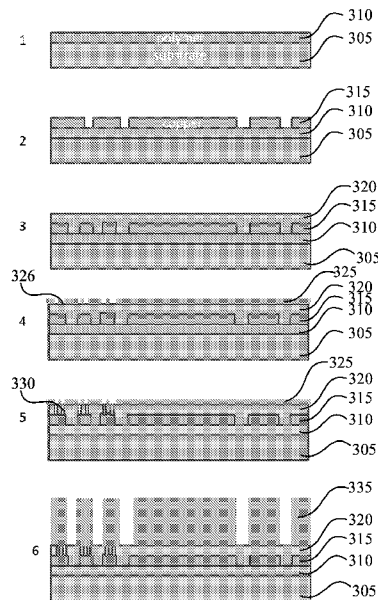




- (51) International Patent Classification:
F28D 15/04 (2006.01) *B23P 15/26* (2006.01)
- (74) Agents: SANDERS, Jason A. et al.; Maschoff Brennan,
1389 Center Drive, Suite 300, Park City, UT 84098 (US).
- (21) International Application Number:
PCT/US2015/057885
- (81) Designated States (unless otherwise indicated, for every
kind of national protection available): AE, AG, AL, AM,
AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY,
BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM,
DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT,
HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR,
KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG,
MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM,
PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC,
SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN,
TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.
- (22) International Filing Date:
28 October 2015 (28.10.2015)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:
62/069,564 28 October 2014 (28.10.2014) US
- (84) Designated States (unless otherwise indicated, for every
kind of regional protection available): ARIPO (BW, GH,
GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ,
TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU,
TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE,
DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU,
LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK,
- (71) Applicant: KELVIN THERMAL TECHNOLOGIES,
INC. [US/US]; 5429 Illini Way, Boulder, CO 80303 (US).
- (72) Inventors: LEWIS, Ryan John; 4415 Laguna Place, Apt.
208, Boulder, CO 80303 (US). LEE, Yung-Cheng; 5429
Illini Way, Boulder, CO 80303 (US). LIEW, Li-Anne;
11523 Benton Way, Westminster, CO 80020 (US).
WANG, Yunda; 1800 Grant Street, 8th Floor, Denver, CO
80203 (US).

[Continued on next page]

(54) Title: POLYMER-BASED MICROFABRICATED THERMAL GROUND PLANE



(57) Abstract: Embodiments described herein relate to the concept and designs of a polymer-based thermal ground plane. In accordance with one embodiment, a polymer is utilized as the material to fabricate the thermal ground plane. Other embodiments include an optimized wicking structure design utilizing two arrays of micropillars, use of lithography-based microfabrication of the TGP using copper/polymer processing, micro-posts, throttled releasing holes embedded in the micro-posts, atomic layer deposition (ALD) hydrophilic coating, throttled fluid charging structure and sealing method, defect-free ALD hermetic coating, and compliant structural design.

Figure 3A

WO 2016/114840 A2

SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG). **Published:**

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

POLYMER-BASED MICROFABRICATED THERMAL GROUND PLANE**STATEMENT AS TO RIGHTS TO INVENTIONS MADE UNDER
FEDERALLY SPONSORED RESEARCH AND DEVELOPMENT**

5 This invention was made with government support under Grant No. N66001-08-C-2006 awarded by DOD/DARPA. The government has certain rights in the invention.

SUMMARY

Some embodiments of the invention relate to polymer-based microfabricated thermal ground planes (TGP) and methods for manufacturing the same. In accordance with some
10 embodiments, a polymer is utilized as the material to fabricate the thermal ground plane. Other embodiments include an optimized wicking structure utilizing two arrays of micropillars, use of lithography-based microfabrication of the TGP using copper/polymer processing, micro-posts, throttled releasing holes embedded in the micro-posts, atomic layer deposition (ALD) hydrophilic and hydrophobic coatings, throttled fluid charging
15 structure and sealing method, defect-free ALD hermetic coating, and compliant structural design.

Some embodiments of the invention include a method for forming a thermal ground plane. The method can include the following depositing a first polymer layer on a substrate; depositing a first sacrificial layer in a first pattern on the first polymer layer;
20 depositing a second polymer later on the first sacrificial layer; depositing a second sacrificial layer on the second polymer layer. depositing a first masking layer on the second polymer layer having a plurality of exposed regions that expose portions of the second polymer layer; etching portions of the second polymer layer that are exposed by the first masking layer; removing the first masking layer; depositing a sacrificial vapor
25 core layer in a pattern on the second sacrificial layer; depositing a third polymer layer on the sacrificial vapor core layer; depositing a second masking layer on the third polymer layer having a plurality of exposed regions that expose portions of the third polymer layer; etching portions of the third polymer layer that are exposed by the second masking layer; removing the second masking layer; removing portions of the sacrificial vapor core
30 layer using the holes in the third polymer layer; removing the substrate; and/or sealing the holes in the third polymer layer.

In some embodiments, after removing portions of the sacrificial vapor core layer the third polymer layer forms a plurality of pillars.

In some embodiments, the first pattern comprises a negative of a plurality of pillars.

In some embodiments, the second polymer layer comprises a mesh layer.

In some embodiments, the masking layer comprises a metal. In some embodiments, the masking layer comprises a plurality of exposed regions.

5 In some embodiments, the sacrificial vapor core layer may be electroplated on the second polymer layer. In some embodiments, the vapor core layer may include a plurality of pillars.

In some embodiments, removing portions of the sacrificial vapor core layer using the holes in the third polymer layer further comprises introducing an acid through the holes in the third polymer layer.

10 In some embodiments, the sacrificial vapor core layer has a thickness of less than 200 microns. In some embodiments, the second polymer layer has a thickness of less than 50 microns. In some embodiments, the first polymer layer has a thickness of less than 50 microns.

15 In some embodiments, removing portions of the sacrificial vapor core layer using the holes in the third polymer layer further comprises removing portions of the first sacrificial layer.

In some embodiments, depositing a third polymer layer on the sacrificial vapor core layer further comprises depositing the third polymer layer into cavities or channels in the sacrificial vapor core layer.

20 Some embodiments include thermal ground plane. The thermal ground plane may include a bottom layer; a mesh layer bonded with the bottom layer a vapor core having a plurality of pillars bonded with the mesh layer; and a top layer.

25 In some embodiments, either or both the top layer and the bottom layer comprise an in-plane wavy structure. In some embodiments, either or both the top layer and the bottom layer comprise an out-of-plane wavy structure.

In some embodiments, either or both the top layer and the bottom layer comprise a polymer. In some embodiments, the plurality of pillars comprise a polymer. In some embodiments, the mesh layer comprises a polymer.

30 In some embodiments, the mesh layer comprises one or more pillars and/or one or more microposts. In some embodiments, the one or more pillars have a star cross-section shape.

These illustrative embodiments are mentioned not to limit or define the disclosure, but to provide examples to aid understanding thereof. Additional embodiments are discussed in the Detailed Description, and further description is provided there. Advantages offered

by one or more of the various embodiments may be further understood by examining this specification or by practicing one or more embodiments presented.

BRIEF DESCRIPTION OF THE DRAWINGS

5 These and other features, aspects, and advantages of the present disclosure are better understood when the following Detailed Description is read with reference to the accompanying drawings.

Figure 1A illustrates the operational principle of a TGP according to some embodiments.

Figure 1B illustrates a TGP with an evaporator, vapor core, condenser, and liquid wicking structure according to some embodiments.

10 Figure 2A is a graph illustrating a range of possible micropost geometries for a given constraint to prevent dry-out, with capillary pressure calculated according to the Young-Laplace equation and viscous pressure drops calculated according to Poiseuille's Law.

Figure 2B is a schematic of a micropost design for a wicking structure 120 with two different array geometries in two different regions.

15 Figures 3A and 3B illustrate an example process for fabricating a TGP according to some embodiments.

Figure 4 shows an example array of micro pillars.

Figure 5A illustrates throttled releasing holes in a TGP after copper release, before a releasing hole is filled with epoxy.

20 Figure 5B illustrates throttled releasing holes in a TGP after a releasing hole is filled with epoxy.

Figure 6 illustrates an example structure and/or sealing method.

Figure 7A illustrates an out of plane structure schematic according to some embodiments.

Figure 7B illustrates an out of plane compliant structure according to some embodiments.

25 Figure 7C illustrates an example process flow to fabricate an out-of-plane wavy structure according to some embodiments.

Figure 8 illustrates an example in plane structure.

Figure 9 illustrates a structure fabricated using a PDMS mold.

Figure 10 illustrates a TGP with a laminated perimeter according to some embodiments.

30 Figure 11A is a schematic illustration of a pillar spacing problem.

Figure 11B illustrates an optimization curve for optimized pillar spacing according to some embodiments.

Figures 12A and 12B illustrate an example process for fabricating a TGP according to some embodiments.

Figure 13 illustrates an example thermal ground plane.

Figure 14 is a graph illustrating optimal considerations for vapor core thickness.

Figure 15 is a graph illustrating optimal considerations for vapor core thickness.

5 Figure 16 illustrates a thermal ground plane integrated with a printed circuit board according to some embodiments.

Figure 17 illustrates a cross-sectional view of a TGP coupled with a PCB according to some embodiments.

Figures 18A and 18B illustrate an example process for fabricating a TGP integrated with a PCB according to some embodiments.

10 Figure 19A illustrates electrical vias fabricated through the polymer layers in a TGP according to some embodiments.

Figure 19B illustrates electrical vias in a TGP that can be connected to electrical interconnects, vias or bonding pads on the PCB.

15 Figure 20 illustrates several pre-fabricated flexible circuit boards laminated into a single PCB with a TGP according to some embodiments

Figure 21 illustrates a top view of a TGP according to some embodiments.

Figure 22A shows a side view of TGP cut through Section A shown in Figure 21.

Figure 22B shows a side view of TGP cut through Section B shown in Figure 21.

Figure 22C shows an end view of TGP 700 cut through Section C shown in Figure 21.

20

DETAILED DESCRIPTION

Thermal management can be an important element in micro systems in order to remove heat away from sensitive electronic and photonic components. Among passive thermal management techniques, heat pipes using phase-change heat transfer processes can have effective thermal conductivities an order of magnitude higher than any solid.

25 Embodiments described herein may use polymer material to fabricate the entire TGP structure. This may allow for ultra-thin and/or flexible device. The polymer may allow monolithic fabrication process to minimize the assembly and even ease the integration with the cooling target.

30 Some embodiments may have many features such as, for example, a wicking structure design utilizing two or more arrays of micro-posts, microfabrication of the TGP using copper/polymer processing, micro-posts supporting the vapor core to minimize deformation under high pressure, throttled releasing holes embedded in the micro-posts, atomic layer deposition (ALD) hydrophilic and/or hydrophobic coatings, throttled fluid

charging structure, defect-free ALD hermetic coating, and/or compliant structural design, etc.

In some embodiments, a thermal ground plane may be a passive thermal management device that uses phase -change processes to achieve thermal transport with low thermal resistance. Figures 1A and 1B shows an example of a polymer-based super-thin TGP 100 according to some embodiments. Figure 1A illustrates the operational principle of TGP 100, showing heat flow with dotted lines, vapor flow in dashed lines, and liquid flow in solid lines.

The TGP 100 shown in Figure 1B includes an evaporator 105, vapor core 115, condenser 110, and liquid wicking structure 120. In TGP 100, a heat transfer fluid (HTF) such as, for example, water and/or ammonia, in both liquid and vapor phases may be disposed within an internal cavity of the TGP. Heat may be absorbed at one section (the evaporator 105), causing the HTF in that area to evaporate. The heat may be carried by the evaporated HTF through the vapor core 115 to the cold section (the condenser 110) where the HTF condenses and rejects the heat from the condenser 110 to the outside. The now liquid-phase HTF is pulled back to the evaporator 105 with capillary forces that result from the geometry and surface chemistry of the liquid wicking structure 120, resulting in a closed fluid circulation cycle which experiences liquid-vapor phase-change including evaporation and condensation. The liquid wicking structure 120 may include pillars and/or a mesh (e.g., a woven metallic or polymer mesh).

In some embodiments, the wicking structure 120 may be fabricated as an array of microposts. The design of such a micropost array can be optimized in such a manner to minimize the thermal resistance between the evaporator 105 and the condenser 110, while maintaining certain geometric constraints such as a prescribed height, width, and/or length of the entire device, and/or operation parameters such as average temperature and wattage of heat to be transported. The optimization process may include two steps: first an acceptable range of pillar array geometries may be determined that prevents the system from experiencing dry-out, then the geometry which minimizes thermal resistance may be found from within that range.

Dry-out may occur when liquid is not pumped back to the evaporator 105 from the condenser 110 through the wick as fast as it is evaporated in the evaporator 105. The liquid wicking structure 120 may provide enough capillary pumping pressure to overcome pressure losses associated with the vapor flow through the vapor core 115 and liquid flow through the wicking structure 120. A denser array of pillars may, for example,

lead to greater capillary pumping pressure but also higher liquid pressure drop. In some embodiments, in order to lower the pressure drop associated with the wicking structure 120, a second array of microposts with a wider geometry may be fabricated between the evaporator 105 and the condenser 110.

5 Figure 2A is a graph illustrating a range of possible micropost geometries for a given constraint to prevent dry-out, with capillary pressure calculated according to the Young-Laplace equation and viscous pressure drops calculated according to Poiseuille's Law. In this example, the constrained total height is 0.2 mm, the operating temperature is 325 K, and the dissipating heat is 5 W.

10 Figure 2B is a schematic of a micropost design for a wicking structure 120 with two different array geometries in two different regions. A first region may include either or both the evaporator region 105 and/or the condenser region 110. A second region may include an axis region 135. For example, the cross-sectional area of the pillars in the first region may be greater than the cross-sectional area of the pillars in the second region. As
15 another example, the space between adjacent pillars (e.g., the average space between adjacent pillars) in the first region may be different than the space between adjacent the pillars in the second region.

Once a range of geometries is found, the thermal resistance of all acceptable geometries may also be found. Some details about finding thermal resistances may include thermal
20 conduction through the solid casing material and/or vapor transport losses. Total thermal resistances in an acceptable regime are shown in Figure 2b for given constraints according to some embodiments.

