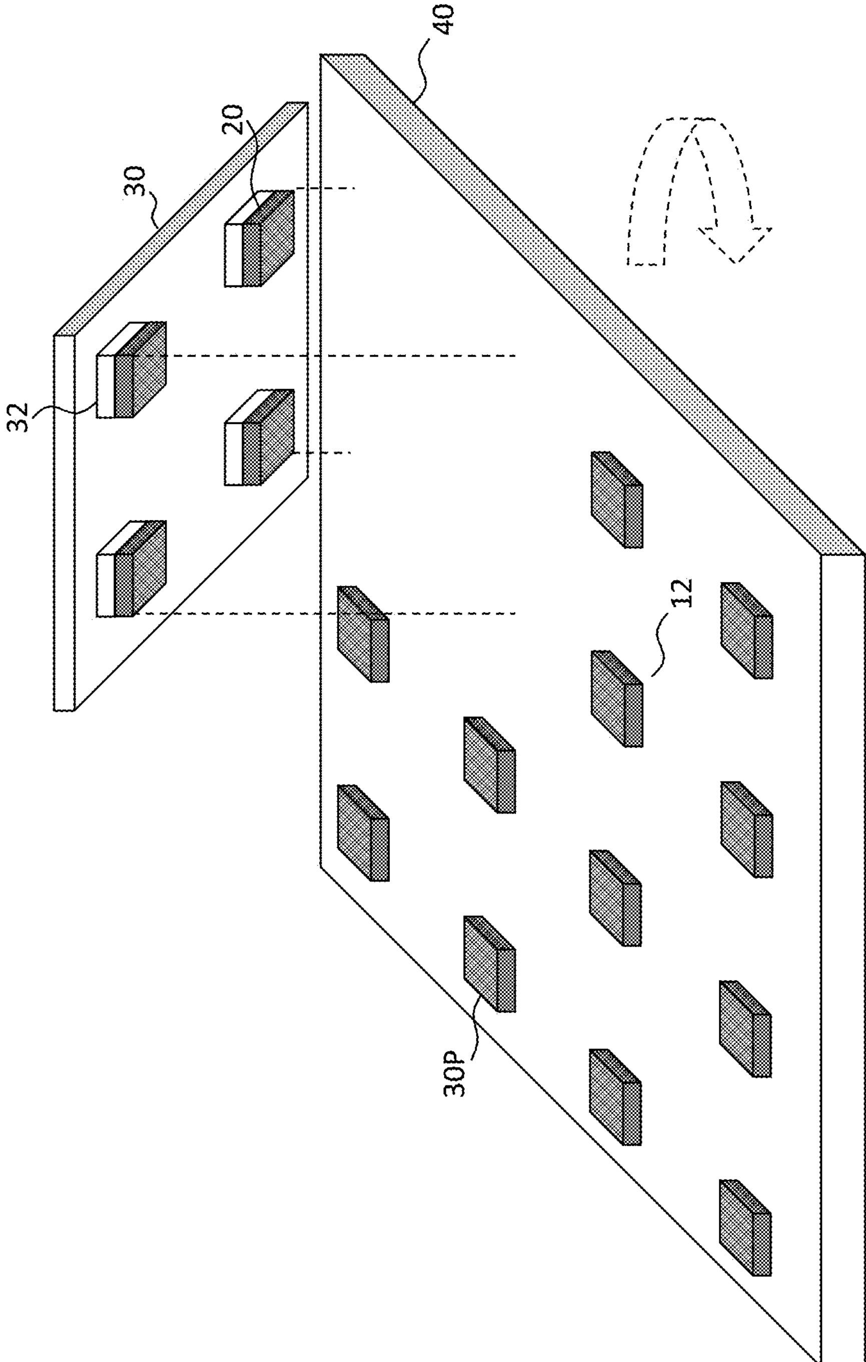

FIG. 22

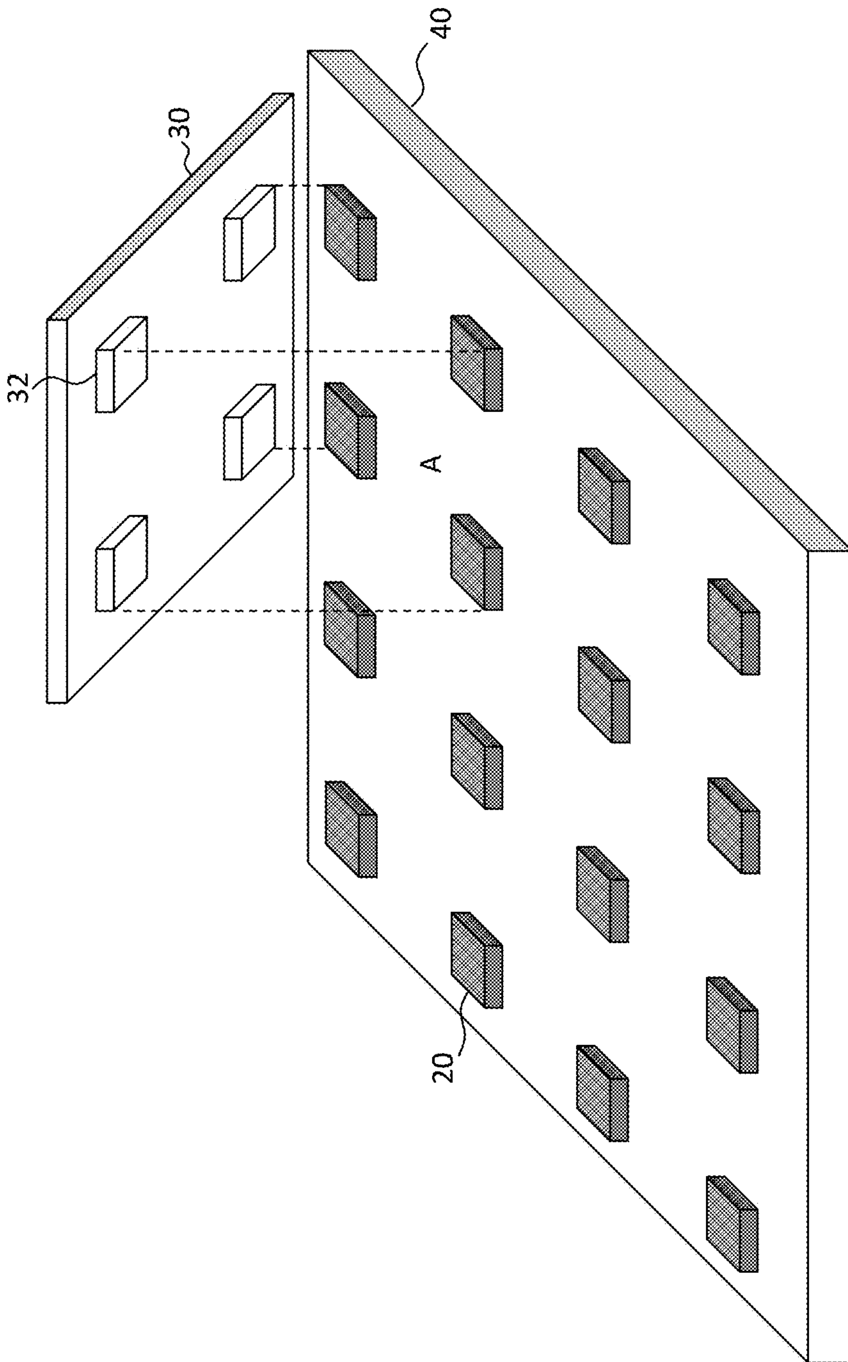

FIG. 23

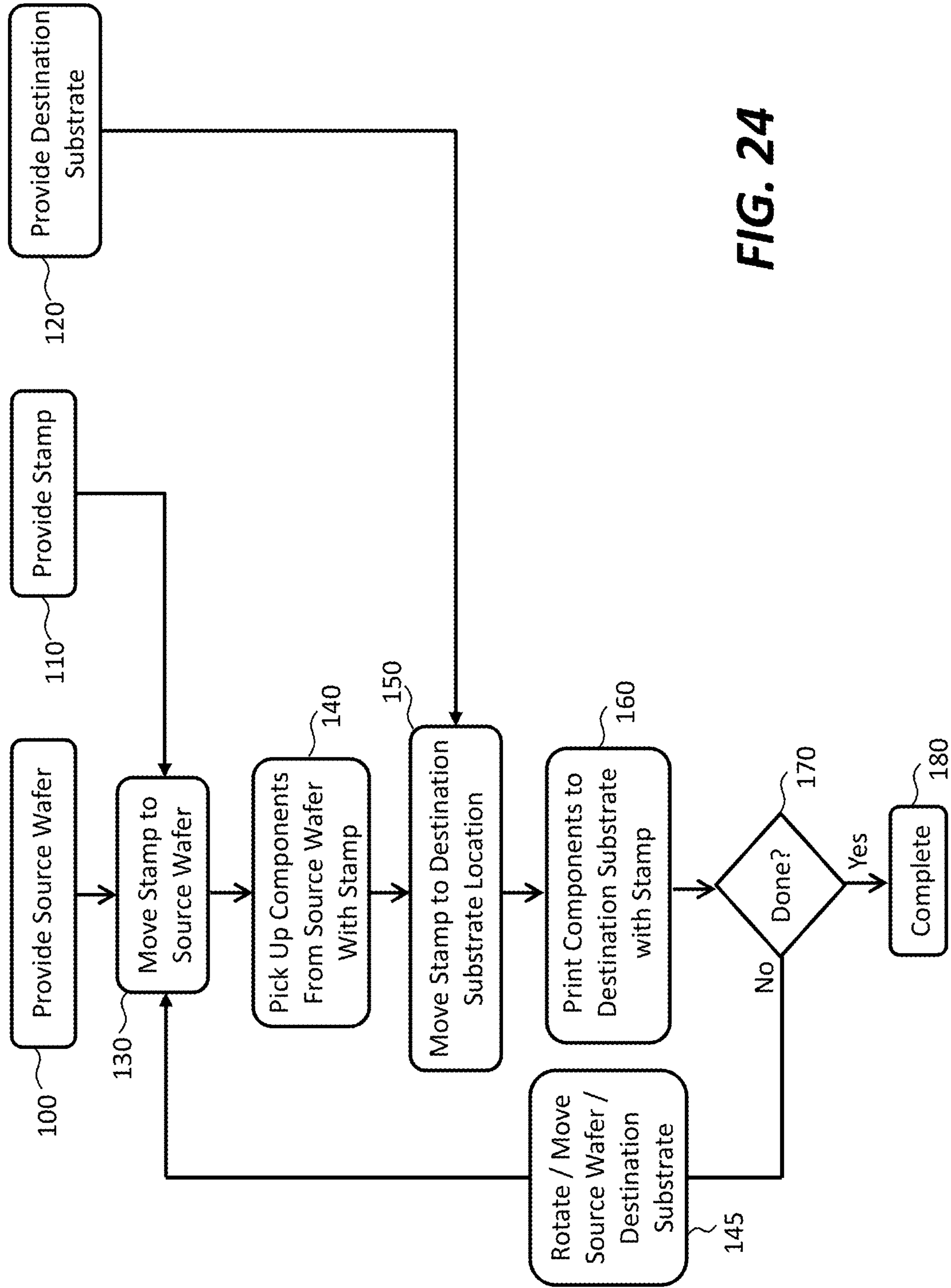

FIG. 24

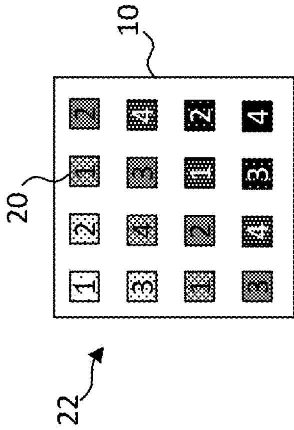

FIG. 25

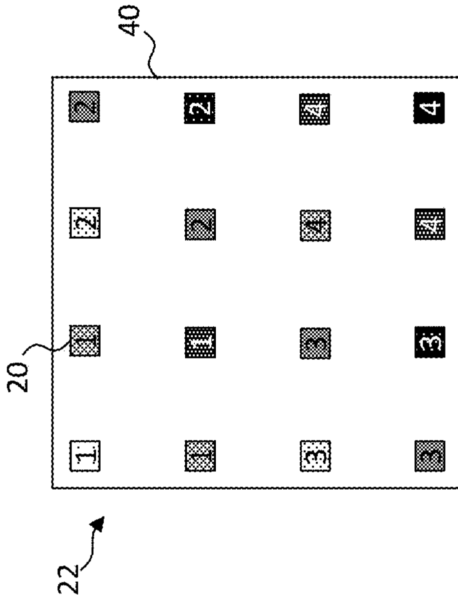

FIG. 26

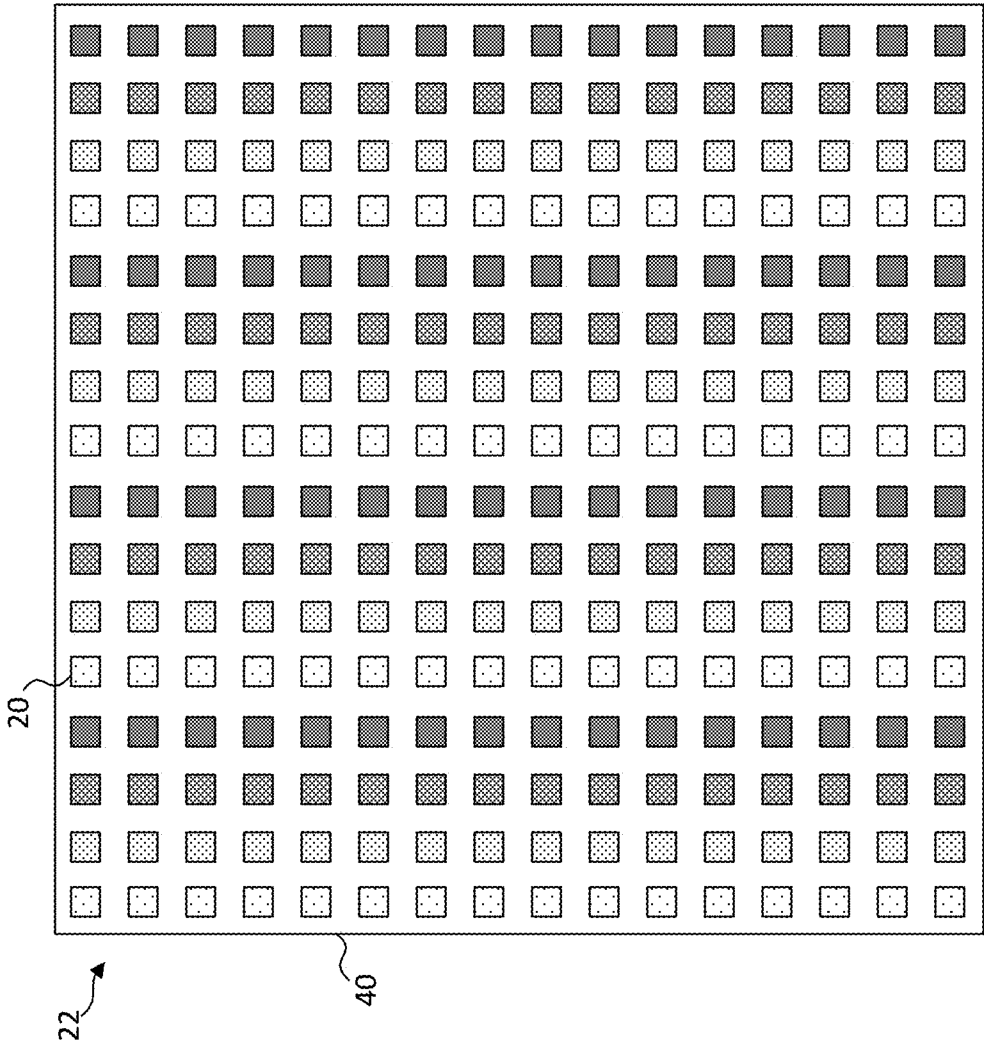

FIG. 27

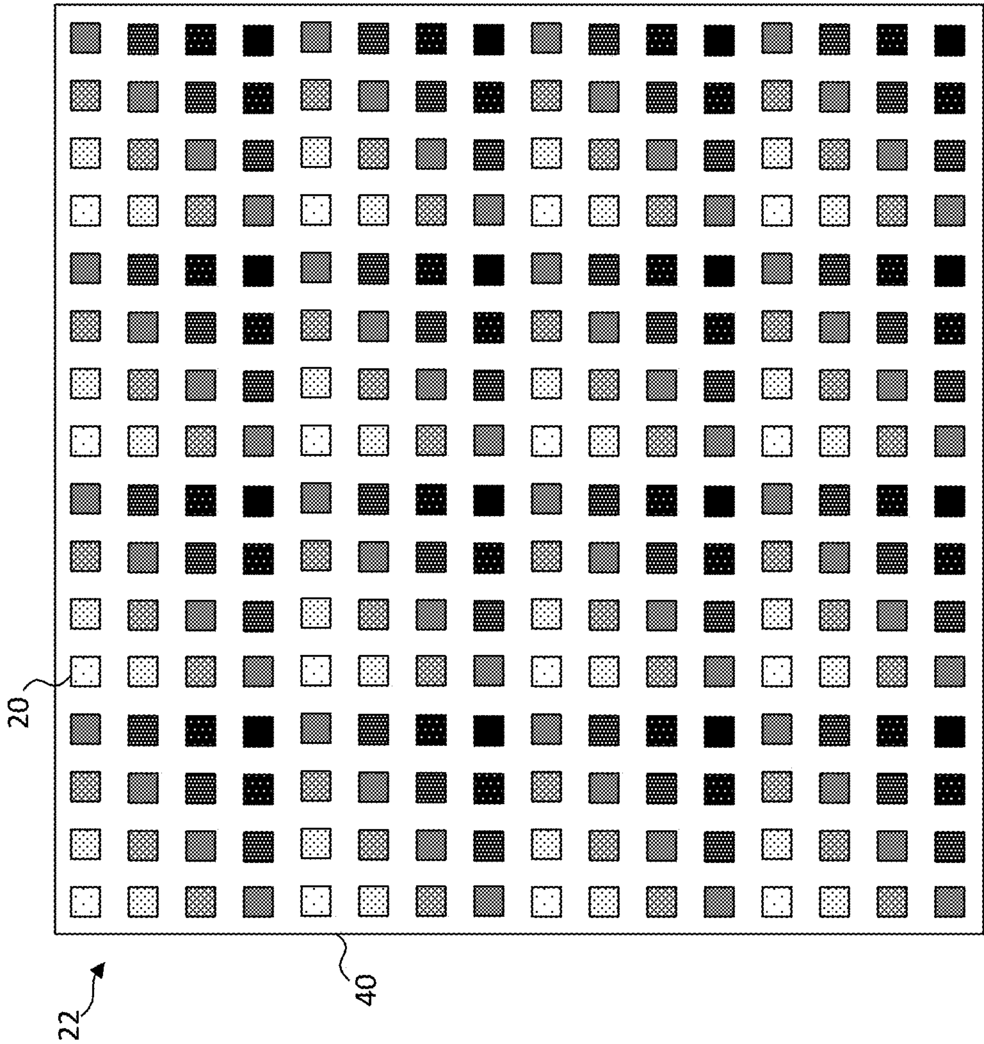

FIG. 28

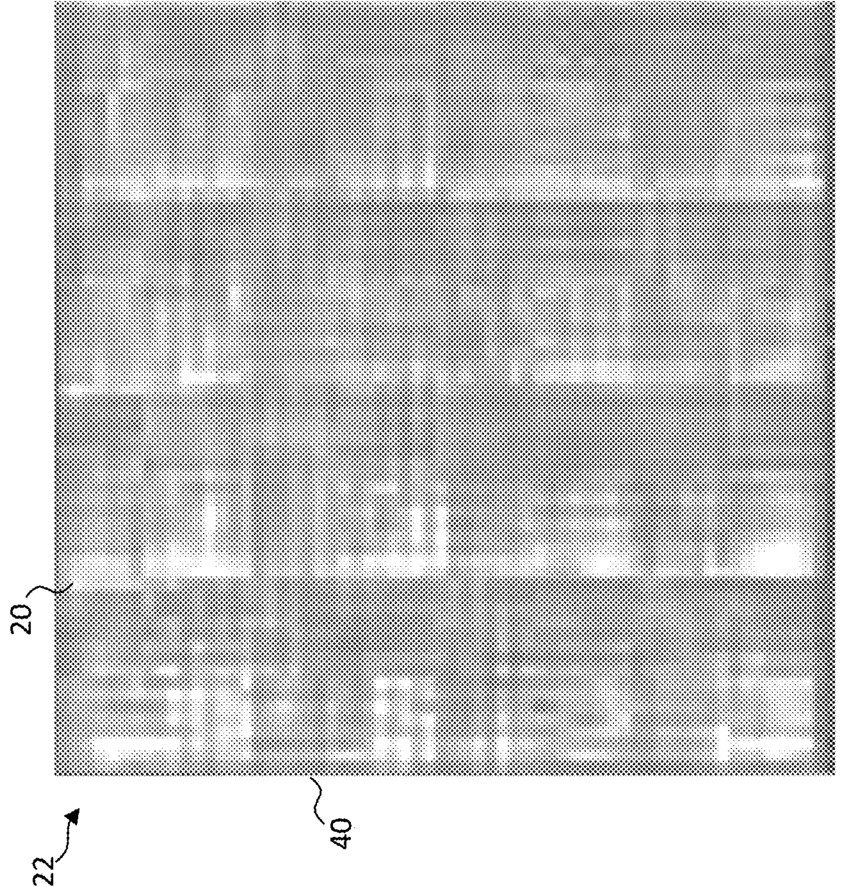

FIG. 29

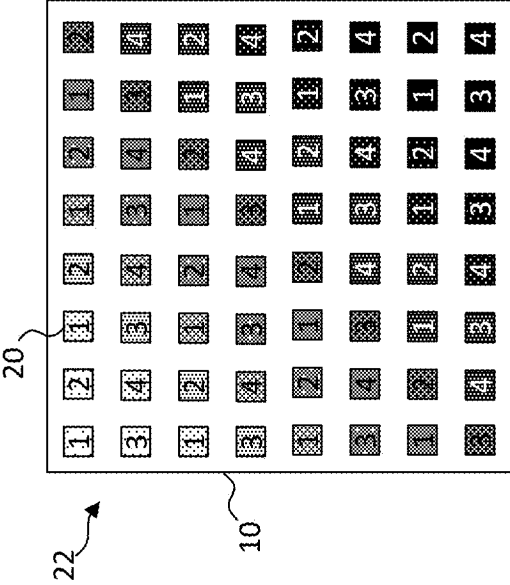

FIG. 30

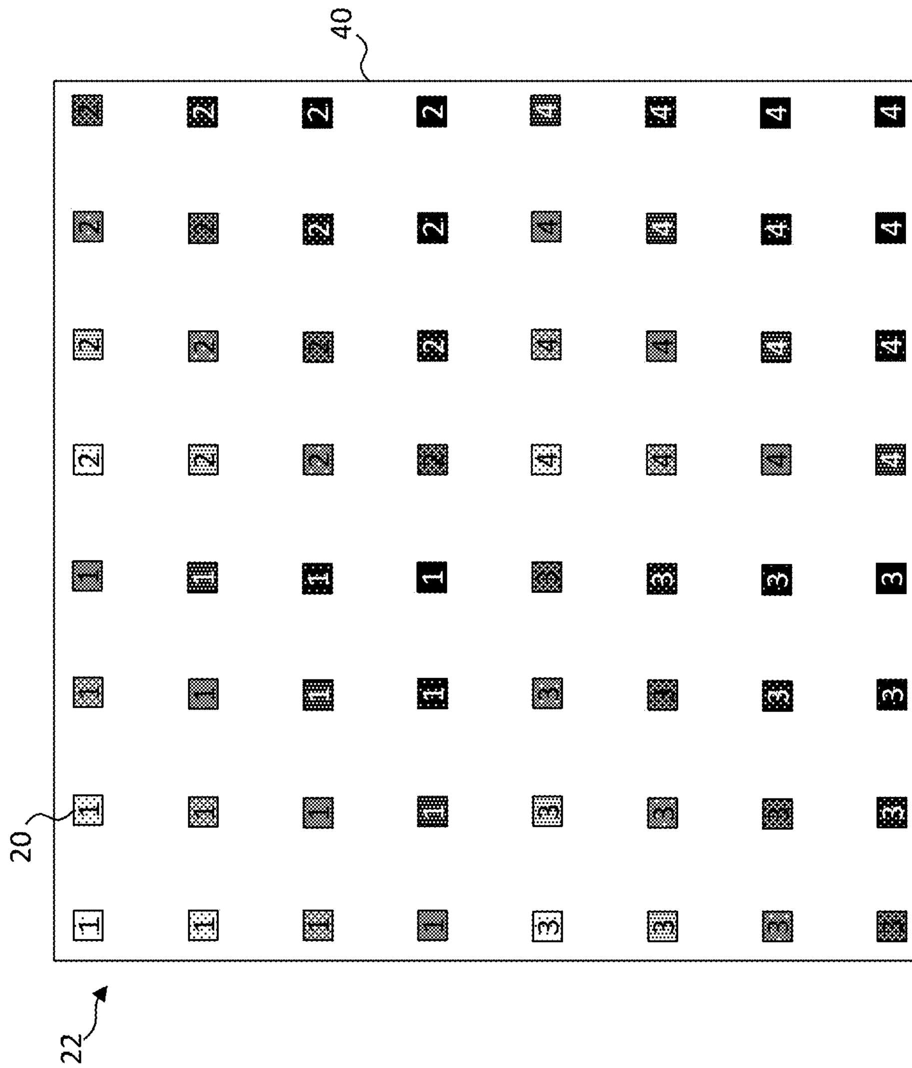

FIG. 31

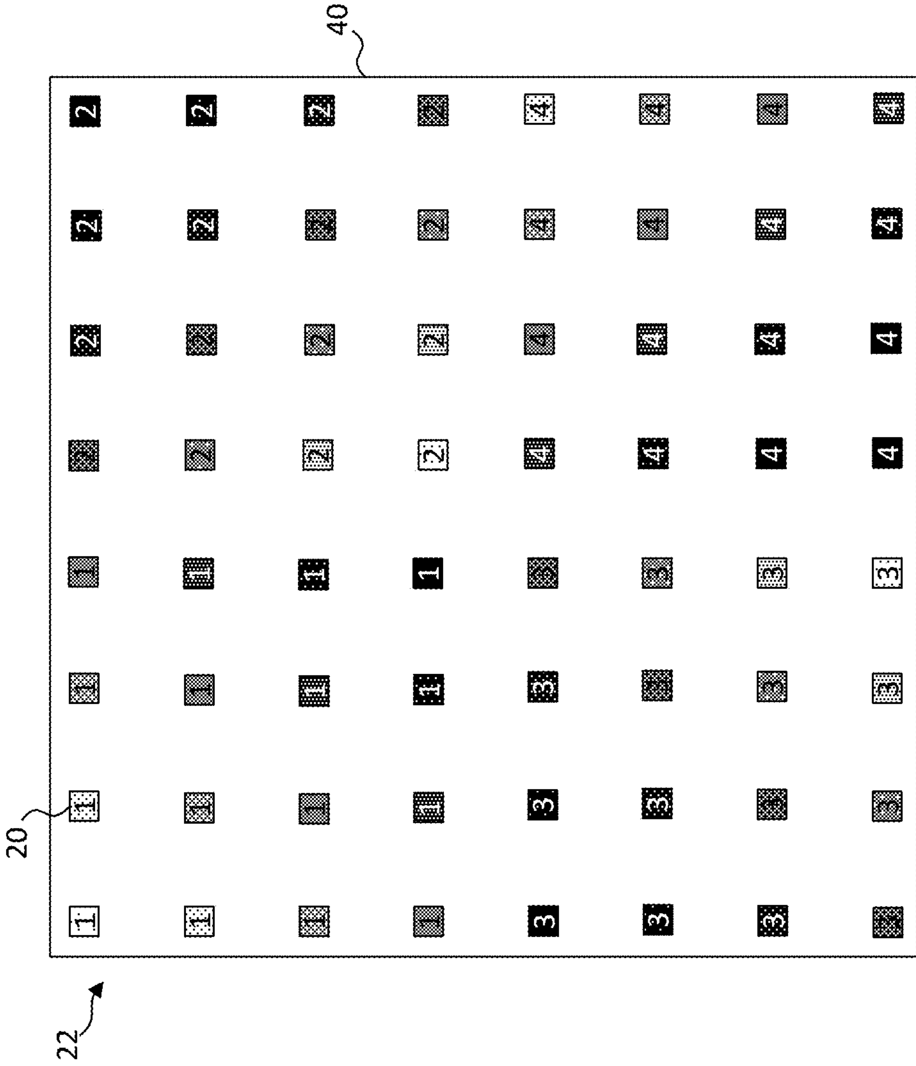

FIG. 32

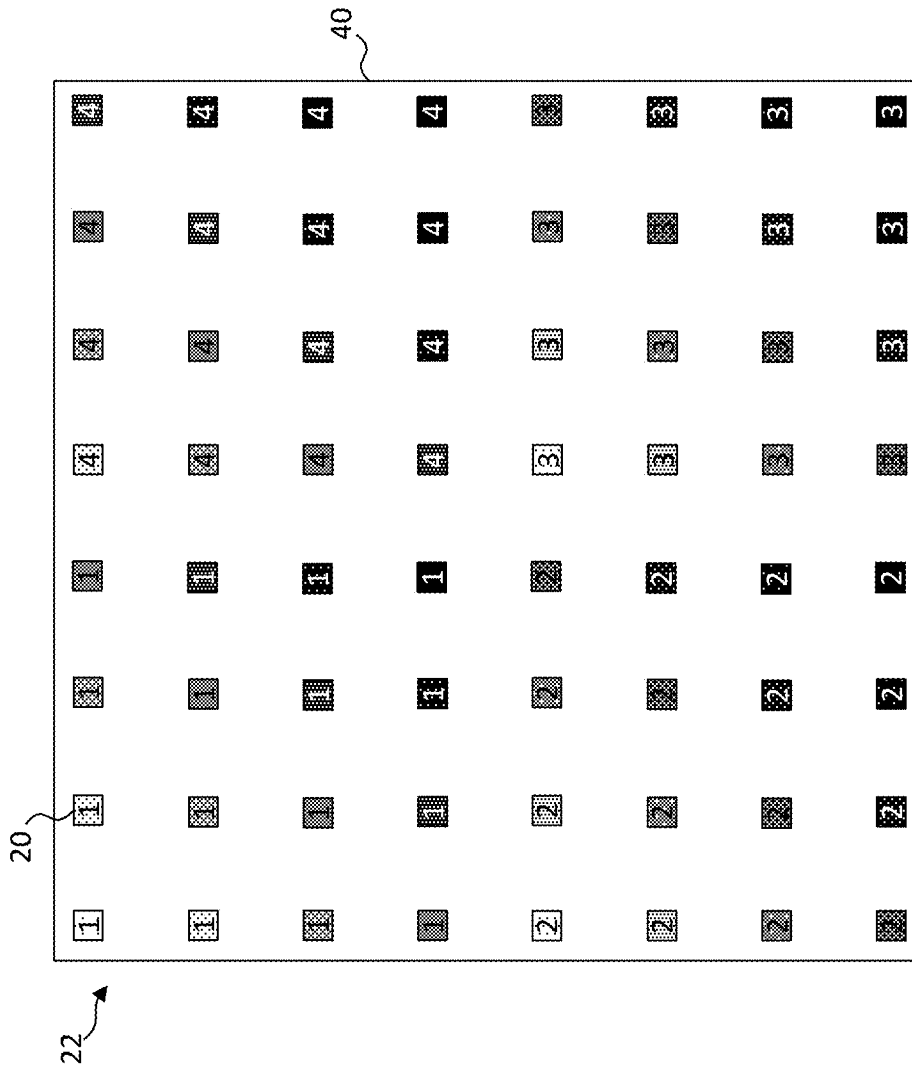

FIG. 33

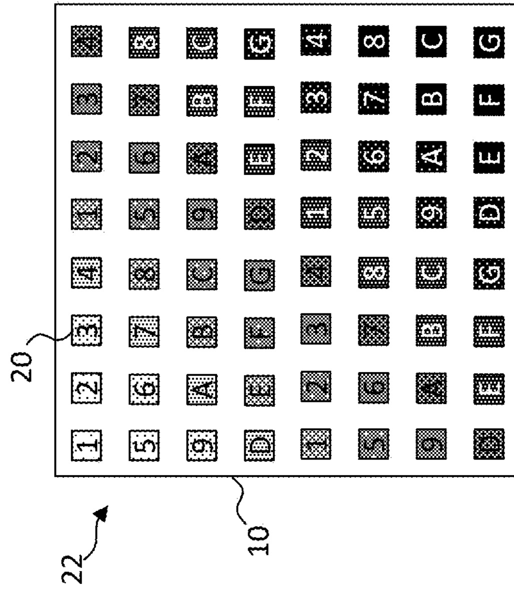

FIG. 34

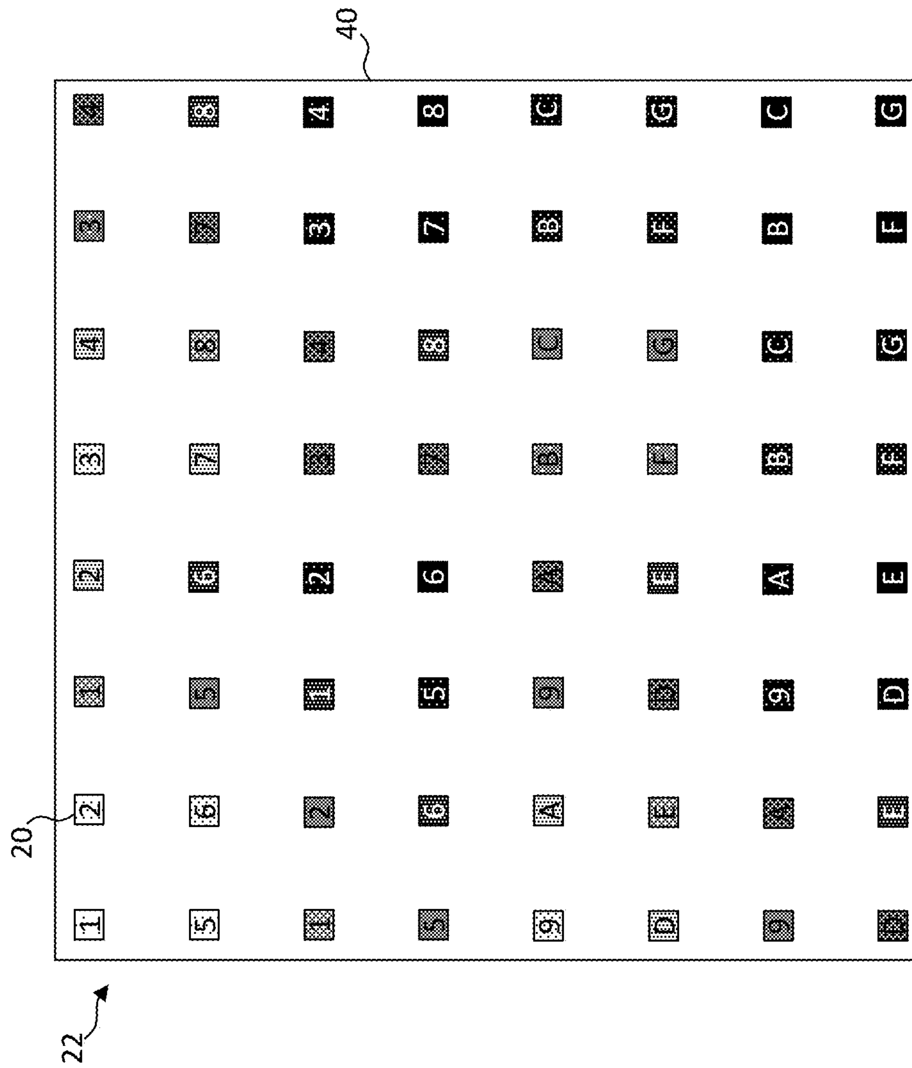

FIG. 35

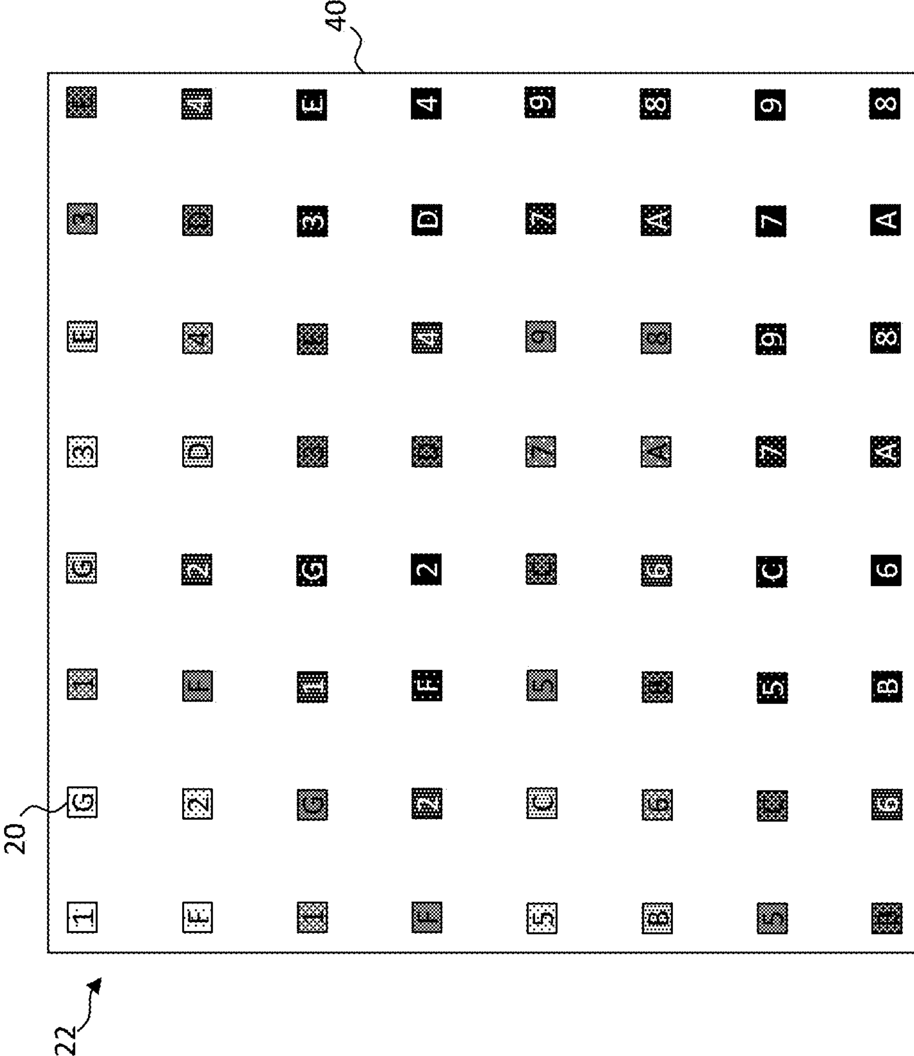

FIG. 36

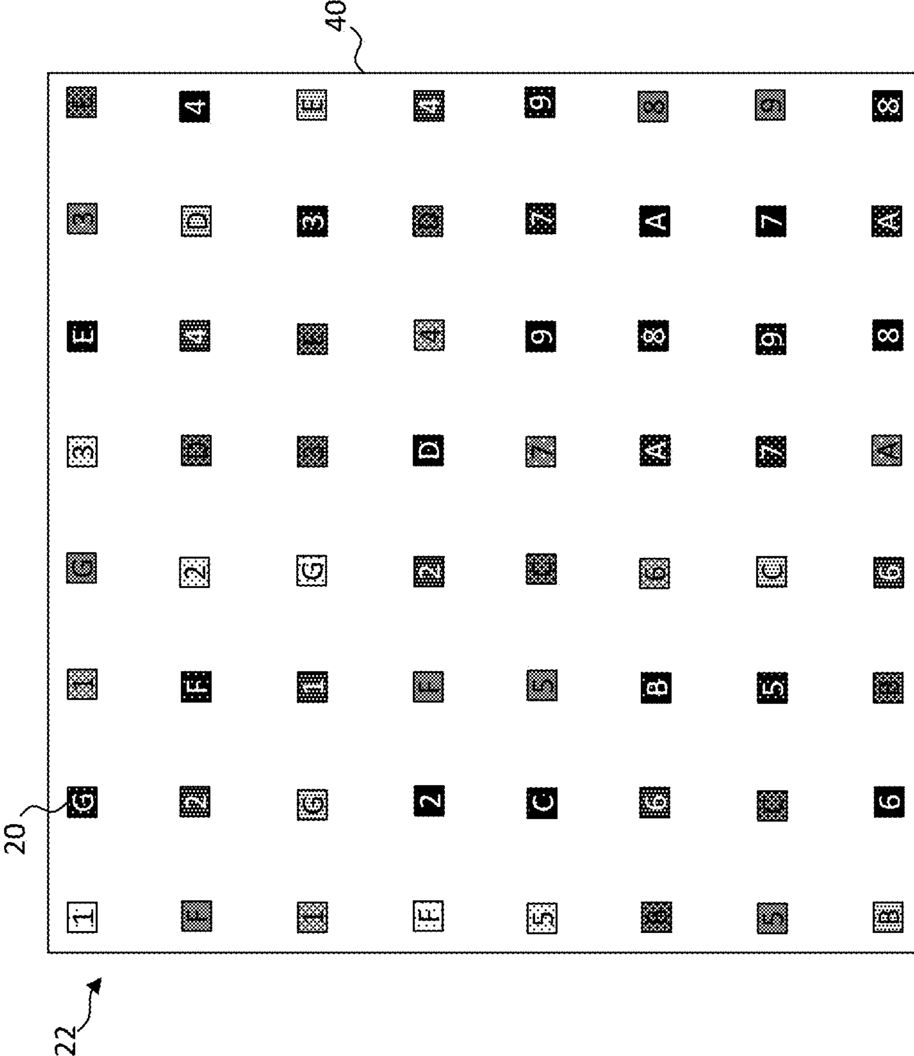

FIG. 37

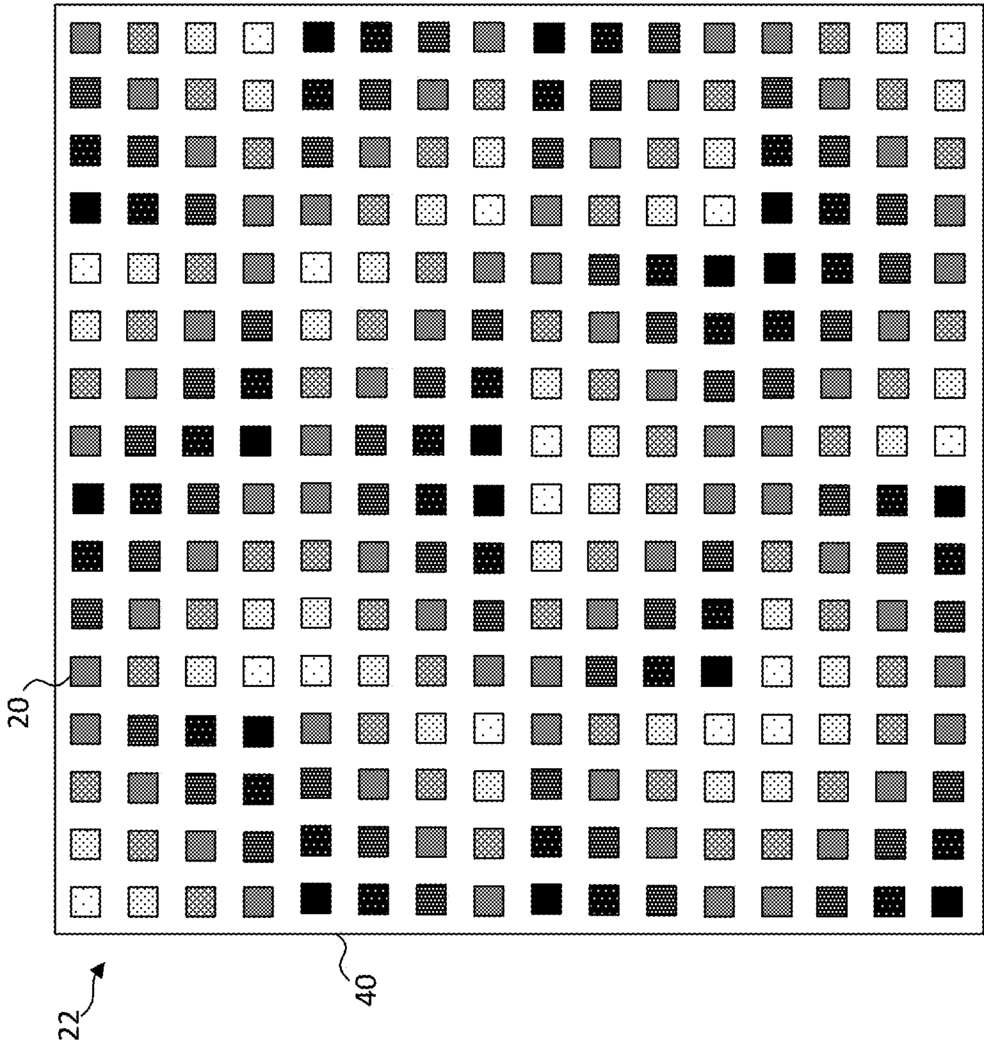

FIG. 38

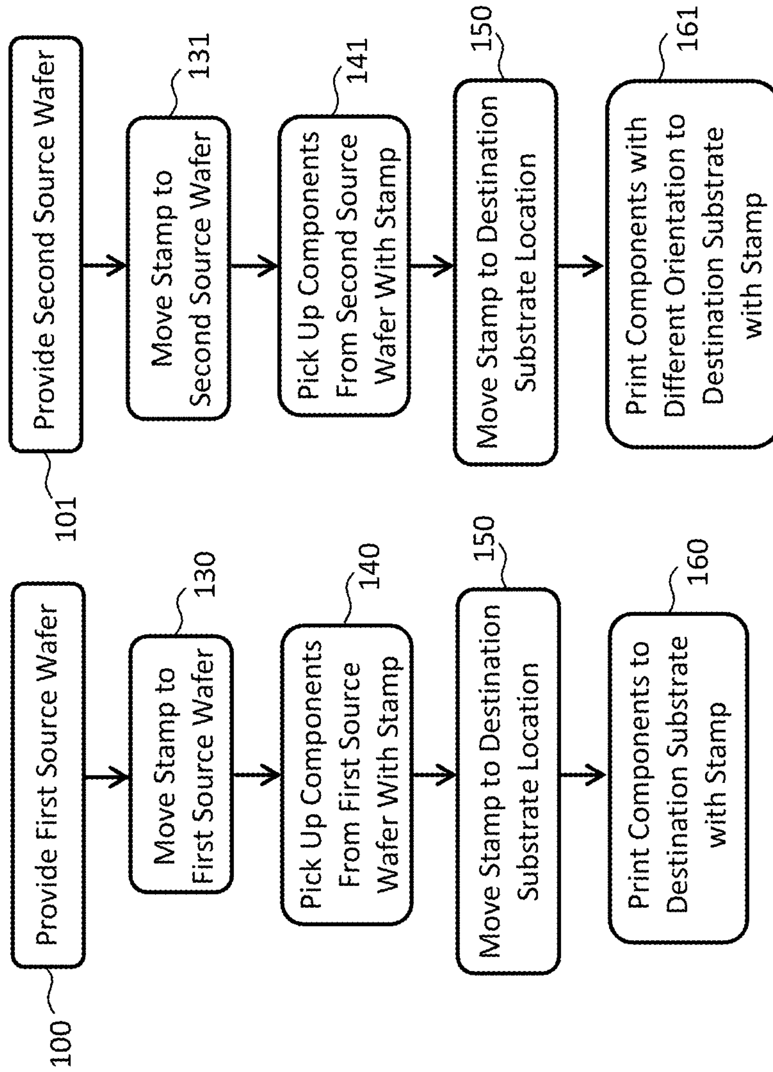

FIG. 39

PRINTING COMPONENT ARRAYS WITH DIFFERENT ORIENTATIONS

TECHNICAL FIELD

[0001] The present disclosure relates generally to structures and methods for transferring (e.g., micro-transfer printing) multiple arrays of micro-components onto a substrate.

BACKGROUND

[0002] Substrates with electronically active components distributed over the extent of the substrate may be used in a variety of electronic systems, for example, in flat-panel display devices such as flat-panel liquid crystal or organic light emitting diode (OLED) displays, in imaging sensors, and in flat-panel solar cells. The electronically active components are typically either assembled on the substrate, for example using individually packaged surface-mount integrated-circuit devices and pick-and-place tools, or by sputtering or spin coating a layer of semiconductor material on the substrate and then photolithographically