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(54) **SLOPED HIERARCHICALLY-STRUCTURED SURFACE DESIGNS FOR ENHANCED CONDENSATION HEAT TRANSFER**

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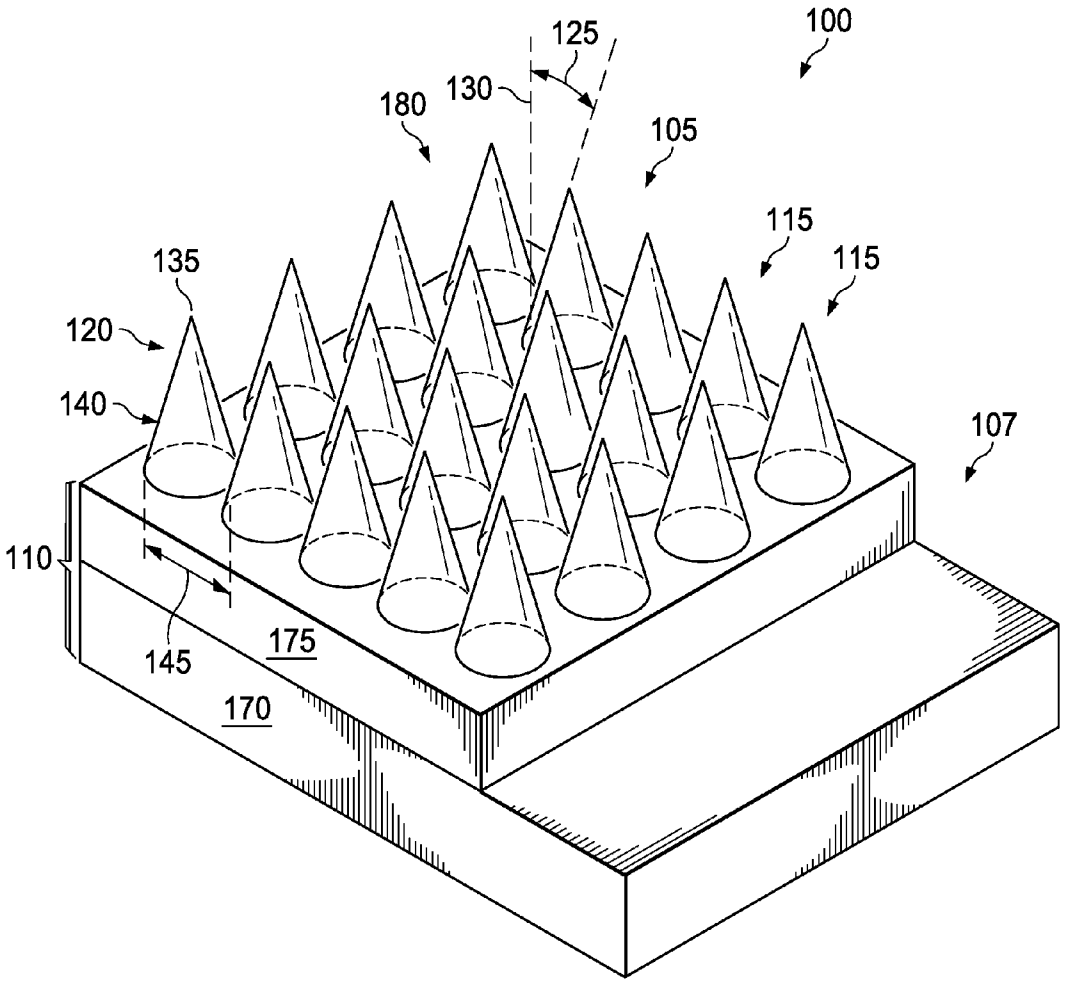
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(57) **ABSTRACT**

An apparatus. The apparatus comprises a distribution of microstructures on an area of a surface, each of the microstructures having one or more sloping sides. The apparatus comprises a distribution of nanostructures being located on the one or more sloping sides. The distribution of microstructures on the area of the surface is configured to nucleate and grow droplets of liquid from a gas. The distribution of nanostructures forms a superhydrophobic surface for the liquid.



