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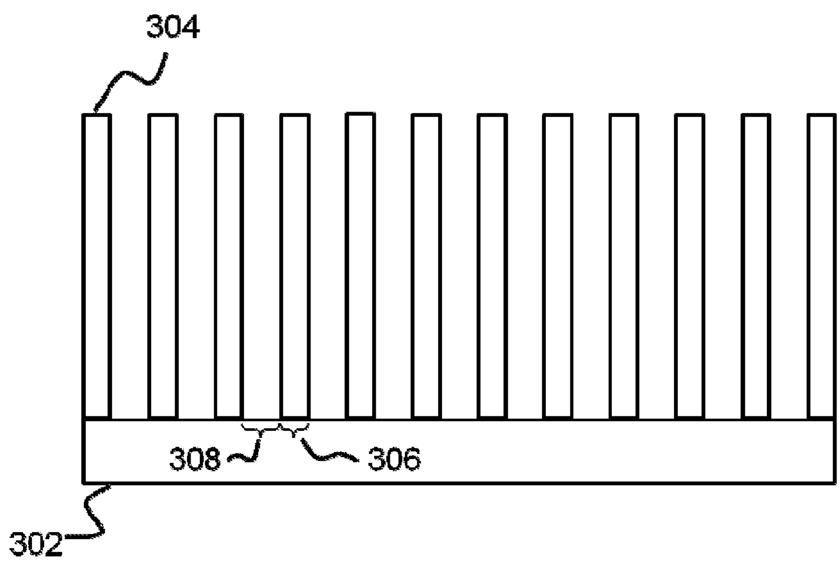
(54) **Title**: LOW STRESS-INDUCING HEAT SINK

FIG. 3



(57) **Abstract**: A low stress-inducing heat sink may reduce thermally induced stress and strain in the heat source. The low stress-inducing heat sink may be made of materials with low thermal conductivity. The heat sink may have in-plane flexibility and hence reduce thermally induced stress and strain generated in the heat source and at the interface of the heat sink and the heat source.

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LOW STRESS-INDUCING HEAT SINK

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This patent application claims the benefit of US Provisional Patent No. 61/167,685 filed April 8, 2009. The contents of US Provisional Patent No. 61/167,685, are incorporated herein by reference.

FIELD OF THE INVENTION

[0002] The devices described herein relate generally to heat sinks. More specifically, the devices described herein relate to heat sinks which may lower stress and strain in a heat source that undergoes expansion and/or contraction.

BACKGROUND OF THE INVENTION

[0003] A heat sink is a device used to absorb and dissipate heat from a heat source. Heat sinks are widely used in a variety of applications, where heat dissipation is needed. For example, heat sinks are commonly used in conjunction with computer processors, heat engines, and many other electronic devices. A heat sink functions by first transferring thermal energy from the heat source to the heat sink and then transferring thermal energy from the heat sink to the surrounding cooling fluid, such as air.

[0004] The most common design of a heat sink comprises a continuous base with multiple extended surfaces (e.g., fins) mounted on the base and extending from the base. The base of the heat sink is generally positioned in direct thermal contact with the heat source. Traditionally, heat will be first conducted from the heat source to the base of the heat sink and then be conducted from the base to multiple fins. Heat will then be dissipated from the fins into the surrounding cooling fluid through convection.

BRIEF SUMMARY

[0005] In one aspect of the invention, a heat sink is provided. The heat sink comprises a plurality of protrusions with surfaces that are suitable for direct thermal communication with a heat source. A sum of the surface areas of these surfaces is less than an area defined by a set of outer-most coordinates of the surfaces.

[0006] In another aspect of the invention, a method of cooling a heat source is provided. In one step, heat energy is conducted from the heat source to a plurality of protrusions on a heat sink connected to the heat source. The protrusions have surfaces that are in direct thermal communication with the heat source. A sum of the surface areas of these surfaces is less than an area defined by a set of outer-most coordinates of said surfaces. In another step, heat energy is convected from the plurality of protrusions via fluid channels between the protrusions.

[0007] In another aspect of the invention, a method of fabricating a heat sink is provided. In one step, a protrusion pattern is stamped on a base sheet to form a plurality of protrusions. In another step each of the protrusions is separated from said base sheet while leaving a base portion of each of the protrusions attached to the base sheet. In another step, each of the protrusions is bent upwardly away from a plane formed by the base sheet while a bottom portion of each of the protrusions remains attached to the base sheet.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] Fig. 1 schematically depicts a traditional heat sink design with a continuous base and a plurality of fins.

[0009] Fig. 2 schematically illustrates an increase in thermal resistance due to a surface layer on a heat source.

[0010] Fig. 3 is a schematic side view of a low stress-inducing minimal-base heat sink.

[0011] Fig. 4 is a schematic top view of one embodiment of a low stress-inducing minimal-base heat sink comprising a fin grid with one embodiment of a mesh of connecting struts.

[0012] Fig. 5 illustrates convective and radiative heat transfer directly from the heat source surface in a low stress-inducing minimal-base heat sink.

[0013] Fig. 6A is a schematic top view of another embodiment of a low stress-inducing minimal-base heat sink; Figs. 6B and 6C illustrate other possible strut patterns.

[0014] Fig. 7A is a schematic top view of another embodiment of a low stress-inducing minimal-base heat sink comprising a fin grid and one embodiment of a mesh of straight connecting struts; Fig. 7B is a perspective view of the embodiment in Fig. 7A.

[0015] Fig. 8 is a schematic top view of another embodiment of a low stress-inducing minimal-base heat sink comprising a fin grid and another embodiment of a mesh of curved connecting struts.

[0016] Fig. 9 is a schematic top view of another embodiment of a low stress-inducing minimal-base heat sink comprising a staggered fin grid with one embodiment of a mesh of mixed straight and curved connecting struts.

[0017] Fig. 10 is a schematic top view of another embodiment of a low stress-inducing minimal-base heat sink comprising a staggered fin grid with another embodiment of a mesh of connecting struts.

[0018] Fig. 11A is a schematic top view of another embodiment of a low stress-inducing minimal-base heat sink comprising rectangular-fins. Fig. 11B is a single rectangular fin with slots cut in the sides.

[0019] Figs. 12A and 12B are schematic top views of two embodiments of a low stress-inducing minimal-base heat sink comprising rectangular-fins with two different embodiments of a mesh of connecting struts.

[0020] Fig. 13A and 13B are schematic perspective views of two embodiments of a connecting strut.

[0021] Fig. 14A is a schematic side view of another embodiment of a low stress-inducing minimal-base heat sink with pin-fins; Fig. 14B is a schematic top view of the embodiment in Fig. 14A.

[0022] Fig.15A is a schematic side view of one embodiment of a low stress-inducing minimal-base heat sink with pin-fins; Fig. 15B is a schematic top view of the embodiment in Fig. 15A.

[0023] Fig. 16A is a schematic side view of one embodiment of a low stress-inducing minimal-base heat sink with pin-fins having curved surfaces; Fig. 16B is a schematic top view of the embodiment in Fig. 16A.

[0024] Fig. 17A is a schematic side view of another embodiment of a low stress-inducing minimal-base heat sink with pin-fins having curved surfaces; Fig. 17B is a schematic top view of the embodiment in Fig. 17A.

[0025] Fig. 18A is a schematic perspective view of one embodiment of a stamped sheet metal heat sink with one fin; Fig. 18B is a top view of the embodiment of the stamped sheet metal heat sink in Fig. 18A with a plurality of fins.

[0026] Figs. 19A to 19C are illustrations of a heat sink during one embodiment of a method to make one embodiment of a stamped sheet metal heat sink with a minimal base.

[0027] Figs. 20A and 20B are illustrations of a heat sink during another embodiment of a method to make another embodiment of a stamped sheet metal heat sink with a minimal base.

[0028] Figs. 21A and 21B are illustrations of one embodiment of a segmented-base heat sink.

[0029] Figs. 22A and 22B are illustrations of another embodiment of a segmented-base heat sink with base segments interconnected with struts.

[0030] Figs. 23A and 23B are illustrations of another embodiment of a segmented-base heat sink with base segments interconnected with a connecting sheet.

[0031] Figs. 24A and 24B are illustrations of another embodiment of a segmented-base heat sink with interleaved base segments.

DETAILED DESCRIPTION

[0032] The following description is presented to enable a person of ordinary skill in the art to make and use the invention. Descriptions of specific materials, techniques, and applications are provided only as examples. Various modifications to the examples described herein will be readily apparent to those of ordinary skill in the art, and the general principles defined herein may be applied to other examples and applications without departing from the spirit and scope of the invention. Thus, the present invention is not intended to be limited to the examples described and shown, but is to be accorded the scope consistent with the appended claims.

[0033] Described herein are various heat sinks that may have in-plane flexibility (e.g., flexibility in direction substantially parallel to the attachment surface between the heat sink and a heat source), thereby reducing thermally induced stress and strain in the heat source and/or at the interface between the heat sink and the heat source, as well as various applications in which these heat sinks may be used, e.g., use with photovoltaic devices such as cells, arrays, and modules, or with planar electronics, such as circuit boards or display devices. Such heat sinks may reduce thermally induced damage to the heat source while providing enhanced heat transfer efficiency.

[0034] Fig. 1 schematically depicts a traditional heat sink design that uses ambient air as cooling fluid. A heat sink 100 comprises a base 102 and multiple fins 104, which are mounted on the base 102 and extend substantially perpendicular to the surface of the heat sink base 102. The heat sink 100 is in direct thermal contact with a heat source 106 through its base 102. The heat dissipation from the heat source 106 through the heat sink 100 is primarily a two-step process: heat conduction from the heat source 106 to the heat sink 100 and then heat convection from the heat sink 100 to surrounding air. The heat transfer from the heat source 106 to the heat sink 100 can be further divided into two parts: First, heat generated by the heat source 106 is conducted to the base 102 and spreads across the base 102 transversely as marked by 101. The heat is then conducted from the base 102 to the fins 104 via vertical pathways along the longitudinal length of the fins 104 as marked by 103.

[0035] Heat sink performance is a function of many factors, including heat sink material, geometry and overall surface heat transfer coefficient. Heat sink performance may be improved by increasing the conduction efficiency. For example, the thermal performance of a heat sink may be improved by using a base with high thermal conductivity, or by inserting a conforming conductive layer between the base and the heat source to improve the thermal contact. Heat sink performance may also be enhanced by improving the convective heat transfer from the fins to the surrounding fluid. For example, to enhance the convection and hence improve the overall heat transfer performance, one may increase the surface area of the fins or use a fan to increase the cooling fluid velocity through the spaces between fins.

[0036] In many applications, the efficiency of the heat transfer in the heat sink base is a significant factor that affects the heat sink's performance. The constriction resistance of this step of heat transfer is determined, in part, by the surface area of the heat source in contact with the heat sink base (A_s) and the area of the heat sink base (A_p). In general, the larger A_p is relative to A_s, the thicker the heat sink base must be in order to conduct the heat transversely through the base with sufficiently low constriction resistance, thereby providing good overall heat sink performance. As a result, in applications where the surface area of the heat source is relatively small, heat sinks with thicker bases are required to provide satisfactory performance. The associated costs are often higher for choosing such heat sinks because more material is consumed to make the base.

[0037] In addition to extra material usage, a thicker base may affect the overall performance of a heat sink. Placing a layer of material over a surface to be cooled may increase the thermal resistance by adding an element of conductive heat transfer between the heat source surface and the environment. The insulation effect of such a covering layer is illustrated in Fig. 2. Without a covering layer 210, the total thermal resistance of the system *R(total)* from the surface of a heat source 206 to the ambient environment is the resistance of convection *R(convection to air)* 201. With a covering layer 210 on top of the heat source 206, *R(total)* then includes the resistance of conductive heat transfer in the vertical direction within the covering layer *R(conduction)* 202. In some cases, the covering layer 210 may add significant resistance and therefore, decrease the overall performance of the heat sink.

[0038] Objects may experience thermal expansion and contraction from temperature excursions. If a heat sink is used with a heat source that is made of a material with a different thermal expansion coefficient from that of the heat sink material, there may be a significant amount of stress and/or strain in the structure of the heat source and/or at the interface between the heat sink and the heat source. In some applications of a heat sink, a conforming thermal interface material (TIM) may be used to fill tiny voids in the interface between the heat sink and the heat source, thereby decreasing the thermal resistance of the interface and improving overall heat transfer. This TIM interface may comprise a strong mechanical connection between the heat source and the heat sink. Such mechanical connections may join the two surfaces during thermally-induced expansion and contraction, and as a result, stress and/or strain may be induced in the heat source if the coefficients of thermal expansion of two materials are different. The magnitude of the stress and strain increases with larger differences in coefficient of thermal expansion between the heat sink and the heat source. In some cases this stress can damage the heat source and/or cause delamination of the heat sink from the heat source.

[0039] For example, a photovoltaic (PV) module assembly may include a heat sink to remove heat generated in photovoltaic cells. The thermal expansion coefficient of one photovoltaic module may differ from that of a heat sink made from a thermally conductive polymer material by up to two orders of magnitude. Such a mismatch in thermal properties between the photovoltaic module and the heat removal device may result in thermally induced module cracking, fracture and/or other forms of undesirable module deformation. Minimizing a continuous and rigid heat sink base may provide multi-directional flexibility to heat sink fins, thereby significantly reducing the thermally induced stress and strain in the bulk of the heat source. If a heat sink is less rigid mechanically as compared to the object it is cooling, the expansion of the object will be met with far less resistance and resultant stress on the object.

[0040] Described herein are low stress-inducing heat sinks that are configured to have in-plane flexibility, thereby reducing thermally induced stress and/or strain in the bulk of the heat source and/or at the interface of the heat sink and the heat source. It is noted that “in-plane flexibility” refers to flexibility of a heat sink along a vector substantially within the plane defined by the attachment surface between the heat sink and the heat source. In some embodiments, the attachment surface between the heat sink and the heat source may be planar, cylindrical, spherical, or of other geometric configurations, depending in part upon the geometric configurations of the heat sink and/or the heat source. A low stress-inducing heat sink may be a heat sink that when operating under the maximum expected thermal excursion for a particular application (e.g., from - 40 °C to + 90°C under the industry standard UL 1703 Temperature Cycling Test for Flat-Plate Photovoltaic Modules and Panels), induces stress and strain in the bulk of the heat source that is lower than the observed fracture strength of the heat source. It is noted that the observed fracture strength of a heat source may be lower than the theoretical fracture strength of the heat source material because of various structural defects formed in the heat source during common manufacturing process. For example, a commonly reported value of fracture strength for silicon is from about 7000 MPa to about 12800 MPa. However, the observed fracture strength of a silicon photovoltaic cell may be much lower than the reported fracture strength of silicon. This is because common fabrication methods for silicon, such as sawing or cutting, may create micro-cracks in the surface of the silicon cells, which will in turn serve as stress concentration points from which cracks may develop. As a result, in some cases, failure of a silicon photovoltaic cell may be observed when the cell is under stress of about 300 MPa. In some embodiments, the low stress-inducing heat sink may be fabricated to be weak and therefore flexible in directions in which it may apply stress and strain to the adjoining part (e.g., the TIM and/or the heat sink), thereby minimizing the stress and strain it may induce when undergoing thermal contraction and/or expansion.

[0041] Minimizing or segmenting a continuous and rigid heat sink base may provide multi-directional flexibility to heat sink fins, thereby significantly reducing the thermally induced stress and strain in the interface between the heat source and the heat sink. Low stress-inducing heat sinks are particularly desirable in applications where the object to be cooled is relatively delicate or brittle and may be damaged by the thermally induced stress and strain if attached to a more rigid heat sink. Photovoltaic modules, plasma, LCD and other display panels may be a good example of such a delicate heat source. In the cases where thermally induced structural damage is likely to occur due to the different thermal properties between the heat sink and the heat source, it may be desirable to provide structural flexibility to the assembly in the surface of attachment such that thermal expansion and contraction of the assembly may occur without causing high stresses and strains.

[0042] In one embodiment, a low stress-inducing heat sink may be a minimal-base heat sink. A minimal-base heat sink, as described herein, is a heat sink having a contact area between a heat source surface and the heat sink ($A_{contact}$) that is less than the total area between the heat source and the heat sink (A_{total}). In the preceding definition, $A_{contact}$ refers to the total area of direct thermal communication (e.g., two objects exchange thermal energy through a direct physical contact) between the heat sink and the heat source. A_{total} refers to the total area within the perimeter defined by the outer-most coordinates of the area of direct thermal communication. For example, in some cases where individual heat sink fins are directly mounted on the heat source surface without being connected to each other, $A_{contact}$ is the total area of the bottom cross-section of each fin and A_{total} is the area of a polygon whose vertices are the outermost fins of the heat sink. In some cases where individual heat sink fins are connected to each other with one or more connecting members and such members are also in direct physical contact with the heat source, A_{total} is still the area of a polygon whose vertices are the outermost fins of the heat sink whereas $A_{contact}$ is the total area of the bottom cross-section of each fin plus the contact area between these connecting members and the heat source. In some embodiments where the base of a heat sink comprises a plurality of segments, $A_{contact}$ is the total area of the bottom surface of each base segment and A_{total} is the area of a contiguous surface defined by the outermost base segments.

[0043] In some cases, the heat source may provide sufficient transverse heat conduction such that there is little need for a continuous base to spread the heat transversely before conducting it away through the fins of the heat sink. As a result, eliminating or minimizing a continuous base may have little effect on the overall performance of the heat sink but may reduce the base material usage and hence manufacturing cost. Further, if the overall heat transfer is dominated by convection in such cases, the heat sink may be made from a material with relatively low thermal conductivity, which is usually less expensive. Moreover, eliminating or minimizing the continuous base also exposes a large portion of the heat source surface to the surrounding cooling fluid (e.g., air), thereby allowing convection and radiation to take place directly from the heat source surface rather than requiring conduction through an extra layer of heat sink base.

[0044] Additional cost saving may also result from the use of heat sink materials with low thermal conductivity. Moreover, low stress-inducing heat sinks with a minimal base may be much lighter than traditional heat sinks with a continuous base, thereby making them easier and cheaper to distribute, handle and mount. This benefit of low stress-inducing minimal-base design may be more valuable when the object to be cooled has a large surface area, since attaching a traditional heat sink with a continuous base would use a large amount of material. In addition, heavy heat sinks may damage the object to be cooled due to the gravity load.

[0045] In some embodiments, a low stress-inducing minimal-base heat sink with one or more fins (e.g., pin-fins or rectangular-fins) does not comprise a continuous surface in contact with the bottom surfaces of one or more fins. In some embodiments, a low stress-inducing minimal-base heat sink may comprise a plurality of fins, which may or may not be connected by any connecting means (e.g., struts, strips, sheets, etc.). In some embodiments, the connecting mechanism may comprise one or more struts. The connecting mechanism, e.g., one or more struts, may or may not be in contact with the top surface of the heat source. For example, a strut that connects one fin to another may be positioned between the bottom surfaces of the two fins and the top surface of a heat source. In this way, the strut is in thermal contact with both the two fins and the heat source. In other embodiments, a strut that connects one fin to another may be elevated above the top surface of the heat source. In such embodiments, the strut is not in direct thermal contact with the heat source.

[0046] Fig. 3 illustrates a profile view of a low stress-inducing minimal-base heat sink. A heat source 302 may be connected to one or more protrusions (e.g., pin-fins or rectangular-fins) 304. The protrusions may contact the heat source 302 and may have any contact area 306 as described herein. The spacing 308 between the protrusions 304 may be any suitable distance to provide sufficient conduction and convection properties and improved thermal efficiency. In some embodiments, as described below in greater detail, the protrusions 304 may be interconnected by one or more struts (not shown). In other embodiments, the protrusions 304 may be individually mounted on the heat source 302 without being connected to each other.

