TRAY CARRIER WITH ULTRAPHOBIC SURFACES

RELATED APPLICATIONS

This application claims the benefit of U.S. Utility Patent Application Serial No. 10/454,740, filed June 3, 2003 and U.S. Provisional Patent Application Serial No. 60/462963, entitled "Ultraphobic Surface for High Pressure Liquids", filed April 15, 2003, hereby fully incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates generally to tray carriers for delicate electronic components, and more particularly to a tray carrier having ultrahydrophobic or ultralyophobic surfaces formed thereon.

BACKGROUND OF THE INVENTION

Trays are used in the micro-electronic industry for storing, transporting, fabricating, and generally holding small components such as, but not limited to, semi-conductor chips, ferrite heads, magnetic resonant read heads, thin film heads, bare dies, bump dies, substrates, optical devices, laser diodes, preforms, and miscellaneous mechanical articles such as springs and lenses.

Semi-conductor chips (chips) are illustrative of the issues associated with handling the above-defined components. Semi-conductor chips are very small electronic devices which, for purposes of economy and scale, are manufactured en-masse from a larger semi-conductor wafer (wafer). Typically, a single wafer will yield several tens or hundreds of chips. Often, after the wafer has been segmented into individual chips, additional processing is necessary. This usually entails transporting a plurality of chips from one workstation to another for processing by specialized equipment.

To facilitate processing of chips on a large scale, specialized carriers called matrix trays (trays) have been developed. These trays are designed to hold a plurality of chips in individual processing cells or pockets arranged in a matrix or grid. The size of the matrix or grid can range from two to several hundred, depending upon the size of the chips to be processed. Examples of specialized chip carriers are disclosed in U.S. Patent Nos.

6,079,565 and 5,791,486 assigned to the owner of the present invention, and which are hereby fully incorporated herein by reference.

Electronic device fabrication processes, particularly where semiconductors are involved, are often extremely sensitive to contamination. Contamination and contaminants can be generated in many different ways. For example, particulates can be generated mechanically by wafers as they are processed, or they can be generated chemically in reaction to different processing fluids. Contamination can also be the result of out-gassing from chemical fabrication processes, or biological in nature due to human activity.

As a tray carrier is used through a fabrication process, it will generally accumulate some amount of contamination. After use, the carrier may be discarded or recycled, or the contamination may be cleaned off and the carrier reused. In the past, cleaning of tray carriers has often been considered uneconomical in view of the relatively low cost of new tray carriers and the relatively high cost and difficulty of cleaning and reusing contaminated tray carriers.

Previously, cleaning of tray carriers has been made more difficult and expensive due to the need to dry the tray after cleaning with water or other solvents. The tray carrier may have intricate arrangements of surfaces that are difficult to dry. In addition, a residual amount of the cleaning fluid may adhere to the surfaces of a carrier as a film or in a multiplicity of small droplets after the washing step. Any contaminants suspended in the residual cleaning fluid may be redeposited on the surface as the fluid dries, leading to contaminant carryover when the carrier is reused. Consequently, process efficiency and effectiveness is diminished overall. Reuse of tray carriers is discouraged, leading to environmentally undesirable proliferation of solid waste.

What is still needed in the industry is a tray carrier with features that promote more effective cleaning and drying of the carrier with reduced levels of residual process contamination.

SUMMARY OF THE INVENTION

The present invention includes a tray carrier with ultraphobic surfaces for promoting more effective cleaning and drying of the carrier. In the invention, entire surfaces or portions of surfaces of a carrier are made ultraphobic. The ultraphobic

surfaces of the carrier cause liquids that may come in contact with the surface, such as may be used in cleaning, to quickly and easily "roll off" without leaving a liquid film or substantial number of liquid droplets. As a result, less time and energy is expended in drying the surfaces, and redeposited residue is minimized, thereby improving overall process quality. In addition, the ultraphobic surfaces may be resistant to initial deposition of contaminants, where the contaminants may be in liquid or vapor form.

