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(54) **ADHESIVE WAFER BONDING WITH SACRIFICIAL SPACERS FOR CONTROLLED THICKNESS VARIATION**

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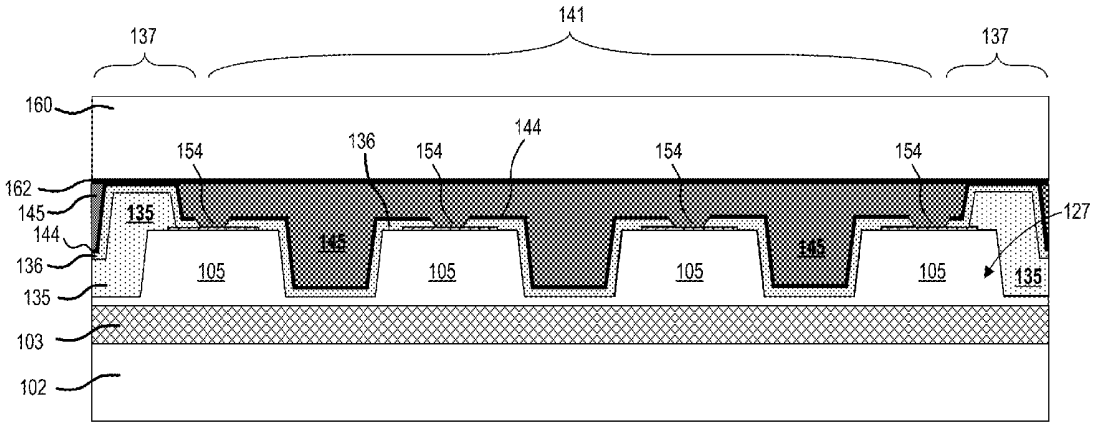
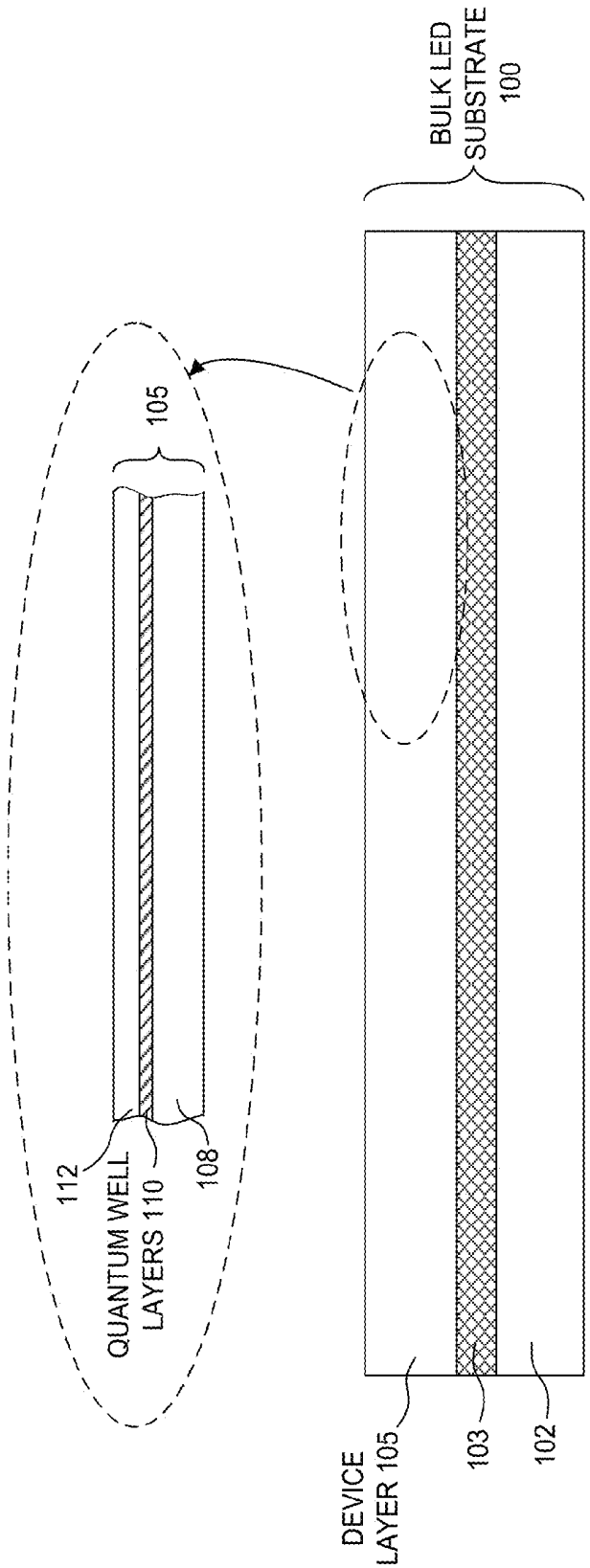
USPC **257/88**; 438/34

(57) **ABSTRACT**

A method and structure for forming an array of micro devices is disclosed. An array of micro devices is formed over an array of stabilization posts included in a stabilization layer. Patterned sacrificial spacers are formed between the stabilization posts and between the micro devices. The patterned sacrificial spacers are disposed upon the patterned sacrificial spacers.




BULK LED SUBSTRATE 100
105
112
QUANTUM WELL LAYERS 110
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DEVICE LAYER 105
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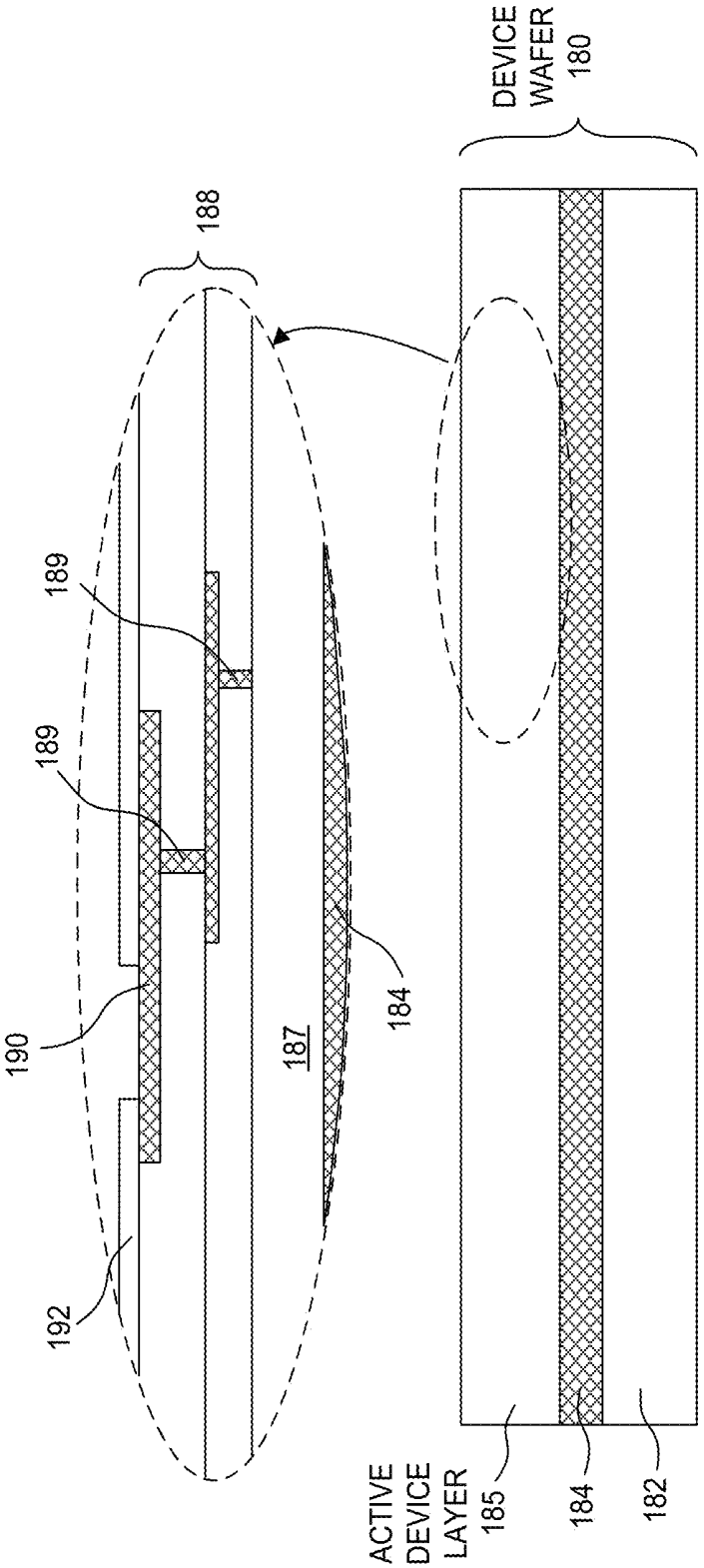
FIG. 1A


DEVICE WAFER 180
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ACTIVE DEVICE LAYER 185
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FIG. 1B

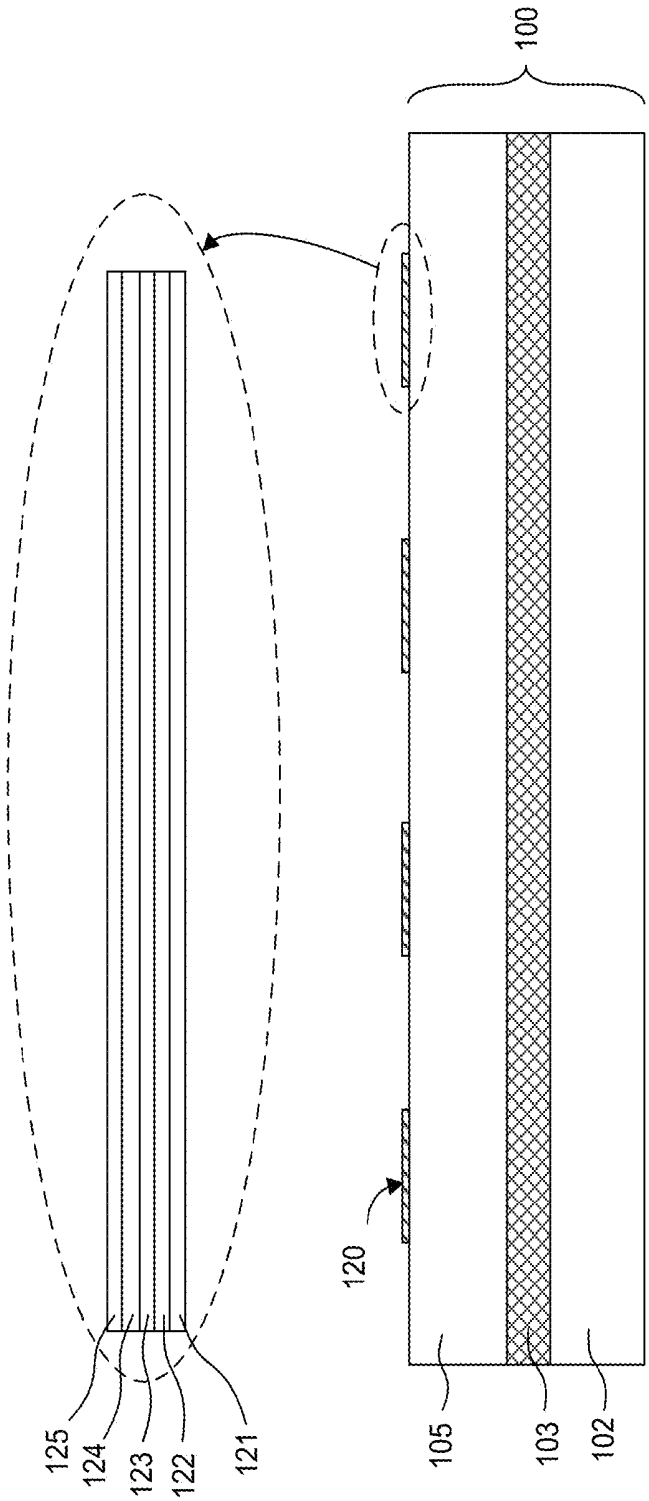

FIG. 2A

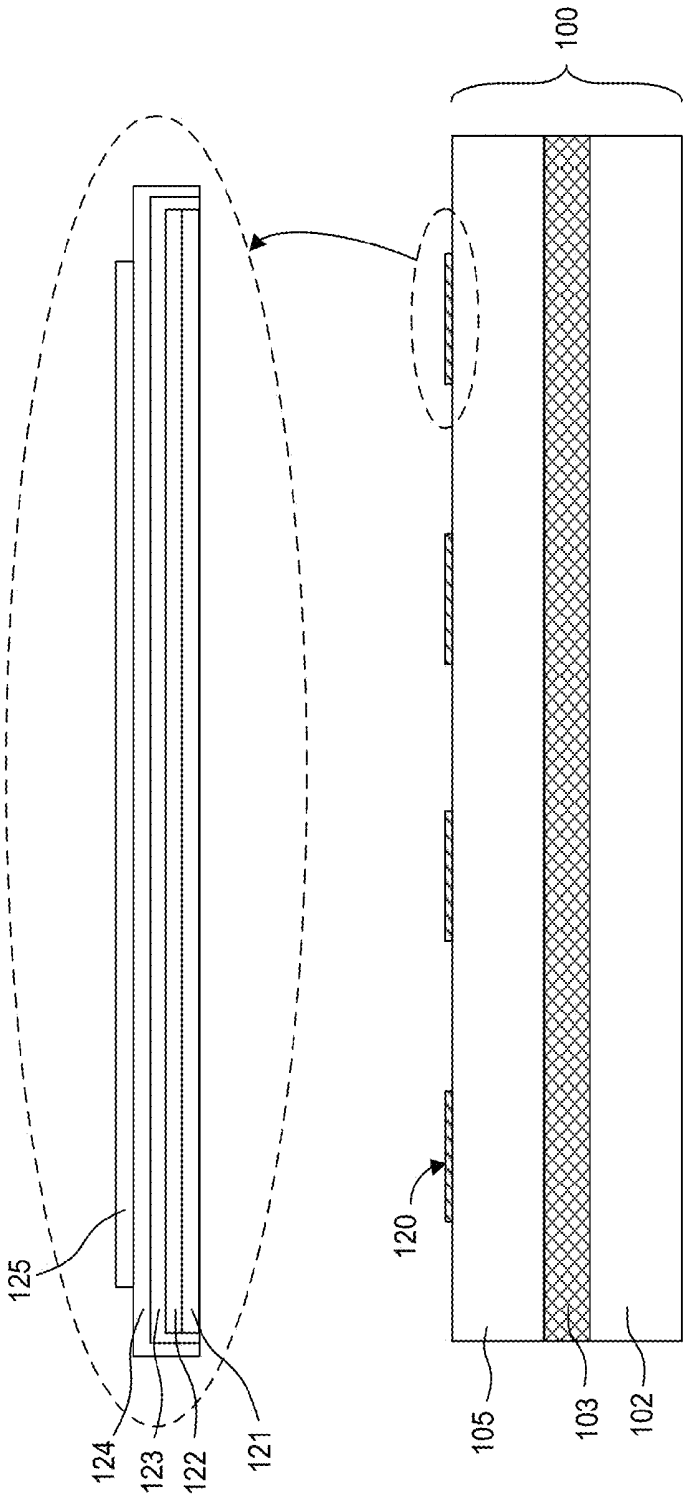

FIG. 2B

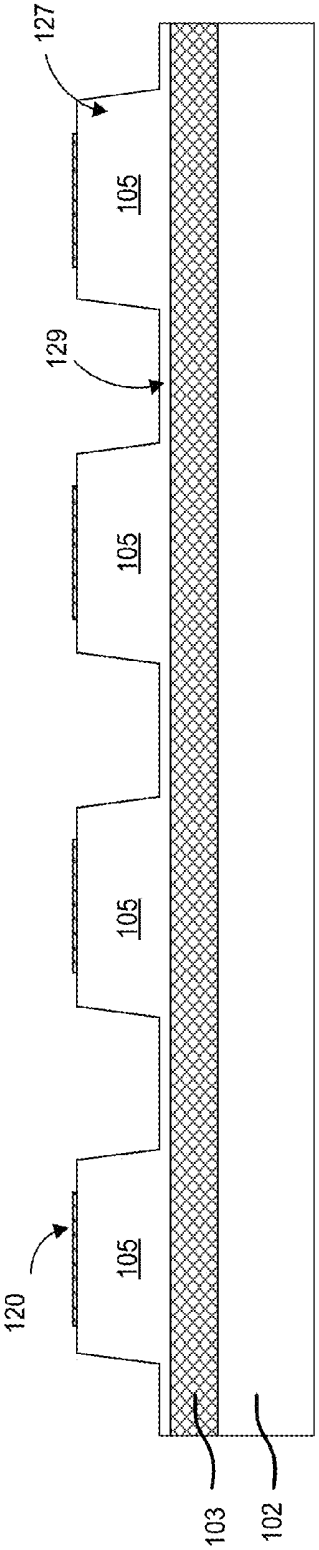
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FIG. 3