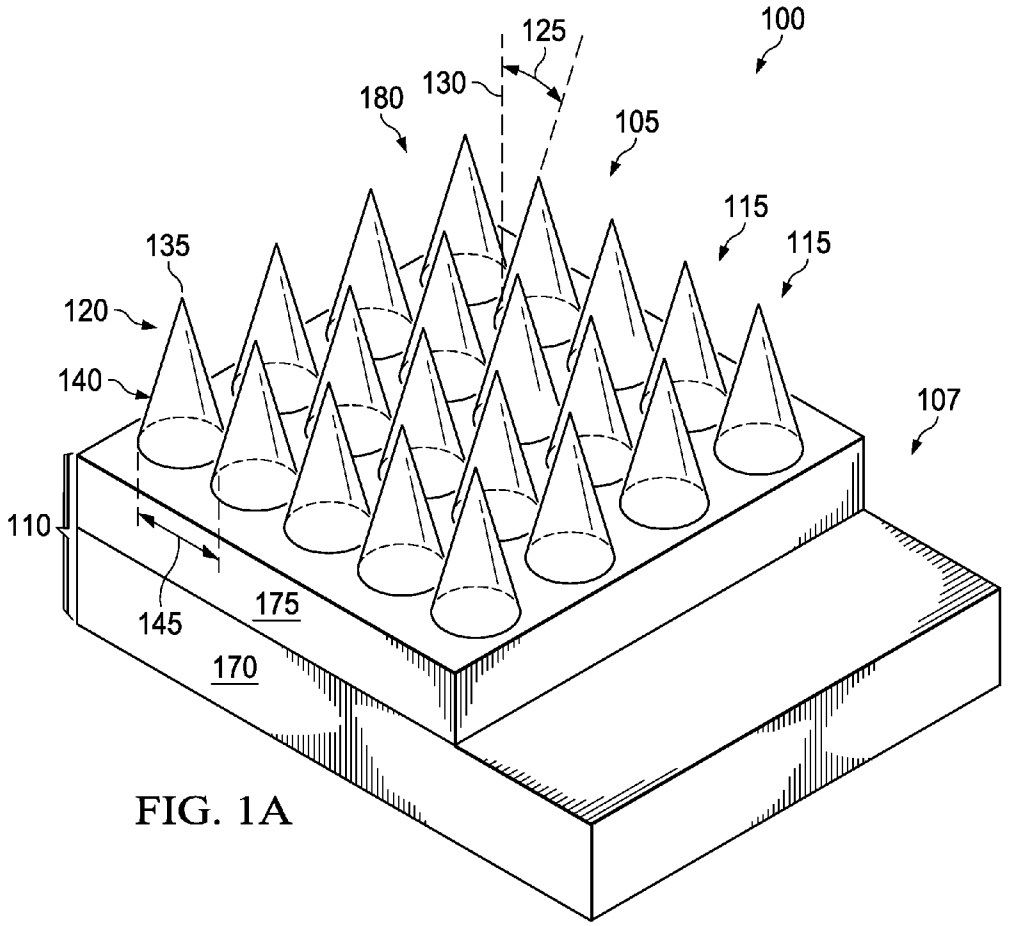


FIG. 1A

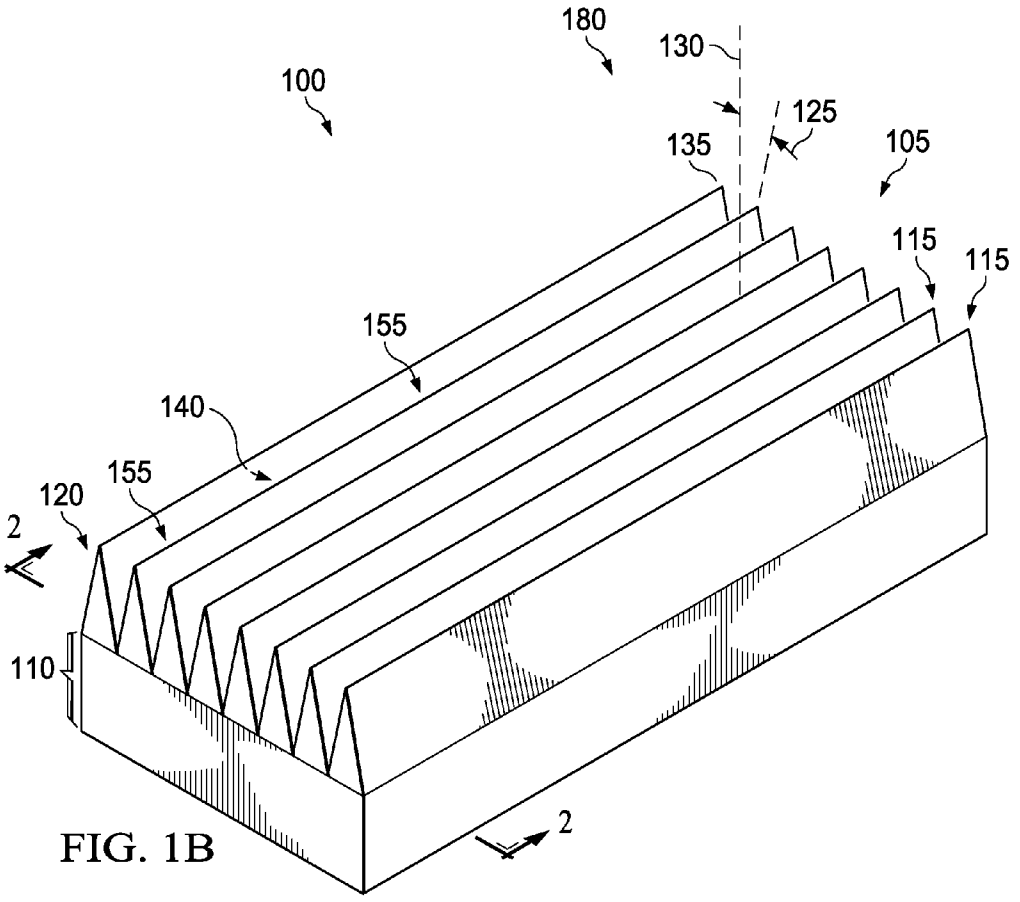


FIG. 1B

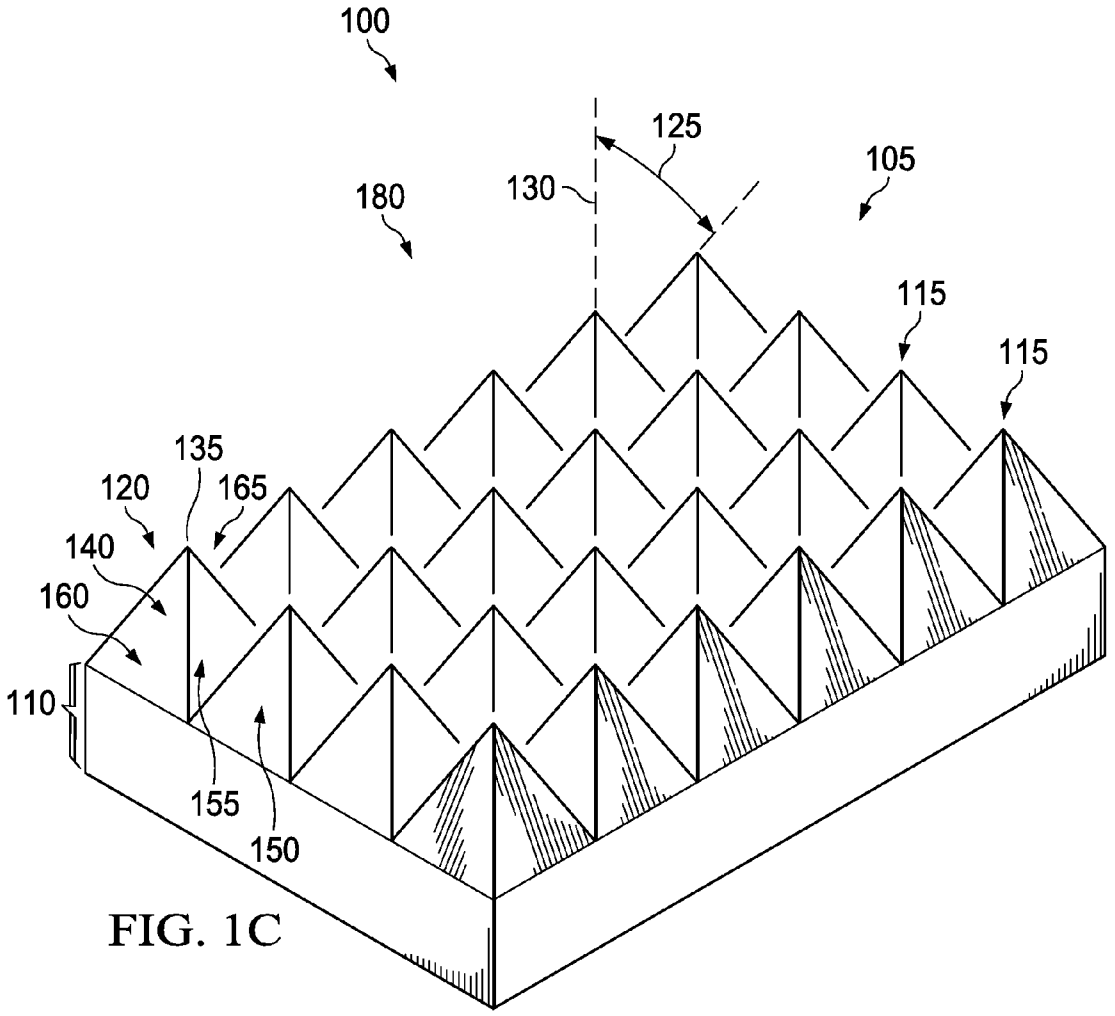


FIG. 1C

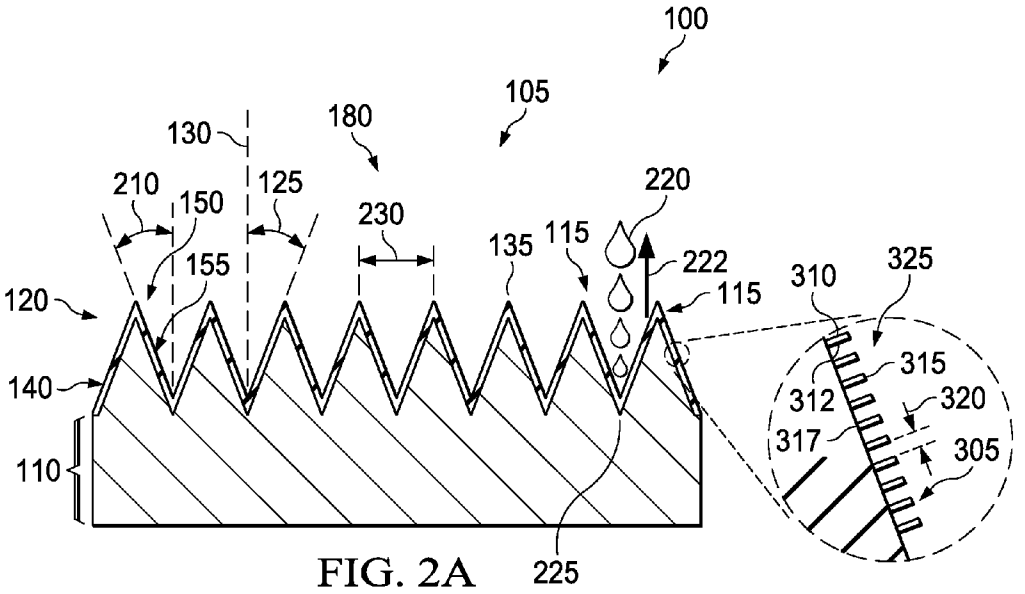


FIG. 2A

FIG. 3

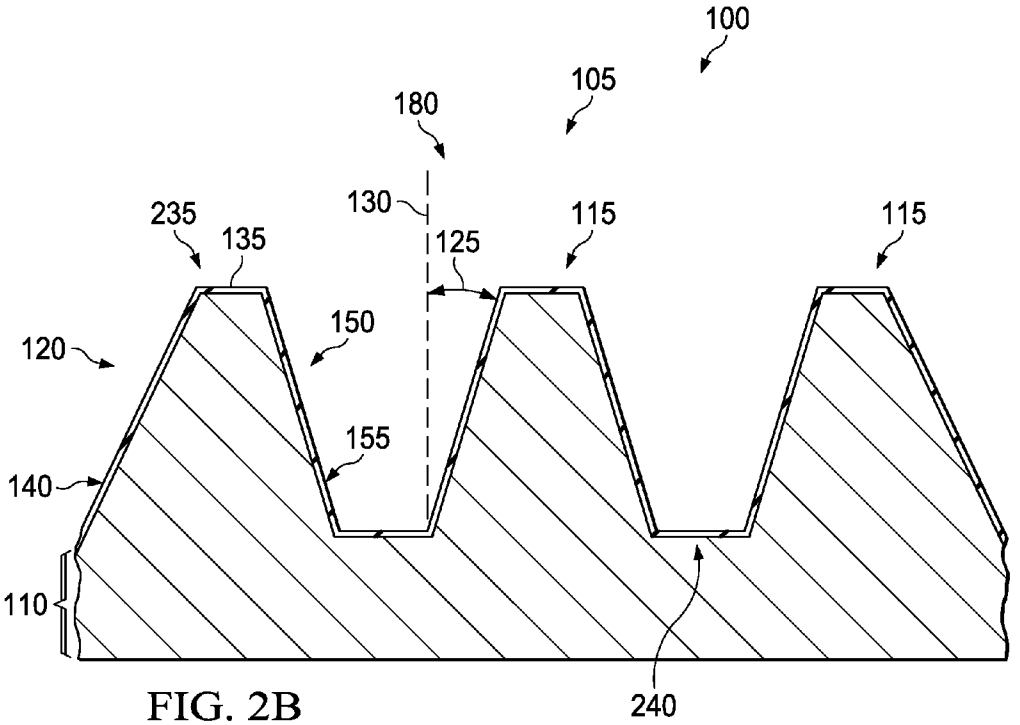


FIG. 2B

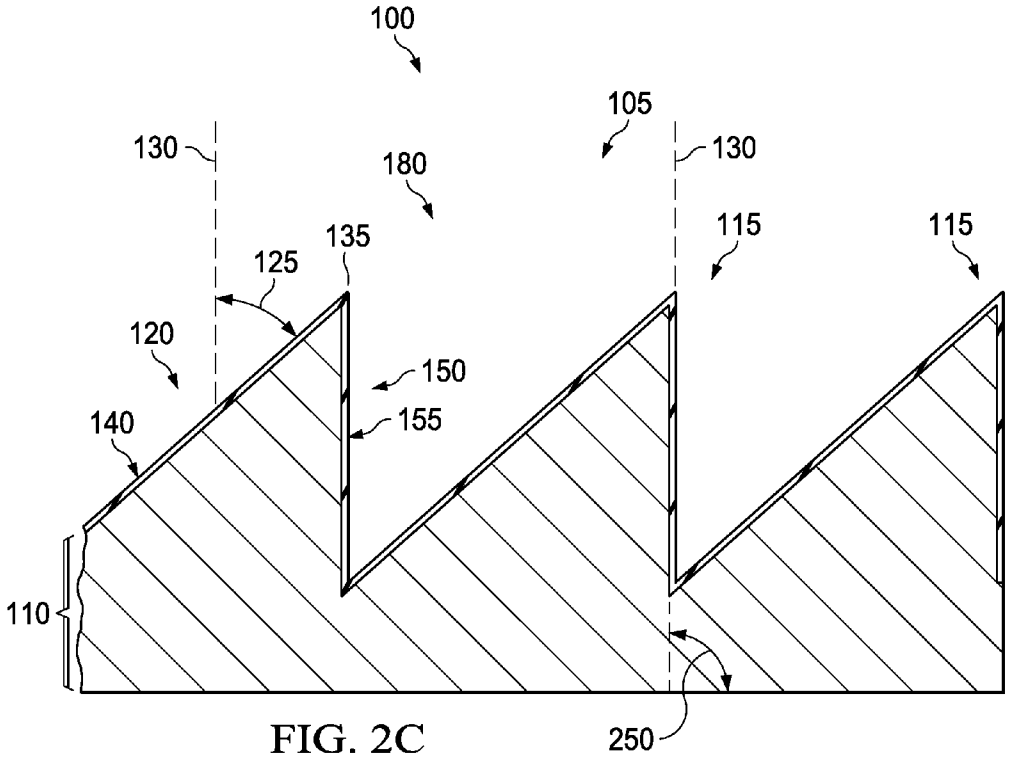

100
105
130
180
130
135
115
115
125
120
150
155
140
110
250

FIG. 2C

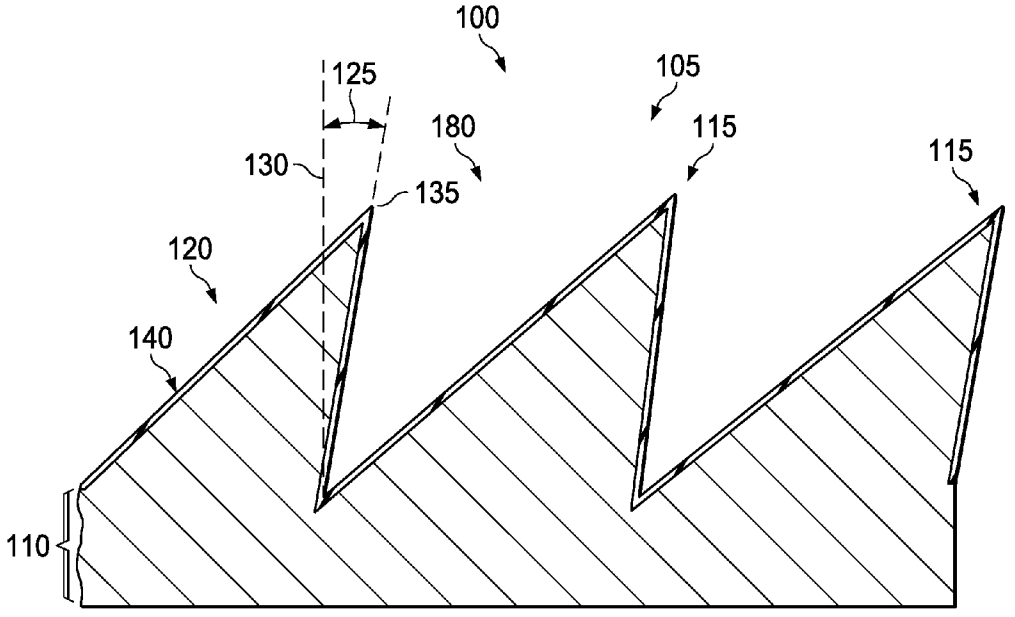

100
125
105
180
115
130
115
135
120
140
110

FIG. 2D

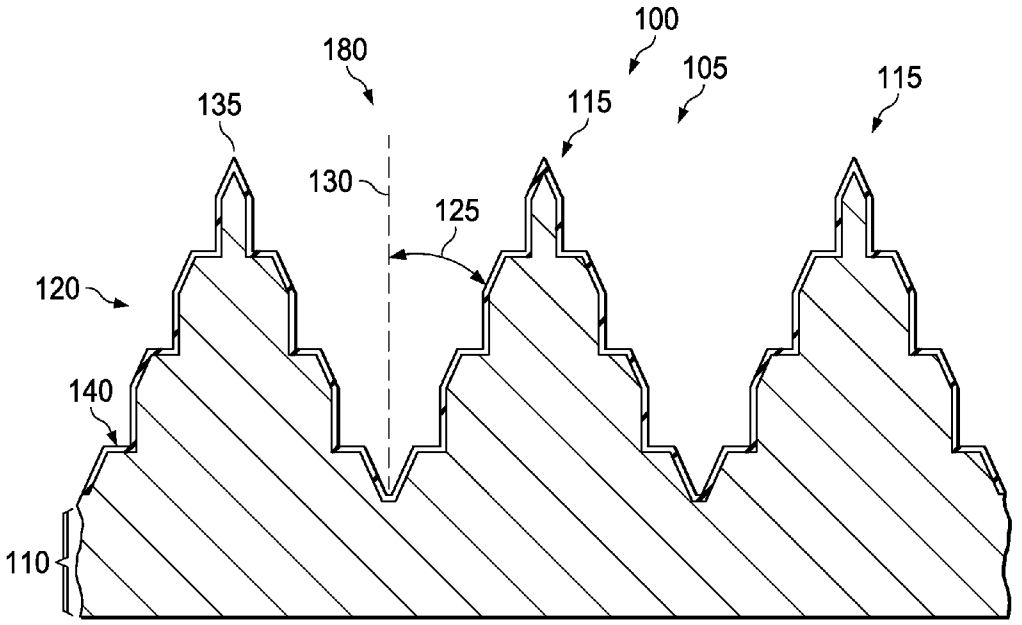


FIG. 2E

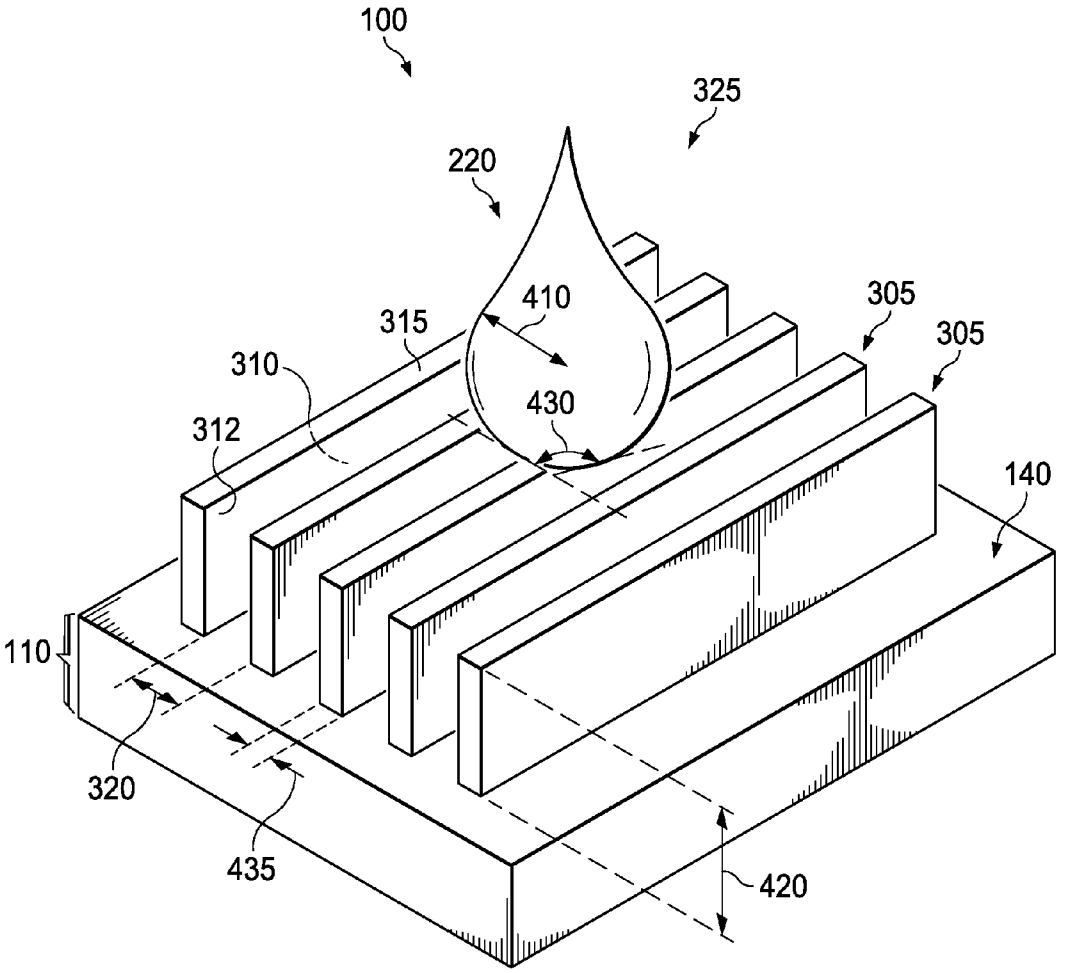


FIG. 4

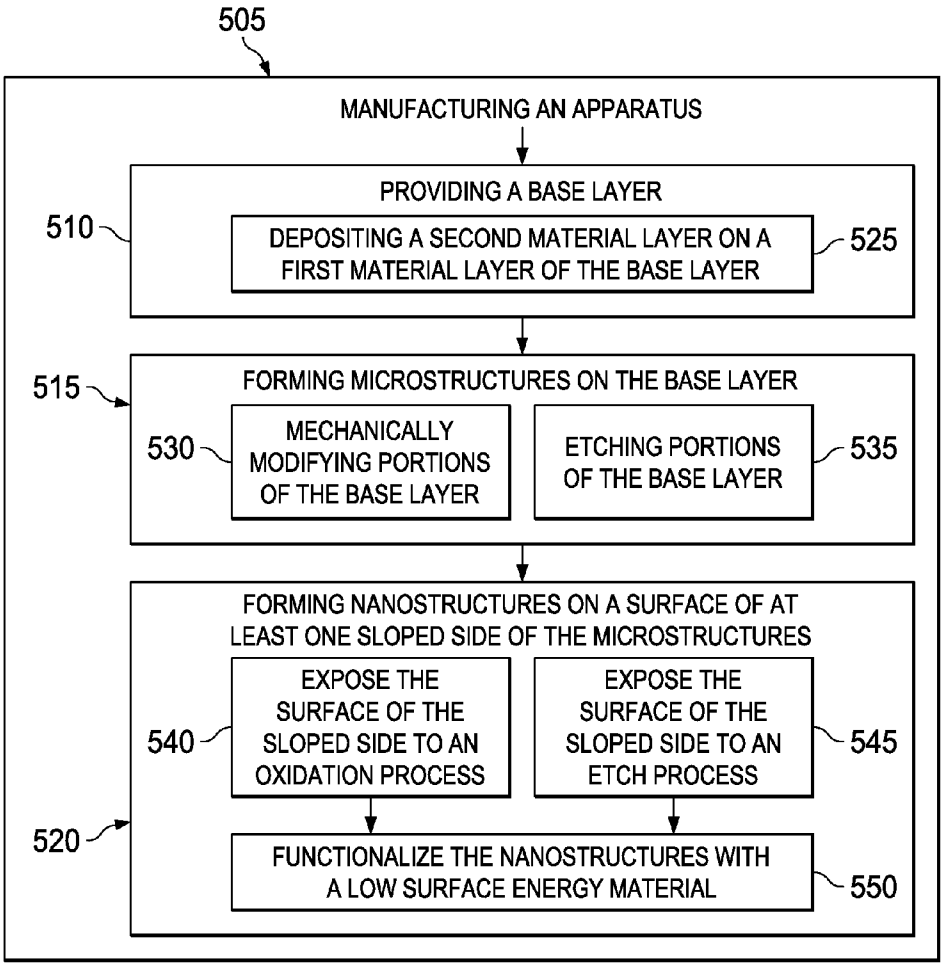

505
MANUFACTURING AN APPARATUS
PROVIDING A BASE LAYER
510
DEPOSITING A SECOND MATERIAL LAYER ON A FIRST MATERIAL LAYER OF THE BASE LAYER
525
FORMING MICROSTRUCTURES ON THE BASE LAYER
515
530
MECHANICALLY MODIFYING PORTIONS OF THE BASE LAYER
ETCHING PORTIONS OF THE BASE LAYER
535
FORMING NANOSTRUCTURES ON A SURFACE OF AT LEAST ONE SLOPED SIDE OF THE MICROSTRUCTURES
540
EXPOSE THE SURFACE OF THE SLOPED SIDE TO AN OXIDATION PROCESS
EXPOSE THE SURFACE OF THE SLOPED SIDE TO AN ETCH PROCESS
545
520
FUNCTIONALIZE THE NANOSTRUCTURES WITH A LOW SURFACE ENERGY MATERIAL
550

FIG. 5

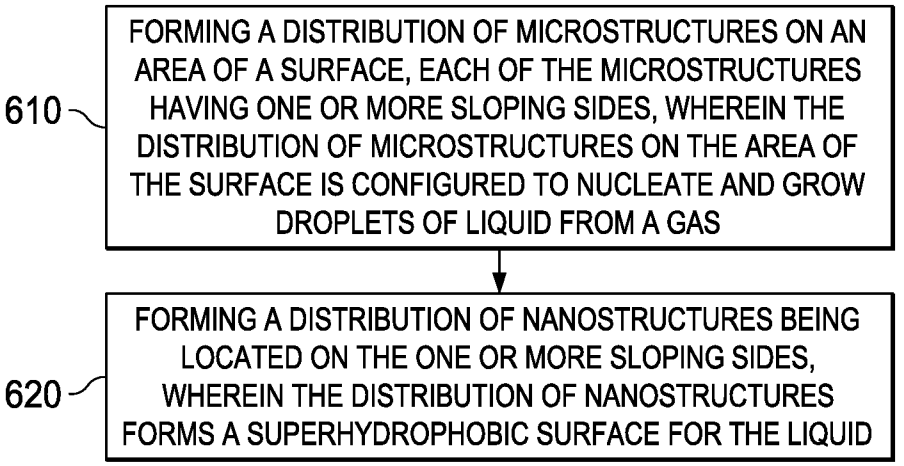

610
FORMING A DISTRIBUTION OF MICROSTRUCTURES ON AN AREA OF A SURFACE, EACH OF THE MICROSTRUCTURES HAVING ONE OR MORE SLOPING SIDES, WHEREIN THE DISTRIBUTION OF MICROSTRUCTURES ON THE AREA OF THE SURFACE IS CONFIGURED TO NUCLEATE AND GROW DROPLETS OF LIQUID FROM A GAS
620
FORMING A DISTRIBUTION OF NANOSTRUCTURES BEING LOCATED ON THE ONE OR MORE SLOPING SIDES, WHEREIN THE DISTRIBUTION OF NANOSTRUCTURES FORMS A SUPERHYDROPHOBIC SURFACE FOR THE LIQUID

FIG. 6

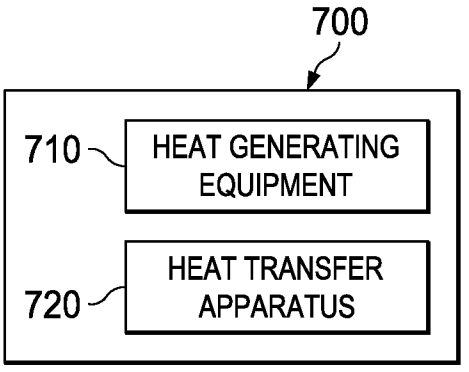