Some embodiments may include fabrication of a TGP. For example, some embodiments may include microfabrication of a TGP using copper/polymer processing that may allow
25 the geometric features to be controlled by lithography. This may allow, for example, for control of the geometry in order to attain any type of thermal performance.

Figures 3A and 3B illustrate a process 300 for fabricating a TGP according to some embodiments. Although illustrated as discrete blocks, various blocks may be divided into additional blocks, combined into fewer blocks, or eliminated, depending on the desired
30 implementation.

At block 1, a polymer 310 may be deposited onto a substrate 305 using any polymer deposition technique known in the art, such as, for example, casting, painting, thermal spray, dipping, and/or spin-coating. The substrate 305 may include a glass substrate. The

polymer may include any type of polymer material such as, for example, polyimide or any other polymer material.

At block 2, a first sacrificial layer 315 may be deposited on the polymer 305. In some embodiments, the first sacrificial layer may include a plurality of pillars. The plurality of
5 pillars, for example, may have any number of sizes and/or patterns. The first sacrificial metallic layer 315 may include a metal such as, for example, copper, aluminum, etc. In some embodiments, the first sacrificial layer 315 may be deposited on the polymer layer 310 by first depositing a seed layer and then electroplating the sacrificial layer 315 to the desired height. In some embodiments, the first sacrificial layer 315 may be etched into a
10 negative having a pillar pattern using a photolithographic technique. In some embodiments, the etched away regions of the metal may become polymer pillars using a polymer processing technique including casting, painting, thermal spray, dipping, and spin-coating.

At block 3, a second polymer 320 may be deposited onto the sacrificial layer 315 and/or
15 the first polymer layer 310. The second polymer 320, for example, may include a pillar and mesh layer (e.g., a woven metallic or polymer mesh layer). The second polymer 320, for example, may fill at least a portion of etched portions of the sacrificial layer 315 and/or cavities in the sacrificial layer 315.

At block 4, a masking layer 325, for example, comprising a metal such as copper, may be
20 deposited on the polymer 320. The shape, designed and/or pattern of the masking layer 325 may be defined by photolithography and/or may be etched. For instance, the masking layer 325 may have exposed regions 326.

At block 5, etching such as, for example, reactive ion etching (RIE) or any other etching
25 technique may be used to remove portions of the second polymer layer 320 exposed by the exposed regions of the masking layer 325. This etching may create the mesh structure 330 within the second polymer 320 layer. Following the etching, the masking layer 325 may be removed.

At block 6, a sacrificial vapor core layer 335 may be deposited on the second polymer
30 layer 320. The sacrificial vapor core layer 335 may comprise a metal such as, for example, copper. In some embodiments, the sacrificial vapor core layer 335 may be electroplated on the second polymer layer 320. Support cavities and/or inverted pillars and/or sidewalls in the sacrificial vapor core layer 335, for example, may be defined into the vapor core layer using any type of photolithography and/or etching technique.

Turning to Figure 3B, at block 7, a third polymer layer 340 may be deposited onto and/or into cavities in the sacrificial vapor core layer 335. The third polymer layer 340 may include pillars 341, side-walls, and/or a top layer 343. In some embodiments, the pillars may have a circular, polygonal, square, rectangular, or star shaped cross-section.

5 At block 8, a second masking layer may be deposited in a pattern to form release holes using a lithography technique. The second masking layer may be etched away along with the portions of the third polymer layer 340 beneath the release holes creating release holes 345 through the polymer layer.

10 At block 9 the sacrificial vapor core layer 335 may be removed with an acid that is introduced through the release holes 345 creating the vapor core 350. The sacrificial layer 315 may be removed with the acid that is introduced through the release holes 345 creating the liquid channel 355.

At block 10, the device may be removed from the substrate 305 with a substrate etchant (for example, hydrofluoric acid for a glass substrate).

15 At block 11, the releasing holes 345 may be filled with a polymer or epoxy to seal the top layer.

In some embodiments, the polymer layer 310 may have a thickness less than about 50 microns such as, for example, less than 25, 20, 15, 10, etc. microns.

20 In some embodiments, the third polymer layer 340 may have a thickness less than about 50 microns such as, for example, less than 25, 20, 15, 10, etc. microns.

In some embodiments, the vapor core 350 may have a thickness less than about 500 microns such as, for example, less than 250, 200, 150, 100, etc. microns.

In some embodiments, the liquid channel may have a thickness less than about 50 microns such as, for example, less than 25, 20, 15, 10, etc. microns.

25 Although process 300 is illustrated as discrete blocks, the various blocks of Figure 3 may be divided into additional blocks, combined into fewer blocks, or eliminated, depending on the desired implementation.

30 In some embodiments, materials other than copper can be used as the sacrificial layer(s) 315. These materials may include metals, as well as other polymers that can be subsequently released, for example thermally or photolithically decomposable polymers such as polycarbonate or norbornene-based polymers.

Various other manufacturing techniques may be used. For example, a sheet of rolled copper forming a copper base may be used for the vapor core. On this copper base, for example, the mesh structure 330 may be formed. The mesh structure 330, for example,

may be electroplated through lithographically-defined polymer electroplating masks. In some embodiments, the copper may grow into the shape desirable for the formation of a negative of the wicking structure. Once the wicking structure is electroplated, the masks may be removed, and replaced by a structural polymer. The copper composing the vapor
5 core can then be patterned and etched to define the supporting pillars and sidewalls. This fabrication method may, for example, replace all or portions of blocks 1-6.

In some embodiments, if the heat transfer fluid (HTF) experiences temperatures above its normal boiling temperature, there may be a positive pressure difference between the vapor core of the TGP and the outside ambient. In some embodiments, if the HTF ever
10 experiences temperatures below its normal boiling temperature, there will be a negative pressure difference between the vapor core of the TGP and the atmosphere around it. In some embodiments, pillars 360 may be embedded into the vapor core 350 to eliminate deformation of the top layer in the presence of pressure differentials. The pillars 360, for example, may be defined by etching the sacrificial copper that forms the vapor core. An
15 example, of such micro pillars is shown in Figure 4. In some embodiments, the pillars 360 may have a circular, oval, polygonal, square, star cross-sectional shape.

In some embodiments, the releasing holes 345 may be filled with sealing material in order to seal the top polymer layer. In some embodiments, the sealing material may be introduced as a viscous fluid into the releasing holes 345 that are suspended above the
20 vapor core channel may provide some control over where the fluid will flow. Capillary forces may pull the fluid away from the releasing hole, preventing sealing and causing flow resistance in the vapor core after the sealing fluid solidifies. Furthermore, when the TGP is flexed, the polymer or epoxy may crack. In order to gain control of the flow of the sealing fluid before it solidifies; the releasing holes may be embedded in the pillars,
25 with a throttled channel connecting the releasing hole to the sacrificial copper of the vapor core, as shown in Figures 5A and 5B. When polymer or epoxy is introduced as sealing fluid into the releasing hole 345, the throttled structure may prevent it from spreading into the vapor core 350. In some embodiments, when the TGP is flexed, the solid structure of the pillar will lower the stress around the polymer or epoxy material and
30 decrease the chances of cracks forming.

Figure 5A illustrates throttled releasing holes in a TGP after copper release, before a releasing hole is filled with epoxy. Figure 5B illustrates throttled releasing holes in a TGP after a releasing hole is filled with epoxy. In some embodiments, epoxy is prevented from entering the vapor core by the throttled design.

In some embodiments, the mesh structure 330 may have a surface chemistry that results in a low or high contact angle with the heat transfer fluid. For example, a hydrophilic and/or a hydrophobic coating may be applied to the mesh structure 330 to enhance evaporation or condensation. Atomic layer deposition (ALD), for example, may be used
5 to provide a conformal layer of hydrophobic or hydrophilic coatings onto the surfaces of the mesh structure 330. This deposition may take place before the release holes 345 are filled. Precursors to the ALD film can diffuse from a flow area above the TGP through the releasing holes, such that they deposit on the interior surface. In some embodiments, an adhesion layer of Al₂O₃ may be followed by a hydrophilic or hydrophobic layer.

10 In some embodiments, the TGP may be evacuated with a vacuum, charged with a heat transfer fluid, and/or the charging region may be subsequently sealed. To facilitate this, a charging structure may be fabricated. The charging structure may include a “T” junction . This structure may be patterned into the vapor core layer, and may include microposts to prevent the channel from collapsing when the system is evacuated. One arm of the “T”
15 connects to a macro-scale vacuum purge and fluid-charge system, while the other arm of the “T” connects to an epoxy injection system. Once the system is evacuated of non-condensable gasses and charged with heat transfer fluid, epoxy may be injected into the charging structure. A throttle at the end of the charging structure may prevent the epoxy from entering the vapor core. In some embodiments, once the epoxy is cured, the
20 charging structure may be cut away. An example structure and/or sealing method is/are shown in Figure 6.

Polymers may not be hermetic, and they may allow diffusion of small molecules including air molecules through them. In some embodiments, the flow of gas molecules into the vapor core of the TGP introduces non-condensable gasses, and the flow of HTF
25 out of the TGP constitutes a leak—both of which can be stopped by applying an ALD inorganic barrier coating to the outer area and/or surface of the TGP. ALD films will further prevent leaks through the epoxy used to seal the fluid charging structures and releasing holes. In some embodiments, to provide a defect-free film, a polymer thin film may be used to encapsulate any micron-sized particles or surface roughness associated
30 with the processing or charging. Furthermore, after the ALD films are deposited, a polymer thin film may be used to encapsulate and protect the ALD films.

Although polymers can provide a naturally compliant material for the TGP, the ALD inorganic films may crack under moderate strain. In order to prevent cracking or similar damage when the TGP is bent with a small radius, in some embodiments, a compliant

structure may be implemented. The compliant structure, for example, may reduce the strain associated with bending. In some embodiments, there may be two components to a compliant structure: an out-of-plane structure and an in-plane structure. In various embodiments, one or both may be used.

5 An example out-of-plane structure, which involves wavy structures in the top-most polymer layer, is shown in Figure 7A. The wavy structures can reduce the stiffness of the top-most layer, moving the neutral axis closer to the bottom layer, therefore reducing the stress and strain at the bottom when the TGP is bent, as shown in Figure 7B. Such a structure can be fabricated by forming a base micro-patterned mold (either by isotropic
10 etching in the vapor-core sacrificial copper layer, or patterning with other photo-definable polymers), coating the top polymer layer, and pressing of the top polymer layer with a micro-patterned mold as the polymer cures, as shown in Figure 7C.

Figure 7A illustrates an out of plane structure schematic according to some embodiments. Figure 7B illustrates an out of plane compliant structure reducing strain in the top and
15 bottom layers to less than 1%.

Figure 7C illustrates an example process flow to fabricate the out-of-plane wavy structures, including photographs of out-of-plane polymer wavy structures fabricated with this process. This process shows method to produce the structure using photo-definable
20 SU-8 followed by a polydimethyl siloxane (PDMS) layer to round the corners of the SU-8 and provide a barrier to prevent solvent incompatibility between the PDMS and the polyimide (PI).

An example in-plane structure is shown in Figure 8. Multiple parallel channels through which the liquid and vapor may flow are fabricated where the TGP will experience flexing. These channels will be given a wavy-profile in the plane of the polymer casting.
25 In some embodiments, no additional processing may be needed to fabricate these structures. Both the gap between the parallel channels and the walls of the channels will be minimized in size, in order to maximize the flow area and reduce the associated pressure drop. Wavy structures with large amplitude, short pitch, and thin channels may increase the compliance, while at increasing the pressure drop. In some embodiments, an
30 optimization process may be used to select the geometry of the wavy structure that meets both the compliance criteria and minimize the associated pressure drop.

In some embodiments, strain can be reduced if just one side of the layers includes sinusoidal-wavy structures, which may have an amplitude that is significantly thinner than the layer thickness and/or thicker than the ALD film thickness. In some

embodiments, the sinusoidal-wavy may have a wavelength no more than 5x the amplitude. For example, the optimized wavy structure may have an amplitude of 2 μm and wavelength of 10 μm .

In some embodiments, this structure can be fabricated using a PDMS mold that is stamped into polyimide as it cures, as shown in Figure 9.

In some embodiments, the fabrication of a TGP can be made without release-holes. For example, the pillars may be completely solid and/or etchant may be allowed to enter the TGP from the perimeter. In this case, the perimeter can be sealed by a flexible thermoforming or thermo-setting polymer, such as fluorinated ethylene propylene (FEP), through a lamination process. Figure 10 illustrates a TGP with a laminated perimeter according to some embodiments.

In some embodiments, the size and/or spacing of the pillars may vary based on need. For example, a wide spacing can cause the top and bottom layers to collapse, narrowing the hydraulic diameter and increasing the internal pressure drop. For example, a narrow spacing may result in too many pillars taking up the cross-sectional area that should be devoted to a flow path, resulting in a higher pressure drop.

In some embodiments, an optimum or nearly optimum pillar spacing can be found by minimizing the pressure drop through a given cross-sectional geometry as a function of pillar spacing, as shown in Figure 11B. In this example geometry, the optimal spacing is 0.4mm.

Figure 11A is a schematic illustration of a pillar spacing problem and Figure 11B illustrates an optimization curve for optimized pillar spacing according to some embodiments.

Some fabrication methods can cause leakage through the final spin-coating layers. To avoid these leaks, in some embodiments, further sealing of the structure may be facilitated by laminating a continuous sheet of thermosetting or thermoforming polymer covering the surface.

In some embodiments, condensation of the liquid along the top layer of the TGP may result in restrictions to the flow of vapor, and thus degrading the performance. The liquid can be dispersed through a mesh structure along the top layer. This can be formed for example by etching or electroplating an array micropillars into the sacrificial copper after the pillar-structure has been defined. This can occur, for example, after step 6 in Figure 3.

Some embodiments may include an alternative to the fabrication scheme shown in Figure 3. For example, the fabrication may be based around metal foil as the sacrificial layer which eventually defines the largest layer, e.g. the vapor core. Starting with the foil, the fabrication may proceed as shown in Figure 12A.

5 At block 1, a micropillar scaffold 1210 may be photo-patterned onto the bottom of a foil 1205.

At block 2, micropillars may be etched through the scaffold 1210 to form the image of the wicking structure 1215.

10 At block 3, a polymer-coating 1220 may be deposited on the foil 12-5, which may form at least a portion of the wicking structure.

