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(12) United States Patent
Purchase et al.

(10) Patent No.: US 12,394,657 B2
(45) Date of Patent: Aug. 19, 2025

(54) **TRANSFER PRINTING STAMPS AND METHODS OF STAMP DELAMINATION**

(71) Applicant: **X-Celeprint Limited**, Dublin (IE)

(72) Inventors: **Ken G. Purchase**, Morrisville, NC (US); **Ronald S. Cok**, Rochester, NY (US)

(73) Assignee: **X-Celeprint Limited**, Dublin (IE)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **18/378,493**

(22) Filed: **Oct. 10, 2023**

(65) **Prior Publication Data**

US 2024/0038570 A1 Feb. 1, 2024

Related U.S. Application Data

(63) Continuation-in-part of application No. 17/886,985, filed on Aug. 12, 2022.

(60) Provisional application No. 63/414,985, filed on Oct. 11, 2022, provisional application No. 63/233,946, filed on Aug. 17, 2021.

(51) **Int. Cl.**
H01L 23/00 (2006.01)
H01L 21/683 (2006.01)

(52) **U.S. Cl.**
CPC ***H01L 21/6835*** (2013.01); ***H01L 24/75*** (2013.01); ***H01L 24/94*** (2013.01); *H01L 2221/68318* (2013.01); *H01L 2224/75305* (2013.01); *H01L 2224/75315* (2013.01); *H01L 2224/94* (2013.01)

(58) **Field of Classification Search**
CPC H01L 21/6835; H01L 24/75; H01L 24/94; H01L 2221/68318; H01L 2224/75305; H01L 2224/75315; H01L 2224/94
See application file for complete search history.

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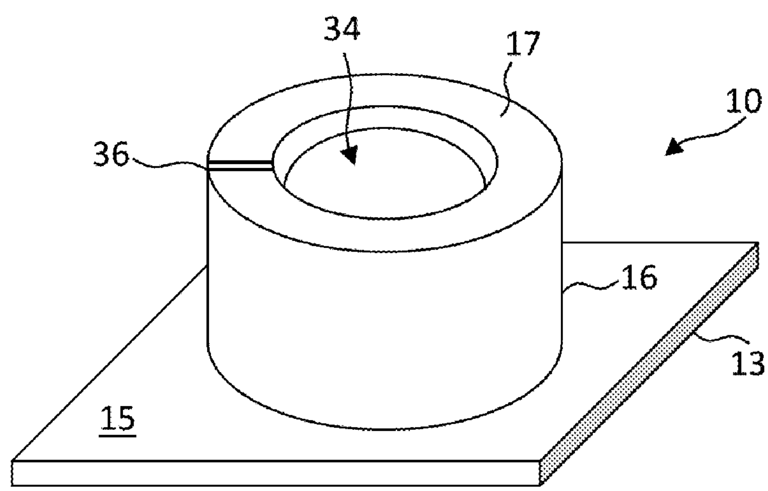
Primary Examiner — Christopher E Mahoney
Assistant Examiner — Marissa Ferguson-Samreth
(74) *Attorney, Agent, or Firm* — Choate, Hall & Stewart LLP; Michael D. Schmitt

(57) **ABSTRACT**

A stamp for micro-transfer printing includes a support having a support surface and posts disposed on the support surface. Each post has a proximal end in contact with the support and a distal end extending away from the support. The post has a post surface on the distal end. The post surface is a structured surface comprising spatially separated ridges that extend in a ridge direction entirely across the post surface and can be operable to form multiple delamination fronts when a first side of a micro-device is in contact with the post surface, a second side of the micro-device is in contact with a target surface of a target substrate, and the support is moved in a horizontal direction parallel to the target substrate surface. The post surface or ridges can be rectangular or non-rectangular with opposing edges having different lengths.

22 Claims, 26 Drawing Sheets



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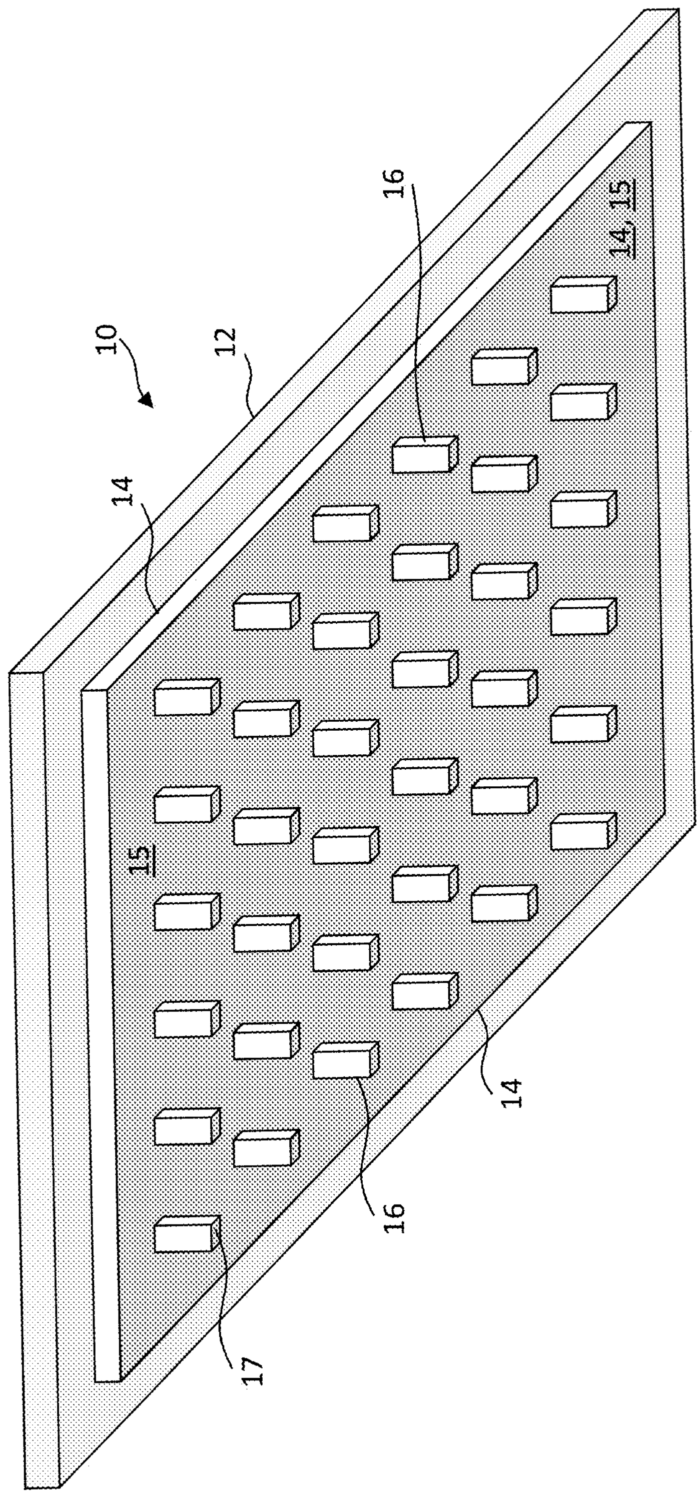


FIG. 1A

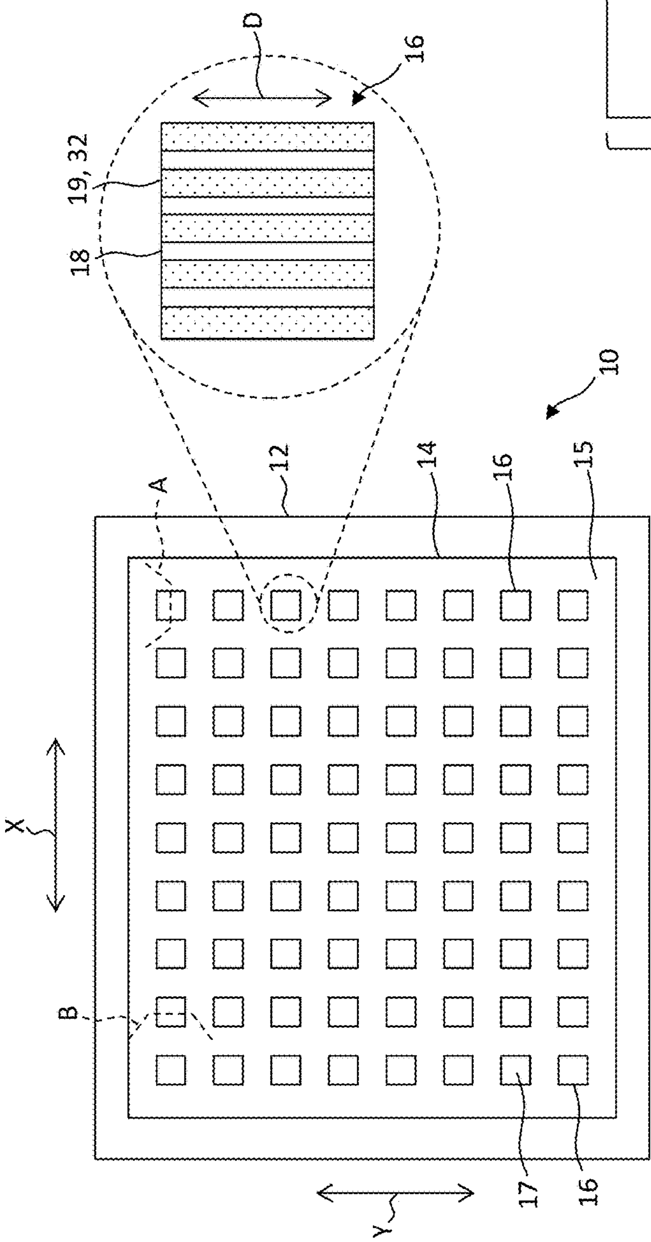


FIG. 1B

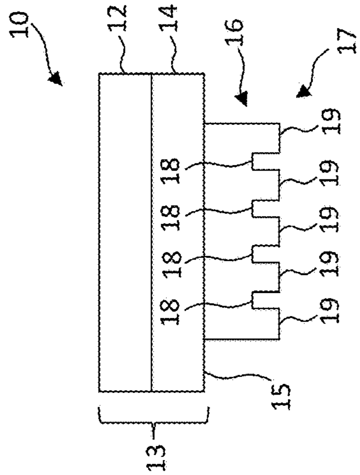


FIG. 1C

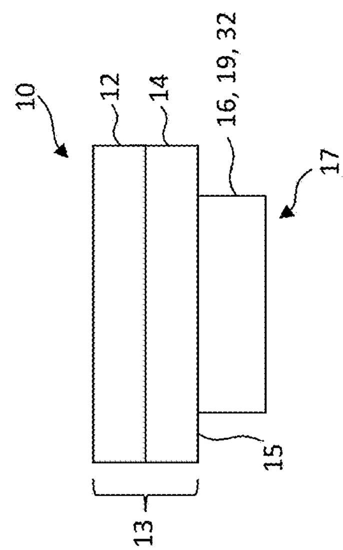


FIG. 1D

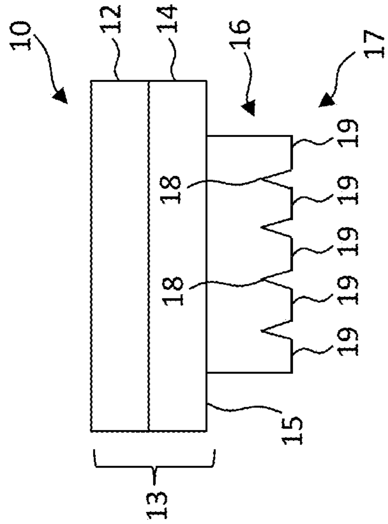


FIG. 3A

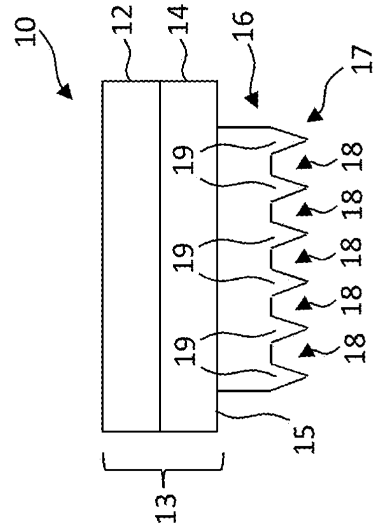


FIG. 3B

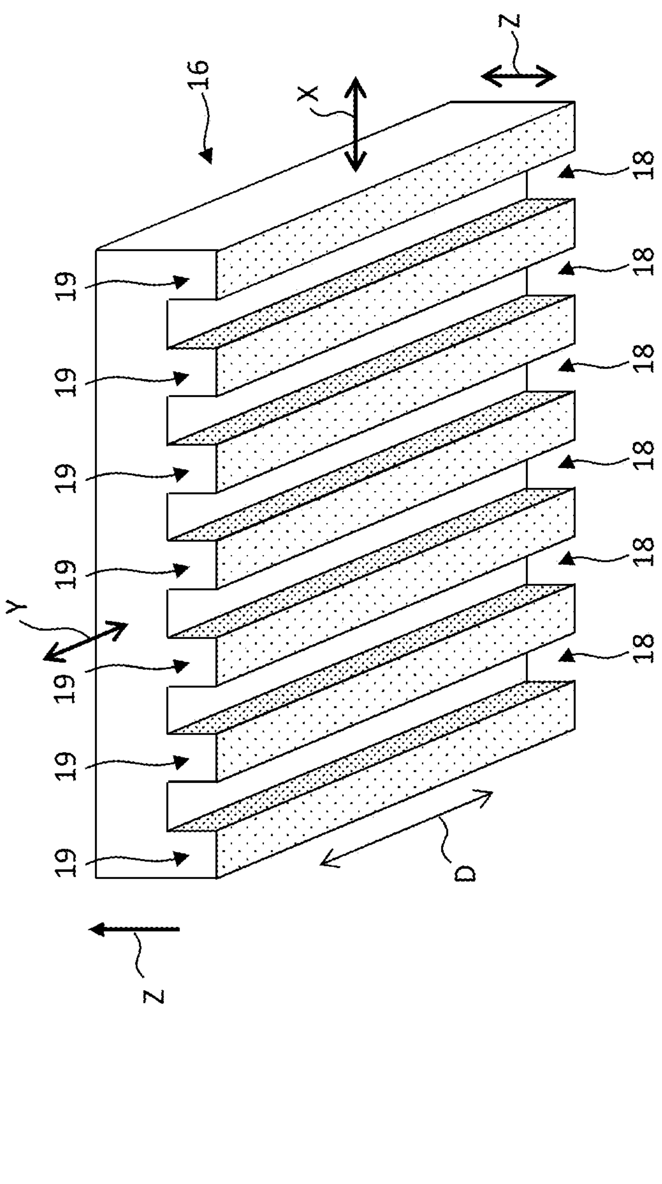


FIG. 2

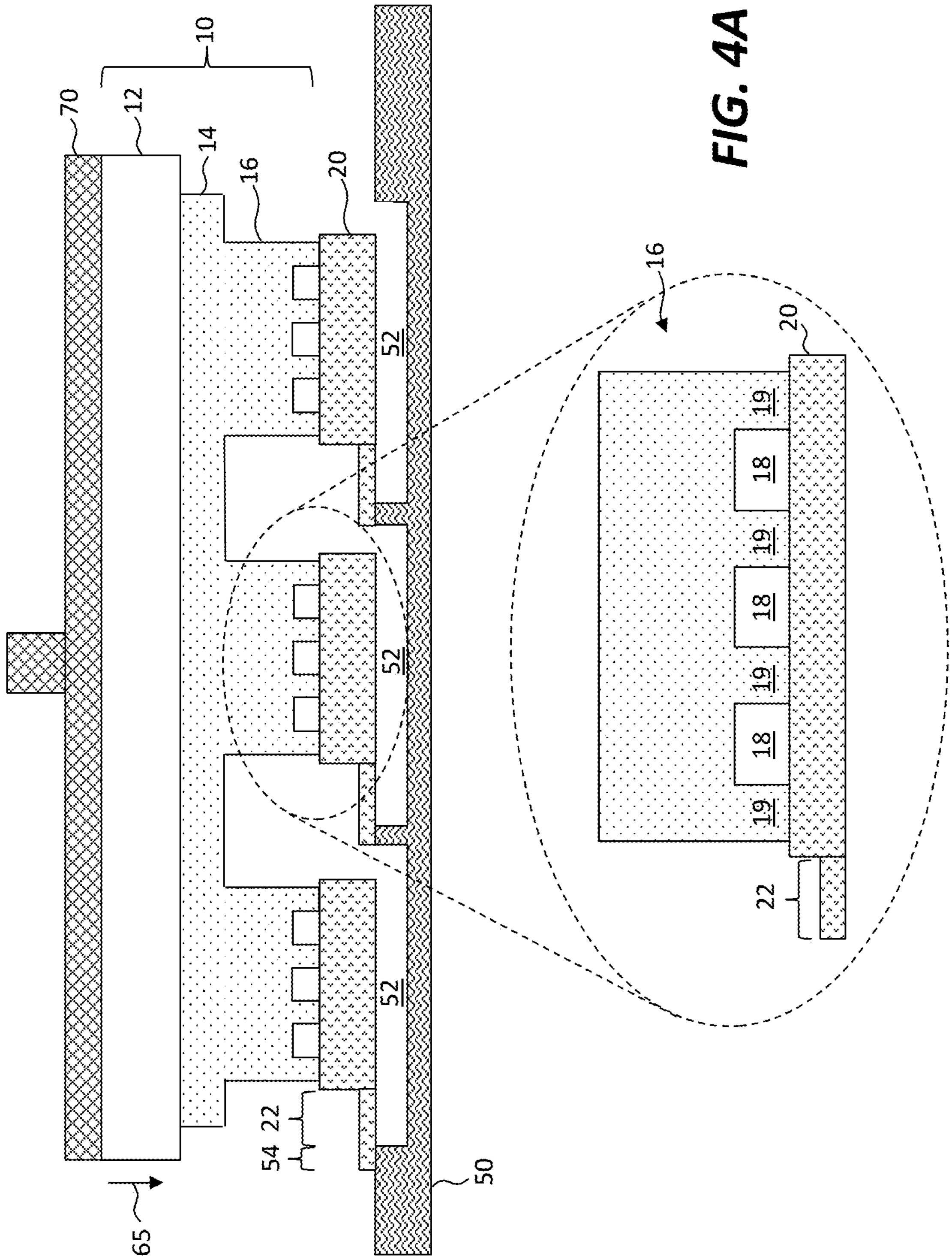
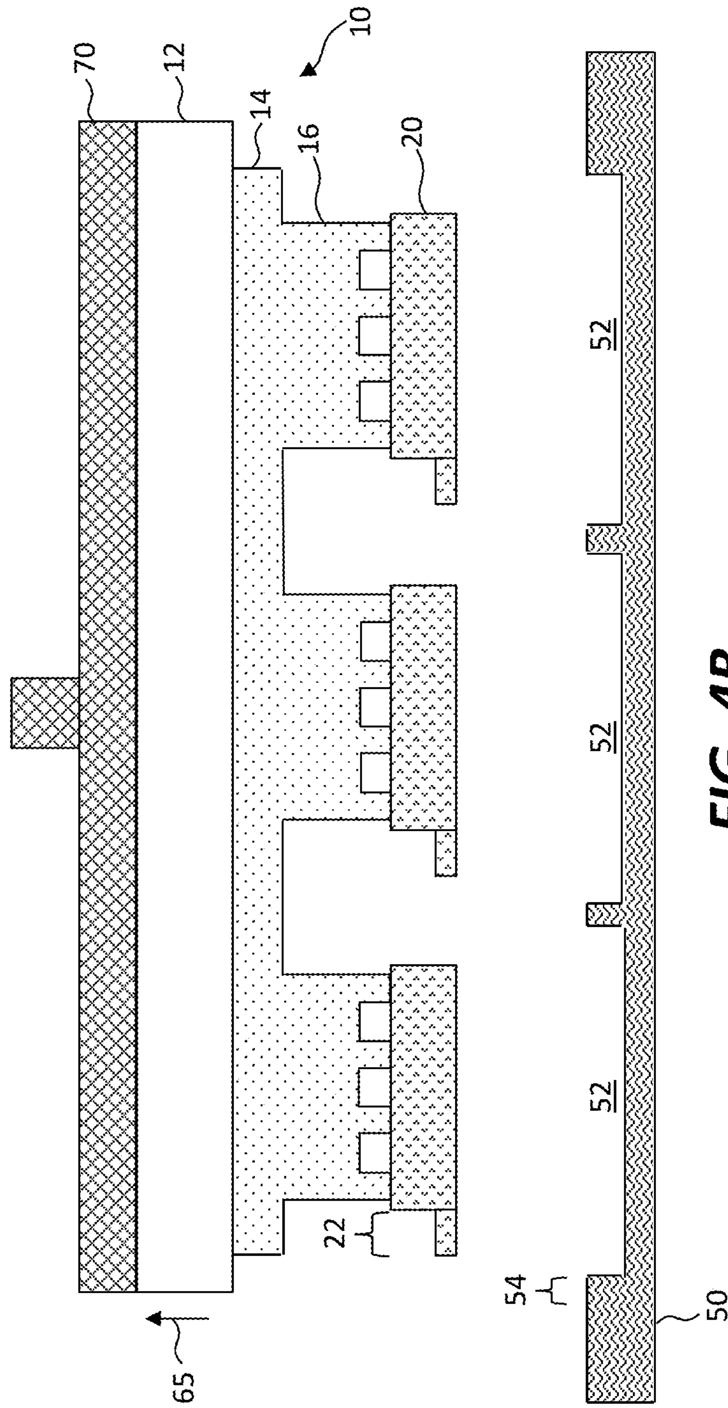


FIG. 4A



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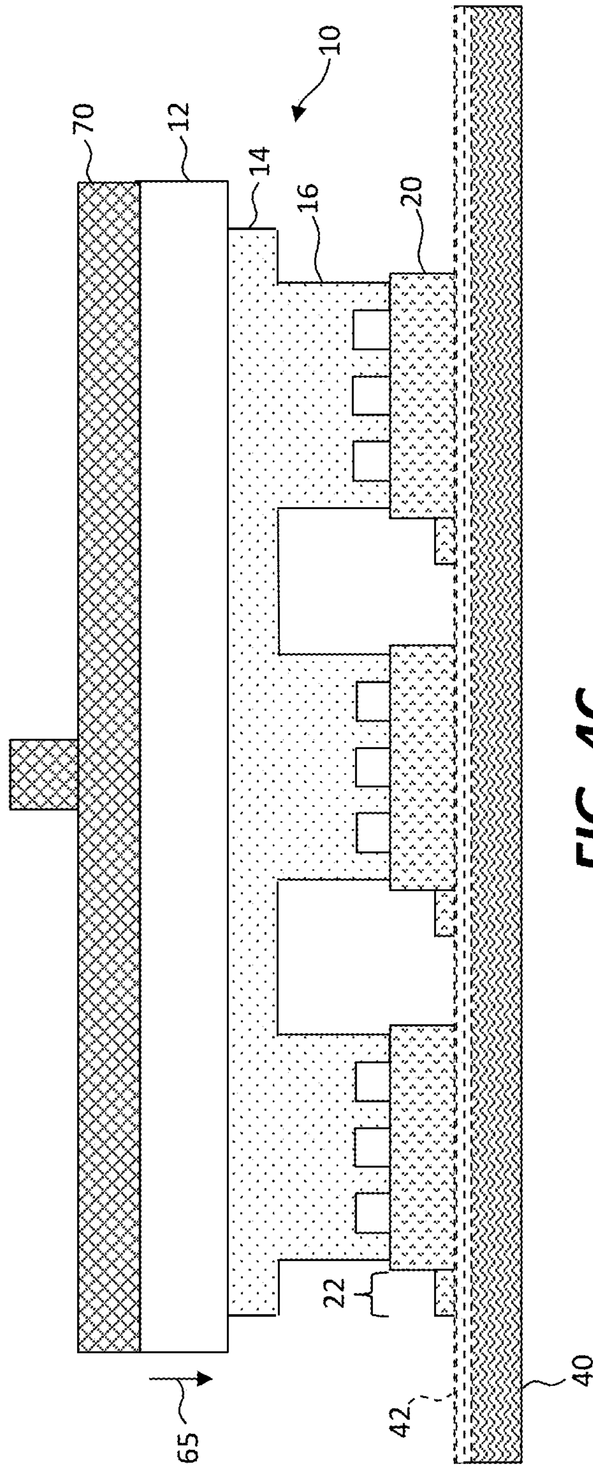