700
710
HEAT GENERATING EQUIPMENT
720
HEAT TRANSFER APPARATUS

FIG. 7

SLOPED HIERARCHICALLY-STRUCTURED SURFACE DESIGNS FOR ENHANCED CONDENSATION HEAT TRANSFER

TECHNICAL FIELD

[0001] The invention relates to in general, heat transfer apparatuses, and methods for manufacturing the same.

BACKGROUND

[0002] This section introduces aspects that may help facilitate a better understanding of the inventions. Accordingly, the statements of this section are to be read in this light and are not to be understood as admissions about what is prior art or what is not prior art.

[0003] Condensation is an important process in a number of two-phase heat transfer apparatuses implemented for thermal management. Improving the efficiency of such condensation heat transfer processes has the potential to enable size reductions of heat transfer apparatuses while still achieving the same overall heat transfer performance.

SUMMARY

[0004] One embodiment is an apparatus. The apparatus comprises a distribution of microstructures on an area of a surface, each of the microstructures having one or more sloping sides. The apparatus comprises a distribution of nanostructures being located on the one or more sloping sides. The distribution of microstructures on the area of the surface is configured to nucleate and grow droplets of liquid from a gas. The distribution of nanostructures forms a superhydrophobic surface for the liquid.

[0005] In any of the above embodiments of the apparatus, the microstructures are configured to nucleate the droplets between the nanostructures. In some embodiments, the microstructures are ridges. In some embodiments, the microstructures are pointed structures. Any of the above embodiments of the apparatus can further