At block 4, an image of pillars 1225 may be photo-patterned and/or etched through the foil 1205 to form pillars 1225 in the foil 1205. The pillars, for example, may be made from copper.

15 At block 5 in Figure 12B, an additional micropillar scaffold may be created as a top wicking structure 1230.

At block 6, a polymer-coating may be applied on top of the wicking structure 1230, forming a secondary wick, pillars, and/or topmost structural layer.

At block 7, the pillars 1225 may be etched away leaving a vapor chamber.

20 At block 8, an ALD coating may be applied and/or the perimeter may be sealed. In some embodiments, a charge port 1245 may also be added for charging the TGP and may be sealed once charged.

Although illustrated as discrete blocks, various blocks of Figures 12A and 12B may be divided into additional blocks, combined into fewer blocks, or eliminated, depending on the desired implementation.

25 Figure 13 illustrates a TGP 1300. The TGP 1300, for example, may be fabricated using the process shown in Figure 12. The TGP 1300, for example, may have a thickness less than about 0.5 mm, 0.2 mm, 0.1 mm, 0.05 mm, etc.

30 The TGP 1300 includes a top cover coat 1305 and/or a bottom cover coat 1306. The top cover coat 1305 and/or the bottom cover coat 1306 may comprise fluorinated ethylene propylene or other polymer material.

The TGP 1300 may also include a top polymer layer 1310 and/or a bottom polymer layer 1311. The top polymer layer 1310 and/or the bottom polymer layer 1311 may comprise any type of polymer material such as, for example, polyimide.

A bottom mesh 1320 may be deposited on or may be coupled with the bottom polymer layer 1310. The bottom mesh 1320 may comprise a polymer layer that may include a woven mesh or a plurality of pillars.

A top mesh 1325 may be deposited on or may be coupled with the top polymer layer 1311.

5 The top mesh 1325 may comprise a polymer layer that may include a woven mesh or a plurality of pillars. The top mesh 1325, for example, may be a condensate collection mesh.

10 The vapor core 1330 may be formed between the top mesh 1325 and the bottom mesh 1320. The vapor core may include a plurality of pillars 1315 that are disposed throughout the vapor core in any type of spacing between pillars 1315 and/or configurations. The bottom mesh 1320, for example, may be a condensate collection mesh.

Edge seal 1335 may form a seal the vapor chamber 1330. The edge seal 1335 may comprise fluorinated ethylene propylene or other polymer material.

15 In some embodiments, the TGP 1300 can be designed with a vapor-core 1330 and/or liquid-channel thickness designed by minimizing the thermal resistance through the TGP 1300 while adhering to the physical constraints that the TGP 1300 be less than 0.1 mm in total thickness and that the pressure drops associated with the liquid and vapor are smaller than the capillary pumping pressure.

20 This can be done, for example, as shown in Figure 14 and/or Figure 15, showing an example or optimal vapor core thickness of 0.065 mm for a device with a total thickness of 0.1 mm.

In some embodiments, a thermal ground plane 1600 can be integrated with a printed circuit board (PCB) 1605 as shown in Figure 16. The TGP 1600 includes liquid channels 1610, wicking mesh 1615, and/or vapor core pillars 1620. While two wicking mesh and liquid channels 1610 are shown, in some embodiments only one may be used. In some
25 embodiments, heat may be transferred from one side of the TGP 1600 to the other side of TGP 1600. The liquid condensed on the bottom of the TGP 1600 may be collected and delivered back to the top of the TGP 1600. In some embodiments, one or two sets of wicking layers 1615 and/or liquid returning channels 1610 may be used. In some
30 embodiments, electrical vias 1625 may pass through the TGP 1600. For example, vias 1625 may pass through the TGP 1600 through the vapor core pillars 1620. In some embodiments, heat generated in different components on the PCB 1605 may be transferred to the TGP 1600 through thermal vias 1630.

Figure 17 illustrates a cross-sectional view of a TGP coupled with a PCB according to some embodiments. Thermal vias and electrical vias and their connections to the TGP or through the TGP are illustrated in the figure. The double sets of wicking layers and liquid returning channels are also illustrated.

5 Figures 18A and 18B illustrate an example process for fabricating a TGP integrated with a PCB according to some embodiments. A PCB 1800 is provided in block (a). Thermal vias 1805 may be fabricated in the PCB 1800 as shown in block (b).

At block (c), various TGP layers may be fabricated on top of the PCB 1800. These TGP layers may include any TGP layer or structure described in this document. These layers
10 may include, for example, a bottom polymer layer 1815; a bottom sacrificial layer 1820; and a bottom wicking polymer layer 1825. The bottom sacrificial layer 1820 may be a copper layer.

At block (d) the wicking polymer layer 1825 may be etched with a micro-structured pattern 1830.

15 At block (e) pillars 1835 may be fabricated. The pillars 1835 may comprise a polymer. The pillars 1835, for example, may be surrounded by a thick sacrificial copper layer 1840. When the sacrificial copper layer 1840 is removed, the resulting space may form the vapor core of the TGP.

At block (f) a top polymer wicking layer 1850 and/or a liquid returning channel 1845
20 layer may be fabricated.

At block (g) in Figure 18B the fabrication of the multilayered structures may be completed with the top enclosure layer 1855 with release holes 1860 etched. These release holes 1860 may be needed to introduce liquid or vapor etchant to remove the sacrificial copper layer 1840 and/or other layers.

25 At block (h) the sacrificial copper layer 1840 and/or other layers may be removed by etchant introduced through the release holes 1860. The vapor core 1865 may be created with the removal of the sacrificial copper layer 1840. Other wicking and/or mesh layers may also be formed with the removal of the sacrificial copper layer 1840.

At block (i) various portions within the TGP structure may be coated with atomic layer
30 deposition layers for hydrophilic or hydrophobic properties and/or for sealing polymer from water to be charged. Hermetic sealing of polymer may be important in some embodiments because outgassing from the polymer could generate non-condensable gas that would degrade TGP performance. In addition, the release holes will be sealed by another polymer, glass or metal materials.

At block (j) the air inside the structure may be sealed and/or may be vacuum-removed, after which water may be charged into the structure. In some embodiments, the charging port can be a copper tube or polymer connectors to be hermetically sealed by additional atomic layer deposition.

5 At block (k) the charging port may be sealed after charging.

At block (i) an ALD coating may be applied to encapsulate the entire exterior surface of the TGP to hermetically seal the entire system. Various other sealing techniques may be used before or after charging of the TGP. It should be noted that all the ALD coatings mentioned herein can be replaced by other coating processes such as chemical vapor
10 deposition or physical metal deposition processes.

In some embodiments a single set of wicking layer and/or liquid returning channel layers may be applied for a thinner TGP with evaporators and condensers placed on the same side of the TGP.

Figure 19A illustrates electrical vias fabricated through the polymer layers in a TGP
15 according to some embodiments. Such a via fabrication process can include hole drilling process followed by electroplating used by PCB manufacturing. Figure 19B illustrates electrical vias in a TGP that can be connected to electrical interconnects, vias or bonding pads on the PCB.

In some embodiments, several pre-fabricated flexible circuit boards can be laminated into
20 a single PCB with TGP integrated as illustrated in Figure 20. The top and the bottom flexible circuit boards can carry electronic components. The flexible circuit boards can be fabricated with different structures for wicking, vapor core and liquid returning channels.

Some embodiments of the invention may use a mixture of liquids as the heat transfer fluid. For example, some embodiments, may use some combination of water, acetone,
25 isopropanol, ethanol, methanol, etc., as the heat transfer fluid. Some embodiments may use other natural and artificial fluids as the components of the heat transfer fluid. Some embodiments may use azetropic fluid mixtures whereby the vapor and liquid compositions are the same. Some embodiments may use non-azetropic mixtures, whereby the vapor-phase composition differs from the liquid-phase composition.

30 Some embodiments of the invention may use a fluid composed of a high surface tension liquid (e.g. water, ammonia, etc., or mixtures thereof) and a high vapor pressure fluid (e.g. acetone, isopropanol, ethanol, etc. and mixtures thereof).

Figure 21 illustrates a top view of another TGP 700 and Figures 22A, 22B, and 22C illustrate side views of the TGP 700 according to some embodiments. The TGP 700

includes a top layer (805 in Figure 22) and a bottom layer 705. Figure 21 shows the TGP 700 with the top layer 805 removed. The top layer 805 and/or the bottom layer 705 may include copper and/or polyimide material. In some embodiments, the top layer 805 and/or the bottom layer 705 may include layers of both copper and polyimide.

5 The TGP 700 includes a mesh return layer 715 that includes a plurality of return arteries 710 formed or cut within the mesh return layer 715. In some embodiments, the return arteries 710 may not extend into the evaporator region 720 of the TGP 700. In some embodiments, the width of the return arteries 710 may be less than 30 microns. In some
10 embodiments, the width of the return arteries 710 may be less than 100 microns. In some embodiments, the mesh return layer 715 may include a wick. In some embodiments, the mesh return layer 715 may include a steel mesh such as, for example, a mesh with wires that are less than 50 microns or 25 microns thick. In some embodiments, the mesh return layer 715 may include a mesh with a simple weave at 200, 300, 400, 500, 600, 700, etc. wires/inch. In some embodiments, the mesh return layer 715 may be electroplated with
15 copper. The mesh return layer 715 may include a specified evaporator region that may provide a specific location for a heat source. In some embodiments, the mesh return layer 715 may have a thickness of about 40 microns.

The mesh return layer 715 may have any number of shapes and/or configurations. In some embodiments, the mesh return layer 715 may have a polygonal or circular shape. In
20 some embodiments, the mesh return layer 715 may have multiple sections without return arteries 710. In some embodiments, the mesh return layer 715 may include any number, shape or configuration of return arteries 710. In some embodiments, the return arteries 710 may have one or more pillars or other mechanisms disposed within the return arteries 710.

25 In some embodiments, return pillars 835 (see Figure 22) may extend from the bottom layer 705 through the return arteries 710 of the mesh return layer 715. In some embodiments, the return pillars 835 may form vapor regions running parallel to the mesh return layer 715. In some embodiments, the return pillars 835 may form arteries in the adiabatic and/or condenser regions of the TGP 700.

30 The return pillars 835 may have at least one dimension that is smaller than the width of the return arteries 710. In some embodiments, these pillars may have at least one dimension (e.g., height, width, length, diameter, etc.) that is less than 10 microns. In some embodiments, these pillars may have at least one dimension (e.g., height, width, length, diameter, etc.) that is less than 50 microns. In some embodiments, these pillars

may have at least one dimension (e.g., height, width, length, diameter, etc.) that is less than 100 microns.

Figure 22A shows a side view of TGP 700 cut through Section A shown in Figure 21. In Figure 22A, the TGP 700 is cut through a region where a return arteries 710 extends along a portion of the mesh return layer 715. As shown in Figure 22A, the mesh return layer 715 is present in the evaporator region. The return pillars 835 are shown extending through the return arteries 710. The TGP 700 also includes a plurality of top pillars 825 disposed on the top layer 805. The top pillars 825 may have at least one dimension (e.g., height, width, length, diameter, etc.) that is larger than the return pillars 835. The top pillars 825 may have at least one dimension (e.g., height, width, length, diameter, etc.) that is larger than 0.25 mm, 0.5 mm, 0.75 mm, 1.0 mm, 1.25 mm, etc.

In some embodiments, the TGP 700 may include a micro wick layer 815. The micro wick layer 815, for example, may include a plurality of pillars (e.g., electroplated pillars). The micro wick layer 815 may have at least one dimension (e.g., pillar height, width, length, diameter, pitch, etc.) that is smaller than the return pillars 835. The micro wick layer 815 may have at least one dimension (e.g., height, width, length, diameter, etc.) that is smaller than 5 μm , 10 μm , 15 μm , 20 μm , 25 μm , etc. The micro wick layer 815 may be aligned with the return arteries 710.

Figure 22B shows a side view of TGP 700 cut through Section B shown in Figure 21. In Figure 22B, the TGP is cut through a region without the return arteries 710 extending along a portion of the mesh return layer 715. Instead, the mesh return layer 715 extends along the length of the TGP 700 along this section of the TGP 700.

Figure 22C shows an end view of TGP 700 cut through Section C shown in Figure 21. In Figure 22C, the TGP is cut through the mesh return layer 715 showing both the mesh return layer 715 and the return arteries 710 formed in the mesh return layer 715. In some embodiments, the return pillars 835 may extend through the return arteries 710. In some embodiments, one or more of the return pillars 835 may contact one or more of the top pillars 825.

In some embodiments, the top layer 805 and the bottom layer 705 are sealed along at least one edge of the top layer 805 and along at least one edge of the bottom layer 705. In some embodiments, the top layer 805 and the bottom layer 705 are sealed along at least two edges of the top layer 805 and along at least two edges of the bottom layer 705.

In some embodiments, a buffer region can be created by design to collect and store any non-condensable gas through passive convection. For example, a space of a few

millimeters can be formed in the area outside the mesh (e.g., outside the mesh region shown in Figure 6). This space can be added prior to bonding. This space may collect any non-condensable gases that would move to this space because of its different density, and thus its effect on evaporation and condensation can be reduced substantially.

5 Various other sealing techniques may be used such as, for example, thermosonic or thermo-compression bonding, ultrasonic welding, laser welding, electron beam welding, electroplating; , solder sealing with alloys with negligible reaction with water;, and polymer bonding encapsulated by moisture barrier coatings such as atomic layer deposition (ALD)-based coatings.

10 Some embodiments may include a pillar-enabled TGP. In some embodiments, the TGP may include a copper-cladded Kapton film that includes three layers. These layers may, for example, include copper and Kapton layers. Each layer may be about 12 um thick. In some embodiments, a stainless steel woven mesh may be included and may have a thickness less than 75 um. In some embodiments, the pillars may allow for fluid and/or
15 vapor transport between the pillars under different mechanical loadings.

In some embodiments, a plurality of pillars may be formed on a copper layer (e.g., the top layer and/or the bottom layer) using any of various lithography lithographic patterning processes.

In some embodiments, a copper-encapsulated stainless steel mesh may be sandwiched
20 between the top layer and the bottom layer. The stainless steel mesh, for example, may have a weave that is less than 75 microns in thickness. In some embodiments, the mesh may be copper encapsulated. In some embodiments, the mesh may be hydrophilic. In some embodiments, the reaction of the mesh with water may be negligible.