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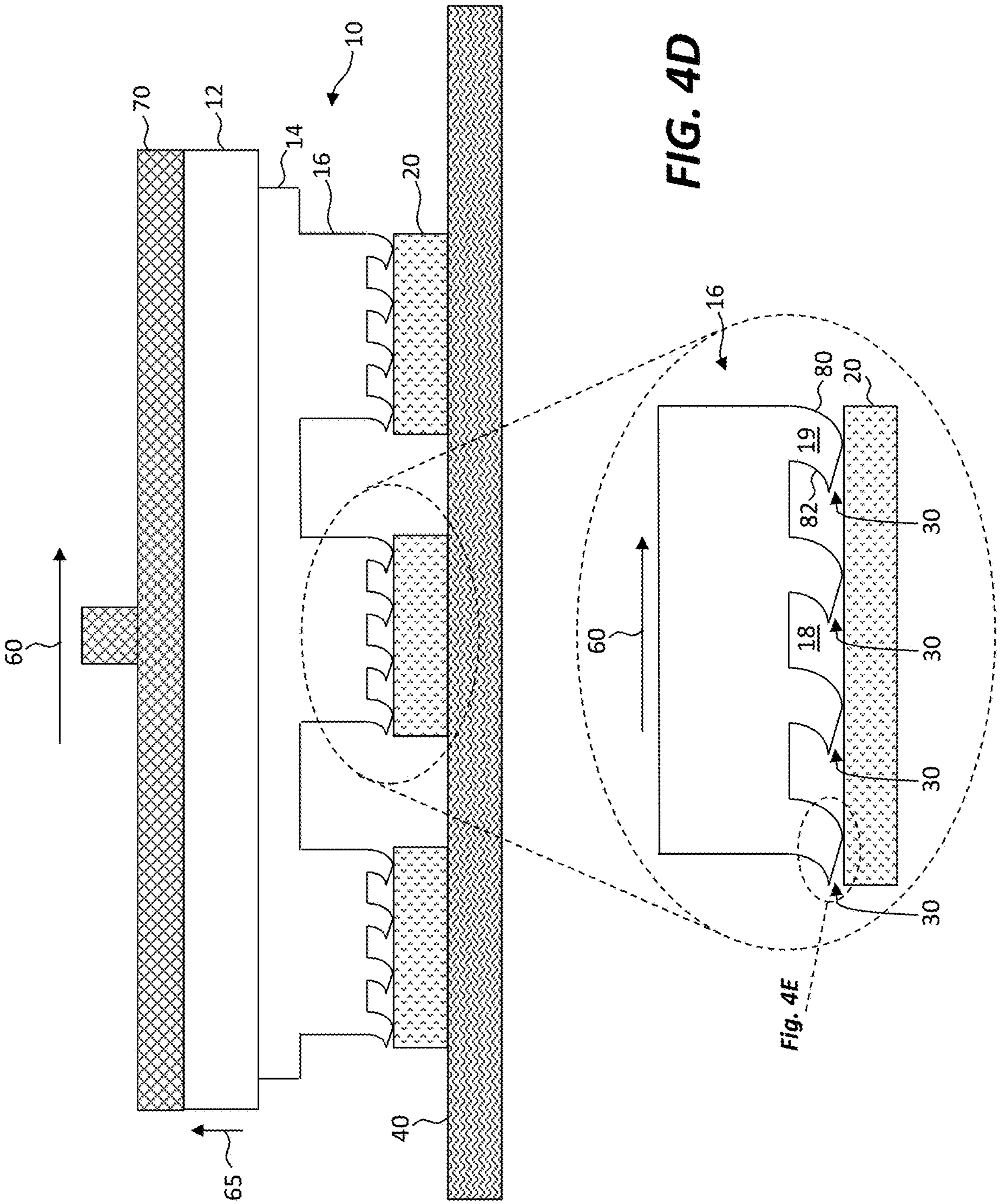


FIG. 4D

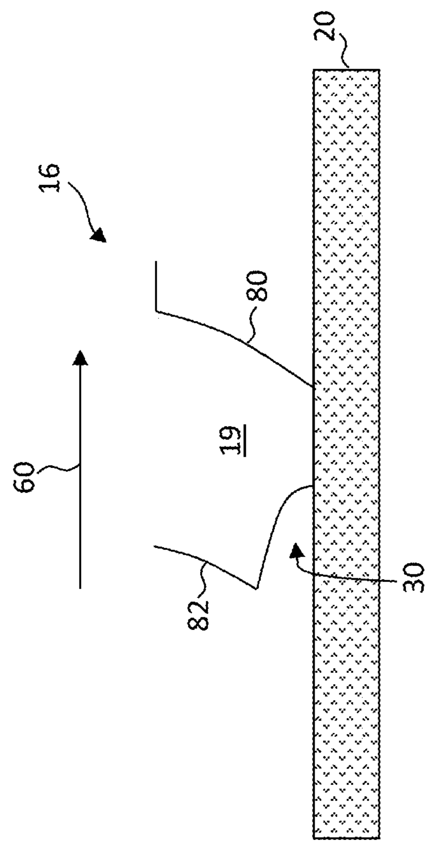


FIG. 4E

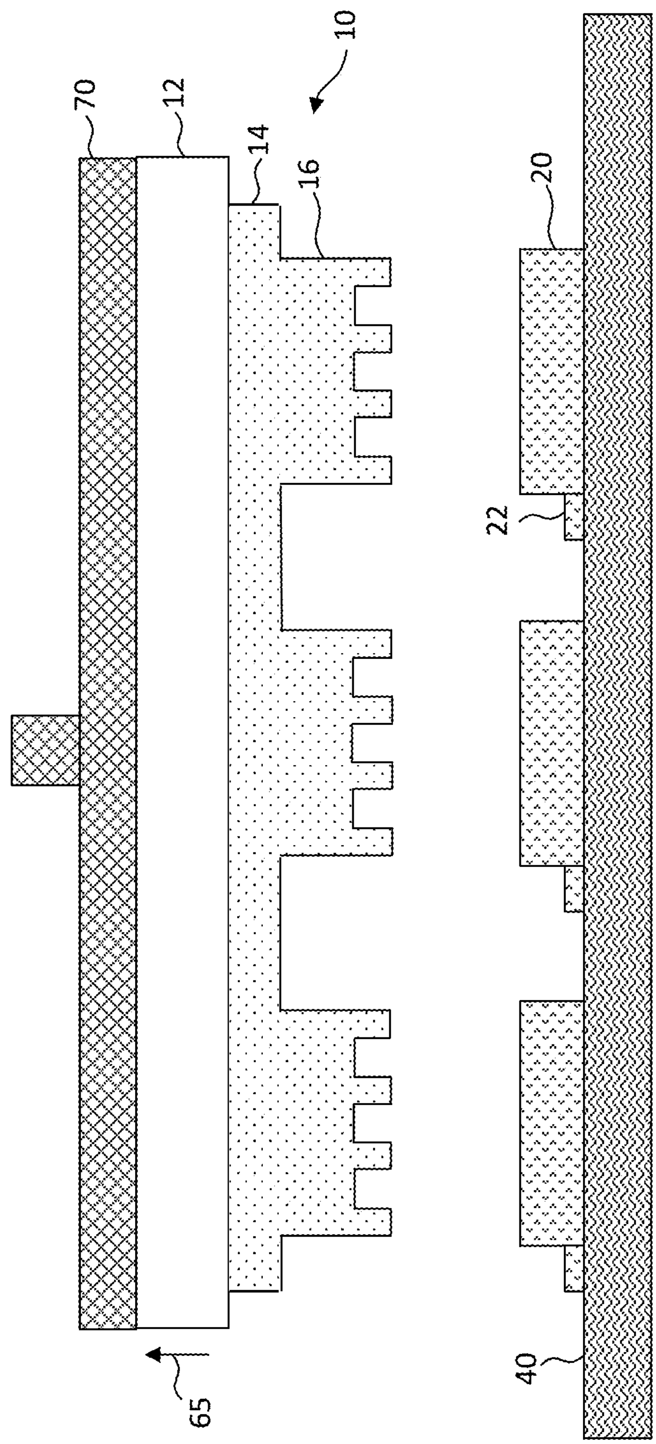


FIG. 4F

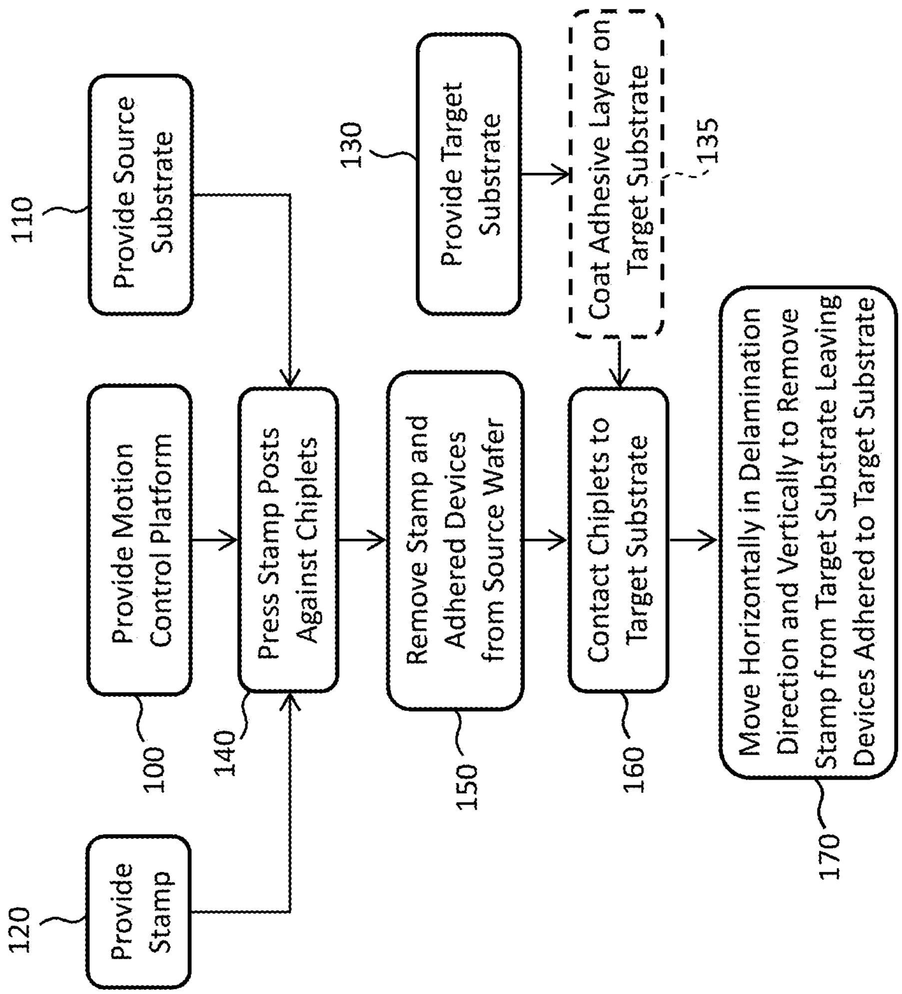

Provide Motion Control Platform
100
Provide Source Substrate
110
Provide Stamp
120
Provide Target Substrate
130
Coat Adhesive Layer on Target Substrate
135
Press Stamp Posts Against Chiplets
140
Remove Stamp and Adhered Devices from Source Wafer
150
Contact Chiplets to Target Substrate
160
Move Horizontally in Delamination Direction and Vertically to Remove Stamp from Target Substrate Leaving Devices Adhered to Target Substrate
170

FIG. 5

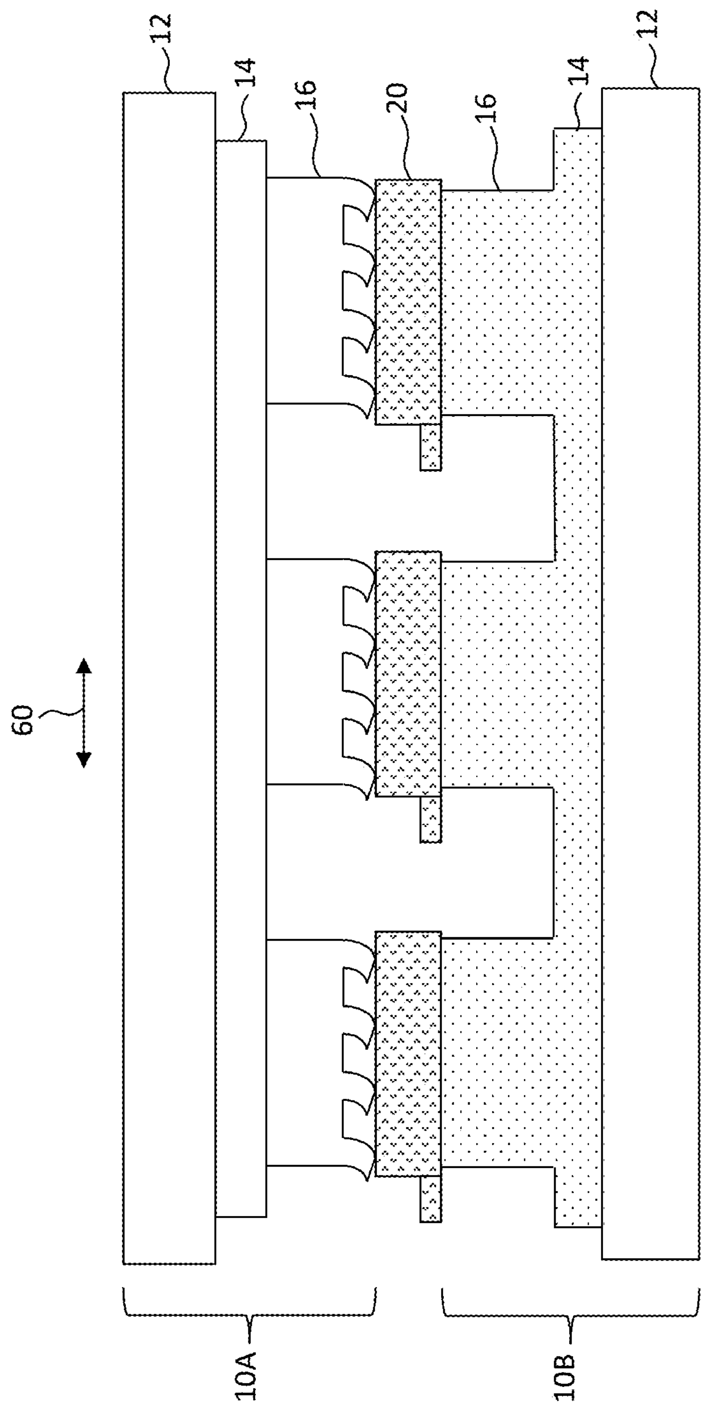


FIG. 6

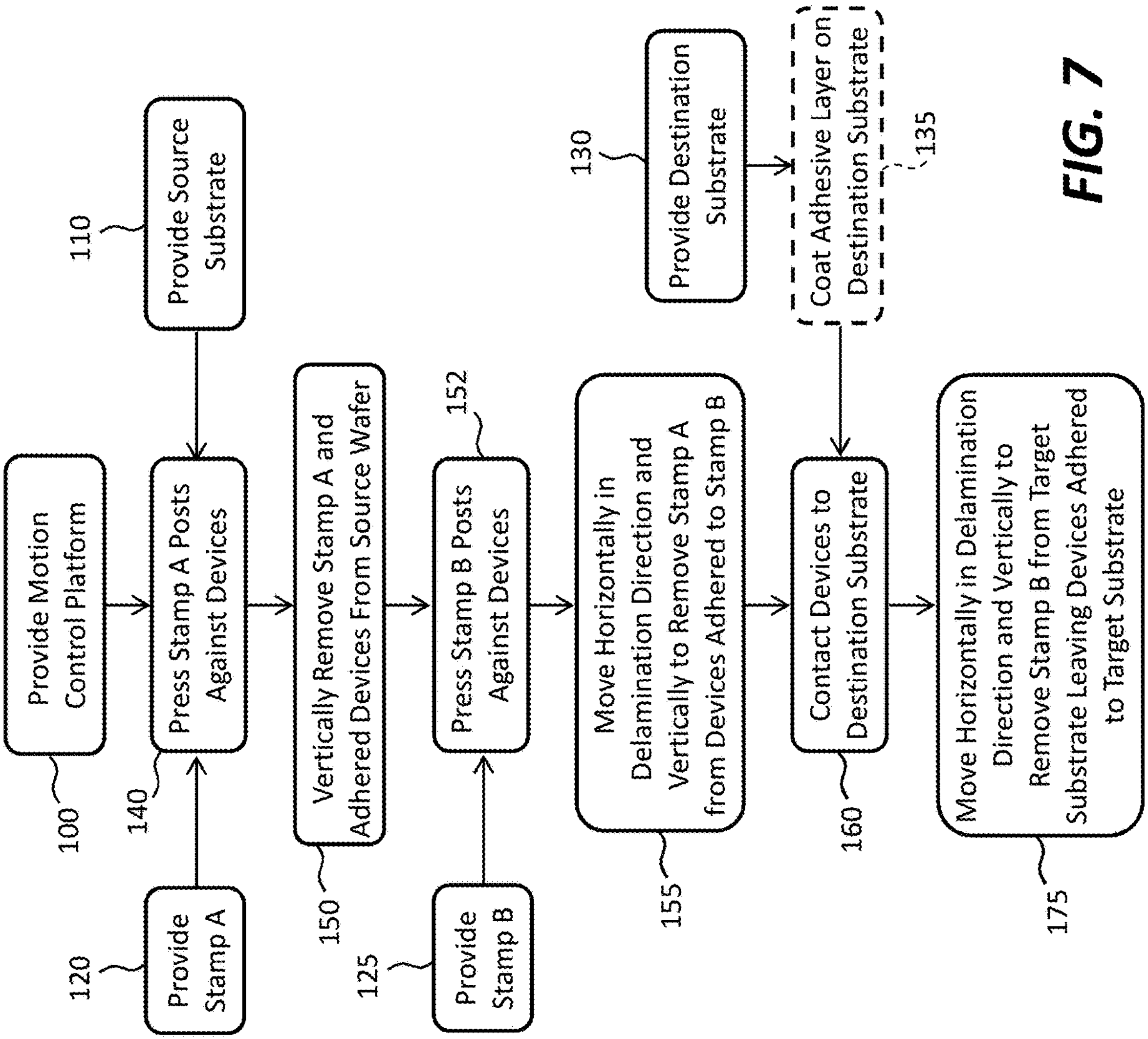

Provide Motion Control Platform
100
Provide Source Substrate
110
Provide Stamp A
120
Press Stamp A Posts Against Devices
140
Vertically Remove Stamp A and Adhered Devices From Source Wafer
150
Provide Stamp B
125
Press Stamp B Posts Against Devices
152
Move Horizontally in Delamination Direction and Vertically to Remove Stamp A from Devices Adhered to Stamp B
155
Provide Destination Substrate
130
Coat Adhesive Layer on Destination Substrate
135
Contact Devices to Destination Substrate
160
Move Horizontally in Delamination Direction and Vertically to Remove Stamp B from Target Substrate Leaving Devices Adhered to Target Substrate
175

FIG. 7

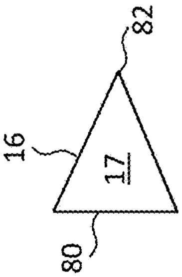


FIG. 8E

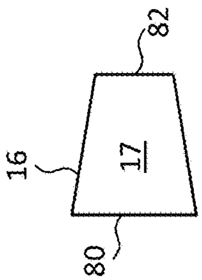


FIG. 8D

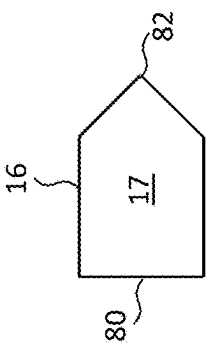


FIG. 8C

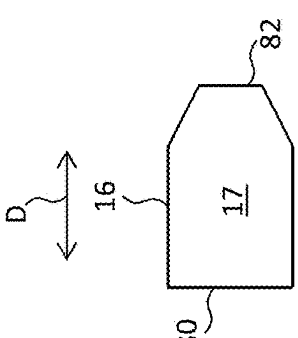
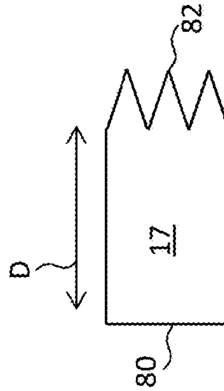


FIG. 8B



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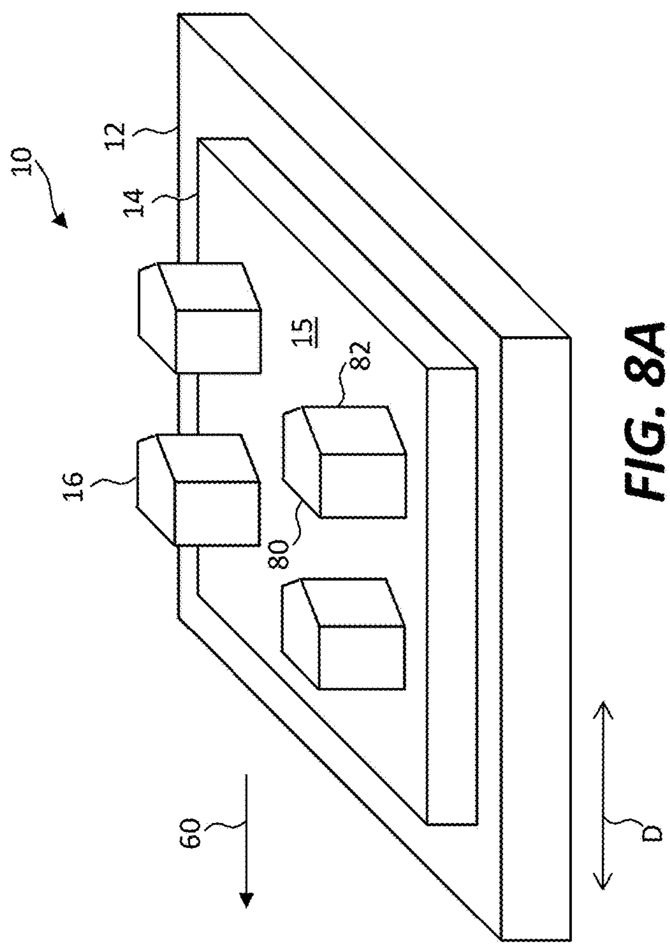