include a heat pipe or a vapor chamber, the distribution of microstructures being located in a condenser portion of the heat pipe or the vapor chamber. In some embodiments, the one or more sloping sides intersects with at least one side of the microstructure to form an apex shaped as a peak. In some embodiments, the separation distance between apexes of adjacent ones of the microstructures is equal to or less than about 10 microns. In some embodiments, at least one of the sloping sides intersects with at another side of an adjacent one of the microstructures at a base layer to form a valley. In some embodiments, at least one of the sloping sides and another side of the one microstructure separately intersect with a third side of the one microstructure to form an apex shaped as a mesa. In some embodiments, at least one of the sloping sides and another side of an adjacent one of the microstructures separately intersect with a horizontally oriented layer that is covered with the nanostructures and is adjacent to a base layer. In some embodiments, at least one of the sloping sides intersects with another side which forms a right angle with respect to a base layer. In some embodiments, at least one of the sloping sides intersects with another side of the one microstructure, and, the other side forms a different acute angle with respect to the line perpendicular to a base layer. In some embodiments, for at least one of the sloping sides, there are sloped portions that have the acute angle interspersed horizontal portions that are parallel with a base layer. In some embodiments, a distance between adjacent ones of the nanostructures is greater than a critical condensation radius for a nucleating one of the liquid droplet.