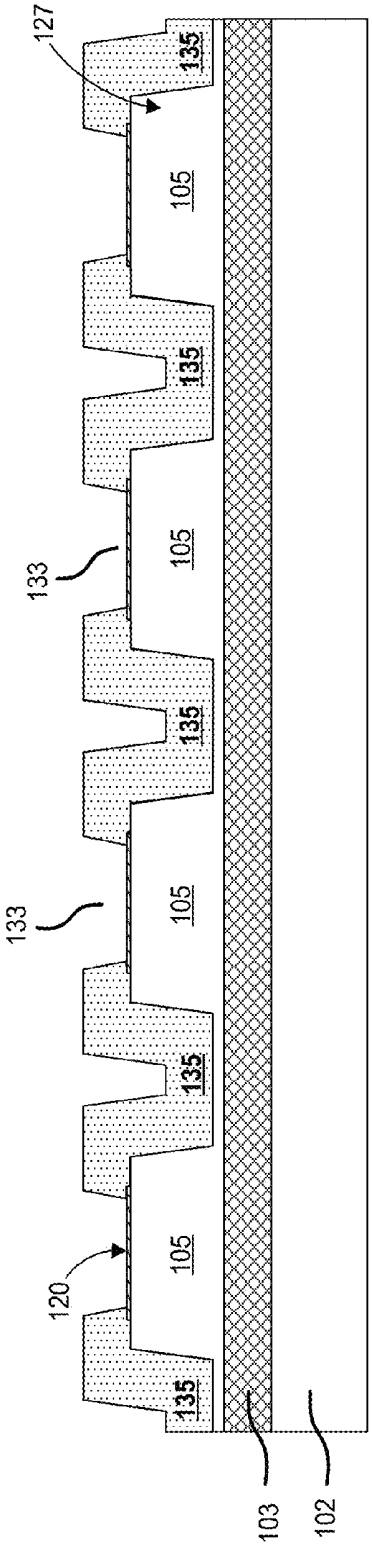
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FIG. 4

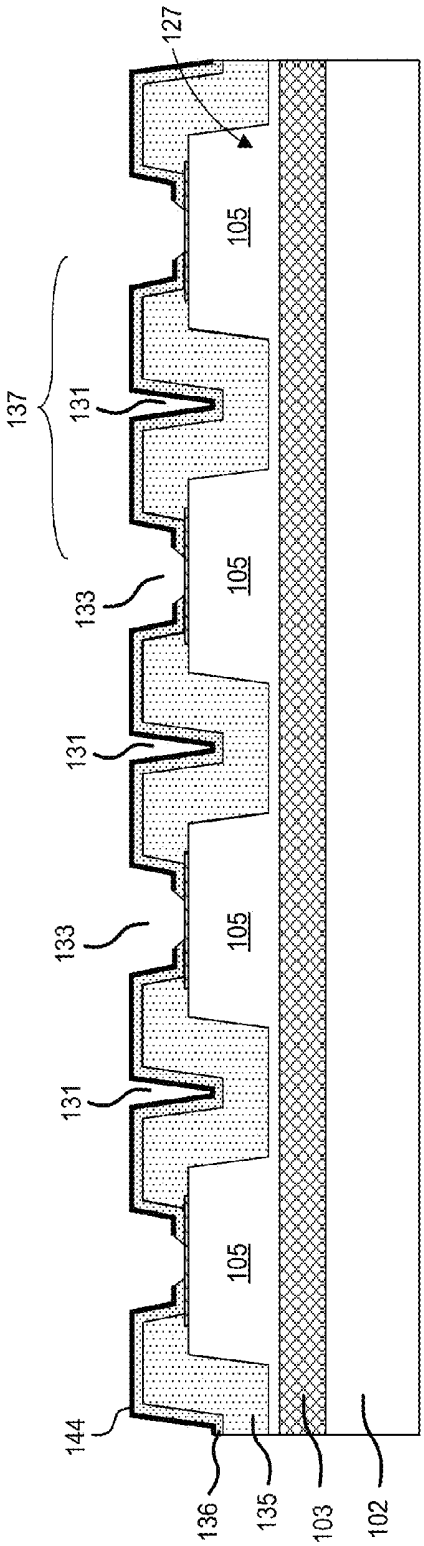
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FIG. 5

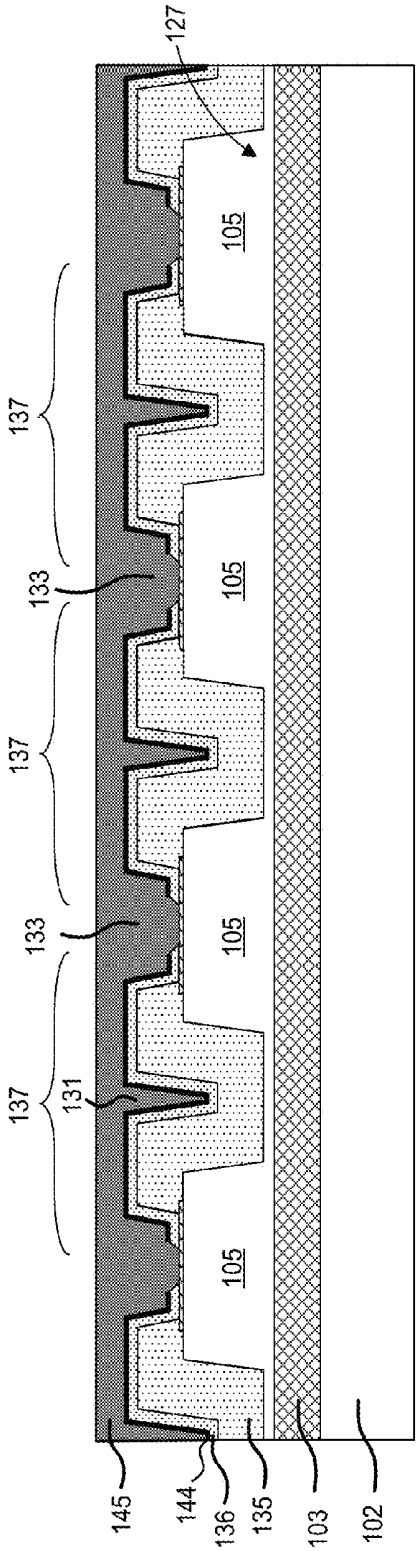
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FIG. 6

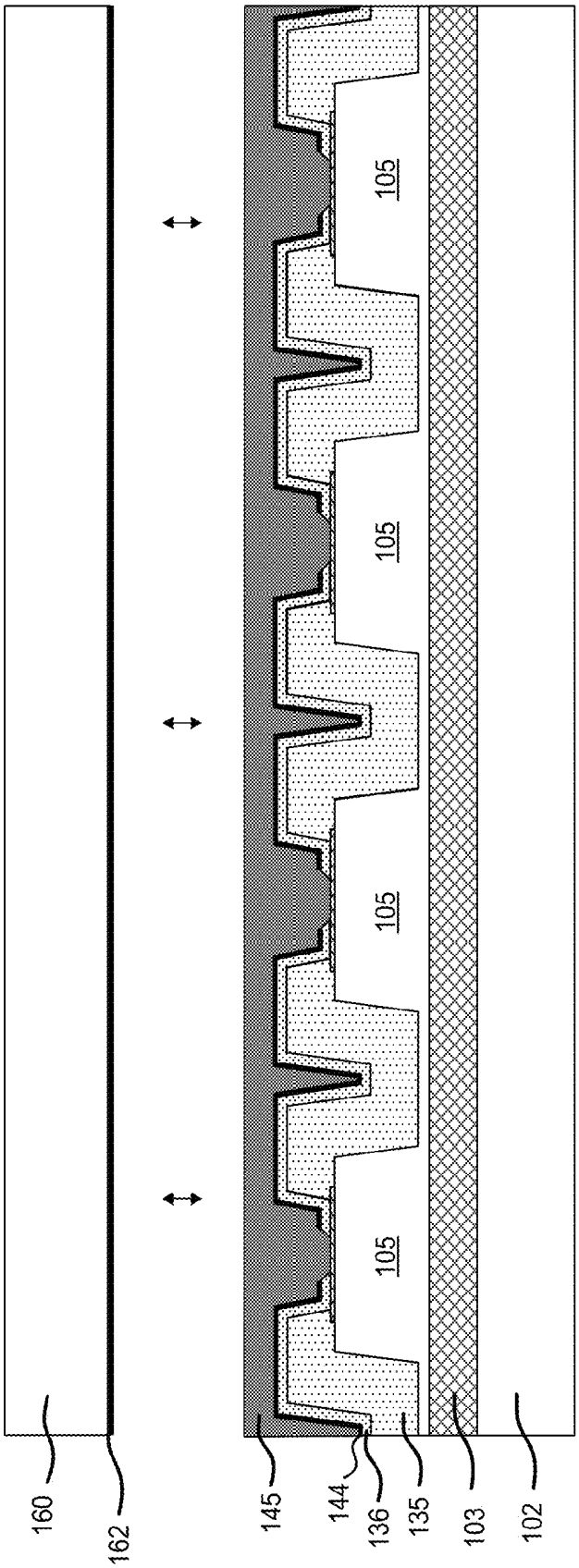

FIG. 7

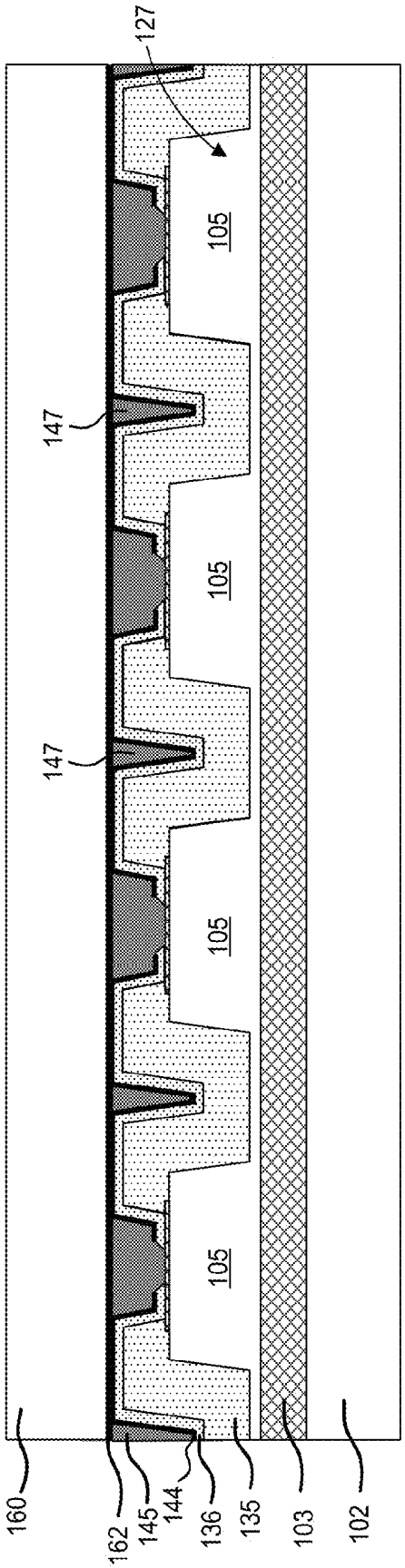

FIG. 8

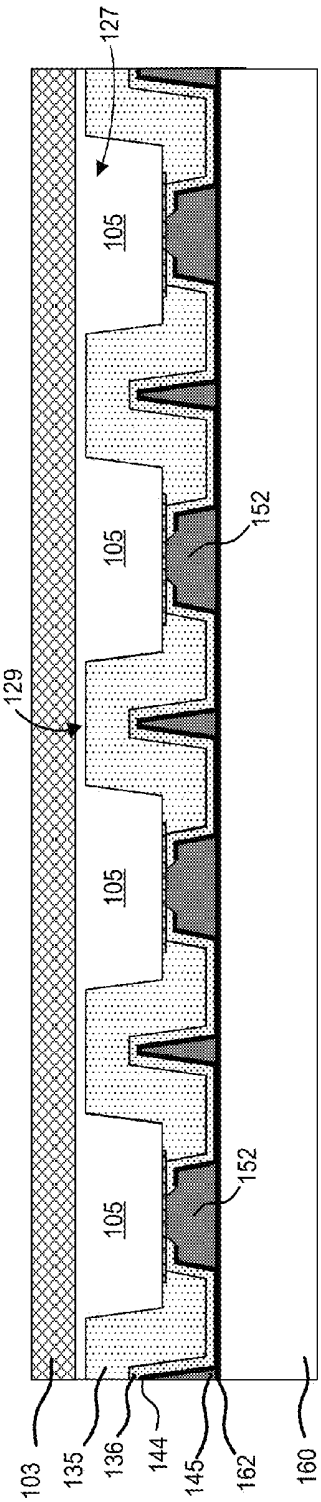
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FIG. 9

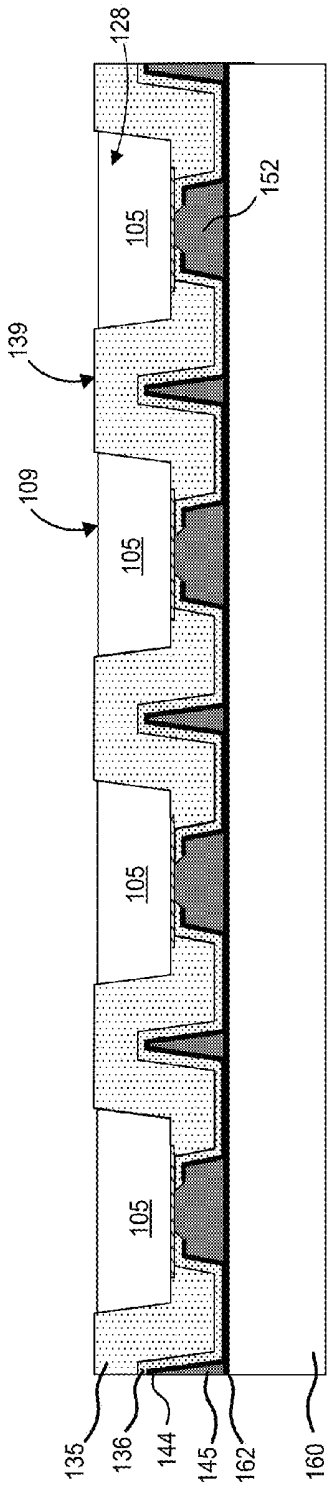
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FIG. 10