In a particularly preferred embodiment of the invention, the ultraphobic surface includes a multiplicity of closely spaced microscale to nanoscale asperities formed on a substrate. For the purpose of the present application, "microscale" generally refers to dimensions of less than 100 micrometers, and "nanoscale" generally refers to dimensions of less than 100 nanometers. The surface is designed to maintain ultraphobic properties up to a certain predetermined pressure value. The asperities are disposed so that the surface has a predetermined contact line density measured in meters of contact line per square meter of surface area equal to or greater than a contact line density value "Λ_L" determined according to the formula:

$$\Lambda_L = \frac{-P}{\gamma \cos\left(\theta_{a,0} + \omega - 90^\circ\right)}$$

where P is the predetermined pressure value, γ is the surface tension of the liquid, and $\theta_{a,0}$ is the experimentally measured true advancing contact angle of the liquid on the asperity material in degrees, and ω is the asperity rise angle. The predetermined pressure value may be selected so as to be greater than the anticipated liquid pressures expected to be encountered during cleaning or use of the carrier.

The asperities may be formed in or on the substrate material itself or in one or more layers of material disposed on the surface of the substrate. The asperities may be any regularly or irregularly shaped three dimensional solid or cavity and may be disposed in any regular geometric pattern or randomly. The asperities may be formed using photolithography, or using nanomachining, microstamping, microcontact printing, self-assembling metal colloid monolayers, atomic force microscopy nanomachining, sol-gel molding, self-assembled monolayer directed patterning, chemical etching, sol-gel

stamping, printing with colloidal inks, or by disposing a layer of parallel carbon nanotubes on the substrate.

Alternatively, randomly patterned surfaces may be produced by any of a variety of known processes, including chemical vapor deposition (CVD),

The invention may also include a process for producing a tray carrier with surfaces having ultraphobic properties at liquid pressures up to a predetermined pressure value. The process includes steps of selecting an asperity rise angle; determining a critical contact line density "Λ_L" value according to the formula:

$$\Lambda_L = \frac{-P}{\gamma \cos\left(\theta_{a,0} + \omega - 90^\circ\right)}$$

where P is the predetermined pressure value, γ is the surface tension of the liquid, and $\theta_{a,0}$ is the experimentally measured true advancing contact angle of the liquid on the asperity material in degrees, and ω is the asperity rise angle; providing a carrier with a surface portion; and forming a multiplicity of projecting asperities on the surface portion so that the surface has an actual contact line density equal to or greater than the critical contact line density.

The process may further include the step of determining a critical asperity height value "Z_c" in meters according to the formula:

$$Z_c = \frac{d\left(1 - \cos\left(\theta_{a,0} + \omega - 180^\circ\right)\right)}{2 \sin\left(\theta_{a,0} + \omega - 180^\circ\right)}$$

where d is the distance in meters between adjacent asperities, $\theta_{a,0}$ is the true advancing contact angle of the liquid on the surface in degrees, and ω is the asperity rise angle in degrees.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1a is a perspective view of one embodiment of a tray carrier with ultraphobic surfaces thereon according to the present invention;

Fig. 1b is a side elevation view of the tray carrier of Fig.1a;

Fig. 1c is a partial cross-sectional view of the tray carrier of Fig. 1a;

Fig. 1d is a perspective, enlarged view of an ultraphobic surface according to the present invention, wherein a multiplicity of nano/micro scale asperities are arranged in a rectangular array;

Fig.2 is a top plan view of a portion of the surface of Fig. 1;

Fig. 3 is a side elevation view of the surface portion depicted in Fig. 2;

Fig. 4 is a partial top plan view of an alternative embodiment of the present invention wherein the asperities are arranged in a hexagonal array;

Fig. 5 is a side elevation view of the alternative embodiment of Fig. 4;

Fig. 6 is a side elevation view depicting the deflection of liquid suspended between asperities;

Fig. 7 is a side elevation view depicting a quantity of liquid suspended atop asperities;

Fig. 8 is a side elevation view depicting the liquid contacting the bottom of the space between asperities;