FIG. 8A

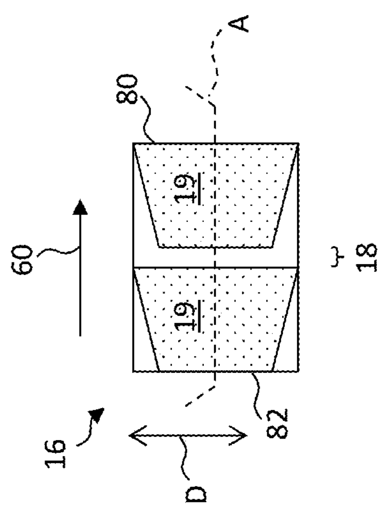
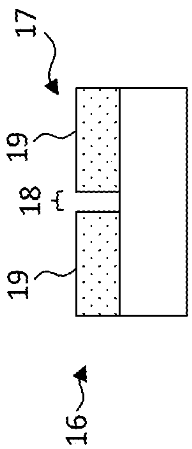


FIG. 9A



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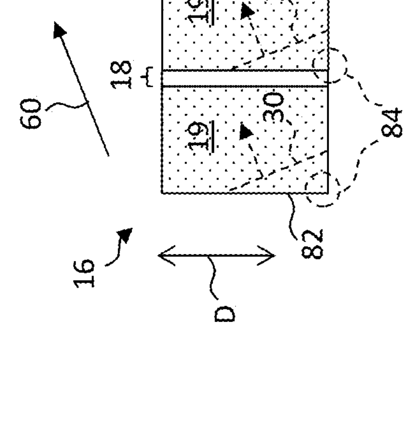

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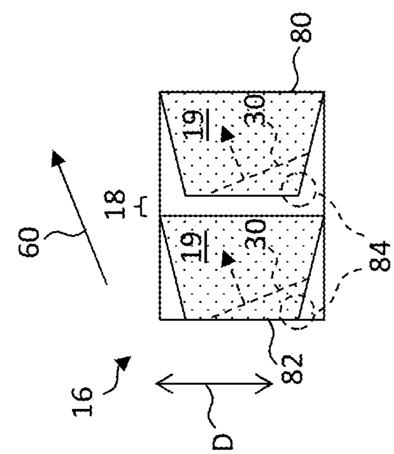


FIG. 10B

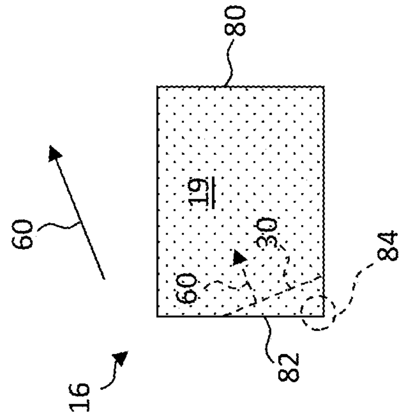


FIG. 10C

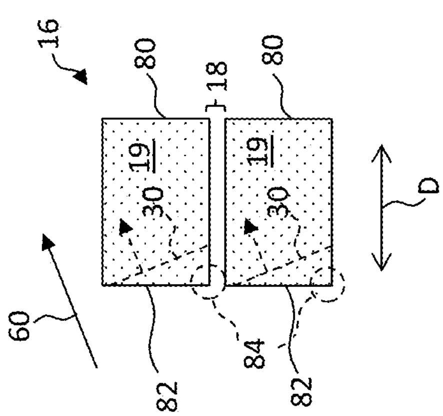


FIG. 11

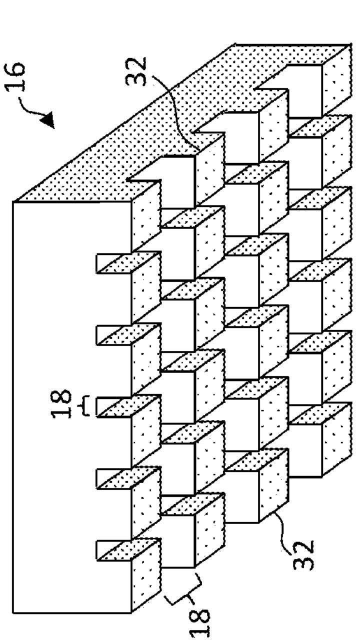


FIG. 12A

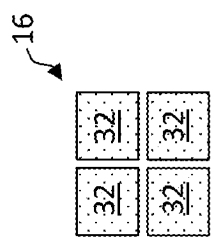


FIG. 12B

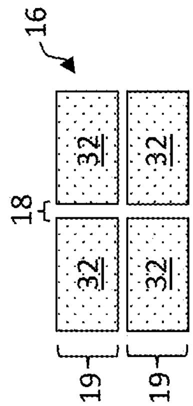


FIG. 12C

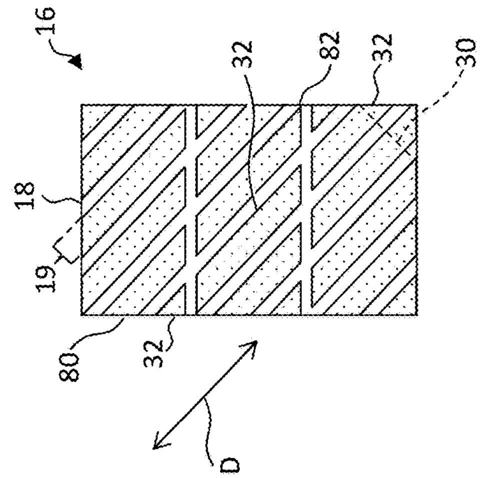


FIG. 14

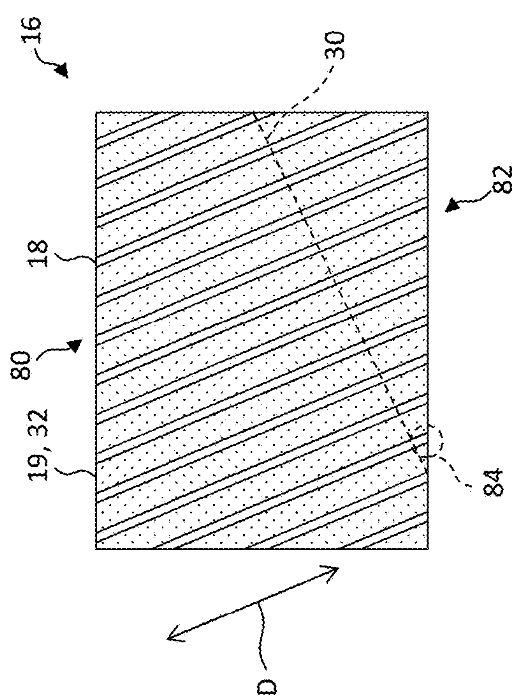
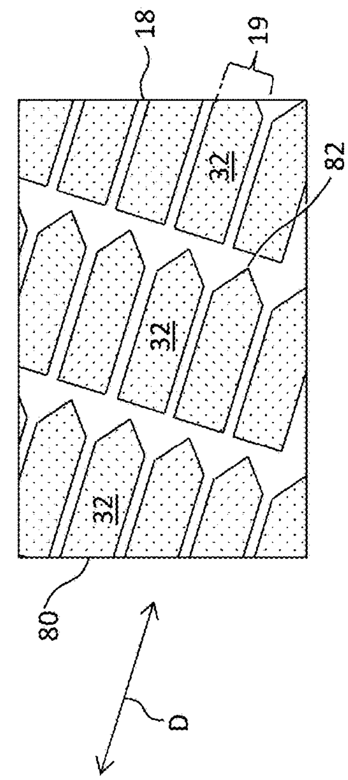


FIG. 13



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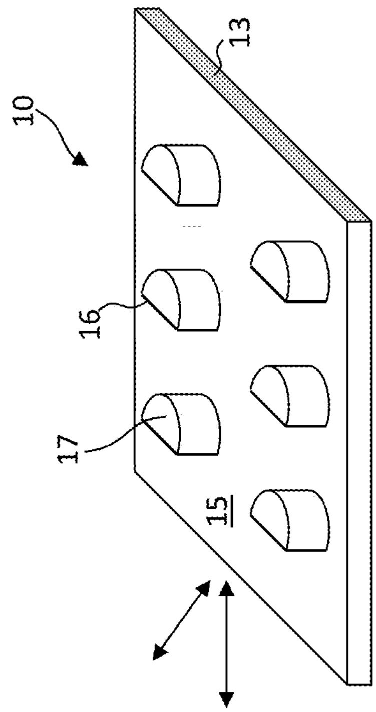


FIG. 16B

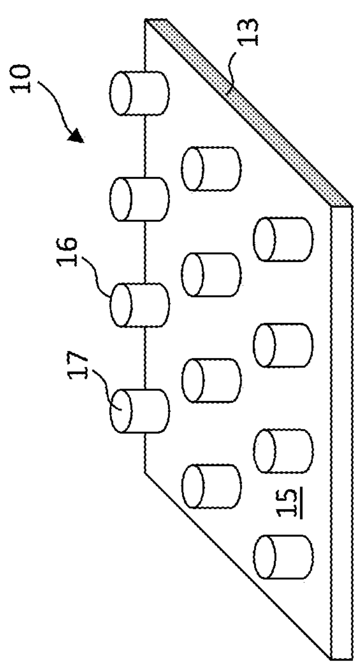


FIG. 16A

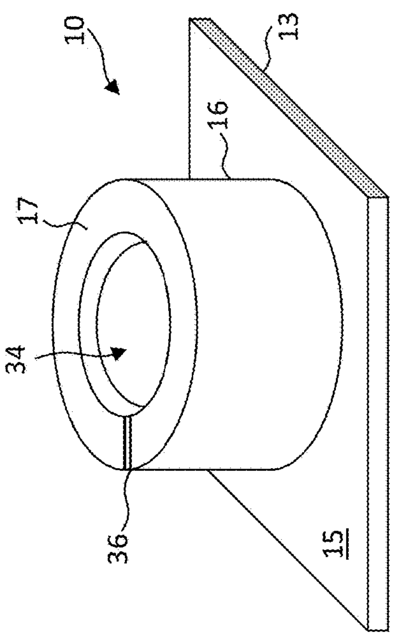
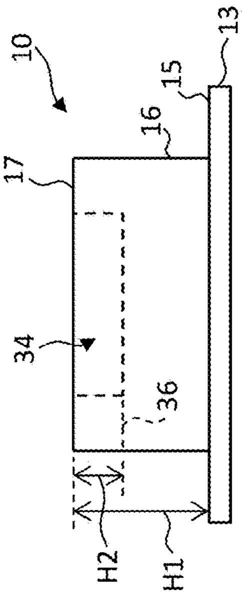


FIG. 17A



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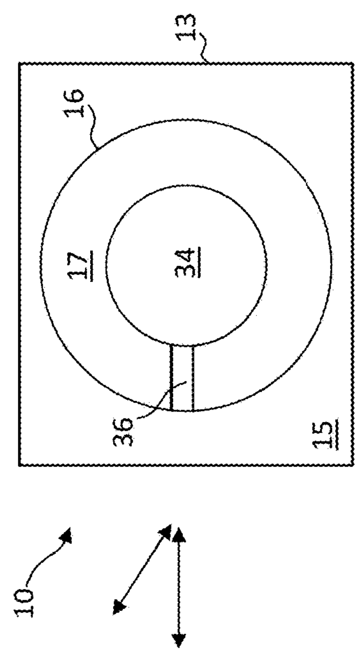

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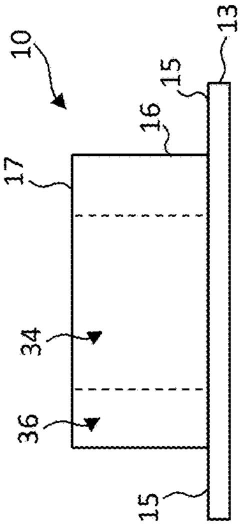

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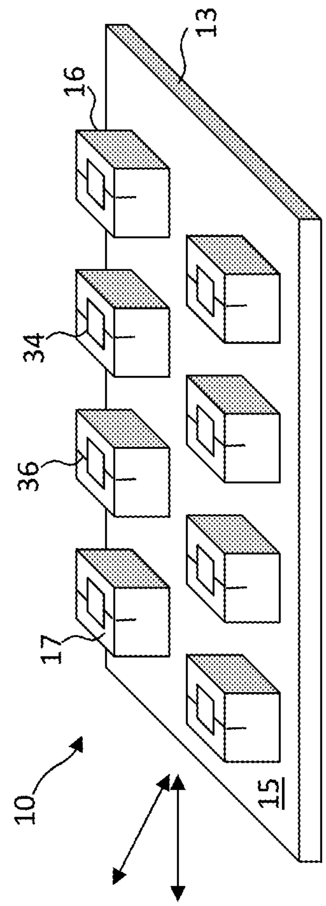


FIG. 18A

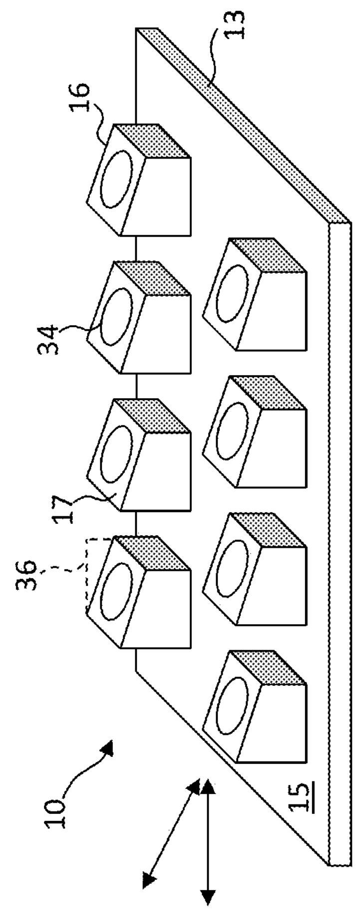
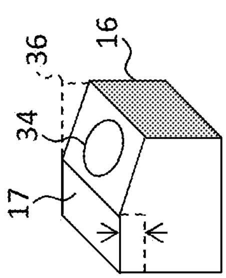


FIG. 18B



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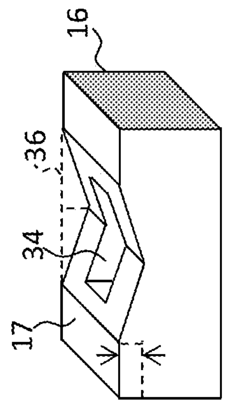


FIG. 18D

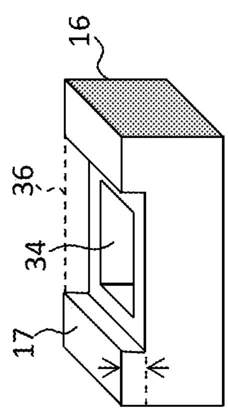


FIG. 18E

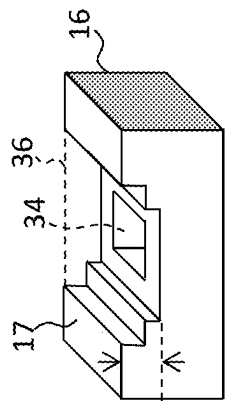


FIG. 18F

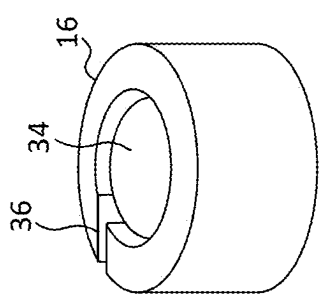


FIG. 18G

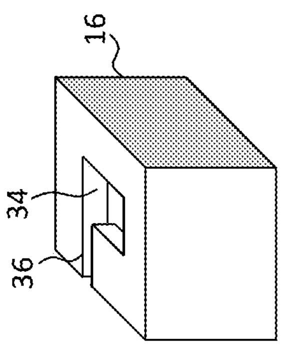


FIG. 18H

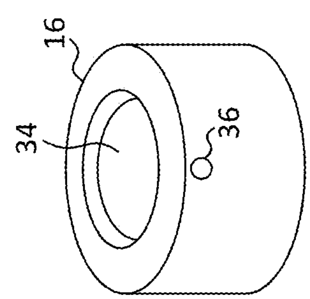


FIG. 18I

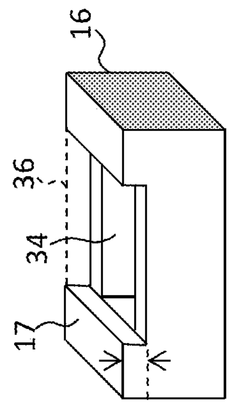


FIG. 18J

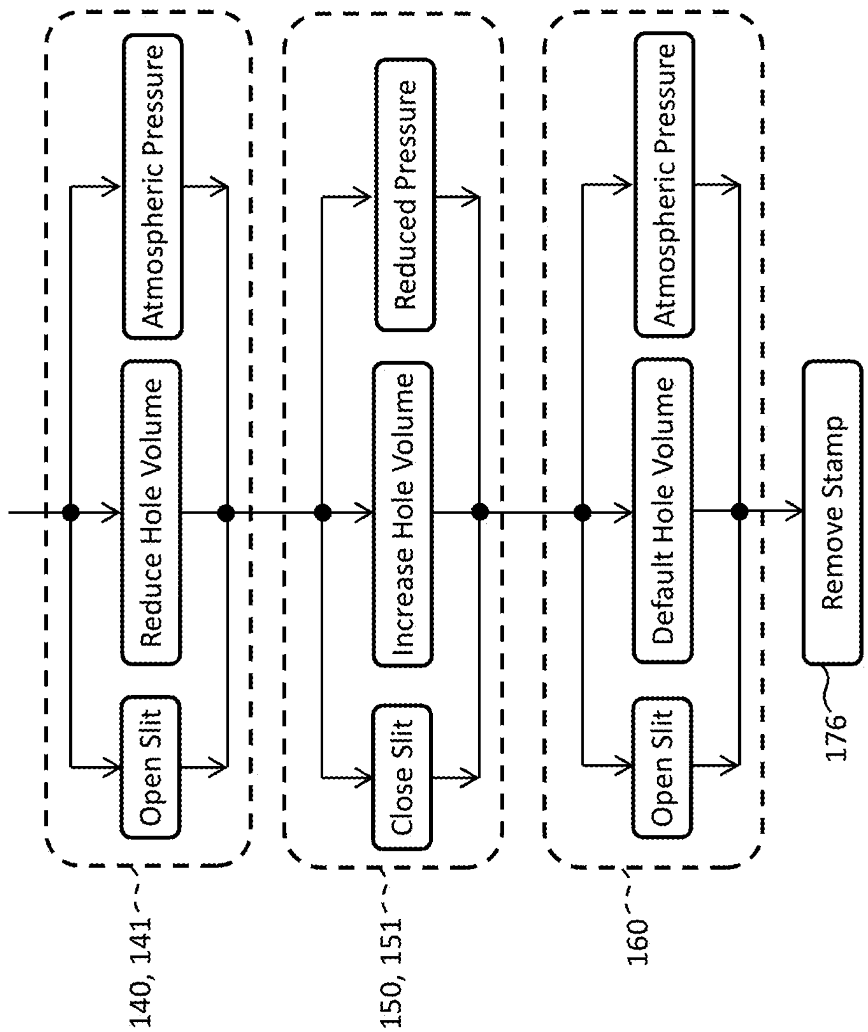

Open Slit
Reduce Hole Volume
Atmospheric Pressure
Close Slit
Increase Hole Volume
Reduced Pressure
Open Slit
Default Hole Volume
Atmospheric Pressure
Remove Stamp
140, 141
150, 151
160
176

FIG. 19

FIG. 20A

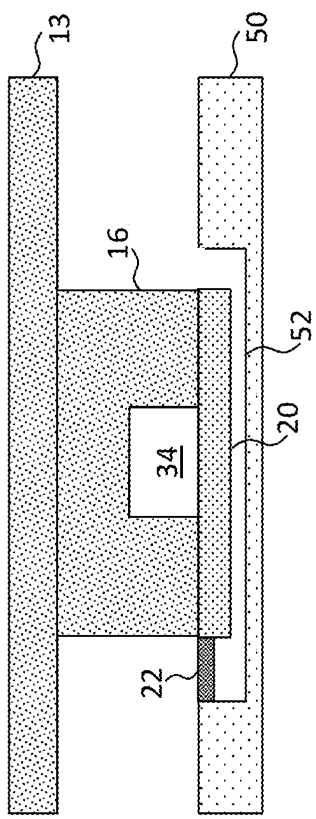


FIG. 20B

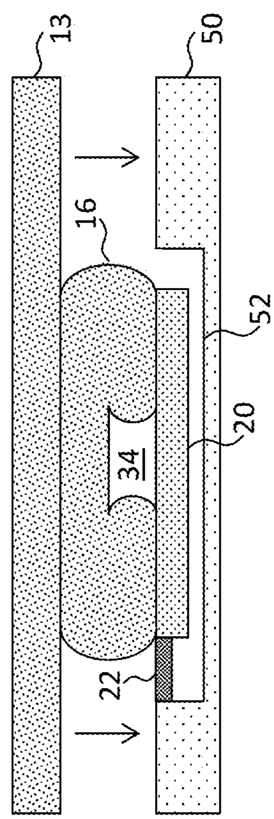


FIG. 20C

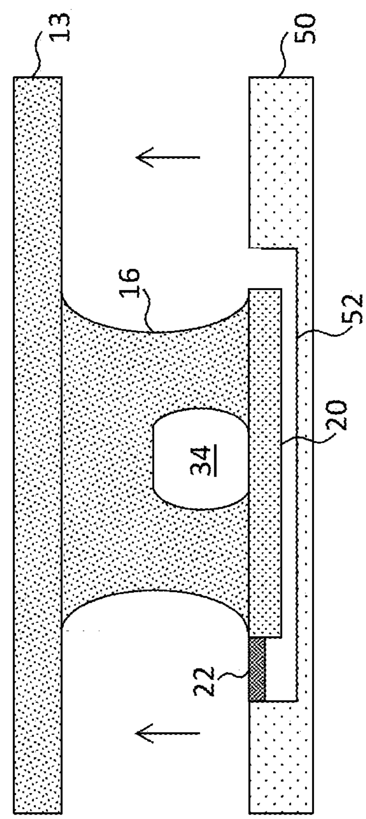


FIG. 20D

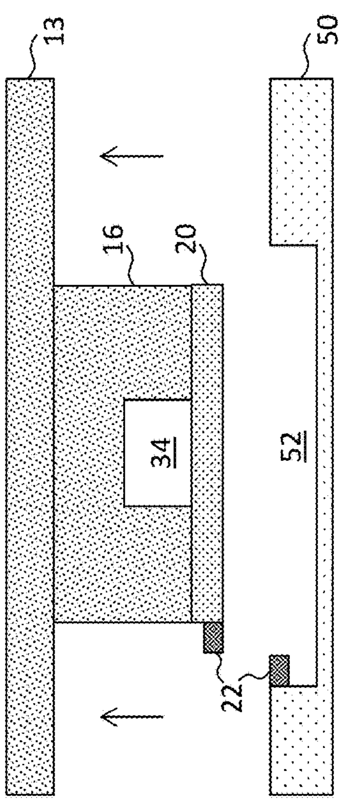


FIG. 20E

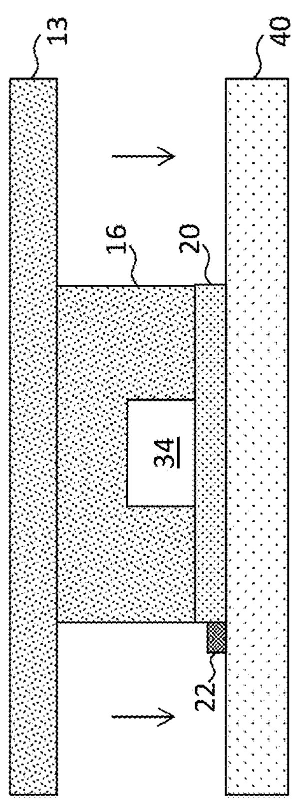
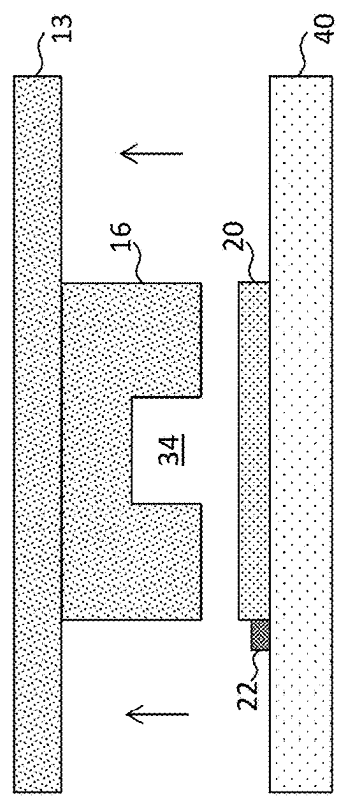