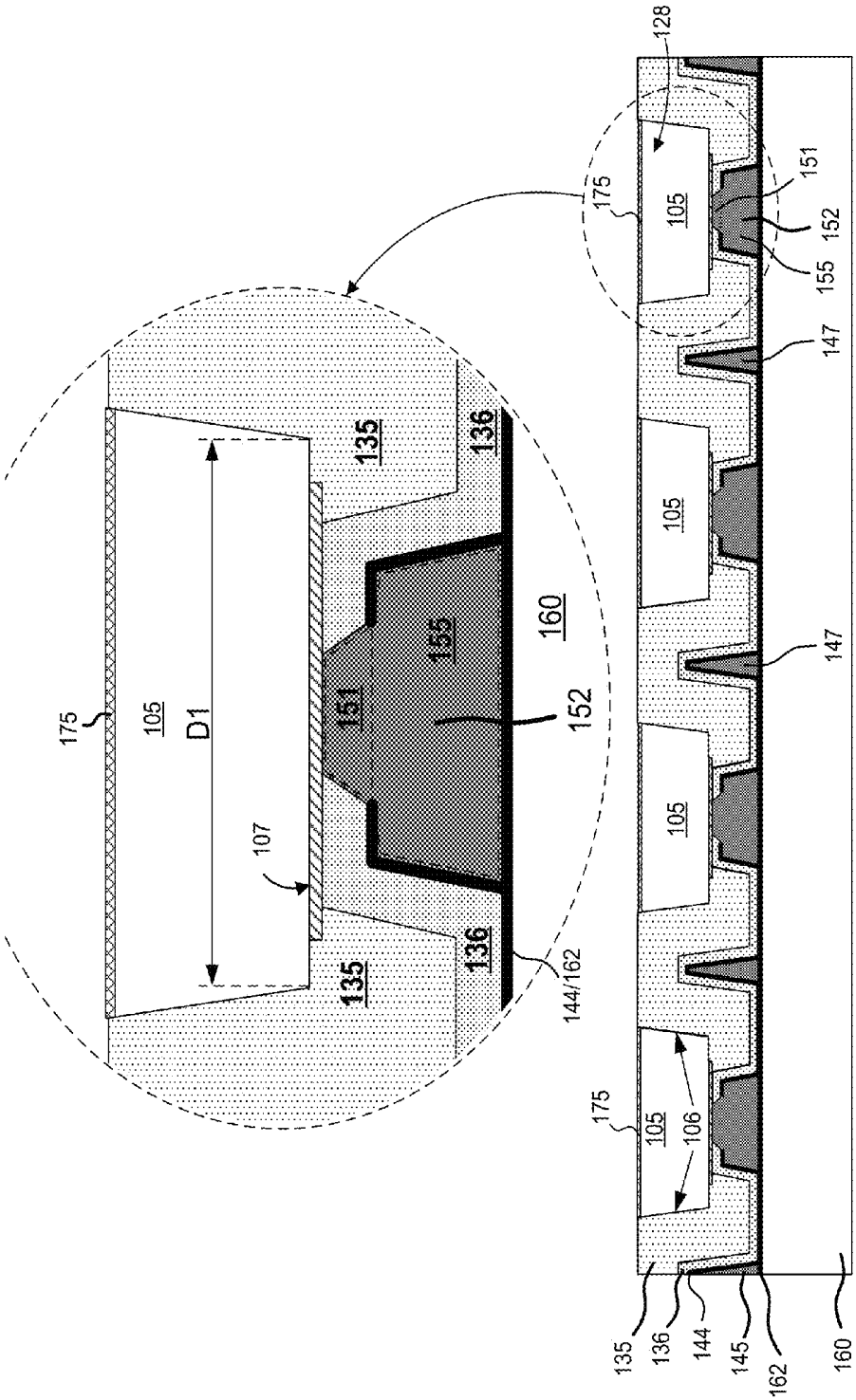
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FIG. 11