[0047] Fig. 4 is a schematic top view of one embodiment of a low stress-inducing minimal-base heat sink 400. In this depicted embodiment, a heat sink 400 comprises a plurality of fins 402 that are connected by a plurality of struts 404. Fins 402 comprise a pin-like configuration (e.g., pin-fins) and may have a generally circular cross-sectional shape. Fins 402 are individually mounted to the surface 401 of a heat source and may extend substantially perpendicular to that surface 401. In this specific example, a plurality of elongate struts 404 are used to connect fins 402. The struts may or may not be in contact with the heat source surface. In this particular embodiment, each fin (except those located near the edges of the heat source surface) is connected to three surrounding fins with struts and a mesh of struts holds the fins together in lieu of a traditional continuous base. In other embodiments, each fin (except those located near the edges of the heat source surface) may be connected to, for example, 1, 2, 3, 4, 5, 6, 7, 8, etc. surrounding fins with struts. In some embodiments, fins that are located near the edges of the heat source surface may be connected to, for example, 1, 2, 3, 4, 5, etc. surrounding fins with struts. In still other embodiments, fins that are located near the edges of the heat source surface may not be connected to any of surrounding fins. In still other embodiments, fins that are located near the edges of the heat source surface and are not connected to any surrounding fins may be removed from the fin array.

[0048] The strut-mesh may provide structural integrity as well as in-plane flexibility to the pin-fins assembly since the pin-fins are retained in a fixed relative orientation to each other by the connecting struts while still maintaining the ability to flex in multiple directions within the surface of the heat source.

[0049] In some embodiments, a low stress-inducing minimal-base heat sink may comprise an array of one or more fins with a pin-like configuration (e.g., pin-fin array shown in Fig. 4). A pin-fin array has an ominidirectional structure that permits cooling medium, e.g., air, to enter the array from every direction regardless of the direction of the incoming air. In some embodiments, a low stress-inducing minimal-base heat sink may comprise pin-fins that have a round cross-sectional shape. This shape configuration may enhance air turbulence between the pin-fins, which in turn improves the performance of the convective heat transfer. In addition, pin-fins with large surface areas may also contribute to a pin-fin heat sink's highly efficient cooling ability. In other embodiments, a low stress-inducing minimal-base heat sink may comprise one or more fins that have other configurations, for example, a planar configuration, e.g., rectangular-fins.

[0050] In some embodiments, the contact area between the heat sink and the heat source is less than or any of about 95%, 90%, 85%, 80%, 75%, 70%, 65%, 60%, 55%, 50%, 40%, 30%, 20%, or 10% of the total area between the heat sink and the heat source. In some embodiments, the contact area between the heat sink and the heat source is less than or any of about 95%, 90%, 85%, 80%, 75%, 70%, 65%, 60%, 55%, 50%, 40%, 30%, 20%, or 10% of the total area of the heat source surface.

[0051] In some embodiments, the cross-sectional shape of a fin may be circular, crescent, tear-drop, squared, rectangular, triangular, polygonal, or any other shape. The cross-sectional shape of the fins may or may not be the same along the longitudinal length of the fins. For example, in some embodiments, the fins may have a generally cylindrical shape; in other embodiments, the fins may have a shape of pyramid (including frustum pyramid) or cones (including frustum cones). In still other embodiments, the surfaces of the fins (e.g., pin-fins) may be curved along the longitudinal length of the fins. Non-limiting examples of the surface profile of a curved fin (e.g., pin-fin) include a hyperbolic curve, a quadratic curve, a polynomial curve with an order higher than two, a circular arc, or a combination thereof. In some embodiments, the fins are solid structures, but in other embodiments, the fins may be hollow. In some embodiments the fins may be partially hollow and partially solid. Hollow fins may allow efficient heat transfer while further reducing the amount of material to be used to make the heat sink, thereby further reducing production costs. Alternatively or additionally, a pattern formed by the fins may be broken by channels along the perimeter of the heat sink to provide additional openings to the interior of the heat sink and to increase airflow to the internal fins. The resultant channels may be of any pattern, such as general cross-cut, herringbone, or undulating.

[0052] Minimizing or segmenting a continuous base may also enhance convective and radiative heat transfer, thereby improving a heat sink's overall heat transfer efficiency. As noted above, in applications where heat sinks are made of materials with relatively low thermal conductivity (e.g., thermal conductivity from about 1 W/mK to about 20 W/mK), a continuous base may cause an insulation effect and add significant thermal resistance to the heat transfer process. Minimizing the base may decrease the insulating effect, allowing heat to be directly convected and radiated from the heat source, which may enhance the overall heat transfer performance. Fig. 5 illustrates this direct heat transfer process. In this figure, a heat sink 500 comprises a plurality of fins (e.g., pin-fins) 502, which are mounted on the surface 501 of a heat source. Heat sink

500 does not comprise a continuous base and each fin is connected to another fin with a strut 504. In this depicted embodiment, the struts 504 are positioned between the bottom surfaces of the fins 502 and the heat source surface 501. In this way, the struts 504 not only provide structural integrity to fins 502 by holding them altogether, but may also function as thermal contacts between fins 502 and the heat source surface 501. The struts may add to the heat transfer function of the heat sink. The struts 504 may also provide heat exchange in a cooler area, away from the heat source. In other embodiments, one or more struts may be elevated above the heat source surface and therefore, not in direct thermal contact with the heat source. Replacing a continuous heat sink base with a mesh of struts 504 exposes a large portion of the heat source surface 501 to the surrounding cooling air, thereby enhancing the convective heat transfer from the heat source to the ambient air and radiation heat transfer between surface 501 and the environment. Arrows 510 in Fig. 5 illustrate one possible pathway of incoming air to access the hot heat source surface 501 and take away the heat. Arrows 512 in Fig. 5 illustrate one possible pathway for direct radiation heat transfer from the surface 501 to the environment.

[0053] There are numerous ways to connect fins of a heat sink with struts. Those that have been shown in Figs. 4 and 5 are only exemplary embodiments. Any other suitable strut-mesh pattern, which may hold fins together and/or minimize the fins' in-plane rigidity, may be used. In another embodiment as shown in Fig. 6A, for example, some horizontal connecting struts used in Fig. 4 may be eliminated such that the entire array of fins 600 may be divided into several narrow sub-arrays 610, some of which may or may not be connected to each other. This type of strut-mesh pattern maintains the fins' in-plane flexibility when under thermally induced stress and/or strain while providing additional flexibility to handling and mounting the mesh. For example, each narrow sub-array 610 may be independently handled and mounted onto a heat source surface that may have a rectangular shape. As illustrated in Fig. 6B, fins 602 may optionally be connected with struts 604 along the Y axis of the heat source surface 601 in a zigzag pattern. The resulting sub-arrays 612 may be independently handled and mounted. Figure 6C shows a configuration in which short struts 604 connect only two fins 602 into two-pin units 614.

[0054] Figs. 7A and 7B illustrate yet another embodiment of a low stress-inducing minimal-base heat sink. Fig. 7A is a schematic top view of a low stress-inducing minimal-base heat sink 700 and Fig. 7B provides a partial perspective view of the same embodiment. In this specific embodiment, multiple fins (e.g., pin-fins) 702 are connected by multiple struts 704 in a similar pattern as the one illustrated in Fig. 4. In this depicted embodiment, some stand alone fins (i.e., pin-fins not connected to any adjacent pin-fin) located at the edge of the pin-fin grid are removed. In other embodiments, struts may be used to connect these stand alone pin-fins to adjacent pin-fins in order to maintain the integrity of the pin-fin grid. As illustrated in Fig. 7B, the pin-fin 702 of the low stress-inducing minimal-base heat sink 700 has a general frustum-conical configuration but with a curved surface along its longitudinal length. As noted before, such curved fins may have a quadratic, a hyperbolic, a higher order polynomial or a circular section profile, or a combination thereof. Construction of such pin-fins with curved surface may further reduce the material consumption required to manufacture the heat sink.

[0055] In some embodiments of a low stress-inducing minimal-base heat sink, non-straight struts may be used to connect a plurality of fins. Fig. 8 illustrates such a heat sink 800 comprising a plurality of fins (e.g., pin-fins) 802 without a continuous base. Fins 802 are connected with a plurality of curved struts 804 and mounted on the surface of a heat source 801. When under tension from connected fins, curved struts may bend instead of supporting the axial load as straight struts would do in similar situations. Bending allows the fins to flex in order to absorb thermally induced stress and/or strain. Similar to straight struts, curved struts may be used to connect an array of fins (e.g., pin-fins) in many different ways. Fig. 8 is only an exemplary strut-mesh pattern of curved struts and other suitable patterns may be applied as well. Curved struts may be located at or above the heat source surface. In some embodiments, additional horizontal struts, either straight or curved, may be added to the heat sink in Fig. 8 to connect each narrow sub-array of fins to form a larger mesh. In some embodiments, straight and curved struts may both be used in a single embodiment. In other embodiments, struts with other geometric configuration may be used to connect heat sink fins and/or to minimize in-plane rigidity of the heat sink.

[0056] In some embodiments of the current invention, fins (e.g., pin-fins) may comprise a grid (e.g., pin-fin grid) configuration (as shown in Figs. 4 to 8), but in other embodiments, other configurations, such as a radial fin array, may be employed. In some embodiments where fins are arranged in a fin grid (e.g., a pin-fin grid), the distance between rows may be equal to the distance between columns, but in some embodiments, the distance between rows may be different from the distance between columns. In some embodiments of a pin-fin grid, the distance between rows or columns may be the same, but in other embodiments, the distance between rows or columns may be different. These distances may also change within one heat sink or one assembly of heat sinks. Pin lengths may also change across one heat sink or one array of heat sinks. In some embodiments, a large pin-fin grid may be divided into some smaller grid arrays to provide air channels in certain directions.

[0057] In the fin grid shown in Figs. 4 to 8, fins (e.g., pin-fins) are aligned in parallel rows and columns across the width and length of the heat source surface. In alternative embodiments shown in Figs. 9 and 10, fins (e.g., pin-fins) may be disposed as a staggered grid. Figs. 9 and 10 illustrate two exemplary embodiments of low stress-inducing minimal-base heat sinks comprising staggered fin grids. In Fig. 9, straight struts 904 are used to connect fins 902 in a zigzag pattern in one direction of the heat source surface 901 while curved struts 906 are used to connect fins 902 in another direction of the surface 901. Fig. 10 illustrates another flexible fin array, of fins 1002, with each fin (except for those located in the edge-rows or edge-columns) on surface 1001 connected to four surrounding ones with straight struts 1004. Even though straight struts are used in this specific embodiment, curved struts, struts with other configurations, and/or combination thereof may be used as well.

[0058] In some embodiments, fins (e.g., pin-fins) of a low stress-inducing minimal-base heat sink may independently have a height (*h*) and a center-to-center spacing (*s*). In some embodiments, the selected height *h* and spacing *s* may provide sufficiently improved heat sink efficiency (e.g., via improved convection) when compared to a non-minimal-base heat sink (e.g., a heat sink with a continuous base). The height *h* of any fin (e.g., pin-fin) may be independently greater than 0.1", or greater than 0.25", or greater than 0.5", or greater than 0.75", or greater than 1", or greater than 2", or greater than 3.5", or between 0.25" and 7", or between 0.5" and 6", or between 0.75" and 5", or between 0.8" and 2.5", or between 0.9" and 2", or between 0.9" and 1.25", or 1". The center to center spacing (*s*) between pin-fins may be independently between 0.05" and 1", or between 0.075" and 0.9", or between 0.1" and 0.8", or between 0.2" and 0.7", or between 0.25" and 0.6", or between 0.3" and 0.5", or between 0.4" and 0.48" or between 0.42" and 0.46", or between 0.43" and 0.45", or about 0.44".

[0059] In some embodiments where fins (e.g., pin-fins) have a general cylindrical shape (with curved or non-curved surface), fins have a width designated *w* as the outer diameter of the cylinder. In some embodiments, the selected width *w* may provide sufficiently improved heat sink efficiency (e.g., via improved convection) when compared to a non-minimal-base heat sink (e.g., a heat sink with a continuous base). The width *w* of any fin may be independently less than 1 inch, or less than 0.75", or less than 0.5", or less than 0.3", or less than 0.2", or less than 0.15", or less than 0.1", or less than 0.05", or less than 0.025", or less than 0.01", or less than 0.005", or less than 0.0025", or less than 0.001", or between 0.001" and 0.25", or between 0.002" and 0.1", or between 0.005" and 0.075", or between 0.01" and 0.06", or between 0.02" and 0.05", or 0.02". In embodiments where fins (e.g., pin-fins) have a general frustum-conical shape (with curved or non-curved surface), fins may have a base width (*bw*) designated as the outer diameter of the frustum-cone base and a top width *tw* designated as the outer diameter of the frustum-cone top. The base width *bw* of any fin (e.g., pin-fin) may be independently less than 1 inch, or less than 0.75", or less than 0.5", or less than 0.3", or less than 0.2", or less than 0.15", or less than 0.1", or less than 0.05", or less than 0.025", or less than 0.01", or less than 0.005", or less than 0.0025", or less than 0.001", or between 0.01" and 0.75", or between 0.05" and 0.5", or between 0.1" and 0.3", or between 0.12" and 0.25", or between 0.15" and 0.2", or 0.16". The ratio between the top width *tw* and the base width *bw* may be in the range of between about 10% and about 90%, between about 20% and about 80%, between about 30% and about 70%, between about 40% and about 60%, or about 50%, or about 40%, or about 30%, or about 20%.

[0060] In some embodiments, a low stress-inducing minimal-base heat sink may comprise multiple fins with planar configurations, e.g., rectangular-fins. Figs. 11A, 11B, 12A and 12B illustrate two such examples. In the specific embodiment depicted in Figs. 11A and 11B, a plurality of rectangular-fins 1102 are mounted on the surface of a heat source 1101 without a continuous base and project from the surface 1101 substantially parallel to each other. Each fin 1102 is connected to its neighboring fin with multiple curved struts 1104, which are substantially parallel to each other and disposed orthogonally with respect to the heat dissipation surfaces of the connected fins. Fig. 11B is a side view of a fin and it illustrates slots 1106 cut into the rectangular fin 1102 to enable the fin 1102 to stretch and compress easily and impart less stress to the heated surface. Figs. 11A and 11B only illustrate one exemplary embodiment of a strut-mesh used to connect multiple heat sink fins. In some variations, only one strut is used to connect two neighboring fins. In some embodiments, such connecting strut may be disposed orthogonally with respect to the heat dissipation surfaces of the connected fins. In other embodiments depicted in Figs. 12A and 12B, the strut 1204 may form an angle with the heat dissipation surfaces of the connected fins 1202 that are placed on surface 1201. The angle between the strut and the fin surface may independently be any of about 5°, 10°, 15°, 20°, 25°, 30°, 35°, 40°, 45°, 50°, 55°, 60°, 65°, 70°, 75°, 80° or 85°. In some embodiments, all connecting struts may be substantially parallel to each other (as shown in Fig. 12A); in other embodiment, they may form a zigzag pattern (as shown in Fig. 12B). In the embodiments depicted in Figs. 12A and 12B, each connecting strut is coupled to two neighboring fins at two ends of the fins. In other embodiments, the strut may be coupled to the fins at other spots along the long axis of the fins. In the embodiments depicted here, straight struts are used, but in other embodiments, curved struts may be used. In each of these cases slots may be cut into the rectangular fins.

[0061] In the embodiment described above, the fins (e.g., pin-fins or rectangular-fins) extend substantially perpendicular with respect to the surface of the heat source. In alternative embodiments, the long axis of the fins may be substantially parallel to the long axis of the heat source. Here, a “long axis” is an axis that is parallel to the longest straight edge of the object. A long axis is implied if no axis is referenced. "Substantially perpendicular" describe a configuration in which two referenced axes form an angle between 85° and 95°. "Substantially parallel" describe a configuration in which two referenced axes form an angle of less than 10°. In some embodiments, the angle between the long axis of the fins and the long axis of the surface of the heat source may be in the range of about 10° to about 85°, sometimes from about 15° to about 80°, sometimes from about 20° to about 75°, sometimes from about 25° to about 70°, sometimes from about 30° to about 65°, sometimes from about 35° to about 60°, sometimes from about 40° to about 55° and other times from about 45° to about 50°. In some variations, fins may not all form the same angle with respect to the long axis of the heat source surface, so that air may pass freely through many of the channels formed by adjacent fins regardless of incoming wind direction. In some embodiments, the fins contact the heat source at a severe angle providing a low profile. In some embodiments, surface of fins may have features such as ridges or bumps that may help induce eddies in air flowing past the fins and hence enhance convection. In some embodiments the fins may have slots 1106 or strain reliefs cut or formed into the fin to allow it to expand and contract more freely along the direction of its long axis as show in Fig. 11B.

[0062] The struts may have a cross-sectional shape of a square, a rectangle, a trapezoid, a triangle, a parallelogram, or any suitable shape. In some embodiments, the struts are straight and/or curved. In some embodiments, a strut has an elongate configuration with two ends coupled to two adjacent fins. As illustrated in Fig. 13A, such elongate struts may independently have a length (*sl*), a width (*sw*), and a thickness (*st*). In some embodiments, struts may have a curved configuration and in such a case, the length (*sl*) of a strut is the linear distance between two ends of the strut. The length (*sl*) of any strut may be independently between 0.05" and 1", or between 0.075" and 0.9", or between 0.1" and 0.8", or between 0.2" and 0.7", or between 0.25" and 0.6", or between 0.3" and 0.5", or between 0.4" and 0.48" or between 0.42" and 0.46", or between 0.43" and 0.45", or about 0.44". The width (*sw*) of any strut may be independently less than 1 inch, or less than 0.75", or less than 0.5", or less than 0.3", or less than 0.2", or less than 0.15", or less than 0.1", or less than 0.05", or less than 0.025", or less than 0.01", or less than 0.005", or less than 0.0025, or between 0.0025" and 0.75", or between 0.0075" and 0.5", or between 0.025" and 0.4", or between 0.05" and 0.3", or between 0.075" and 0.2", or between 0.09" and 0.15", or between 0.09" and 0.12", or about 0.11". The thickness (*st*) of any strut may independently less than 1 inch, or less than 0.75", or less than 0.5", or less than 0.3", or less than 0.2", or less than 0.15", or less than 0.1", or less than 0.05", or less than 0.025", or less than 0.01", or less than 0.005", or less than 0.0025, or between 0.0025" and 0.75", or between 0.0075" and 0.5", or between 0.025" and 0.4", or between 0.05" and 0.3", or between 0.075" and 0.2", or between 0.09" and 0.15", or between 0.09" and 0.12", or about 0.11".

[0063] As illustrated in Fig. 13B, in some embodiments, an elongate strut may have a draft angle θ, which may independently be any of about 5°, 10°, 15°, 20°, 25° or 30°. In such an embodiment, the strut may have a trapezoidal cross-sectional shape along its longitudinal length. The strut in this embodiment may independently have a length (*sl*), a base width (*bsw*), and a thickness (*st*). In some embodiments, struts may have a curved configuration and in such a case, the length (*sl*) of a strut is the linear distance between two ends of the strut. The length (*sl*) of any strut may be independently between 0.05" and 1", or between 0.075" and 0.9", or between 0.1" and 0.8", or between 0.2" and 0.7", or between 0.2" and 0.5", or between 0.25" and 0.45", or between 0.25" and 0.4" or between 0.25" and 0.35", or between 0.25" and 0.3", or between 0.27" and 0.29", or between 0.28" and 0.29", or about 0.285". The base width (*bsw*) of any strut may be independently less than 1 inch, or less than 0.75", or less than 0.5", or less than 0.3", or less than 0.2", or less than 0.15", or less than 0.1", or less than 0.05", or less than 0.025", or less than 0.01", or less than 0.005", or less than 0.0025, or between 0.0025" and 0.25", or between 0.0075" and 0.5", or between 0.025" and 0.4", or between 0.05" and 0.3", or between 0.075" and 0.02", or between 0.09" and 0.015", or between 0.1" and 0.012", or about 0.011". The thickness (*st*) of any strut may independently less than 1 inch, or less than 0.75", or less than 0.5", or less than 0.3", or less than 0.2", or less than 0.15", or less than 0.1", or less than 0.05", or less than 0.025", or less than 0.01", or less than 0.005", or less than 0.0025, or between 0.0025" and 0.25", or between 0.0075" and 0.5", or between 0.025" and 0.4", or between 0.05" and 0.3", or between 0.075" and 0. 2", or between 0.09" and 0.15", or between 0.1" and 0.12", or about 0.11".