In some embodiments, a TGP may include a mesh-pillar wicking structure. The mesh-
25 pillar wicking structure may allow the TGP to achieve a low capillary radius (high p umping pressure) in the evaporation regions and/or a higher flow hydraulic radius (low flow pressure drop) in the fluid channel.

In some embodiments, a TGP may include pillars with rounded heads. For example, the pillars may be formed with controlled over-plating. In some embodiments, the pillars
30 may form very sharp angle at the interface between a pillar and the mesh bonded. In some embodiments, these sharp angles may be used, for example, to enhance the capillary p umping force pulling the liquid returned from the condenser to the evaporator.

In some embodiments, a plurality of star-shaped pillars may be constructed on either the top layer and/or the bottom layer that have a star-shaped polygon various cross section.

In some embodiments, a plurality of hydrophilic pillars may be constructed on either the top layer and/or the bottom layer.

In some embodiments, heat rejection through condensation can be distributed throughout the external surface of the TGP.

- 5 In some embodiments, pillars and/or spacers may be disposed on a layer with densities (spacing between pillars or spacers) that vary across the layer, with diameters that vary across the layer, with spacing that vary across the layer, etc.

The Figures are not drawn to scale.

- 10 The term “substantially” means within 5% or 10% of the value referred to or within manufacturing tolerances.

- Numerous specific details are set forth herein to provide a thorough understanding of the claimed subject matter. However, those skilled in the art will understand that the claimed subject matter may be practiced without these specific details. In other instances, methods, apparatuses, or systems that would be known by one of ordinary skill have not
15 been described in detail so as not to obscure claimed subject matter.

- Some portions are presented in terms of algorithms or symbolic representations of operations on data bits or binary digital signals stored within a computing system memory, such as a computer memory. These algorithmic descriptions or representations are examples of techniques used by those of ordinary skill in the data processing art to
20 convey the substance of their work to others skilled in the art. An algorithm is a self-consistent sequence of operations or similar processing leading to a desired result. In this context, operations or processing involves physical manipulation of physical quantities. Typically, although not necessarily, such quantities may take the form of electrical or magnetic signals capable of being stored, transferred, combined, compared, or otherwise
25 manipulated. It has proven convenient at times, principally for reasons of common usage, to refer to such signals as bits, data, values, elements, symbols, characters, terms, numbers, numerals, or the like. It should be understood, however, that all of these and similar terms are to be associated with appropriate physical quantities and are merely convenient labels. Unless specifically stated otherwise, it is appreciated that throughout
30 this specification discussions utilizing terms such as “processing,” “computing,” “calculating,” “determining,” and “identifying” or the like refer to actions or processes of a computing device, such as one or more computers or a similar electronic computing device or devices, that manipulate or transform data represented as physical, electronic, or

magnetic quantities within memories, registers, or other information storage devices, transmission devices, or display devices of the computing platform.

The system or systems discussed herein are not limited to any particular hardware architecture or configuration. A computing device can include any suitable arrangement
5 of components that provides a result conditioned on one or more inputs. Suitable computing devices include multipurpose microprocessor-based computer systems accessing stored software that programs or configures the computing system from a general-purpose computing apparatus to a specialized computing apparatus implementing one or more embodiments of the present subject matter. Any suitable programming,
10 scripting, or other type of language or combinations of languages may be used to implement the teachings contained herein in software to be used in programming or configuring a computing device.

Embodiments of the methods disclosed herein may be performed in the operation of such computing devices. The order of the blocks presented in the examples above can be
15 varied—for example, blocks can be re-ordered, combined, and/or broken into sub-blocks. Certain blocks or processes can be performed in parallel.

The use of “adapted to” or “configured to” herein is meant as open and inclusive language that does not foreclose devices adapted to or configured to perform additional tasks or steps. Additionally, the use of “based on” is meant to be open and inclusive, in
20 that a process, step, calculation, or other action “based on” one or more recited conditions or values may, in practice, be based on additional conditions or values beyond those recited. Headings, lists, and numbering included herein are for ease of explanation only and are not meant to be limiting.

While the present subject matter has been described in detail with respect to specific
25 embodiments thereof, it will be appreciated that those skilled in the art, upon attaining an understanding of the foregoing, may readily produce alterations to, variations of, and equivalents to such embodiments. Accordingly, it should be understood that the present disclosure has been presented for-purposes of example rather than limitation, and does not preclude inclusion of such modifications, variations, and/or additions to the present
30 subject matter as would be readily apparent to one of ordinary skill in the art.

WHAT IS CLAIMED IS:

1. A method for forming a thermal ground plane comprising:
depositing a first sacrificial layer in a first pattern on a first polymer layer;
depositing a second polymer later on the first sacrificial layer;
5 depositing a second sacrificial layer on the second polymer layer.
depositing a first masking layer on the second polymer layer having a plurality of
exposed regions that expose portions of the second polymer layer;
etching portions of the second polymer layer that are exposed by the first masking
layer;
10 removing the first masking layer;
depositing a sacrificial vapor core layer in a pattern on the second sacrificial layer;
depositing a third polymer layer on the sacrificial vapor core layer;
depositing a second masking layer on the third polymer layer having a plurality of
exposed regions that expose portions of the third polymer layer;
15 etching portions of the third polymer layer that are exposed by the second
masking layer;
removing the second masking layer;
removing portions of the sacrificial vapor core layer using the holes in the third
polymer layer; and
20 sealing the holes in the third polymer layer.
2. The method according to claim 1, further comprising depositing the first
polymer layer on a substrate.
3. The method according to claim 1, wherein after removing portions of the
sacrificial vapor core layer the third polymer layer forms a plurality of pillars.
- 25 4. The method according to claim 1, wherein the first pattern comprises a
negative of a plurality of pillars.
5. The method according to claim 1, wherein the second polymer layer
comprises a mesh layer.
6. The method according to claim 1, wherein the masking layer comprises a
30 metal.
7. The method according to claim 1, wherein the masking layer comprises a
plurality of exposed regions.
8. The method according to claim 1, where the sacrificial vapor core layer
may be electroplated on the second polymer layer.

9. The method according to claim 1, where the vapor core layer form a plurality of pillars.

10. The method according to claim 1, wherein removing portions of the sacrificial vapor core layer using the holes in the third polymer layer further comprises
5 introducing an acid through the holes in the third polymer layer.

11. The method according to claim 1, wherein the sacrificial vapor core layer has a thickness of less than 200 microns.

12. The method according to claim 1, wherein the second polymer layer has a thickness of less than 50 microns.

10 13. The method according to claim 1, wherein the first polymer layer has a thickness of less than 50 microns.

14. The method according to claim 1, wherein removing portions of the sacrificial vapor core layer using the holes in the third polymer layer further comprises removing portions of the first sacrificial layer.

15 15. The method according to claim 1, wherein depositing a third polymer layer on the sacrificial vapor core layer further comprises depositing the third polymer layer into cavities or channels in the sacrificial vapor core layer.

16. A thermal ground plane comprising:
a bottom layer;
20 a mesh layer bonded with the bottom layer
a vapor core having a plurality of pillars bonded with the mesh layer; and
a top layer.

17. The thermal ground plane according to claim 16, wherein either or both the top layer and the bottom layer comprise an in-plane wavy structure.

25 18. The thermal ground plane according to claim 1, wherein either or both the top layer and the bottom layer comprise an out-of-plane wavy structure.

19. The thermal ground plane according to claim 16, wherein either or both the top layer and the bottom layer comprise a polymer.

30 20. The thermal ground plane according to claim 16, wherein the plurality of pillars comprise a polymer.

21. The thermal ground plane according to claim 16, wherein the mesh layer comprises a polymer.

22. The thermal ground plane according to claim 16, wherein the mesh layer comprises one or more pillars and/or one or more microposts.