processing the semiconductor material to form thin-film circuits on the substrate. Individually packaged integrated-circuit devices typically have smaller transistors with higher performance than thin-film circuits but the packages are larger than can be desired for highly integrated systems.

[0003] Methods for transferring active components from one substrate to another are described in U.S. Pat. No. 7,943,491. In examples of these approaches, small integrated circuits are formed on a native semiconductor source wafer. The small unpackaged integrated circuits, or chiplets, are released from the native source wafer by etching a layer formed beneath the circuits. A PDMS stamp is pressed against the native source wafer and the process side of the chiplets is adhered to individual stamp posts. The chiplets are pressed against a destination substrate or backplane with the stamp and adhered to the destination substrate. In other examples, 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.

[0004] In order to populate a large destination substrate with components from a native source wafer, the stamp repeatedly picks up components from different locations on the native source wafer with stamp posts and prints the components to different locations on the destination substrate. The arrangement of components on the destination substrate is at least partly defined by the arrangement of the components on the native source wafer and the arrangement of posts on the stamp. The location of the stamp with respect to the native source wafer and the destination substrate is controlled by an opto-electro-mechanical control system.

SUMMARY

[0005] It has been found that because of variation in materials and photolithographic processes on the native source wafer, the performance or other attributes of components formed on a native source wafer can also vary. This variation in source materials can cause operational non-uniformities in components transferred to the destination substrate. There is a need, therefore, for systems, structures, devices, materials, and methods that reduce variability in arrangements of multiple arrays of micro-transfer-printed micro-components on destination substrates. The present disclosure provides, inter alfa, structures, materials, and methods that provide reduced large-scale component variation on a substrate.

[0006] In accordance with certain embodiments of the present disclosure, a method of micro-transfer printing comprises providing a component source wafer and components disposed in, on, or over the component source wafer, providing a destination substrate, and providing a stamp for transferring the components from the component source wafer to the destination substrate, wherein the component source wafer has an attribute or structure that varies across the component source wafer such that different ones of the components in different locations have a different structure, operation, appearance, or performance of the components, transferring a first array of components from the component source wafer to the destination substrate with a first orientation, and transferring a second array of components from the component source wafer to the destination substrate with a second orientation, wherein the second orientation is different from the first orientation.

[0007] In some embodiments, methods of the present invention comprise transferring the first array and transferring the second array with micro-transfer printing (e.g., dry contact printing).