[0064] In some embodiments, the strut may be coupled to a fin on the bottom surface of the fin and hence when the heat sink is in use, the struts, with or without the fins, is in direct thermal contact with the surface of the heat source. In some embodiments, the entire strut may be in thermal contact with the heat source, but in other embodiments, only end portions of a strut, which are coupled to the bottom surfaces of fins, are in thermal contact with the heat source. In embodiments where the struts are in direct thermal contact with the heat source, thermally induced loads and gravity loads on the heat sink may be distributed over a larger surface area. In other embodiments, the strut may be coupled to a fin at other spots along the long axis of a fin. For example, a strut may be coupled to a fin near the top of the fin. Such connecting configuration may expose more surface area of the heat source to the surrounding cooling fluid and hence improves convection and overall heat transfer efficiency. The ratio between the length of the fin above the spot where the strut is coupled to the fin and the height (h) of the fin may independently be any of about 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5, 0.55, 0.6, 0.65, 0.7, 0.75, 0.8, 0.85, 0.9, 0.95, or 1. In some embodiments, the strut may be substantially parallel to the surface of the heat source, but in other embodiments, the strut may form an angle with respect to the surface of the heat source. In some embodiments, such an angle may independently be in the range of about 10° to about 60°, sometimes in the range of about 20° to about 50° and other times in the range of about 30° to about 40°.

[0065] Strut is only one exemplary embodiment that may be used to connect fins of a low stress-inducing minimal-base heat sink. Other type of suitable connecting structures known to those skilled in the art may be used. Non-limiting examples include pins, bars, sheets, straps, leaf springs, bending beams or the like. In some embodiments, fins of a heat sink are directly mounted on the surface of a heat source as individual structures without using any connecting struts.

[0066] In some embodiments of low stress-inducing minimal-base heat sinks disclosed here, fins of a heat sink may be made of one or more thermally conductive materials, such as aluminum or aluminum alloy (e.g., 6063 aluminum alloy, 6061 aluminum alloy, and 6005 aluminum alloy), copper, graphite, or conductive polymer (e.g., CoolPoly® thermally conductive plastics, PolyOne Therma-Tech thermally conductive plastics, nylon 6-6, filled nylon 6-6, and/or a polyphenylene sulfide, optionally mixed with one or more thermally conductive fillers such as metal, ceramic, graphite, nanotubes, etc.).

[0067] Struts may be made of, but not limited to metals, metal alloys (e.g., stainless steel, a shape memory nickel titanium alloy, etc.), polymeric materials or any other suitable materials known to the ordinary skilled in the art. In some embodiments, struts are made from a flexible material. Struts may or may not be made from a thermally conductive material. Struts may or may not be made from the same material as fins. Fins and/or struts of a heat sink may be of any color, such as blue, black, gray or brown. In some embodiments, dark color may improve heat sink performance. In some embodiments, fins and/or struts of a heat sink constructed of metal may be anodized or plated.

[0068] In some embodiments, struts may be integrally formed with fins of a heat sink. Such integrally formed heat sinks may be constructed by common manufacturing techniques such as extrusion, casting, forging, machining, and/or injection molding. In some embodiments, machining may be operated in addition to (e.g., subsequent to or preceding to) any of other steps performed to make a low stress-inducing minimal-base heat sink. In other embodiments, struts may be separately manufactured and then attached to fins. Struts may be coupled to fins by welding, brazing, bolting, pinning, riveting, adhesive, overmolding, using a friction or an interference fit or any suitable technique known to those skilled in the art. In some embodiments, the struts are made of metal (e.g., metal strips) which connect one or more injection molded fins (e.g., thermally conductive polymer fins, such as pin-fins). In other embodiments, the fins (e.g., pin-fins) are made from metal and are connected to one or more injection molded struts.

[0069] In some embodiments, fins (e.g., pin-fins) may protrude through a connecting sheet such that individual fins of the heat sink are connected through the connecting sheet while the bottom surfaces of fins are exposed for connection to the heat source. In some embodiments, the connecting sheet may be located at a position with a vertical distance *d* from the heat source surface. The ratio between such distance *d* and the height of the heat sink fins may independently be 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5, 0.55, 0.6, 0.65, 0.7, 0.75, 0.8, 0.85, 0.9, 0.95, or 1. In some embodiments, the surface of the connecting sheet may be substantially perpendicular with respect to the long axis of the fins (e.g., pin-fins). In other embodiments, the surface of the connecting sheet may form an angle with respect to the long axis of the fins (e.g., pin-fins). The angle between the surface of the connecting sheet and the long axis of the fins may independently be any of about 5°, 10°, 15°, 20°, 25°, 30°, 35°, 40°, 45°, 50°, 55°, 60°, 65°, 70°, 75°, 80° or 85°. In some embodiments, the connecting sheet may have a configuration of an open mesh with surface openings large enough to receive pin-fins of a heat sink. In other embodiments, the connecting sheet may be continuous but have holes with matching number, dimension, and geometric arrangement with the pin-fin array to be inserted. The connecting sheet may or may not be made from the same material as the fins of the heat sink. In some embodiments, the connecting sheet is made from a soft or flexible material, such as (but not limited to) a polymer or elastomer. The flexible sheet may allow the inserted fins to flex when under thermally induced stress and/or strain, thereby providing in-plane flexibility to the heat sink. In other embodiments, the connecting sheet may be made from a metal or metal alloy of such dimension and shape to provide flexibility in the surface of attachment of the heat sink to the heat source. The connecting sheet may be secured to the fins of the heat sink by welding, brazing, adhesive, or using a friction or an interference fit or any suitable technique known to those skilled in the art.

[0070] The material of one or more components of the low stress-inducing minimal-base heat sink (e.g., the fins and/or struts) may have a thermal conductivity in the range of about 0.5 W/mK to about 400 W/mK, sometimes in the range of about 1 W/mK to about 150 W/mK, sometimes in the range of about 1 W/mK to about 100 W/mK, sometimes in the range of about 1 W/mK to about 50 W/mK, and other times in the range of about 1 W/mK to about 20 W/mK. In some embodiments, a low stress-inducing minimal-base heat sink may be made from a material having a thermal conductivity lower than about 20 W/mK, or lower than about 15 W/mK, or lower than about 10 W/mK, or lower than about 5 W/mK, or lower than about 2 W/mK, or lower than about 1 W/mK.

[0071] Heat sink with a low stress-inducing minimal base as described here may have an overall heat transfer coefficient greater than 0.5 $W/m^2 \cdot {}^\circ C$, or greater than 1 $W/m^2 \cdot {}^\circ C$, or greater than 2 $W/m^2 \cdot {}^\circ C$, or greater than 3 $W/m^2 \cdot {}^\circ C$, or greater than 4 $W/m^2 \cdot {}^\circ C$, or greater than 5 $W/m^2 \cdot {}^\circ C$, or greater than 6 $W/m^2 \cdot {}^\circ C$, or greater than 7 $W/m^2 \cdot {}^\circ C$, or greater than 8 $W/m^2 \cdot {}^\circ C$, or greater than 9 $W/m^2 \cdot {}^\circ C$, or greater than 10 $W/m^2 \cdot {}^\circ C$, or greater than 11 $W/m^2 \cdot {}^\circ C$, or greater than 12 $W/m^2 \cdot {}^\circ C$, or greater than 13 $W/m^2 \cdot {}^\circ C$, or greater than 14 $W/m^2 \cdot {}^\circ C$, or greater than 15 $W/m^2 \cdot {}^\circ C$, or greater than 20 $W/m^2 \cdot {}^\circ C$.

[0072] In some embodiments as described above, a fan, pump or other type of power source may be used to propel the cooling fluid, e.g., air and create an artificially induced convection channels (i.e., forced convection). The external source of the driving force may be placed on top of the heat sink, on side of the heat sink or other locations that may enhance the convective heat transfer. The power source may deliver the forced cooling fluid to the heat sink by direct exposure or remotely through a duct system. In another embodiment, natural convection may be used so that the driving force of the cooling fluid is temperature differential across the fins, which drives the cooler and less dense fluid to rise and therefore forms a convection current. In yet another embodiment, wind could be used as the driving force for the air flow.

[0073] A low stress-inducing heat sink with minimal base may be attached to the surface of a heat source by a number of methods, such as welding, soldering, ultrasonic bonding, adhesive (e.g., polyurethane, silicone, etc.) or other suitable technique known to those skilled in the art. In some embodiments, pre-shaped adhesive sheets (e.g., pre-shaped to the same shape as the contact area of the fins) may be used to attach the heat sink to the heat source. In other embodiments, the adhesive may be applied to the surface of the heat source first by methods, such as (but not limited to) stencil or screen printing. In some variations, one or more adhesive materials in a molten state may be applied to the surface of heat source and cured in place when the heat sink is attached. Applying the adhesive material in a molten state may fill any voids, ridges or other type of defections on the surface of the object to be cooled, which in turn will provide a better thermal contact between the heat source and the heat sink. Moreover, by using stencil or screen printing methods, one may precisely control the geometric location, shape, and the thickness of the adhesive used to attach the heat sink. The print head may be custom-designed for heat sinks with different configurations of pin-fin array and/or strut-mesh pattern. In some embodiments, molten adhesive may be applied to the heat sink before the heat sink is united with the heat source.

[0074] In some embodiments, the heat sink may be attached directly to the surface of a heat source. In other embodiments, the surface of the heat source may first be covered with a layer of intervening material and the heat sink may then be attached to the intervening layer. An example of an intervening layer is an intervening thermal interface layer, which can be made of any material used in the art, such as thermally conductive grease or adhesive (e.g., conductive epoxy, silicone, or ceramic) or an intervening conductive polymer (such as a thermally conductive polymer available from Cool Polymers, Inc., PolyOne Therma-Tech thermally conductive plastics, nylon 6-6, filled nylon 6-6, and/or a polyphenylene sulfide, optional mixed with one or more metallic, ceramic, graphite, carbon nanotube or other thermally conductive fillers). The thermal interface layer may be of any material commonly used in the art (e.g., ethyl-vinyl-acetate (EVA), polyester, Tedlar®, EPT). The intervening layer may be constructed of material that is both electrically isolative and thermally conductive. The intervening layer may be a thin layer of polymer that is not intrinsically thermally conductive but, due to its thinness, conducts heat at a sufficient rate that it is considered thermally conductive. Other layers may be present separately or in addition to an intervening layer, such as one or more electrically insulating layers. The intervening layer may be in simultaneous contact with both the heat source and the heat sink.

[0075] Figs. 14A and 14B depict one exemplary embodiment of a low stress-inducing minimal-base heat sink comprising frustum cones 1402, connected with struts 1404.

The frustum cones 1402 may have a height, a width (*w*), a wall thickness (*wt*), a bottom width (*bw*), and a center to center spacing (*s*). The frustum cones 1402 are connected with each other with struts 1404 having a length, a width and a thickness. As depicted in these two figures, the frustum cones 1402 may be hollow from the bottom width of each cone to the top of each cone (and optionally hollow completely through the top of each cone) to decrease production cost. In one instance of the embodiment exemplified in Figs. 14A and 14B, the heat sink is comprised of hollow frustum cones each 1402 having a height (*h*) of about 30 mm to about 100 mm, width (*w*) of about 1.5 mm to about 3 mm, a bottom width (*bw*) of about 4 mm to about 6 mm, a wall thickness (*wt*) of about 1.5 mm, a center to center spacing (*s*) of about 14 mm; struts 1404 having a length of about 9 mm, a width of about 2 mm and a thickness of about 1mm. The frustum cones 1402 can be aligned in staggered parallel rows and columns. Even though in this embodiment the frustum cones 1402 are disposed in staggered parallel rows and columns, in other embodiments, they may be disposed in non-staggered parallel rows and columns. The total area of the bottom surfaces of the cones 1402 may be less than or any of about 10 %, 20 %, 30 %, 40 %, 50 %, 60 %, 70 %, 80 %, or about 90 % of the area of the heat source surface 1401. The heat sink may be made of, for example, Nylon 1020, Nylon 1040, Nylon 1240, Froton 6165A, Froton 6165D, or polyphenylene sulfide, or any other polymer described herein, and may comprise one or more UV stabilizers and/or one or more heat stabilizers. The frustum cones may comprise channels across the width of one or more cones to allow increased ambient air access. In another embodiment, there may be no struts present, with the protrusions being held only by their attachment to the surface 1401.

[0076] Figs. 15A and 15B illustrate another exemplary embodiment of a low stress-inducing minimal-base heat sink comprising multiple frustum cones 1502, connected with struts 1504. The frustum cones 1502 may be hollow from the top of each cone down through the center of each cone to decrease production cost. The hollow bore 1510 arrangement may allow increased surface area of the frustum cones 1502 to promote heat dissipation from the heat sink. The hollow bore 1510 depicted in Figs. 15A and 15B may have a constant bore diameter (*bd*), or may have varying diameter (such as decreasing in diameter as the bore is closer to bottom surface of the cone 1502). In one instance of the embodiment exemplified in Figs. 15A and 15B the heat sink comprises hollow frustum cones 1502 having a height (*h*) of about 30 mm to about 70 mm, a top width (*w*) of about 1.5 mm to about 3 mm, a base width (bw) of about 4 mm to about 6 mm, and a center to center spacing (s) of about 14 mm; struts 1504 having a length of about 9 mm, a width of about 2 mm and a thickness of about 1mm. The frustum cones 1502 can be aligned in staggered parallel rows and columns. Even though in this embodiment the frustum cones 1502 are disposed in staggered parallel rows and columns, in other embodiments, they may be disposed in non-staggered parallel rows and columns. The total area of the bottom surfaces of the cones 1502 may be less than or about any of 10 %, 20 %, 30 %, 40 %, 50 %, 60 %, 70 %, 80 %, or about 90 % of the area of the heat source surface 1501. In another embodiment, there may be no struts present, with the protrusions being held only by their attachment to the surface 1501.

[0077] Figs. 16A and 16B illustrate another exemplary embodiment of a low stress-inducing minimal-base heat sink comprising multiple pin-fins 1602, connected with struts 1604. The pin-fins 1602 have a general frustum-conical configuration with curved surfaces. In some embodiments, pin-fins 1602 may comprise the surface profile of a hyperbolic curve, a quadratic curve, a polynomial curve with an order higher than two, a circular arc, or a combination thereof. Pin-fins with curved surface may reduce material usage. Further, such surface curvature may create additional air channels cross pin-fins and hence enhance the convection heat transfer efficiency. Pin-fins 1602 may be hollow from the top of each pin-fin down through the center of each pin-fin to further decrease production cost. The hollow bore 1610 arrangement may allow increased surface area of the pin-fins 1602 to promote heat dissipation from the heat sink. The hollow bore 1610 depicted in Figs. 16A and 16B may have a constant bore diameter (*bd*), or may have varying diameter (such as decreasing in diameter as the bore is closer to the bottom surface of the pin-fin 1602). In one instance of the embodiment exemplified in Figs. 16A and 16B the heat sink comprises hollow pin-fins 1602 having a height of about 30 mm to about 70 mm, a top width (*w*) of about 2 mm, a base width (*bw*) of about 6 mm, a constant bore diameter (*bd*) of about 1.5 mm and a fin open spacing (s) (e.g., the center-to-center spacing between two fins minus the base width of a fin) of about 7.25 mm; struts 1604 having a length of about 7.25 mm, a width of about 2.5 mm to about 3 mm, and a thickness of about 2.5 mm to about 3 mm; and wherein the pin-fins 1602 are aligned in parallel rows and columns to form a rectangular pin-fin array. In another embodiment, there may be no struts present, with the protrusions being held only by their attachment to the surface 1601.

[0078] Figs. 17A and 17B depict another exemplary embodiment of a low stress-inducing minimal-base heat sink comprising pin-fins 1702 connected to surface 1701, and connected to other protrusions 1702 with struts 1704. The pin-fins 1702 with curved surface may have a height, a width (*w*), a wall thickness (*wt*), a bottom width (*bw*), a center to center spacing (*s*). The wall thickness (*wt*) may vary along the longitudinal length of the pins and/or around the circumference of the pins. The pin-fins 1702 are connected with each other with struts 1704 having a length, a width and a thickness. As depicted in these two figures, the pin-fins 1702 may be hollow from the bottom width of each pin-fin to the top width of each pin-fin (and optionally hollow completely through the top of each pin-fin) to decrease production cost. The hollow bore 1710 arrangement may allow increased surface area of the pin-fins 1702 to promote heat dissipation from the heat sink. In one instance of the embodiment exemplified in Figs. 17A and 17B, the heat sink comprises hollow pin-fins 1702 having a height of about 30 mm to about 70 mm, a width (*w*) of about 2 mm, a bottom width (*bw*) of about 5 mm, a wall thickness (*wt*) of about 0.5 mm to about 1.5 mm, and an open fin spacing (e.g., the center-to-center spacing between two fins minus the base width of a fin) of about 7.25 mm; struts 1704 having a length of about 7.25 mm, a width of about 2.5 mm to about 3 mm and a thickness of about 2.5 mm to about 3 mm; and wherein the pin-fins 1702 are aligned in parallel rows and columns to form a rectangular pin-fin array. In some embodiments, the protrusions may be arranged in random patterns for ease of manufacture.

[0079] The low stress-inducing minimal-base heat sinks shown in Figs. 13A to 14B and in Figs. 16A to 17B are only exemplary embodiments. Although the heat sinks in these embodiments comprise frustum cones fins, fins with other configurations may be used. Further, in other embodiments, fins may or may not be hollow and may or may not substantially vertically extend from the heat source surface. Although straight struts are shown in these embodiments to connect fins, struts with other configurations, e.g., curved struts or the combination of straight and curved struts may be used. In addition to or in lieu of struts, other type of connecting structures known by the ordinary skilled in the art may be used as well. There may be no struts or other protrusion-interconnecting structures present, with the fins being held only by their attachment to the surface. Further, although the struts in Figs. 13A to 14B and in Figs. 16A to 17B are shown in contact with the heat source surface, in other embodiments, the struts may be elevated above the heat source surface.

Stamped Sheet Heat Sink

[0080] In some embodiments, a low stress-inducing minimal-base heat sink may be made from a stamped sheet. In one embodiment, at least one fin may be stamped on a sheet metal (e.g., a thin metal sheet). All sides except one that connects the fin to the sheet metal may be punched through such that the fin can be separated and bent away from the sheet metal. Fig. 18A schematically illustrates one embodiment of a method to make one stamped sheet metal fin. As illustrated in this figure, a fin 1802 with a rectangular shape is stamped on a sheet metal 1801. Three sides 1804, 1805 and 1806 of the rectangular fin 1802 are punched through the sheet metal 1801 while the fin 1802 is still attached to the sheet metal 1801 through a base side 1803. In this way, the fin 1802 may be separated from the sheet metal 1801 and be bent upwardly away from the surface of the sheet metal 1801, thereby leaving an opening 1807 on the sheet metal 1801. In some variations, the fin 1802 may be bent to a position where the fin 1802 extends substantially perpendicular to the surface of the sheet metal 1801. In other variations, there may be an angle between the longitudinal axis of the fin 1802 and the surface of the sheet metal 1801. More than one fin 1802 may be made in a similar way from the sheet metal 1801 to form a heat sink. As illustrated in Fig. 18B, heat sink 1800 comprising one or more protrusions 1802 and a non-continuous base 1808, may be attached to a surface of a heat source (e.g., a photovoltaic cell or module). The base sides 1803 of the protrusions 1802 are optionally disposed in an offset fashion along the Y axis of the sheet metal. This design of offsetting stamping pattern may provide a higher degree of in-plane flexibility than a design where the base portions 1803 are in a straight line, because the former arrangement may allow the base area to flex along the Y axis when the base is under thermally induced stress and/or strain. Such a heat sink 1800 is a low stress-inducing minimal-base heat sink because the contact area between the heat source surface and the heat sink ($A_{contact}$) (e.g., the total area of the base sides 1803 of the protrusions 1802) is less than the total area between the heat source and the heat sink (A_{total}) (e.g., the area within the perimeter defined by the outer-most coordinates of the base sides 1803), as defined in the previous section.