FIG. 20F



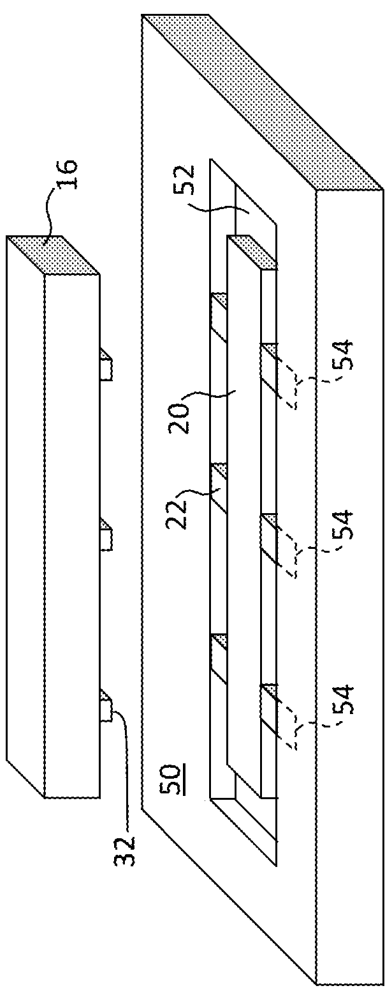


FIG. 21A

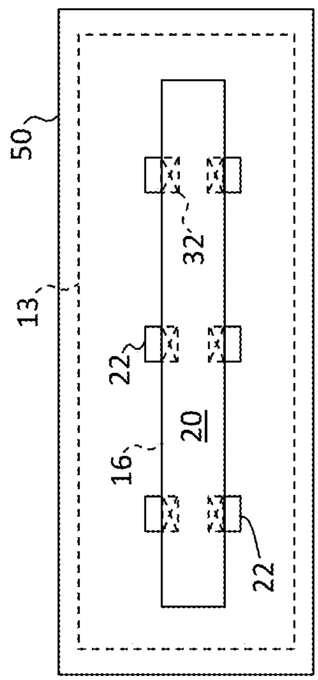


FIG. 21B

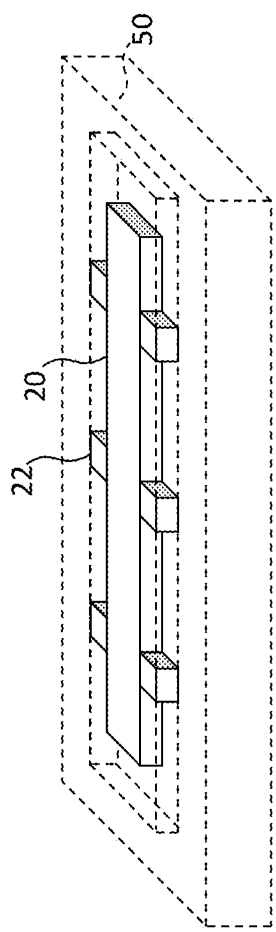


FIG. 21C

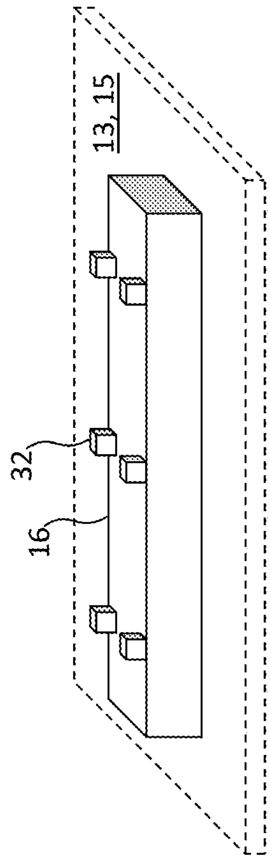


FIG. 21D

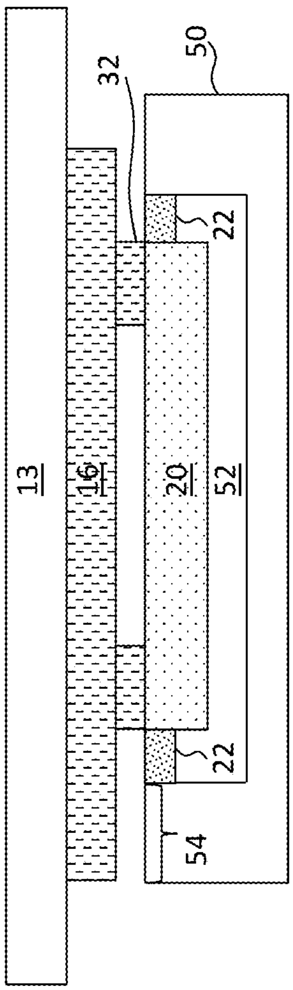


FIG. 21E

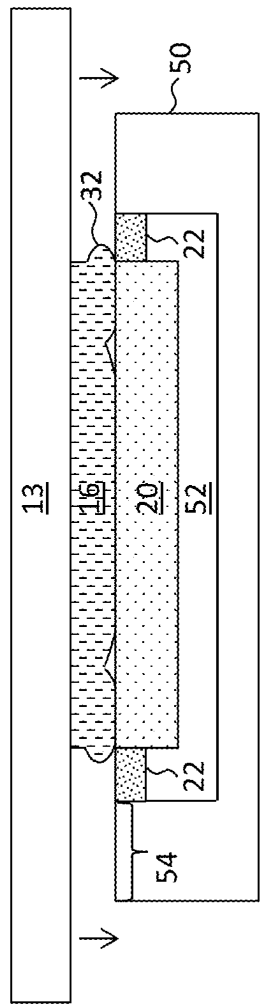


FIG. 21F

TRANSFER PRINTING STAMPS AND METHODS OF STAMP DELAMINATION

CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation-in-part of U.S. patent application Ser. No. 17/886,985, filed Aug. 12, 2022, entitled Transfer Printing Stamps with Multiple Delamination Fronts, which claims priority to U.S. Provisional Application No. 63/233,946, filed Aug. 17, 2021, entitled Transfer Printing Stamps and Methods of Stamp Delamination. This application also claims priority to U.S. Provisional Application No. 63/414,985, filed Oct. 11, 2022, entitled Transfer Printing Stamps and Methods of Stamp Delamination. The disclosures of each of the above-referenced applications are incorporated by reference herein in their entireties.

TECHNICAL FIELD

The present disclosure relates to stamps used in micro-transfer printing.

BACKGROUND

Conventional methods for applying integrated circuits to a destination substrate, such as pick-and-place, are limited to relatively large devices, for example having a dimension of a millimeter or more. It is often difficult to pick up and place ultra-thin, fragile, or small micro-devices using such conventional technologies. More recently, micro-transfer printing methods have been developed that permit the selection and application of these ultra-thin, fragile, or small micro-devices without causing damage to the micro-devices themselves.

Micro-transfer-printing enables deterministically removing arrays of micro-scale, high-performance micro-devices from a native source wafer, typically a semiconductor wafer on which the micro-devices are constructed and assembling and integrating the micro-devices onto non-native target (destination) substrates. Embodiments of micro-transfer-printing processes leverage engineered elastomer stamps coupled with high-precision motion-controlled print-heads to selectively pick-up and print large arrays of micro-scale devices from a source native wafer onto non-native target substrates.

Adhesion between an elastomer transfer device (e.g., stamp) and a printable element can be selectively tuned by varying the speed of the print-head on which the stamp is mounted. This rate-dependent adhesion is a consequence of the viscoelastic nature of the elastomer used to construct the stamp. When the stamp is moved quickly away from a bonded interface, the adhesion is large enough to "pick" the printable elements away from their native substrates, and conversely, when the stamp is moved slowly away from a bonded interface the adhesion is low enough to "let go" or "print" the element onto a foreign, non-native surface. This process may be performed in massively parallel operations in which the stamps can transfer, for example, hundreds to thousands of discrete structures in a single pick-up and print operation. Element printing can be enhanced by using shear offset between the stamp and the target substrate, for example as described in U.S. Pat. No. 8,506,867, whose contents are incorporated by reference herein.

Micro-structured stamps may be used to pick up micro-devices from a source wafer, transport the micro-devices to the target substrate, and print the micro-devices onto the target substrate. The transfer device (e.g., micro-structured stamp) can be made using various materials. Posts on the transfer device can be constructed to pick up material from a pick-able object and then print the material to the target substrate. The posts can be generated in an array fashion and can have a range of heights depending on the size of the printable material. Embodiments of micro-transfer printing stamps are described, for example, in U.S. Pat. Nos. 8,506,867, 7,943,491, 9,412,727, 7,195,733 and 9,704,821.

Micro-transfer printing enables parallel assembly of high-performance semiconductor micro-devices onto virtually any substrate material, including glass, plastics, metals, or semiconductors. The substrates may be flexible, thereby permitting the production of flexible systems. Flexible substrates may be integrated in a large number of configurations, including configurations not possible with brittle silicon-based electronic micro-micro-devices. Additionally, plastic substrates, for example, are mechanically rugged and may be used to provide electronic, opto-electronic, or photonic systems that are less susceptible to damage or performance degradation caused by mechanical stress. Moreover, micro-transfer printing techniques can print semiconductor micro-devices at temperatures compatible with assembly on plastic polymer substrates. Thus, these materials may be used to fabricate electronic, opto-electronic, or photonic systems by continuous, high-speed, printing techniques capable of disposing electronic, opto-electronic, or photonic micro-devices over large substrate areas at low cost (e.g., roll-to-roll manufacturing).

In some applications, in particular photonic or opto-electronic systems, alignment between printed micro-devices on a target substrate or between a printed micro-device and a structure on a target substrate is important. Moreover, it is important to print with a high yield to reduce manufacturing costs. There is a need, therefore, for stamps having an improved accuracy and yield in printing micro-devices on a target substrate.

SUMMARY

The present disclosure provides, inter alia, structures and methods that enable micro-transfer printing for micro-devices (e.g., a component) provided on a source wafer (e.g., a micro-device source wafer or a component source wafer). (As used herein, the terms micro-devices and components can be used interchangeably.) The micro-devices on the source wafer are contacted by a stamp to adhere the micro-devices to the stamp and release them from the source wafer. The micro-devices are then pressed against a target (or destination) substrate to adhere the micro-devices to the target substrate. The stamp is moved away from the target substrate, leaving the micro-devices on the target substrate. In some embodiments, an adhesive layer is disposed on the target substrate to enhance adhesion between the micro-devices and the target substrate. In some embodiments, no adhesive layer is disposed on the target substrate and the micro-devices are adhered directly to the target substrate. The present disclosure provides, among other things, stamps used for micro-transfer printing that have an improved accuracy and yield in printing micro-devices to a desired location on a non-native target substrate with or without an adhesive layer disposed on the target substrate.

According to embodiments of the present disclosure, a stamp for micro-transfer printing comprises a support having a support surface and posts disposed on the support surface, each of the posts comprising a distal end extending away from the support, the post having a post surface on the

distal end. The posts can be compressible and can return to their former shape after compression (or tension) is removed, e.g., the posts can exhibit elastic deformation. The post surface can be a structured surface comprising spatially separated ridges that extend in a ridge direction entirely across the post surface. The ridges can be separated by grooves that extend in the ridge direction entirely across the post surface [e.g., wherein area of the ridges is greater than area of the grooves (e.g., at least twice, at least four times, at least six times, or at least eight times greater)]. The grooves can have a rectangular cross section in a direction that is orthogonal to the ridge direction and to the support surface. The grooves can have a triangular cross section in a direction that is orthogonal to the ridge direction and to the support surface. The ridges can have a rectangular or trapezoidal cross section in a direction that is orthogonal to the ridge direction and to the support surface. The ridges can have a triangular cross section in a direction that is orthogonal to the ridge direction and to the support surface. Each of the ridges can have a same shape, some of the ridges can have a shape different from others of the ridges, or a surface of the ridges can have a rectangular shape or forms a line. In some embodiments, the ridges have a first end and an opposing second end in a direction that is orthogonal to the ridge direction and parallel to the support surface, and the first end has a length that is different from a length of the second end.

According to embodiments of the present disclosure, the support or a layer of the support and the posts can comprise polydimethylsiloxane. At least a portion of the support and the posts can be a common structure (e.g., formed in a single molding step).

According to embodiments of the present disclosure, a stamp for micro-transfer printing can comprise a support having a support surface and posts disposed on the support surface. Each of the posts can comprise a distal end extending away from the support and a post surface on the distal end. A proximal end of the post can be in contact with or supported by the support. The post surface can be a surface structured such that, when the post surface is being separated from a component temporarily adhered to the surface, multiple delamination fronts are formed at the post surface. The post surface can be structured such that the multiple delamination fronts are formed when separation is performed while the component is at least partially in contact with a target surface of a target substrate. The post surface can be structured such that the multiple delamination fronts are formed when the support is moved at least partially in a horizontal direction.

According to embodiments of the present disclosure, a stamp for micro-transfer printing comprises a support having a support surface and posts disposed on the support surface. Each of the posts can comprise a distal end extending away from the support and a post surface on the distal end. The post surface can be non-rectangular and can have opposing edges with different lengths. In some embodiments, the post surface is triangular or trapezoidal or has an edge that is triangular or trapezoidal.

According to embodiments of the present disclosure, a stamp for micro-transfer printing comprises a support having a support surface and posts disposed on the support surface. Each of the posts can comprise a distal end extending away from the support and a post surface on the distal end. The post surface can have a first edge and a second edge and the first edge can be longer than the opposing second edge or point (e.g., the post surface has a triangular, trapezoidal, or house-shaped pentagonal shape). The post surface can be a structured surface comprising spatially separated ridges that extend in a ridge direction entirely across the post surface.

According to embodiments of the present disclosure, a method of micro-transfer printing comprises providing a stamp, a source wafer comprising components (e.g., micro-devices) disposed in an arrangement corresponding to an arrangement of the posts, and a target substrate, contacting the posts to the micro-devices, removing the components from the source wafer, and contacting the components to a substrate surface of the target substrate. Contacting the components to the substrate surface can comprise moving the components toward and in contact with the target substrate, moving the components in a direction parallel to the substrate surface, and moving the stamp away from the target substrate. The direction parallel to the substrate surface can be orthogonal or diagonal to the ridge direction.

A method of micro-transfer printing can comprise providing a stamp comprising posts, components temporarily adhered to the posts, and a target substrate, and separating the stamp from the components to print the components to the target substrate. Separating the stamp can comprise forming multiple delamination fronts for each of the posts. Contact surfaces of the posts that temporarily adheres the components (e.g., post surfaces) can be structured surfaces comprising spatially separated ridges. Separating the stamp can comprises moving the stamp horizontally relative to the target substrate (e.g., shearing the stamp from the components), moving the stamp vertically, or both.

Methods of the present disclosure can comprise providing a motion-control platform attached to the stamp for controlling the stamp. Contacting the posts to the components, removing the components from the source wafer, and contacting the components to the substrate surface can be performed using the motion-control platform.

Methods of the present disclosure can comprise providing a first stamp and a first side of a micro-device temporarily adhered to each of the posts of the first stamp, providing a second stamp, the second stamp comprising a support having a support surface and posts disposed on the support surface, each of the posts comprising a distal end extending away from the support, the post having a post surface on the distal end, providing a motion-control platform attached to the first stamp or the second stamp, and using the motion-control platform to contact and adhere the posts of the second stamp to a second side of the micro-devices opposite the first side and remove the micro-devices from the first stamp. Removing the micro-devices from the first stamp can comprise moving the first stamp relative to the second stamp in a direction at least partially orthogonal to the ridge direction, at least partially orthogonal to the delamination fronts, or at least partially in a direction orthogonal to one of the opposing sides. The second stamp can be a stamp having a structured distal end and the second stamp can be rotated with respect to the first stamp. The direction parallel to the substrate surface can be orthogonal or diagonal to the ridge direction of the first stamp.

Methods of the present disclosure can comprise providing a first stamp comprising posts, components temporarily adhered to the posts of the first stamp, and a second stamp comprising posts, and separating the first stamp from the components to transfer the components to the posts of the second stamp, wherein separating the stamp comprises forming multiple delamination fronts for each of the posts of the first stamp. Contact surfaces of the posts of the first stamp that temporarily adheres the components (e.g., post surfaces) can be structured surfaces comprising spatially separated ridges. Separating the stamp can comprise moving the first stamp horizontally relative to the second stamp (e.g., shearing the first stamp from the components). The posts of the second stamp can have unstructured (e.g., flat) surfaces or can have structured surface having spatially separated ridges aligned in a different direction from spatially separated ridges comprised in structure surfaces of the posts of the first stamp (e.g., aligned orthogonally to each other). Methods of the present disclosure can comprise printing the components to a target substrate from the second stamp.

Methods of the present disclosure can comprise providing a stamp comprising a support having a support surface and posts disposed on the support surface, each of the posts comprising a distal end extending away from the support, the post having a post surface on the distal end, the post surface having edges and corners, and a micro-device temporarily adhered to each post surface, providing a target substrate having a target substrate surface, providing a motion-control platform attached to the stamp, and using the motion-control platform to contact the micro-devices to the target substrate surface. Contacting the micro-devices to the target substrate surface can comprise moving the micro-devices toward and in contact with the target substrate surface, moving the micro-devices in a direction parallel to the target substrate surface at least partially in a direction non-parallel to one of the edges, and moving the stamp away from the target substrate. The post surface can be a structured surface comprising spatially separated ridges that extend in a ridge direction entirely across the post surface and the direction parallel to the substrate surface can be orthogonal, diagonal, or diagonally at 45 degrees with respect to the ridge direction.

Methods of the present disclosure can comprise providing a stamp comprising posts, components temporarily adhered to the posts of the stamp, and a target substrate, and separating the stamp from the components to print the components to the target substrate. The posts can have a post surface to which the components are temporarily adhered. The post surface can comprise edges and corners and separating the stamp can comprise moving the stamp in a direction non-parallel to one of the edges.

Methods of the present disclosure can comprise providing a first stamp comprising posts, providing components temporarily adhered to the posts of the first stamp, providing a second stamp comprising posts, and separating the first stamp from the components to transfer the components to the posts of the second stamp, wherein the posts of the first stamp have a post surface to which the components are temporarily adhered, the post surface comprises edges and corners, and separating the first stamp comprises moving the first stamp in a direction non-parallel to one of the edges.

According to some embodiments of the present disclosure, a stamp for micro-transfer printing comprises a support having a support surface and posts disposed on the support surface. Each post can comprise a proximal end in contact with the support and a distal end extending away from the support. The post can have a post surface on the distal end that has a first edge having a first length and a second edge opposing the first edge having a second length less than the first length. The second length can be a point or multiple points, the post surface can form a triangle or a trapezoid, and the post surface can form a quadrilateral, a five-sided area, or a six-sided area.

According to some embodiments of the present disclosure, a stamp for micro-transfer printing can comprise a support having a support surface and posts disposed on the support surface. Each post can comprise a proximal end in contact with the support and a distal end extending away from the support. The post can have a post surface on the distal end that is a structured surface comprising an array of sub-posts and the sub-posts cover no less than one half, no less than one third, no less than one quarter, no less than one fifth, or no less than one tenth of the post surface. The array of sub-posts can be a one-dimensional array or a two-dimensional array. The sub-posts can have a flat distal end.

According to embodiments of the present disclosure, a stamp for micro-transfer printing comprises a support having a support surface and posts disposed on the support surface. Each of the posts can comprise a distal end extending away from the support, the post having a post surface with a curved edge or a straight edge on the distal end. The curved edge can substantially form a portion of a circle or a semicircle.

According to embodiments of the present disclosure, a stamp for micro-transfer printing comprises a support having a support surface and posts disposed on the support surface. Each of the posts can comprise a distal end extending away from the support, a post surface on the distal end, and a hole extending to the post surface. The hole can be a blind hole that does not extend through the support. In some embodiments, a cutout extends from the hole to an exterior edge of the post and can extend only partially through the post. The cutout can be a channel or opening in the post. The cutout an extend from a post surface of the post, where the post surface is parallel to the substrate surface. In some embodiments, a cutout extends from the hole to an exterior edge, surface, or perimeter of the post. In some embodiments, at least a portion of the post surface is non-parallel to the support surface. In some embodiments, the cutout is disposed along a line intersecting a center of the hole. In some embodiments, the cutout is disposed along a line that does not intersect a center of the hole. In some embodiments, the cutout is disposed along a line tangent to the hole. In some embodiments, the cutout is disposed along a line parallel to and in contact with an edge of the hole.

The post can have a circular cross section except for the cutout. The hole can have a circular cross section except for the cutout. In some embodiments, the hole extends to the support surface, e.g., from the post surface. In some embodiments, the hole extends less than all of the way (e.g., less than entirely) to the support surface, e.g., from the post surface, for example no greater than halfway, no greater than one quarter of the way, or no greater than one tenth of the way. The hole can have a circular cross section and the post can have a polygonal cross section, e.g., a rectangular cross section. In some embodiments, the hole has a polygonal (e.g., rectangular or square) cross section and the post has a polygonal (e.g., rectangular or square) cross section.