[0008] In some embodiments of the present invention, the second orientation is rotated relative to the first array to provide different first and second orientations. The second orientation can be rotated 90 degrees, 180 degrees, or 270 degrees with respect to the first orientation.

[0009] In some embodiments, methods of the present invention comprise transferring the second array of components adjacent to the first array of components on the destination substrate. In some embodiments, methods of the present invention comprise repeatedly transferring arrays of components from the component source wafer to the destination substrate with adjacent arrays on the destination substrate transferred at different orientations. In some embodiments, methods of the present invention comprise repeatedly transferring arrays of components from the component source wafer to the destination substrate N times in one dimension, where N/2 pairs of adjacent arrays on the destination substrate comprise array i and array (N−1−i) for each i from 0 to (N/2)−1. In some embodiments, methods of the present invention comprise repeatedly transferring arrays of components from the component source wafer to the destination substrate N×M times in two dimensions, where N/2×M/2 two-by-two adjacent component arrays on the destination substrate comprise array (i, j), array (N−1−i, j), array (i, M−1−j), and array (N−1−i, M−1−j) for each i from 0 to (N/2)−1 and each j from 0 to (M/2)−1.

[0010] In some embodiments, methods of the present invention comprise interlacing the second array with respect to the first array in at least one dimension to provide different first and second orientations. The interlacing can be in one dimension or in two dimensions. The first array and the second array can each be regular, arrangements of components in one dimension or regular arrangements of components in two dimensions.