[0081] In some embodiments, the sheet may be metal and the metal may be, but is not limited to, copper, aluminum, zinc, nickel, bronze, steel, and/or other alloys thereof. The thickness of the sheet metal may be independently between about 0.01 mm and about 5 mm, or between about 0.05 mm and about 4 mm, or between about 0.075 mm and about 3 mm, or between about 0.1 mm and about 2 mm, or between about 0.25 mm and about 1 mm, or between about 0.5 mm and about 0.75 mm, or between about 0.6 mm and about 0.7 mm. In some embodiments, the sheet may be a thermally conductive polymer. In these cases, the forming process may include heat to help the protrusions retain the bends. The thickness of the polymer sheet may be independently between about 0.1 mm and about 5 mm, or between about 0.2 mm and about 4 mm, or between about 0.3 mm and about 3.5 mm, or between about 0.4 mm and about 3 mm, or between about 0.5 mm and about 2.8 mm, or between about 0.6 mm and about 2.3 mm, or between about 0.9 mm and about 2 mm.

[0082] In some embodiments, a pre-determined fin-pattern may be stamped on a sheet metal. The pattern may comprise multiple fins with similar or different configurations. Similar to the process as described above, all sides but one base side of each fin may be punched through the sheet metal, thereby leaving the fin attached to the sheet metal through its base side. Such a fin then may be bent upwardly away from the surface of the sheet metal and form a heat sink fin extending from a non-continuous base (e.g., the sheet metal). Figs. 19A and 19B schematically illustrate a top-down view of one embodiment of a pre-determined fin-pattern 1900. In this embodiment, a plurality of fins 1902 with a substantially triangular configuration is stamped on a sheet metal. Fins

1902 may be punched at all its sides except for the base side 1906. Fig. 19B illustrates the top view of the heat sink with all fins 1902 bent upwardly and extending substantially perpendicular with respect to the surface of the sheet metal. Areas 1908 in this figure represent the openings on the sheet metal left by the bent fins 1902. The size of the heat sink 1900 and the extent of the array of fins 1902 can be large or small. Fig. 19C illustrates the base of the heat sink 1900 formed by the stamped sheet metal with fins 1902 removed. In this embodiment, each column of rectangular base portions 1909, which connect two horizontally adjacent fins 1902 and contact a heat source surface, are connected by a narrow curved connector 1910 area of metal. This design with a narrow curved connector 1910 may provide a higher degree of in-plane flexibility then a design where the base portions 1909 are continuous because the former arrangement may allow the curved connector 1910 to flex along the Y axis when the base is under thermally induced stress and/or strain.

[0083] The pre-determined fin stamping pattern on the sheet metal may be designed to maximize the number of fins to be formed. (*See* Fig. 19A). This design may not only reduce material usage, but also reduce the area of the base, which in turn may reduce in-plane rigidity of the heat sink. The fin pattern illustrated in Fig. 19A is only an exemplary embodiment. Any other patterns that maximize the amount of material used for fins and/or minimize the area of the base may be used.

[0084] The rectangular fin 1802 and the substantially triangular fin 1902 as described above are two exemplary embodiments. Fins of a stamped sheet metal heat sink may comprise any suitable shape so as to provide heat dissipation.

[0085] Figs. 20A and 20B illustrate another embodiment of a stamped sheet metal heat sink 2000 with substantially triangular fins 2002. Fig. 20A illustrates a pre-determined fin-pattern stamped onto a sheet metal that will result in the sheet separating into strips with facing pairs of fins 2002 along the punched-through fin outlines 2003. The fin strips then may be handled independently and attached to a heated surface. Fig. 20B illustrates a pattern of outlines 2003 that produce single strip of fins 2002. This may further reduce material use because the fin strips can be spaced independent of the width of the base portion 2009. In some embodiments, triangular fins may provide more efficient use of material because less cross sectional area of fin is required to conduct heat farther from the heat source.

[0086] In some embodiments, fins of a stamped sheet metal heat sink may independently have a height (*h*) and a base width (*bw*). In some embodiments, the selected *h* and *bw* may provide sufficiently improved heat sink efficiency when compared to a non-minimal-base heat sink (e.g., a heat sink with a continuous base). The height *h* of any fin may be independently greater than 0.1", or greater than 0.25", or greater than 0.5", or greater than 0.75", or greater than 1", or greater than 2", or greater than 3.5", or between 0.25" and 7", or between 0.5" and 6", or between 0.75" and 5", or between 0.8" and 2.5", or between 0.9" and 2", or between 0.9" and 1.25", or 1". The base width *bw* may be independently between about 0.1 mm and about 20 mm, or between about 0.2 mm and about 15 mm, or between about 0.5 mm and about 10 mm, or between about 0.75 mm and about 7.5 mm, or between about 1 mm and about 5 mm, or between about 2 mm and about 2.5 mm.

[0087] In some embodiments, all fins of a stamped sheet metal heat sink may be bent to form a same angle with respect to the surface of the sheet metal. The angle between the long axis of the fins and the surface of the sheet metal may independently be any of about 5°, 10°, 15°, 20°, 25°, 30°, 35°, 40°, 45°, 50°, 55°, 60°, 65°, 70°, 75°, 80°, 85°, or 90°. In some embodiments, the angle between the long axis of some fins and the surface of the sheet metal is different from the angle between the long axis of other fins and the surface of the sheet metal. The angle between the long axis of each fin and the surface of the sheet metal may be independently selected to form additional air channels. Some fins may have two or more bends to alter the shape of the fin and the position of the upper part of the fin. In some embodiments, connecting members (e.g., connecting struts described herein) may be used to connect stamped sheet metal fins to maintain fins' relative orientation.

[0088] In some embodiments, a fin of a stamped sheet metal heat sink may comprise a straight base line (e.g., 1803 in Fig. 18A), where the fin is attached to the base (e.g., the stamped sheet metal). In other embodiments, the base line may have a non-linear configuration. For example, the base line may be curved or may have a step pattern along the base line. In still other embodiments, other sides of a stamped fin, which are punched through the sheet metal, may also have a non-linear configuration. In such a way, once the fins are bent upwardly away from the base sheet, they are connected at the base with one or more non-linear parts. This design may further reduce in-plane rigidity of the heat sink because the non-linear connecting parts on the base may bend when under tension from the connected fins. As a result, fins may be allowed to flex more compared to fins connected with straight connecting parts.

[0089] In some embodiments, standard metal stamping machine may be used to make the low stress-inducing minimal-base stamped sheet metal heat sink described herein. For example, dies and punches may be custom-designed for heat sinks with different fin-patterns. In some embodiments, progressive stamping may be applied to make heat sinks comprising fins with different dimensions and/or configurations (e.g., rectangular, triangular, picket-like or rounded). In still other embodiments, the sheet metal may be coated in a polymer or other material that may be electrically insulative.

Segmented-base Heat Sink

[0090] In some embodiments, a low stress-inducing heat sink may be a segmented-base heat sink, which may comprise a base that further comprises a plurality of segments. A segmented base heat sink is considered to have a base area greater than that required for heat conduction away from the surface. The fins depicted in figures 3 through 9 and in figures 13, 14, 16 and 17 generally have a base only large enough to efficiently conduct heat to the upper part of the fin. The larger base area of a segmented-base heat sink may improve heat transfer by spreading heat in the plane of the surface being cooled and/or it may improve mechanical strength of the fin connection. The segmented base may comprise any number of segments with same or different geometric configurations, including but not limited to square, rectangular, triangular, parallelogram, trapezoid, polygon, etc. In some embodiments, a segmented-base heat sink may comprise, for example, 4, 6, 9, 12, 16, 20, 25, 30, 36, 42, 49, 56, 64, 72, 81, 90, 100, 110, 121, or more base segments. The spacing between each segment may be any suitable distance that may provide sufficient room for segments to contract and expand during thermal excursions, thereby passing less thermally induced stress and strain to the heat source than a non-segmented (e.g., continuous) base. In some embodiments, each base segment may be mounted on the surface of a heat source individually and may be not connected with another segment. In some embodiments, the base segments of a segmented-base heat sink may be interconnected with one or more connecting members, e.g., struts. Each segment of the heat sink base may have any contact surface area with the heat source that would be small enough such that thermally induced stress and strain occurred at each base segment would not damage the heat source. The contact surface area may be sized in part based upon the difference in thermal expansion coefficient between the base material and the heat source material and/or the range of the temperature excursion under consideration.

[0091] Figs. 21A and 21B are schematic side view and top view of one embodiment of a segmented-base heat sink, respectively. In this specific embodiment, heat sink 2100 comprises a plurality of base segments 2110 with square configurations. In other embodiments, the base segment 2110 may be of any other suitable shape, such as rectangular or triangular. In the depicted embodiment, each base segment 2110 comprises a fin 2120 with a pin-like configuration mounted in the center of the base segment 2110 and extending substantially perpendicular to the base segment 2110. In other embodiments, each base segment 2110 may comprise any number, for example, 1, 2, 3, 4, 5, 8, 10, 20 or more of fins. Each base segment 2110 may or may not comprise the same number of fins. In some variations, fins mounted on each base segment may be disposed as a grid array, with either aligned or staggered parallel rows and columns. In other variations, fins on each base segment may be disposed as a radial array. In some embodiments, fins may have a pin-like configuration (e.g., pin-fins) with a general cylindrical shape (with curved or non-curved surface). In other embodiments, fins may be rectangular-fins. In some variations, the cross-sectional area of each fin may independently vary along the longitudinal length of the fin. In some embodiments, fin(s) on each base segment may form an angle between the longitudinal axis of the fin and the surface of the base segment. The angle may independently be any of about 5°, 10°, 15°, 20°, 25°, 30°, 35°, 40°, 45°, 50°, 55°, 60°, 65°, 70°, 75°, 80° or 85°. The segmented-base heat sink 2100 in Fig. 21B comprises a segmentation pattern with parallel rows and columns of base segments. The distance between each row may be independently in the range of about 1 mm to about 50 mm, sometimes in the range of about 5 mm to about 40 mm, sometimes in the range of about 10 mm to about 30 mm, and other times in the range of about 15 mm to about 25 mm. The distance between each column may be independently in the range of about 1 mm to about 50 mm, sometimes in the range of about 5 mm to about 40 mm, sometimes in the range of about 10 mm to about 30 mm, and other times in the range of about 15 mm to about 25 mm. The distance between each row and the distance between each column in one segmented-base may or may not be the same.

[0092] In the embodiment depicted in Figs. 21A and 21B, each base segment 2110 may be mounted on the surface of a heat source individually and is not connected to another segment. In some embodiments, base segments may be interconnected with one or more connecting members, such as struts, pins, bars, sheets, straps, leaf springs, bending beam, or the like. Figs. 22A and 22B schematically illustrate one embodiment of a segmented-base heat sink 2200 with base segments 2210 interconnected with a plurality of struts 2230. In the depicted embodiment, each base segment 2210 comprises a fin 2220 with a pin-like configuration mounted in the center of the base segment 2210 and extending substantially perpendicular to the base segment 2210. In some embodiments, each base segment may be connected to, for example, 1, 2, 3, 4, 5, 6, 7, 8, etc. surrounding base segments. Struts 2230 may be coupled to base segments 2210 by welding, brazing, bolting, pinning, riveting, adhesive, overmolding, a friction or an interference fit or any suitable technique known to those skilled in the art. The strut 2230 in this specific embodiment has a straight configuration. In other embodiments, it may have a curved configuration, which may further facilitate reducing the stress and/or strain in the heat source. In some embodiments, the struts 2230 may be in thermal contact with the heat source surface, whereas in other embodiments, the struts 2230 may be elevated from the heat source surface, as illustrated in Fig. 22A.

Struts 2230 may be made of, but not limited to metals, metal alloys, polymeric materials or any other suitable materials known to the ordinary skilled in the art. Struts 2230 may or may not be made from the same material as the base segments 2210. The strut may be of any shape and/or dimension that may provide in-plane flexibility to the heat sink while maintaining relative orientation of the base segments with respect to each other. Some exemplary strut configurations and dimensions that may be used in a segmented-base heat sink have been described in greater detail above and will not be repeated here for sake of brevity.

[0093] In some embodiments, fins or base segments may be interconnected with a connecting sheet. Figs. 23A and 23B schematically illustrate such an embodiment. In this depicted embodiment, a connecting sheet 2330 comprises a plurality of openings configured to receive base segments 2310 of a segmented-base heat sink 2300. In the depicted embodiment, each base segment 2310 comprises a fin 2320 with a pin-like configuration mounted in the center of the base segment 2310 and extending substantially perpendicular to the base segment 2310. The connecting sheet 2330 may have a mesh-like configuration with multiple openings that are large enough to receive base segments of a segmented-base heat sink. In other embodiments, the connecting sheet may comprise a complementary pattern of openings that is configured to be used with a specific segmentation pattern. The connecting sheet may be made of a flexible or semi-flexible material, such as a polymer or elastomer. The connecting sheet may be secured to the base segments by welding, brazing, adhesive, overmolding or using a friction or an interference fit or any other suitable techniques known to those skilled in the art. The connecting sheet may or may not be in thermal contact with the heat source surface. Such a connecting sheet may also be used with fins that do not have a base segment.

[0094] Figs. 24A and 24B illustrate another embodiment of a segmented-base heat sink 2400 with interleaved base segments 2410. In the depicted embodiment, each base segment 2410 comprises a fin 2420 with a pin-like configuration mounted in the center of the base segment 2410 and extending substantially perpendicular to the base segment 2410. In this depicted embodiment, each base segment 2410 comprises a zigzag interface 2430 with an adjacent base segment. In other embodiments, the interface may comprise a sinusoidal, a square-wave or other types of non-linear configuration. The interleaved interface between base segments may provide enhanced transverse heat conduction within the heat sink base while still providing in-plane flexibility. In some embodiments, adjacent base segments may be in thermal contact with each other. In other embodiments, there may be a distance between the edges of two adjacent base segments. Such a distance may be in the range of about 1mm to about 10 mm, sometimes in the range of about 2 mm to about 8 mm, sometimes in the range of about 4 mm to about 6 mm. In some embodiments, the distance between two adjacent base segments may vary along their interface. In some embodiments, the protrusions may be arranged in random patterns for ease of manufacture.

[0095] While in the exemplary embodiments shown in Fig. 21A to Fig. 24B, there is only one fin mounted on each base segment, more than one, for example, 2, 3, 4, 5, 10, or more fins may be mounted on one base segment in other embodiments. In some variations, each base segment may comprise different number of fins from other base segments.

[0096] In some embodiments, a low stress-inducing heat sink may comprise a flexible base that retains the heat sink in intimate thermal contact with the heat source while allowing the heat sink to flex in the direction of thermal expansion and/or contraction of the heat source, thereby reducing mechanical stress and strain imparted by the heat sink to the heat source. In some embodiments, the flexible base of a low stress-inducing heat sink may be independently construed of one or more flexible and thermally conductive materials. Examples of flexible base material include, but not limited to, thermally conductive polymer available from Cool Polymers, Inc., nylon 6-6, and/or a polyphenylene sulfide, optionally mixed with one or more conductive fillers. In some embodiments, the stress and strain imparted to a heat source by a low stress-inducing heat sink with a flexible base, when tested under the maximum expected thermal excursion for a particular application by an industry standard test (e.g., from -40 °C to + 90 °C under the industry standard UL 1703 Temperature Cycling Test for

Flat-Plate Photovoltaic Modules and Panels), is less than any of about 90%, 80%, 70%, 60%, 50%, 40%, 30%, 20%, 10%, or less of the observed fracture strength of the heat source.

[0097] In any embodiment disclosed herein, regardless of what has been described in examples, figures, claims or elsewhere, the heat source may be a photovoltaic cell, a plurality of photovoltaic cells, or a photovoltaic module formed by a plurality of photovoltaic cells. The heat source may also be an electronic Printed Circuit Board (PCB), Printed Wiring Board (PWB), or LED, plasma, or similar display panel.

Photovoltaic Cells/Modules with Low Stress-Inducing Heat Sink

[0098] The low stress-inducing heat sinks described herein may be particularly useful with photovoltaic (PV) cells, arrays, and/or modules to remove heat generated during their usage. Part of the energy absorbed by a solar cell is converted to heat, which limits the electrical energy output and the overall conversion efficiency of the cell. As a result, solar cells generally operate less efficiently at high temperatures. The loss in efficiency is about 10% for every 25 degrees Kelvin (K) increase in temperature, although the exact loss in efficiency may depend on the specific cell. Therefore, efficient heat exchange will improve total efficiency of e.g., photovoltaic modules. The low stress-inducing heat sinks described herein may be particularly suitable to use with photovoltaic cells, arrays, and/or modules for several reasons. First, the photovoltaic cell may have a different thermal expansion coefficient from the heat sink attached to the cell. For example, a photovoltaic cell may have a thermal expansion coefficient of about 3.2×10^{-6} /K at 20 °C while a heat sink made of a thermally conductive polymer may have a thermal expansion coefficient of about 70×10^{-6}/K at the same temperature. Similarly, the thermal expansion coefficient of a typical module assembly is less than 10×10^{-6}/K at the same temperature, which is also significantly lower than that of a heat sink made from a thermally conductive polymer. Such mismatch in thermal characteristics between the heat sink and photovoltaic cells/modules may generate thermally induced stress and strain on the solar cells, which in turn may result in crack, fracture or other types of deformation of the cells. The mismatch in thermal characteristics may result in delamination of the heat sink from the module. Low stress-inducing heat sinks that have multi-directional in-plane flexibility can be used to improve the durability of the cells. Secondly, a typical photovoltaic module may have an overall length of 1 meter to 4 meters and an overall width of 0.25 meter to 2 meters. In a typical configuration, 4 to 20 modules are installed in a solar module assembly on the roof-top of a house. Many more modules may be installed on larger roofs of commercial buildings. As a result, using traditional heat sinks with a continuous base to cool off solar modules will need a large amount of materials and is very expensive. Use of low stress-inducing heat sinks may lower the cost and make solar energy more affordable. Further, since solar modules are usually installed on roof-tops, light-weight materials, such as conductive polymers, are preferred. Conductive polymers generally have low thermal conductivity (e.g., lower than 30 W/mK). As explained in previous sections, a base with low thermal conductivity may act as an insulating layer on the heat source. Removal of such an insulating base may improve the overall heat transfer performance of the heat sink.

[0099] Photovoltaic modules may be particularly prone to stress and strain induced by a rigid-base heat sink. The modules commonly are processed at temperature over 100 °C to cure the materials used to make modules. However, modules often operate at temperature below the processing temperature and therefore in a stressed state. The photovoltaic modules are composed of materials with a wide range of thermal expansion coefficients. For example, the thermal expansion coefficient of silicon is about 3.2×10^{-6} /K at 20 °C, thermal expansion coefficient of glass is about 8×10^{-6} /K at 20 °C, and thermal expansion coefficient of Tedlar™ back sheet is about 70×10^{-6} /K at 20 °C. The mismatch in the thermal properties of the materials in a photovoltaic module may result in significant internal stress even when the module operates at a uniform room temperature. When operating under thermal excursion, the addition of thermally induced stress and strain to the initial internal stress may result in module cracking, fracture and/or other types of module deformation. Further, when the photovoltaic module operates in a harsh environment (e.g., high wind loading, snow and ice loading, uneven temperature distribution in the module, etc.), the internal stress and strain of the module may be even higher.

[00100] Photovoltaic cells, arrays, and modules comprising a heat sink, as well as methods of making and installation, are described WO 2008/073905, the content of which is incorporated by reference in its entirety. Any low stress-inducing heat sink described herein, such as pin-fin heat sinks with pin-fins interconnected with struts, heat sinks made from stamped sheet metal or segmented-base heat sinks, may be used with the photovoltaic cells, arrays, and/or modules according to any particular embodiment described in WO 2008/073905.

[00101] In some embodiments, a low stress-inducing heat sink may reduce temperature of a photovoltaic cell in ambient quiescent air that is at standard temperature and pressure and an irradiance (*E*) by white light individually or in any combination of 800 $W*m^{-2}$, 1000 $W*m^{-2}$, or 1200 $W*m^{-2}$ by at least about 1 ^{o}C; or by at least about 2 ^{o}C; or by at least about 5 ^{o}C; or by at least about 7 ^{o}C; or by at least about 10 ^{o}C; or by at least about 12 ^{o}C; or by at least about 15 ^{o}C; or by at least about 20 ^{o}C as compared to an identical cell lacking the low stress-inducing heat sink. The size, number, and spacing of fins, the pattern of the strut-mesh, and the materials of construction of the heat sink fins and struts may be selected based on the desired decrease in temperature over the comparative PV cell. A low stress-inducing heat sink may be configured to maintain the photovoltaic cell at a temperature below about 175^{o}F, or below about 160^{o}F, or below about 150^{o}F, or below about 140^{o}F, or below about 130^{o}F, or below about 120^{o}F, or below about 110^{o}F, or below about 100^{o}F, or below about 90^{o}F, or below about 80^{o}F in ambient air at a temperature of 70^{o}F.