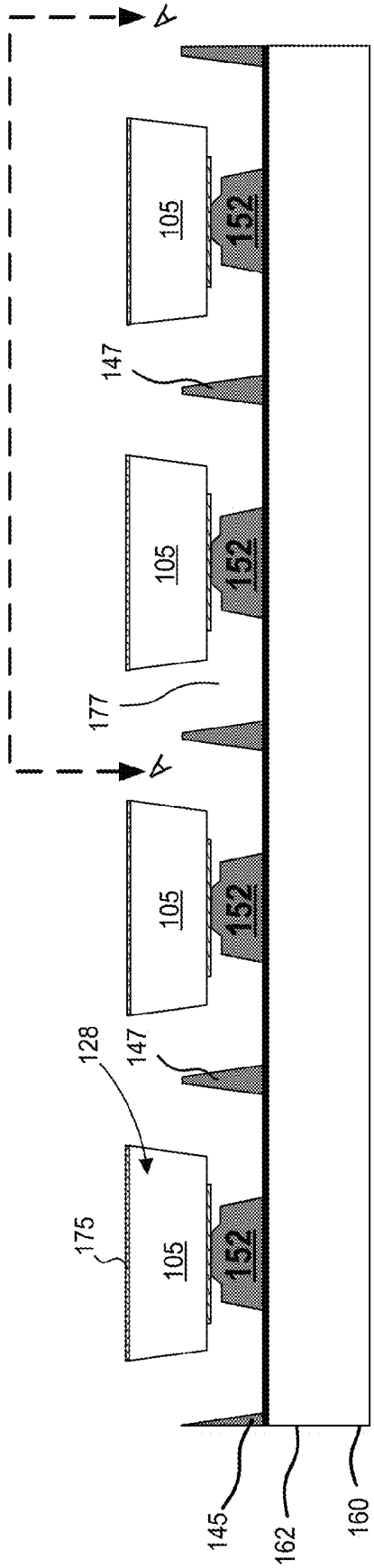

FIG. 12A

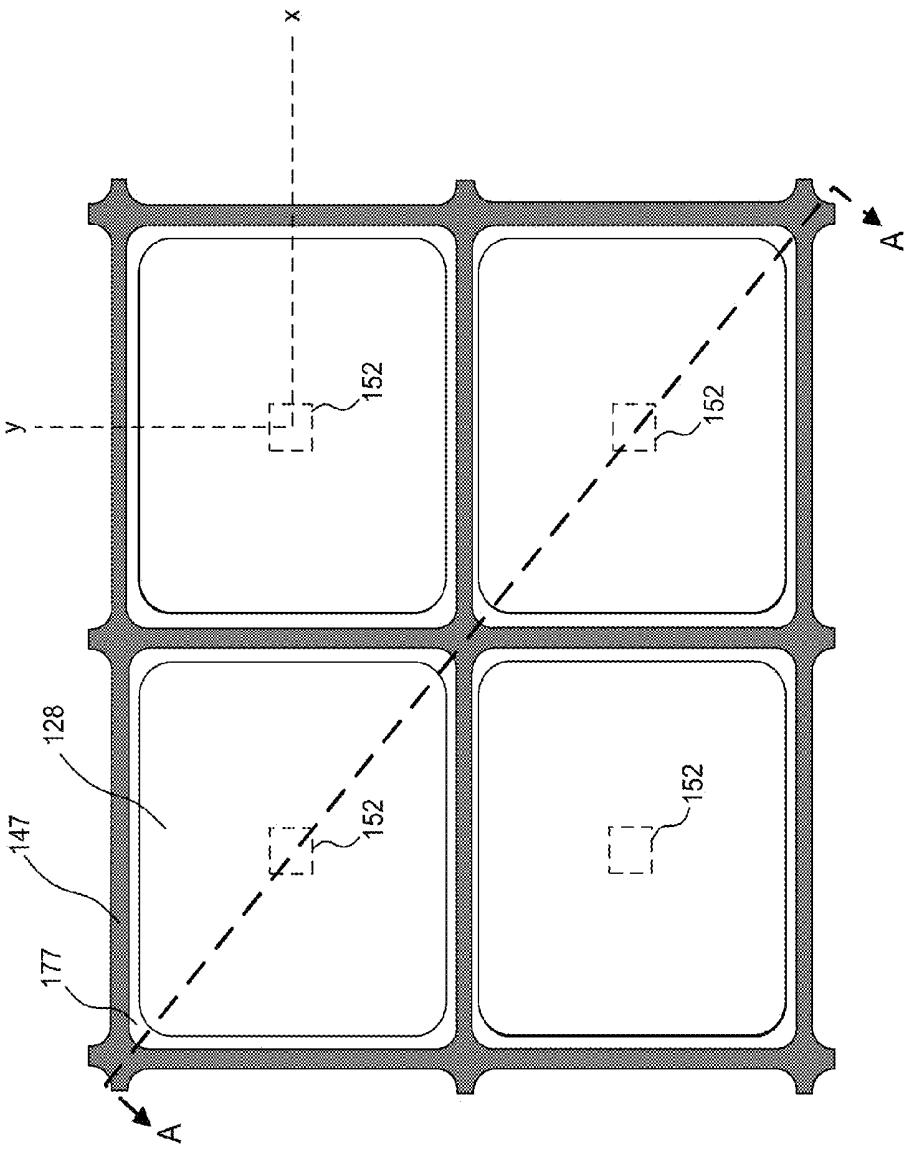

FIG. 12B

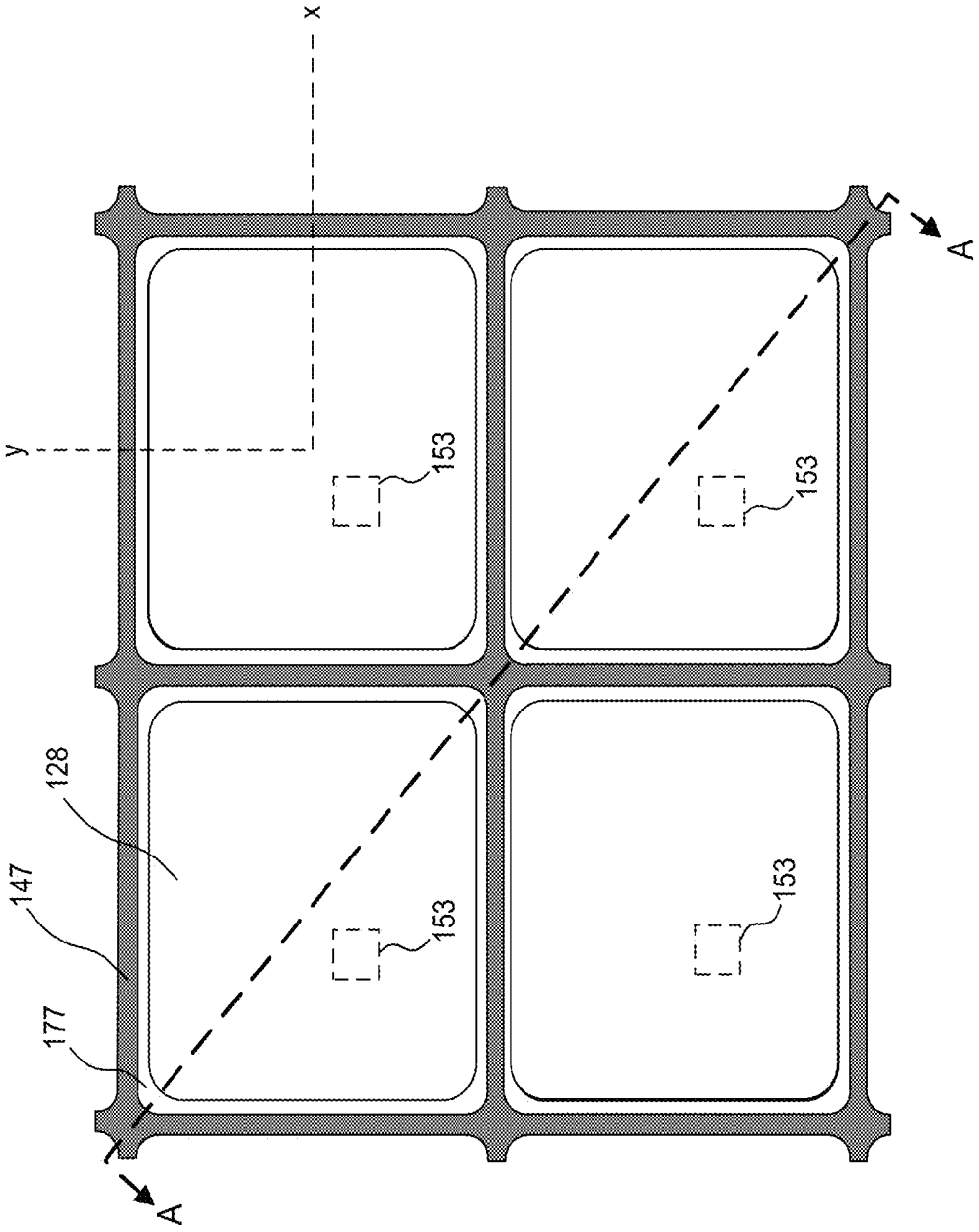

FIG. 12C

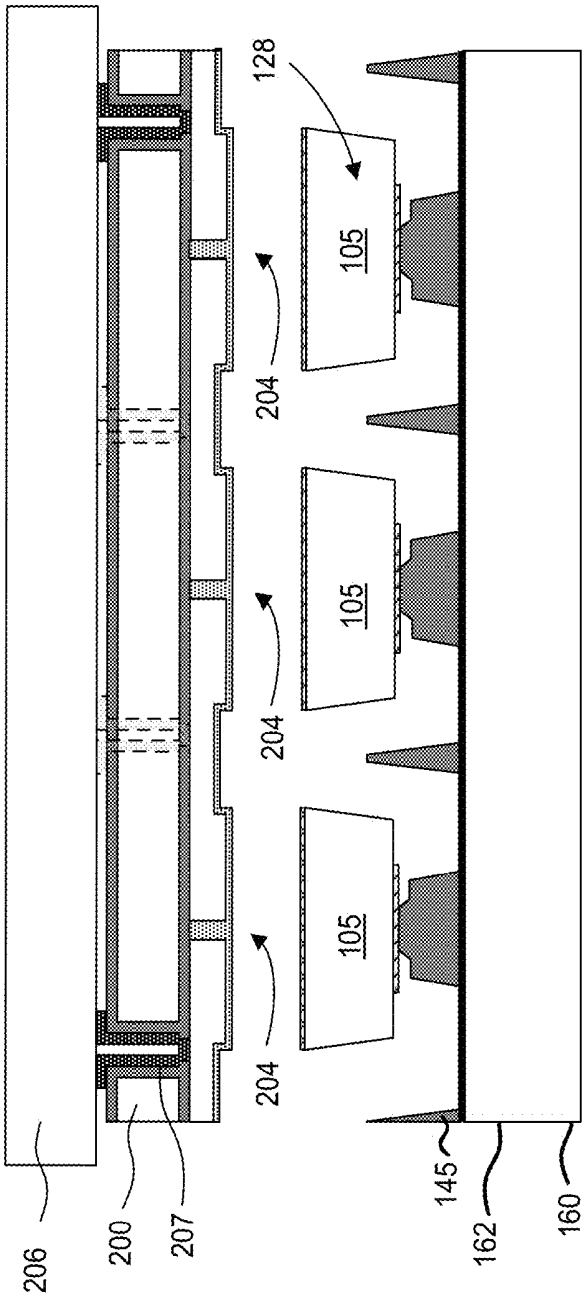

FIG. 13A

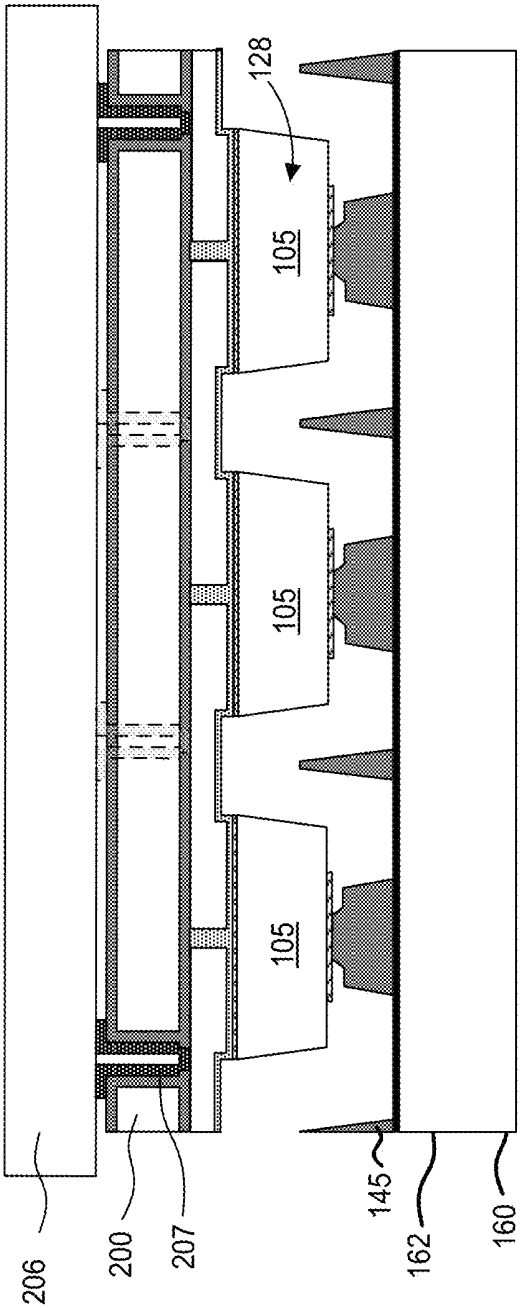

FIG. 13B

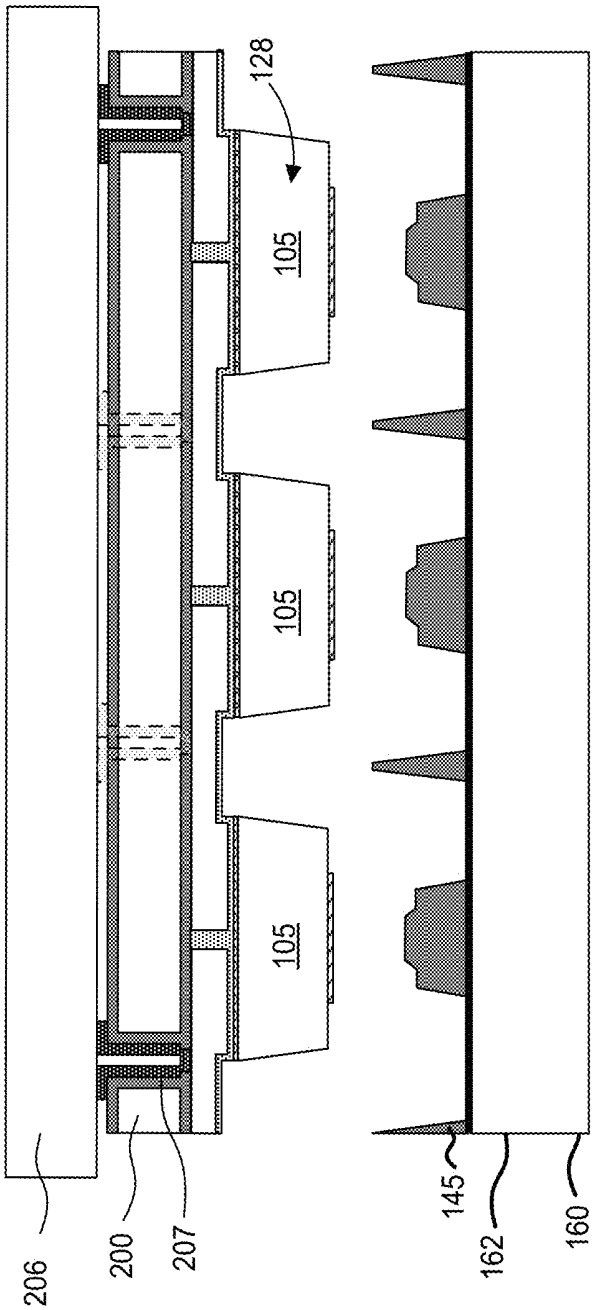

FIG. 13C

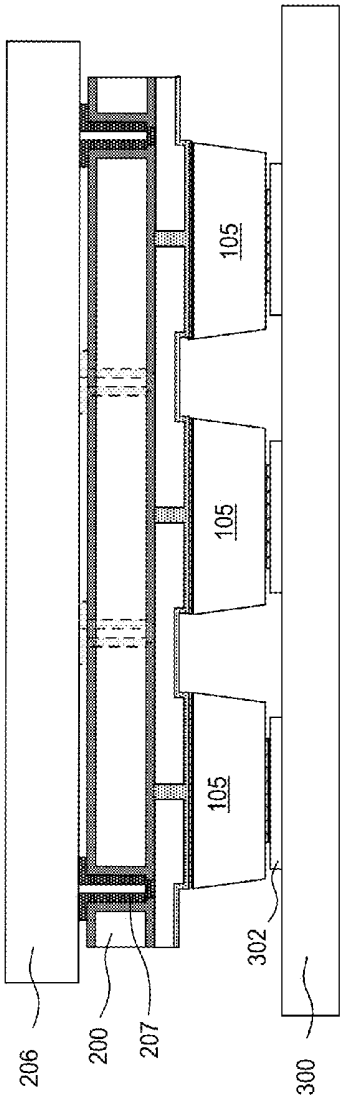

FIG. 13D

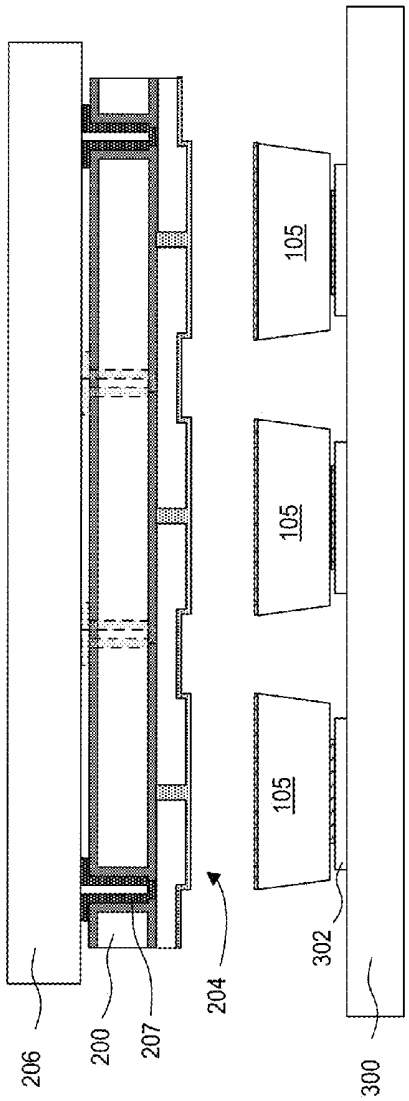

FIG. 13E

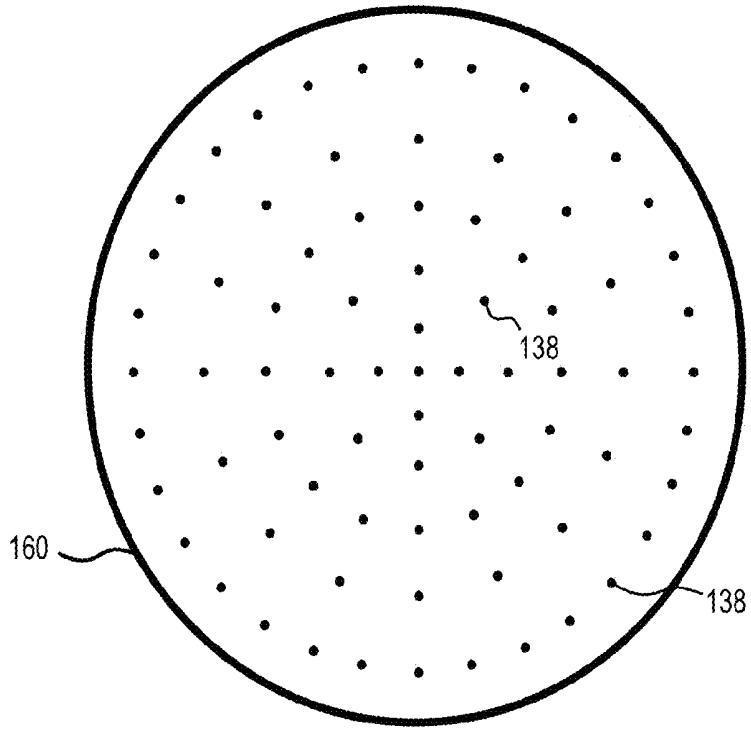

FIG. 14A

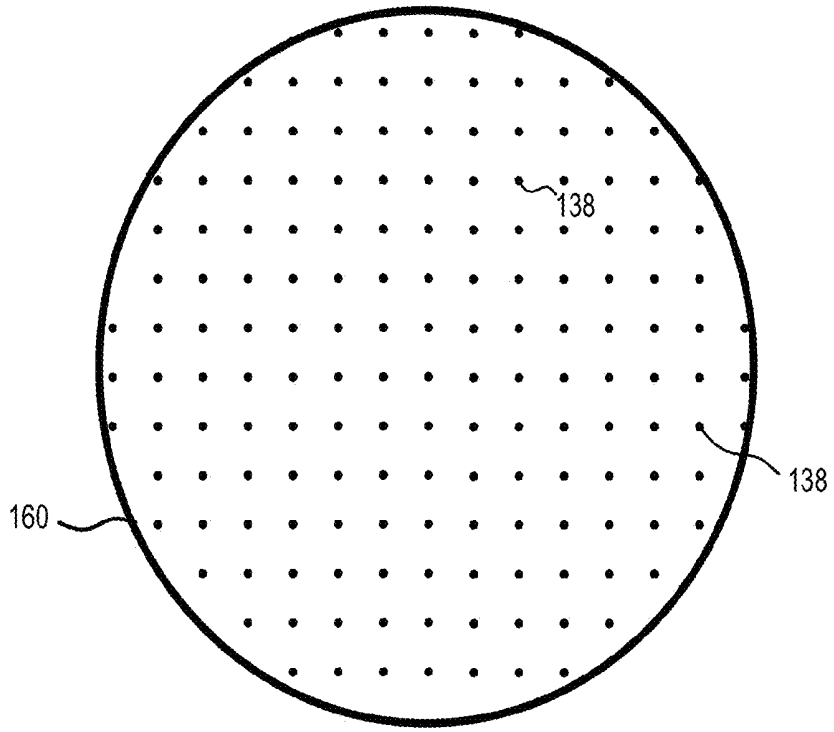

FIG. 14B

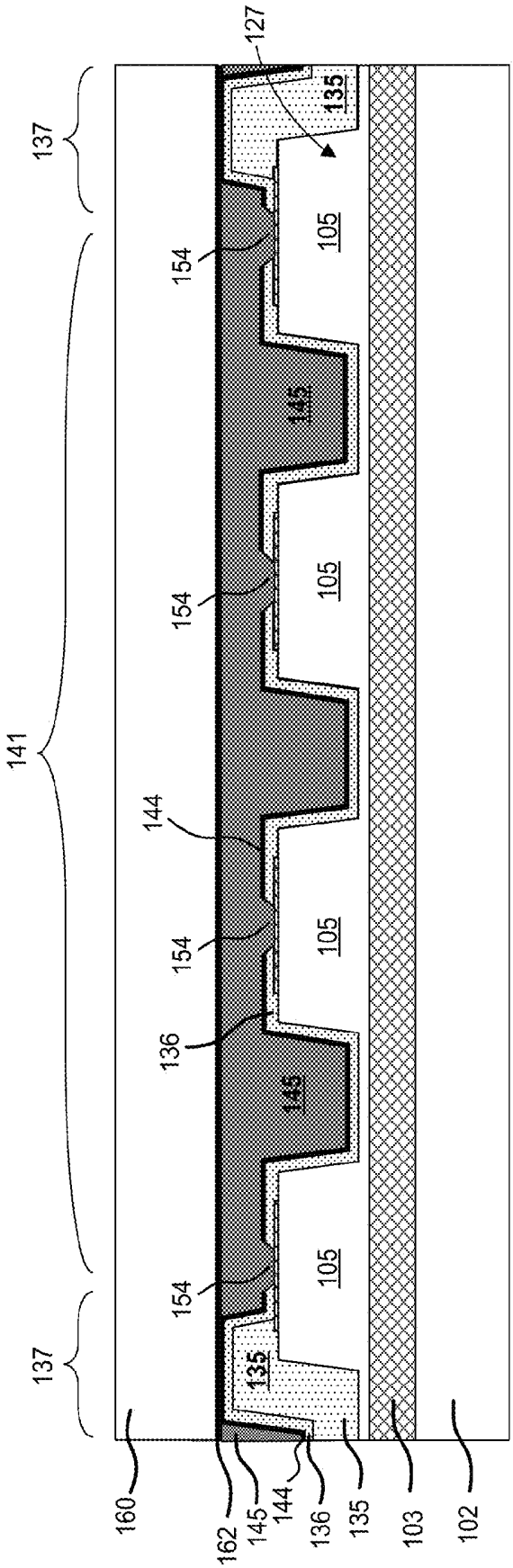
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FIG. 14C

ADHESIVE WAFER BONDING WITH SACRIFICIAL SPACERS FOR CONTROLLED THICKNESS VARIATION

BACKGROUND

[0001] 1. Field

[0002] The present invention relates to micro devices. More particularly, embodiments of the present invention relate to the stabilization of micro devices on a carrier substrate.

[0003] 2. Background Information

[0004] Commercial manufacturing and packaging of micro devices often becomes more challenging as the scale of the micro devices decreases. Some examples of micro devices include radio frequency (RF), microelectromechanical systems (MEMS), microswitches, light-emitting diode (LED) display systems, and MEMS or quartz-based oscillators.