The cutout can have a height greater than a width or a width greater than a height (where height is in a direction orthogonal to the support surface and width is parallel to the support surface). The post surface can be parallel to the support surface or can be non-parallel to the support surface, or only portions of the post surface can be parallel to the support surface. If one or more portions of the post surface are non-parallel to the support surface, the non-parallel portion(s) can form cutouts that extend to an edge of the post surface (e.g., to an edge perpendicular to the support surface). According to embodiments of the present disclosure, a method of micro-transfer printing comprises providing a stamp with a post with a cutout, providing a micro-device (e.g., a component) physically connected to a micro-device source wafer (e.g., a component source wafer) by a tether, pressing the post against the micro-device thereby compressing the post and open (or keeping open) the cutout, and removing the micro-device (e.g., component) from the source wafer (e.g., component source wafer). The step of removing can comprise pulling the support surface away from the micro-device (e.g., pulling apart the support surface from the micro-device) thereby tensioning the post and close the cutout (e.g., seal the hole) and remove the micro-device from the micro-device source wafer, thereby breaking or separating the tether. Compressing the post can temporarily reduce the volume of the hole. Tensioning (e.g., stretching, elongating, or pulling on) the post can temporarily increase the volume of the hole, reducing the air pressure in the hole. Thus, in some embodiments, the air pressure within the hole is greater when the post is in compression and smaller when the post is in tension.

Embodiments can comprise providing a target substrate, contacting the micro-device to the target substrate, and moving the stamp at least horizontally with respect to the target substrate. In some embodiments, the direction of motion opens the cutout or increases the area of the cutout. Some embodiments can comprise providing a target substrate, pressing the micro-device to the target substrate, and removing the stamp from the micro-device, thereby printing the micro-device to the target substrate. Pressing the micro-device to the target substrate can comprise moving the micro-device horizontally (e.g., parallel) with respect to a surface of the target substrate against which the micro-device is pressed. In some embodiments, the post is pressed against the micro-device on the micro-device source wafer with a first force and the post is pressed against the micro-device on the target substrate with a second force less than the first force. In some such embodiments, pressing the stamp post against the micro-device on the micro-device wafer reduces the volume of the hole more than pressing the stamp post against the micro-device on the target substrate. In some embodiments, pressing the stamp post against the micro-device on the target substrate does not substantially compress the stamp post or substantially reduce the volume of the hole, at least in comparison to pressing the stamp post against the micro-device on the micro-device wafer. Thus, in embodiments, the air pressure in the hole is relatively less when the micro-device is removed from the micro-device source wafer and relatively greater when the stamp is removed from the micro-device.

In some embodiments, a method of printing a component comprises removing a component from a component source wafer with a stamp by simultaneously applying adhesion and suction to the component with a compressible post of the stamp while separating the stamp and the component source wafer from each other. In some embodiments, the post is elastomeric, compressible, or exhibits elastic deformation.

In some embodiments, the adhesion is a rate-dependent adhesion.

In some embodiments, the component is initially physically connected to the component source wafer and the removing comprises breaking or fracturing the tether while the stamp and the component source wafer are relatively separated from each other.

In some embodiments, removing comprises contacting the post to the component by pressing the post against the component thereby compressing the post and tensioning the post while separating the stamp and the component source wafer such that the post applies the adhesion and the suction to the component. In some embodiments, the adhesion is insufficient to break or separate the tether but the adhesion and the suction together are sufficient to break or separate the tether.

In some embodiments, the post comprises a blind hole (e.g., does not extend entirely through the stamp) and the suction is applied to the component by (i) contacting the blind hole to component to seal the blind hole and (ii) placing the blind hole under tension. Some embodiments comprise printing the component to a target substrate, and the printing comprises releasing the suction. Some embodiments comprise applying horizontal (e.g., and vertical) motion between the stamp and the component source wafer, and the horizontal motion causes the suction to be released. A system for micro-transfer printing can comprise a component source wafer comprising a sacrificial portion, a micro-device disposed completely and directly over the sacrificial portion, tethers connecting the micro-device to one or more anchor portions of the micro-device source wafer at tether locations, and a stamp comprising a stamp support having a support surface and one or more posts disposed on the support surface. The distal end of the post can have a structured three-dimensional surface comprising sub-posts that extend away from the support surface at sub-post locations. The sub-post locations can be disposed adjacent to the tether locations when the sub-posts are in contact with the micro-device when the micro-device is disposed on the micro-device source wafer.

In some embodiments, the component is native to the component source wafer.

According to some embodiments of the present disclosure, a system for micro-transfer printing comprises a component attached to a component source wafer exclusively by tethers and a stamp comprising a stamp post comprising sub-posts. Each of the sub-posts can be disposed on a distal end of the stamp post to correspond to one of the tethers for one of the one or more components. Some embodiments comprise a plurality of components each attached to the component source wafer exclusively by tethers and the stamp comprises a plurality of stamp posts each comprising sub-posts disposed on a distal end of the stamp post to correspond to one of the tethers for one of the plurality of components.

According to some embodiments, the component is native to the component source wafer. In some embodiments, the stamp posts are elastomeric. In some embodiments, the sub-posts are compressible and portions of the distal end of the post between the sub-posts are in a common plane when the sub-posts are under mechanical pressure. In some embodiments, the micro-posts are compressible and portions of the distal end of the post between the sub-posts and the sub-posts are in a common plane when the sub-posts are under mechanical pressure. The sub-posts can be pyramidal, cylindrical, cubic, or have rectangular or polygonal faces and, in some embodiments, can have holes with or without cutouts.

According to some embodiments of the present disclosure, a stamp for micro-transfer printing comprises a support having a support surface and posts disposed on the support surface, each post comprising a distal end extending away from the support, the post having a post surface on the distal end. The post surface can have a first edge and a second edge and a third edge both opposing the first edge. The first edge can have a first length, the second edge can have a second length, the third edge can have a third length, and a total of the second length and the third length can be less than the first length. In some embodiments, the second edge is a point, the third edge is a point, or both the second edge and the third edge are each a point. In some embodiments, the second edge and the third edge are coplanar with a line parallel to the first edge.

In some embodiments, the post surface further has a fourth edge that has a fourth length, the fourth edge is also opposing the first edge, and a total of the second length, the third length, and the fourth length is less than the first length. In some embodiments, the fourth edge is a point.

According to some embodiments of the present disclosure, a stamp for micro-transfer printing comprises a support having a support surface and posts disposed on the support surface. Each post can have a distal end extending away from the support, the post having a post surface on the distal end. The post surface can be a structured surface comprising an array of sub-posts and the sub-posts can cover no less than one tenth (e.g., no less than one fifth, no less than one quarter, no less than one third, or no less than one half) of the post surface. The array of sub-posts can be a one-dimensional array. The array of sub-posts can be a two-dimensional array. In some embodiments, the sub-posts have a flat distal end.

Embodiments of the present disclosure provide stamps with improved print yields and accuracy.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, aspects, features, and advantages of the present disclosure will become more apparent and better understood by referring to the following description taken in conjunction with the accompanying drawings, in which:

FIG. **1**A is a perspective of the bottom side of a micro-transfer printing stamp, FIG. **1**B is a bottom plan view of a micro-transfer printing stamp with a detail view of a micro-transfer printing stamp post surface, FIG. **1**C is a cross section taken along cross section line A of a micro-transfer printing stamp post of FIG. **1**B, and FIG. **1**D is a cross section taken along cross section line B of a micro-transfer printing stamp post of FIG. **1**B according to illustrative embodiments of the present disclosure;

FIG. **2** is a perspective of a micro-transfer printing stamp post and post surface according to illustrative embodiments of the present disclosure;

FIGS. **3**A and **3**B are cross sections of a micro-transfer printing stamp post and post surface according to illustrative embodiments of the present disclosure;

FIGS. **4**A-**4**F are successive cross sections of a method and structures for micro-transfer printing according to illustrative embodiments of the present disclosure, where FIG. **4**A shows a printing system with a motion platform and stamp with stamp posts in contact with micro-devices on a source wafer with a detail of a stamp post and micro-device, FIG. **4**B shows micro-devices adhered to stamp posts removed from the source wafer, FIG. **4**C shows micro-devices adhered to stamp posts in contact with a target substrate, FIG. **4**D shows horizontal shear offset between the stamp and the target substrate, FIG. **4**E is a detail illustrating delamination of a single post of FIG. **4**D, FIG. **4**F shows the stamp removed from and the micro-devices adhered to the target substrate;

FIG. **5** is a flow diagram of micro-transfer printing from a source wafer to a target substrate according to illustrative embodiments of the present disclosure;

FIG. **6** is a cross section of a first stamp transferring micro-devices to a second stamp according to illustrative embodiments of the present disclosure;

FIG. **7** is a flow diagram of picking up micro-devices from a source wafer with a first stamp, transferring the micro-devices to a second stamp, and printing the micro-devices to a target substrate according to illustrative embodiments of the present disclosure;

FIG. **8**A is a perspective of a stamp with posts and FIGS. **8**B-**8**F are plan views of stamp posts having different post surface shapes with different-length opposing edges according to illustrative embodiments of the present disclosure;

FIG. **9**A is a plan view and FIG. **9**B is a corresponding cross section taken across cross section line A of a stamp post having ridges with different-length opposing sides according to illustrative embodiments of the present disclosure;

FIGS. **10**A-**10**C are plan views of stamp posts according to illustrative embodiments of the present disclosure;

FIG. **11** is a plan view of the distal end of a stamp post according to illustrative embodiments of the present disclosure;

FIG. **12**A is a perspective of a stamp post having a two-dimensional array of sub-posts and FIG. **12**B is a plan view of the distal end of a portion of the stamp post of FIG. **12**A, according to illustrative embodiments of the present disclosure;

FIG. **12**C is a plan views of distal ends of stamp posts having sub-posts with rectangular cross sections according to illustrative embodiments of the present disclosure;

FIGS. **13**-**15** are plan views of the distal end of a stamp post according to illustrative embodiments of the present disclosure;

FIG. **16**A is a perspective of a stamp with cylindrical posts and FIG. **16**B is a perspective of a stamp with semi-cylindrical posts, according to illustrative embodiments of the present disclosure;

FIG. **17**A is a perspective, FIG. **17**B is a cross section through the cutout of FIG. **17**A, FIG. **17**C is a top view, and FIG. **17**D is a cross section of a stamp comprising a cylindrical post with a hole and a cutout according to illustrative embodiments of the present disclosure;

FIG. **18**A is a perspective of a stamp comprising a cubic post with a hole according to illustrative embodiments of the present disclosure;

FIG. **18**B is a perspective of a stamp comprising a post with an angled post surface and a hole according to illustrative embodiments of the present disclosure;

FIGS. **18**C-**18**J are perspectives of stamp posts with a hole according to illustrative embodiments of the present disclosure;

FIG. **19** is a flow diagram of methods according to illustrative embodiments of the present disclosure;

FIGS. **20**A-**20**F are successive cross sections corresponding to the flow diagram of FIG. **19** according to illustrative embodiments of the present disclosure; and

FIG. **21**A is perspective of a system comprising a micro-device and stamp, FIG. **21**B is a bottom view of the system, FIG. **21**C is a perspective detail of the micro-device, FIG. **21**D is an inverted perspective detail of the stamp, FIG. **21**E is a cross section along the width of the system, and FIG. **21**F is a cross section along the width of the system under compression according to illustrative embodiments of the present disclosure.

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, or structurally similar elements. The figures are not drawn to scale since the variation in size of various elements in the Figures is too great to permit depiction to scale.

DETAILED DESCRIPTION OF CERTAIN EMBODIMENTS

The present disclosure provides, inter alia, structures and methods that enable micro-transfer printing for micro-devices (chiplets) provided on a source wafer. The terms "micro-device" and "chiplet" are used interchangeably and have the same meaning herein. Generally, the following description refers to printing "micro-devices" as an example of printing components, which can be micro-devices or can be not micro-devices, for example a mass of material (e.g., seed crystal or piezoelectric material) or a passive electronic component (e.g., jumper). The micro-devices are formed on the source wafer, released from the source wafer, contacted by a stamp to adhere the micro-devices to the stamp, removed from the source wafer, and pressed against a target (or destination) substrate to adhere the micro-devices to the target substrate. The stamp is then moved away from the target substrate, leaving the micro-devices adhered to the target substrate. The micro-devices can be disposed on the target substrate with improved accuracy and yield. In some embodiments, an adhesive layer is disposed on the target substrate to enhance adhesion between the micro-devices and the target substrate. In some embodiments, no adhesive layer is disposed on the target substrate and the micro-devices are adhered directly to the target substrate. The present disclosure provides, among other things, stamps used for micro-transfer printing that have an improved accuracy and yield in printing micro-devices to a desired location on a non-native target substrate with or without an adhesive layer disposed on the target substrate.

Materials used in micro-transfer printing stamps can comprise visco-elastic and elastomeric materials such as polydimethylsiloxane (PDMS). As shown in FIG. **1**A, a stamp **10** typically includes a rigid support **12** and, optionally, a body from which a post **16** (sometimes called a pillar) extends. Each post **16** is used to contact a single component **20** (e.g., micro-device **20**) (shown in FIG. **4**A, discussed below) or micro-structure such as a chiplet **20**, and each micro-device **20** is contacted by a single post **16** to perform a release and print of micro-device **20** from a source wafer **50** (shown in FIG. **4**A, discussed below) to a non-native target substrate **40** (shown in FIG. **4**C, discussed below). According to some embodiments, the optional body of stamp **10** comprises a mesa **14** or pedestal disposed on rigid support **12** and posts **16** extend from mesa **14**. In some embodiments, posts **16** extend directly from rigid support **12** or stamp **10** comprises multiple separate mesas **14** from each of which posts **16** extend. Rigid support **12** and any one or more mesas **14**, or stamp body, form a support **13** having a support surface **15** on which posts **16** are disposed and from which posts **16** extend. In some embodiments, support **13** does not comprise a rigid support **12**. As shown in FIGS. **1**B-**1**D, posts **16** comprise a proximal end in contact with support **13** and a distal end extending away from support **13** and support surface **15**. Post **16** has a post surface **17** on the distal end. According to some embodiments of the present disclosure and as discussed below with respect to FIGS. **6**A-**6**E, post **16** has a non-rectangular cross section parallel to support surface **15** and post surface **17** is non-structured and substantially planar.

According to some embodiments of the present disclosure and as discussed below with respect to FIGS. **8**A-**8**E, post **16** can have a non-rectangular cross section parallel to support surface **15** and post surface **17** is non-structured and substantially planar. According to some embodiments of the present disclosure and as illustrated in FIGS. **1**B and **1**C, post **16** can have a rectangular cross section parallel to support surface **15** and post surface **17** is non-planar and has a structured surface comprising spatially separated ridges **19** that extend in a ridge direction D entirely across post surface **17**. Post surface **17** has opposing sides or edges and ridges **19** extend from one side (or edge) of post surface **17** to an opposite side (or edge) of post surface **17**. For example, ridges **19** can be separated by grooves **18** that likewise extend entirely and all of the way across post surface **17** so that both ridges **19** and grooves **18** contact an edge or side of post **16** and post surface **17** at two or more spatially separate locations. Ridges **19** can each be a sub-post **32** extending from a distal end of post **16**. By extending entirely across post surface **17** is meant that post surface **17** has opposing sides or edges and ridges **19** extend from one side (or edge) of post surface **17** to an opposite side (or edge) of post surface **17**. For example, ridges **19** can be separated by grooves **18** that likewise extend entirely and all of the way across post surface **17** so that both ridges **19** and grooves **18** contact an edge or side of post **16** and post surface **17** at two or more spatially separate locations. For example, if post **16** has a rectangular cross section parallel to support surface **15** with parallel opposing sides, ridges **19** extend from one side to the parallel opposing side of post surface **17**. However, posts **16** are not limited to structures with rectangular cross sections and can have, for example, a quadrilateral or other polygonal, curved, or irregular cross section. Ridges **19** can, but do not necessarily, extend substantially or entirely (e.g., all the way) from one side (or edge) of post surface **17** to another, different side (or edge) of post surface **17**, for example a different side parallel to the one side. By substantially is meant that ridges **19** extend far enough across post surface **17** so that each ridge **19** at the same time can effectively delaminate from a common chiplet **20** when micro-transfer printing chiplet **20** to a target substrate **40** by moving stamp **10** in a horizontal direction **60** parallel to a surface of chiplet **20** or parallel to a surface of target substrate **40** (shown in more detail in, e.g., FIGS. **4**A-**4**E discussed below). As shown in FIGS. **1**B and **1**D, ridges **19** are continuous and contiguous and each form a single sub-post **32**. In some embodiments, and as discussed further below, ridges **19** comprise multiple spatially separate sub-posts **32**.

FIG. **1**A is a perspective bottom view of stamp **10** having a rigid support **12** with a mesa **14** disposed on rigid support **12**. Rigid support **12** can comprise, for example glass. Posts **16** are disposed on mesa **14** and extend away from mesa **14** and rigid support **12**, for example in a direction orthogonal to a surface of mesa **14**. Mesa **14** (and optionally rigid support **12**, or vice versa) provides a support **13** having a support surface **15** on which posts **16** are disposed and from which posts **16** extend. Mesa **14** (if present) and posts **16** can comprise a common material, for example polydimethylsiloxane (PDMS), that has a greater coefficient of thermal expansion than rigid support **12**. At least a portion of support **13** (e.g., excluding rigid support **12**) and posts **16** can be a common structure (e.g., formed in a single molding step). In some embodiments, mesa **14** can comprise a different material or material with different component concentrations than posts **16** and a different, e.g., larger, coefficient of thermal expansion than posts **16**. FIG. **1**B is a bottom plan view of stamp **10** with posts **16** on mesa **14** and rigid support **12**. The FIG. **1**B inset illustrates a structured distal end of a post **16** with parallel ridges **19** spatially separated by grooves **18** extending in a ridge direction D across post surface **17**. The cross sections of FIGS. **1**C and **1**D taken across cross section lines A and B, respectively, of FIG. **1**B show post surface **17** at the distal end of post **16** with grooves **18** and ridges **19** both with rectangular cross sections taken in a direction orthogonal to ridge direction D and orthogonal to support surface **15**.

FIG. **2** is a perspective of the distal end of a post **16** with a post surface **17** structured with rectangular-cross-section ridges **19** and grooves **18**. Ridges **19** and grooves **18** extending in ridge direction D are arbitrarily labeled as a direction or dimension Y and the direction or dimension orthogonal to ridge direction D is consequently labeled X. Directions X and Y define a horizontal plane and the vertical direction Z is the direction in which posts **16** extend from support surface **15**. FIGS. **3**A and **3**B illustrate embodiments of the present disclosure in which ridges **19** have a trapezoidal cross section and grooves **18** have a triangular cross section (as shown in FIG. **3**A) or ridges **19** have a triangular cross section and grooves **18** have a trapezoidal cross section (as shown in FIG. **3**B) cross section spatially separated by grooves **18** with a triangular cross section in a direction orthogonal to ridge direction D and orthogonal to support surface **15**. In general, there is no limitation to the cross sectional shapes of ridges **19** or grooves **18**. Nor is there a limitation on the shape of ridges **19** on the distal end of post **16**. For example, a surface of ridges **19** can have a rectangular shape (e.g., as in FIGS. **2** and **3**A) or can form a line (e.g., as in FIG. **3**B).

According to some embodiments, all of ridges **19** or grooves **18** have a same shape. In some embodiments, some of ridges **19** or grooves **18** can have different shapes. According to some embodiments, and as discussed further below with respect to FIGS. **8**A-**8**E, ridges **19** can have first and second sides (edges) **80**, **82** that extend in a direction parallel to ridge direction D, are opposed (e.g., are on opposite sides of post **16** or ridge **19**) in a direction orthogonal to ridge direction D and orthogonal to the direction of first and second sides **80**, **82** (e.g., in direction X), and first edge **80** has a length that is different from a length of second edge **82**. For example, a distal surface of post **16** can comprise one or more trapezoidal or triangular cross sections. According to some embodiments, each ridge **19** or post **16** has a post surface **17** with a shape comprising any one of the shapes illustrated in FIGS. **8**A-**8**E, for example a trapezoidal or triangular cross section or has a trailing second edge **82** that is shorter than a leading first edge **80** or comes to one or more points on a side of post **16** that is opposite leading first edge **80**. According to embodiments, second edge **82** can be one or more points. According to embodiments, one or more ridges **19** or posts **16** has a post surface **17** that is a quadrilateral, a five-sided shape or area, or a six-sided shape or area, for example a rectangle with a trapezoid or a triangle on one edge of the rectangle. Ridges **19** can have the same shape or some ridges **19** in a post **16** can have a different shape **19** in the post **19**.

According to embodiments of the present disclosure and as illustrated in the successive cross sections of FIGS. **4**A-**4**F and the flow diagram of FIG. **5**, stamps **10** can be used for micro-transfer printing micro-devices **20** (e.g., micro-modules, chiplets, or micro-components) from a source wafer **50** to a target substrate **40** (a destination substrate). A motion-control platform **70** is provided in step **100**, a chiplet source wafer (e.g., a source substrate) is provided in step **110**, a stamp **10** is provided in step **120**, and a target substrate **40** is provided in step **130**. As shown in FIG. **4**A, chiplet source wafer **50** can comprise a sacrificial layer comprising sacrificial portions **52** separated by anchors **54** attached to chiplets **20** by chiplet tethers **22**. Chiplets **20** are disposed directly and entirely over sacrificial portions **52**. Chiplets **20** are released from source wafer **50** by etching sacrificial portions **52** to form gaps between chiplets **20** and source wafer **50**. Stamp **10** comprising rigid substrate **12**, optional mesa **14**, and posts **16** with a structured post surface **17** comprising ridges **19** spatially separated by grooves **18** is moved by motion-control platform **70** into position in a vertical direction **65** toward and in alignment with source wafer **50** so that the distal end of posts **16** and at least a portion of ridges **19** contact chiplets **20**, temporarily adhering chiplets **20** to posts **16**, in step **140** and as shown in FIG. **4**A. Motion-control platform **70** then removes stamp **10** from source wafer **50** with chiplets **20** adhered to posts **16** in step **150** by moving stamp **10** and chiplets adhered to stamp **10** away from source wafer **50** as shown in FIG. **4**B, fracturing or separating chiplet tethers **22** and detaching chiplets **20** from source wafer **50**. The stamp motion can be in a vertical direction **65** or a combination vertical **65** and horizontal **60** direction either at the same time or sequentially.

In step **160**, motion-control platform **70** moves stamp **10** vertically in direction **65** toward target substrate **40** so that chiplets **20** adhered to posts **16** contact target substrate A layer **42** of adhesive can, but is not necessarily, coated in optional step **135** on target substrate **40** before chiplets **20** are contacted to target substrate **40** (or to adhesive layer **42** if present) as shown in FIG. **4**C. Motion-control platform **70** can also move stamp in a horizontal direction **60** (direction X or direction Y or a combination of directions X and Y) parallel to a surface of target substrate **40** in step **160**. As used herein, a stamp movement is a relative movement of stamp **10** with respect to a substrate (e.g., target substrate **40**) and in some embodiments, the substrate is moved instead of stamp **10** in a direction opposite to the stamp movement. Horizontal can mean substantially horizontal, for example within the tolerance of mechanical motion-control platform **70**, for example no greater than ten, no greater than five, no greater than two, or no greater than one degrees of a motion parallel to target substrate **40** surface (an in-plane motion). Horizontal motion can be at any effective rate, for example motion at a rate of 1 mm/s or more. Horizontal motion can be a distance of no less than one, five, ten, twenty, fifty microns, or no greater than one hundred microns.