[00102] A low stress-inducing heat sink may be configured to increase the energy conversion efficiency (defined by the equation: $\eta = (P_m /(E \times A_c))$, where P_m is maximum electrical power in watts, E is the input light irradiance in $W*m^{-2}$ and A_c is the surface area of the solar cell in m^2) or total-area efficiency of a photovoltaic cell (which may be defined by the relative change in current (*I*) and/or voltage (*V*) or relative change in the product of *I* and *V*) in ambient quiescent air that is at standard temperature and pressure and an irradiance (*E*) by white light individually or in any combination of 800 W*m^{-2}, 1000 W*m^{-2}, or 1200 W*m^{-2} by at least about 0.5%; or by at least about 1%; or by at least about 1.5%; or by at least about 2%; or by at least about 2.5%; or by at least about 3%; or by at least about 3.5%; or by at least about 4%; or by at least about 4.5%; or by at least about 5%; or by at least about 5.5%; or by at least about 6%; or by at least about 6.5%; or by at least about 7%; or by at least about 7.5%; or by at least about 8%; or by at least about 8.5%; or by at least about 9%; or by at least about 9.5%; or by at least about 10%, or by at least about 10.5%, or by at least about 11%, or by at least about 11.5%, or by at least about 12%, or by at least about 12.5%, or by at least about 13%, or by at least about 13.5%, or by at least about 14%, or by at least about 14.5%, or by at least about 15% as compared to an identical cell lacking the low stress-inducing heat sink. In some embodiments, the energy conversion efficiency achieved by a low stress-inducing heat sink under conditions as specified above may be greater than 15% compared to an identical call lacking the low stress-inducing heat sink.

[00103] In some embodiments where an assembly of one or more low stress-inducing heat sinks placed upon a photovoltaic module/array/cell that contains silicon cells is tested using the industry standard UL 1703 Temperature Cycling Test for Flat-Plate Photovoltaic Modules and Panels (e.g., from about -40 °C to about 90 °C), the stress in the bulk of the silicon cells may be less than about 500 MPa, sometimes less than 450 MPa, sometimes less than 400 MPa, sometimes less than 350 MPa, sometimes less than 300 MPa, sometimes less than 250 MPa, sometimes less than 200 MPa, sometimes less than 150 MPa, sometimes less than 100 MPa, or less.

WHAT IS CLAIMED IS:

1. A heat sink, comprising:

a plurality of protrusions with surfaces, said surfaces suitable for direct thermal communication with a heat source, and said surfaces having surface areas;

wherein a sum of said surface areas is less than an area defined by a set of outer-most coordinates of said surfaces.

2. The heat sink of claim 1, wherein said plurality of protrusions have one of pin-like configurations, tear drop configurations, triangular configurations, rectangular configurations, frustum pyramid configurations, frustum cone configurations, cylindrical configurations, or fin configurations.

3. The heat sink of claim 1, further comprising:

a base sheet; wherein

said protrusions are cut from said base sheet; and

said protrusions are bent upwardly away from a plane formed by said base sheet while a bottom portion of each of said protrusions remains attached to said base sheet.

4. The heat sink of claim 1, wherein said heat sink is less rigid mechanically than said heat source.

5. The heat sink of claim 1, wherein a pattern formed by said protrusions is discontinuous along a perimeter of said area to form air escape and entry channels.

6. The heat sink of claim 5, wherein said pattern is comprised of zigzagging columns of directly connected protrusions.

7. The heat sink of claim 1, wherein said heat source is a photovoltaic device.

8. The heat sink of claim 7, wherein when said photovoltaic device is in a module, and said module is tested by a test known as UL 1703 Temperature Cycling test for Flat

Plate Photovoltaic Modules and Panels, a stress caused by said test does not induce fracture in said photovoltaic device.

9. The heat sink of claim 7, further comprising at least one intervening layer configured to be interspersed between said photovoltaic device and said surfaces.

10. The heat sink of claim 8, wherein one of said intervening layers is integrated with said surfaces during a manufacturing stage.

11. The heat sink of claim 1, wherein a set of said protrusions are interconnected by one or more connecting members.

12. The heat sink of claim 11, wherein said connecting members are flexible.

13. The heat sink of claim 12, wherein:
said surfaces are within a single plane; and
a cross-section of each of said protrusions decreases monotonically with the distance of said cross-section from said plane.

14. The heat sink of claim 13, wherein said protrusions are hollow.

15. The heat sink of claim 1, wherein each of said protrusions has a center to center spacing with at least one other protrusion that is less than 15 mm.

16. The heat sink of claim 15, wherein a set of said protrusions are interconnected by one or more connecting members.

17. The heat sink of claim 16, wherein said connecting members are flexible.

18. The heat sink of claim 15, wherein said heat source is a photovoltaic device.

19. The heat sink of claim 18, further comprising:

at least one intervening layer configured to be interspersed between said photovoltaic device and said surfaces;

wherein one of said intervening layers is integrated with said surfaces during a manufacturing stage.

20. The heat sink of claim 19 wherein when said photovoltaic device is in a module, and said module is tested by a test known as UL 1703 Temperature Cycling test for Flat-Plate Photovoltaic Modules and Panels, a stress caused by said test does not induce fracture in said photovoltaic device.

21. A method of cooling a heat source comprising the steps of:

conducting heat energy from said heat source to a plurality of protrusions on a heat sink connected to said heat source, said protrusions having surfaces that have surface areas that are in direct thermal communication with said heat source; and

convecting said heat energy from said plurality of protrusions via fluid channels between said plurality of protrusions having surfaces in direct thermal communication with said heat source; wherein

a sum of said surface areas is less than an area defined by a set of outer-most coordinates of said surfaces.

22. The method of claim 21, wherein said heat sink is less rigid mechanically than said heat source.

23. The method of claim 21, wherein a set of said protrusions are interconnected by one or more flexible connecting members.

24. The method of claim 21, wherein said heat source is a photovoltaic device.

25. The method of claim 24, wherein each of said protrusions has a center to center spacing with at least one other protrusion that is less than 15 mm.

26. A method of fabricating a heat sink comprising the steps of:

stamping a protrusion pattern on a base sheet to form a plurality of protrusions;

separating each of said protrusions from said base sheet while leaving a base portion of each of said protrusions attached to said base sheet; and

bending each of said protrusions upwardly away from a plane formed by said base sheet while a bottom portion of each of said protrusions remains attached to said base sheet.

27. The method of claim 26, wherein each of said protrusions is disposed on said base sheet in an offset fashion with respect to an adjacent protrusion.

28. The method of claim 26, wherein said heat sink is configured for direct thermal communication with a photovoltaic device.