[0005] During fabrication of active devices, it is common bond two wafers or substrates. For example, a growth substrate may be bonded with a carrier substrate to position the device structure on a different wafer or substrate in order to perform processing operations on an alternate side of the micro device structure. The growth substrate may also be bonded with a carrier substrate because the carrier substrate is better suited to continue on in the fabrication process.

[0006] To bond one substrate/wafer to another, an adhesive bonding material may be applied as an adhesive layer between the two substrates. A wafer bonding fixture may be used to facilitate the process. The wafer bonding fixture may assist on exerting a controlled amount of pressure on the two wafers to encourage a close and uniform bonding of the two wafers. In some instances, the wafers to be bonded have alignment marks to promote a uniform bonding distance between the two wafers. In addition, the wafer bonding fixture may include fixture spacers positioned around the circumference of the two wafers in order to determine a thickness of the adhesive bonding material, and consequently, the spacing between the two wafers.

SUMMARY OF THE INVENTION

[0007] A structure and method of forming an array of micro devices which are poised for pick up are disclosed. In an embodiment, a structure includes a stabilization layer including an array of stabilization posts and an array of micro devices over the array of stabilization posts. Patterned sacrificial spacers are between the stabilization posts and between the micro devices. The patterned sacrificial spacers are disposed upon a carrier substrate.

[0008] In an embodiment, the patterned sacrificial spacers include a fine sacrificial layer and a course sacrificial layer. Each stabilization post may include a stabilization post protrusion disposed above a stabilization post platform and the stabilization post platform may be disposed between the stabilization post protrusion and the carrier substrate. The stabilization post platform is wider than the stabilization post protrusion, in some embodiments. In an embodiment, the micro devices are micro LED devices. In some embodiments, each micro device in the array of micro devices includes a bottom surface that is wider than a corresponding stabilization post directly underneath the bottom surface. The stabilization posts may extend through a thickness of the patterned sacrificial spacers. In an embodiment, the patterned sacrificial spacers span along a side surface of at least a portion of the micro devices in the array of micro devices. An array of bottom conductive contacts may be disposed on bottom surfaces of the array of micro devices. The stabilization layer includes an array of stabilization cavities that include stabilization cavity sidewalls surrounding the stabilization posts, in some embodiments. The stabilization layer may be formed of a thermoset material. In an embodiment, the stabilization layer also includes truncated stabilization posts in contiguous portions of the stabilization layer that support additional micro devices and the stabilization posts are in non-contiguous portions of the stabilization layer. The stabilization posts in the array of stabilization posts may be separated by a pitch of 1 μm to 10 μm.

[0009] In an embodiment, a method of forming an array of micro devices includes patterning a device layer to form an array of micro device mesa structures over a handle substrate. A layer of patterned sacrificial spacers is formed that includes an array of openings between the patterned sacrificial spacers. The array of openings are formed over the corresponding array of micro device mesa structures. The method further includes forming a stabilization layer over the patterned sacrificial spacers and within the array of openings and bonding the stabilization layer to a carrier substrate. Bonding the stabilization layer to the carrier substrate includes bringing the patterned sacrificial spacers to rest upon the carrier substrate.

[0010] Forming the layer of patterned sacrificial spacers may include forming a fine sacrificial layer over a course sacrificial layer. A thickness of the fine sacrificial layer defines a height of an array of stabilization posts formed of the stabilization layer within the array of openings, in an embodiment. In an embodiment, each micro device mesa structure includes a p-doped layer, an n-doped layer, and a quantum well layer between the p-doped layer and the n-doped layer. The method may include forming an array of conductive contacts over the device layer and the array of openings between the patterned sacrificial spacers may be formed directly over the array of conductive contacts. In an embodiment, bonding the stabilization layer to the carrier substrate includes curing the stabilization layer. The stabilization layer can be formed of a thermoset material. In an embodiment, the method further includes removing the handle substrate after bonding the stabilization layer to the carrier substrate. The patterned sacrificial spacers are removed after removing the handle substrate, in an embodiment. The array of openings may be separated by a pitch of 1 μm to 10 μm. In an embodiment, the micro device mesa structures outnumber the patterned sacrificial spacers. In one embodiment of the method, patterning the device layer to form the array of micro device mesa structures leaves unremoved portions of the device layer between the array of micro device mesa structures and the unremoved portions of the device layer are removed to form an array of laterally separate micro LED devices after removing the handle substrate.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. **1**A is a cross-sectional side view illustration of a bulk LED substrate in accordance with an embodiment of the invention.

[0012] FIG. **1**B is a cross-sectional side view illustration of a device wafer including circuitry in accordance with an embodiment of the invention.

[0013] FIG. **2**A is a cross-sectional side view illustration of a patterned conductive contact layer on a bulk LED substrate in accordance with an embodiment of the invention.

[0014] FIG. **2**B is a cross-sectional side view illustration of a patterned conductive contact layer on a bulk LED substrate in accordance with an embodiment of the invention.

[0015] FIG. **3** is a cross-sectional side view illustration of a device layer patterned to form an array of micro device mesa structures over a handle substrate in accordance with an embodiment of the invention.

[0016] FIG. **4** is a cross-sectional side view illustration of a course sacrificial layer for patterned sacrificial spacers formed over an array of micro device mesa structures in accordance with an embodiment of the invention.

[0017] FIG. **5** is a cross-sectional side view illustration of an adhesion promoter layer and a fine sacrificial layer for patterned sacrificial spacers formed over a course sacrificial layer in accordance with an embodiment of the invention.

[0018] FIG. **6** is a cross-sectional side view illustration of a stabilization layer formed over an adhesion promoter layer and a layer of patterned sacrificial spacers and within an array of openings between the patterned sacrificial spacers in accordance with an embodiment of the invention.

[0019] FIG. **7** is a cross-sectional side view illustration of bringing together a carrier substrate and micro device mesa structures formed on a handle substrate in accordance with an embodiment of the invention.

[0020] FIG. **8** is a cross-sectional side view illustration of a carrier substrate bonded to micro device mesa structures in accordance with an embodiment of the invention.

[0021] FIG. **9** is a cross-sectional side view illustration of the removal of a growth substrate in accordance with an embodiment of the invention.

[0022] FIG. **10** is a cross-sectional side view illustration of the removal of an epitaxial growth layer and a portion of a device layer in accordance with an embodiment of the invention.

[0023] FIG. **11** is a cross-sectional side view illustration of patterned conductive contacts formed over an array of laterally separate micro devices in accordance with an embodiment of the invention.

[0024] FIG. **12**A is a cross-sectional side view illustration of an array of micro devices formed on an array of stabilization posts after removal of patterned sacrificial spacers in accordance with an embodiment of the invention.

[0025] FIGS. **12**B and **12**C are schematic top view illustrations of example stabilization post locations relative to a group of micro devices in accordance with an embodiment of the invention.

[0026] FIGS. **13**A-**13**E are cross-sectional side view illustrations of an array of electrostatic transfer heads transferring micro devices from a carrier substrate to a receiving substrate in accordance with an embodiment of the invention.

[0027] FIGS. **14**A and **14**B illustrate a top view of carrier substrates with example placements of groups of patterned sacrificial spacers in relation to carrier substrates in accordance with embodiments of the invention.

[0028] FIG. **14**C is a cross-sectional side view illustration of one example of a selective distribution of patterned sacrificial spacers in accordance with an embodiment of the invention.

DETAILED DESCRIPTION OF THE INVENTION

[0029] Embodiments of the present invention describe a method and structure that utilize patterned sacrificial spacers for stabilizing an array of micro devices such as micro light emitting diode (LED) devices and micro chips on a carrier substrate so that they are poised for pick up and transfer to a receiving substrate. For example, the receiving substrate may be, but is not limited to, a display substrate, a lighting substrate, a substrate with functional devices such as transistors or integrated circuits (ICs), or a substrate with metal redistribution lines. While embodiments of some of the present invention are described with specific regard to micro LED devices comprising p-n diodes, it is to be appreciated that embodiments of the invention are not so limited and that certain embodiments may also be applicable to other micro semiconductor devices which are designed in such a way so as to perform a predetermined electronic function (e.g. diode, transistor, integrated circuit) or photonic function (LED, laser). Other embodiments of the present invention are described with specific regard to micro devices including circuitry. For example, the micro devices may be based on silicon or SOI wafers for logic or memory applications, or based on GaAs wafers for RF communications applications.

[0030] In various embodiments, description is made with reference to figures. However, certain embodiments may be practiced without one or more of these specific details, or in combination with other known methods and configurations. In the following description, numerous specific details are set forth, such as specific configurations, dimensions and processes, etc., in order to provide a thorough understanding of the present invention. In other instances, well-known semiconductor processes and manufacturing techniques have not been described in particular detail in order to not unnecessarily obscure the present invention. Reference throughout this specification to "one embodiment," "an embodiment" or the like means that a particular feature, structure, configuration, or characteristic described in connection with the embodiment is included in at least one embodiment of the invention. Thus, the appearances of the phrase "in one embodiment," "an embodiment" or the like in various places throughout this specification are not necessarily referring to the same embodiment of the invention. Furthermore, the particular features, structures, configurations, or characteristics may be combined in any suitable manner in one or more embodiments.

[0031] The terms "upon", "over", "spanning", "to", "between", and "on" as used herein may refer to a relative position of one layer with respect to other layers. One layer "upon", "over", "spanning", or "on" another layer or bonded "to" another layer may be directly in contact with the other layer or may have one or more intervening layers. One layer "between" layers may be directly in contact with the layers or may have one or more intervening layers.

[0032] The terms "micro" device, "micro" LED device, or "micro" chip as used herein may refer to the descriptive size of certain devices, devices, or structures in accordance with embodiments of the invention. As used herein the term "micro device" specifically includes "micro LED device" and "micro chip". As used herein, the terms "micro" devices or structures may refer to the scale of 1 to 100 μm. However, it is to be appreciated that embodiments of the present invention are not necessarily so limited, and that certain aspects of the embodiments may be applicable to larger, and possibly smaller "micro" device or structure size scales. In an embodiment, a single micro device in an array of micro devices, and a single electrostatic transfer head in an array of electrostatic transfer heads both have a maximum dimension, for example length or width, of 1 to 100 μm. In an embodiment, the top contact surface of each micro device or electrostatic transfer head has

a maximum dimension of 1 to 100 μm, or more specifically 3 to 20 μm. In an embodiment, a pitch of an array of micro devices, and a corresponding array of electrostatic transfer heads is (1 to 100 μm) by (1 to 100 μm), for example a 20 μm by 20 μm pitch or 5 μm by 5 μm pitch.

[0033] In the following embodiments, the mass transfer of an array of pre-fabricated micro devices with an array of transfer heads is described. For example, the pre-fabricated micro devices may have a specific functionality such as, but not limited to, an LED for light-emission, silicon IC for logic and memory, and gallium arsenide (GaAs) circuits for radio frequency (RF) communications. In some embodiments, arrays of micro LED devices which are poised for pick up are described as having a 20 μm by 20 μm pitch, or 5 μm by 5 μm pitch. At these densities, a 6 inch substrate, for example, can accommodate approximately 165 million micro LED devices with a 10 μm by 10 μm pitch, or approximately 660 million micro LED devices with a 5 μm by 5 μm pitch. A transfer tool including an array of transfer heads matching an integer multiple of the pitch of the corresponding array of micro LED devices can be used to pick up and transfer the array of micro LED devices to a receiving substrate. In this manner, it is possible to integrate and assemble micro LED devices into heterogeneously integrated systems, including substrates of any size ranging from micro displays to large area displays, and at high transfer rates. For example, a 1 cm by 1 cm array of micro device transfer heads can pick up and transfer more than 100,000 micro devices, with larger arrays of micro device transfer heads being capable of transferring more micro devices.

[0034] In one aspect, embodiments of the invention describe a structure utilizing patterned sacrificial spacers for stabilizing an array of micro devices such as micro light emitting diode (LED) devices on a carrier substrate so that they are poised for pick up and transfer to a receiving substrate. In an embodiment, an array of micro devices are held in place on an array of stabilization posts that are between patterned sacrificial spacers on a carrier substrate. In an embodiment, the stabilization posts are formed of an adhesive bonding material. In this manner, the array of stabilization posts may retain the array of micro devices in place on a carrier substrate while also providing a structure from which the array of micro devices are readily picked up. In an embodiment, the adhesive bonding material includes a thermoset material such as, but not limited to, benzocyclobutene (BCB) or epoxy. In an embodiment, the thermoset material may be associated with 10% or less volume shrinkage during curing, or more particularly about 6% or less volume shrinkage during curing. In this manner low volume shrinkage during curing of the adhesive bonding material may not cause delamination between the array of stabilization posts and the array of micro devices, and may allow for uniform adhesion between the array stabilization posts and the array of micro devices supported by the array of stabilization posts.

[0035] In one aspect of embodiments of the invention, patterned sacrificial spacers are formed between the array of micro devices and a carrier substrate to increase the planarity of the micro devices that are poised for pick up. It has been observed that the thickness of an adhesive bond layer between two wafers bonded using a conventional adhesive bonding fixture can be non-uniform across the area between the two bonded wafers, despite the use of alignment marks when aligning the two wafers, starting with substantially flat wafers and the use of fixture spacers between the two wafers around the circumference of the wafers. In one scenario, it was observed that when bonding an unpatterned GaN device layer of FIG. **1**A described below to a silicon carrier substrate with a BCB adhesive bonding layer of approximately 2 μm thickness, the thickness of the final cured adhesive bonding layer was measured as being in the range between 1.5-9 μm across the carrier substrate. It is believed that the resultant non-uniformity in thickness of the adhesive bonding material (referred to as a stabilization layer in this disclosure below) may be attributed to factors such as particulate contamination, wafer bowing, and local stresses within the wafers. For example, wafer bowing of a sapphire growth substrate supporting an epitaxially grown GaN device layer may be from 50-100 μm in some instances. While the thickness of the GaN device layer remained constant across the substrate, the thickness variation profile of the BCB adhesive bonding material was found to be translated to the GaN device layer surface profiles. Since the micro devices that are formed from the device layer and the transfer heads that transfer the micro devices in accordance with embodiments of the invention may be of the "micro" scale, increasing the planarity of the micro devices with respect to each other and with respect to their carrier substrate may increase the yield of successful transfers of the micro devices from their carrier substrate to a target substrate. During an adhesive bonding operation of the stabilization layer and the carrier substrate, the patterned sacrificial spacers can extend through the stabilization layer to the carrier substrate which results in a more uniform thickness of the stabilization layer beneath the micro devices. With the patterned sacrificial spacers causing a more uniform thickness in the stabilization layer, the micro devices also have a more planar relationship to each other as they more closely conform to the carrier substrate rather than following a curvature of a bowed handle substrate. As a result, the micro devices have an improved planar positioning across the carrier substrate and the height variation of the top surfaces of the micro devices is reduced, promoting a more consistent pick-up location of the micro devices for successful transfer by the electrostatic transfer heads. Furthermore, the patterned sacrificial spacers can be sized to control the thickness of the stabilization layer to be close to a desired dimension.