[0006] One embodiment is a system. The system comprises heat generating equipment and a heat transfer apparatus configured to remove heat generated by the electronic equipment. The apparatus includes a distribution of microstructures on an area of a surface, each of the microstructures having one or more sloping sides. The apparatus comprises a distribution of nanostructures being located on the one or more sloping sides. The distribution of microstructures on the area of the surface is configured to nucleate and grow droplets of liquid from a gas. The distribution of nanostructures forms a superhydrophobic surface for the liquid.

[0007] In some embodiments of the system, the distribution of microstructures is located on the surface of a condenser of the apparatus. In some embodiments, the condenser is part of a heat pipe. In some embodiments, the condenser is part of a vapor chamber.

[0008] One embodiment is a method. The method comprises forming a distribution of microstructures on an area of a surface, each of the microstructures having one or more sloping sides, wherein the distribution of microstructures on the area of the surface is configured to nucleate and grow droplets of liquid from a gas. The method comprises forming a distribution of nanostructures being located on the one or more sloping sides, wherein the distribution of nanostructures forms a superhydrophobic surface for the liquid.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The embodiments of the disclosure are best understood from the following detailed description, when read with the accompanying FIGUREs. Some features in the figures may be described as, for example, "top," "bottom," "vertical" or "lateral" for convenience in referring to those features. Such descriptions do not limit the orientation of such features with respect to the natural horizon or gravity. Various features may not be drawn to scale and may be arbitrarily increased or reduced in size for clarity of discussion. Reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

[0010] FIG. **1**A presents a perspective view of an embodiment heat transfer apparatus;

[0011] FIG. **1**B presents a perspective view of an alternative embodiment of a heat transfer apparatus;

[0012] FIG. **1**C presents a perspective view of another alternative embodiment of a heat transfer apparatus;

[0013] FIG. **2**A presents a cross-sectional view of the apparatus shown in FIG. **1**B along view line **2-2**;

[0014] FIG. **2**B presents a cross-sectional view of an alternative embodiment of a heat transfer apparatus, analogous to the view along line **2-2** in FIG. **1**B;

[0015] FIG. **2**C presents a cross-sectional view of an alternative embodiment of the heat transfer apparatus, analogous to the view along line **2-2** in FIG. **1**B;

[0016] FIG. **2**D presents a cross-sectional view of an alternative embodiment of a heat transfer apparatus, analogous to the view along line **2-2** in FIG. **1**B;

[0017] FIG. **2**E presents a cross-sectional view of an alternative embodiment of a heat transfer apparatus, analogous to the view along line **2-2** in FIG. **1**B;

[0018] FIG. **3** presents a detailed cross-sectional view of a portion of the apparatus shown in FIG. **2**A;

[0019] FIG. **4** presents a perspective view of the portion of apparatus presented in FIG. **3**;

[0020] FIG. **5** presents a flow diagram of an example method of manufacturing a heat transfer apparatus, such as any of the example apparatuses described in the context of FIGS. **1**A-**4**;

[0021] FIG. **6** presents a flow diagram of a method; and

[0022] FIG. **7** presents a block diagram of a system.

[0023] In the Figures and text, similar or like reference symbols indicate elements with similar or the same functions and/or structures.

[0024] In the Figures, the relative dimensions of some features may be exaggerated to more clearly illustrate one or more of the structures or features therein.

[0025] Herein, various embodiments are described more fully by the Figures and the Detailed Description. Nevertheless, the inventions may be embodied in various forms and are not limited to the embodiments described in the Figures and Detailed Description of Illustrative Embodiments.

DETAILED DESCRIPTION

[0026] The description and drawings merely illustrate the principles of the inventions. It will thus be appreciated that a person of ordinary skill in the relevant arts will be able to devise various arrangements that, although not explicitly described or shown herein, embody the principles of the inventions and are included within its scope. Furthermore, all examples recited herein are principally intended expressly to be for pedagogical purposes to aid the reader in understanding the principles of the inventions and concepts contributed by the inventor(s) to furthering the art, and are to be construed as being without limitation to such specifically recited examples and conditions. Moreover, all statements herein reciting principles, aspects, and embodiments of the inventions, as well as specific examples thereof, are intended to encompass equivalents thereof. Additionally, the term, "or," as used herein, refers to a non-exclusive or, unless otherwise indicated. Also, the various embodiments described herein are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0027] Various heat transfer apparatuses of the disclosure have hierarchically structured condensation surfaces which enhance condensation heat transfer. The hierarchically structured surfaces may, e.g., have both micron-scaled structural features ("microstructures") and nanometer-scaled structural features ("nanostructures").

[0028] The use of non-wetting surfaces (synonymous with the term superhydrophobic surface as used herein) can enhance heat transfer coefficients, in comparison to the heat transfer via smooth surfaces. Surprisingly, when the non-wetting surface is a surface covered with nanostructures, similar enhancements to heat transfer coefficients have typically not been realized. As droplets form and grow on a surface covered with nanostructures, the droplet gets to a certain critical size, and heat conduction through the bulk of the droplet begins to limit the heat transfer rate. It is therefore desirable for the droplet to leave the surface (often referred to droplet jumping) before the droplet reaches its critical size. However, there is a characteristic droplet diameter, below which dissipation effects, e.g., viscous effects, form drag, surface adhesion, etc., can dominate or suppress droplet jumping. Furthermore, droplet jumping typically requires the coalescence of two or more droplets, which, in turn, is dictated by the number density of droplets nucleated on the surface. Thus, the minimum jumping droplet diameter may be also restricted by a small number of nucleated droplets (large droplet spacing).

[0029] Providing a hierarchically structured condensation surface, with separated microstructures having nanostructures thereon, may provide an efficient heat transfer surface. Providing microstructures having at least one sloped side may help to move larger droplets to the apexes of the microstructures, thereby freeing up surfaces for new droplet nucleation on condensation surfaces and promoting droplet jumping before a droplet reaches a critical size, which is heat-conduction limiting. Providing nanostructures on the microstructures can create a non-wetting surface that increases the apparent contact angle and reduces the contact angle hysteresis of droplets forming on the microstructures. Thus, such nanostructures may facilitate the movement of the droplets away from droplet nucleation sites and towards apexes of the nanostructures. A further benefit of using a hierarchically structured condensation surface with both microstructures and nanostructures thereon is that the effective heat transfer surface area is increased. Thus, there can be an increased number of nucleation sites on the condensing surface, leading to greater heat transfer rates compared to a condensing surface having only nanostructures.

[0030] FIGS. **1**A-**1**C presents perspective views of different embodiments of heat transfer apparatuses **100**. FIG. **2**A presents a cross-sectional view of the apparatus shown in FIG. **1**B along view line **2**A-**2**A. FIG. **2**A could also depict analogous cross-sectional views of the apparatuses shown in FIGS. **1**A or **1**C. FIG. **3** presents a detailed view of a portion of the apparatus shown in FIG. **2**A, although this figure could also depict analogous detailed views of the apparatuses shown in FIG. **1**A or **1**C.

[0031] In some embodiments, the apparatus **100** comprises a condenser **105**. The condenser **105** can be part of a variety of different two-phase heat transfer apparatuses such as, but not limited to, heat pipes, vapor chambers, looped heat pipes, two-phase forced convection flow loops or shell-and-tube surface condensers. For example, in some cases, the condenser **105** can be a portion of the heat transfer apparatus **100** configured as a heat pipe which further includes an evaporator portion **107**. In still other embodiments the condenser **105** can be used in heat transfer apparatuses such as compact condensers for electronics thermal management, e.g., in telecommunications and data centers, industrial condensation heat exchangers, evaporator coils, dehumidifying coils, and/or water harvesting apparatuses.

[0032] The condenser **105** includes a base layer **110** and microstructures **115** (e.g., a distribution of microstructures) located on the base layer **110**. Each microstructure **115** includes at least one sloped side **120** that forms an acute angle **125** with respect to a line **130** perpendicular to the base layer **110**.

[0033] The at least one sloped side **120** connects to an apex **135** of the microstructure **115** located above the base layer **110**. An outer surface **140** of the sloped side **120** has nanostructures **305** (e.g., a distribution of nanostructures) thereon, wherein the nanostructures **305** are spaced apart from each other and project out from the outer surfaces **140**, e.g., as shown in FIG. **3**.

[0034] As used herein, the term microstructure **115**, as used herein, refers to a structure that has at least linear one-dimen-

sion **145** adjacent to the base layer **110** (e.g., a base width or depth) that extends a distance across the microstructure **115** in a range of 1 to 1000 microns.

[0035] As used herein, the term nanostructure **305**, as used herein, refers to a structure that has at least one linear dimension (e.g. height, width, or depth) that extends a distance from one side to an opposing side (e.g., opposing lateral sides **310**, **312**, or, top and bottom sides **315**, **317**) of the nanostructure **305** in a range from 1 to 1000 nanometers. Additionally, the one linear dimension of the nanostructure **305** is at least 10 times smaller than the one dimension **145** of the microstructure **115**. As a non-limiting example, when the one dimension **145** of the microstructure **115** equals 1 micron, then the one dimension of the nanostructure **305** can be up to 100 nanometers. Consequently, in this example, the at least one linear dimension of the nanostructure **305** (e.g., height, width, or depth), can be in a range of 1 to 100 nanometers. As another non-limiting example, when the one dimension **145** of the microstructure **115** equals 100 microns, then the one dimension of the nanostructure **305** (e.g., height, width, or depth), can be up to 1000 nanometers. Consequently, in this example, the one dimension of the nanostructure **305**, can be in a range of 1 to 1000 nanometers.