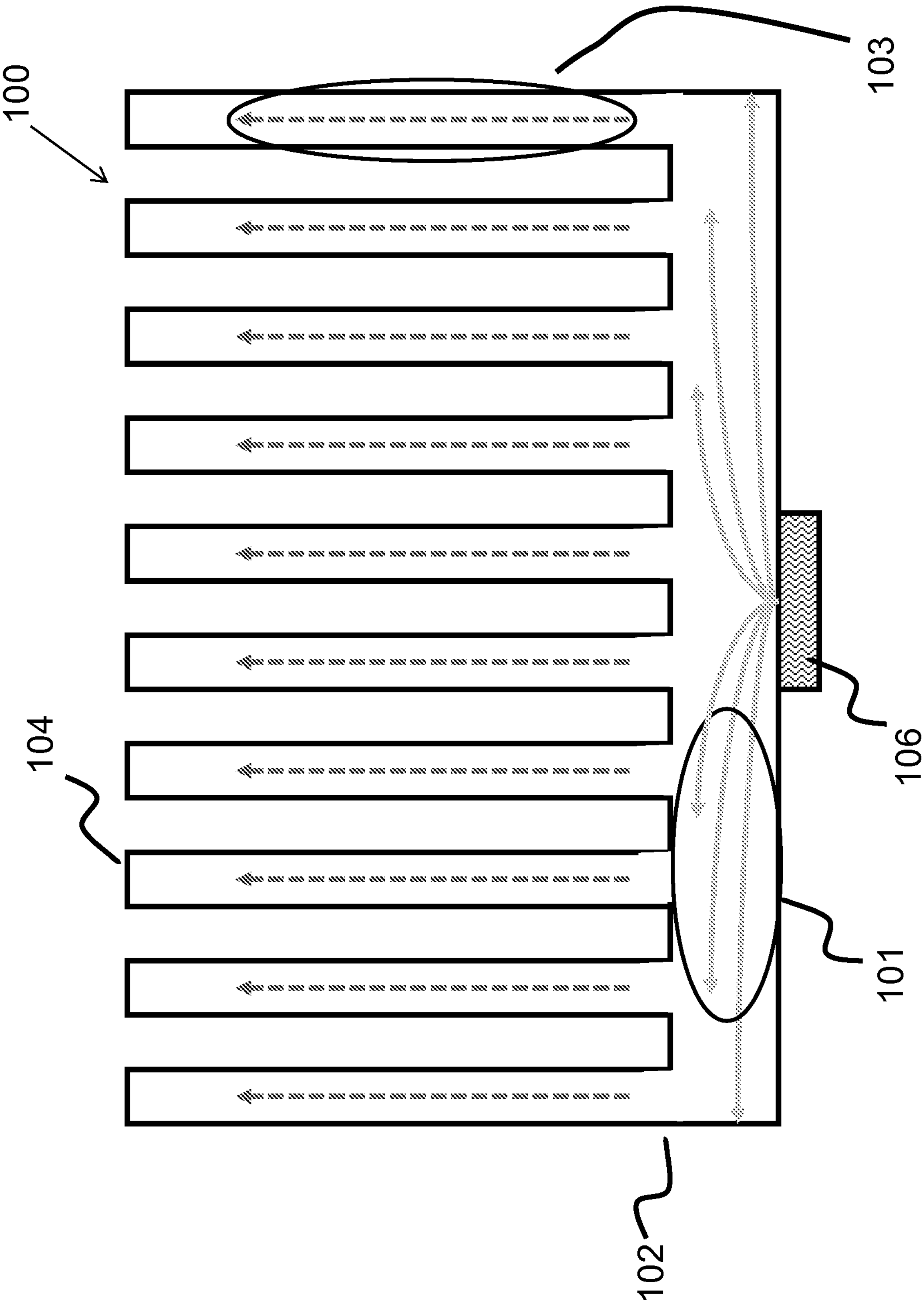


FIG. 1
Prior Art

FIG. 2
Prior Art

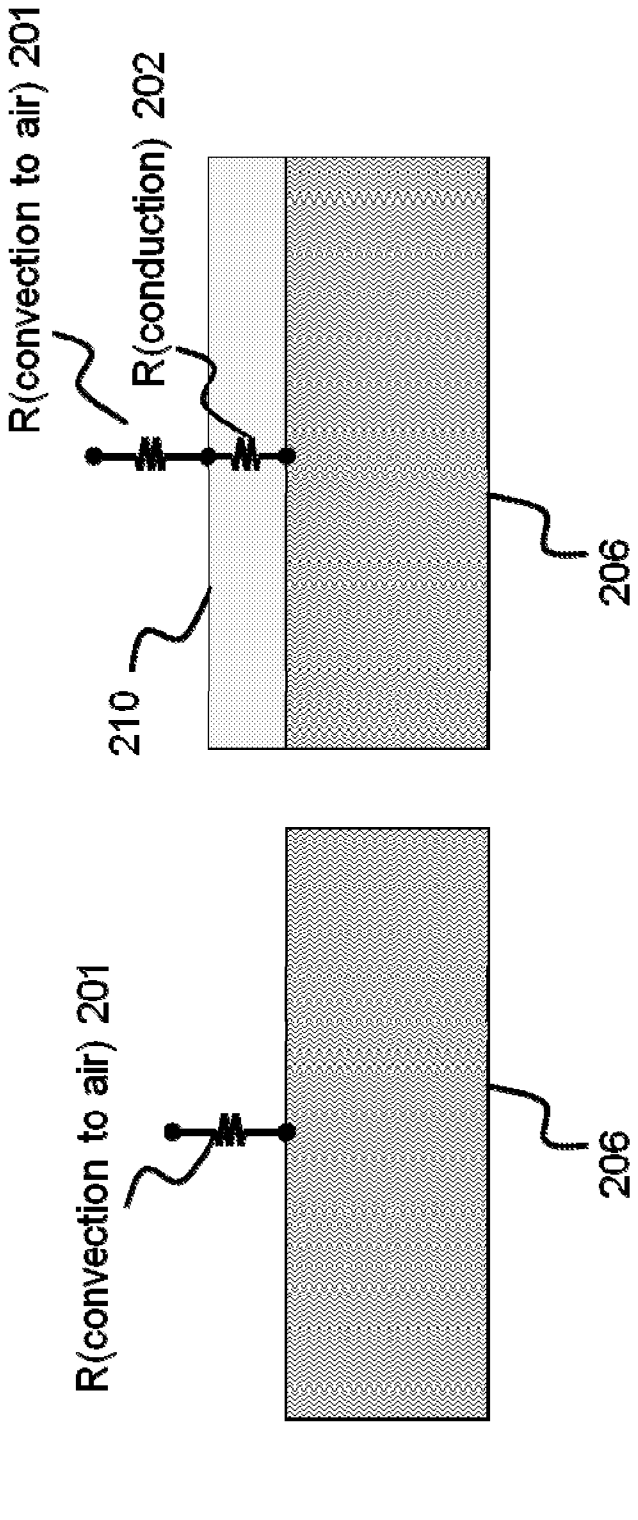


FIG. 3

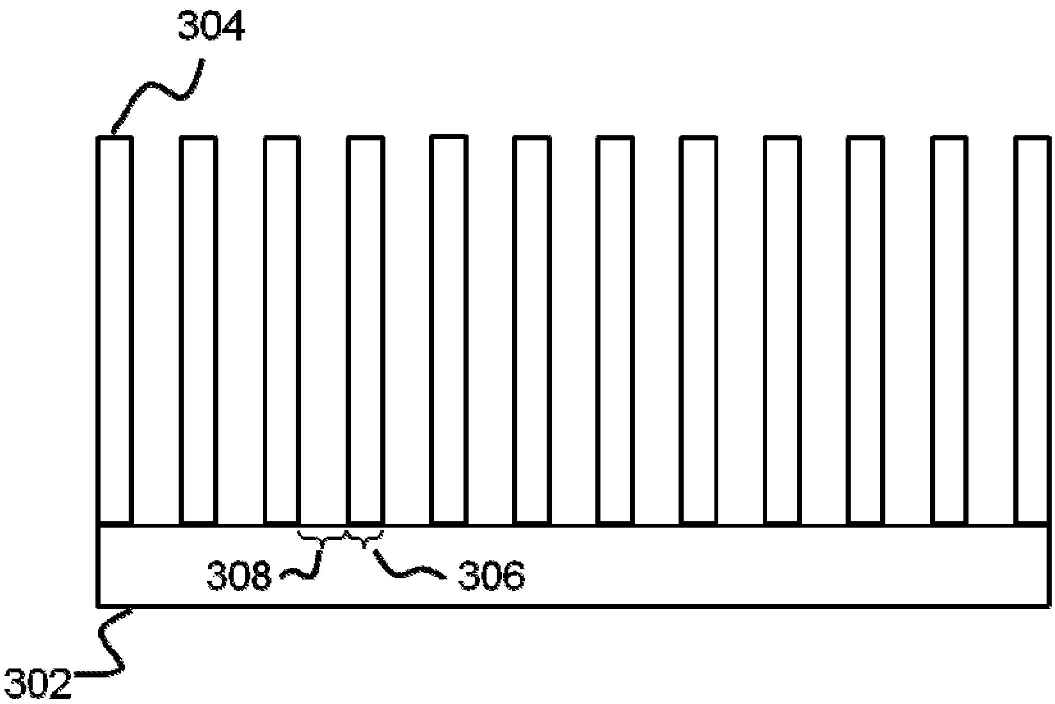


FIG. 4

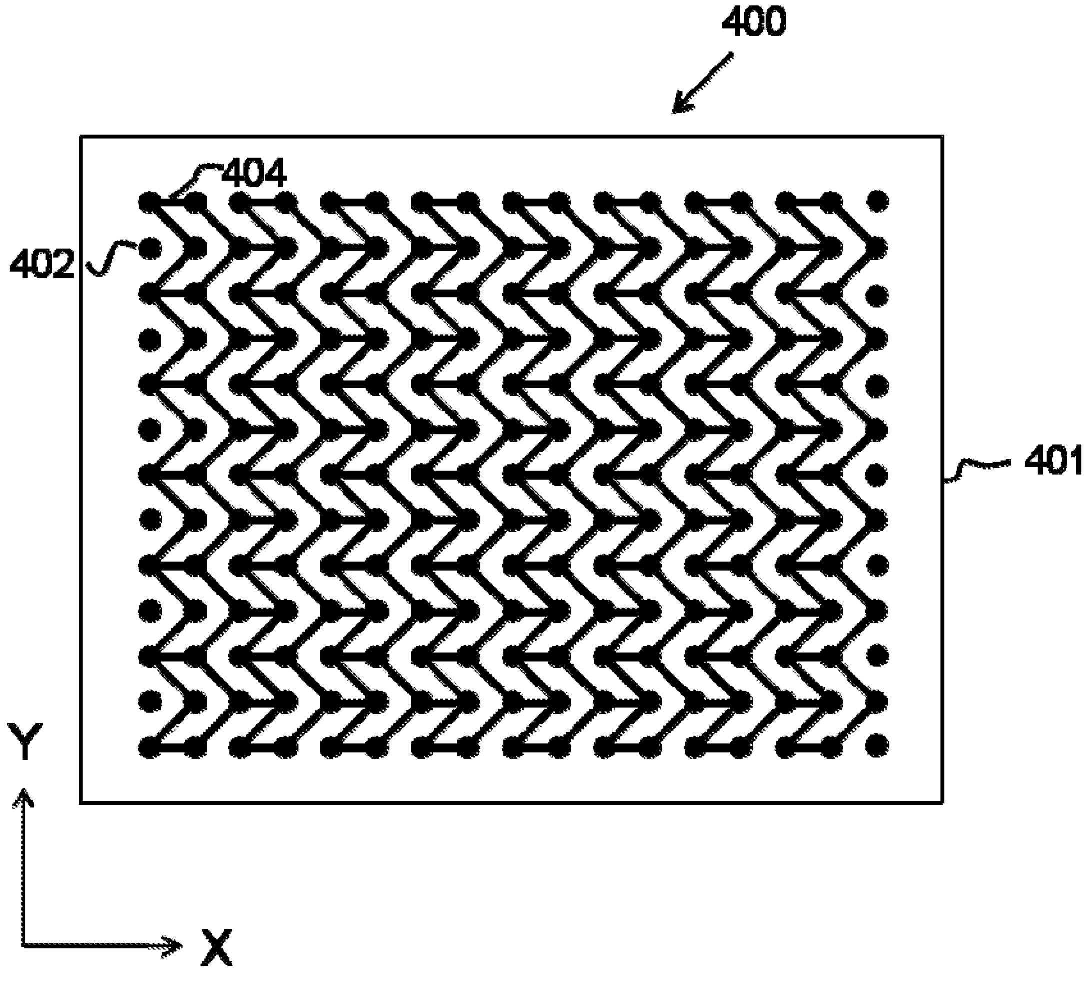


FIG. 5

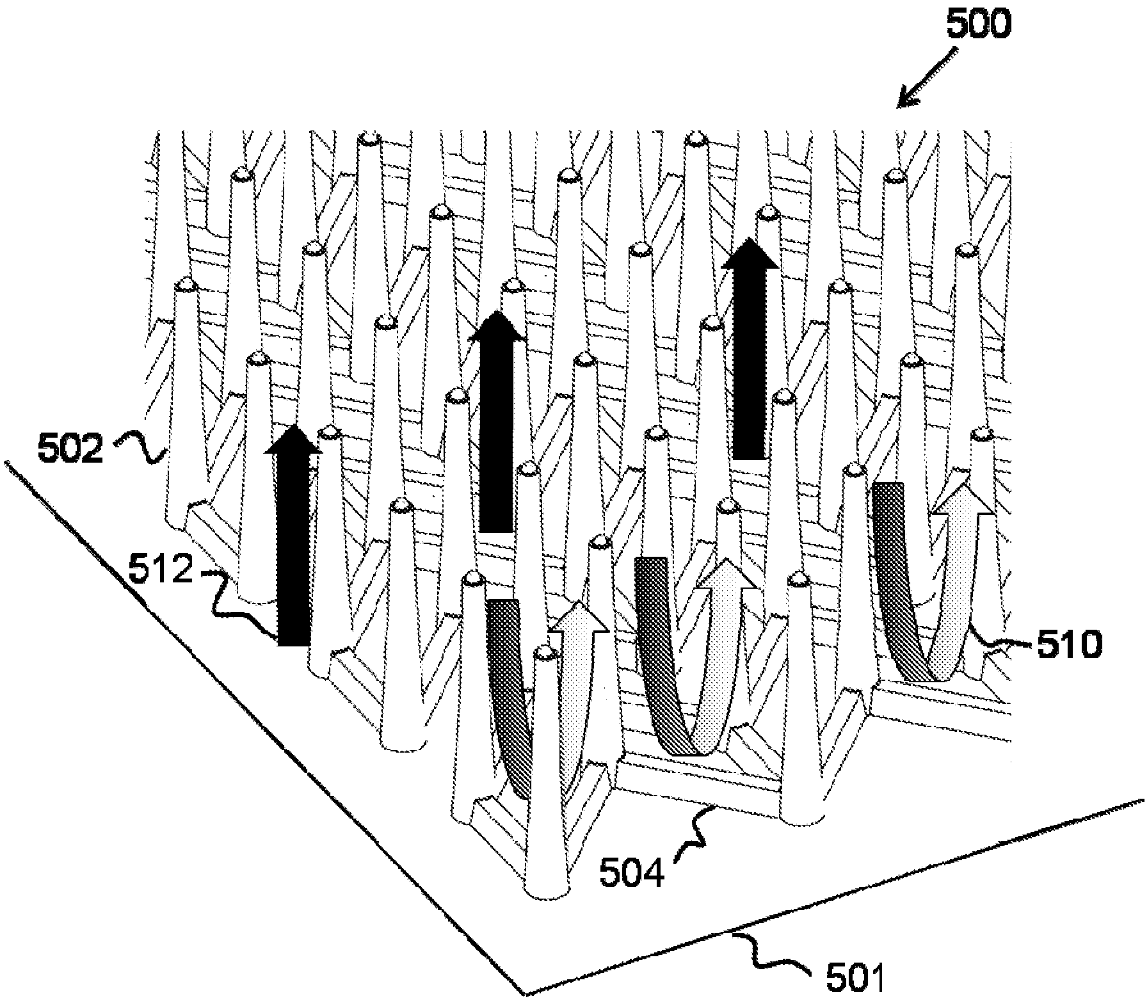


FIG. 6A

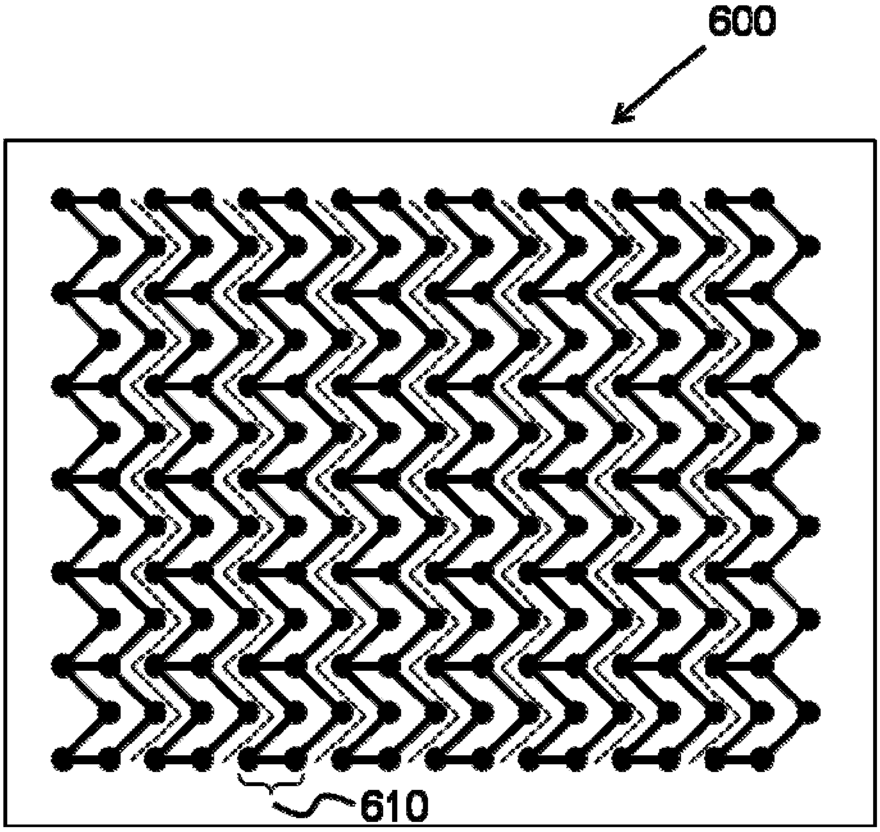


FIG. 6B

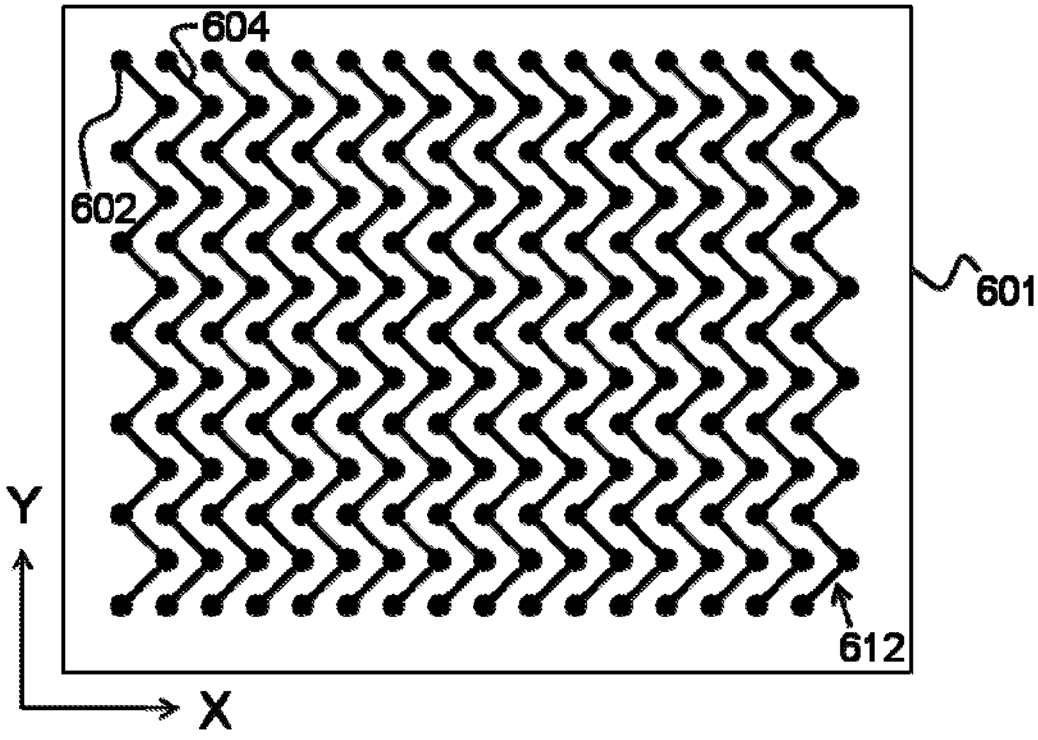


FIG. 6C

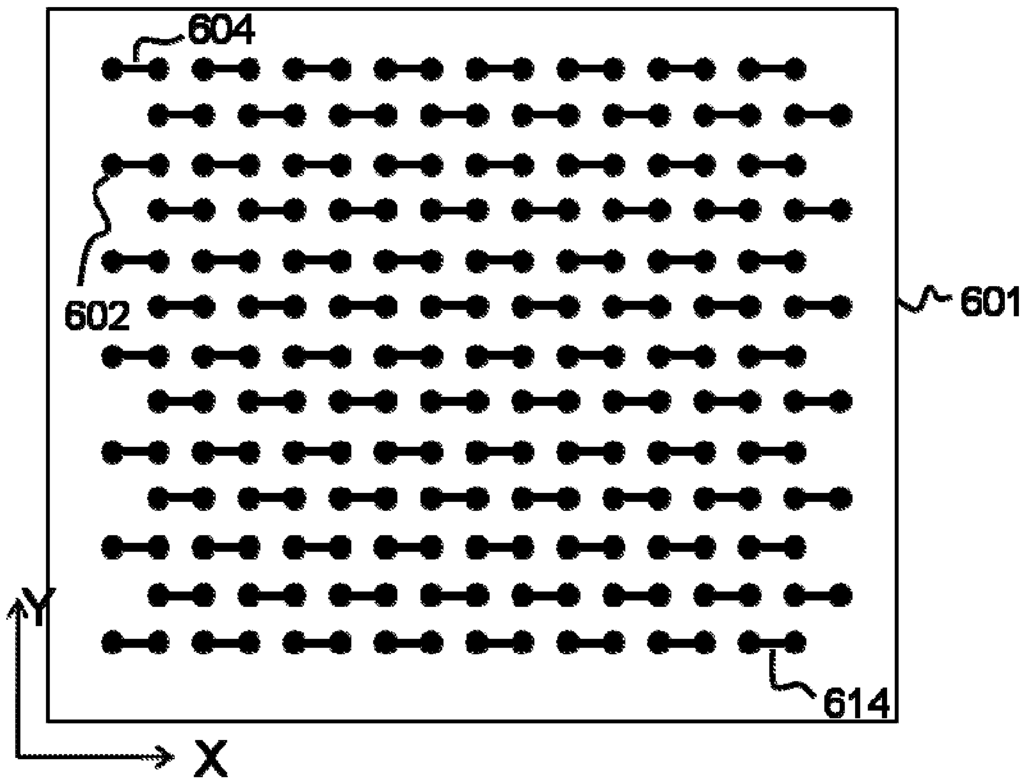


FIG. 7A

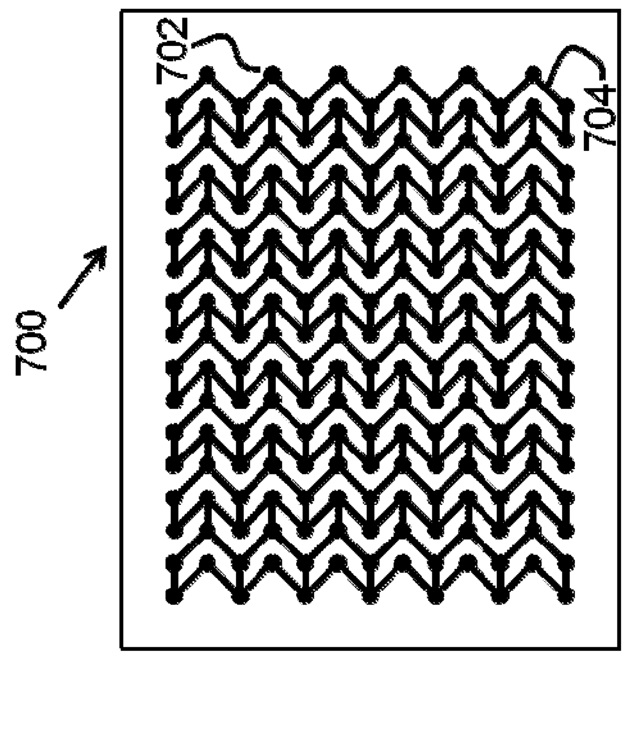


FIG. 7B

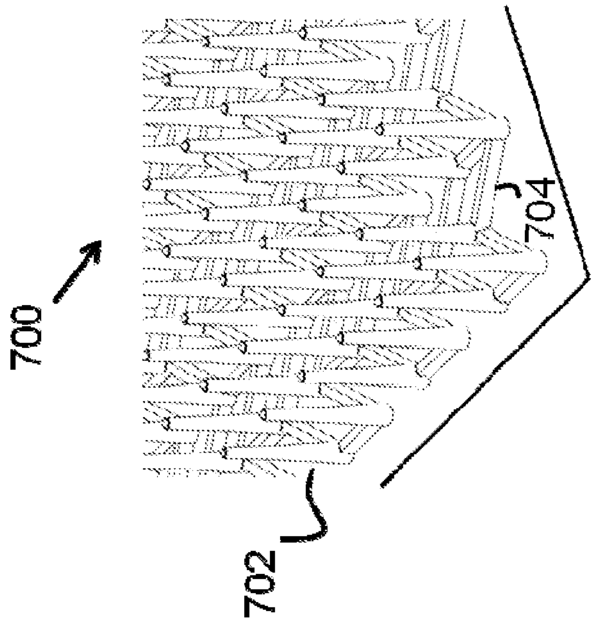


FIG. 8

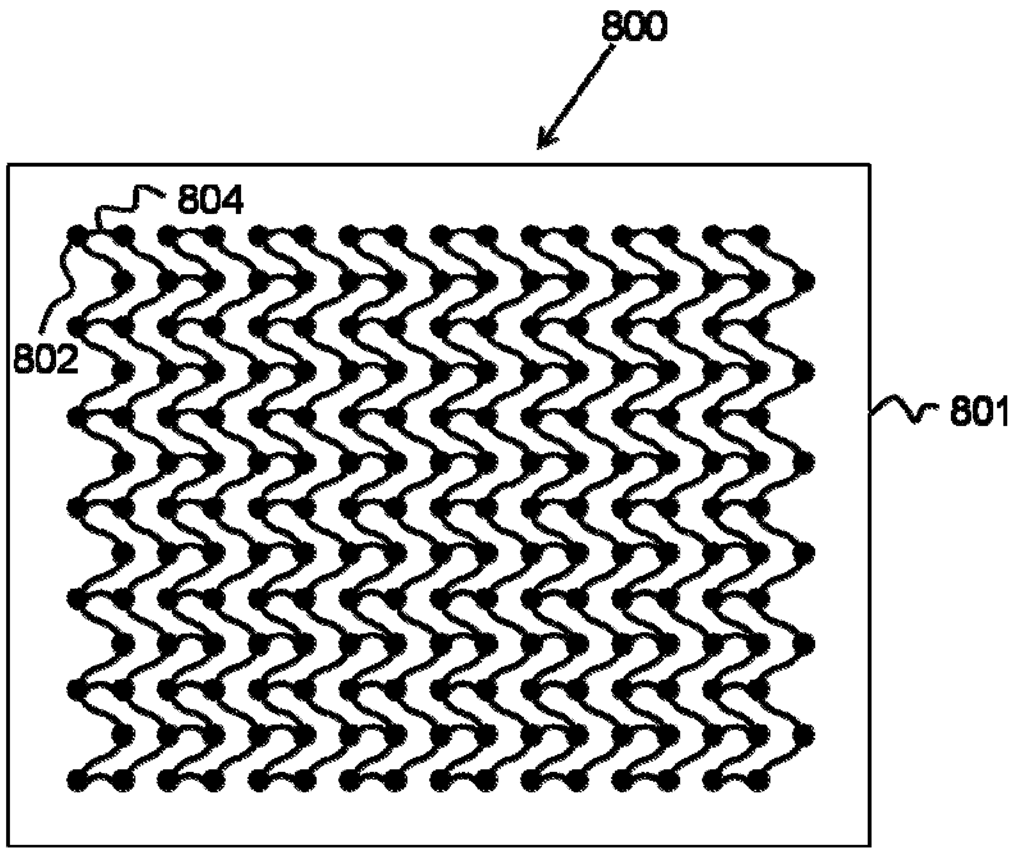


FIG. 9

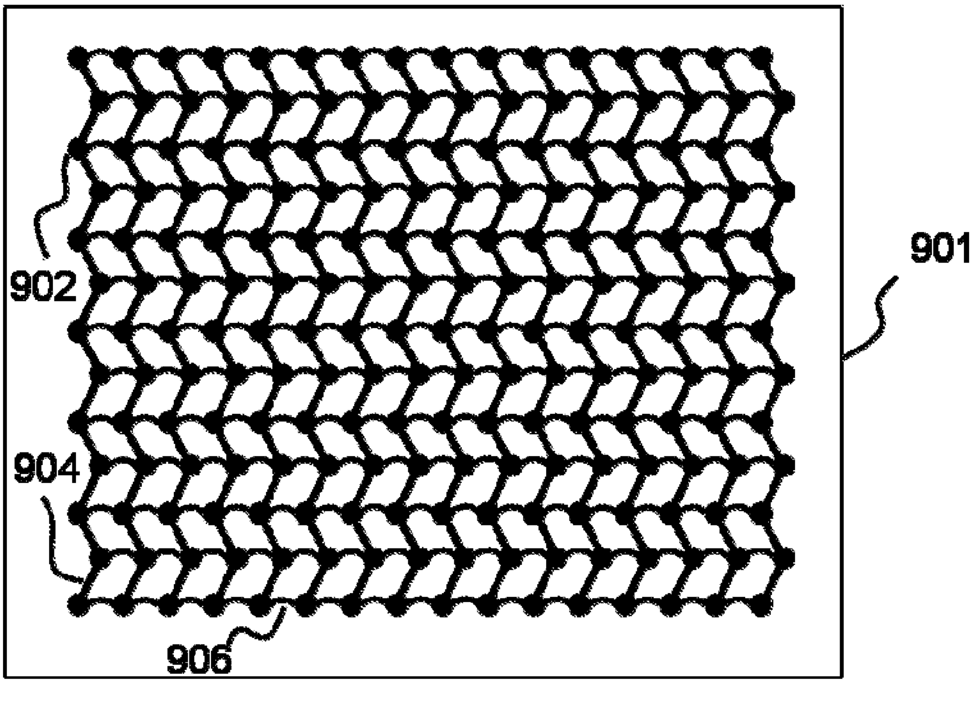


FIG. 10

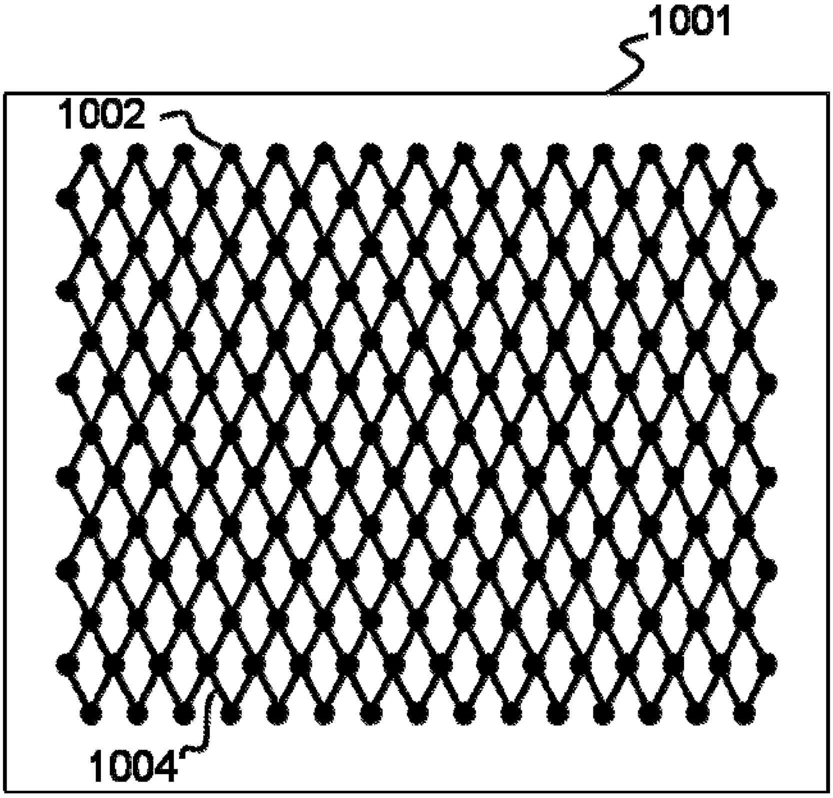


FIG. 11A

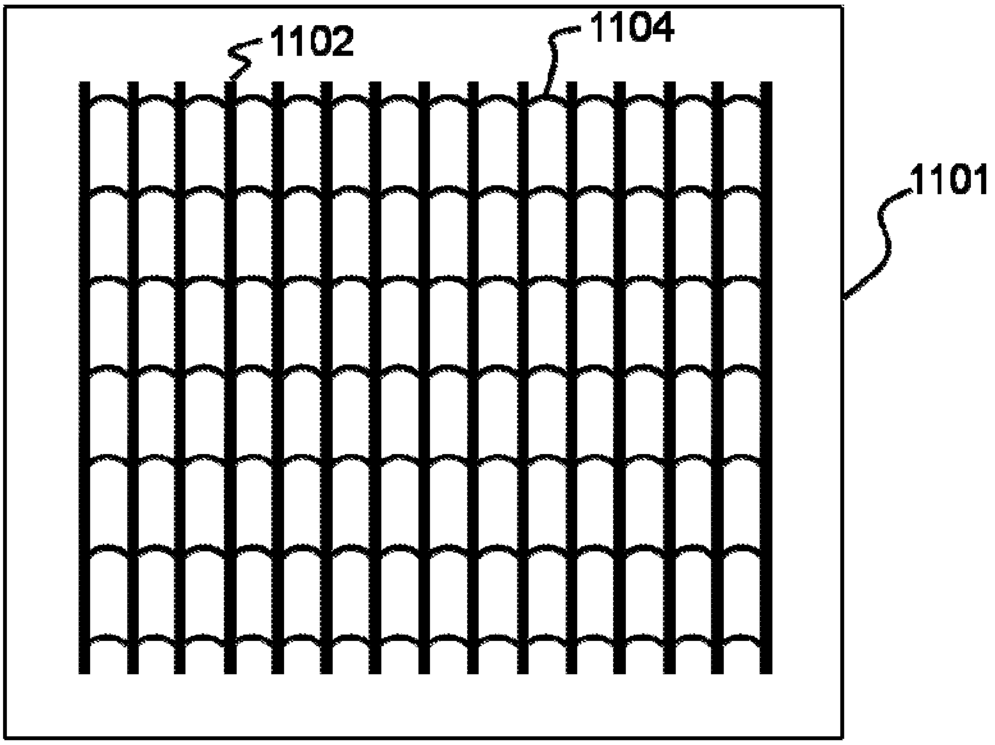