[0036] In one aspect of embodiments of the invention, the array of micro devices are formed in a one-sided process sequence in which a device layer is etched to form an array of micro device mesa structures prior to applying a stabilization layer (the stabilization layer having the adhesive bonding material that forms the stabilization posts). Using this one-sided process may be particularly suitable for certain system requirement and materials. For example, where the micro devices are micro LED devices, the devices layers may be formed from different materials selected for different emission spectra. By way of example, a blue-emitting or green-emitting micro LED device may be formed of a GaN (5.18 Å lattice constant) based material grown on a sapphire substrate (4.76 Å lattice constant), resulting in a lattice mismatch of approximately 0.42 Å. An increased amount of lattice mismatch between a device layer grown on a growth substrate may result in a greater amount of stress in the device layer. It has been observed that when fabricating devices at the "micro" scale, stress in a device layer may cause the device layer to shift laterally upon removal of a growth substrate that the device layer is grown upon. This stress may potentially cause misalignment between the array of micro devices that are formed over an array of stabilization posts. In accordance

with embodiments of the invention, a one-sided process sequence is performed in order to reduce the amount of shifting between the micro devices and stabilization posts by forming micro device mesa structures on stabilization posts prior to removing the growth substrate.

[0037] Without being limited to a particular theory, embodiments of the invention utilize transfer heads and head arrays which operate in accordance with principles of electrostatic grippers, using the attraction of opposite charges to pick up micro devices. In accordance with embodiments of the present invention, a pull-in voltage is applied to a transfer head in order to generate a grip pressure on a micro device and pick up the micro device. In accordance with embodiments of the invention, the minimum amount of pick up pressure required to pick up a micro device from a stabilization post can be determined by the adhesion strength between the adhesive bonding material from which the stabilization posts are formed and the micro device (or any intermediate layer), as well as the contact area between the top surface of the stabilization post and the micro device. For example, adhesion strength which must be overcome to pick up a micro device is related to the minimum pick up pressure generated by a transfer head as provided in equation (1):

$$P_1A_1=P_2A_2 \quad (1)$$

[0038] where P_1 is the minimum grip pressure required to be generated by a transfer head, A_1 is the contact area between a transfer head contact surface and micro device contact surface, A_2 is the contact area on a top surface of a stabilization post, and P_2 is the adhesion strength on the top surface of a stabilization post. In an embodiment, a grip pressure of greater than 1 atmosphere is generated by a transfer head. For example, each transfer head may generate a grip pressure of 2 atmospheres or greater, or even 20 atmospheres or greater without shorting due to dielectric breakdown of the transfer heads. Due to the smaller area, a higher pressure is realized at the top surface of the corresponding stabilization post than the grip pressure generate by a transfer head. In an embodiment, a bonding layer is placed between each micro device and stabilization post in order to aid in bonding each micro device to a receiving substrate. A variety of different bonding layers with different melting temperatures are compatible with embodiments of the invention. For example, heat may or may not be applied to the transfer head assembly, carrier substrate, and/or receiving substrate during the pick up, transfer, and bonding operations. In some embodiments, the bonding layer may be a comparatively higher melting temperature material such as gold. In some embodiments the bonding layer is a comparatively lower melting temperature material such as indium. In some embodiments, the transfer head assembly may be maintained at an elevated temperature during the pick up and transfer operations in order to assist bonding to the receiving substrate without thermal cycling of the transfer head assembly. In one embodiment, the bonding layer is gold, and the bonding layer is not liquefied during the pick up or transfer operations. In one embodiment the bonding layer is indium, and the bonding layer is liquefied during the pick up and transfer operations. In such an embodiment, the bonding layer may be partially picked up and transferred to the receiving substrate.

[0039] In another embodiment, the bonding layer is formed of a material characterized by a low tensile strength. For example, indium is characterized by a tensile strength of approximately 4 MPa which can be less than or near the adhesion strength between a gold/BCB bonding interface of 10 MPa or less, and which is significantly lower than an exemplary 30 MPa adhesion strength between a gold/BCB bonding interface (determined with stud pull test) when treated with adhesion promoter AP3000, an organosilane compound in 1-methoxy-2-propoanol available from The Dow Chemical Company. In an embodiment, the bonding layer is cleaved during the pick up operation due to the lower tensile strength, and a phase change is not created during the pick up operation. Though, a phase change may still be created in the portion of the bonding layer which is picked up with the micro device during placement of the micro device onto a receiving substrate to aid in bonding of the micro device to the receiving substrate.

[0040] In another aspect, embodiments of the invention describe a manner of forming an array of micro devices which are poised for pick up in which conductive contact layers can be formed on top and bottom surfaces of the micro devices, and annealed to provide ohmic contacts. Where a conductive contact is formed on a top surface of a micro device, the stabilization layer is formed of a material which is capable of withstanding the associated deposition and annealing temperatures. For example, a conductive contact may require annealing at temperatures between 200° C. to 350° C. to form an ohmic contact with the micro device. In this manner, embodiments of the invention may be utilized to form arrays of micro LED devices based upon a variety of different semiconductor compositions for emitting various different visible wavelengths. For example, micro LED growth substrates including active devices layers formed of different materials for emitting different wavelengths (e.g. green and blue wavelengths) can all be processed within the general sequence of operations of the embodiments.

[0041] FIG. **1**A is an example cross-sectional side view illustration of a bulk LED substrate **100** in accordance with an embodiment of the invention. In the illustrated embodiment, bulk LED substrate **100** includes a growth substrate **102**, an epitaxial growth layer **103**, and a device layer **105**. In an embodiment, growth substrate **102** is sapphire and may be approximately 500 μm thick. Using a sapphire growth substrate may correspond with manufacturing blue emitting LED devices (e.g. 450-495 nm wavelength) or green emitting LED devices (e.g. 495-570 nm wavelength). It is to be appreciated, that while the specific embodiments illustrated and described in the following description may be directed to formation of green or blue emitting LED devices, the following sequences and descriptions are also applicable to the formation of LED devices that emit wavelengths other than blue and green. Epitaxial growth layer **103** may be grown on growth substrate **102** using known epitaxial growth techniques. Epitaxial growth layer **103** may be grown on growth substrate **102** at a relatively high temperature to facilitate gliding out dislocations in the layer. In an embodiment, epitaxial growth layer **103** is a gallium nitride (GaN) based material.

[0042] Device layer **105** may be formed on epitaxial growth layer **103**, as shown in FIG. **1**A. In an embodiment the growth substrate **102** is approximately 200 μm thick. The epitaxial growth layer **103** may be any suitable thickness such as between 300 Å-5 μm. In the illustrated embodiment, device layer **105** includes layers for forming LED devices. In FIG. **1**A, a zoomed-in view of an example device layer **105** illustrates one or more quantum well layers **110** between doped semiconductor layer **108** (e.g. n-doped) and doped semiconductor layer **112** (e.g. p-doped), although the doping of layers

108 and 112 may be reversed. In an embodiment, doped semiconductor layer 108 is formed of GaN and is approximately 0.1 μm to 3 μm thick. The one or more quantum well layers 110 may have a thickness of approximately 0.5 μm. In an embodiment, doped semiconductor layer 112 is formed of GaN, and is approximately 0.1 μm to 2 μm thick.

[0043] FIG. 1B is a cross-sectional side view illustration of a device wafer 180 including circuitry in accordance with an embodiment of the invention. In accordance with embodiments of the invention, the device wafer 180 may be formed of a variety of materials depending upon the desired function. For example, in an embodiment, the device wafer 180 is a silicon wafer, or silicon-on-insulator (SOI) wafer for logic or memory. In an embodiment, the device wafer 180 is a gallium arsenide (GaAs) wafer for radio frequency (RF) communications. These are merely examples, and embodiments of the invention envision are not limited to silicon or GaAs wafers, nor are embodiments limited to logic, memory, or RF communications.

[0044] In an embodiment, the device wafer 180 includes an active device layer 185, optional buried oxide layer 184, and base substrate 182. In the interest of clarity, the following description is made with regard to an SOI device wafer 180, including an active device layer 185, buried oxide layer 184, and base silicon substrate 182, though other types of devices wafers may be used, including bulk semiconductor wafers. In an embodiment, the active device layer 185 may include working circuitry to control one or more LED devices. In some embodiments, back-end processing may be performed within the active device layer 185. Accordingly, in an embodiment, the active device layer 185 includes an active silicon layer 187 including devices such as transistors, metal build-up layers 188 including interconnects 189, bonding pads 190, and passivation 192.

[0045] In the interest of clarity, the portion of the disclosure associated with FIGS. 2A-14C is made with regard to the bulk LED substrate of FIG. 1A for fabricating micro LED devices. However, it is appreciated that the process sequences in the following description may be used to fabricate other micro devices. For example, micro chips may be similarly manufactured by substituting bulk LED substrate 100 with device wafer 180 and using the same or similar processes as described with reference to bulk LED substrate 100. Accordingly, in the following description, both the growth substrate 102 and base substrate 182 can alternatively be referred to more generically as a "handle" substrate so as to not preclude the processing sequence on a growth substrate 102 from being applied to the processing sequence on a base substrate 182.

[0046] FIG. 2A is a cross-sectional side view illustration of a patterned conductive contact layer on bulk LED substrate 100 in accordance with an embodiment of the invention. A conductive contact layer may be formed over device layer 105 using a suitable technique such as sputtering or electron beam physical deposition followed by etching or liftoff to form the array of conductive contacts 120. In an embodiment, the array of conductive contacts 120 have a thickness of approximately 0.1 μm-2 μm, and may include a plurality of different layers. For example, a conductive contact 120 may include an electrode layer 121 for ohmic contact, a mirror layer 122, an adhesion/barrier layer 123, a diffusion barrier layer 124, and a bonding layer 125. In an embodiment, electrode layer 121 may make ohmic contact to a p-doped semiconductor layer 112, and may be formed of a high work-function metal such as nickel. In an embodiment, a mirror layer 122 such as silver is formed over the electrode layer 121 to reflect the transmission of the visible wavelength. In an embodiment, titanium is used as an adhesion/barrier layer 123, and platinum is used as a diffusion barrier 124 to bonding layer 125. Bonding layer 125 may be formed of a variety of materials which can be chosen for bonding to the receiving substrate and/or to achieve the requisite tensile strength or adhesion or surface tension with the stabilization posts (yet to be formed). Following the formation of layers 121-125, the substrate stack can be annealed to form an ohmic contact. For example, a p-side ohmic contact may be formed by annealing the substrate stack at 510° C. for 10 minutes.

[0047] In an embodiment, bonding layer 125 is formed of a conductive material (both pure metals and alloys) which can diffuse with a metal forming a contact pad on a receiving substrate (e.g. gold, indium, or tin contact pad) and has a liquidus temperature above 200° C. such as tin (231.9° C.) or bismuth (271.4° C.), or a liquidus temperature above 300° C. such as gold (1064° C.) or silver (962° C.). In some embodiments, bonding layer 125 such as gold may be selected for its poor adhesion with the adhesive bonding material used to form the stabilization posts. For example, noble metals such as gold are known to achieve poor adhesion with BCB. In this manner, sufficient adhesion is created to maintain the array of micro LED devices on the stabilization posts during processing and handling, as well as to maintain adjacent micro LED devices in place when another micro LED device is being picked up, yet also not create too much adhesion so that pick up can be achieved with an applied pick up pressure on the transfer head of 20 atmospheres or less, or more particularly 5-10 atmospheres.

[0048] In the embodiment illustrated in FIG. 2A, where bonding layer 125 has a liquidus temperature above the annealing temperature for forming the p-side ohmic contact, the anneal (e.g. 510° C. for 10 minutes) can be performed after the formation of the patterned conductive contact layer 120, including bonding layer 125. Where bonding layer 125 has a liquidus temperature below the annealing temperature for forming the p-side ohmic contact, the bonding layer 125 may be formed after annealing.

[0049] FIG. 2B is a cross-sectional side view illustration of a patterned conductive contact layer on a bulk LED substrate 100 in accordance with an embodiment of the invention. The embodiment illustrated in FIG. 2B may be particularly useful where bonding layer 125 is formed of a material with a liquidus temperature below the annealing temperature of the p-side ohmic contact, though the embodiment illustrated in FIG. 2B is not limited to such and may be used where the bonding layer 125 is formed of a material with a liquidus temperature above the annealing temperature of the p-side ohmic contact. In such embodiments, electrode layer 121 and mirror layer 122 may be formed similarly as described with regard to FIG. 2A. Likewise, adhesion/barrier layer 123 and diffusion barrier 124 may be formed similarly as described with regard to FIG. 2A with one difference being that the layers 123 and 124 may optionally wrap around the sidewalls of the layers 121 and 122. Following the formation of layers 121-124, the substrate stack can be annealed to form an ohmic contact. For example, a p-side ohmic contact may be formed by annealing the substrate stack at 510° C. for 10 minutes. After annealing layers 121-124 to form the p-side ohmic contact, the bonding layer 125 may be formed. In an embodiment, the bonding layer 125 has a smaller width than for layers 121-124.

[0050] In an embodiment, bonding layer **125** has a liquidus temperature or melting temperature of approximately 350° C. or lower, or more specifically of approximately 200° C. or lower. At such temperatures the bonding layer may undergo a phase change without substantially affecting the other components of the micro LED device. In an embodiment, the resultant bonding layer may be electrically conductive. In accordance with some embodiments, the bonding layer **125** may be a solder material, such as an indium, bismuth, or tin based solder, including pure metals and metal alloys. In a particular embodiment, the bonding layer **125** is indium.

[0051] FIG. **3** is a cross-sectional side view illustration of device layer **105** patterned to form an array of micro device mesa structures **127** over a handle substrate that includes growth substrate **102** and epitaxial growth layer **103** in accordance with an embodiment of the invention. Etching of layers **108**, **110**, and **112** of device layer **105** may be accomplished using suitable etch chemistries for the particular materials. For example, n-doped semiconductor layer **108**, quantum well layer(s) **110**, and p-doped layer **112** may be dry etched in one operation with a BCl_3 and Cl_2 chemistry. As FIG. **3** illustrates, device layer **105** may not be etched completely through which leaves unremoved portions **129** of device layer **105** that connect the micro device mesa structures **127**. In one example, the etching of device layer **105** is stopped in n-doped semiconductor layer **108** (which may be n-doped GaN). A height of the micro device mesa structures **127** (not including the thickness of the unremoved portions **129**) may correspond substantially to the height of the laterally separate micro devices to be formed. In accordance with embodiments of the invention, the device layer **105** may alternatively be completely etched through. For example, where the bulk LED substrate **100** is replaced with a device wafer **180** in the processing sequence, etching may stop on the buried oxide layer **184**.

[0052] FIG. **4** is a cross-sectional side view illustration of a sacrificial layer **135** for patterned sacrificial spacers formed over an array of micro device mesa structures **127** in accordance with an embodiment of the invention. In an embodiment, sacrificial layer **135** is between approximately 2 and 5 microns thick. In an embodiment, sacrificial layer **135** is formed of an oxide (e.g. SiO_2) or nitride (e.g. SiN_x), though other materials may be used which can be selectively removed with respect to the other layers. In an embodiment, sacrificial layer **135** is deposited by sputtering, low temperature plasma enhanced chemical vapor deposition (PECVD), or electron beam evaporation to create a low quality layer, which may be more easily removed than a higher quality layer deposited by other methods such as atomic layer deposition (ALD) or high temperature PECVD.

[0053] After forming sacrificial layer **135**, sacrificial layer **135** is patterned to form an array of openings **133** over the array of conductive contacts **120**. In an example embodiment, a fluorinated chemistry (e.g. HF vapor, CF_4, or SF_6 plasma) is used to etch the SiO_2 or SiN_x sacrificial layer **135**.