[0036] As used herein, the term acute angle refers to an angle that is greater than zero degrees and less than 90 degrees. In some embodiments, to increase the surface area of the condenser **105**, the acute angle **125** is more preferably in a range from about 25 degrees to 65 degrees, and even more preferably, in a range from about 40 to 55 degrees.

[0037] In some embodiments of the apparatus **100**, such as illustrated in FIG. **1**A, there is a single sloped side **120** that curves continuously around the entire microstructure **115**, and each one of the microstructures **115** is a cone-shaped structure.

[0038] In other embodiments, such as illustrated in FIG. **1**B or **1**C, the at least one sloped side **120** joins with at least one other side **150** of the microstructure **115** at the apex **135**, wherein an outer surface **155** of the at least other side **150** have the nanostructures **305** thereon.

[0039] For instance, as illustrated in FIG. **1**B, the at least one sloped side **120** can have a planar surface **140** and join with at least one other side **150** which also has a planar surface **155** to form ridge-shaped microstructures **115**. Similar ridge-shaped microstructures could be formed where one or both of the surfaces **140**, **155** of the sides **120**, **150** are curved (e.g., curving inwards or curving outwards).

[0040] For instance, as illustrated in FIG. **1**C, the at least one sloped side **120** can join with two or more other sides **150**, **160**, **165** at the apex **135** to form pyramidal-shaped microstructures structures (e.g., structures with three or more planar or curved sides joining at the apex **135**).

[0041] As further illustrated in FIG. **2**A, in some cases, the at least one other side **150** that joins the sloped side **120** at the apex **135** is another sloped side that forms another acute angle **210** with respect to the line **130** perpendicular to the base layer **110**. For instance, the other sloped side **150** can form an acute angle **210** that is about equal in magnitude but opposite in sign to the acute angle **125** of the sloped side **120**. Similarly, in some embodiments, with more than two sides, such as illustrated in FIG. **1**C, each of the other sides **150**, **160**, **165** can be sloped sides and form about the same acute angles with respect to the line **130**.

[0042] Referring to FIG. **2**A, it is believed that the sloped side **120** (or other sloped sides **150**, **160**, **165** in some cases) helps to force a growing droplet **220** in a direction **222** away from droplet nucleation sites, e.g., sites in-between the nanostructures **305**, towards the apexes **135** of the microstructures **115**. E.g., the sloped side **120** may help such droplets **220** to move towards the apexes **135** of the microstructures **115**. Although, in FIG. **2**A, droplet nucleation is depicted as originating at a valley **225** between adjacent microstructures **115**, a person of ordinary skill in the relevant arts would understand that droplet nucleation could originate at sites anywhere on the surfaces **140**, **155**, of the sides **120**, **150**.

[0043] Referring again to FIG. **2**A, the apexes **135** of the microstructures **115** are separated from each other by a separation distance **230**. The selection of the separation distance **230** between adjacent microstructures **115** is important to aiding the droplet **220** moving away the droplet nucleation sites, and to promote droplet jumping, before the droplet growth rate becomes heat conduction limited. As an example, water droplet growth become heat conduction limited at a droplet radius of about 5 microns or greater. Therefore, for certain embodiments of the apparatus **100**, where heat transfer involves water condensation (e.g., occurs through a water condensation heat transfer processes), the separation distance **230** is preferably equal or less than about 10 microns. A person of ordinary skill in the relevant arts would understand how to determine a preferred maximal allowable droplet radius for different types of fluids, before the fluid's droplet growth rate becomes heat conduction limited. Accordingly, the separation distances **230** of a distribution of microstructures **115** could be set equal to or less than two times the preferred maximal allowable droplet radius. For instance, in some embodiments the separation distance **230** between the apexes **115** of adjacent ones of the microstructures **115** is in a range of 100 microns to 1 micron, and in some cases a range of 10 microns to 1 micron.

[0044] As further illustrated in FIG. **2**A, in some embodiments of the apparatus **100**, the sloped side **120** intersects with at least one other side **150** of the microstructure **115** to form the apex **135** shaped as a peak. It is believed that a peaked-shaped apex **135** can reduce a growing droplet's **220** surface contact with the microstructures **115**, and, thereby facilitate droplet jumping.

[0045] As further illustrated in FIG. **2**A, in some embodiments of the apparatus **100**, the sloped side **120** of the microstructure **115** intersects with at least one side (one of sides **120**, **150**) of an adjacent microstructure **115** at the base layer **110** to form a valley **225**. Configuring the condenser **105** such that the sides of the adjacent microstructures **115** intersect at the base layer **110** helps to increase the total surface area of the condensation surface, and, can enhance condensation heat transfer by also providing a number of potential droplet nucleation sites.

[0046] In still other embodiments of the apparatus **100**, however, the at least one sloped side **120** does not intersect with other sloping sides of the same microstructure **115** or of adjacent microstructures **115**. For example, as illustrated in FIG. **2**B, the sloped side **120** and another side **150** of the same microstructure **115** can separately intersect with a third side **235** (e.g., a planar horizontally oriented side) of the microstructure **115** to form the apex **135** shaped as a mesa. For example, as further illustrated in FIG. **2**B, the sloped side **120** of one of the microstructures **115**, and, another side **150** of an adjacent one of the microstructures **115** can separately intersect with a nanostructure **305** covered horizontally oriented layer **240** that is adjacent to the base layer **110**.

[0047] The microstructures **115** can have various other shapes to increase the surface area upon which condensation can occur.

[0048] For instance, in other embodiments of the apparatus **100**, as illustrated in FIG. **2**C, the at least one sloped side **120** can intersect with another side **150** of the microstructure **115** which forms a right angle **250** with respect to the base layer **110**, to form the apex **135**, e.g., shaped as a peak. That is, the other side **150** has a surface **155** that is parallel with respect to a line **130** perpendicular to the base layer **110**.

[0049] In other embodiments of the apparatus **100**, as illustrated in FIG. **2**D, the at least one sloped side **120** of one microstructure **115** can intersect with another side **150** of the same microstructure **115**. The other sloped side forms a different magnitude acute angle **210** (e.g., at least about 10 percent different than the acute angle **125**) with respect to the line **130** perpendicular to the base layer **110**, to form the apex **135**, e.g., shaped as a peak.

[0050] A person of ordinary skill in the relevant arts would appreciate how the sloped side **120** and the other sloped side **150**, such as depicted in FIGS. **2**C and **2**D, could separately intersect with a third layer **235** or fourth layer **240** to form structures analogous to that shown in FIG. **2**B.

[0051] In still other embodiments of the apparatus **100**, as illustrated in FIG. **2**E, the at least one sloped side **120**, and in some cases, the other side **140**, (or sides **140**, **160**, **165**, FIG. **1**C) which are sloped, includes sloped portions **250** that have the acute angle **125** interspersed with horizontal portions **255** which are parallel with the base layer **110**.

[0052] In some embodiments of the apparatus, such as depicted in FIGS. **1**A-**2**E, the microstructures **115** of the condenser **105** can have the same shape and be about uniformly separated from each other. However, in other embodiments, microstructures **115** of the condenser **105** can have a variety of different shapes, such as, but not limited to, combinations of any of the shapes discussed in the context of FIGS. **1**A-**2**E, and/or, the microstructures **115** can have different separation distances **230**, such as progressively increasing or decreasing distances **230** along one or more directions parallel to the base layer **110**. For example, the separation distance **230** may monotonically increase or decrease with along one direction parallel to the base layer **110**.

[0053] FIG. **4** presents a perspective view of the portion of example apparatus **100** presented in FIG. **3**, depicting example nanostructures **305** of the apparatus **100**. As illustrated, the nanostructures **305** can be ridged-shaped, and, the ridges are spaced apart from each other. In other embodiments, the nanostructures **305** can be pillar-shaped and the pillars are spaced apart from each other. The nanostructures **305** can cover the sloped side **120**, and any of the other sides **150**, **160**, **165**, peaked or mesa shaped apex **135**, or horizontal layer **240** discussed in the context of FIGS. **1**A-**2**E.

[0054] The use of nanostructures **305** to provide a non-wetting surface can be advantageous over conventional non-wetting condensing surfaces. Droplet adhesion to the condensation surface can be reduced with the appropriate nanostructure configuration. For instance, to reduce droplet adhesion, it is desirable for nanostructures to be configured to facilitate the droplet taking on a Cassie wetting state through contact line pinning at the base of the droplet. A person of ordinary skill in the relevant arts would understand that Cassie state refers to wetting state of the droplet where the droplet rests on the tops **315** of the nanostructures **305** in the vicinity of the droplet. For instance, in some cases, less than 10 percent of the nanostructure **305** nearest the top **315** is in contact with the droplet when the droplet is in a Cassie state. When in a Cassie state, most of the droplet is not in contact with the nanostructures **305**, so that the droplet's adhesion to the nanostructures **305** is reduced. Additionally, because most of the droplet in a Cassie state rests on the tops **315** of the nanostructures **305**, the sides **310**, **312**, and the surfaces **140**, **155** that support the nanostructures **305**, are available as sites for new droplet nucleation.

[0055] There are several structural attributes that the nanostructures **305** can have to facilitate a droplet in attaining a Cassie state.

[0056] For instance, in some preferred embodiments, it is desirable for the nanostructures **305** to provide the condensation surface with a certain amount of surface roughness to deter a droplet from taking on an undesirable Wenzel state. A Wenzel state refers to a wetting state where the droplet substantially contacts the entire surfaces of the nanostructures in the vicinity of the droplet. For example, in a Wenzel state, substantially the entire height of the droplet may contact the sides **310**, **312** and tops **315** of the nanostructures **305** support surfaces **140**, **155**. In various embodiments, it is often undesirable that a droplet take Wenzel states, because the large contact area of the droplet in such a state can provide a large adhesion that pins the droplet in-between the nanostructures **305**.