[0011] In some embodiments, methods of the present invention comprise offsetting the second array with respect to the first array on the destination substrate by an amount that is different from an offset of the first array with respect to the second array on the component source wafer to

provide different first and second orientations. The second array can be disposed with respect to the first array on the destination substrate in a different direction than the second array is disposed with respect to the first array on the component source wafer. The first array and second array can be adjacent on the component source wafer before transferring but not adjacent on the destination substrate after transferring.

[0012] In some embodiments, methods of the present invention comprise providing a plurality of component source wafers, wherein the plurality of component source wafers comprises the component source wafer, and transferring arrays of components from each of the component source wafers onto the destination substrate with two or more different orientations.

[0013] In some embodiments of the present invention, the plurality of component source wafers comprises a first component source wafer and a second component source wafer different from the first component source wafer, and some methods of the present invention comprise interlacing components from the first component source wafer between components from the second component source wafer.

[0014] In some embodiments of the present invention, the components are light-emitting components such as inorganic light-emitting diodes.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] 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:

[0016] FIG. **1** is a schematic cross section of a native source wafer comprising an array of components useful in understanding embodiments of the present disclosure;

[0017] FIG. **2** is a schematic plan view of a native source wafer comprising an array of components having a common variable attribute that varies in one dimension across the array useful in understanding embodiments of the present disclosure;

[0018] FIG. **3** is a schematic plan view of a native source wafer comprising an array of components having a common variable attribute that varies in two dimensions across the array useful in understanding embodiments of the present disclosure;

[0019] FIG. **4**A is a perspective and FIG. **4**B is a schematic cross section taken along cross section line A of FIG. **4**A of a stamp and component source wafer according to illustrative embodiments of the present disclosure;

[0020] FIG. **5** is a schematic cross section of the stamp in contact with a first subset of components on the component source wafer according to illustrative embodiments of the present disclosure;

[0021] FIG. **6**A is a perspective and FIG. **6**B is a schematic cross section taken along cross section line A of FIG. **6**A of the stamp with the first subset of components removed from the component source wafer according to illustrative embodiments of the present disclosure;

[0022] FIG. **7**A is a perspective and FIG. **7**B is a schematic cross section taken along cross section line A of FIG. **7**A of the stamp before micro-transfer printing the first subset of components from the stamp to a destination substrate according to illustrative embodiments of the present disclosure;

[0023] FIG. **8** is a schematic cross section of the stamp micro-transfer printing the first subset of components to the destination substrate according to illustrative embodiments of the present disclosure;

[0024] FIG. **9**A is a perspective and FIG. **9**B is a schematic cross section taken along cross section line A of FIG. **9**A of the stamp and destination substrate after micro-transfer printing the first subset of components from the stamp to the destination substrate according to illustrative embodiments of the present disclosure;

[0025] FIG. **10**A is a perspective and FIG. **10**B is a schematic cross section taken along cross section line A of FIG. **10**A of the stamp and component source wafer before picking up a second subset of components with the stamp according to illustrative embodiments of the present disclosure;

[0026] FIG. **11** is a schematic cross section of the stamp in contact with the second subset of components on the component source wafer according to illustrative embodiments of the present disclosure;

[0027] FIG. **12**A is a perspective and FIG. **12**B is a schematic cross section taken along cross section line A of FIG. **12**A of the stamp with the second subset of components removed from the component source wafer according to illustrative embodiments of the present disclosure;

[0028] FIG. **13**A is a perspective and FIG. **13**B is a schematic cross section taken along cross section line A of FIG. **13**A of the stamp before micro-transfer printing the second subset of components from the stamp to the destination substrate in a rotated configuration according to illustrative embodiments of the present disclosure;

[0029] FIG. **14** is a cross section of the stamp micro-transfer printing the second subset of components to the destination substrate in a rotated configuration according to illustrative embodiments of the present disclosure;

[0030] FIG. **15**A is a perspective and FIG. **15**B is a cross section taken along cross section line A of FIG. **15**A of the stamp and destination substrate after micro-transfer printing the second subset of components from the stamp to the destination substrate in a rotated configuration according to illustrative embodiments of the present disclosure;

[0031] FIG. **16** is a perspective of the stamp and component source wafer before picking up a third subset of components with the stamp according to illustrative embodiments of the present disclosure;

[0032] FIG. **17** is a perspective of the stamp with the third subset of components removed from the component source wafer according to illustrative embodiments of the present disclosure;

[0033] FIG. **18** is a perspective of the stamp before micro-transfer printing the third subset of components from the stamp to the destination substrate in a rotated configuration according to illustrative embodiments of the present disclosure;

[0034] FIG. **19** is a perspective of the stamp after micro-transfer printing the third subset of components from the stamp to the destination substrate in a rotated configuration according to illustrative embodiments of the present disclosure;

[0035] FIG. **20** is a perspective of the stamp and component source wafer in a rotated configuration before micro-transfer printing a fourth subset of components according to illustrative embodiments of the present disclosure;

[0036] FIG. **21** is a perspective of the stamp with the fourth subset of components removed from the component source wafer according to illustrative embodiments of the present disclosure;

[0037] FIG. **22** is a perspective of the stamp before micro-transfer printing the fourth subset of components from the stamp to the destination substrate in a rotated configuration according to illustrative embodiments of the present disclosure;

[0038] FIG. **23** is a perspective of the stamp after micro-transfer printing the fourth subset of components from the stamp to the destination substrate in a rotated configuration according to illustrative embodiments of the present disclosure;

[0039] FIG. **24** is a flow diagram according to illustrative embodiments of the present disclosure;

[0040] FIG. **25** is a plan view of a native source substrate with components labeled according to a stamp pick-up method useful in understanding embodiments of the present disclosure;

[0041] FIG. **26** is a plan view of a destination substrate with components printed according to the native source substrate and stamp pick-up method of FIG. **24** useful in understanding embodiments of the present disclosure;

[0042] FIG. **27** is a plan view of a destination substrate with printed components from a native source substrate corresponding to FIG. **2** useful in understanding embodiments of the present disclosure;

[0043] FIG. **28** is a plan view of a destination substrate with printed components from a native source substrate corresponding to FIG. **3** useful in understanding embodiments of the present disclosure;

[0044] FIG. **29** is a micrograph of a destination substrate with printed components from a native source substrate corresponding to FIG. **3** in operation useful in understanding embodiments of the present disclosure;

[0045] FIG. **30** is a plan view of a native source substrate with an 8×8 array of components labeled according to a stamp pick-up method useful in understanding embodiments of the present disclosure;

[0046] FIG. **31** is a plan view of a destination substrate with printed components from the native source substrate corresponding to FIG. **30** useful in understanding embodiments of the present disclosure;

[0047] FIG. **32** is a plan view of a native source substrate with an 8×8 array of components labeled according to a stamp pick-up method according to illustrative embodiments of the present disclosure;

[0048] FIG. **33** is a plan view of a native source substrate with an 8×8 array of components labeled according to a stamp pick-up method according to illustrative embodiments of the present disclosure;

[0049] FIG. **34** is a plan view of a native source substrate with an 8×8 array of components labeled according to a stamp pick-up method according to illustrative embodiments of the present disclosure;

[0050] FIG. **35** is a plan view of a destination substrate with printed components from the native source substrate corresponding to FIG. **32** according to illustrative embodiments of the present disclosure;

[0051] FIG. **36** is a plan view of a destination substrate with printed components from the native source substrate corresponding to FIG. **32** according to illustrative embodiments of the present disclosure;

[0052] FIG. **37** is a plan view of a destination substrate with printed components from the native source substrate corresponding to FIG. **32** according to illustrative embodiments of the present disclosure;

[0053] FIG. **38** is a plan view of a destination substrate with printed components from the native source substrate corresponding to FIG. **3** according to illustrative embodiments of the present disclosure; and

[0054] FIG. **39** is a flow diagram according to illustrative embodiments of the present disclosure.

[0055] The perspectives shown in FIGS. **4**A, **6**A, **7**A, **9**A, **10**A, **12**A, **13**A, **15**A, and **16**-**23** are exploded illustrations with exaggerated viewing angles and the two cross section lines A indicated in some of the perspective Figures are actually congruent.

[0056] 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 necessarily drawn to scale.

DETAILED DESCRIPTION OF CERTAIN EMBODIMENTS

[0057] Certain embodiments of the present disclosure are directed toward methods of micro-transfer printing arrays of components from a component source wafer to a destination substrate using a stamp, wherein an attribute or structure of the components varies systematically over the component source wafer so that different ones of the components in different locations on the component source wafer have a different structure, operation, appearance, or performance. The attribute variation can, in the absence of structures, devices, systems, and methods of the present disclosure, result in unwanted large-scale non-uniformity in component operation, structure, or appearance on the destination substrate. According to some embodiments of the present disclosure, the large-scale operation can be mitigated by providing components on a destination substrate at different orientations with respect to the attribute variation on a component source wafer. The components can be provided in arrays so that a first array is disposed with a first orientation and a second array is disposed with a second orientation, where the second orientation is different from the first orientation. Different orientations can, for example, comprise different spatial rotations, offsets, interlacings (e.g., interdigitations), or interlacing in one or two directions (dimensions) in which the attribute varies. Arrays of components **20** can be for example regular one-dimensional arrays or regular two-dimensional arrays.

[0058] FIG. **1** is a cross section of a component source wafer **10** comprising an array **22** of components **20** (e.g., **20***a*-**20***j*). Components **20** can be native to component source wafer **10**, that is components **20** can be constructed on, in, or over component source wafer **10** using, for example, photolithographic materials and methods useful for integrated circuit technology. Any manufacturing process experiences variation in materials and process control that can result in variation in native component source wafers **10**. According to some embodiments, a plurality of components **20** (e.g., components **20***a*-**20***j*) are disposed in, on, or over component source wafer **10**. In some embodiments, com-

ponent source wafer **10** has an attribute or structure **12** that varies across component source wafer **10** (e.g., across a surface of component source wafer **10**) that affects the structure, operation, appearance, or performance of components **20**. The variation can be, but is not necessarily, monotonic with respect to one or more directions (e.g., orthogonal directions) over a component source wafer. For simplicity in explanation and to aid understanding, an attribute or structure **12** is referred to herein as an attribute **12**. For example, attribute **12** can be an epitaxial layer whose thickness (as shown in FIG. **1**), material purity, doping, or crystallinity varies across component source wafer **10**. Attribute **12** can be particle contamination or any other variable attribute or structure **12** of component source wafer **10** that affects the structure, operation, or performance of components **20**. The variation of attribute **12** can be linear (or non-linear) in one or two dimensions over component source wafer **10** or a surface of component source wafer **10**. The variation of an attribute **12** can be spatially monotonic, so that attribute **12** is always increasing (or decreasing) in one or more directions either across the entire component source wafer **10** or portions of component source wafer **10** much larger than an extent or size of a component **20**, for example the spatial extent of 10, 100, or 1000 components **20** over component source wafer **10** in one or two directions, or can be otherwise systematic, for example repetitive. Components **20** can be provided in an array **22**, for example a regular array, in one or two dimensions over component source wafer **10** or a surface of component source wafer **10**.

[0059] FIGS. **2** and **3** illustrate an array **22** of components **20** distributed regularly in two dimensions over a component source wafer **10**, for example a rectangular portion of component source wafer **10**. A variation of an attribute **12** is visually represented by the shading of component **20**. A darker shading implies a greater amount or quantity of attribute **12**, for example a greater epitaxial layer thickness. The shading of component **20** is merely illustrative of the variation of attribute **12** and does not imply that components **20** vary in color or appearance. By shading the illustration of component source wafer **10** in the figures, the variation in structure, operation, appearance, or performance of components **20** is visually apparent in the figures and is more readily understood. As shown in FIG. **2**, the quantity of attribute **12** increases in one direction (e.g., horizontally), as shown by the arrow. Referring to FIG. **3**, the quantity of attribute **12** increases in two directions (e.g., both horizontally and vertically), as shown by the arrow.

[0060] Referring to the sequential cross sections and perspectives of FIGS. **4**A-**23** and the flow diagram of FIG. **24**, according to embodiments of the present disclosure, a method of micro-transfer printing comprises providing a component source wafer **10** comprising components **20** in step **100** and providing a stamp **30** in step **110** (as shown in the exploded FIG. **4**A perspective and corresponding cross section FIG. **4**B taken along cross section line A of FIG. **4**A). Stamp **30** can, but does not necessarily, comprise stamp posts **32** each with a stamp post area on a distal end of stamp posts **32**. The stamp posts **32** protrude from stamp **30** to contact components **20** when stamp **30** is pressed against components **20**. As shown in FIG. **4**B, components **20** are entirely disposed over, and can be formed on (e.g., in direct contact with), sacrificial portions **14** spatially separated by anchors **50** in sacrificial layer **11** of component source wafer **10**. Sacrificial layer **11** can be a patterned sacrificial layer **11**. Components **20** can be, but are not necessarily, arranged in a rectangular array **22**, for example in a regular two-dimensional arrangement, as shown in FIG. **4**A. A dielectric layer **54** disposed over destination substrate **40** and sacrificial portions **14** connects each component **20** with a component tether **52** to an anchor **50**. Component tethers **52** are not necessarily made from a dielectric or in a dielectric layer. Component tethers **52** can be laterally connected to anchors **50** (as shown) or disposed in other locations, for example beneath components **20**.