23. The thermal ground plane according to claim 16, wherein the one or more pillars have a star cross-section shape.

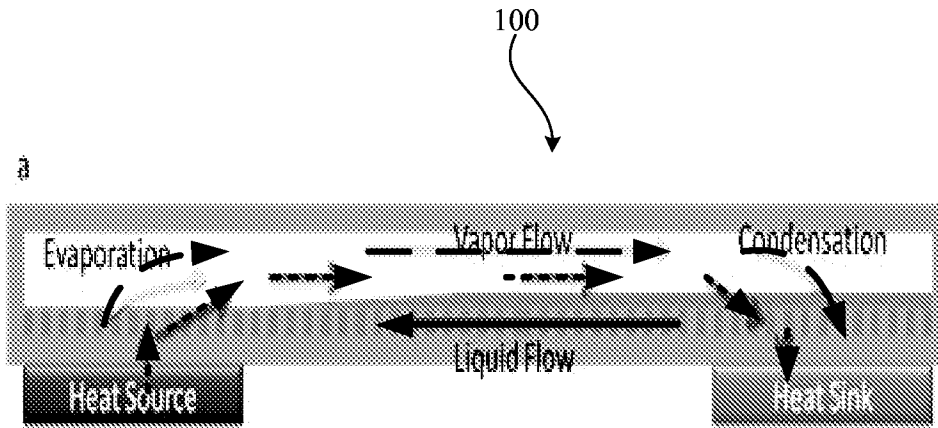


Figure 1A

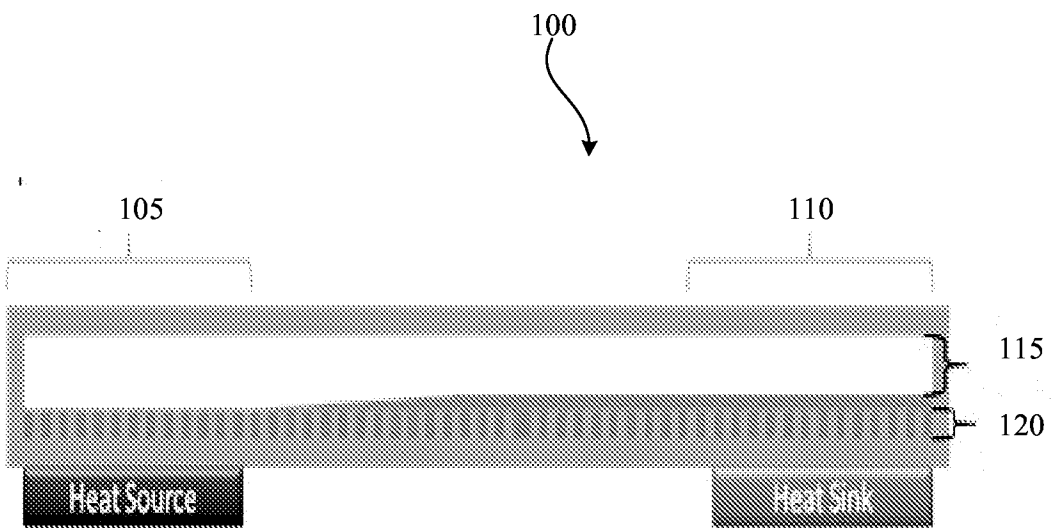


Figure 1B

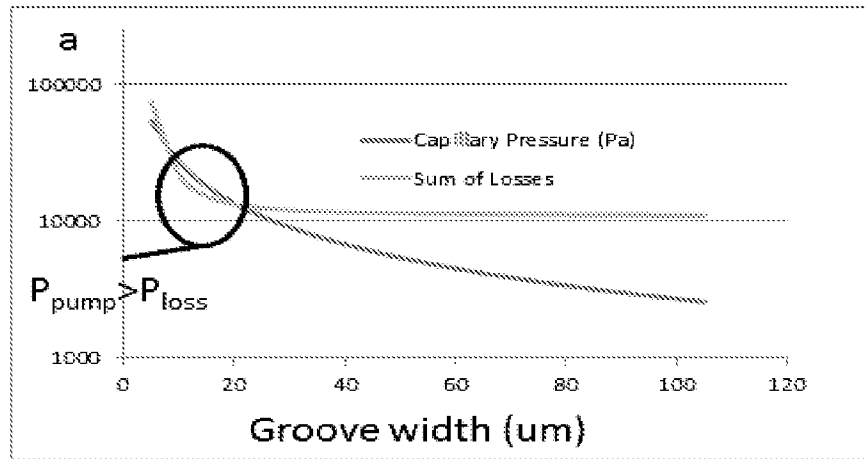


Figure 2A

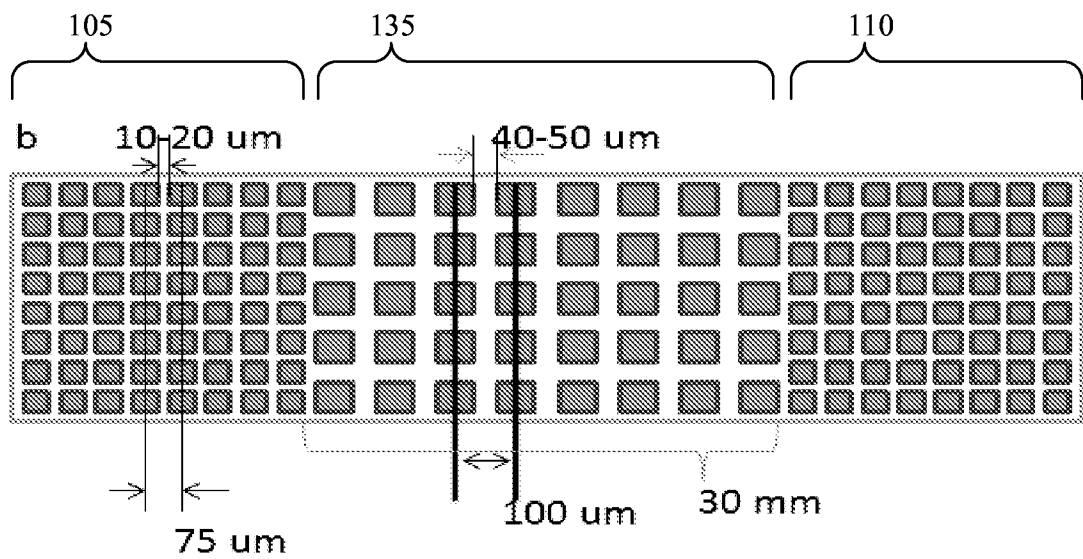


Figure 2B

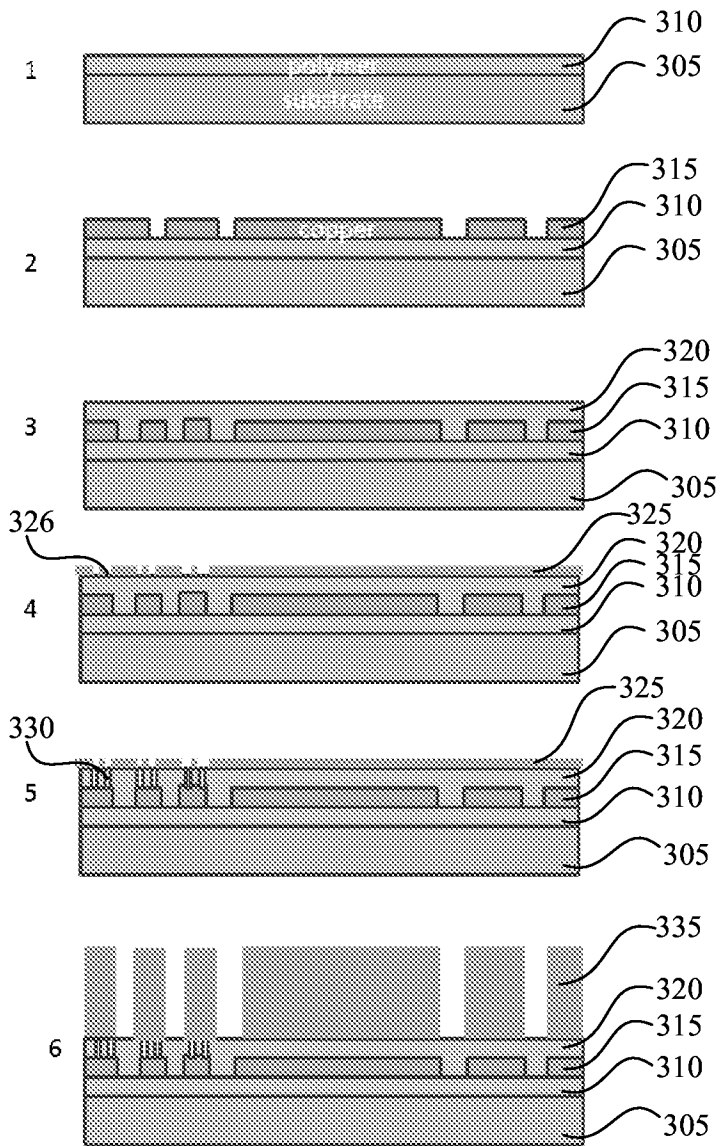


Figure 3A

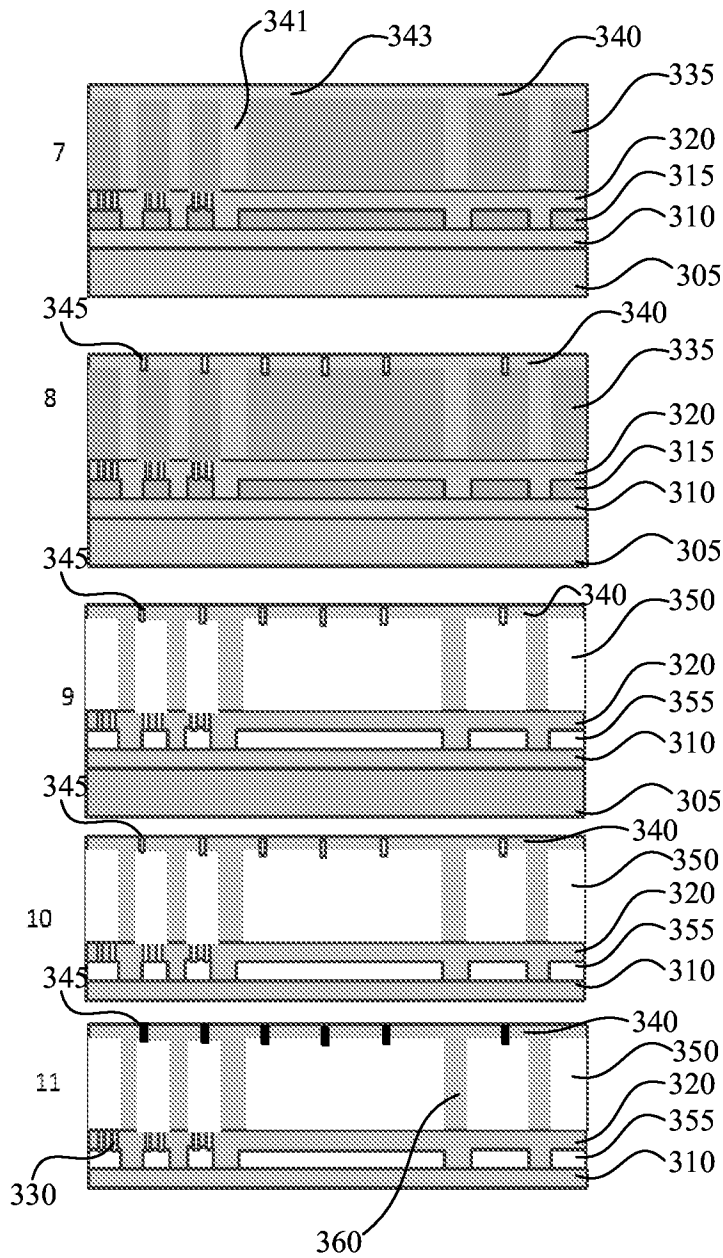
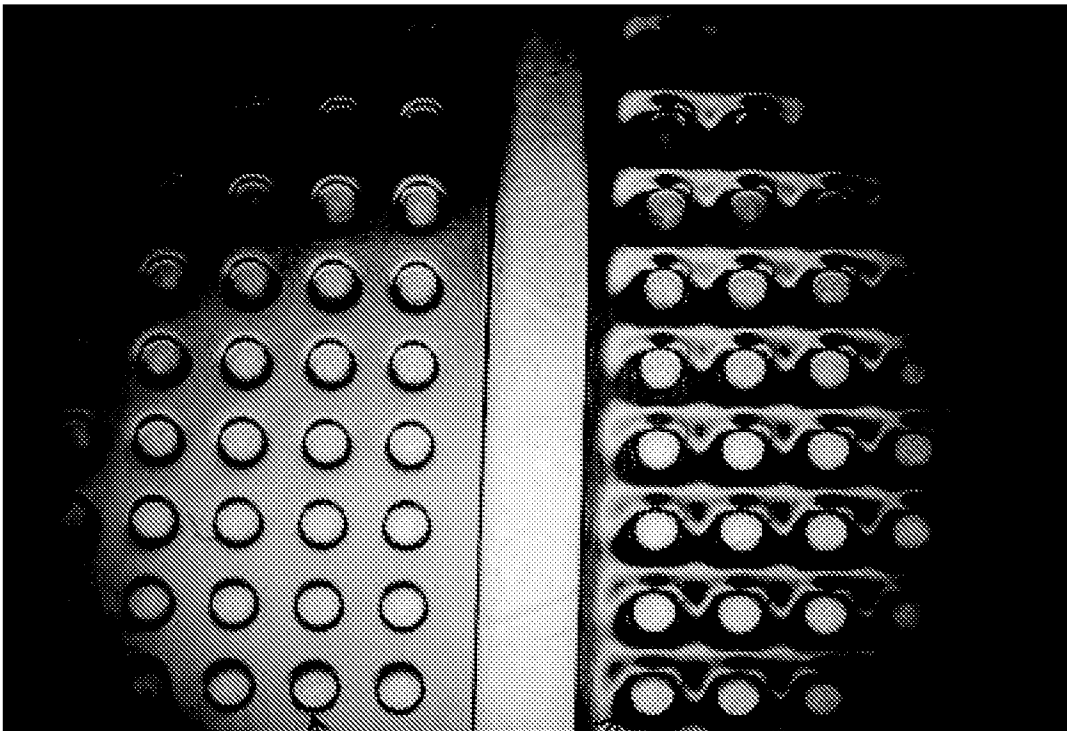