[0057] Wenzel state formation therefore impedes the droplet from moving away from its nucleation site to the apexes **135** of the microstructures **115**, which in turn may reduce the efficiency of condensation heat transfer.

[0058] To help avoid growing droplets taking such a Wenzel state, it is desirable for the surface **140**, or surfaces **140**, **155** that have the nanostructures **305** thereon, to satisfy the following condition when a liquid droplet rests on the surface: $-1/r*\cos\theta a<1$. Here, the parameter r is the surface roughness factor of the surfaces of the nanostructure, and θa is an intrinsic advancing contact angle of the liquid droplet. Herein, the surface roughness factor, r, is defined as the total surface area, including the areas of the sides **310**, **312**, and tops **315** and support surfaces **140**, **150** in between the nanostructures divided by projected surface area of the surfaces **140**, **150**, e.g., the area support surfaces **140**, **150** with no nanostructures **305** thereon. The intrinsic advancing contact angle, θa, refers to the contact angle that the fluid droplet would have on a smooth surface, e.g., the support surfaces **140**, **150** with no nanostructures **305** thereon.

[0059] For instance, in some preferred embodiments, it is desirable for the adjacent nanostructures **305** to be spaced apart by a minimum separation distance **320** (e.g., the distance from the side **310** of one nanostructure **305** to the side **312** of an adjacent nanostructure **305**). The suitable minimum separation distance **320** is that which allows the droplets to form and grow in-between the nanostructures **305** while avoiding undesirable capillary evaporation effects.

[0060] Preferably, the distance **320** is greater than a critical condensation radius **410**, r_c, for a nucleating fluid droplet. The critical condensation radius can be estimated by the formula:

$$r_c=2\mathrm{Y}\cup/(kT\ln S),$$

Here, Y is the ratio of liquid to vapor surface tension, $\cup$ is a molecular volume of the liquid phase, k is the Boltzmann constant, S is defined as the ratio of the vapor pressure pv to the saturation pressure at the condensing surface temperature

T. For example, in some embodiments of the apparatus **100**, for a water droplet, the distance **320** separating adjacent nanostructures is equal to of greater than about 10 nanometers. For example, in some embodiments of the device **100**, the distance **320** is in a range of about 1 to 100 nanometers, and in some cases in a range of about 10 to 20 nanometers.

[0061] Preferably, the distance **320** between adjacent ones of the nanostructures **305** has a value that promotes a droplet to attain the Cassie state before the droplet radius **410**, R, grows to size that is heat conduction limiting. For example, for water droplet this value of the radius **410** is about 5 microns or larger. The Cassie state, in turn, is promoted by spacing the nanostructures apart by a preferred distance **320** and by having a height **420** that facilitates the growing droplet to have a receding contact angle **430**, θr, of at least about 90 degrees.

[0062] For instance, in some preferred embodiments, the nanostructures satisfies the relationship:

$$\cos\theta_r < -(1+h/R)/(1+2h/w),$$

Here, θr is a receding contact angle **430** of at least 90 degrees for a maximally desired size of droplet located on tops of the nanostructures, h is the uniform height **420** of the nanostructures **305**, R is a radius **410** of the fluid droplet and w is a uniform separation distance **320** between adjacent ones of the nanostructures **305**.

[0063] The term receding contact angle **430** as used herein is defined as the minimum stable angle that the droplet achieves while on the nanostructures **305**. A person of ordinary skill in the relevant arts would be familiar with methods to measure the receding contact angle **430** of a droplet **220** (see e.g., "Condensation on Superhydrophobic Surfaces: The Role of Local Energy Barriers and Structure Length Scale" and Supporting Information, by Enright et al., Langmuir pub. Aug 29, 2012 ("Enright-1"), incorporated by reference herein in its entirety).

[0064] Herein, the term receding contact angle **430** is defined as the minimum stable angle that the droplet achieves while on the nanostructures **305**. A person of ordinary skill in the relevant arts would be familiar with methods to measure the receding contact angle **430** of a droplet **220** (see e.g., "Condensation on Superhydrophobic Surfaces: The Role of Local Energy Barriers and Structure Length Scale" and Supporting Information, by Enright et al., Langmuir pub. Aug 29, 2012 ("Enright-1"), incorporated by reference herein in its entirety).

[0065] The receding contact angle **140** for a droplet to spontaneously achieve a Cassie state can be reduced by reducing the ratio h/R, and/or, increasing the ratio h/w.

[0066] For instance, consider a fluid whose critical size, where heat conduction through the bulk of the droplet begins to limit the heat transfer rate, and, that critical size corresponds to a droplet radius **410** of 5 microns or greater. Assuming a desired receding contact angle **430**, θ_r, equal to 120 degrees, to make the ratio of h, the uniform height **420** of the nanostructures **305** to R, a radius **410** of the fluid droplet less than or equal to 0.1 (i.e., h/R≤0.1) requires h≤0.5 μm. For a h/R ratio equal to 0.1 and the height **420**, h, equal to 0.5 μm, the separation distance **320** between microstructures, w, is then equal to 833 nanometers and the h/w ratio equals 0.6. Continuing with the same example, where the h/R ratio equals 0.1 and h equals 0.5 μm, for a receding contact angle **430**, θ_r, equal to 110 degrees, w, is then equal to 451 nanometers and the h/w ratio equals 1.1, or, for a receding contact angle **430**, θ_r, equal to 100 degrees, w, is then equal to 187 nanometers, and the h/w ratio equals 2.7, or, for a receding contact angle **430**, θ_r, equal to 90 degrees, w, is then equal to 16 nanometers, and the h/w ratio equals 31.3.

[0067] In some embodiments of the apparatus **100**, reduce the adhesion of a de-wetted droplet (e.g., a droplet in a Cassie state) it is desirable to reduce the fraction of space occupied by the nanostructures **305** relative to the open space in-between adjacent ones of the nanostructures. For instance, in some embodiments, the solid fraction occupied by the nanostructures **305** is equal to or less than 0.1. As used herein the term solid fraction herein is equal to d/(d+w), where d is the width **435** of the nanostructure and w is the separation distance **320** between adjacent ones of the nanostructures **305**.

[0068] As a non-limiting example, in cases where the separation distance **320** is equal to 833 nanometers, then the width **435** is preferably equal or less than 93 nanometers. Or, when the separation distance **320** is equal to 451 nanometers, then the width **435** is preferably equal or less than 50 nanometers. Or, when the separation distance **320** is equal to 451 nanometers, then the width **435** is preferably equal or less than 50 nanometers. Or, when the separation distance **320** is equal to 187 nanometers, then the width **435** is preferably equal or less than 21 nanometers. Or, when the separation distance **320** is equal to 16 nanometers, then the width **435** is preferably equal or less than 1.8 nanometers.

[0069] Referring to any of FIGS. **1A-4**, another apparatus **100** embodiment comprises a distribution of microstructures **115** on an area of a surface **180** (e.g., a condensation surface), each of the microstructures **115** having one or more sloping sides **120**, **155**, **160**, **165**. The apparatus **100** also comprises a distribution of nanostructures **310** being located on the one or more sloping sides **120**, **155**, **160**, **165**. The distribution of microstructures **115** on the area of the surface **180** is configured to nucleate and grow droplets **230** of liquid from a gas. The distribution of nanostructures **310** forms a superhydrophobic surface **325** for the liquid.

[0070] As used herein, a surface **325** is considered to be a superhydrophobic surface **325** (synonymous with the term non-wetting surface as used herein) when a fluid droplet **230** of the fluid laying on the surface **325** has a contact angle **325** of equal to or greater than about 90 degrees. This is in contrast to a hydrophillic surface (synonymous with the term wetting surface as used herein) where a fluid droplet **145** laying on the surface **325** has a contact angle **140** of less or equal to 90 degrees.

[0071] In some embodiments of the apparatus **100** the microstructures **115** are configured to nucleate the droplets between the nanostructures **310**. In some embodiments, the microstructures **115** are ridges. In some embodiments, the microstructures **115** are pointed structures (e.g., the apexes **135** have a pointed shape). In some embodiments, the apparatus **100** further includes a heat pipe **170** or a vapor chamber **170**, the distribution of microstructures being located in a condenser **105** portion of the heat pipe **170** or vapor chamber **170**.

[0072] The distribution of microstructures **115** and the distribution of nanostructures **310** could include any combination of any or all of the microstructures **115** or nanostructures **310** configurations disclosed herein.

[0073] Still another embodiment is a method that comprises manufacturing a heat transfer apparatus. With continuing reference to FIGS. **1A-4** throughout, FIG. **5** presents a flow diagram of an example method of manufacturing a heat

transfer apparatus of the disclosure, such as any of the example apparatuses **100** described in the context of FIGS. **1A-4**.

[0074] As illustrated in FIG. **5**, the method includes a step **505** of manufacturing a condenser. Manufacturing the condenser (step **505**) includes a step **510** providing a base layer **110** and step **515** of forming microstructures **115** on the base layer **110**. Each microstructure **115** includes at least one sloped side **120** that forms an acute angle **125** with respect to a line **130** perpendicular to the base layer **110**. The at least one sloped side **120** connects to an apex **135** of the microstructure **115** located above the base layer **110**. The method also includes a step **520** of forming nanostructures **305** on a surface **140** of the at least one sloped side **120**, wherein the nanostructures **305** are spaced apart from each other and project out from the surface **140**.