[0054] FIG. **5** is a cross-sectional side view illustration of an adhesion promoter layer **144** and a sacrificial layer **136** including an array of openings **133** for patterned sacrificial spacers formed over a sacrificial layer **135** in accordance with an embodiment of the invention. In an embodiment, sacrificial layer **136** is between approximately 0.5 and 2 microns thick. Sacrificial layer **136** may be made from the same material and formed using a similar method as sacrificial layer **135**. Together, sacrificial layers **135** and **136** combine to make patterned sacrificial spacers **137**. Sacrificial layer **135** may be referred to as "course" sacrificial layer **135** and sacrificial layer **136** may be referred to as "fine" sacrificial layer **136**. The combined thickness of sacrificial layers **135** and **136** (and any intervening layers) will set the standoff height of the patterned sacrificial spacers **137**, which will consequently define the spacing height between laterally separate micro devices **128** and carrier substrate **160**, in FIG. **10**. Additionally, the shape of patterned sacrificial spacers **137** defines the shape of openings **133**, which will later define the shape of stabilization posts **152**, as shown in FIG. **9**. Furthermore, a thickness of fine sacrificial layer **136** will define a height of a stabilization post protrusion **151** that is included in each stabilization post **152**, which will be discussed in association with FIG. **11**. Sacrificial layer **135** may be used to provide the bulk of the standoff height of patterned sacrificial spacers **137**, while sacrificial layer **136** may be used to define the shape of stabilization post protrusions **151**. Finer patterning of sacrificial layer **136** may allow for more uniform definition of the shapes of stabilization post protrusions **151**, which will consequently make the pull force required to separate micro devices **128** from the stabilization post protrusions **151** more uniform. Furthermore, the finer patterning offered by sacrificial layer **136** may allow for more exact positional placement of the stabilization post protrusions **151** in relation to conductive contacts **120**. It is appreciated that although the illustrated embodiments show patterned sacrificial spacers **137** being made of two sacrificial layers (**135** and **136**), patterned sacrificial spacers **137** may be made from only one layer with the shape of openings **133** achieved using a series of masking and etching steps.

[0055] Still referring to FIG. **5**, after the formation of sacrificial layer **136**, an adhesion promoter layer **144** may optionally be formed in order to increase adhesion of the stabilization layer **145** (not yet formed) to the sacrificial layer **136**. A thickness of 100-300 angstroms may be sufficient to increase adhesion.

[0056] Specific metals (for use in conductive contacts **120**) that have good adhesion to both the sacrificial layer **136** and a BCB stabilization layer (not yet formed) include, but are not limited to, titanium and chromium. For example, sputtered or evaporated titanium or chromium can achieve an adhesion strength (stud pull) of greater than 40 MPa with BCB.

[0057] FIG. **5** illustrates the optional adhesion promoter layer **144** being patterned with the sacrificial layer **136** to continue defining openings **133**. In other embodiments, adhesion promoter layer **144** may optionally be formed after patterning sacrificial layer **136**. In such embodiments, the adhesion promoter layer **144** may be formed within the openings **133** and on conductive contacts **120**. This may have the effect of increasing the pull force required to subsequently separate conductive contacts **120** and stabilization layer **145** (yet to be formed). In one embodiment, the structure including patterned sacrificial layer **136** is treated with an adhesion promoter such as AP3000, available from The Dow Chemical Company, in the case of a BCB stabilization layer **145** in order to condition the underlying structure. AP3000, for example, can be spin coated onto the underlying structure, and soft baked (e.g. 100° C.) or spun dry to remove the solvents prior to applying the stabilization layer **145** over the sacrificial layer **136**.

[0058] Forming fine sacrificial layer **136** defines the dimensions of the stabilization post protrusions **151**. As will become more apparent in the description of FIG. **11**, the height,

length, and width of the stabilization post protrusion portion of openings **133** between sacrificial layer **136** correspond to the height, length, and width (area) of the stabilization post protrusions **151** to be formed, and resultantly the adhesion strength that must be overcome to pick up the array of micro devices (e.g. micro LED devices) poised for pick up on the array of stabilization post protrusions **151**. In an embodiment, the stabilization post protrusion portions of openings **133** are formed using lithographic techniques and have a length and width of approximately 1 μm by 1 μm, though the stabilization post protrusion portion of openings **133** may be larger or smaller so long as the openings have a width (or area) that is less than the width (or area) of the conductive contacts **120** and/or micro LED devices. Furthermore, the height, length and width of the openings **131** between the micro device mesa structures **127** will correspond to the height, length and width of the stabilization cavity sidewalls to be formed. Accordingly, adjusting thickness of the sacrificial layers **135** and **136** and the space separating adjacent micro device mesa structures **127** will effect the size of the stabilization cavity sidewalls.

[0059] FIG. **6** is a cross-sectional side view illustration of a stabilization layer **145** formed over an adhesion promoter layer **144** and a layer of patterned sacrificial spacers **137**, within an array of openings **133** between the patterned sacrificial spacers **137**, and within an array of openings **131** between micro device mesa structures **127** in accordance with an embodiment of the invention. Stabilization layer **145** may be formed of an adhesive bonding material. The adhesive bonding material may be a thermosetting material such as benzocyclobutene (BCB) or epoxy. In an embodiment, the thermosetting material may be associated with 10% or less volume shrinkage during curing, or more particularly about 6% or less volume shrinkage during curing so as to not delaminate from the conductive contacts **120** on the micro device mesa structures **127**.

[0060] In an embodiment, stabilization layer **145** is spin coated or spray coated over the patterned sacrificial layer **136**, though other application techniques may be used. For spin coating, the structure may be spun at 5,000 RPM to form the stabilization layer **145** at a thickness of 5 μm±0.5 μm. The thickness of 5 μm±0.5 μm for the stabilization layer **145** may correspond to a dimension from the bottom of an opening **131** to the top of stabilization layer **145**, while stabilization layer **145** in other locations (measured from the top of patterned sacrificial spacers **137**) may ultimately be thinner than the 5 μm±0.5 μm thickness. It is understood that a 5 μm±0.5 μm thickness of stabilization layer **145** is an example and may vary depending on the thickness of layers **135** and **136**. Following application of the stabilization layer **145**, the structure may be pre-baked at between 120 and 200° C. for 10-30 minutes to remove solvents, resulting in a b-staged layer. In an embodiment, the stabilization layer **145** is thicker than the height of openings **131** (when present) between micro device mesa structures **127**. In this manner, the thickness of the stabilization layer **145** filling openings **133** (between patterned sacrificial spacers **137**) will become stabilization posts **152**, the thickness of the stabilization layer **145** filling openings **131** will become stabilization cavity sidewalls **147** (discussed further in association with FIG. **11**), and the remainder of the thickness of the stabilization layer **145** over the filled openings **131** and **133** can function to adhesively bond the bulk LED substrate **100** to a carrier substrate. In one embodiment, the height of patterned sacrificial spacers **137** is 80-90% of a thickness of a stabilization layer **145**. It is thought that patterned sacrificial spacers **137** that are taller than stabilization layer **145** can cause air gaps to form between stabilization layer **145** and carrier substrate **160**, yet patterned sacrificial spacers **137** that are too short may make it difficult to force excess stabilization layer **145** away.

[0061] FIG. **7** is a cross-sectional side view illustration of bringing together a carrier substrate **160** and micro device mesa structures **127** formed on handle substrate in accordance with an embodiment of the invention. FIG. **8** is a cross-sectional side view illustration of carrier substrate **160** after being bonded to micro device mesa structures **127** with stabilization layer **145** in accordance with an embodiment of the invention. FIG. **8** shows that patterned sacrificial spacers **137** are brought to rest upon carrier substrate **160** so that carrier substrate **160** is supporting patterned sacrificial spacers **137**. Since carrier substrate **160** is supporting patterned sacrificial spacers **137** (although intervening layers such as adhesion promotion layers **144**/**162** may come between) stabilization layer **145** is pushed away making stabilization layer **145** non-contiguous between the illustrated patterned sacrificial spacers **137** and the illustrated cavity sidewalls **147**. In the illustrated embodiment, adhesion promoter layer **144** and **162** may be disposed between sacrificial layer **136** and carrier substrate **160**, but in other embodiments, carrier substrate **160** may contact sacrificial layer **136**.

[0062] Since during bonding patterned sacrificial spacers **137** extends through stabilization layer **145** to the more solid carrier substrate **160**, the planar alignment of micro devices **128** (illustrated in FIGS. **10** and **11**) and uniformity in thickness of the stabilization layer **145** across the carrier substrate **160** may improve. The improvement may manifest in comparison to having micro devices **128** and associated structure "float" atop stabilization layer **145** without any solid underpinning to carrier substrate **160**. Since the micro devices and the transfer heads that transfer the micro devices may be on the micro scale, increasing the planarity of the micro devices with respect to each other and with respect to their carrier substrate **160** may increase the yield of successful transfers of the micro devices from their carrier substrate to a target substrate. Due to the improved planar positioning of the micro devices, the pick-up location of the micro devices becomes better defined for successful transfer by the electrostatic transfer heads.

[0063] Still referring to FIG. **8**, carrier substrate **160** is bonded to the micro device mesa structures **127** via the adhesion properties of stabilization layer **145**. In one embodiment, 1,100 kg of force is applied for between two and three hours to bond carrier substrate **160** to the micro device mesa structures **127**. Bonding may take place at approximately 200° C. In order to increase adhesion with the stabilization layer **145**, an adhesion promoter layer **162** can be applied to the carrier substrate **160** prior to bonding the micro device structure (e.g. bulk LED substrate **100**) to the carrier substrate **160** similarly as described above with regard to adhesion promoter layer **144**. Likewise, in addition to, or in alternative to adhesion promoter layer **162**, an adhesion promoter such as AP3000 may be applied to the surface of the carrier substrate **160** or adhesion promoter layer **162**. Alternatively, stabilization layer **145** can be formed on carrier substrate **160** prior to bonding the carrier substrate **160** to the handle substrate. For example, the micro device structure including the patterned sacrificial layers **135** and **136** and micro device mesa struc-

tures **127** can be embossed into an a-staged or b-staged stabilization layer **145** formed on the carrier substrate **160**.

[0064] Depending upon the particular material of stabilization layer **145**, stabilization layer **145** may be thermally cured, or cured with application of UV energy. In an embodiment, stabilization layer **145** is a-staged or b-staged prior to bonding the carrier substrate to the micro device structure, and is cured at a temperature or temperature profile ranging between 150° C. and 300° C. Where stabilization layer **145** is formed of BCB, curing temperatures should not exceed approximately 350° C., which represents the temperature at which BCB begins to degrade. In accordance with embodiments including a bonding layer **125** material characterized by a liquidus temperature (e.g. gold, silver, bismuth) greater than 250° C., full-curing of a BCB stabilization layer **145** can be achieved in approximately 1 hour or less at a curing temperature between 250° C. and 300° C. Other bonding layer **125** materials such as Sn (231.9° C.) may require between 10-100 hours to fully cure at temperatures between 200° C. and the 231.9° C. liquidus temperature. In accordance with embodiments, including a bonding layer **125** material characterized by a liquidus temperature below 200° C. (e.g. indium), a BCB stabilization layer **145** may only be partially cured (e.g. 70% or greater). In such an embodiment the BCB stabilization layer **145** may be cured at a temperature between 150° C. and the liquidus temperature of the bonding layer (e.g. 156.7° C. for indium) for approximately 100 hours to achieve at least a 70% cure.

[0065] Achieving a 100% full cure of the stabilization layer **145** is not required in accordance with embodiments of the invention. More specifically, the stabilization layer **145** may be cured to a sufficient curing percentage (e.g. 70% or greater for BCB) at which point the stabilization layer **145** will no longer reflow. Moreover, it has been observed that such partially cured (e.g. 70% or greater) BCB stabilization layer **145** may possess sufficient adhesion strength with the carrier substrate **160** and sacrificial layer **136** (or any intermediate layer (s)).

[0066] FIG. **9** is a cross-sectional side view illustration of the removal of growth substrate **102** in accordance with an embodiment of the invention. When growth substrate **102** is sapphire, laser lift off (LLO) may be used to remove the sapphire. Removal may be accomplished by other techniques such as grinding and etching, depending upon the material selection of the growth substrate **102**.

[0067] FIG. **10** is a cross-sectional side view illustration of the removal of epitaxial growth layer **103** and a portion of a device layer **105** in accordance with an embodiment of the invention. The removal of epitaxial growth layer **103** and a portion of device layer **105** may be accomplished using one or more of chemical-mechanical-polishing (CMP), dry polishing, or dry etch. FIG. **10** illustrates that that unremoved portions **129** of device layer **105** that connected the micro device mesa structures **127** in FIG. **9** are removed in FIG. **10**, which leaves laterally separated micro devices **128**. In an embodiment, removing unremoved portions **129** of device layer **105** includes thinning the array of micro device mesa structures **127** so that an exposed top surface **109** of each of the laterally separate micro devices **128** is below an exposed top surface **139** of sacrificial layer **135**.

[0068] In embodiments where the bulk LED substrate **100** includes epitaxial growth layer **103**, a portion of the doped semiconductor layer **108** adjacent the epitaxial growth layer **103** may also function as a "buffer". For example, epitaxial growth layer **103** may or may not be doped, while semiconductor layer **108** is n-doped. It may be preferred to remove the epitaxial growth layer **103** using any suitable technique such as wet or dry etching, or CMP, followed by a timed etch of the remainder of the doped semiconductor layer **108** resulting in the structure illustrated in FIG. **10**. In this manner, the thickness of the laterally separate micro devices **128** is largely determined by the etching operation illustrated in FIG. **3** for the formation of the micro device mesa structures **127**, combined with the timed etch or etch stop detection of the etching operation illustrated in FIG. **10**. A timed etch of unremoved portions of device layer **105** may correspond to etching a portion of doped semiconductor layer **108**.

[0069] FIG. **11** is a cross-sectional side view illustration of patterned conductive contacts **175** formed over an array of laterally separate micro devices **128** in accordance with an embodiment of the invention. To form conductive contacts **175**, a conductive contact layer is formed over micro devices **128** and sacrificial layer **135**. The conductive contact layer may be formed of a variety of conductive materials including metals, conductive oxides, and conductive polymers. In an embodiment, conductive contacts are formed of a metal or metal alloy. In an embodiment, the conductive contact layer is formed using a suitable technique such as sputtering or electron beam physical deposition. For example, the conductive contact layer may include BeAu metal alloy, or a metal stack of Au/GeAuNi/Au layers. The conductive contact layer can also be a combination of one or more metal layers and a conductive oxide. In an embodiment, after forming the conductive contact layer, the substrate stack is annealed to generate an ohmic contact between the conductive contact layer and the device layer of micro devices **128**. Where the stabilization layer **145** is formed of BCB, the annealing temperature may be below approximately 350° C., at which point BCB degrades. In an embodiment, annealing is performed between 200° C. and 350° C., or more particularly at approximately 320° C. for approximately 10 minutes. After the conductive contact layer is deposited, it can be patterned and etched to form conductive contacts **175**, which may be n-metal conductive contacts.

[0070] The resultant structures illustrated in FIG. **11** are robust enough for handling and cleaning operations to prepare the substrate structure for subsequent sacrificial layer removal and electrostatic pick up. In an exemplary embodiment where the array of micro devices **128** have a pitch of 5 microns, each micro device **128** may have a minimum width (e.g. along the top surface **109**) of 4.5 μm, and a separation between adjacent micro devices **128** of 0.5 μm. It is to be appreciated that a pitch of 5 microns is exemplary, and that embodiments of the invention encompass any pitch of 1 to 100 μm as well as larger, and possibly smaller pitches.