FIG. 11B

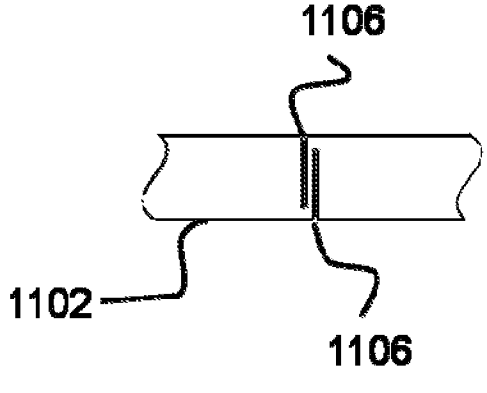


FIG. 12A

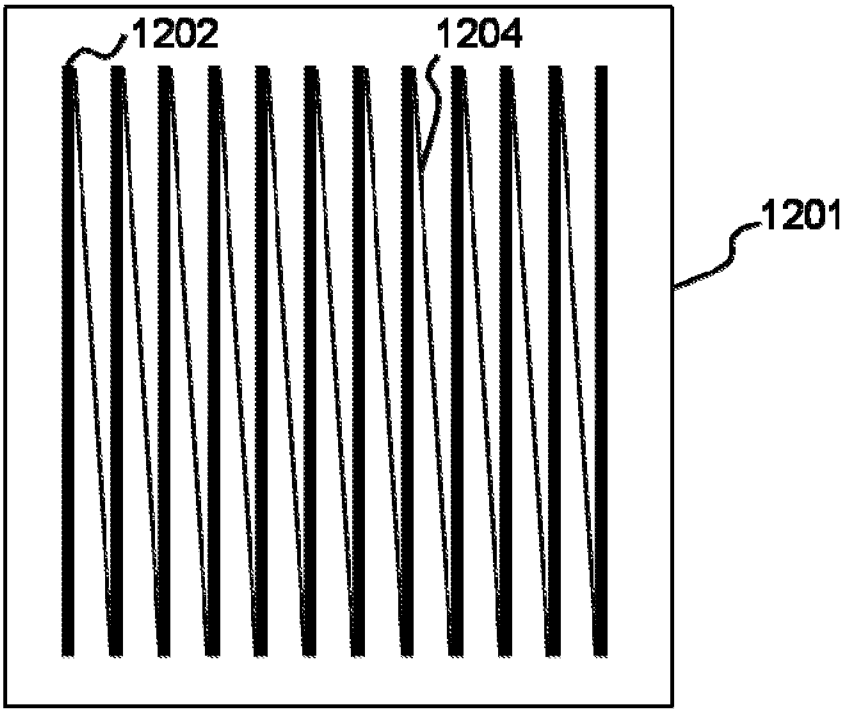
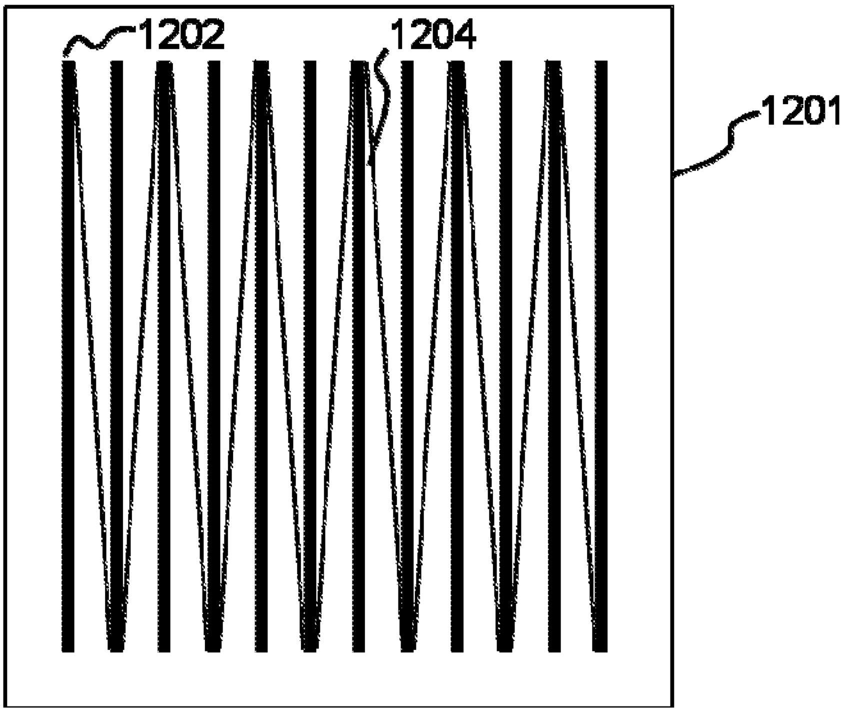


FIG. 12B



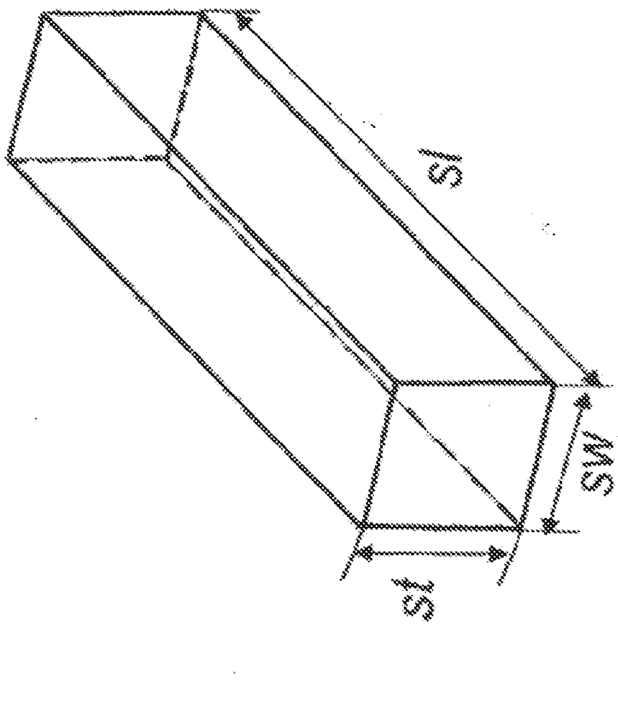


FIG. 13A

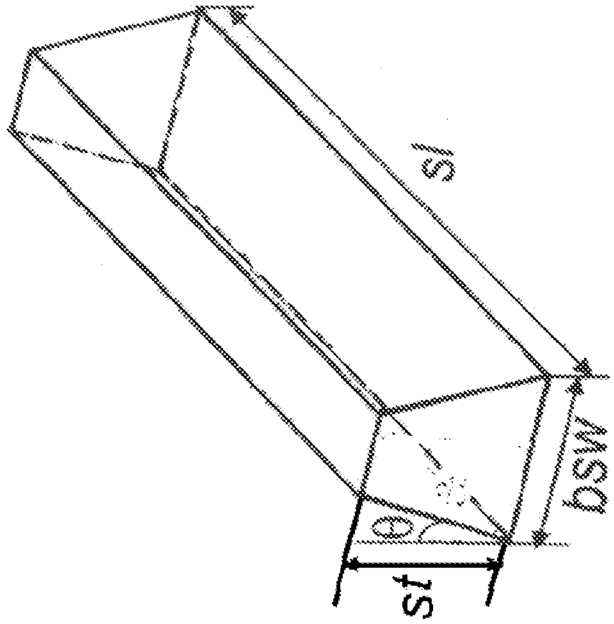


FIG. 13B

FIG. 14A

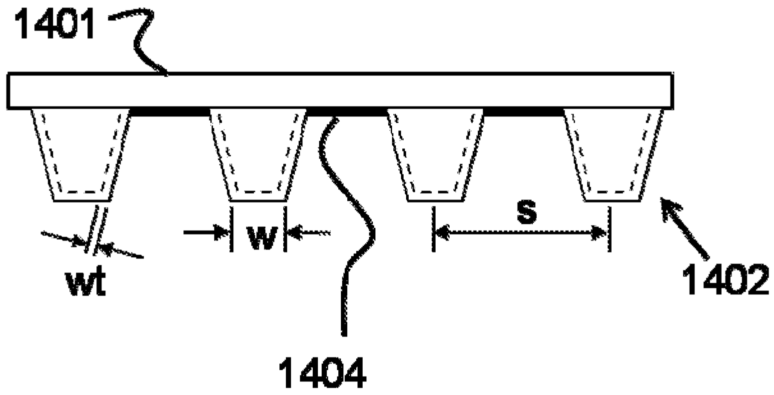


FIG. 14B

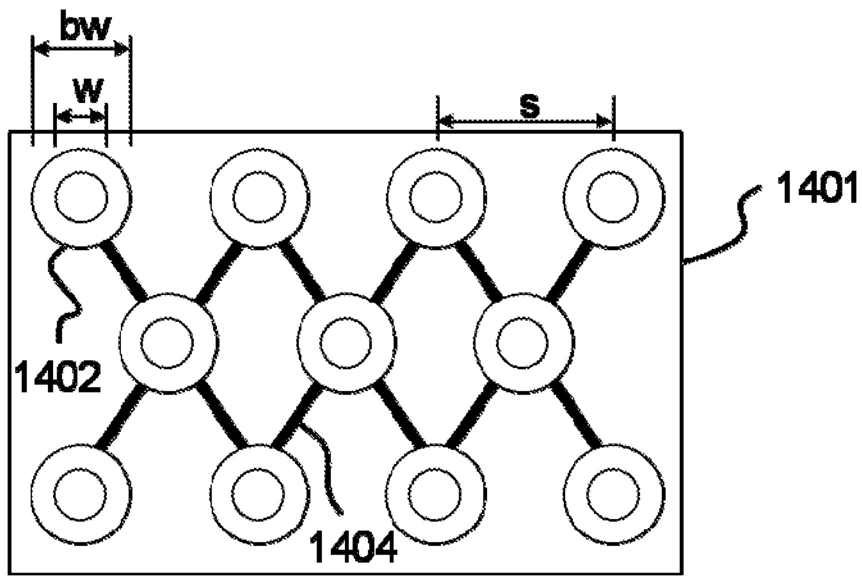


FIG. 15A

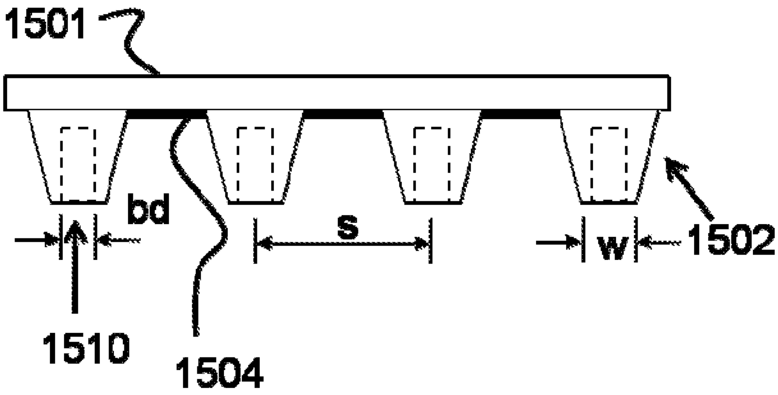


FIG. 15B

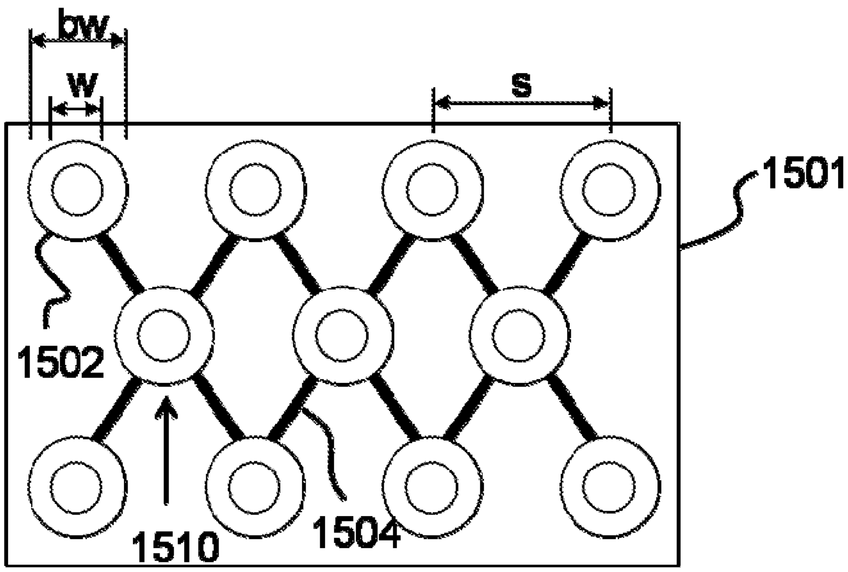


FIG. 16A

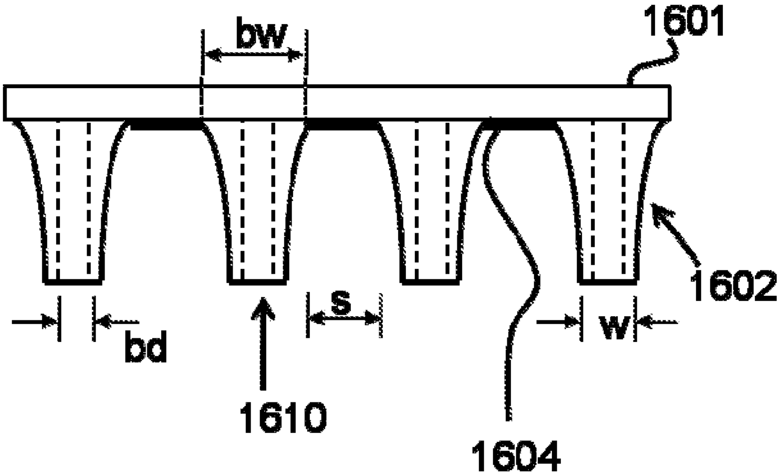


FIG. 16B

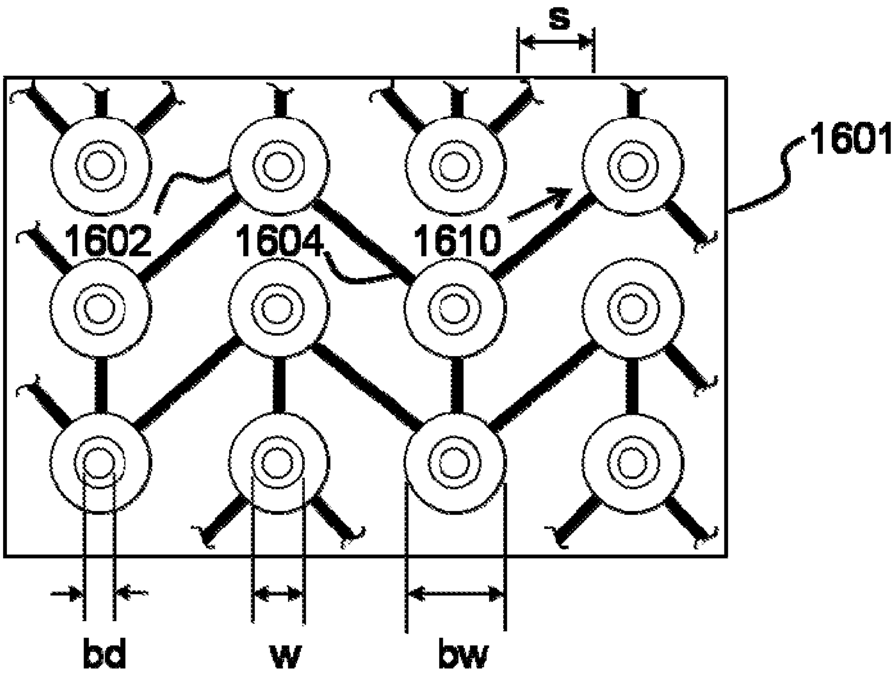


FIG. 17A

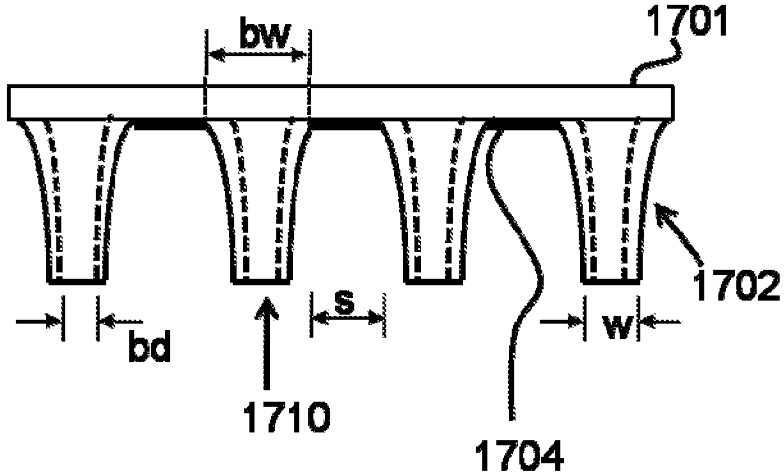


FIG. 17B

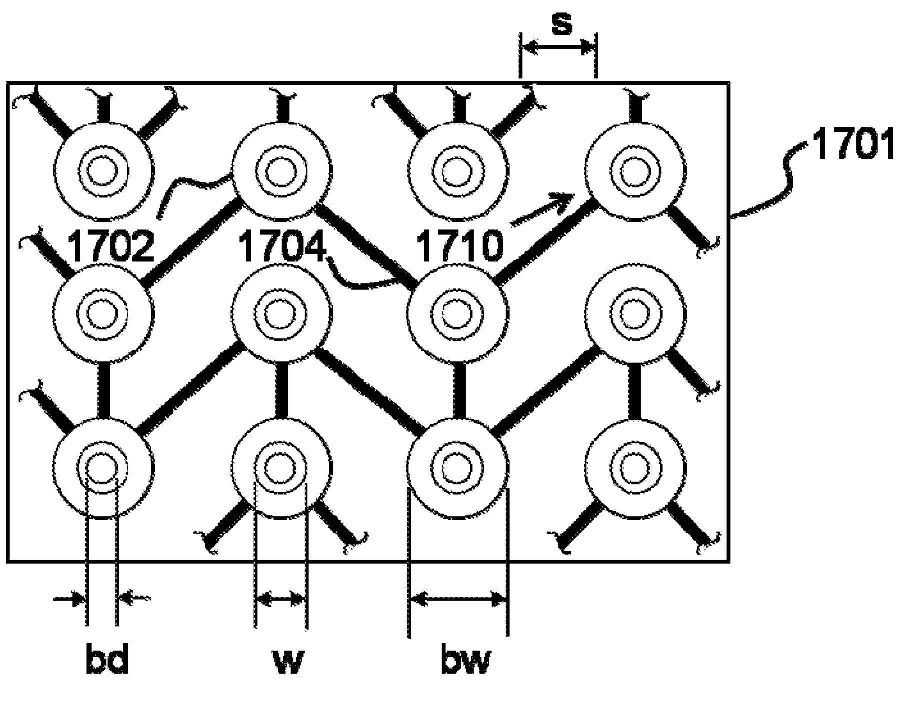
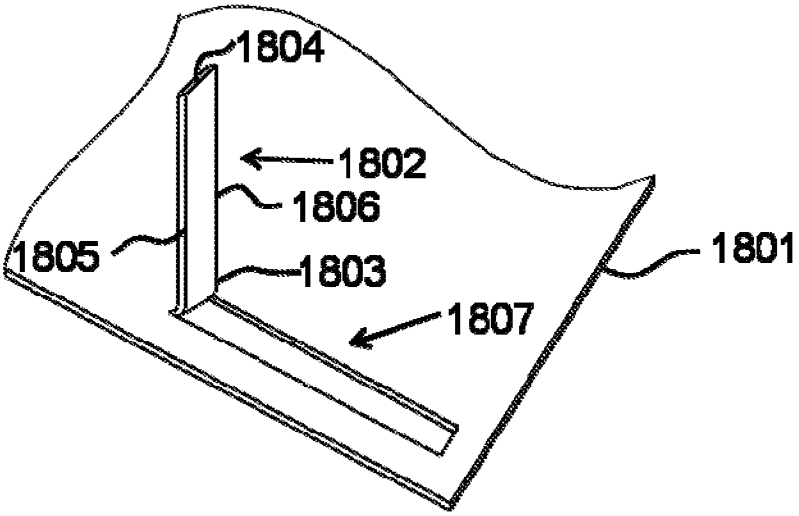