[0075] In some cases, providing the base layer **110** in step **510** can simply include providing a material layer **170**, e.g., of copper, aluminum, semiconductor material upon which the microstructures **115** are directly formed from in step **515**. In some cases the use of a highly heat conductive material layer **170** such copper, aluminum is preferred. In other cases, the providing the base layer **110** in step **510** can include a step **525** of depositing a second material layer **175** on the first material layer **170**, where the microstructures **115** is formed from the second material layer **175**. For instance, a second material layer **175** of copper or aluminum could be deposited on a first material layer **170** of steel, via electrolytic, electroless or other deposition processes familiar to a person of ordinary skill in the relevant arts.

[0076] In some embodiments of the method, forming the microstructures **115** (step **515**) includes a step **530** of mechanically modifying portions of the base layer **110**. For instance, a base layer **110** of copper or aluminum, or, a second layer **175** of the base layer **110**, can be mechanically indented, machined, stamped, embossed or otherwise mechanically modified to form any of the microstructure **115** shapes discussed in the context of FIGS. **1A-4**.

[0077] In some embodiments of the method, forming microstructures **115** (step **515**) includes a step **535** of etching portions of the base layer **110**. For instance, a base layer **110** or a second layer **175**, composed of a semiconductor material, such as a silicon layer, can be etched by wet or dry etching processes, or laser etching processes, familiar to a person of ordinary skill in the relevant arts to form the microstructures **115**.

[0078] In some embodiments of the method, forming the nanostructures **305** (step **520**) includes a step **540** of wherein forming the nanostructures includes exposing the surface **140** of the sloped side **120**, (or surfaces **140**, **155** of the sides **120**, **150**) of the microstructure **115** to an oxidation process. For instance a copper base layer **110** of second layer **175** can be exposed to chemical oxidation conditions such as in "Condensation on Superhydrophobic Copper Oxide Nanostructures," by Enright et al. Proceedings of the 3rd Micro/Nanoscale Heat and Mass Transfer International Conference, Atlanta, Ga., Mar. 3-6, 2012, MNHMT2012-75277 ("Enright-2"), incorporated by reference herein in its entirety, to form the nanostructures **305** therefrom. For instance, an aluminum base layer **110** or second layer **175** can be exposed to well-known hydrothermal oxidation processes to form the nanostructures **305** therefrom.

[0079] In some embodiments of the method, forming the nanostructures **305** (step **520**) includes exposing the surface **140** of the sloped side **120**, (or surfaces **140**, **155** of the sides **120**, **150**) of the microstructure **115** to an etch process in step **545**. For instance, microstructures **115** composed of a semiconductor material, such as silicon, can be subjected to a reactive ion etching process to form the nanostructures **305**, such as black silicon nanostructures. Other examples of etching process for forming nanostructures are presented in Enright-1.

[0080] In some embodiments of the method, part of forming the nanostructures **305** (step **520**) includes functionalizing the nanostructures **305** in step **550** with a low surface energy material. The term low surface energy material, as used herein, refers to a material having a surface energy of about 22 dynes/cm (about 22×10-5 N/cm) or less as disclosed in U.S. Pat. No. 7,695,550 to Krupenkin et al. ("Krupenkin"), incorporated by reference herein in its entirety.

[0081] Non-limiting examples of functionalizing nanostructures in accordance with step **550** includes coating nanostructures **305** with chlorosilanes, fluorosilanes or fluorinated polymers, such as disclosed in Krupenkin, Enright-1 or Enright-2.

[0082] With continuing reference to FIGS. **1A-4** throughout, FIG. **6** presents a flow diagram of another method embodiment of the disclosure. The method comprises a step **610** of forming a distribution of microstructures **115** on an area of a surface **180**, each of the microstructures **115** having one or more sloping sides **120**, **155**, **160**, **165**. The distribution of microstructures **115** on the area of the surface **180** is configured to nucleate and grow droplets **230** of liquid from a gas. The method comprises a step **620** of forming a distribution of nanostructures **310** being located on the one or more sloping sides **120**, **155**, **160**, **165**. The distribution of nanostructures forms a superhydrophobic surface **325** for the liquid.

[0083] The steps **610**, **620** of forming the distribution of microstructures **115** and the distribution of nanostructures **310** could include any or all of the microstructures **115** or nanostructures **310** configurations disclosed herein and any combination of any or all of the method steps for of forming the microstructures **115** or nanostructures **310** disclosed herein.

[0084] FIG. **7** illustrates another embodiment of the disclosure, a system **700**. In some embodiments the system **700** can be communication system such as a telecommunication system or a system component (e.g., electronic cabinet) of a communication system. The system **700** comprises heat generating equipment **710**, such electrical equipment, e.g., circuit boards having heat generating components thereon. The system **700** also comprises a heat transfer apparatus **720**. The heat transfer apparatus **720** can be configured to remove heat generated by the equipment **710** of the system **700**.

[0085] The heat transfer apparatus **720** can be or include any apparatuses described herein. In some cases, for instance, referring to FIGS. **1A-4**, the apparatus **720** can include a distribution of microstructures **115** on an area of a surface **180** (e.g., a condensation surface), each of the microstructures **115** having one or more sloping sides **120**, **155**, **160**, **165**. The apparatus **720** also comprises a distribution of nanostructures **310** being located on the one or more sloping sides **120**, **155**, **160**, **165**. The distribution of microstructures **115** on the area of the surface **180** is configured to nucleate and grow droplets **230** of liquid from a gas. The distribution of nanostructures **310** forms a superhydrophobic surface **325** for the liquid.

[0086] In some cases, for instance, with continuing reference to FIGS. **1**A-**4**, in some embodiments of the system **700**, the distribution of microstructures **115** is located on the surface **180** of a condenser **105** of the apparatus **710**. In some embodiments, the condenser **105** is part of a heat pipe **170**, while in other embodiments, the condenser **105** is part of a vapor chamber **170**.

[0087] Although the present disclosure has been described in detail, a person of ordinary skill in the relevant arts should understand that they can make various changes, substitutions and alterations herein without departing from the scope of the invention.

What is claimed is:

1. An apparatus, comprising:

a distribution of microstructures on an area of a surface, each of the microstructures having one or more sloping sides;

a distribution of nanostructures being located on the one or more sloping sides; and

wherein the distribution of microstructures on the area of the surface is configured to nucleate and grow droplets of liquid from a gas; and

wherein the distribution of nanostructures forms a superhydrophobic surface for the liquid.

2. The apparatus of claim **1**, wherein the microstructures are configured to nucleate the droplets between the nanostructures.

3. The apparatus of claim **1**, wherein the microstructures are ridges.

4. The apparatus of claim **1**, wherein the microstructures are pointed structures.

5. The apparatus of claim **1**, wherein each of the microstructures are pyramidal-shaped structures.

6. The apparatus of claim **1**, further including:

a heat pipe or a vapor chamber, the distribution of microstructures being located in a condenser portion of the heat pipe or the vapor chamber.

7. The apparatus of claim **1**, wherein the one or more sloping sides intersects with at least one side of the microstructure to form an apex shaped as a peak.

8. The apparatus of claim **1**, wherein the separation distance between apexes of adjacent ones of the microstructures is equal to or less than about **10** microns.

9. The apparatus of claim **1**, wherein at least one of the sloping sides intersects with at another side of an adjacent one of the microstructures at a base layer to form a valley.

10. The apparatus of claim **1**, wherein at least one of the sloping sides and another side of the one microstructure separately intersect with a third side of the one microstructure to form an apex shaped as a mesa.

11. The apparatus of claim **1**, wherein at least one of the sloping sides and another side of an adjacent one of the microstructures separately intersect with a horizontally oriented layer that is covered with the nanostructures and is adjacent to a base layer.

12. The apparatus of claim **1**, wherein at least one of the sloping sides intersects with another side which forms a right angle with respect to a base layer.

13. The apparatus of claim **15**, wherein at least one of the sloping sides intersects with another side of the one microstructure, and, the other side forms a different acute angle with respect to the line perpendicular to a base layer.

14. The apparatus of claim **1**, wherein for at least one of the sloping sides, there are sloped portions that have the acute angle interspersed horizontal portions that are parallel with a base layer.

15. The apparatus of claim **1**, wherein a distance between adjacent ones of the nanostructures is greater than a critical condensation radius for a nucleating one of the liquid droplet.

16. A system, comprising:

heat generating equipment; and

a heat transfer apparatus configured to remove heat generated by the electronic equipment, wherein the apparatus includes:

a distribution of microstructures on an area of a surface, each of the microstructures having one or more sloping sides;

a distribution of nanostructures being located on the one or more sloping sides; and

wherein the distribution of microstructures on the area of the surface is configured to nucleate and grow droplets of liquid from a gas; and

wherein the distribution of nanostructures forms a superhydrophobic surface for the liquid.

17. The system of claim **16**, wherein the distribution of microstructures is located on the surface of a condenser of the apparatus

18. The system of claim **16**, wherein the condenser is part of a heat pipe.

19. The system of claim **16**, wherein the condenser is part of a vapor chamber.

20. A method, comprising:

forming a distribution of microstructures on an area of a surface, each of the microstructures having one or more sloping sides, wherein the distribution of microstructures on the area of the surface is configured to nucleate and grow droplets of liquid from a gas; and

forming a distribution of nanostructures being located on the one or more sloping sides, wherein the distribution of nanostructures forms a superhydrophobic surface for the liquid.

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