[0071] FIG. **11** illustrates a structure having a stabilization layer **145** that includes an array of stabilization posts **152**. The zoomed-in portion of FIG. **11** shows that each stabilization post **152** includes a stabilization post protrusion **151** and a stabilization post platform **155** defined by the dashed lines. Stabilization post protrusion **151** is disposed above stabilization post platform **155** and stabilization post platform **155** is disposed between stabilization post protrusion **151** and the carrier substrate **160**. The zoomed-in portion of FIG. **11** also illustrates that stabilization post platform **155** is wider than the stabilization post protrusion **151**. In the illustrated

embodiment, the stabilization post platform **155** and the stabilization post protrusion **151** are part of a monolithic portion of stabilization layer **145**.

[0072] FIG. **11** also illustrates stabilization layer **145** including an array of stabilization cavities defined by cavity sidewalls **147** (which may be coated with adhesion promoter layer **144**) of stabilization layer **145** that surround stabilization posts **152**. In FIG. **11**, the bottom surface **107** (having dimension D1) of each micro device **128** is wider that the corresponding stabilization post **152** that is directly under the micro device **128**. In one embodiment (not illustrated), bottom surface **107** is wider than stabilization post protrusion **151**, but not wider than stabilization post **152** as a whole. In FIG. **11**, sacrificial layer **135** spans along side surfaces **106** of micro devices **128**. Side surfaces **106** run between top surface **109** and a bottom surface **107** of each micro device in the array. In the illustrated embodiments, the stabilization cavity sidewalls **147** of the stabilization layer **145** are taller than the stabilization posts **152**.

[0073] In the cross-sectional side view illustration of FIG. **11**, patterned sacrificial spacers **137** are distributed across the illustrated structure. In some embodiments, patterned sacrificial spacers **137** are distributed throughout structure. However, in other embodiments, patterned sacrificial spacers **137** are not distributed throughout the structure, but instead they are selectively distributed.

[0074] FIGS. **14**A and **14**B illustrate a top view of carrier substrates **160** with example placements of groups **138** of patterned sacrificial spacers **137** in relation to the carrier substrates **160** in accordance with embodiments of the invention. Carrier substrate **160** may be approximately six inches in diameter and be made of silicon. FIG. **14**A shows groups **138** arranged in a pattern following concentric circles. FIG. **14**B shows groups **138** arranged in a rectangular grid pattern. Of course, other configurations than those illustrated can be implemented. Additionally, although groups **138** of patterned sacrificial spacers **137** are illustrated as circular, the groups **138** of patterned sacrificial spacers **137** may also have a rectangular shape, when viewed from the view point illustrated in FIGS. **14**A and **14**B. In an embodiment, group **138** includes patterned sacrificial spacers **137** between an area that is five micro devices **128** wide, resulting in patterned sacrificial spacers between a total of approximately 25 micro devices **128**. In an embodiment, the patterned sacrificial spacers **137** are singularly interspersed between only a small percentage (e.g. <5%) of the micro devices **128** to offset carrier substrate **160** by a standoff height during bonding.

[0075] FIG. **14**C illustrates a cross-sectional side view illustration of one example of a selective distribution of patterned sacrificial spacers **137** in accordance with an embodiment of the invention. FIG. **14**C is at a similar step in the fabrication process as FIG. **8** and could be fabricated using similar processes as shown in FIGS. **2**A-**7**. The structure of FIG. **14**C could also be completed and utilized using similar processes that are described in FIGS. **9**-**13**E with appropriate adjustments, if needed.

[0076] In FIG. **14**C, a portion of a patterned sacrificial spacer **137** is illustrated on the right and left side of the illustrated structure. In contrast to FIG. **8**, FIG. **14**C shows that between the two partial patterned sacrificial spacers **137** is an area **141** of the structure that does not include patterned sacrificial spacers **137** for offsetting carrier substrate **160**. Area **141** includes truncated stabilization posts **154** disposed between fine sacrificial layer **136**. In FIG. **14**C, the truncated stabilization posts **154** are in a contiguous portion of stabilization layer **145**, whereas in FIG. **8**, the stabilization posts **152** are isolated in non-contiguous portions of stabilization layer **145**. It is appreciated that the process used to dispose fine sacrificial layer **136** in FIG. **14**C may be the same as what was used to dispose fine sacrificial layer **136**, as the thickness of fine sacrificial layer **136** is similar whether or not it covers course sacrificial layer **135**. Since the thickness of (and patterning of) fine sacrificial layer **136** may stay the same, the size of truncated stabilization posts **154** may be the same as stabilization post protrusions **151**. It is appreciated that a given structure may have an array of stabilization posts **152** (disposed as non-contiguous portions of stabilization layer **145**) and an array of truncated stabilization posts **154** (disposed in contiguous portions of stabilization layer **145**), in accordance with embodiments of the invention.

[0077] Turning to FIG. **12**A, FIG. **12**A continues from the structure illustrated in FIG. **11**. FIG. **12**A is a cross-sectional side view illustration of an array of micro devices **128** formed on an array of stabilization posts **152** after removal of patterned sacrificial spacers **137** in accordance with an embodiment of the invention. In the embodiment illustrated, patterned sacrificial spacers **137** are removed resulting in an open space **177** between each micro device **128** and the features of stabilization layer **145**. As illustrated, open space **177** includes the open space below each micro device **128** as well as the open space between each micro device **128** and stabilization cavity sidewalls **147** of stabilization layer **145**. A suitable etching chemistry such as HF vapor, CF_4, or SF_6 plasma may be used to etch the SiO_2 or SiN_x of the patterned sacrificial spacers **137**.

[0078] After the patterned sacrificial spacers **137** are removed, the array of micro devices **128** on the array of stabilization posts **152** are supported only by the array of stabilization posts **152**. At this point, the array of micro devices **128** are poised for pick up and transferring to a target or receiving substrate. After the patterned sacrificial spacers **137** are removed, it is possible that a micro device **128** may shift off of its corresponding stabilization post **152**. However, in the illustrated embodiment, the stabilization cavity sidewalls **147** may be advantageously positioned to contain the shifted micro device **128** within the stabilization cavity between the cavity sidewalls **147**. Therefore, even when a micro device **128** loses adherence to a stabilization post **152**, it may still be poised for pick up because it is still positioned within an acceptable tolerance (defined by the stabilization cavity) to be transferred to a receiving substrate.

[0079] To further illustrate, FIGS. **12**B and **12**C are schematic top view illustrations of example stabilization post **152** locations relative to a group of micro devices **128** in accordance with an embodiment of the invention. The cross-sectional side view of FIG. **12**A is illustrated along line A-A in FIGS. **12**B and **12**C. FIG. **12**B shows an embodiment where stabilization posts **152** are centered in the x-y directions relative to a top view illustration of micro devices **128**. FIG. **12**B also shows how stabilization cavity sidewalls **147** can function to contain micro devices **128**, if a micro device **128** loses adhesion to a stabilization post **152**. FIG. **12**C is substantially similar to FIG. **12**B except that stabilization posts **153** have replaced stabilization posts **152**. Stabilization posts **153** differ from stabilization posts **152** in that they are not centered in the x-y direction relative to a top view illustration of the micro devices **128**. Of course, positions of stabilization posts other than the illustrated positions of stabilization posts **152** and

153 are possible. In an embodiment, during the pick up operation described below the off-centered stabilization posts 153 may provide for the creation of a moment when the array of transfer heads contact the array of micro devices in which the micro devices tilt slightly as a result of the applied downward pressure from the array of transfer heads. This slight tilting may aid in overcoming the adhesion strength between the stabilization posts 153 and the array of micro devices 128. Furthermore, such assistance in overcoming the adhesion strength may potentially allow for picking up the array of micro devices with a lower grip pressure. Consequently, this may allow for operation of the array of transfer heads at a lower voltage, and impose less stringent dielectric strength requirements in the dielectric layer covering each transfer head required to achieve the electrostatic grip pressure. It is appreciated that the dashed lines showing stabilization posts 152 and 153 in FIGS. 12A and 12B may illustrate stabilization posts 152 and 153 at their most narrow point, which may be at the stabilization post protrusion 151 of each stabilization post 152 as it meets conductive contact 120. Of course, truncated stabilization posts 154 may be positioned similarly to stabilization posts 152 and 153 with regard to their x-y positioning associated with a micro device that the truncated stabilization post 154 supports.

[0080] FIGS. 13A-13E are cross-sectional side view illustrations of an array of electrostatic transfer heads 204 transferring micro devices 128 from carrier substrate 160 to a receiving substrate 300 in accordance with an embodiment of the invention. FIG. 13A is a cross-sectional side view illustration of an array of micro device transfer heads 204 supported by substrate 200 and positioned over an array of micro devices 128 stabilized on stabilization posts 152 of stabilization layer 145 on carrier substrate 160. The array of micro devices 128 are then contacted with the array of transfer heads 204 as illustrated in FIG. 13B. As illustrated, the pitch of the array of transfer heads 204 is an integer multiple of the pitch of the array of micro devices 128. A voltage is applied to the array of transfer heads 204. The voltage may be applied from the working circuitry within a transfer head assembly 206 in electrical connection with the array of transfer heads through vias 207. The array of micro devices 128 is then picked up with the array of transfer heads 204 as illustrated in FIG. 13C. The array of micro devices 128 is then placed in contact with contact pads 302 (e.g. gold, indium, or tin) on a receiving substrate 300, as illustrated in FIG. 13D. The array of micro devices 128 is then released onto contact pads 302 on receiving substrate 300 as illustrated in FIG. 13E. For example, the receiving substrate may be, but is not limited to, a display substrate, a lighting substrate, a substrate with functional devices such as transistors or ICs, or a substrate with metal redistribution lines.

[0081] In accordance with embodiments of the invention, heat may be applied to the carrier substrate, transfer head assembly, or receiving substrate during the pickup, transfer, and bonding operations. For example, heat can be applied through the transfer head assembly during the pick up and transfer operations, in which the heat may or may not liquefy the micro device bonding layers 125. The transfer head assembly may additionally apply heat during the bonding operation on the receiving substrate that may or may not liquefy one of the bonding layers on the micro device or receiving substrate to cause diffusion between the bonding layers.

[0082] The operation of applying the voltage to create a grip pressure on the array of micro devices can be performed in various orders. For example, the voltage can be applied prior to contacting the array of micro devices with the array of transfer heads, while contacting the micro devices with the array of transfer heads, or after contacting the micro devices with the array of transfer heads. The voltage may also be applied prior to, while, or after applying heat to the bonding layers.

[0083] Where the transfer heads 204 include bipolar electrodes, an alternating voltage may be applied across a the pair of electrodes in each transfer head 204 so that at a particular point in time when a negative voltage is applied to one electrode, a positive voltage is applied to the other electrode in the pair, and vice versa to create the pickup pressure. Releasing the array of micro devices from the transfer heads 204 may be accomplished with a varied of methods including turning off the voltage sources, lower the voltage across the pair of silicon electrodes, changing a waveform of the AC voltage, and grounding the voltage sources.

[0084] Furthermore, the method of pickup up and transferring the array of micro devices from a carrier substrate to a receiving substrate described with regard to FIGS. 13A-13E is applicable in contexts where the micro devices are micro LEDs or other examples of micro devices described herein.

[0085] In utilizing the various aspects of this invention, it would become apparent to one skilled in the art that combinations or variations of the above embodiments are possible for stabilizing an array of micro devices on a carrier substrate, and for transferring the array of micro devices. Although the present invention has been described in language specific to structural features and/or methodological acts, it is to be understood that the invention defined in the appended claims is not necessarily limited to the specific features or acts described. The specific features and acts disclosed are instead to be understood as particularly graceful implementations of the claimed invention useful for illustrating the present invention.

1-12. (canceled)

13. A structure comprising:

a stabilization layer including an array of stabilization posts;

an array of micro devices over the array of stabilization posts;

patterned sacrificial spacers between the stabilization posts and between the micro devices; and

a carrier substrate, wherein the patterned sacrificial spacers are disposed upon the carrier substrate.

14. The structure of claim 13, wherein the patterned sacrificial spacers include a fine sacrificial layer and a course sacrificial layer.

15. The structure of claim 14, wherein each stabilization post in the array of stabilization posts includes a stabilization post protrusion disposed above a stabilization post platform, wherein the stabilization post platform is disposed between the stabilization post protrusion and the carrier substrate, and wherein the stabilization post platform is wider than the stabilization post protrusion.

16. The structure of claim 13, wherein the micro devices are micro LED devices.

17. The structure of claim 13, wherein each micro device in the array of micro devices includes a bottom surface that is wider than a corresponding stabilization post directly underneath the bottom surface.

18. The structure of claim **17**, wherein the stabilization posts extend through a thickness of the patterned sacrificial spacers.

19. The structure of claim **13**, wherein the patterned sacrificial spacers span along a side surface of at least a portion of the micro devices in the array of micro devices.

20. The structure of claim **13**, further comprising an array of bottom conductive contacts on bottom surfaces of the array of micro devices.

21. The structure of claim **13**, wherein the stabilization layer includes an array of stabilization cavities that include stabilization cavity sidewalls surrounding the stabilization posts.

22. The structure of claim **13**, wherein the stabilization layer is formed of a thermoset material.

23. The structure of claim **13**, wherein the stabilization layer also includes truncated stabilization posts in contiguous portions of the stabilization layer that support additional micro devices, wherein the stabilization posts in the array are in non-contiguous portions of the stabilization layer.

24. The structure of claim **13**, wherein the stabilization posts in the array of stabilization posts are separated by a pitch of 1 μm to 10 μm.

25. The structure of claim **13**, including a fine sacrificial layer and a course sacrificial layer on the fine sacrificial layer, the fine sacrificial layer and the course sacrificial layer together forming the patterned sacrificial spacers.

26. The structure of claim **25**, wherein the course sacrificial layer is thicker than the fine sacrificial layer.

27. The structure of claim **25**, wherein the stabilization layer is substantially completely removed directly between the patterned sacrificial spacers and the carrier substrate.

28. The structure of claim **25**, wherein the fine sacrificial layer spans directly underneath every micro device of the array of micro devices.

29. The structure of claim **28**, wherein the coarse sacrificial layer spans directly underneath a portion of the micro devices of the array of micro devices, the portion being less than every micro device.

30. The structure of claim **29**, wherein the array of stabilization posts includes a first array of truncated stabilization posts with a first post height, and a second array of stabilization posts with a second post height greater than the first post height.

31. The structure of claim **29**, wherein the first array of truncated stabilization posts protrude from the stabilization layer directly beneath the first array of truncated stabilization posts.

32. The structure of claim **29**, wherein the first post height is approximately the same as a thickness of the fine sacrificial layer directly underneath the array of micro devices.

33. The structure of claim **29**, wherein the second post height is approximately the same as a combined thickness of the fine sacrificial layer and the coarse sacrificial layer directly underneath the array of micro devices.

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摘要(译)

公开了一种用于形成微器件阵列的方法和结构。在包括在稳定层中的稳定柱阵列上形成微型器件阵列。图案化的牺牲间隔物形成在稳定柱之间和微型器件之间。图案化的牺牲间隔物设置在图案化的牺牲间隔物上。