In step **170** and as shown in FIG. **4**D, chiplets **20** adhered to target substrate **40** (and optionally adhesive layer **42**) are removed from stamp posts **16**. Motion-control platform **70** moves stamp **10** in a horizontal direction **60** parallel to a surface of target substrate **40** and, at the same time, or subsequently, moves stamp **10** in a vertical direction **65** away from target substrate **40**. Horizontal motion **60** is at least partially orthogonal to ridge direction D so that the stress of relative horizontal motion **60** between chiplets **20** (adhered to target substrate **40** or adhesive layer **42**) and posts **16** causes delamination between ridges **19** on the distal end of posts **16**, for example on the trailing edge of posts **16** with respect to the relative stamp **10** motion as shown in FIG. **4**D and the detail of FIG. **4**E, separating posts **16** from chiplets **20** and leaving chiplets **20** disposed on target substrate **40**, as shown in FIG. **4**F. Stamp **10** horizontal and vertical movement in steps **160** and **170** can be, but is not necessarily, continuous and can be separate or combined motions. Stamp **10** horizontal and vertical movement in step **170** can be continuous or separate motions and can be combined so that stamp **10** moves both horizontally along and vertically away from target substrate surface at the same time.

According to embodiments of the present disclosure, the presence of multiple ridges **19** on the distal end of posts **16** causes multiple delamination fronts **30** to form, e.g., one delamination front **30** for each ridge **19**, decreasing the adhesion between chiplets **20** and the distal end of posts **16**. A delamination front **30** is a line separating a portion of post **16** (or ridge **19**) in contact with chiplet **20** from a portion of post **16** (or ridge **19**) that is not in contact with and is separated from chiplet **20** at a given time. Local delamination between post **16** or ridge **19** and chiplet **20** progresses over time along the surface of chiplet **20** as ridge **19** (and post **16**) is peeled from chiplet **20** in a direction substantially parallel to horizontal motion **60** so that delamination front **30** progresses from a starting point or edge **82** of post **16** or ridge **19** and proceeds along a surface of post **16** or ridge **19** until post **16** or ridge **19** is completely separated from chiplet **20**. Multiple delamination fronts **30** reduce the adhesion between chiplets **20** and the distal end of posts **16** relative to a non-structured post surface **17**, thereby increasing the likelihood that chiplet **20** will adhere to target substrate **40** or adhesive layer **42** rather than remaining attached to stamp **10** (improving print yields) and reducing the amount of shear offset experienced or needed by chiplet **20** (e.g., the distance chiplet **20** moves with respect to target substrate **40**), thereby improving print accuracy. Grooves **18** can be narrower than ridges **19** in a direction orthogonal to ridge direction D. In some embodiments, the area of ridges **19** is greater than the area of grooves **18** (for example much greater, e.g., twice, four times, six time, eight times greater, or more). Consequently, initial adhesion between chiplets **20** and posts **16** when detaching (picking) chiplets **20** from source wafer **50** is not greatly reduced (since the area of ridges **19** can be only slightly less than the area of post surface **17**) and print accuracy and yield are improved.

Thus, according to embodiments of the present disclosure, a stamp **10** for micro-transfer printing can comprise a support **13** having a support surface **15** and posts **16** disposed on support surface **15** (e.g., as shown in FIGS. **1**C, **1**D, **3**A, and **3**B). Each post **16** comprises a proximal end in contact with support **13** and a distal end extending away from support **13** and support surface **15**. The distal end of post **16** can comprise a post surface **17**. Post surface **17** can be a structured surface operable to form multiple delamination fronts **30** when (i) a first side of a micro-device **20** (e.g., chiplet **20**) is in contact with at least a portion of post surface **17**, (ii) a second side of the micro-device **20** (e.g., chiplet **20**) opposed to the first side is at least partially in contact with a target surface of a target substrate **40** (or a layer such as adhesive layer **42** disposed on target substrate **40**) or another structure having a target surface, and (iii) support **13** is moved at least partially in a horizontal direction **60** parallel to the target surface. The direction of horizontal motion **60** can be orthogonal to a direction of delamination fronts **30** and in a direction of the propagation of delamination fronts **30**. The delamination fronts **30** are between chiplets **20** and post surface **17** (a surface of ridges **19**). Delamination front **30** can extend in ridge direction D and propagate in a direction orthogonal to direction D or in the direction of horizontal motion **60**, as shown in FIG. **4**E. Delamination is similar to or the equivalent of peeling post **16** from chiplet **20**.

According to some embodiments of the present disclosure, micro-devices **20** (chiplets **20**) can be disposed in an upside-down configuration on target substrate **40** with respect to the configuration of chiplets **20** on source wafer **50**. Such an upside-down configuration can be implemented by picking up chiplets **20** from source wafer **50** with a first stamp **10**A, transferring chiplets **20** from first stamp **10**A to a second stamp **10**B, and printing chiplets **20** from second stamp **10**B to target substrate **40**. The transfer of chiplets from first stamp **10**A to second stamp **10**B is illustrated in the cross section of FIG. **6**. The relative motion between first stamp **10**A and second stamp **10**B can be in a direction that is not parallel to ridge direction D of first stamp **10**A, for example orthogonal or diagonal to ridge direction D of first stamp **10**A. Thus, adhesion between the first side of chiplets **20** and first stamp **10**A can be less than adhesion between the second side of chiplets **20** and second stamp **10**B, transferring chiplets **20** from first stamp **10**A to second stamp **10**B. According to some embodiments, the distal end (e.g., post surface **17**) of second stamp B is not structured. According to some embodiments, the distal end (e.g., post surface **17**) of second stamp B is structured and second stamp **10**B is similar or identical to first stamp **10**A, but is spatially rotated, for example orthogonally, about an axis perpendicular to support surface **15** with respect to first stamp **10**A. Moving first stamp **10**A in a direction orthogonal to ridge direction D of first stamp **10**A relative to second stamp **10**B can move second stamp **10**B relative to first stamp **10**A in a direction parallel to ridge direction D of second stamp **10**B. Thus, first stamp **10**A can experience multiple delamination fronts **30** (reducing adhesion between chiplet **20** and first stamp posts **16**) while second stamp **10**B does not experience multiple delamination fronts (and does not experience reduced adhesion between chiplet **20** and second stamp **10**B posts **16**), thus transferring chiplets **20** from first stamp **10**A to second stamp **10**B.

FIG. **7** is a flow diagram illustrating the process. According to embodiments of the present disclosure and as illustrated in the successive cross sections of FIGS. **4**A-**4**F, FIG. **6**, and the flow diagram of FIG. **7**, first and second stamps **10**A, **10**B can be used for micro-transfer printing chiplets (micro-devices) **20** from a source wafer **50** to a target substrate **40**. A motion-control platform **70** is provided in step **100**, a chiplet source wafer is provided in step **110**, a first stamp **10**A is provided in step **120**, a second stamp **10**B is provided in step **125**, and a target substrate **40** is provided in step **130**. Chiplet source wafer **50** can comprise a sacrificial layer comprising sacrificial portions **52** separated by anchors **54** attached to chiplets **20** by tethers **22**. Chiplets **20** are disposed directly and entirely over sacrificial portions **52**. Chiplets **20** are released from source wafer **50** by etching sacrificial portions **52** to form gaps. First stamp **10**A comprising rigid substrate **12**, optional mesa **14**, and posts **16** with a structured post surface **17** comprising ridges **19** spatially separated by grooves **18** is moved by motion-control platform **70** into position in a vertical direction **65** toward and in alignment with source wafer **50** so that the distal end of posts **16** and at least a portion of ridges **19** contact a first side of chiplets **20**, temporarily adhering chiplets **20** to posts **16**, in step **140** as shown in FIG. **4**A. Motion-control platform **70** then removes first stamp **10**A from source wafer **50** with chiplets **20** adhered to posts **16** in step **150** by moving first stamp **10**A and chiplets **20** adhered to first stamp **10**A in a vertical direction **65** away from source wafer **50** as shown in FIG. **4**B. The stamp motion can be only in a vertical direction **65** or a combination vertical **65** and horizontal **60** direction either at the same time or sequentially in one or more straight lines or curves.

In step **152**, motion-control platform **70** contacts posts **16** of second stamp **10**B to a second side of chiplets **20** opposite the first side. Motion-control platform **70** then horizontally moves first stamp **10**A relative to second stamp **10**B in a direction non-parallel (e.g., orthogonal or diagonal) to ridge direction D of first stamp **10**A, as shown in FIG. **6**. At the same time or subsequently, motion-control platform **70** can move first stamp **10**A relative to second stamp **10**B in a vertical direction **65** to separate first stamp from second stamp **10**B and chiplets **20** adhered to second stamp **10**B posts **16** in step **155**. Because the relative horizontal motion **60** between first stamp **10**A and second stamp **10**B can form multiple delamination fronts **30** between posts **16** of first stamp **10**A, reducing the adhesion of chiplets **20** to posts **16** of first stamp **10**A, chiplets **20** can preferentially adhere to posts **16** of second stamp **10**B. In some embodiments, second stamp **10**B is similar or identical to first stamp **10**A (e.g., has a post surface **17** comprising spatially separated ridges **19** that extend entirely across post surface **17**) and, during the transfer in step **152** and as illustrated in FIG. **6**, is rotated (e.g., orthogonally) with respect to first stamp **10**A so that, during step **152**, post surface **17** of posts **16** of first stamp **10**A experience multiple delamination fronts **30** and second post surface **17** of posts **16** of second stamp **10**B does not, or at least experiences fewer or smaller delamination fronts **30**, so that chiplets **20** can preferentially adhere to posts **16** of second stamp **10**B.

In step **160**, motion-control platform **70** moves second stamp **10**B vertically in direction **65** toward target substrate **40** so that chiplets **20** adhered to posts **16** of second stamp **10**B contact target substrate **40**. A layer **42** of adhesive can, but is not necessarily, coated in optional step **135** on target substrate **40** before chiplets **20** are contacted to target substrate **40** (or to adhesive layer **42** if present) as shown in FIG. **4**C. Motion-control platform **70** can also move second stamp **10**B in a horizontal direction **60** (direction X or direction Y or a combination of directions X and Y) parallel to a surface of target substrate **40** in step **160**. As used herein, a stamp movement is a relative movement of stamp **10** with respect to a substrate (e.g., target substrate **40** or another stamp) and in some embodiments, the substrate or other stamp is moved instead of stamp in a direction opposite to the direction of stamp movement.

In step **175** and as shown in FIG. **4**D, chiplets **20** adhered to target substrate **40** (and optionally adhesive layer **42**) are removed from stamp posts **16**. Motion-control platform **70** optionally moves second stamp **10**B in a horizontal direction **60** parallel to a surface of target substrate **40** and, at the same time, before, or after moves second stamp in a vertical direction **65** away from target substrate **40** leaving chiplets **20** adhered to target substrate **40**. If second stamp **10**B comprises spatially separated ridges **19** on the distal end of posts **16**, horizontal stamp motion **60** can be at least partially orthogonal to ridge direction D so that the stress of the relative horizontal motion **60** between chiplets (adhered to target substrate **40** or adhesive layer **42**) and posts **16** causes delamination between ridges **19** on the distal end of posts **16**, for example on the trailing edge of posts **16** with respect to the relative stamp **10** motion, separating chiplets **20** from posts **16**. If second stamp **10**B comprises multiple ridges **19** on the distal end of posts **16**, the presence of multiple ridges **19** causes multiple delamination fronts **30** to form, decreasing the adhesion between chiplets **20** and the distal end of posts **16**. Stamp **10** horizontal and vertical movements in steps **155**, **160**, and **175** can be, but are not necessarily, continuous and can be separate or combined motions in linear or curved directions. Stamp **10** horizontal and vertical movement in steps **155** and **175** can be continuous or separate, linear or curved, movements and can be combined so that stamp **10** moves both horizontally along and vertically away from target substrate **40** surface at the same time or separately. Similarly, step **160** can comprise both a vertical motion toward and a horizontal motion along the target substrate **40** surface in either continuous or separate movements.

Multiple delamination fronts **30** reduce the adhesion between chiplets **20** and the distal end of posts **16** relative to a non-structured post surface **17**, thereby increasing the likelihood that chiplet **20** will adhere to target substrate **40** or adhesive layer **42** (improving print yields) and reducing the amount of shear offset necessary to or experienced by chiplet **20** (e.g., the distance chiplet **20** moves with respect to target substrate **40**), thereby improving print accuracy. Grooves **18** can be narrower than ridges **19** in a direction orthogonal to ridge direction D. In some embodiments, the area of ridges **19** is greater than the area of grooves **18** (for example much greater, e.g., twice, four times, six time, eight times greater, or more). Consequently, adhesion between chiplets **20** and posts **16** is not greatly reduced (since the area of ridges **19** is only slightly less than the area of post surface **17**) and print accuracy and yield are improved.

Relative motion between a stamp **10** and target substrate **40** (or between a first stamp **10**A and second stamp **10**B) can form delamination fronts **30** along the trailing edge of each ridge **19**, as illustrated in FIGS. **4**D and **6**. If the relative motion is orthogonal to ridge direction D, the delamination fronts **30** will initially form along a line corresponding to an edge of ridges **19** in contact with chiplets **20**. However, if the relative motion has a diagonal component (e.g., neither parallel nor orthogonal to ridge direction D), the greatest trailing edge delamination stress can be at a corner of ridges **19**, for example on an edge or side of post **16**. Thus, delamination can begin at a corner of ridge **19**, theoretically at a point, that has less resistance to delamination because the adhesion at the corner of ridge **19** is much smaller and has a much smaller area (theoretically a point) than the adhesion along the edge of ridges **19** (theoretically a line). Thus, posts **16** can delaminate from chiplet **20** easier. Therefore, according to embodiments of the present disclosure, relative motion between a stamp **10** and chiplet **20** or target substrate can be in a diagonal, non-perpendicular, and non-parallel direction relative to ridge direction D of stamp **10**. The diagonal direction can be, but is not necessarily, at 45 degrees to the ridge direction D.

The use of a diagonal relative motion is generally useful when printing from a stamp **10** having posts **16** with cross sections parallel to support surface **15** that have straight edges and corners (e.g., a rectangular cross section) where the diagonal motion is diagonal with respect to an edge (or side) of post surface **17**. In such embodiments, posts **16** of stamps **10** are peeled from a corner of post **16** to detach chiplets **20** from posts **16**. Thus, according to embodiments of the present disclosure, a method of micro-transfer printing comprises providing a stamp **10** comprising a support **13** having a support surface **15** and posts **16** disposed on support surface **15**, providing a target substrate **40** having a target substrate surface, and providing a motion-control platform **70** attached to stamp **10**. Each post **16** comprises a proximal end in contact with support **13** and a distal end extending away from support **13**. Post **16** has a post surface **17** on the distal end of post **16** having edges and corners. A micro-device **20** (e.g., a chiplet **20**) is temporarily adhered to each post surface **17**. Motion-control platform **70** contacts micro-devices **20** to the target substrate surface. Contacting the micro-devices **20** to the target substrate surface comprises moving micro-devices **20** toward and in contact with the target substrate surface, moving micro-devices **20** in a direction parallel to the target substrate surface at least partially in a direction non-parallel to an edge (e.g., diagonally), and moving stamp **10** away from target substrate **40**. Moving stamp **10** away from target substrate **40** can be done at the same time, before, or after moving the micro-devices **20** in a direction parallel to the target substrate surface at least partially in a direction non-parallel to an edge. Where stamp **10** comprises posts **16** with structured post surface **17** having spatially separated ridges **19**, the direction parallel to the target substrate surface can be orthogonal, diagonal (e.g., at 45 degrees) to ridge direction D.

Separation between posts **16** and chiplets **20** is achieved with less force where delamination fronts **30** can propagate from a corner of post surface **17** or corners of ridges **19** by moving stamp **10** diagonally with respect to an edge of post surface **17** or ridge direction D compared to moving stamp **10** orthogonally to the edge of post surface **17** or ridge direction D. Similarly, separation between posts **16** and chiplets **20** is achieved with less force and in less distance where multiple delamination fronts **30** can propagate from an edge of post surface **17** or edges of ridges **19** by moving stamp **10** orthogonally with respect to an edge of post surface **17** or ridge direction D compared to moving stamp **10** vertically (in vertical direction **65**) away from target substrate **40**.

Embodiments of the present disclosure have been constructed and demonstrated to micro-transfer print chiplets **20** onto a substrate both without an adhesive layer and with an adhesive layer, for example a 30-60 nm adhesive layer on the substrate.

According to some embodiments, if post **16** has a cross section parallel to support surface **15** that has a point or a shorter trailing edge with respect to a direction of stamp movement, the point or shorter edge can delaminate easier, e.g., requiring less force, so that less force is needed to initially remove stamp **10** from chiplets **20**. As delamination proceeds across the post surface **17** of post **16**, the delamination front can increase in length from a smaller length (e.g., a point) to a larger length so that the delamination force is initially smaller but increases as the delamination front increases in length. In some embodiments, delamination fronts can grow smaller in length from a greater length to a smaller length (e.g., to a point) so that the delamination force is initially relatively greater but requires less force as delamination proceeds.

As shown in FIGS. **8**A-**8**E, posts **16** can have a cross section parallel to support surface **15** that has first and second edges (sides or ends) **80**, **82** in a horizontal stamp motion **60** (delamination direction **60**). First edge **80** is the leading edge **80** and second edge **82** is the trailing edge **82** of horizontal stamp motion **60** relative to a chiplet **20** or target substrate **40**. Thus, horizontal stamp motion **60** can be in a direction orthogonal to first edge **80** or second edge **82**. As shown, first edge **80** is longer than second edge **82**, where second edge **82** is the portion of the post edge farthest from the first edge. Second edge **82** can be a line segment, multiple line segments, a point, or multiple points. Thus, the trailing edge (second edge **82**) is shorter than the leading edge (first edge **80**) so that delamination occurs with less force. FIG. **8**A is a perspective illustrating stamp **10** with posts **16** that has a second edge **82** that is a point. FIG. **8**B is a plan view of a post **16** with post surface **17** having a shorter edge, FIG. **8**C has a point at trailing second edge **82** (corresponding to FIG. **8**A), FIG. **8**D is a plan view of a post **16** with a trailing second edge **82** forming a trapezoidal post surface **17**, FIG. **8**E is a plan view of a post **16** with a trailing second edge **82** forming a point of a triangular trapezoidal post surface **17**, and FIG. **8**F is a plan view of a post **16** with a trailing second edge **82** forming multiple points. The trailing point(s) or second edge **82** can concentrate stress from post **16** movement with respect to chiplets **20** that can more readily initiate delamination between post **16** and chiplet **20** when post **16** is moved in a horizontal direction **60** orthogonal to first edge or second edge **82**. When moved in direction D, stress at the trailing point(s) or second edge **82** can be reduced. Thus stamps **10** comprising posts **16** with trailing point or second edge **82** can require different amounts of force to detach from chiplets **20** when moved in different directions with respect to chiplets **20**, enabling chiplet **20** transfer from first stamp **10**A to second stamp **10**B, as shown in FIG. **6**. According to some embodiments, each post **16** can comprise a single ridge **19** that can extend in a length direction of ridge **19** (e.g., where length is greater than width), for example as shown in FIGS. **8**A-**8**F.

According to some embodiments, stamps **10** comprising posts **16** with one or multiple ridges **19** and grooves **18**, a trailing point, or second edge **82** can require less force to micro-transfer print to a target substrate **40**, enabling chiplet **20** transfer to target substrate **40** with higher accuracy and precision. According to some embodiments, such transfers can be done to a target substrate **40** with no optional adhesive layer **42** or with a thinner optional adhesive layer **42**. According to some embodiments, such transfers can be done to a target substrate **40** having reduced contact adhesion, for example reduced vander Waals forces such as relatively rougher surfaces (e.g., having an RMS surface roughness greater than 0.5 nm) or surfaces comprising metal or a metal alloy.

Thus, according to embodiments of the present disclosure, a stamp **10** for micro-transfer printing can comprise a support **13** having a support surface **15** and posts **16** disposed on support surface **15**. Each post **16** comprises a proximal end in contact with support **13** and a distal end extending away from support **13** and has a post surface **17** on the distal end. Post surface **17** (e.g., a cross section of post **16** in a direction parallel to support surface **15**) is non-rectangular and has opposing edges or sides with different lengths. Post surface **17** can be triangular or trapezoidal, can have an edge or a side that is triangular or trapezoidal, or can come to a point or corner. A point or corner can be considered to have a length of zero and therefore a post surface **17** with a point on a second edge or side **82** opposing a first edge or side **80** has a different length than the first edge or side **80**. A length of the trailing second edge **82** can be shorter or less than the length of the leading first edge **80**. Thus, in some embodiments, a stamp **10** for micro-transfer printing comprises a support **13** having a support surface **15** and posts **16** disposed on support surface **15**. Each post **16** comprises a proximal end in contact with support **13** and a distal end extending away from support **13**. Post **16** has a post surface **17** on the distal end. Post surface **17** can have a first edge **80** having a first length and a second edge **82** opposing first edge **80** having a second length less than the first length. When using stamp **10** for micro-transfer printing, moving stamp **10** in horizontal direction **60** will delaminate from chiplet **20** more readily than moving stamp **10** horizontally in direction D thus enabling transfer with less force or a transfer from one stamp **10** to another rotated stamp **10** as illustrated in FIG. **6**.

Non-rectangular post surface **17** shapes as shown in FIGS. **8**A-**8**E can be ridges **19** in stamps **10** according to embodiments of the present disclosure. FIG. **9**A is a plan view and FIG. **9**B a corresponding cross section taken along cross section line A of FIG. **9**A of post **16** having spatially separated non-rectangular ridges **19** with opposing sides (e.g., first edge or side **80** and second edge or side **82**) having different lengths separated by grooves **18**.

FIGS. **10**A and **10**B are plan views illustrating delamination corners **84** for posts **16** moved in a diagonal delamination direction **60** for a post **16** with rectangular ridges **19** (as shown in FIG. **10**A) and a post **16** with non-rectangular ridges **19** (as shown in FIG. **10**B). FIG. **10**C illustrates diagonal delamination for post **16** with a single rectangular post surface **17**. As stamp **10** and post **16** move in delamination direction **60**, post **16** can delaminate from chiplets **20** starting at delamination corners **84** and progressing in delamination direction **60** with delamination fronts **30** orthogonal to delamination direction **60**.

FIG. **11** illustrates a stamp post **16** where ridges **19** extend in a direction D orthogonal to the direction D of FIGS. **10**A and **10**B. This arrangement is equivalent to FIG. **10**A rotated by 90 degrees. The posts **16** of FIGS. **10**A and **11** can both provide multiple delamination fronts and different amounts of adhesion depending on horizontal direction **60** of shear offset.

FIGS. **12**A-C illustrate a post **16** with a two-dimensional array of sub-posts **32**. Each row or column of sub-posts **32** can be a ridge **19** that is separated into separate sub-posts **32**. A two-dimensional array of sub-posts **32** extending across post **16** to define post surface **17** can provide a greater number of delamination fronts **30** during printing. If the spaces (e.g., grooves **18**) between sub-posts **32** are relatively small compared to the area of sub-posts **32** and/or post surface **17**, the use of sub-posts **32** does not significantly reduce the area of post **16** in contact with chiplet **20**. For example, a total surface area of sub-posts **30** at a post surface at a distal end of post **16** can be at least 50%, at least 60%, at least 70%, at least 80%, at least 90%, at least 95%, or at least 98% of a total area of a cross section of a post surface at a distal end of post **16**. Sub-posts **32** can have a square cross section at post surface **17**, as shown in FIG. **12**A and FIG. **12**B, or can have a rectangular cross section, as shown in FIG. **12**C and can have asymmetric adhesion in different directions, for example as shown in FIG. **11**. FIG. **12**C illustrates sub-posts **32** in a row (or column) forming ridge **19** (a discontinuous ridge), where the ridge is defined by the long direction of sub-posts **32**. Hence, ridges **19** can comprise separate and individual sub-posts **32**. In some embodiments, movement of post **16** during printing can be parallel to ridge direction D (where ridge direction D is the length greater than the width of ridge **19**). In some embodiments, movement of post **16** during printing can be orthogonal to ridge direction D.