[0061] Referring to FIG. **5**, sacrificial portions **14** (shown in FIG. **4**B) are sacrificed, for example by etching sacrificial portions **14** to form gaps **16**, so that components **20** are suspended over gaps **16** and attached to anchors **50** of component source wafer **10** by component tethers **52** that maintain the physical position of components **20** with respect to component source wafer **10** after sacrificial portions **14** are etched. In some embodiments, each component is attached to each of one or more anchors **50** by one or more component tethers **52**. Stamp **30** is moved into position with respect to component source wafer **10**, for example by an opto-mechatronic motion platform, in step **130** and components **20** are picked up from component source wafer **10** by adhering components **20** to stamp **30**, for example by pressing stamp **30** against components **20** on component source wafer **10** with the motion platform and adhering components **20** to the distal ends of stamp posts **32**, for example with van der Waals or electrostatic forces.

[0062] As shown in the FIG. **6**A perspective and FIG. **6**B cross section taken along cross section line A of FIG. **6**A, stamp **30** in contact with components **20** suspended over gaps **16** is then removed from component source wafer **10** by the motion platform, fracturing component tethers **52** from anchors **50** to form separated or fractured component tethers **53** and picking up components **20** from component source wafer **10** with stamp **30** in step **140**, providing picked-up stamp components **20**. Picked-up stamp components **20** can comprise a separated or fractured component tether **53**.

[0063] Referring to the perspective of FIG. **7**A and cross section of FIG. **7**B taken along cross section line A of FIG. **7**A, a destination substrate **40** is provided in step **120**. In step **150**, stamp **30** and stamp components **20** with fractured component tethers **53** are moved into position and aligned with respect to destination substrate **40**.

[0064] Referring to FIG. **8**, in step **160** picked-up stamp components **20** with fractured component tethers **53** are micro-transfer printed to a surface of destination substrate **40** in step **160** and, referring to FIGS. **9**A and **9**B, stamp **30** is removed from destination substrate **40**.

[0065] If the process is not completed (done step **170**), the process of picking up components **20** from component source wafer **10** is repeated (steps **130** and **140**), possibly more than once. However, for at least one of the repetitions, micro-transfer printed components **20** are disposed with an orientation different from the orientation of the first micro-transfer print step **160**. The orientation for a component source wafer **10** is taken with respect to the direction in which attribute **12** varies, for example the direction of the arrow in FIGS. **2** and **3**. In some embodiments, every print step **160** is performed with a different orientation than the first print step **160**. In some embodiments, only one or only some of the repeated print steps **160** is performed with a different orientation. In some embodiments, every other, every third, or every fourth repeated print step **160** is

performed with a different orientation. An orientation can be repeated for different print steps, for example two orientations can be alternately employed or multiple orientations (such as four orientations) can by cyclically employed.

[0066] As used herein, a different orientation can, but does not necessarily, include components 20 micro-transfer printed (step **160**) with a different rotation, for example rotated in an array **22** adjacent to a micro-transfer printed array **22** of components **20**, for example as shown in FIG. **32** discussed below. In some embodiments, a different orientation can include micro-transfer printed (step **160**) components **20** that overlap with a micro-transfer printed array **22** of components **20**. Overlapping arrays **22** of components **20** can be interlaced (e.g., interdigitated), for example as shown in FIG. **35** discussed below. In some embodiments, a different orientation can include arrays **22** of components 20 micro-transfer printed (step **160**) to adjacent locations on a destination substrate **40** that are micro-transfer printed from locations on a component source wafer **10** that are not adjacent. In some embodiments, multiple different orientations are employed for micro-transfer printed arrays **22** of components **20**, for example as shown in FIG. **33** discussed below. For example, an array **22** of components **20** with a different orientation from another array **22** of components **20** can be rotated and offset with respect to the other array **22** of components **20**. Adjacent arrays **22** of components **20** are arrays **22** of components **20** that do not overlap and are not interlaced (e.g., interdigitated or intermingled) on a destination substrate **40** but that include components **20** that are in neighboring rows or columns(for example as shown in FIGS. **23**, **26**, and **31** discussed below) so that there are no components **20** between components **20** in adjacent arrays **22** on destination substrate **40** that are not in the adjacent arrays **22** of components **20** on component source wafer **10**. That is, components **20** in adjacent arrays **22** on destination substrate **40** are not separated by any components **20** that are not part of the adjacent arrays **22** of components **20** on component source wafer **10**.

[0067] Different orientations for micro-transfer printing can be enabled by moving any one or any combination of component source wafer **10**, stamp **30**, or destination substrate **40**. For example, stamp **30** can be rotated after component **20** pickup from component source wafer **10** and before component **20** printing to destination substrate **40**, destination substrate **40** can be rotated in different directions or in different amounts before each micro-transfer print step **160**, or component source wafer **10** can be rotated in different directions or in different amounts before each micro-transfer pickup step **140**.

[0068] Referring next to the perspective of FIG. **10**A and cross section of FIG. **10**B taken along cross section line A of FIG. **10**A, stamp **30** is aligned with components **20** suspended over gaps **16** (step **130**), brought into contact with components **20** on component source wafer **10** (shown in FIG. **11**), and then removed from component source wafer **10** by the motion platform, fracturing component tethers **52** from anchors **50** to form separated or fractured component tethers **53** and picking up components **20** from component source wafer **10** with stamp **30** in step **140**, as shown in the perspective of FIG. **12**A and the corresponding cross section of FIG. **12**B taken across cross section line A of FIG. **12**A.

[0069] As shown in the perspective of FIG. **13**A and cross section of FIG. **13**B taken along cross section line A of FIG. **13**A, stamp **30** and stamp components **20** with fractured component tethers **53** are moved into position with respect to destination substrate **40** (step **150**). However, before micro-transfer printing components **20** to destination substrate **40** with stamp **30** in step **160**, stamp **30** or destination substrate **40** is provided in a different orientation, for example by rotating stamp **30** or destination substrate **40**, as indicated by the circular arrow in FIGS. **13**A, **13**B. Alternatively, as described below, stamp **30** or component source wafer **10** is provided in a different orientation before component **20** pickup in step **140**, for example by rotating stamp **30** or component source wafer **10**. Referring to FIG. **14**, in step **160** picked-up stamp components **20** with fractured component tethers **53** are micro-transfer printed to destination substrate **40** in step **160** and, referring to FIGS. **15**A and **15**B, stamp **30** is removed from destination substrate **40**.

[0070] Thus, according to some embodiments of the present disclosure, a method of micro-transfer printing comprises providing a component source wafer **10** and components **20** disposed in, on, or over component source wafer **10** (step **100**), providing a destination substrate **40** (step **120**), and providing a stamp **30** for transferring components **20** from component source wafer **10** to destination substrate **40** (step **110**), where component source wafer **10** has an attribute or structure **12** that varies (e.g., monotonically) across component source wafer **10** that affects the structure, operation, appearance, or performance of the components **20**. In steps **130**, **140**, **150**, **160**, a first array **22** of components **20** is transferred from component source wafer **10** to destination substrate **40** with a first orientation and in step **145**, **130**, **140**, **150**, **160** a second array **22** of components **20** is transferred from component source wafer **10** to destination substrate **40** with a second orientation different from the first orientation. Component **20** transfer can be performed using micro-transfer printing (e.g., dry contact printing), for example.

[0071] The process of printing components **20** in different orientations is repeated again. Referring to the perspective of FIG. **16**, stamp **30** is aligned with components **20** on component source wafer **10** (step **130**), brought into contact with components **20** on component source wafer **10**, and then removed from component source wafer **10** by the motion platform, fracturing component tethers **52** from anchors **50** to form separated or fractured component tethers **53** and picking up components **20** from component source wafer **10** with stamp **30** in step **140**, as shown in the perspective of FIG. **17**. As shown in the perspective of FIG. **18**, stamp **30** and stamp components **20** with fractured component tethers **53** are moved into position in a different orientation (illustrated by the circular arrow rotated in an opposite direction with respect to FIG. **13**A, **13**B) with respect to destination substrate **40** (step **150**). Referring to FIG. **19**, in step **160** picked-up stamp components **20** with fractured component tethers **53** are micro-transfer printed to destination substrate **40** in step **160** and stamp **30** is removed from destination substrate **40**.

[0072] The process of printing components **20** in different orientations is repeated again for remaining components **20**. Referring to the perspective of FIG. **20**, stamp **30** is aligned with components **20** on component source wafer **10** (step **130**). In this step, component source wafer **10** is provided in a different orientation (illustrated by the circular arrow), rather than providing the stamp in a different orientation, as in FIGS. **13**A-B and FIG. **18**. Stamp posts **32** of stamp **30** are brought into contact with components **20** on component

source wafer **10**, and then removed from component source wafer **10** by the motion platform, fracturing component tethers **52** from anchors **50** to form separated or fractured component tethers **53** and picking up components **20** from component source wafer **10** with stamp **30** in step **140**, as shown in the perspective of FIG. **21**. As shown in the perspective of FIG. **22**, stamp **30** and stamp components **20** with fractured component tethers **53** are moved into position with respect to destination substrate **40** (step **150**). A dashed circular arrow is illustrated in FIG. **22** to illustrate that destination substrate **40** can be rotated instead of rotating component source wafer **10** in FIG. **20** or stamp **30** in FIG. **16** to provide components **20** in a different orientation on destination substrate **40**. As shown in FIG. **23**, in step **160** picked-up stamp components **20** with fractured component tethers **53** are micro-transfer printed to destination substrate **40** in step **160** and stamp **30** is removed from destination substrate **40**.

[0073] Components **20** are all micro-transfer printed from component source wafer **10** to destination substrate **40** in various orientations (step **170**) and the process is completed (step **180**).

[0074] FIG. **25** is an illustration of a component source wafer **10** having a four-by-four array **22** of components **20** whose attributes **12** vary monotonically (e.g., linearly) in each of two dimensions, indicated by the shading of the components **20** and corresponding to FIG. **3** (in a smaller component array **22**). Components **20** on component source wafer **10** are labeled with a number corresponding to the stamp operation that micro-transfer prints components **20** from component source wafer **10** to destination substrate **40** using a stamp **30** with a two-by-two array of stamp posts **32**, so that four stamp operations are required to complete the transfer, as described with respect to FIGS. **4A-23** above. Stamp operations that do not micro-transfer print components **20** in different orientations result in a distribution of components **20** on destination substrate **40**, for example without different rotations. as shown in FIG. **26**. As shown in FIG. **26** by the shading of components **20**, the attribute **12** variation of component source wafer **10** is repeated multiple times, albeit at a different resolution on destination substrate **40** than on component source wafer **10**.

[0075] FIG. **27** illustrates the result of micro-transfer printing sixteen four-by four arrays **22** of components **20** from a component source wafer **10** (e.g., corresponding to FIG. **2**) onto a destination substrate **40** in a common orientation, for example without different rotations. Similarly, FIG. **28** illustrates the result of micro-transfer printing sixteen four-by four arrays **22** of components **20** from a component source wafer **10** (e.g., corresponding to FIG. **3**) onto a destination substrate **40** in a common orientation, for example without different rotations. As shown by the shading of components **20**, in these cases (FIGS. **26-28**) the attribute **12** variation of component source wafer **10** is repeated multiple times in either one dimension (horizontally, as shown in FIG. **27**) or in two dimensions (horizontally and vertically, as shown in FIG. **28**) albeit at a different resolution on destination substrate **40** than on component source wafer **10**.

[0076] FIG. **29** is a micrograph of sixteen arrays **22** of components 20 micro-transfer printed in a common orientation, for example without different rotations, from a component source wafer **10** (e.g., corresponding to FIG. **3**) to a destination substrate **40**. The regular variation in component attributes **12** is readily visible. Such variation can be considered a form of pattern noise or fixed-pattern noise, often associated with image sensors. Such noise can be addressed by flat-field correction techniques that control the operation of components **20** electronically. However, according to some embodiments of the present disclosure, the variation (non-uniformity) can also be addressed by transferring arrays **22** of components **20** from a component source wafer **10** to a destination substrate **40** using different orientations for components **20**, for example using micro-transfer printing or contact printing.

[0077] FIG. **30** is an illustration of a component source wafer **10** having an eight-by-eight array **22** of components **20** whose attributes **12** vary in two dimensions, indicated by the shading of the components **20** and corresponding to FIG. **3** (in a smaller array **22** of components **20**) and FIG. **25** (in a larger array **22** of components **20**). Components **20** on component source wafer **10** are labeled with a number corresponding to the operation (e.g., stamp operation) that transfers (e.g., micro-transfer prints) components **20** from component source wafer **10** to destination substrate **40**, for example using a stamp **30** with a four-by-four array of stamp posts **32** spaced apart by two components **20**, so that four operations are required to complete the transfer of the shown array. Operations that do not transfer (e.g., micro-transfer print) components **20** in different orientations result in a distribution of components **20** on destination substrate **40** as shown in FIG. **31**. As shown in FIG. **31** by the shading of components **20**, the attribute **12** variation of component source wafer **10** is repeated four times, albeit at a different resolution on destination substrate **40**.