Fig. 9 is a side elevation view of a single asperity in an alternative embodiment of the invention wherein the asperity rise angle is an acute angle;

Fig. 10 is a side elevation view of a single asperity in an alternative embodiment of the invention wherein the asperity rise angle is an obtuse angle;

Fig. 11 a partial top plan view of an alternative embodiment of the present invention wherein the asperities are cylindrical and are arranged in a rectangular array;

Fig. 12 is a side elevation view of the alternative embodiment of Fig. 11;

Fig. 13 is a table listing formulas for contact line density for a variety of asperity shapes and arrangements;

Fig. 14 is a side elevation view of an alternative embodiment of the present invention;

Fig. 15 is a top plan view of the alternative embodiment of Fig. 14; and

Fig. 16 is a top plan view of a single asperity in an alternative embodiment of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to FIGS. 1a, 1b and 1c, an example of a tray carrier for processing and transporting a plurality of electronic devices such as semi-conductor chips is shown and generally designated by the numeral 100. The tray 100 comprises a first peripheral frame 102 having a first end 104, a second end 106, and sides 108, 110. Sides 108, 110 include rails 112, 114 and notches 116, 118, 120, and 122, located at the ends of rails 112 and 114, respectively. Tabs 124, 126, 128, and 130 project into notches 116, 118, 120, and 122 for engagement with flanges (not depicted). Note that the tabs 124, 126, 128, and 130 project in the same direction relative to the tray 100. Together, first end 104, second end 106 and the rails 112, 114 extend substantially around the perimeter of a chip support surface 132. The chip support surface 132 is of a conventional design and is depicted as a matrix of lands 134 which define pockets or cells 136 which hold individual chips. Referring to FIG. 1b, the peripheral frame 102 forms a support base which is vertically offset with respect to a chip support surface 132. This creates a space or plenum beneath the chips to facilitate processing.

Surfaces resistant to wetting by liquids may be referred to as hydrophobic where the liquid is water, and lyophobic relative to other liquids. The surface may be generally referred to as an ultrahydrophobic or ultralyophobic surface if the surface resists wetting to an extent characterized by any or all of the following: very high advancing contact angles of liquid droplets with the surface (greater than about 120 degrees) coupled with low contact angle hysteresis values (less than about 20 degrees); a markedly reduced propensity of the surface to retain liquid droplets; or the presence of a liquid-gas-solid interface at the surface when the surface is completely submerged in liquid,. For the

purposes of this application, the term ultraphobic is used to refer generally to both ultrahydrophobic and ultralyophobic surfaces.

As depicted in Figs. 1a-c, ultraphobic surfaces 20 are formed on all outer surfaces of tray carrier 100. Ultraphobic surfaces 20 may be formed in any of a variety of configurations and using a variety of processes as described hereinbelow. It will of course be appreciated that ultraphobic surfaces 20 may be selectively formed on any desired portion of tray carrier 100. For example, if desired, ultraphobic surface 20 may cover only the chip support surface 132.

Although a matrix tray is depicted herein, it will be appreciated that the present invention includes any tray carrier for electronic or mechanical articles with an ultraphobic surface thereon, whether for a single electrical or mechanical article or for multiple articles.

A greatly enlarged view of one preferred embodiment of an ultraphobic surface 20 according to the present invention is depicted in Fig. 1d. The surface 20 generally includes a substrate 22 with a multiplicity of projecting asperities 24. Each asperity 24 has a plurality of sides 26 and a top 28. Each asperity 24 has a width dimension, annotated "x" in the figures, and a height dimension, annotated "z" in the figures.

As depicted in Figs. 1d-3, asperities 24 are disposed in a regular rectangular array, each asperity spaced apart from the adjacent asperities by a spacing dimension, annotated "y" in the figures. The angle subtended by the top edge 30 of the asperities 24 is annotated φ, and the rise angle of the side 26 of the asperities 24 relative to the substrate 22 is annotated ω. The sum of the angles φ and ω is 180 degrees.