FIG. 18A



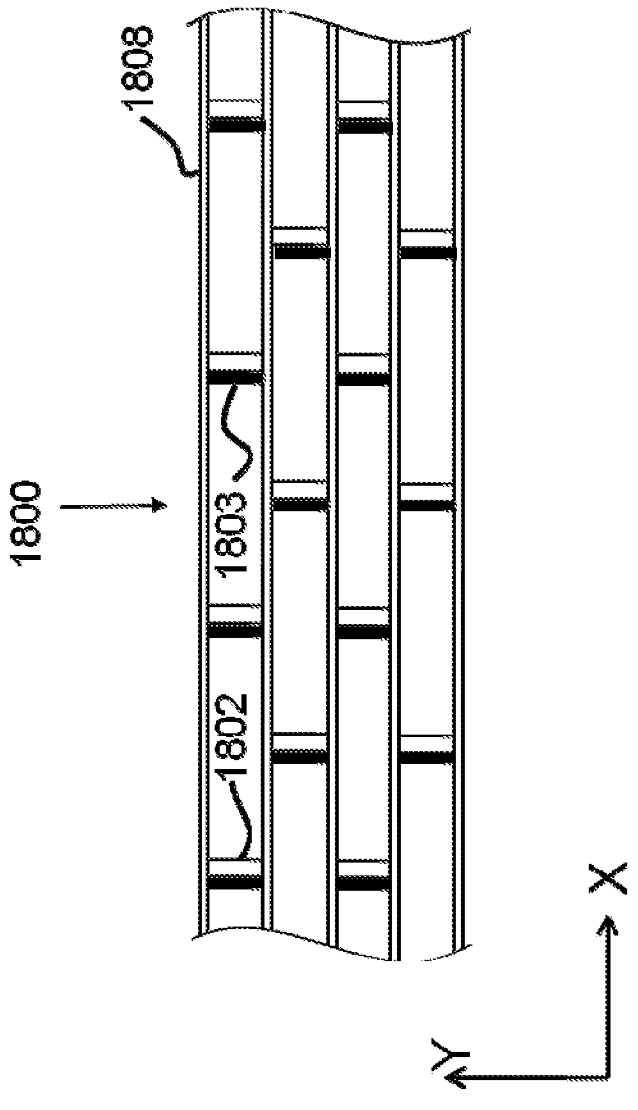


FIG. 18B

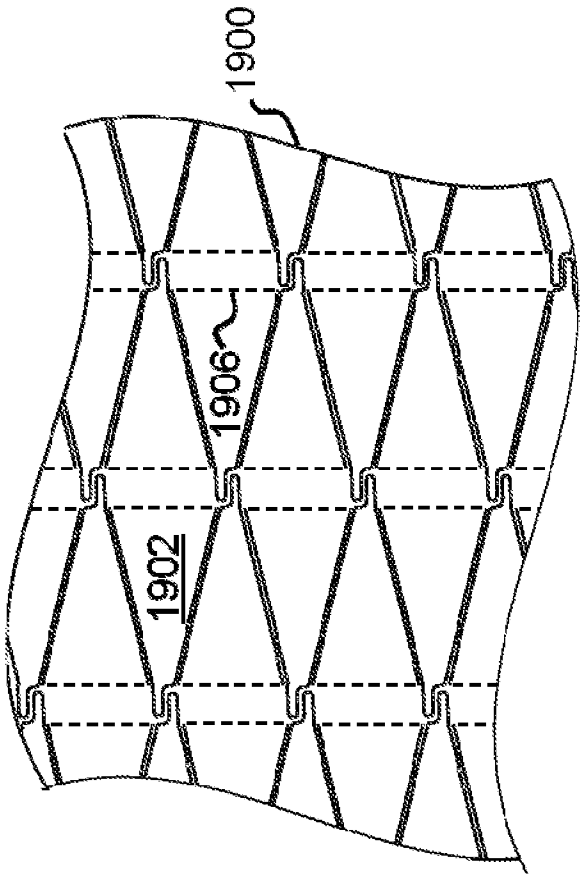


FIG. 19A

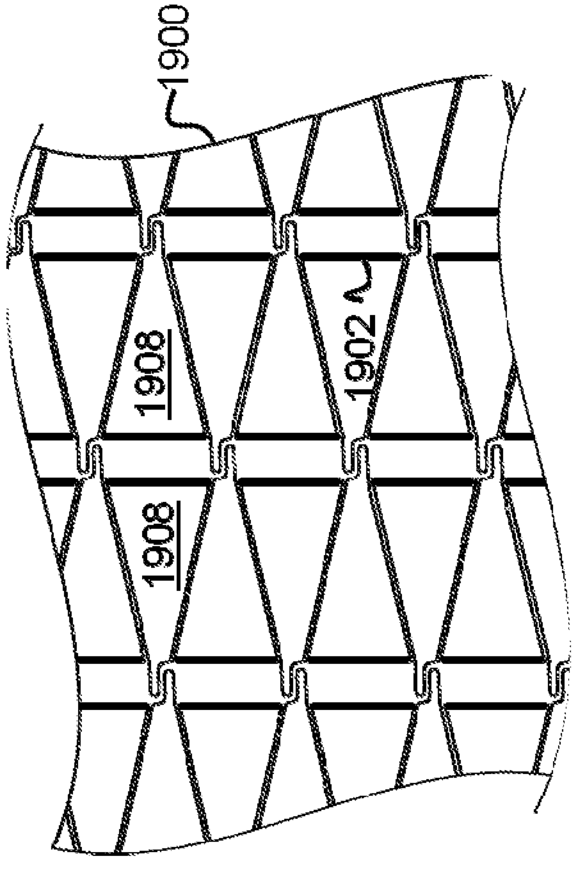


FIG. 19B

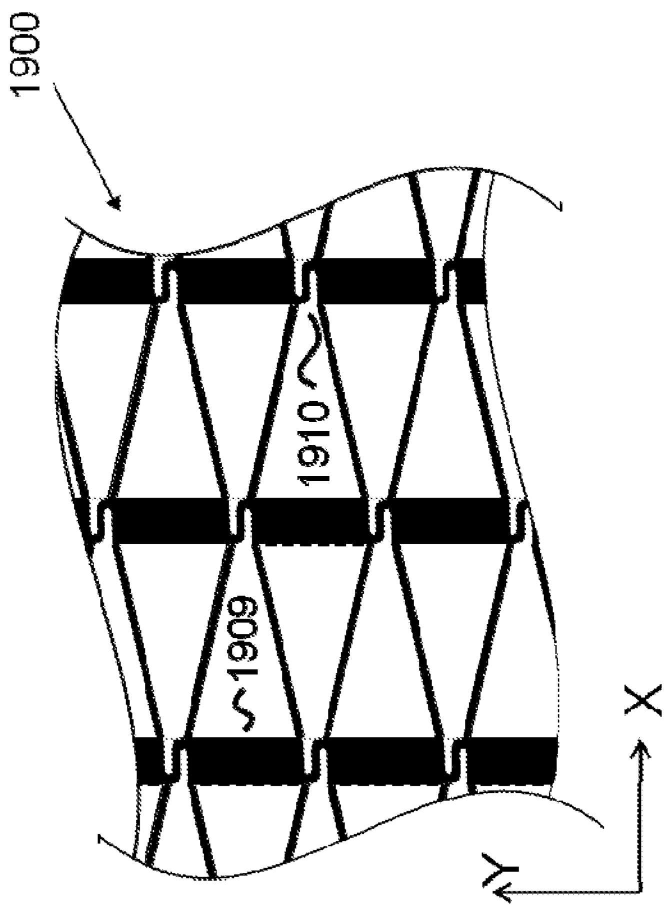


FIG. 19C

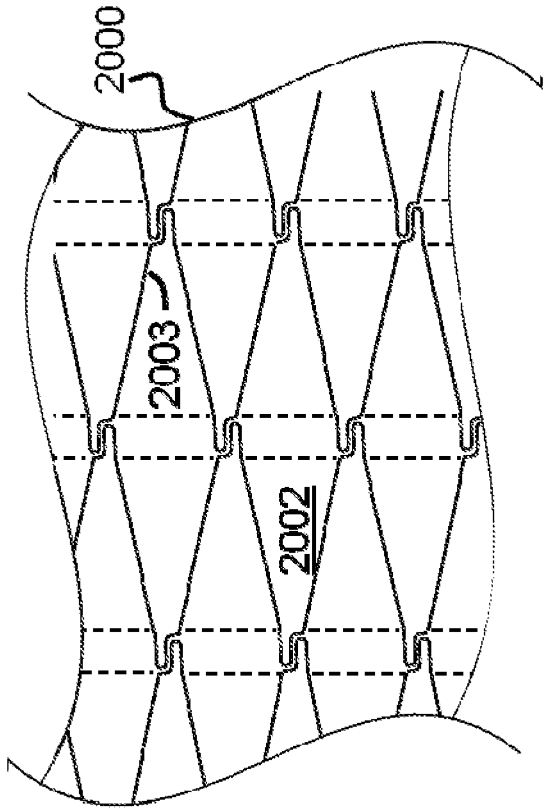


FIG. 20A

FIG. 20B

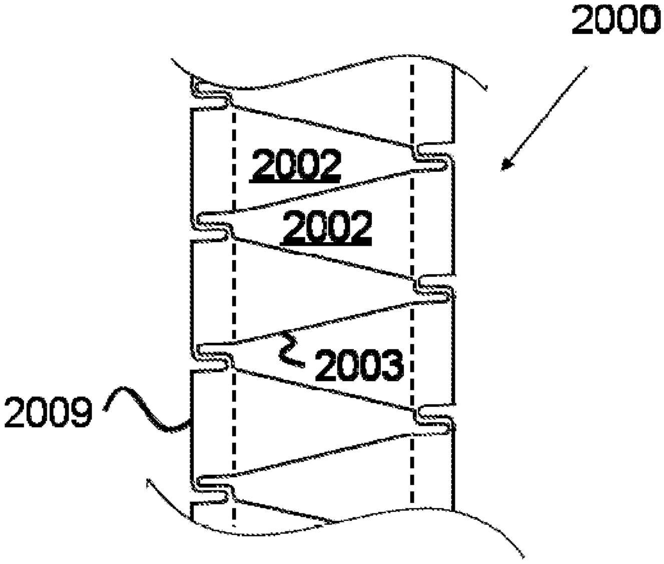


FIG. 21A

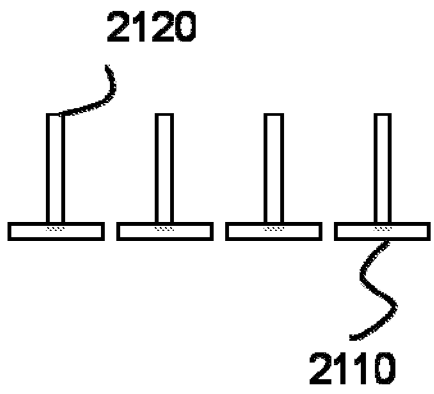


FIG. 21B

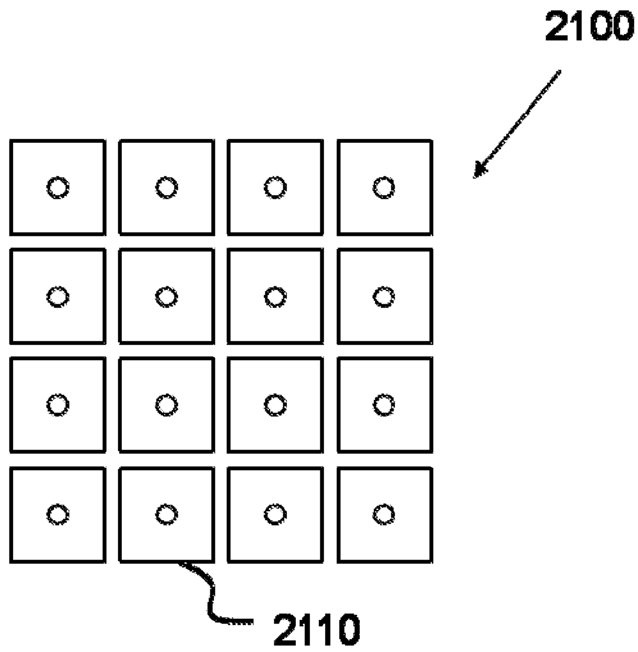


FIG. 22A

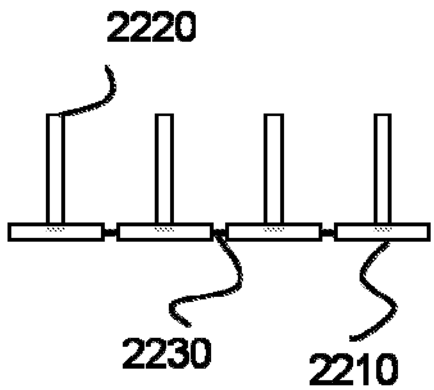


FIG. 22B

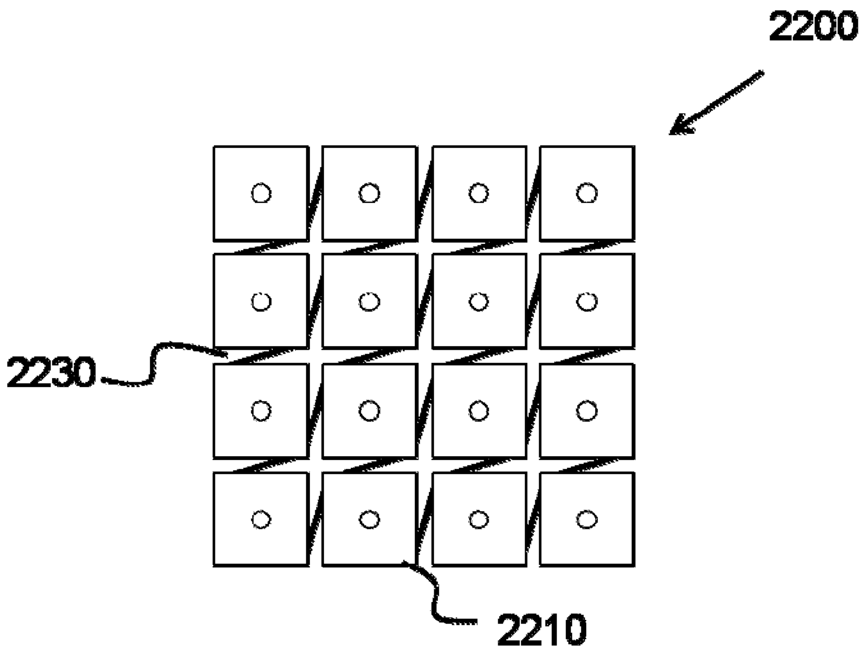


FIG. 23A

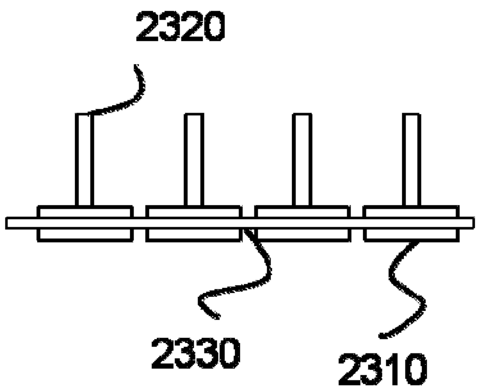


FIG. 23B

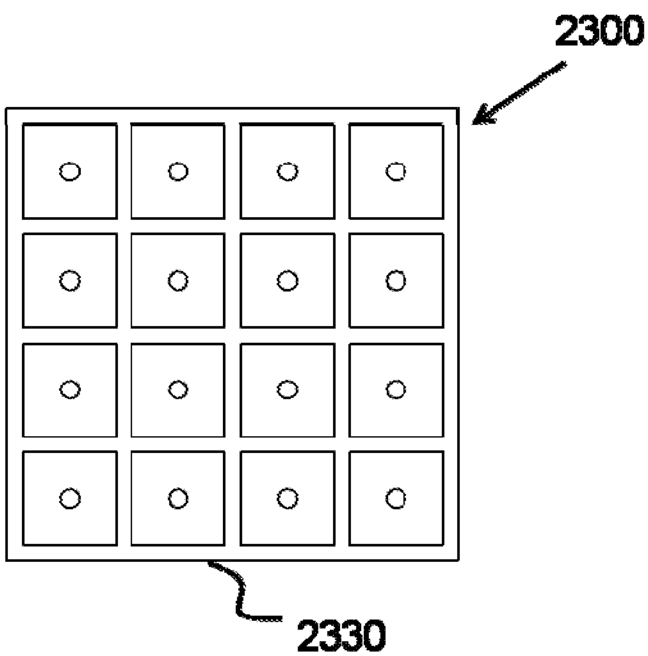


FIG. 24A

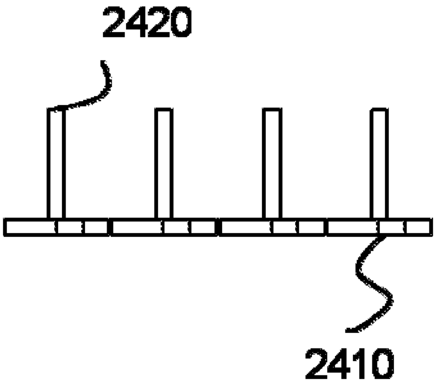


FIG. 24B