[0078] Referring to FIG. **32**, in an illustration according to some embodiments of the present invention, arrays **22** of components **20** transferred (e.g., micro-transfer printed) in operations **2**, **3**, and **4** (e.g., stamp operations) each have different orientations on destination substrate **40** than the array **22** of components **20** transferred (e.g., micro-transfer printed) in operation **1** (e.g., a stamp operation). Each array **22** of components **20** transferred in operations **2**, **3**, and **4** is rotated with respect to array **22** of components **20** and is adjacent to array **22** of components **20** transferred in operation **1**. Referring to FIG. **33**, in an illustration according to some embodiments of the present invention, each array **22** of components **20** transferred (e.g., micro-transfer printed) in operations **2**, **3**, and **4** (e.g., stamp operations) is offset with respect to array **22** of components **20** as distributed on component source wafer **10** (shown in FIG. **30**). Thus, the attribute **12** of components **20** varies less regularly with respect to spatial location on destination substrate **40**.

[0079] Without wishing to be bound by any particular theory, such variation can be less objectionable to a human visual system for a particular application (e.g., if components **20** are light-emitting diodes in a display). For example, the array **22** shown in FIG. **33**, that has been formed using different orientations, has an attribute **12** that varies with some frequency in one or more directions. For example, FIG. **33** shows some variation in the horizontal direction and a diagonal direction (e.g., from top left corner to bottom right corner). The comparative array **22** shown in FIG. **31**, that has been formed using only a single orientation, also has an attribute **12** that varies with some frequency in one or more directions. Comparing the arrays **22** of FIG. **31** and FIG. **33**, one of ordinary skill can appreciate that the frequency (or amplitude) of variation in at least one direc-

tion, for example in the aforementioned diagonal direction, is reduced in the array **22** of FIG. **33**. In some embodiments, transferring using different orientations may also increase the frequency (or amplitude) of variation in a different direction, such as the horizontal direction. In some embodiments, multiple different orientations, such as offset and rotation, are used to further reduce variations, for example in multiple directions.

[0080] FIG. **34** is an illustration of a component source wafer **10** having an eight-by-eight array **22** of components **20** whose attributes **12** vary in two dimensions, indicated by the shading of the components **20** and corresponding to FIG. **3** (in a smaller array **22** of components **20**) and FIG. **25** (in a larger array **22** of components **20**). Components **20** on component source wafer **10** are labeled with a hexadecimal number (starting with '1' and ending with 'G') corresponding to the operation (e.g., stamp operation) that transfers (e.g., micro-transfer prints) components **20** from component source wafer **10** to destination substrate **40**, for example using a stamp **30** with a two-by-two array of stamp posts **32**, so that sixteen operations are required to complete the transfer of the shown array. As shown in FIG. **35**, in an illustration according to some embodiments of the present invention, arrays **22** of components **20** transferred (e.g., micro-transfer printed) in operations **2**-G (e.g., stamp operations) each have different orientations than the transferred (e.g., micro-transfer printed) array **22** of components **20** in operation **1** (e.g., a stamp operation). Each array **22** of components **20** transferred in operations **2**-G is interlaced (e.g., interdigitated) with respect to array **22** of components **20** transferred in operation **1**. As shown in FIG. **36**, in an illustration according to some embodiments, each array **22** of components **20** transferred (e.g., micro-transfer printed) in operations **2**-G (e.g., stamp operations) is offset and interlaced with respect to array **22** of components **20** transferred (e.g., micro-transfer printed) in operation **1** (e.g., a stamp operation) so that adjacent arrays **22** of components 20 micro-transfer printed on destination substrate **40** are not picked up from adjacent arrays **22** of components **20** on component source wafer **10** and the arrays **22** of components **20** are interlaced.

[0081] As shown in FIG. **37**, in an illustration according to some embodiments of the present invention, each array **22** of components **20** transferred (e.g., micro-transfer printed) in operations **2**-G (e.g., stamp operations) is offset, interlaced, and rotated with respect to array **22** of components **20** transferred (e.g., micro-transfer printed) in operation **1** (e.g., a stamp operation) so that adjacent arrays **22** of components **20** transferred to destination substrate **40** are not picked up from adjacent arrays **22** of components **20** on component source wafer **10** and the arrays **22** of components **20** are interlaced and rotated. Thus, without wishing to be bound to any particular theory, the attribute **12** of components **20** varies less regularly or less significantly with respect to a local average with respect to position on destination substrate **40** and can thus be less objectionable to the human visual system (e.g., for example if components **20** are light-emitting diodes in a display). For example, as shown in FIG. **37**, two-by-two or four-by-four arrays **22** of adjacent components **20** on destination substrate **40** can have average attribute **12** values that have less variation than two-by-two or four-by-four arrays **22** of adjacent components **20** on the component source wafer **10**.

[0082] FIG. **38** is an illustration according to some embodiments of the present disclosure wherein some of the arrays **22** of components **20** transferred (e.g., micro-transfer printed) in print steps **160** are rotated by different amounts with respect to others, for example some are not rotated, some are rotated 90 degrees, some are rotated 180 degrees, and some are rotated 270 degrees. The varying rotations reduce the systematic changes in attribute **12** and at least apparently randomize the changes in attribute **12** of components **20** distributed over destination substrate **40**.

[0083] In some embodiments, a method comprises repeatedly transferring arrays **22** of components **20** from component source wafer **10** to destination substrate 40 N times in one dimension, where N/2 pairs of adjacent arrays **22** of components **20** on destination substrate **40** comprise array **22** i and array **22** (N−1−i) for each i from 0 to (N/2)−1.

[0084] For example, referring to FIG. **2**, a horizontal one-dimensional array of sixteen components **20** (e.g., the top row of FIG. **2**) has a monotonically changing attribute **12**. Referring to FIG. **27**, the components **20** are reordered in the same horizontal direction by transferring four groups (arrays **22**) of four components **20** each (thus, in this example N=4 and i equals 0, 1, 2, and 3). (Note that the physical spacing of components **20** in FIG. **27** is one quarter that of FIG. **2**.) If adjacent groups of four are sampled, as in FIG. **27**, then components from group i=**0** are transferred adjacent to components **20** from group i=1. Similarly, components **20** from group i=1 are also adjacent to components **20** from group i=2 and components **20** from group i=2 are also adjacent to components **20** from group i=3, so that the components **20** have attributes **12** ordered as 1, 2, 3, 4 in four horizontally adjacent arrays, as shown in FIG. **27**. In contrast, according to the equation above and for some embodiments of the present invention, for arrays from zero to (N/2)−1=1, if components from group i=0 are disposed adjacent to components from group i=3 (because N−1−I=4−1−0=3) and components from group i=1 are disposed adjacent to components from group i=2 (because N−1−I=4−1−1=2), so that the components **20** have attributes **12** ordered as 1, 4, 2, 3, the changes in attribute **12** in the horizontal direction are no longer monotonic and the visibility or objectionability of the variation can be therefore reduced.

[0085] In some embodiments, a method of the present disclosure, comprises repeatedly transferring arrays **22** of components **20** from component source wafer **10** to destination substrate **40** N×M times in two dimensions, where N/2×M/2 two-by-two adjacent component arrays **22** on destination substrate **40** comprise array **22** (i, j), array **22** (N−1−i, j), array **22** (i, M−1−j), and array **22** (N−1−i, M−1−j) for each i from 0 to (N/2)−1 and each j from 0 to (M/2)−1. Thus, components **20** in different arrays **22** are interlaced in one or two dimensions. By transferring different arrays **22** of components **20** in such a manner, a variation in attributes **12** may be made less regular, less visible, or less objectionable; arrays **22** of components **20** on destination substrate **40** (after transfer) are mixed up with respect to the corresponding arrays **22** of components **20** on component source wafer **10** (before transfer). The two-dimensional case operates as described above with the one-dimensional case except in two orthogonal directions at the same time.

[0086] In some embodiments and as illustrated in FIG. **39**, a method comprises transferring a plurality of component source wafers **10** and arrays **22** of components **20** from each component source wafer **10** onto destination substrate **40**

with two or more different orientations. For example, the plurality of component source wafers **10** can comprise a first component source wafer **10** and a second component source wafer **10** different from the first component source wafer **10**, provided in steps **100** and **101**. The method can comprise interlacing (e.g., interdigitating) components **20** from first component source wafer **10** between components **20** from second component source wafer **10** for example by using the same or different stamps **30** to pick up components **20** from first and second component source wafers **10** in steps **130**, **131** and **140**, **141** respectively, move the stamp **30** to destination substrate **40** in step **150**, and print components **20** to destination substrate **40** in step **160** with an orientation and print components **20** to destination substrate **40** in step **161** with a different orientation. In some embodiments, different component source wafers **10** have different kinds or types of components **20**. For example, components **20** can be LEDs and the different component source wafers **10** can each include LEDs that emit a different color of light. For example, in some embodiments, each of three component source wafers **10** includes one of red, green, and blue LEDs that emit red, green, or blue light, respectively, and the different LEDs are transferred with different orientations. Sets of three different LEDS can comprise pixels in a display and destination substrate **40** can be a display substrate.

[0087] Displays having same and different color arrays **22** of LED components **20** of micro-transfer printed from one or more component source wafers **10** to a destination substrate **40** using multiple orientations have been constructed and visually examined and shown to have less visible variation in color and brightness.

[0088] In some embodiments of the present disclosure, the order in which components **20** are printed (e.g., front right components **20** on a stamp **30** versus back left components **20** on a stamp **30**) is arbitrary.

[0089] According to some embodiments of the present disclosure, micro-transfer printing includes transferring components **20** from a source substrate (e.g., component source wafer **10**) to a destination substrate (e.g., destination substrate **40**) by contacting components **20** on the source substrate with a stamp **30** to remove components **20** from the source substrate, transferring stamp **30** and contacted components **20** to the destination substrate **40**, and contacting components **20** to a surface of the destination substrate **40**. Components **20** can be adhered to stamp **30** or the destination substrate **40** by, for example, one or more of van der Waals forces, electrostatic forces, magnetic forces, chemical forces, and adhesive forces (e.g., from an adhesive). In some embodiments of the present disclosure, components **20** are adhered to stamp **30** with separation-rate-dependent adhesion, for example kinetic control of viscoelastic stamp materials such as can be found in elastomeric devices such as a PDMS stamp **30**. Stamps **30** can comprise stamp posts **32** having a stamp post area on the distal end of stamp posts **32**. Stamp posts **32** can have a length, a width, or both a length and a width, similar or substantially equal to a length, a width, or both a length and a width of component **20**. In some embodiments, as discussed further below, stamp posts **32** of a stamp **30** can be smaller than components **20** in one or two orthogonal directions.

[0090] In exemplary methods, a stamp **30** (e.g., a viscoelastic elastomer stamp, such as a stamp optionally comprising a plurality of stamp posts **32**) is designed and fabricated to retrieve and transfer arrays **22** of components **20** from their native component source wafer **10** onto non-native destination substrates **40**. In some embodiments, stamp **30** mounts onto motion-plus-optics machinery (e.g., an opto-mechatronic motion platform) that can precisely control stamp **30** alignment and kinetics with respect to both component source wafers **10** and destination substrates **40**. During micro-transfer printing, the motion platform brings stamp **30** into contact with components **20** on component source wafer **10**, with optical alignment performed before contact. For example, in some embodiments, light can be transmitted and/or received through stamp **30** (e.g., through one or more stamp posts **32**) in order to perform an optical alignment. Rapid upward movement of the print-head fractures component tether(s) **52** forming fractured component tethers **53**, transferring component(s) **20** to stamp **30** or stamp posts **32**. The populated stamp **30** then travels to destination substrate **40** and one or more components **20** are then aligned (e.g., in a manner similar to for pick-up) to destination substrate **40** and printed.

[0091] A component source wafer **10** can be any source wafer or substrate with micro-transfer printable components **20** that can be transferred with a stamp **30**. For example, a component source wafer **10** can be or include a semiconductor (e.g., silicon) in a crystalline or non-crystalline form, a compound semiconductor (e.g., comprising GaN or GaAs), or a glass, polymer, sapphire, or quartz wafer. Sacrificial portions **14** can be formed of a patterned oxide (e.g., silicon dioxide) or nitride (e.g., silicon nitride) layer or can be an anisotropically etchable portion of sacrificial layer **11** of component source wafer **10**. Typically, but not necessarily, component source wafers **10** are smaller than destination substrates **40**.

[0092] Exemplary components **20** include active, passive, and active and passive components **20**. Exemplary components **20** include, but are not limited to, any one or more of integrated devices, integrated circuits (such as CMOS circuits), light-emitting diodes, photodiodes, sensors, electrical or electronic devices, optical devices, opto-electronic devices, magnetic devices, magneto-optic devices, magneto-electronic devices, and piezo-electric device, materials or structures. Components **20** can comprise electronic component circuits that operate component **20**. Components **20** can be responsive to electrical energy, to optical energy, to electromagnetic energy, to mechanical energy, or to a combination thereof. In some embodiments, a component **20** is a light-emitting diode (LED).

[0093] Components **20** formed or disposed in or on component source wafers **10** can be constructed using, for example, one or more of integrated circuit, micro-electro-mechanical, and photolithographic methods. Components **20** can comprise one or more different component materials, for example, non-crystalline or crystalline semiconductor materials such as silicon or compound semiconductor materials or non-crystalline or crystalline piezo-electric materials.