Generally, surface 20 will exhibit ultraphobic properties when a liquid-solid-gas interface is maintained at the surface. As depicted in Fig. 7, if liquid 32 contacts only the tops 28 and a portion of the sides 26 proximate top edge 30 of asperities 24, leaving a space 34 between the asperities filled with air or other gas, the requisite liquid-solid-gas interface is present. The liquid may be said to be "suspended" atop and between the top edges 30 of the asperities 24.

As will be disclosed hereinbelow, the formation of the liquid-solid-gas interface depends on certain interrelated geometrical parameters of the asperities 24 and the properties of the liquid. According to the present invention, the geometrical properties of

asperities 24 may be selected so that the surface 20 exhibits ultraphobic properties at any desired liquid pressure.

Referring to the rectangular array of Figs. 1d-3, surface 20 may be divided into uniform areas 36, depicted bounded by dashed lines, surrounding each asperity 24. The area density of asperities (δ) in each uniform area 36 may be described by the equation:

$$\delta = \frac{1}{2y^2}, \tag{1}$$

where y is the spacing between asperities measured in meters.

For asperities 24 with a square cross-section as depicted in Figs. 1d-3, the length of perimeter (p) of top 28 at top edge 30:

$$p = 4\text{x}, \tag{2}$$

where x is the asperity width in meters.

Perimeter p may be referred to as a "contact line" defining the location of the liquid-solid-gas interface. The contact line density (Λ) of the surface, which is the length of contact line per unit area of the surface, is the product of the perimeter (p) and the area density of asperities (δ) so that:

$$\Lambda = p\,\delta. \tag{3}$$

For the rectangular array of square asperities depicted in Figs. 1d-3:

$$\Lambda = 4x/y^2. \tag{4}$$

A quantity of liquid will be suspended atop asperities 24 if the body forces (F) due to gravity acting on the liquid are less than surface forces (f) acting at the contact line with the asperities. Body forces (F) associated with gravity may be determined according to the following formula:

$$F = \rho\, gh, \tag{5}$$

where g is the density (ρ) of the liquid, (g) is the acceleration due to gravity, and (h) is the depth of the liquid. Thus, for example, for a 10 meter column of water having an approximate density of 1000 kg/m^3, the body forces (F) would be:

$F = (1000\ \text{kg/m}^3)(9.8\ \text{m/s}^2)(10\ \text{m}) = 9.8 \times 10^4\ \text{kg/m}^2\text{-s}.$

On the other hand, the surface forces (f) depend on the surface tension of the liquid (γ), its apparent contact angle with the side 26 of the asperities 24 with respect to the vertical θ_s, the contact line density of the asperities (Λ) and the apparent contact area of the liquid (A):

$$f = -\Lambda A \gamma \cos \theta_s. \tag{6}$$

The true advancing contact angle ($\theta_{a,0}$) of a liquid on a given solid material is defined as the largest experimentally measured stationary contact angle of the liquid on a surface of the material having essentially no asperities. The true advancing contact angle is readily measurable by techniques well known in the art.

Suspended drops on a surface with asperities exhibit their true advancing contact angle value ($\theta_{a,0}$) at the sides of the asperities. The contact angle with respect to the vertical at the side of the asperities (θ_s) is related to the true advancing contact angle ($\theta_{a,0}$) by φ or ω as follows:

$$\theta_s = \theta_{a,0} + 90^\circ - \varphi = \theta_{a,0} + \omega - 90^\circ. \tag{7}$$

By equating F and f and solving for contact line density Λ, a critical contact line density parameter Λ_L may be determined for predicting ultraphobic properties in a surface:

$$\Lambda_L = \frac{-\rho g h}{\gamma \cos\left(\theta_{a,0} + \omega - 90^\circ\right)}, \tag{8}$$

where g is the density (ρ) of the liquid, (g) is the acceleration due to gravity, (h) is the depth of the liquid, the surface tension of the liquid (γ), ω is the rise angle of the side of the asperities relative to the substrate in degrees, and ($\theta_{a,0}$) is the experimentally measured true advancing contact angle of the liquid on the asperity material in degrees.