Figure 3B



Posts etched through copper,
Filled with polymer structural material

Figure 4



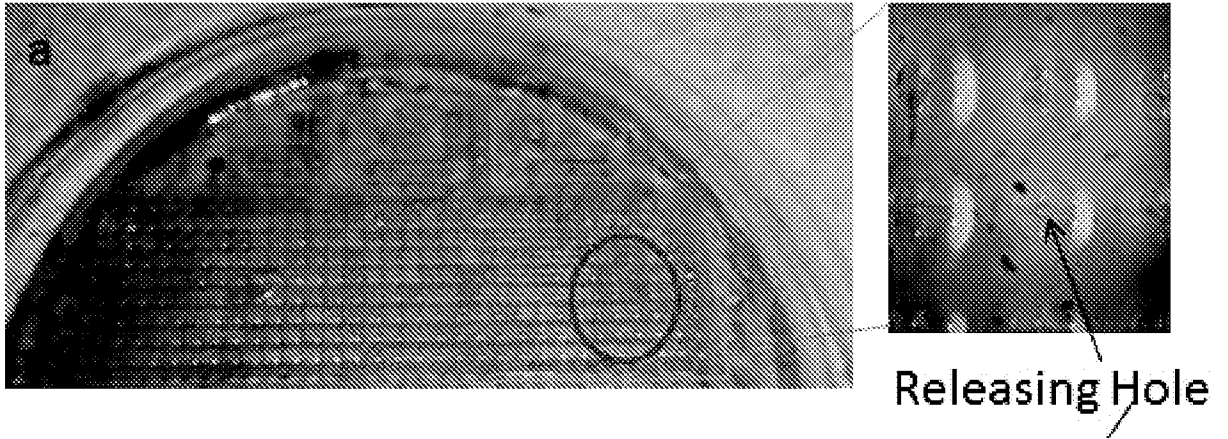


Figure 5A

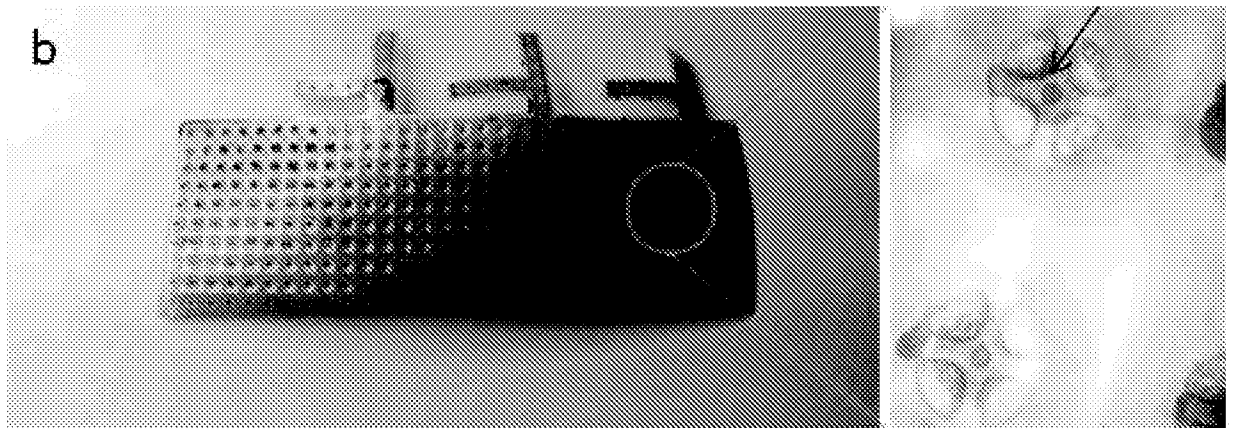


Figure 5B

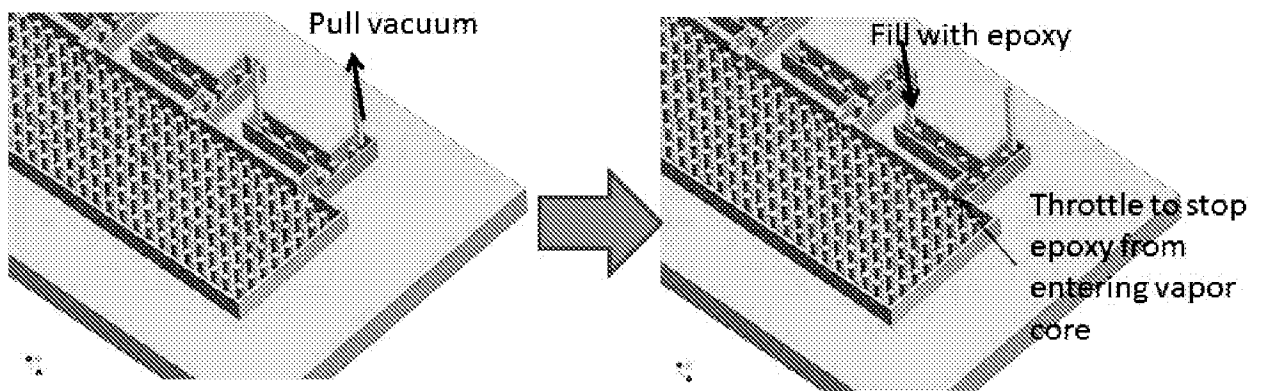


Figure 6



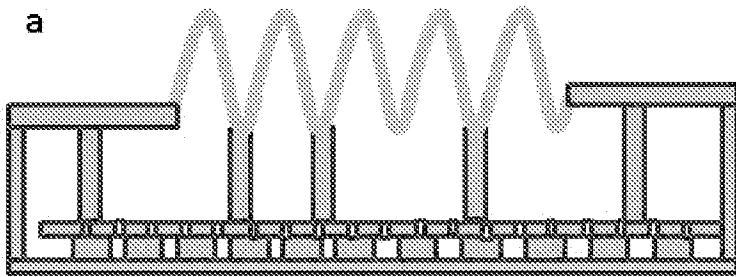


Figure 7A

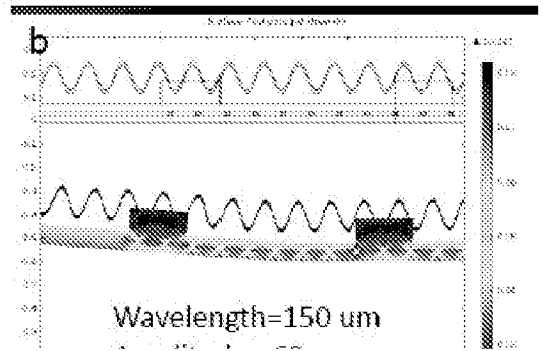


Figure 7B

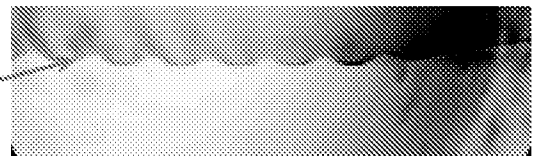
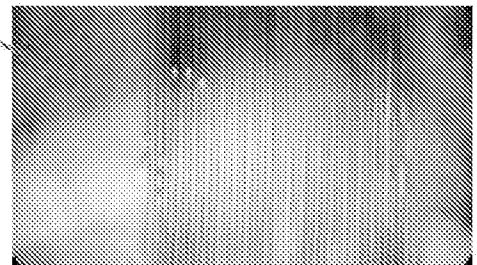
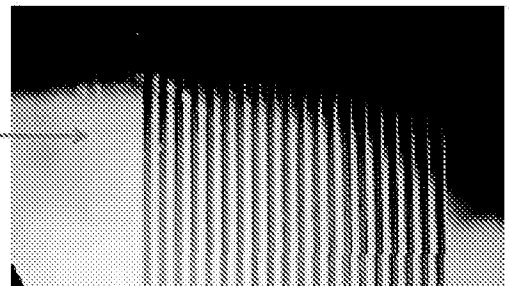
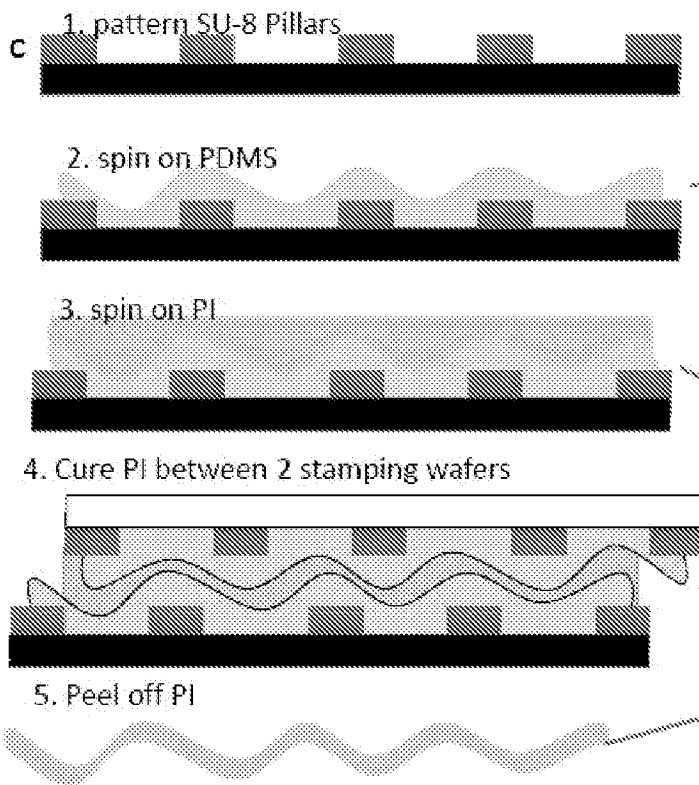