[0094] In some embodiments of the present disclosure, components **20** can be native to and formed on sacrificial portions **14** of component source wafers **10** and can include one or more seed layers used for constructing crystalline layers on or in component source wafers **10**. In some examples, components **20**, sacrificial portions **14**, anchors **50**, and component tethers **52** can be constructed using photolithographic processes. Components **20** can be micro-devices having at least one of a length and width no more

than 200 microns(e.g., no more than 100 microns, no more than 50 microns, no more than 25 microns, no more than 15 microns, no more than 10 microns, or no more than five microns), and, optionally, a thickness of no more than 50 microns (e.g., no more than 25 microns, no more than 15 microns, no more than 10 microns, no more than five microns, no more than two microns, or no more than one micron). In some embodiments, components **20** can be unpackaged dice (each an unpackaged die) transferred directly from native component source wafers **10** on or in which components **20** are constructed to destination substrate **40** (without wafer dicing).

[0095] Anchors **50** and component tethers **52** can be or can comprise portions of component source wafer **10** that are not sacrificial portions **14** and can include layers formed on component source wafers **10**, for example dielectric or metal layers and for example layers formed as a part of photolithographic processes used to construct or encapsulate components **20**.

[0096] Destination substrate **40** can be any destination substrate or target substrate to which components **20** are transferred (e.g., micro-transfer printed), for example flat-panel display substrates, printed circuit boards, or similar substrates. Destination substrates **40** can be, for example substrates comprising glass, polymer, quartz, ceramics, metal, or sapphire. Destination substrates **40** can be semiconductor substrates (for example silicon) or compound semiconductor substrates and can have multiple layers.

[0097] In some embodiments of the present disclosure, a layer of adhesive, such as a layer of resin, polymer, or epoxy, either curable or non-curable, adheres components **20** onto destination substrate **40** and can be disposed, for example by coating or lamination. In some embodiments, the layer of adhesive is disposed in a pattern, for example using inkjet, screening, or photolithographic techniques. In some embodiments, a layer of adhesive is coated, for example with a spray or slot coater, and then patterned, for example using photolithographic techniques.

[0098] Patterned electrical conductors (e.g., wires, traces, or electrical contact pads such as those found on printed circuit boards, flat-panel display substrates, and in thin-film circuits) can be formed on any one or combination of one or more components **20** and destination substrate **40**. One or more electrical contact pads can be in or on destination substrate **40** and/or in or on one or more components **20** to electrically connect components **20**. Such patterned electrical conductors and contact pads can comprise, for example metal, transparent conductive oxides, or cured conductive inks and can be constructed using photolithographic methods and materials, for example metals such as aluminum, gold, or silver deposited by evaporation and patterned using pattern-wise exposed, cured, and etched photoresists, or constructed using imprinting methods and materials or inkjet printers and materials, for example comprising cured conductive inks deposited on a surface or provided in micro-channels in or on destination substrate **40**.

[0099] Micro-transfer printing processes suitable for disposing components **20** onto destination substrates **40** are described in *Inorganic light-emitting diode displays using micro-transfer printing* (Journal of the Society for Information Display, 2017, DOI # 10.1002/jsid.610, 1071-0922/17/2510-0610, pages 589-609), U.S. Pat. 8,722,458 entitled *Optical Systems Fabricated by Printing-Based Assembly*, U.S. patent application Ser. No. 15/461,703 entitled Pressure Activated Electrical Interconnection by Micro-Transfer Printing, U.S. Pat. No. 8,889,485 entitled *Methods for Surface Attachment of Flipped Active Components*, U.S. patent application Ser. No. 14/822,864 entitled *Chiplets with Connection Posts*, U.S. patent application Ser. No. 14/743,788 entitled *Micro-Assembled LED Displays and Lighting Elements*, and U.S. patent application Ser. No. 15/373,865, entitled *Micro-Transfer Printable LED Component*, the disclosure of each of which is incorporated herein by reference in its entirety.

[0100] For a discussion of micro-transfer printing techniques, see also U.S. Pat. Nos. 7,622,367 and 8,506,867, 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 with the present disclosure, 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 also incorporated by reference in its entirety. Accordingly, in some embodiments, printed structure **99** is a compound micro-assembled structure.

[0101] According to various embodiments of the present disclosure, component source wafer **10** can be provided with components **20**, patterned sacrificial portions **14**, component tethers **52**, and anchors **50** already formed, or they can be constructed as part of a method. Component source wafer **10**, components **20**, stamp **30**, and destination substrate **40** can be made separately and at different times or in different temporal orders or locations and provided in various process states.

[0102] The spatial distribution of components **20** on a component source wafer **10** or printed structures **99** is a matter of design choice for the end product desired. In some embodiments of the present disclosure, all components **20** in an array **22** on a component source wafer **10** are transferred to a stamp **30**. In some embodiments, a subset of components **20** in an array **22** on a component source wafer **10** is transferred. By varying the number and arrangement of stamp posts **32** on transfer stamps **30**, the distribution of components **20** on stamp posts **32** of the transfer stamp **30** can be likewise varied, as can the distribution of components **20** on destination substrate **40**.

[0103] Because components **20**, in certain embodiments, can be made using integrated circuit photolithographic techniques having a relatively high resolution and cost and destination substrate **40**, for example a printed circuit board, can be made using printed circuit board techniques having a relatively low resolution and cost, electrical conductors and substrate contact pads on destination substrate **40** can be much larger than electrical contacts or component electrodes on component **20**, thereby reducing manufacturing costs. For example, in certain embodiments, micro-transfer printable component **20** has at least one of a width, length, and height from 0.5 μm to 200 μm (e.g., 0.5 to 2 μm, 2 to 5 μm, 5 to 10 μm, 10 to 20 μm, 20 to 50 μm, 50 to 100 μm, or 100 to 200 μm).

[0104] In certain embodiments, destination substrate **40** is or comprises a member selected from the group consisting of polymer, plastic, resin, polyimide, PEN, PET, metal, metal foil, glass, a semiconductor, and sapphire. In certain embodiments, destination substrate **40** has a thickness from 5 microns to 20 mm (e.g., 5 to 10 microns, 10 to 50 microns, 50 to 100 microns, 100 to 200 microns, 200 to 500 microns,

500 microns to 0.5 mm, 0.5 to 1 mm, 1 mm to 5 mm, 5 mm to 10 mm, or 10 mm to 20 mm).

[0105] Components **20**, in certain embodiments, can be constructed using foundry fabrication processes used in the art. Layers of materials can be used, including materials such as metals, oxides, nitrides and other materials used in the integrated-circuit art. Each component **20** can be or include a complete semiconductor integrated circuit and can include, for example, transistors, diodes, light-emitting diodes, or sensors. Components **20** can have different sizes, for example, each having an area of **100** square microns or larger, 1000 square microns or larger or 10,000 square microns or larger, 100,000 square microns or larger, or 1 square mm or larger. Components **20** can have variable aspect ratios, for example between 1:1 and 10:1 (e.g., 1:1, 2:1, 5:1, or 10:1). Components **20** can be rectangular or can have other shapes.

[0106] Various embodiments of structures and methods are described herein. Structures and methods were variously described as transferring components **20**, printing components **20**, or micro-transfer printing components **20** as examples and the particular word used should be understood to be non-limiting as to the methods that may be used to implement the described embodiments. In some embodiments, micro-transfer-printing includes using a stamp **30** (e.g., an elastomeric stamp **30**, such as a PDMS stamp **30**) to transfer a component **20** using controlled adhesion. For example, an exemplary stamp **30** can use kinetic or shear-assisted control of adhesion between the stamp **30** and a component **20**. It is contemplated that, in certain embodiments, where a method is described as including printing (e.g., micro-transfer-printing) a component **20**, other analogous embodiments exist using a different transfer method. As used herein, transferring a component **20** (e.g., from a component source wafer **10** or wafer to a destination substrate **40**) can be accomplished using any one or more of a variety of known techniques. For example, in certain embodiments, a pick-and-place method can be used. As another example, in certain embodiments, a flip-chip method can be used (e.g., involving an intermediate, handle or carrier substrate). In methods according to certain embodiments, a stamp **30** is a vacuum tool or other transfer device used to transfer components **20**. In some embodiments, a stamp **30** uses one or more of electrostatic forces, magnetic forces, and vacuum forces to transfer components **20** (e.g., applied to individual components **20** by individual stamp posts **32**).

[0107] As is understood by those skilled in the art, the terms "over" and "under" are relative terms and can be interchanged in reference to different orientations of the layers, elements, and substrates included in the present disclosure. Furthermore, a first layer "on" a second layer is a relative orientation of the first layer to the second layer that does not preclude additional layers being disposed therebetween. 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 (e.g., an in mutual contact).

[0108] 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.

[0109] Throughout the description, where apparatus and systems are described as having, including, or comprising specific elements, 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 elements, and that there are processes and methods according to the disclosed technology that consist essentially of, or consist of, the recited processing steps.

[0110] 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 conducted simultaneously. The disclosure has been described in detail with particular reference to certain embodiments thereof, but it will be understood that variations and modifications can be effected within the spirit and scope of the disclosure.

PARTS LIST

[0111] A cross section line
[0112] **10** component source wafer
[0113] **11** sacrificial layer
[0114] **12** attribute/structure/epitaxial (epi) layer
[0115] **14** sacrificial portions
[0116] **16** gap
[0117] **20** component
[0118] **20***a*-**20***j* component
[0119] **22** array
[0120] **30** stamp
[0121] **32** stamp post
[0122] **40** destination substrate
[0123] **50** anchor
[0124] **52** component tether
[0125] **53** fractured component tether
[0126] **54** dielectric layer
[0127] **99** printed structure
[0128] **100** provide component source wafer step
[0129] **110** provide stamp step
[0130] **120** provide destination substrate step
[0131] **130** move stamp to component source wafer step
[0132] **131** move stamp to second component source wafer step
[0133] **140** pick up components from component source wafer with stamp step
[0134] **141** pick up components from second component source wafer with stamp step
[0135] **145** rotate source wafer
[0136] **150** move stamp to destination substrate location step
[0137] **160** print components to destination substrate with stamp step
[0138] **161** print components with different orientation to destination substrate with stamp step
[0139] **170** done step
[0140] **180** complete step

What is claimed:

1. A method of micro-transfer printing, comprising:

providing a component source wafer and components disposed in, on, or over the component source wafer,

providing a destination substrate, and providing a stamp for transferring the components from the component source wafer to the destination substrate, wherein the component source wafer has an attribute or structure that varies across the component source wafer such that different ones of the components in different locations have a different structure, operation, appearance, or performance;

transferring a first array of components from the component source wafer to the destination substrate with a first orientation; and

transferring a second array of components from the component source wafer to the destination substrate with a second orientation, wherein the second orientation is different from the first orientation.

2. The method of claim **1**, comprising transferring the first array and transferring the second array using micro-transfer printing.

3. The method of claim **1**, wherein the second orientation is rotated relative to the first array to provide different first and second orientations.

4. The method of claim **3**, wherein the second orientation is rotated 90 degrees or 270 degrees with respect to the first orientation.

5. The method of claim **3**, wherein the second orientation is rotated 180 degrees with respect to the first orientation.

6. The method of claim **1**, comprising transferring the second array of components adjacent to the first array of components on the destination substrate.

7. The method of claim **1**, comprising repeatedly transferring arrays of components from the component source wafer to the destination substrate with adjacent arrays on the destination substrate transferred at different orientations.

8. The method of claim **7**, comprising repeatedly transferring arrays of components from the component source wafer to the destination substrate N times in one dimension, where N/2 pairs of adjacent arrays on the destination substrate comprise array i and array (N−1−i) for each i from 0 to (N/2)−1.

9. The method of claim **7**, comprising repeatedly transferring arrays of components from the component source wafer to the destination substrate N×M times in two dimensions, where N/2×M/2 two-by-two adjacent component arrays on the destination substrate comprise array (i, j), array (N−1−i, j), array (i, M−1−j), and array (N−1−i, M−1−j) for each i from 0 to (N/2)−1 and each j from 0 to (M/2)−1.

10. The method of claim **1**, comprising interlacing the second array with respect to the first array in at least one dimension to provide different first and second orientations.

11. The method of claim **1**, wherein the interlacing is in two dimensions.

12. The method of claim **1**, wherein the first array and the second array are each regular, arrangements of components in one dimension.

13. The method of claim **1**, wherein the first array and the second array are each regular arrangements of components in two dimensions.

14. The method of claim **1**, comprising offsetting the second array with respect to the first array on the destination substrate by an amount that is different from an offset of the first array with respect to the second array on the component source wafer to provide different first and second orientations.

15. The method of claim **14**, wherein the second array is disposed with respect to the first array on the destination substrate in a different direction than the second array is disposed with respect to the first array on the component source wafer.

16. The method of claim **14**, wherein the first array and second array are adjacent on the component source wafer before transferring but are not adjacent on the destination substrate after transferring.

17. The method of claim **1**, comprising:

providing a plurality of component source wafers, wherein the plurality of component source wafers comprises the component source wafer; and

comprising transferring arrays of components from each of the component source wafers onto the destination substrate with two or more different orientations.

18. The method of claim **17**, wherein the plurality of component source wafers comprises a first component source wafer and a second component source wafer different from the first component source wafer, and the method comprises interlacing components from the first component source wafer between components from the second component source wafer.

19. The method of claim **1**, wherein the components are light-emitting components.

20. The method of claim **1**, wherein the components are inorganic light-emitting diodes.

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