In some embodiments of the present disclosure, ridges **19** comprising one or more sub-posts **32** can extend in a ridge direction D parallel to a print direction of offset shear. FIG. **13** shows a post **16** with ridges **19** each comprising multiple sub-posts **32** arranged in a ridge direction D so that delamination fronts **30** orthogonal to ridge direction D and print direction can move in direction D during printing with offset shear, thus decreasing adhesion between post **16** and component **20** (not shown in FIG. **13**) and potentially optimizing or maximizing print yield. FIG. **14** shows ridges **19** each with multiple sub-posts **32**. FIG. **15** illustrates embodiments in which each sub-post **32** can have a single point as a trailing edge **82**, e.g., as shown in FIGS. **8**A, **8**C, and **8**E. Aligning ridge direction D with the horizontal direction **60** of stamp post **16** movement can improve print yields. In some embodiments, the single point can be the leading edge to improve final delamination rather than initial delamination.

In some embodiments, and as illustrated in FIG. **16**A, stamp posts **16** can have curved edges, can be cylindrical, or can have a curved cross section parallel to support surface **15** that is at least partially or completely circular, ellipsoidal, or oval. As shown in FIG. **16**B, stamp posts **16** can have a combination of planes and curved structures, for example a semi-cylinder with a semicircular cross section parallel to support surface **15**. Thus, according to embodiments of the present disclosure, a stamp **10** for micro-transfer printing can comprise a support **13** having a support surface **15** and posts **16** (e.g., stamp posts **16**) disposed on support surface **15**. Each of posts **16** comprises a distal end extending away from support surface **15** and a post surface **17** on the distal end. The post surface **17** can have a curved or partially curved edge or a portion of post surface **17** can be curved. Post surface **17** can have a straight edge or a portion of post surface **17** can be straight. A curved edge of post surface **17** can substantially form a portion of a circle or a semicircle, an oval, an ellipse, or a curve. Support **13** can comprise multiple layers, for example mesa **14** and flexible or rigid support **12**, as shown, for example, in FIG. **1**D and elsewhere in the Figures. A surface of any such layer from which post(s) **16** extend is a support surface **15**, in some embodiments.

As shown with the arrows of FIG. **16**B, stamp **10** can move in a horizontal direction orthogonal to a straight, planar face of stamp posts **16** to print components **20** (not shown in FIGS. **16**A, **16**B). A trailing edge of stamp post **16** can be curved, thus reducing the initial force necessary to commence peeling post surface **17** from a component **20**, delaminating component **20** from post surface **17**. In some embodiments, stamp **10** can move in a horizontal direction that is angled with respect to and is not orthogonal to a straight, planar vertical face of stamp posts **16** to print components **20** (where vertical is orthogonal to substrate surface **15**). Thus, a trailing edge of stamp post **16** can begin peeling at a point (e.g., a corner of a flat face of stamp post **16**) or at a curve, thus reducing the initial force necessary to commence and complete peeling post surface **17** from a component **20**.

In some embodiments of the present disclosure and as shown in FIGS. **17**A-**17**D, a stamp **10** for micro-transfer printing can comprise a support **13** having support surface **15** and a compressible (e.g., elastomeric) post **16** disposed on support surface **15**. Post **16** can comprise a proximal end in contact with support surface **15** and a distal end with post surface **17** extending away from support **13** and support surface **15** so that post **16** protrudes from support surface **15** to post surface **17** on the distal end of post **16**. Post **16** can comprise a blind hole **34** that extends from post surface **17** into post **16**. (Hole **34** is not a through hole through stamp **10**. That is, a vacuum force cannot be applied through stamp **10** via hole **34**.) In some embodiments, post **16** comprises a cutout **36** extending from blind hole **34** to an exterior edge of post **16**, for example so that air can pass from hole **34** through post **16** to the local ambient environment. In some embodiments, hole **34** extends less than all of the way from support surface **15** to post surface **17**, for example extends only partially from distal end post surface **17** to support surface **15**, as shown in FIGS. **17**A, **17**B. In some embodiments, hole **34** extends entirely from distal end post surface **17** to support surface **15** as shown in FIG. **17**D. Post surface **17** can be parallel to support surface **15**, for example as shown in FIGS. **17**A-**18**A.

According to embodiments of the present disclosure, cutout **36** is an absence of material extending from hole **34** through post **16** (e.g., through a wall of post **16**) to an exterior edge or side of post **16** (e.g., to a perimeter of post **16**) so that gas (e.g., the local atmosphere) can pass in from and out of hole **34** when cutout **36** is open (e.g., not compressed onto component **20**). Cutout **36** can refer to material absent from an otherwise planar surface of post **16** parallel to support surface **15** or the material that would have to be added to post **16** to form a planar surface of post **16** parallel to support surface **15**. Cutout **36** can be an open (exposed) channel through a portion of post **16**, a slit in post **16**, or a tunnel (e.g., a closed channel) in post **16** extending from hole **34** in post **16** to a perimeter or exterior surface of post **16**. FIGS. **17**A-**17**D illustrate a cutout **36** that forms a high-aspect ratio slit in a wall of post **16**.

FIGS. **18**A-**18**B illustrate embodiments with an array of posts **16** on support surface **15** with cutouts **36** in posts **16**. FIG. **18**A illustrates a cutout **36** that forms a high-aspect ratio slit in a wall of post **16** and FIG. **18**B shows a triangular cutout **36** extending from what would otherwise be a flat post surface **17** parallel to support surface **15**, e.g., as with portions of post **16** shown in FIG. **18**C-**18**H. In some embodiments, post **16** has a hole **34** extending to post surface **17**, as shown in FIG. **17**D. Cutout **36** can extend from an exterior of post **16** on one side to hole **34**, as shown in FIGS. **17**A-**17**D, or can extend to an exterior of post **16** on two sides as shown in FIG. **18**A, for example from one side of post **16** to another, for example opposite, side in a direction parallel to support surface **15**.

In some embodiments, the slit is shaped and sized to be open, thereby allowing gas to exit the hole, when the post is compressed and to be closed, thereby preventing gas from entering the hole, when the post is tensioned. In some embodiments, the cutout is shaped and sized to be open, thereby allowing gas to exit the hole, when the post is compressed and to be closed, thereby preventing gas from entering the hole, when the post is tensioned. In some embodiments, the cutout has a width and a height and the width is more than the height (e.g., at least twice the height). In some embodiments, the height of the cutout is no more than 20% (e.g., no more than 10%) of a height of the post. In some embodiments, the post has a height (length) no greater than twenty, ten, five, two, or one microns. In some embodiments, post **16** can be a cylinder or portion of a cylinder or have a circular, oval, or ellipsoidal cross section or portion of a circular, oval, or ellipsoidal cross section parallel to support surface **15**, for example as shown in FIGS. **16**A-**16**B, except for cutout **36**, for example as shown in FIGS. **17**A-**17**B. In some embodiments, post **16** can be a cube or other rectangular solid or can have a polygonal cross section, sides, or faces, e.g., a rectangular cross section, as shown in FIG. **18**A. In some embodiments and as shown in FIGS. **17**A-**17**D, blind hole **34** can be a cylinder or portion of a cylinder or have a circular, oval, or ellipsoidal cross section or portion of a circular, oval, or ellipsoidal cross section parallel to support surface **15**, except for cutout **36**. In some embodiments, hole **34** can be a cube or other rectangular solid or can have a polygonal cross section, sides, or faces, e.g., a rectangular cross section, as shown in FIG. **18**A. A rectangular solid can be a solid with rectangular sides or faces.

In some embodiments, post surface **17** is not, or is not entirely, parallel to support surface **15**. FIG. **18**B shows post surface **17** entirely non-parallel to support surface **15**. In some embodiments and as shown in FIG. **18**C, some portions but not all of post surface **17** of post **16** can be parallel to support surface **15**. FIG. **18**C shows examples of post surfaces **17** with a single angled (non-parallel to support surface **15**) face and a single parallel face (parallel to support surface **15**) with a triangular cutout **36**. (Here the shape of cutout **36** is taken as a cross section orthogonal to support surface **15** from the distal end of post **16**, e.g., along the length of post **16**.) FIGS. **18**D-**18**F illustrate embodiments with two portions of post surface **17** of post **16** parallel to support surface **15** spatially separated by cutout **36** (indicated with the dashed lines). FIG. **18**D shows examples of post surfaces **17** with two angled (non-parallel to support surface **15**) faces and two spatially separated parallel faces (parallel to support surface **15**) separated by a wide V-shaped cutout **36**. FIG. **18**E shows examples of post surfaces **17** with two spatially separated parallel faces (parallel to support surface **15**) separated by a rectangular cutout **36**. FIG. **18**F shows examples of post surfaces **17** with two spatially separated parallel faces (parallel to support surface **15**) separated by a rectangular stepped cutout **36**. Thus, cutouts **36** can be wider or larger at post surface **17** (at the top, distal end) than where cutout **36** is closer to support surface **15** (towards the bottom, proximal end). It can be difficult to construct angled faces (non-parallel or non-orthogonal to a process surface) such as a V-shape as shown in FIGS. **18**C and **18**D. An angled surface can be approximated with a series of small stair-steps (e.g., as shown in FIGS. **18**E, **18**F) and any reference to an angled surface herein can refer to a series of stair steps (alternating vertical and horizontal surfaces) extending from post surface **17** to hole **34** or forming cutout **36**. In these embodiments, cutout **36** can be wider than it is high. In some embodiments, cutout(s) **36** can be higher than they are wide (as shown in FIGS. **17**A-**17**D), e.g., cutouts **36** can be relatively shallow with respect to the height of posts **16**. FIG. **181** illustrates a cutout **36** that is a tunnel through a wall of post **16** to hole **34**. FIG. **18**J illustrate a hole **34** that extends to a step in post surface **17** so that cutout **36** has a rectangular cross section one two sides of post **16** (as shown) or can be present on only one side of post **16** (not shown in the Figures). In some embodiments, cutout **36** has a width and a height and the width is more than the height (e.g., at least twice the height). In some embodiments, a height of cutout **36** is no more than 20% (e.g., no more than 10%) of a height of its post **16**.

In some embodiments and as shown in FIGS. **17**A-**18**A, cutout **36** is arranged on a diagonal of hole **34** or is arranged on a line that intersects a center of hole **34**. In some embodiments, cutout **36** can be arranged so that it is not on a line that intersects a center of hole **34**, for example cutout **36** can be arranged on a tangent to hole **34** or extends parallel to and in contact with an edge of hole **34**, as shown in FIGS. **18**G and **18**H. The location of cutout **36** with respect to hole **34** can enable the opening and closing of cutout **36** when picking up components **20** from source wafer or when printing component **20** to target substrate **40**, and can help to control delamination during shear, for example a diagonal shear. In some embodiments, cutout **36** can be disposed on a side of post **16** that is at the leading edge of the delamination front so as to open as quickly as possible during printing, e.g., during post **16** horizontal (e.g., shear) movement, thereby releasing any suction between post **16** and component **20**.

Blank hole **34** in post **16** provides an ambient gas (e.g., air) reservoir (hole **34**) that, when post **16** is compressible, can decrease in size when post **16** is compressed or increase in size when post **16** is tensioned (e.g., stretched or elongated from support surface **15** to post surface **17** in a direction orthogonal to support surface **15**). Cutouts **36**, as shown in FIGS. **17**A-**18**F, can open or remain open and allow gas (e.g., air) to exit hole **34** when post **16** is compressed and cutout **36** can close to seal hole **34** and prevent gas from entering hole **34** when post **16** is tensioned. Thus, suction can be applied to component **20** when post **16** contacts component **20** and hole **34** is under tension, for example due to change in volume of hole **34** while hole **34** is sealed. In some embodiments, for example in which cutout **36** is wider than high, post **16** can be compressed to an extent (e.g., as shown with the arrows in FIGS. **18**C-**18**F) so that the entire perimeter of hole **34** is in contact with a component **20** so that when post **16** is tensioned (for example, stretched or elongated) the entire perimeter of hole **34** is in contact with component **20**, at least initially or in part, so that gas is prevented or inhibited from entering hole **34**, providing suction between component **20** and stamp post **16**. The inhibition or prevention of gas flow into hole **34** need only be momentary to enable increased force between stamp post **16** and component **20**, for example during the pick-up portion of a micro-transfer printing process.

The post **16** structures with holes **34** can be applied to sub-posts **32** so that one or more sub-posts **32** comprise a hole **34** and cutout **36**. The hole **34** and cutout **36** in sub-posts **32** can operate similarly to hole **34** and cutout **36** in posts **16**.

As shown in the flow diagrams of FIGS. **5**, **7**, and **19** and the successive cross sections of FIGS. **20**A-**20**F, methods of the present disclosure can comprise providing a stamp **10** having a post **16** with a hole **34** and cutout **36** on a support surface **15** in step **120**, providing a component **20** (component **20**) physically connected to a component source wafer **50** by a component tether **22** in step **110**, providing a motion-control platform **70** in step **100** (shown in FIGS. **4**A-**4**F), pressing post **16** against component **20** with motion-control platform **70** (shown in FIG. **20**A) in step **140** to compress post **16** with an open cutout **36** in step **141** (shown in FIG. **20**B), and pulling support surface **15** away from component **20** to tension post **16** with a sealed hole **34** (closed cutout **36**) (shown in FIG. **20**C) in step **151** and remove component **20** from component source wafer with motion-control platform **70** in step **150** (shown in FIG. **20**D). Stamp **10** and source wafer **50** can be separated from each other by moving stamp **10** away from source wafer **50**, moving source wafer **50** away from stamp **10**, or moving both stamp **10** and source wafer **50** in relative motion away from each other.

In some embodiments, for example if cutout **36** is higher than wide, for example as shown in FIGS. **17**A-**17**D, **18**A, compressing post **16** compresses hole **34** and opens cutout **36** to allow the flow of gas (e.g., ambient gas such as air or an ambient local atmospheric gas) from hole **34** and cutout **36** to the local environment external to post **16** in step **141**, so that the gas (e.g., air) pressure in hole **34** and cutout **36** is the ambient, atmospheric pressure. In some embodiments, for example where cutout **36** is wider than high as shown in FIGS. **18**B-**18**F, cutout **36** is open when initially compressing post **16** to allow the flow of gas (e.g., ambient gas, such as air) from hole **34** and cutout **36** to the local environment external to post **16** and then closes when post **16** is compressed until a perimeter of hole **34** is in contact with component **20** thereby sealing hole **34** (shown with the arrows in FIGS. **18**C-**18**F), so that the air pressure in hole **34** and cutout **36** is the ambient, atmospheric pressure. In some embodiments, compressing post **16** reduces the volume of hole **34** and thus the quantity of gas (e.g., air) in hole **34**. In some embodiments, compressing post **16** reduces the volume of cutout **36** and the quantity of gas (e.g., air) in cutout **36**. In some embodiments, compressing post **16** reduces the volume of hole **34** and cutout **36** and the quantity of gas (e.g., air) in hole **34** and cutout **36**. Thus, in some embodiments, cutout **36** is continuously open to allow equilibration with ambient until hole **34** becomes sealed against component **20** and, in some embodiments, cutout **36** opens under compression only while hole **34** is sealed against component **20** to allow gas to exit hole **34** (e.g., which may lead to equilibration depending on the amount of time sufficient compression is applied). In cases where cutout **36** is substantially sealed against component **20**, rapid separation of stamp **10** from source wafer **50** (e.g., as is normal during pick-up in micro-transfer printing) can cause suction, due to tension on post **16**, to be applied before re-equilibration of gas pressure in hole **34** occurs.

Post **16** can be compressed by the movement of stamp **10** controlled by motion-control platform **70** pressing post **16** against component **20** on component source wafer in step **141**. Post **16** can be tensioned (e.g., stretched or elongated in a direction orthogonal to a surface of component **20** in contact with post **16**) by the relatively rapid movement of stamp **10** controlled by motion-control platform **70** pulling post **16** away from component source wafer **50** in step **151**. Post surface **17** of post **16** can remain adhered to the surface of component **20** by means of van der Waals forces so that motion-control platform **70** pulls post **16** and post **16** pulls component **20** physically connected to component source wafer **50** with component tether **22** away from component source wafer **50** relatively quickly, increasing the rate-dependent adhesion between post **16** and component **20**. Since component source wafer **50** is firmly held in position by motion-control platform **70**, motion-control platform **70** provides tension in post **16** by pulling stamp **10** away from component source wafer **50** as component source wafer **50** is held in position. This tension stretches and elongates post **16** (as shown in FIG. **20**C), enlarging and increasing the volume of hole **34**, and optionally cutout **36**, thereby reducing the air pressure in hole **34**, since hole **34** is sealed and gas is prevented or is at least inhibited from flowing into hole **34**, thus providing at least momentary suction between post **16** and component **20**, increasing the force (e.g., tension) applied between post **16** and component **20**. The suction due to reduced gas pressure in hole **34** can be greater than the additional adhesion of post **16** to component **20** if hole **34** were not present and hole **34** in contact with component **20** was filled with post **16** material (e.g., PDMS). Thus, the gas pressure within hole **34** is greater when post **16** is in compression and smaller when post **16** is in tension so that embodiments of the present disclosure provide greater force between post **16** and component **20** when removing component **20** from component source wafer **50** (steps **140**, **141**), increasing process yields for removing component **20** from component source wafer **50** with stamp **10** under the control of motion-control platform **70**.

Once component **20** is removed from component source wafer **50** (e.g., once tether **22** is broken or separated), no tension is applied between post **16**, component **20**, and component source wafer **50** so that post **16** material relaxes and cutout **36** can open, allowing ambient gas (air, atmosphere) to enter cutout **36** and hole **34**, so that the air pressure in hole **34** and cutout **36** is at ambient atmospheric pressure and no longer at a reduced pressure, as shown in FIG. **20**D. Once that has happened, in some embodiments, for example as illustrated with the posts in FIGS. **18**B-**18**F, the post surface **17** area of post **16** in contact with component **20** is also reduced, reducing the adhesion between post surface **17** and component **20**. In some embodiments, the suction is too strong to permit relaxation of post **16** material to open cutout **36** without further force applied to stamp **10** or component **20**. Such suction may increase the force between post **16** and component to the point that successful printing of component **20** to target substrate **40** could be inhibited or prevented. That is, even employing rate-dependent adhesion using a vertical movement to print component **20**, the adhesion between target substrate **40** and component **20** (e.g., especially where no adhesive is used on target substrate **40**) can be too weak to release component **20** from stamp **10** onto target substrate **40** when suction remains. To solve this problem, in some embodiments, cutout **36** can be opened during printing to release the suction, for example when printing with shear. The shear applied as component **20** contacts target substrate **40** can act to open cutout **36** if cutout **36** did not open as post **16** did. As it can be difficult to assess whether cutout **36** opens or remains closed due to suction during normal transit of components **20** between source wafer **50** and target substrate **40**, in some embodiments, shear is employed during printing regardless of the state of cutout **36** to ensure opening.

In some embodiments, further compression is applied to post **16** at target substrate to open cutout **36** and release any suction. Slow separation of stamp **10** from source wafer **50** can ensure that pressure in hole **34** equilibrates with ambient to sufficiently reduce or eliminate any suction. Shear can be used to delaminate post surface **17** from component even if cutout **36** has already been opened after pick-up of components **20** from source wafer **50** and no suction remains, even if the shear would not otherwise be sufficient to open cutout **36** on its own.

Embodiments of the present disclosure can comprise providing a target substrate **40** in step **130** and contacting component **20** to target substrate **40** in step **160**, as shown in FIG. **20**E. As shown in FIG. **20**F, in step **176**, stamp **10** is removed relatively slowly from component **20** to print component **20** to target substrate **40**. Some embodiments comprise moving stamp **10** vertically from target substrate **40** to adhere component **20** to target substrate **40**. The force provided by contacting component **20** to target substrate **40** can be less than the force provided by contacting post **16** to component **20** in steps **140**, **141** so that cutout **36** remains open. Thus, force between component **20** and post **16** is smaller when component **20** is contacted to target substrate **40** in step **160** than when component **20** is removed from component source wafer **50** and adhered to post **16** in step **150** because air pressure in hole **34** is less than ambient atmospheric pressure so that no or little suction is present and, optionally, the area of post **16** in contact with component **20** is smaller, reducing the vander Waals force adhering component **20** to post **16**.

Some embodiments comprise moving stamp **10** at least horizontally with respect to target substrate **40** and the direction of motion opens cutout **36** or causes cutout **36** to remain open, thus avoiding any suction due to air pressure between component **20** and post **16**.

(For clarity of illustration posts **16** and support surface **15** are shown inverted or upside-down in FIGS. **16**A-**18**F with respect to their position when picking or printing components **20**.) As shown in FIGS. **21**A-**21**F, sub-posts **32** of stamp posts **16** can be aligned with and adjacent to component tethers **22** so that mechanical stress created by sub-posts **32** of stamp posts **16** pressing or pulling component **20** with respect to component source wafer can preferentially stress and fracture component tethers **22** instead of stressing the body of component **20** during removal of component **20** from component source wafer **50**, thereby increasing transfer yields and decreasing damage, or at least stress, to components **20**. Such techniques can be especially useful for components **20** with two or more component tethers **22** and components **20** with large length-by-width aspect ratios, for example micro-lasers. FIG. **21**F illustrates post **16** and sub-post **32** compressed with respect to the cross section of FIG. **21**E.

Thus, according to embodiments of the present disclosure, a system for micro-transfer printing comprises a component source wafer **50** (component source wafer **50**) comprising a sacrificial portion **52**, a component **20** (e.g., component **20** or component disposed completely and directly over sacrificial portion **52**, and tethers **22** connecting component **20** to anchor portions **54** of component source wafer **50** at tether locations, and a stamp **10** comprising a stamp support **12** having a support surface **15** and one or more posts **16** disposed on support surface **15**. The distal end of post **16** has a structured three-dimensional surface comprising sub-posts **32** (micro-posts **32**) that extend away from support surface **15** at sub-post locations. The sub-post locations are disposed adjacent to the tether locations when sub-posts **32** are in contact with component **20**. A tether location can be an area of component source wafer **50** comprising only tether **22** and a sub-post location can be an area of component source wafer **50** comprising only the area of component source wafer **50** in contact with sub-post **32**. A sub-post location adjacent to a tether location can be in contact with the tether location (e.g., an edge of a sub-post location can be coterminous with an edge of a tether location, e.g., having a common border), can be closer to a tether location than to a center of component **20**, or can be closer to a tether location than to any other tether location).

Sub-posts **32** can be compressible and portions of the distal end of post **16** between sub-posts **32** and sub-posts **32** can be in a common plane when sub-posts **32** are under mechanical pressure, thereby increasing the area of post surface **17** in physical contact with component **20**, as shown in FIG. **21**F. Sub-posts **32** can be pyramidal, cylindrical, cubic, or have polygonal surfaces or faces. Furthermore, such sub-post structures **32** can enable improved contact between post **16** and components **20** when components **20** have some curl and are not substantially flat.