Figure 7C

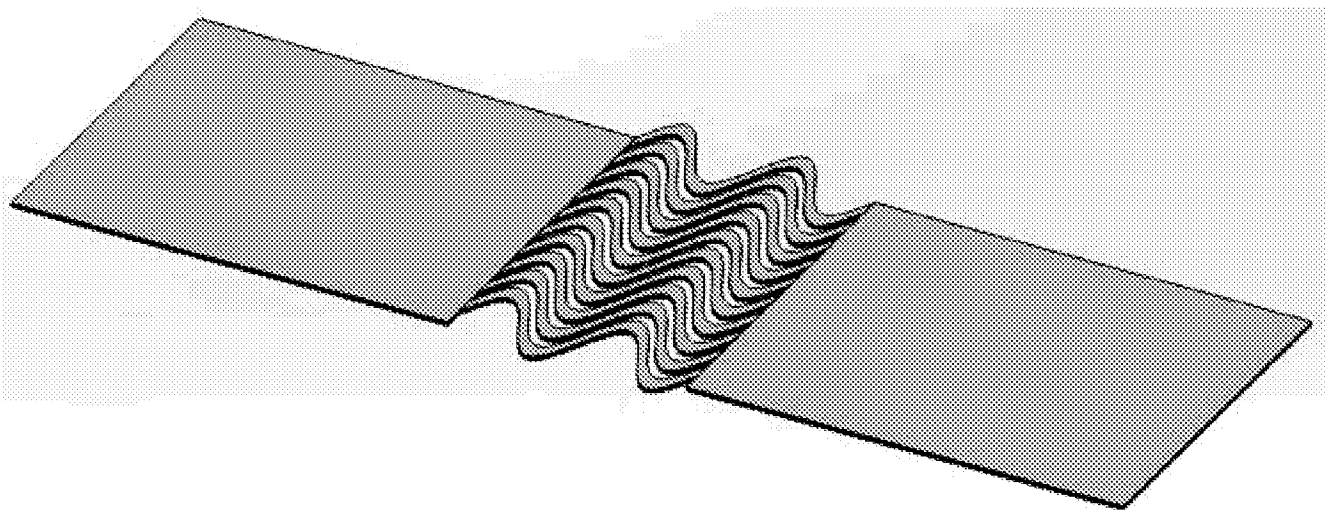


Figure 8



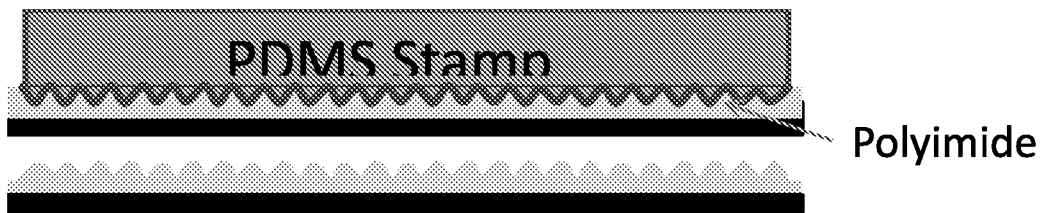


Figure 9



11/25



Figure 10



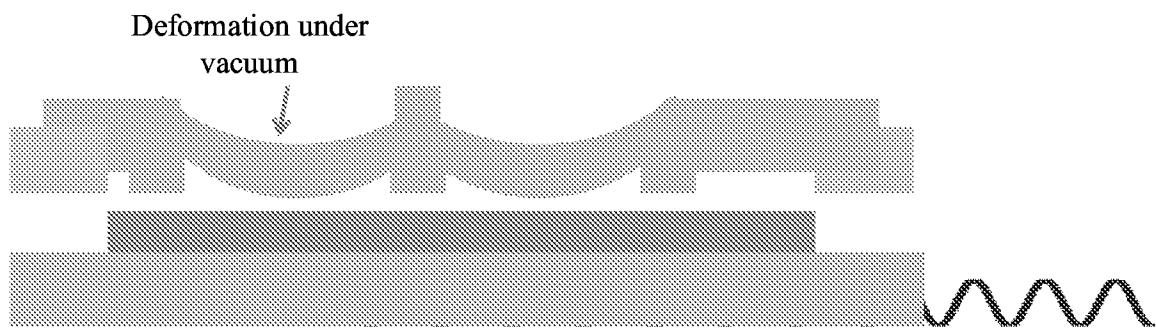


Figure 11A

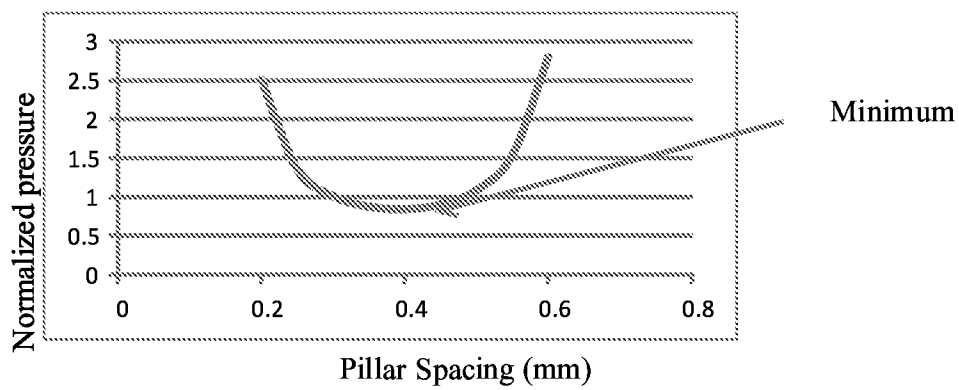


Figure 11B



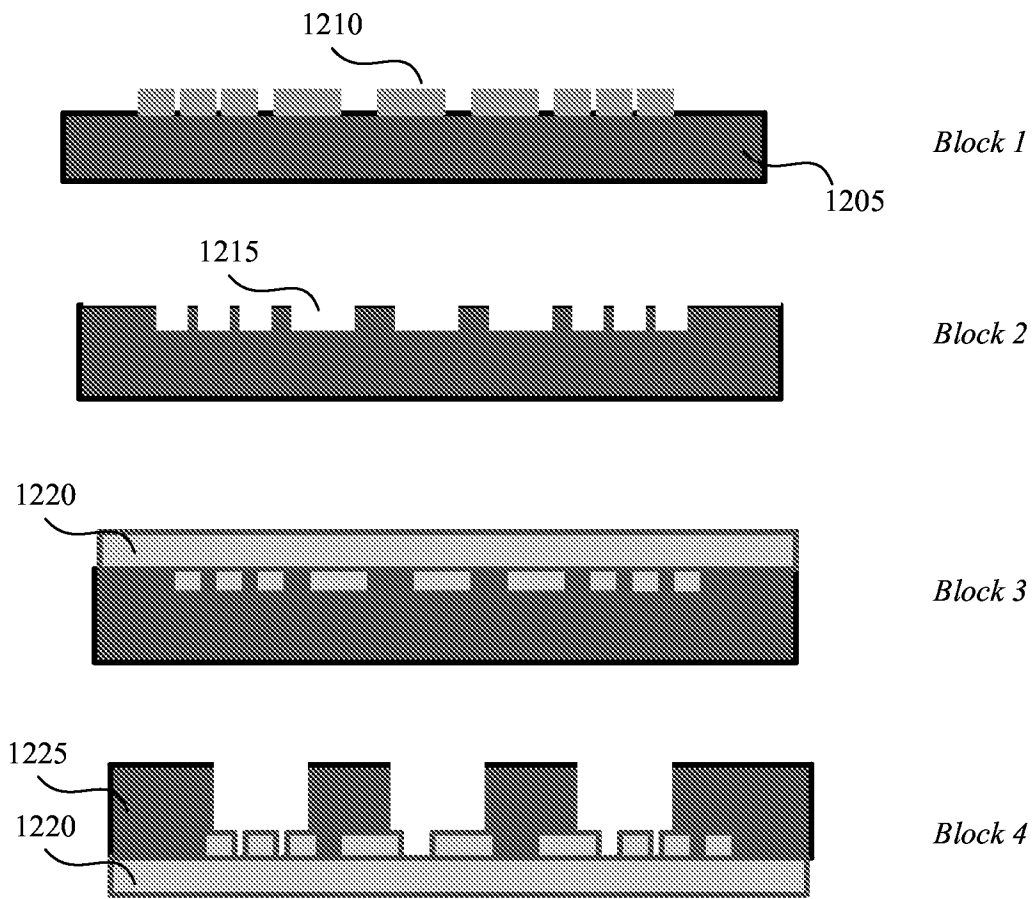


Figure 12A



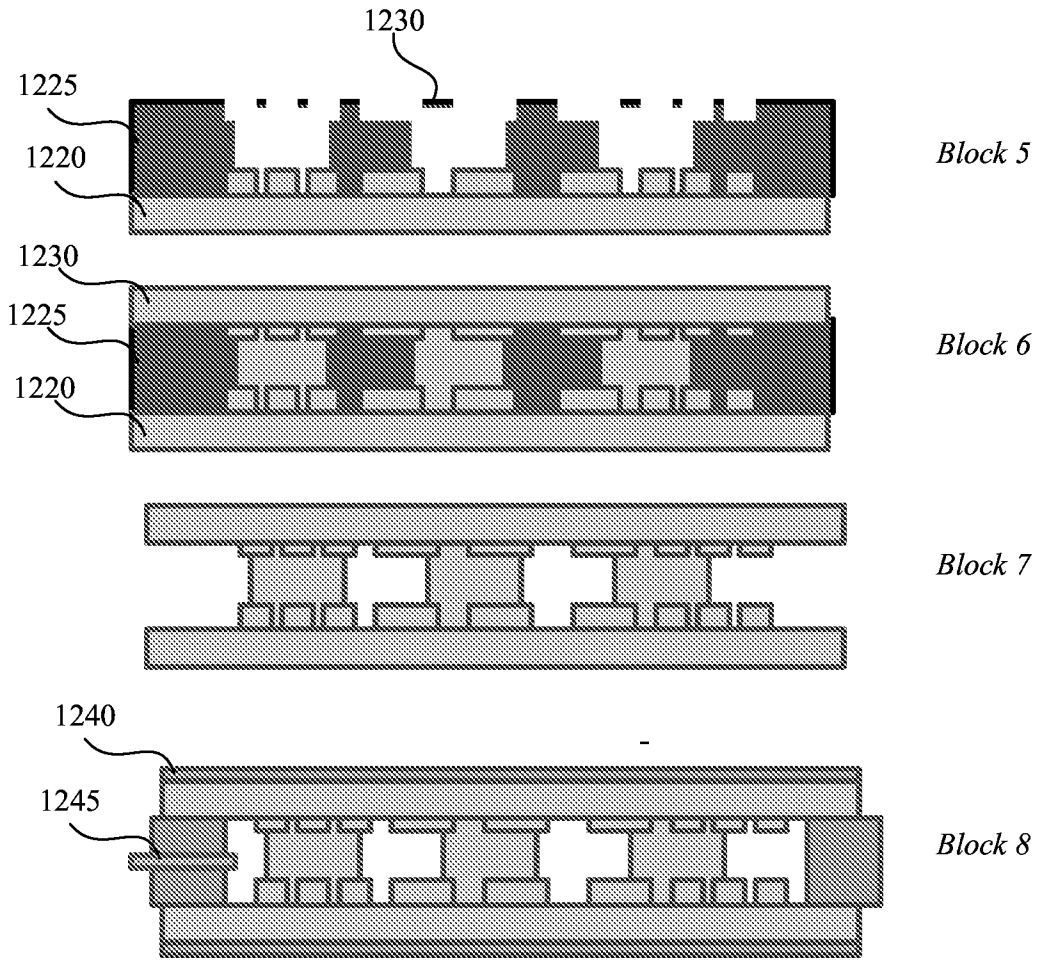


Figure 12B



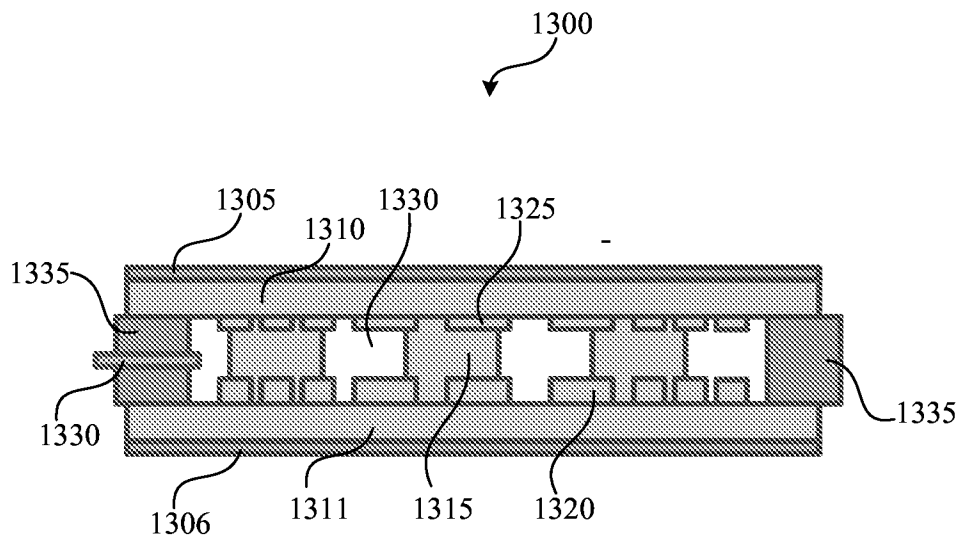


Figure 13



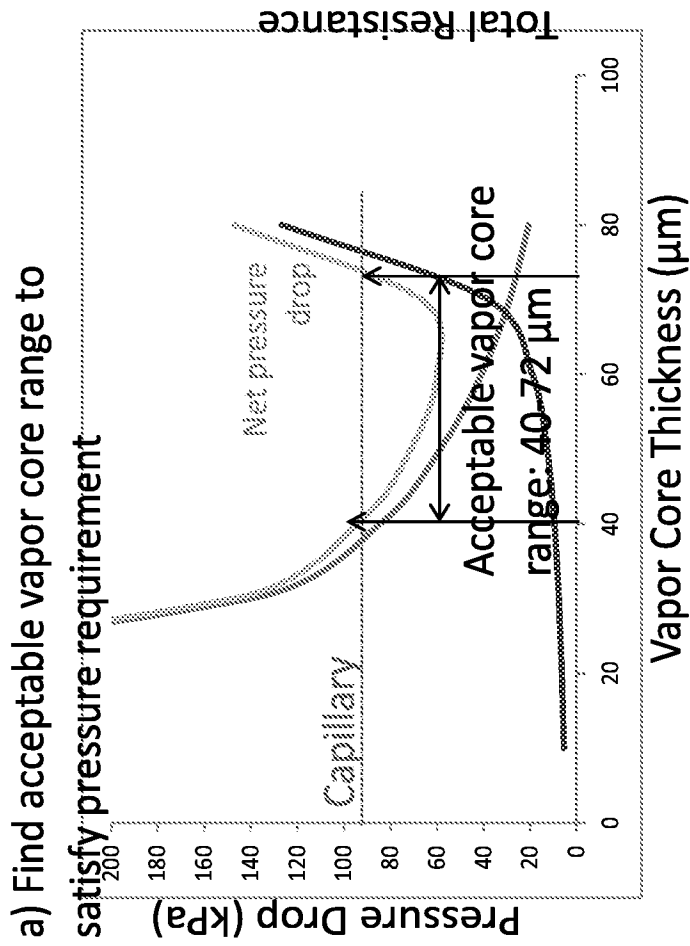
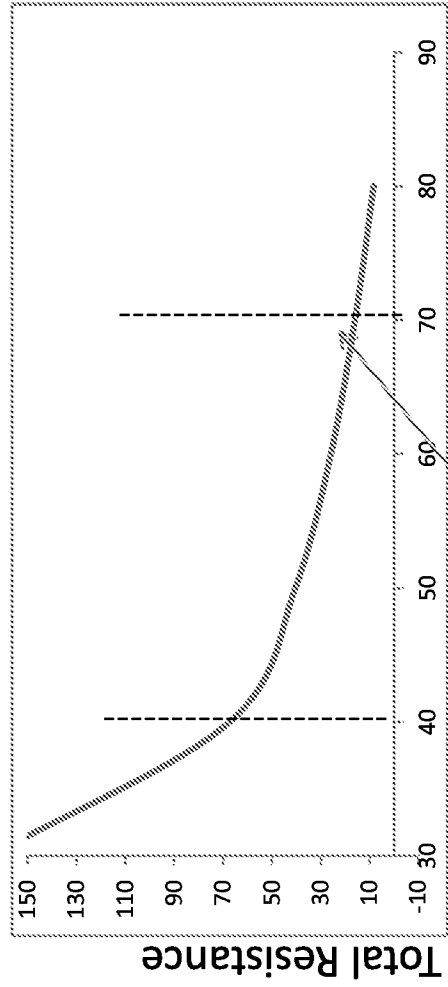


Figure 14



b) Minimize resistance within that range



Vapor Core

Lowest Resistance at
thickest vapor core

Figure 15



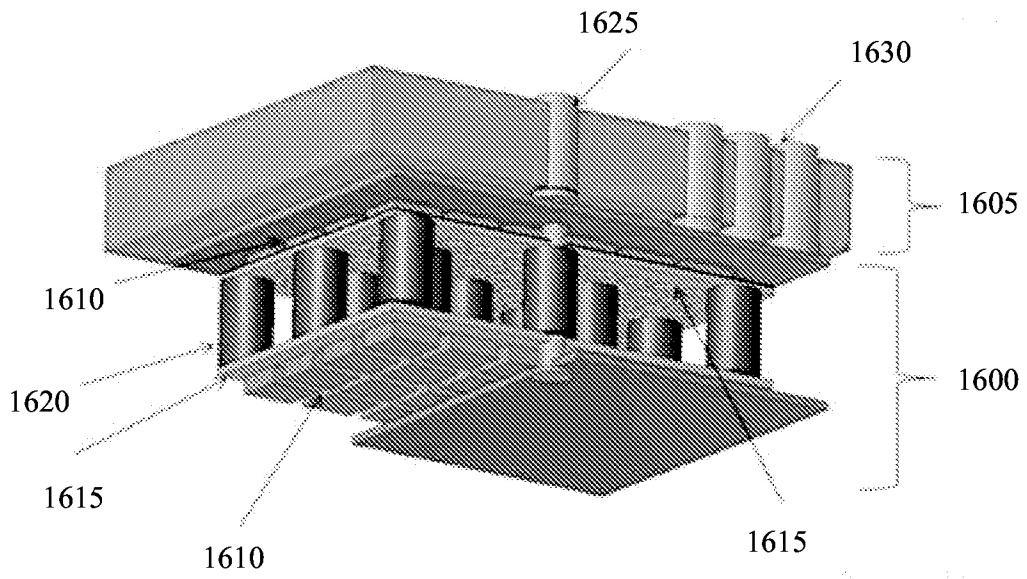


Figure 16



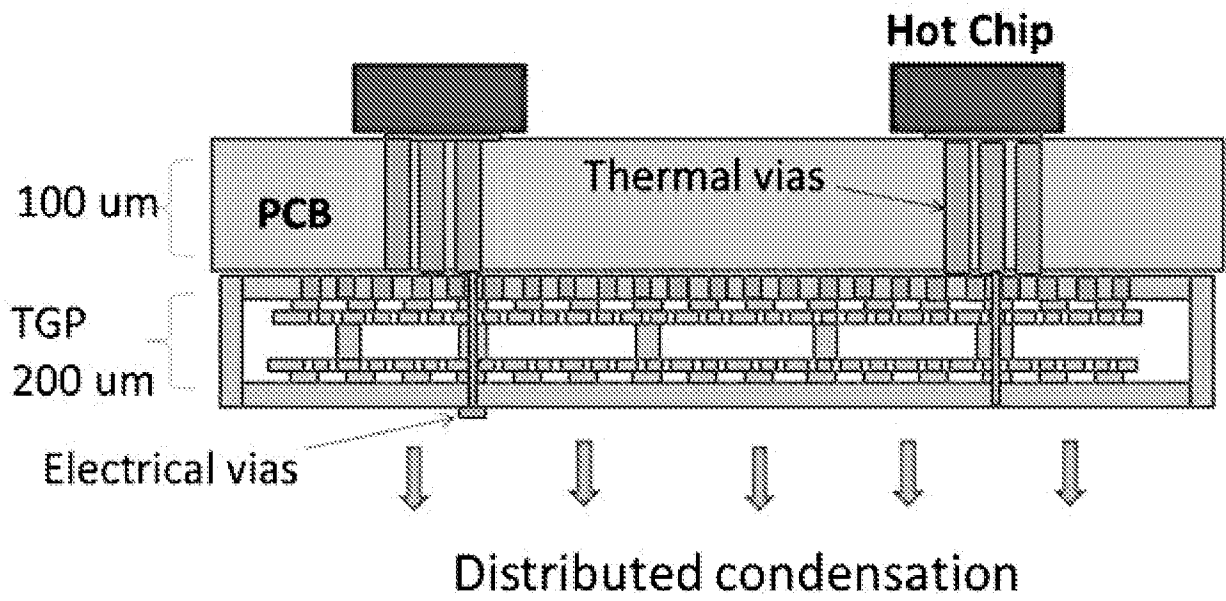


Figure 17



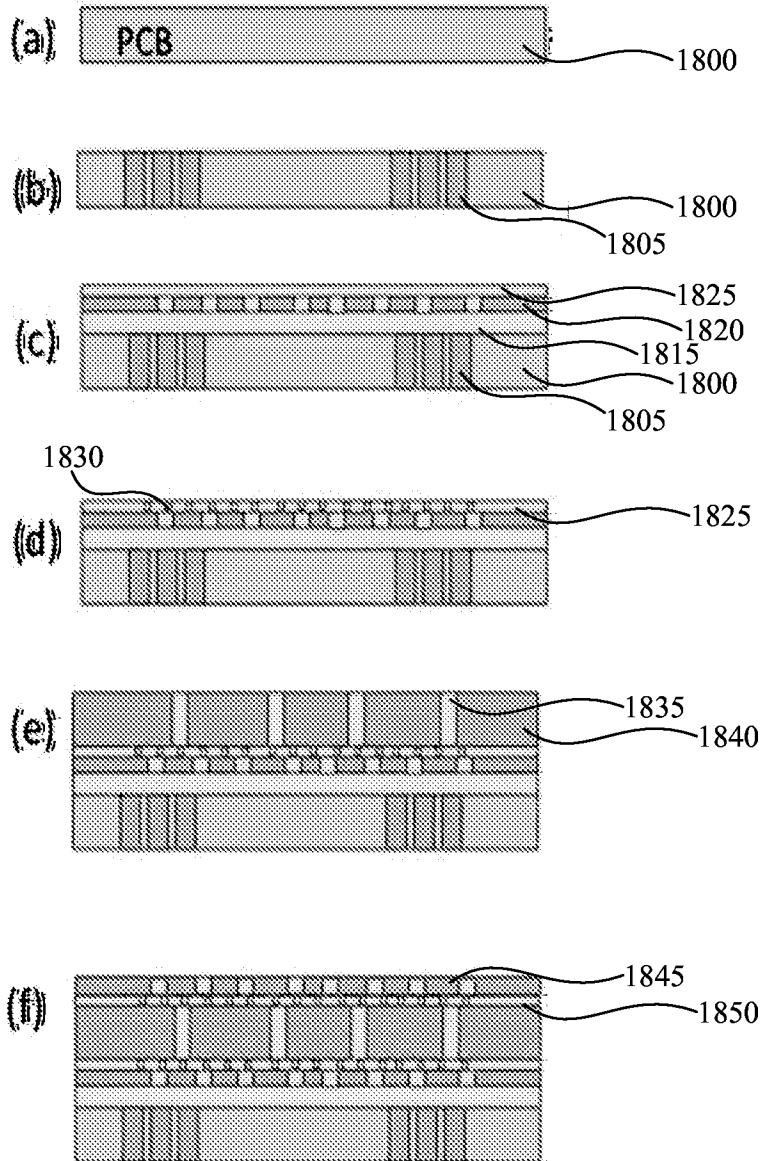
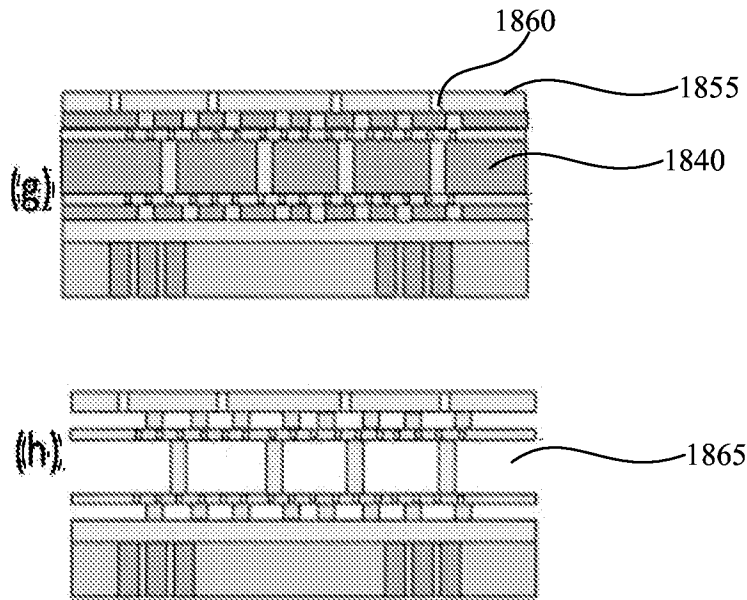