Embodiments of the present disclosure enable micro-transfer printing with transfer stamps having both improved pickup and improved printing. A typical unstructured stamp post **16** has an area of a distal end of stamp post **16** in contact with a micro-device for pickup and print. By using visco-elastic materials and rate-dependent adhesion, stamp post **16** can pick up micro-device **20** at a pickup rate greater than a print rate for printing micro-device **20** on a target substrate **40**. A larger area of stamp post **16** in contact with micro-device **20** improves pickup but makes printing more difficult. A smaller area of stamp post **16** in contact with micro-device **20** improves printing but makes pickup more difficulty. Using a structured stamp post **16** according to embodiments of the present disclosure enables further differentiation between the pickup process and the print process (e.g., a larger process window), for example in pickup and print rate differences and in the amount of shear offset, thus improving yields on both pickup and printing by providing multiple delamination fronts for printing. Thus, a larger stamp area for post **16** can improve pickup yields and at the same time improve print yields by using multiple delamination fronts **30**.

According to some embodiments of the present disclosure, a method of making a stamp **10** for micro-transfer printing comprises providing a mold defining optional mesa

14 and one or more posts 16 disposed on and in direct contact with mesa 14 that extend away from mesa 14, providing a rigid support 12 in or in contact with the mold, providing liquid curable stamp material in the mold (e.g., by injecting at approximately psi pressure), curing the curable stamp material at a cure temperature (e.g., at approximately 60° C. for approximately 240 minutes in an oven) to form cured stamp material, and cooling rigid support 12 and cured stamp material to an operating temperature different from the cure temperature. In some embodiments, methods of the present disclosure comprise removing the mold to provide a stamp 10 for micro-transfer printing. Posts 16 can be disposed in a regular array over rigid support 12 and mesa 14 and posts 16 extending away from mesa 14 and rigid support 12 can be collectively disposed in a regular array over mesa 14 and rigid support 12. Rigid support 12 can have a coefficient of thermal expansion (CTE) that is greater than a post 16 or mesa 14 material CTE. Mesa 14 and posts 16 can comprise a common material (e.g., PDMS). Rigid substrate can be glass. Molds can be silicon masters formed in a silicon substrate (wafer) using photolithographic methods and materials.

The present disclosure provides structures and methods that facilitate micro-transfer printing of micro-devices (chiplets) 20 on a source wafer 50 (e.g., as shown in FIG. 4A), especially substrates such with an extensive surface as an integrated circuit wafer. Micro-devices 20 are formed on a source wafer 50, each micro-device 20 is contacted by a different post 16 of a stamp 10 under the control of a motion-control platform 70 to detach micro-devices 20 from source wafer 50 and adhere micro-devices to posts 16 of stamp 10, and micro-devices 20 are pressed against a target substrate 40 to adhere micro-devices 20 to target substrate 40, forming a micro-transfer printed system. Stamp 10 is then moved away from target substrate 40, leaving micro-devices 20 on target substrate 40. Different stamp steps can be applied to micro-devices 20 from different source wafers 50, for example thereby forming a heterogeneous micro-system on target substrate 40 comprising a variety of different micro-devices 20 constructed in different materials, for example silicon and various compound semiconductors such as GaN or GaAs.

Micro-transfer printable micro-devices 20 can have, for example, one or more of a width from 1-200 μm (e.g., 1-8 μm), a length from 1-400 μm (e.g., 5-10 μm), or a height from 0.5-50 μm (e.g., 0.5-20 μm or 0.5-3 μm). More generally, micro-transfer printable micro-devices 20 can comprise or be a variety of chiplets 20 comprising conductor or semiconductor structures, including, but not limited to, active components such as any one or more of a diode, a light-emitting diode (LED), a transistor, a laser, an integrated circuit, a photonic integrated circuit, and active electrical components, or passive electrical components such as any one or more of resistors, capacitors, conductors, and electrical jumpers. Micro-transfer printable micro-device 20 can be an unpackaged die. In some embodiments, micro-transfer printable micro-device 20 is a compound element having a plurality of active or passive elements, such as multiple semiconductor micro-devices 20 with separate substrates, each with one or more active elements or passive elements, or both. In certain embodiments, the plurality of elements is disposed and interconnected on a compound element substrate separate from the substrates of any semiconductor micro-devices 20 or a different substrate. The compound element can be a micro-device 20 and can be micro-transfer printed itself after the elements have been arranged and interconnected thereon. The micro-transfer printable micro-device 20 can be, include, or comprise electronic processors, controllers, drivers, light-emitting diodes, photodiodes, light-control micro-devices 20, or light-management micro-devices 20.

Micro-transfer printing enables printed structures with low-cost, high-performance heterogeneous arrays of electrically connected micro-devices 20 such as integrated circuits, photonic elements such as lasers, sensors, photodiodes, light pipes, or micro-light-emitting diodes (LEDs) useful, for example, in display or photonic systems. Micro-transfer printable micro-devices 20 can be light emitters or integrated circuits, for example CMOS integrated circuits made on or in a silicon source wafer 50, light-emitting diodes (LEDs) or lasers, for example made on or in a GaN, GaAs, or InP compound semiconductor source wafer 50, or silicon photodiodes. For example, described herein are micro-assembled heterogeneous arrays of micro-devices 20, such as integrated circuits, lasers, or micro-LEDs, that are too small, numerous, or fragile to be assembled by conventional means. Rather, these arrays are assembled using micro-transfer printing technology.

Components 20 (e.g., micro-devices 20) may be prepared on a native source wafer 50 and printed to a target substrate 40 (e.g., plastic, metal, glass, ceramic, sapphire, transparent materials, opaque materials, rigid materials, or flexible materials), thereby obviating the manufacture of micro-devices 20 on target substrate 40. Source wafers 50 can have a dimension (e.g., a diameter) no less than 25 mm (e.g., no less than 51 mm, no less than 76 mm, no less than 10 mm, no less than 150 mm, no less than 200 mm, no less than 300 mm, no less than 450 mm, or no less than 675 mm, e.g., a 2-inch, 4-inch, 8-inch, or 12-inch wafer).

Chiplets 20 (e.g., components 20) can be small integrated circuits. Chiplets 20 can be unpackaged dies released and detached from a source wafer 50 and can be micro-transfer printed and incorporate a broken (e.g., fractured) or separated chiplet tether 22. Chiplets (micro-devices) 20 can have at least one of a width, a length, and a height of, for example, from 2 μm to 1 mm (e.g., 2 to 5 μm, 5 to 10 μm, 10 to 20 μm, 20 to 50 μm, 50 μm to 100 μm, 100 μm to 250 μm, 250 μm to 500 μm, or 500 μm to 1000 μm). Chiplets can, for example, have a doped or undoped semiconductor substrate thickness of 2 to μm, 5 to 10 μm, 10 to 20 μm, or 20 to 50 μm. Chiplets 20 or micro-transfer printable micro-devices 20 can have a length greater than width, for example having an aspect ratio greater than or equal to 2, 4, 8, 10, 20, or 50 and component contact pads that are adjacent to the ends of micro-transfer-printable micro-devices 20 along the length of micro-transfer-printable micro-devices 20.

Components 20 can be any of a wide variety of devices, such as, for example but not limited to, electronic, optical, optoelectronic, mechanical, or piezoelectric devices. Components 20 can be optically emissive or responsive and can be light emitters (such as LEDs), light sensors (such as photodiodes), lasers, or electrical jumpers. Components 20 can be integrated circuits (for example CMOS, bipolar, or mixed circuits) and comprise electronically active or passive electronic elements or both. Components 20 can be constructed using photolithographic methods and materials. Components 20 can have, for example, at least one of a width, length, and height from 2 μm to 1000 μm (for example 2 to 5 μm, 5 to 10 μm, 10 to 20 μm, 20 to 50 μm, 50 μm to 100 μm, 100 μm to 250 μm, 250 μm to 500 μm, or 500 μm to 1000 μm). Components 20, for example, can have a substrate thickness from 2 μm to 50 μm (for example from 2 to 5 μm, 5 to 10 μm, 10 to μm, or 20 to 50 μm). Components 20 can have a length greater than width, for example having an aspect ratio greater than or equal to 2 (for example greater than or equal to 4, 8, 10, 20, or 50).

A component **20** can be an active circuit component, for example including one or more active electronic components such as electronic transistors or diodes or light-emitting diodes or photodiodes that produce an electrical current in response to ambient light. A component **20** can be a passive component, for example including one or more passive elements such as resistors, capacitors, or conductors. In some embodiments, a component **20** includes both active and passive elements. A component **20** can be a semiconductor device having one or more semiconductor layers, such as an integrated circuit. A component **20** can be an unpackaged die. In some embodiments, a component **20** is a compound device **20** having a plurality of active or passive elements, such as multiple semiconductor components with separate substrates, each with one or more active elements or passive elements, or both. Components **20** can be or include, for example, electronic processors, controllers, drivers, light-emitting diodes, photodiodes, light-control devices, light-management devices, piezoelectric devices, acoustic wave devices (e.g., acoustic wave filters), optoelectronic devices, electromechanical devices (e.g., microelectromechanical devices), photovoltaic devices, sensor devices, photonic devices, magnetic devices (e.g., memory devices), or elements thereof.

In certain embodiments, formation of a printable micro-device **20** begins while the semiconductor structure remains on a substrate, such as a sapphire substrate. After partially forming printable micro-device **20**, a handle substrate is attached to the semiconductor structure opposite the substrate such that the semiconductor structure is secured to the handle substrate. The substrate, such as the sapphire substrate, may then be removed from the system using various techniques, such as laser ablation, grinding, etching, and polishing. After the substrate is removed, formation of the semiconductor structure can be completed, if necessary, to form printable micro-device **20** and printable micro-device **20** may be micro-transfer printed to a target substrate **40**, thereby enabling parallel assembly of high-performance semiconductor micro-devices **20** (e.g., to form micro-LED displays or photonic systems) onto virtually any substrate material (e.g., target substrate **40**), including glass, plastics, metals, other semiconductor materials, or other non-semiconductor materials.

Micro-structured stamps **10** (e.g., elastomeric, electrostatic stamps, or hybrid elastomeric/electrostatic stamps) can be used to pick up the disclosed micro-devices **20**, transport micro-devices **20** to a destination, and print micro-devices **20** onto a target substrate **40**. In some embodiments, surface adhesion forces are used to control the selection and printing of these micro-devices **20** onto destination substrate **40**. This process may be performed massively in parallel. Stamps **10** can be designed to transfer a single micro-device **20** or hundreds to thousands of micro-devices **20** or other discrete structures in a single pick-up and print operation. For a discussion of micro-transfer printing generally, see U.S. Pat. Nos. 7,622,367 and 8,506,867, each of which is hereby incorporated by reference in its entirety. Moreover, these micro-transfer printing techniques can be used to print semiconductor micro-devices **20** at temperatures compatible with assembly on plastic polymer substrates (e.g., target substrates **40**). In addition, semiconductor materials may be printed onto large areas of target substrates **40** thereby enabling continuous, high-speed printing of micro-devices **20**.

Posts **16** extend from optional mesa **14**, if present, in a direction away from mesa **14** and away from rigid substrate **12**. Stamp posts **16** can have, for example, a length ranging from 5 μm to 100 μm (e.g., 20 μm). Posts **16** can have an aspect ratio (height-to-width) of, for example from 1:4 to 4:1. Posts **16** can have a size that is larger or smaller than the size of a micro-device **20** that posts **16** are designed to contact. Each post **16** is designed to contact a single different micro-device **20** so that each stamp post **16** contacts only one micro-device **20** and each micro-device **20** is contacted by only one stamp post **16**. In some embodiments, multiple stamp posts **16** can contact a single micro-device **20**. For example, posts **16** can have a length extending from mesa **14** that is no greater than 200 μm (e.g., no greater than 100 μm, no greater than 50 μm, no greater than 20 μm, no greater than 10 μm, no greater than 5 μm, no greater than 3 μm, no greater than 2 μm, no greater than 1 μm, or no greater than 0.5 μm). These ranges and values are illustrative and not limiting and other materials and sizes are contemplated in the present disclosure. Additionally, posts **16** can have a shape that is the same as or different from the shape of micro-device **20** that is picked up by stamp **10**. For example, in an embodiment a circular post **16** is used to pick up an 85 μm square chiplet **20**. In some embodiments, for example, a 60 μm square post **16** is used to pick up an 85 μm square micro-device **20**.

In some embodiments, optional mesa **14** can have a range of thickness from 100 μm to 10 mm. Mesas **14** or posts **16** of the present disclosure can comprise or be made of conformal materials such as a visco-elastic material or an elastomer, for example polydimethylsiloxane (PDMS), an optically clear polymeric organosilicon compound. The stiffness and CTE of PDMS can be controlled by forming PDMS with different ratios of constituents. For example, Dow Sylgard 184 Elastomer Base and Curing Agent by Dow Corning Corporation of Auburn, MI, can be mixed at a ratio from 1 part elastomer base to 1 part curing agent by weight to 50 parts elastomer base to 1 part curing agent by weight (e.g., ten parts elastomer base to one part curing agent by weight) to provide PDMS with varying stiffness and CTE.

Mesas **14** and posts **16** can be formed from a mixture having a ratio of elastomer to curing agent in a range of 1:1 to 15:1, for example made in a ratio of about 10:1 elastomer to curing agent (e.g., varying no more than 10% from a ratio of 10:1). In some embodiments, mesa **14** is made of the same material in the same proportions as posts **16** and have the same stiffness and CTE. Alternatively, mesa **14** includes the same material as posts **16** but in different proportions or includes different materials. Using the same materials in different proportions in mesa **14** and posts **16** enables the stiffness and CTEs of the different layers to be separately controlled. For example, in some embodiments, mesa **14** is stiffer than posts **16** or has a smaller CTE than posts **16**. Thus, in some embodiments, mesa **14** is more rigid than posts **16** and the mesa CTE is smaller than the post CTE. For example, mesa **14** can be made with a ratio of 2:1 to 8:1 elastomer to curing agent, for example about 5:1, and posts **16** can be made in a ratio of 8:1 to 14:1 elastomer to curing agent, for example about 10:1.

According to some embodiments of the present disclosure, rigid support **12** has a dimension (e.g., diameter, length, or width) no less than 25 mm (e.g., no less than 50 mm, no less than 100 mm, no less than 150 mm, no less than 200 mm, no less than 300 mm, no less than 450 mm, or no greater than 675 mm) or a thickness no less than 0.5 mm (e.g., no less than 0.75 mm, no less than 1 mm, no less than 2, no less than 5 mm, or no less than 10 mm). These ranges are illustrative and not limiting and other materials and sizes are contemplated in the present disclosure. According to some embodiments of the present disclosure, rigid support **12** can be or comprise glass (e.g., a portion of a flat-panel display substrate), soda-lime glass, borosilicate glass, quartz, sapphire, pyrex, metal, ceramic, polymer, a cured epoxy, or a semiconductor (e.g., a wafer or portion of a wafer). Rigid support **12** can be made from, for example, glass or plastic (e.g., polycarbonate (PC), poly(methyl methacrylate) (PMMA), polyethylene terephthalate (PET), or polyethylene naphthlate (PEN)). Rigid support **12** can be thicker, the same thickness as, or thinner than mesa **14**. Rigid support **12** can be, for example, no less than 500 microns thick (for example no less than 700 microns, 1 mm, 2 mm, 3 mm, 5 mm, or 1 cm thick). The linear CTE can be from 5×10^{-6}/K to 10×10^{-6}/K (e.g., approximately 8.5×10^{-6}/K). In some embodiments, the CTE of rigid support **12** can be approximately equal to the CTE of micro-devices **20** or target substrate **40**, for example within 10%.

The micro-transfer printable micro-devices **20** can include active elements such as electronic circuits formed using lithographic processes and can include passive elements such as electrical connections, e.g., wires. In some embodiments, micro-transfer printable micro-devices **20** are small integrated circuits, for example chiplets **20**, having a thin substrate with a thickness of only a few microns, for example less than or equal to 25 microns, less than or equal to 15 microns, or less than or equal to 10 microns, and a width or length of 5-10 microns, 10-50 microns, 50-100 microns, or 100-1000 microns. Such chiplet **20** printable component structures can be made in a semiconductor source wafer (e.g., a silicon or GaN wafer) having a process side and a back side used to handle and transport source wafer **50**. Micro-transfer printable micro-devices **20** are formed using lithographic processes in an active layer on or in the process side of source wafer **50**. An empty release layer space (e.g., sacrificial portion **52**) is formed beneath micro-transfer printable micro-devices **20** with tethers **22** connecting micro-transfer printable micro-devices **20** to source wafer **50** in such a way that pressure applied against micro-transfer printable micro-devices **20** breaks (e.g., fractures) or separates tethers **22** to detach micro-transfer printable micro-device **20** from source wafer **50** (e.g., with stamp **10**). Methods of forming such structures are described, for example, in Cok et al., "AMOLED Displays using Transfer-Printed Integrated Circuits," Society for Information Display, Vol. 40, Issue 1, pp. 947-950, and U.S. Pat. No. 8,889,485, entitled Methods of Surface Attachment of Flipped Active Components, issued Nov. 18, 2014.

According to various embodiments, a native source wafer **50** can be provided with micro-transfer printable micro-devices **20**, release layer (e.g., a layer of native source wafer **50** comprising sacrificial portion **52**), and tethers **22** already formed, or they can be constructed as part of a process of the present disclosure.

Source wafer **50** and micro-transfer printable micro-device **20**, stamp **10**, motion-control platform **70**, and target substrate **40** can be made separately and at different times or in different temporal orders or locations and provided in various process states.

Methods, in some embodiments, can be iteratively applied to a single or multiple target substrates **40**. By repeatedly transferring sub-arrays of micro-transfer printable micro-device **20** from a source wafer **50** to a target substrate **40** with a stamp **10** and relatively moving stamp **10** and target substrate **40** between stamping operations by a distance equal to the spacing of the selected micro-transfer printable micro-devices **20** in the transferred sub-array between each transfer of micro-transfer printable micro-device an array of micro-transfer printable micro-device **20** formed at a high density on a source wafer **50** can be transferred to a target substrate **40** at a much lower density. In practice, source wafer **50** is likely to be expensive, and forming micro-transfer printable micro-devices **20** with a high density on source wafer **50** will reduce the cost of micro-transfer printable micro-devices **20**, especially as compared to forming components on target substrate **40**. Transferring micro-transfer printable micro-device **20** to a lower-density target substrate **40** can be used, for example, if micro-transfer printable micro-devices **20** manage elements distributed over target substrate **40**, for example in a display, digital radiographic plate, or photovoltaic system.

In particular, in the case wherein active micro-transfer printable micro-device **20** is an integrated circuit formed in a crystalline semiconductor material, the integrated circuit substrate provides sufficient cohesion, strength, and flexibility that it can adhere to target substrate **40** without breaking as transfer stamp **10** is removed.

In comparison to thin-film manufacturing methods, using densely populated source wafers **50** and transferring micro-transfer printable micro-devices **20** to a target substrate **40** that requires only a sparse array of micro-transfer printable micro-devices **20** located thereon does not waste or require active layer material on a target substrate **40**. The present invention can also be used in transferring micro-transfer printable micro-devices **20** made with crystalline semiconductor materials that have higher performance than thin-film active components. Furthermore, the flatness, smoothness, chemical stability, and heat stability requirements for a target substrate **40** used in certain embodiments of the present disclosure may be reduced because the adhesion and transfer process is not substantially limited by the material properties of the target substrate **40**. Manufacturing and material costs may be reduced because of high utilization rates of more expensive materials (e.g., the source wafer **50**) and reduced material and processing requirements for target substrate **40**.

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

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

It should be understood that the order of steps or order for performing certain action is immaterial so long as operability is maintained. Moreover, two or more steps or actions in some circumstances can be conducted simultaneously.

PARTS LIST

A cross section line
B cross section line
D ridge direction
X x dimension/x direction
Y y dimension/y direction

Z z dimension/z direction
10 stamp
10A first stamp
10B second stamp
12 rigid support/stamp support
13 support
14 mesa/pedestal
15 support surface
16 post
17 post surface
18 groove
19 ridge
20 chiplet/micro-device/component
22 tether/chiplet tether
30 delamination front
32 sub-post
34 blind hole/hole
36 cutout
40 target (destination) substrate
42 optional adhesive layer
50 source wafer
52 sacrificial portion/gap
54 anchor/anchor portion
60 horizontal direction/horizontal stamp motion/delamination direction
65 vertical stamp motion
70 motion-control platform
80 first edge/leading edge/first side
82 second edge/trailing edge/second side
84 delamination corner
100 provide motion-control platform step
110 provide source wafer step
120 provide stamp step/provide stamp A step
125 provide stamp B step
130 provide target substrate step
135 optional coat adhesive layer on destination substrate step
140 press stamp posts against micro-devices step
141 compress stamp posts step
150 vertically remove stamp A from source wafer step
151 tension stamp posts step
152 press stamp B posts against micro-devices step
155 move horizontally in delamination direction and vertically to remove stamp A from micro-devices step
160 contact micro-devices to destination substrate step
170 move horizontally in delamination direction and vertically to remove stamp from destination substrate step
175 move horizontally in delamination direction and vertically to remove stamp B from destination substrate step
176 move vertically to remove stamp from destination substrate step

What is claimed:

1. A stamp for micro-transfer printing, comprising:
a support having a support surface; and
a compressible post disposed on the support surface, the post comprising a distal end extending away from the support, the post having a post surface on the distal end,
wherein the post has a blind hole extending into an interior of the post from the post surface and a cutout extending from the blind hole through the post to an exterior surface of the post.

2. The stamp of claim **1**, wherein the post surface has a curved edge.

3. The stamp of claim **2**, wherein the post surface also has a straight edge.

4. The stamp of claim **2**, wherein the curved edge defines at least a portion of a circle.

5. The stamp of claim **1**, wherein at least a portion of the post surface is not parallel to the support surface.

6. The stamp of claim **1**, wherein the cutout is disposed along a line intersecting a center of the blind hole.

7. The stamp of claim **1**, wherein the cutout is disposed along a line that does not intersect a center of the blind hole.

8. The stamp of claim **1**, wherein the cutout is disposed along a line tangent to the blind hole.

9. The stamp of claim **1**, wherein the cutout is disposed along a line parallel to and in contact with an edge of the blind hole.

10. The stamp of claim **1**, wherein the post has a circular outer perimeter except for the cutout.

11. The stamp of claim **1**, wherein the blind hole has a circular cross section except for the cutout.

12. The stamp of claim **1**, wherein the blind hole has a circular cross section.

13. The stamp of claim **1**, wherein the blind hole extends through the post to the support surface.

14. The stamp of claim **1**, wherein the blind hole extends through the post less than entirely to the support surface.

15. The stamp of claim **1**, wherein the blind hole has a circular cross section and the post has a polygonal cross section.

16. The stamp of claim **1**, wherein the cutout is a channel.

17. The stamp of claim **1**, wherein the cutout is a tunnel.

18. The stamp of claim **1**, wherein the cutout is a slit.

19. The stamp of claim **18**, wherein the slit is shaped and sized to be open, thereby allowing gas to exit the blind hole, when the post is compressed and to be closed, thereby preventing gas from entering the blind hole, when the post is tensioned.

20. The stamp of claim **1**, wherein the cutout is shaped and sized to be open, thereby allowing gas to exit the blind hole, when the post is compressed and to be closed, thereby preventing gas from entering the blind hole, when the post is tensioned.

21. The stamp of claim **1**, wherein the cutout has a width and a height and the width is more than the height.

22. The stamp of claim **1**, wherein a height of the cutout is no more than 20% of a height of the post.

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