Figure 18A





(i) ALD hydrophilic coating; sea

(j) Evacuation; water charging;

(k) Sealing charging ports

(l) ALD hermetic coating

Figure 18B



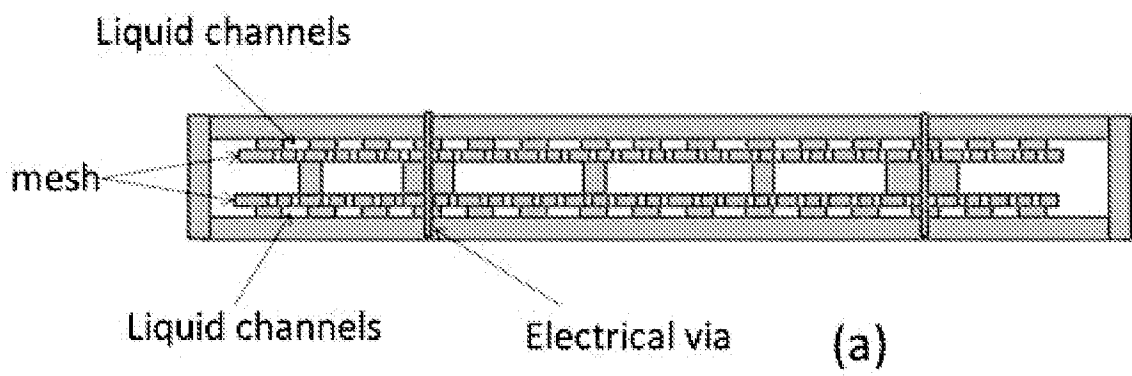


Figure 19A

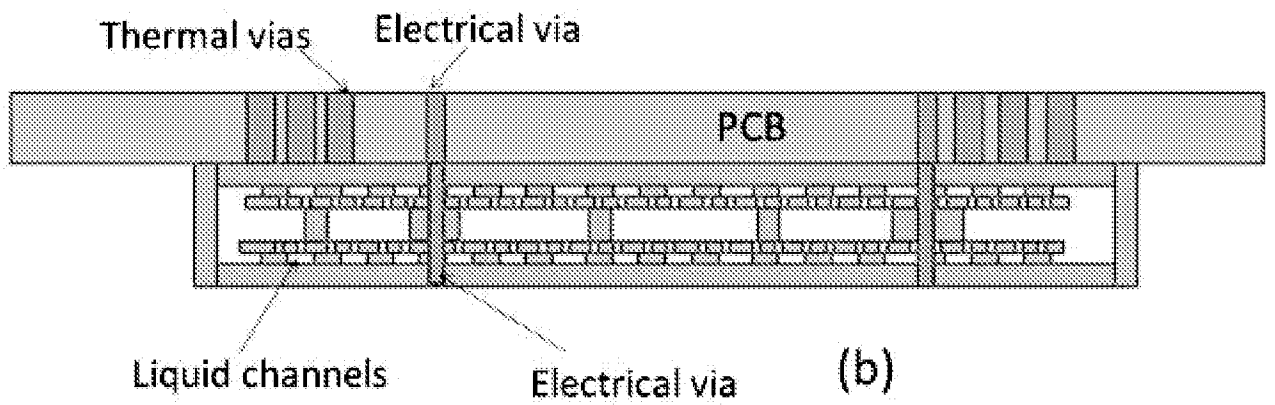


Figure 19B



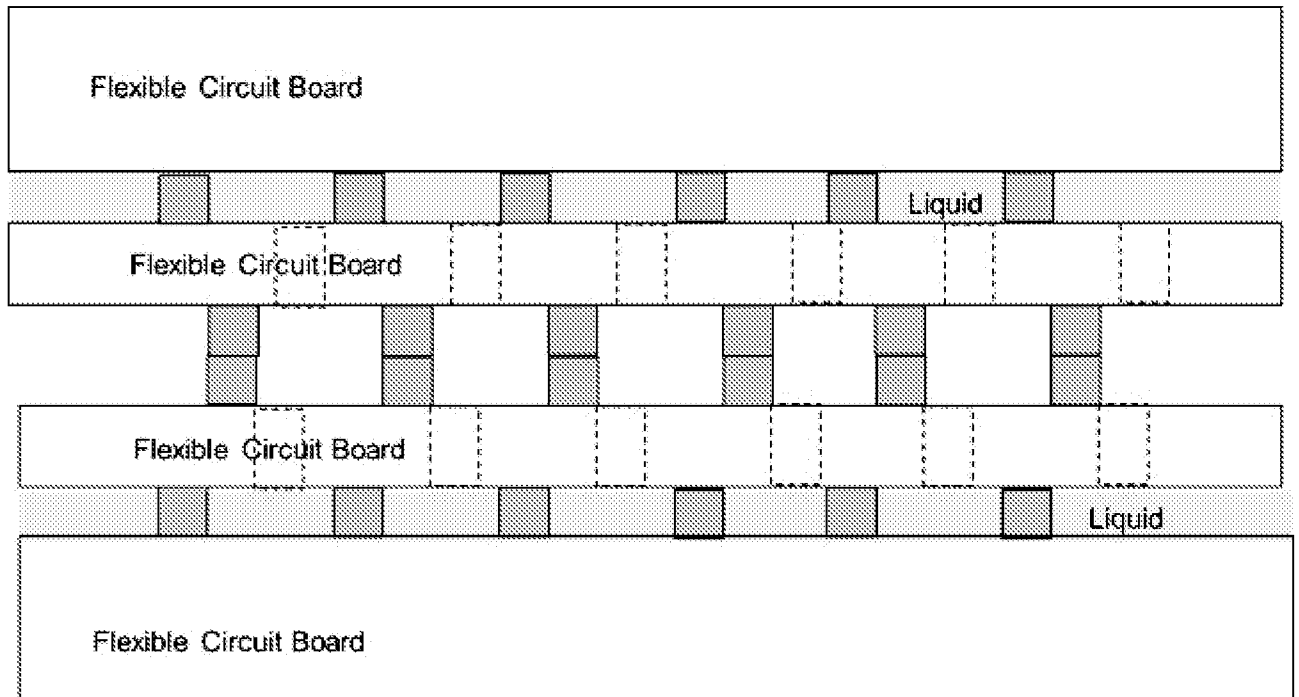


Figure 20



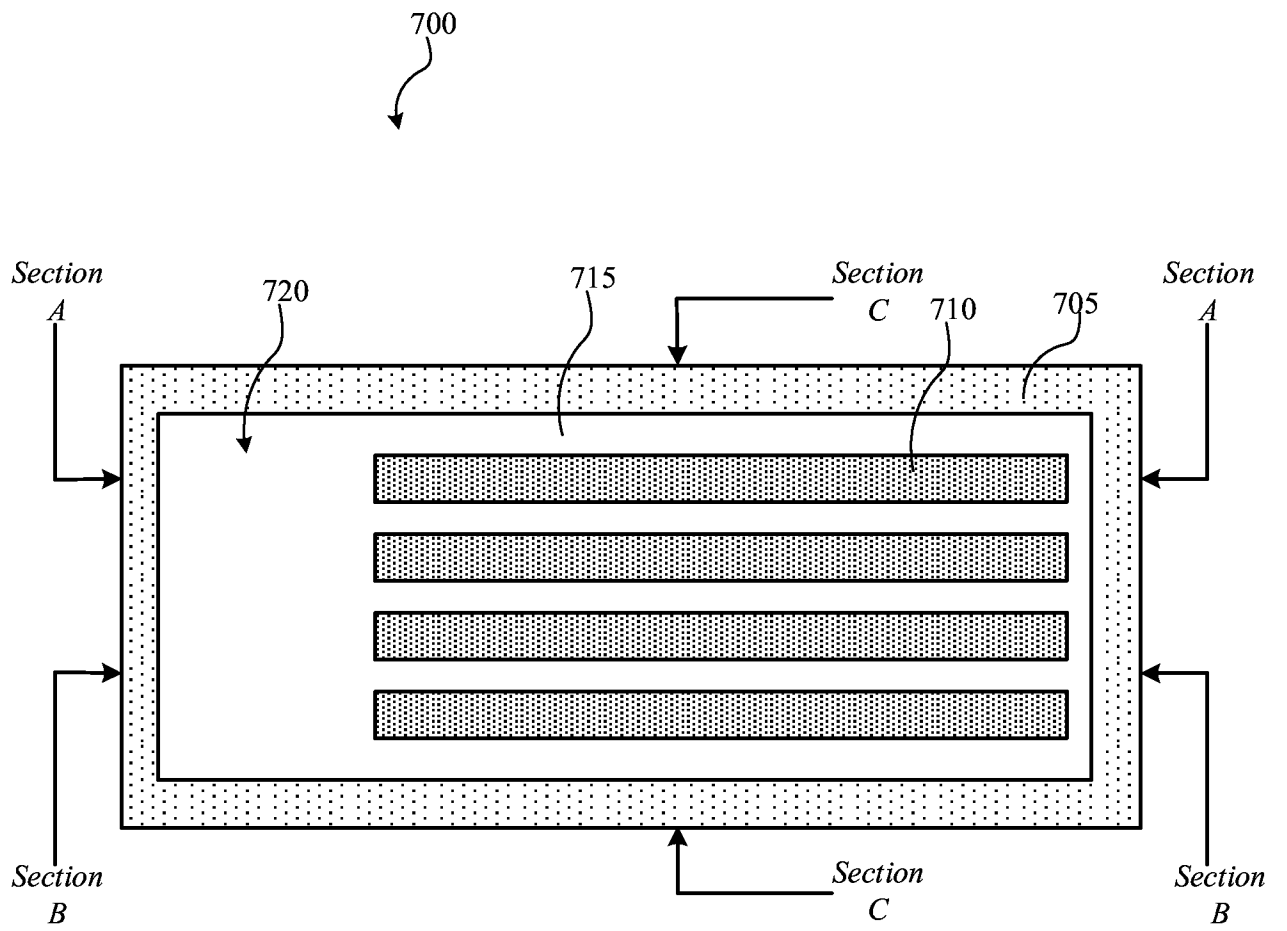
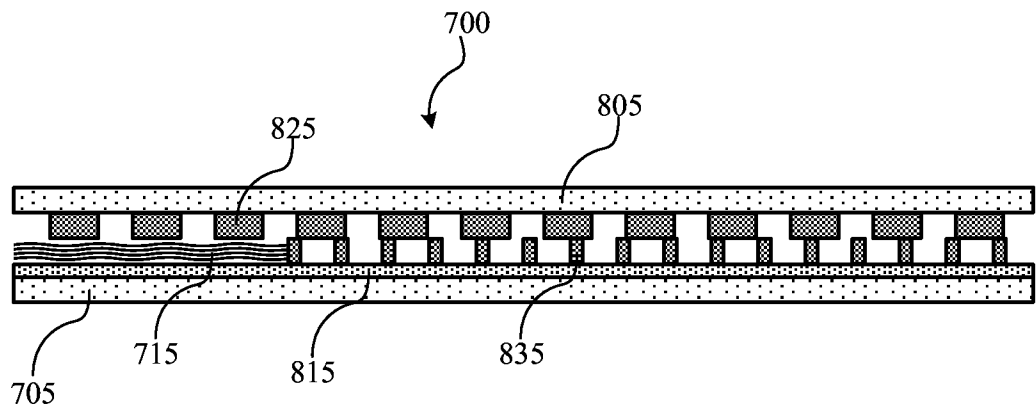


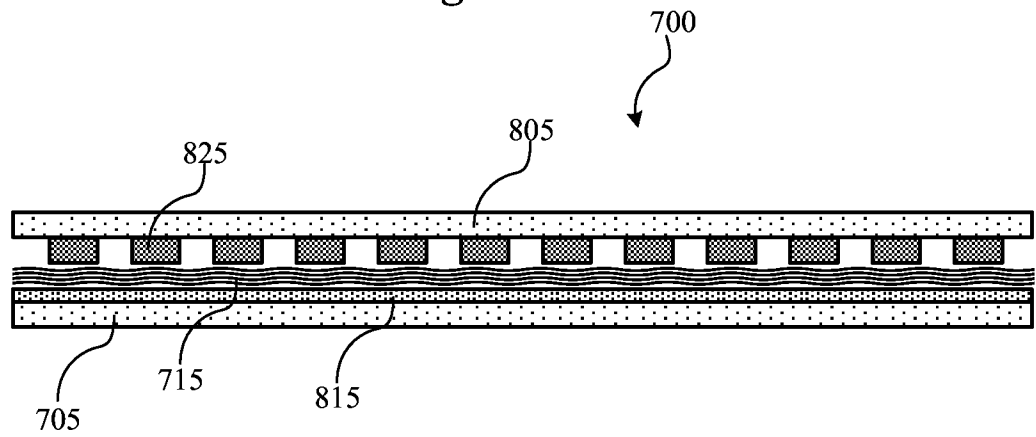
Figure 21





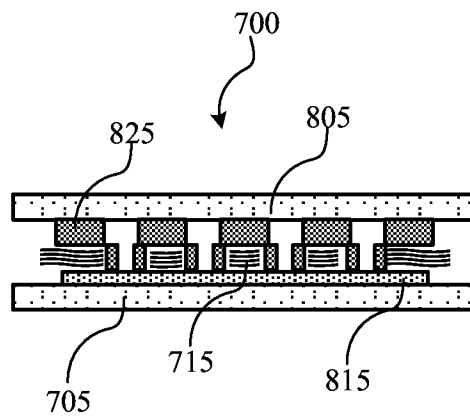
(Section A)

Figure 22A



(Section B)

Figure 22B



(Section C)

Figure 22C