If $\Lambda > \Lambda_L$, the liquid will be suspended atop the asperities 24, producing an ultraphobic surface. Otherwise, if $\Lambda < \Lambda_L$, the liquid will collapse over the asperities and the contact interface at the surface will be solely liquid/solid, without ultraphobic properties.

It will be appreciated that by substituting an appropriate value in the numerator of the equation given above, a value of critical contact line density may be determined to

design a surface that will retain ultraphobic properties at any desired amount of pressure. The equation may be generalized as:

$$\Lambda_L = \frac{-P}{\gamma \cos\left(\theta_{a,0} + \omega - 90^\circ\right)}, \tag{9}$$

where P is the maximum pressure under which the surface must exhibit ultraphobic properties in kilograms per square meter, γ is the surface tension of the liquid in Newtons per meter, $\theta_{a,0}$ is the experimentally measured true advancing contact angle of the liquid on the asperity material in degrees, and ω is the asperity rise angle in degrees.

It is generally anticipated that a surface 20 formed according to the above relations will exhibit ultraphobic properties under any liquid pressure values up to and including the value of P used in equation (9) above. The ultraphobic properties will be exhibited whether the surface is submerged, subjected to a jet or spray of liquid, or impacted with individual droplets. It will be readily appreciated that the pressure value P may be selected so as to be greater than the largest anticipated liquid or vapor pressure to which the carrier will be subjected during use or cleaning.

It will be generally appreciated that the value of P should be selected so as to provide an appropriate safety factor to account for pressures that may be momentarily or locally higher than anticipated, discontinuities in the surface due to tolerance variations, and other such factors.

If the surface 20 is intended for very low values of P where the liquid contact may be in the form of droplets on the surface, the value of P must be selected to account for the smaller apparent contact area of a droplet as opposed to a uniform layer of liquid. In general, the apparent contact area (A) in square meters of a small droplet on the surface is given by the relation:

$$A = \pi^{\frac{1}{3}} (6V)^{\frac{2}{3}} \left(\left(\frac{(1-\cos\theta_a)}{\sin\theta_a} \right) \left(3 + \left(\frac{(1-\cos\theta_a)}{\sin\theta_a} \right)^2 \right) \right)^{-\frac{2}{3}}, \tag{10}$$

where V is the volume of the droplet in cubic meters, and θ_a is the apparent advancing contact angle of the droplet on the surface. The critical contact line density Λ_L parameter for suspending a droplet on the surface becomes:

$$\Lambda_L = \frac{-\rho g (V)^{\frac{1}{3}} \left(\left(\frac{(1-\cos\theta_a)}{\sin\theta_a} \right) \left(3 + \left(\frac{(1-\cos\theta_a)}{\sin\theta_a} \right)^2 \right) \right)^{\frac{2}{3}}}{(36\pi)^{\frac{1}{3}} \gamma \cos\left(\theta_{a,0} + \omega - 90^\circ\right)}, \qquad (11)$$

where V is the volume of the droplet in cubic meters, g is the density (ρ) of the liquid, (g) is the acceleration due to gravity, (h) is the depth of the liquid, the surface tension of the liquid (γ), ω is the rise angle of the side of the asperities relative to the substrate in degrees, θ_a is the apparent advancing contact angle of the droplet on the surface, and ($\theta_{a,0}$) is the experimentally measured true advancing contact angle of the liquid on the asperity material in degrees. Equation 11 may be useful to check the value of P selected for low pressure ultraphobic surfaces to ensure that the surface will suspend droplets.

Once the value of critical contact line density is determined, the remaining details of the geometry of the asperities may be determined according to the relationship of x and y given in the equation for contact line density. In other words, the geometry of the surface may be determined by choosing the value of either x or y in the contact line equation and solving for the other variable.

The liquid interface deflects downwardly between adjacent asperities by an amount D_1 as depicted in Fig. 6. If the amount D_1 is greater than the height (z) of the asperities 24, the liquid will contact the substrate 22 at a point between the asperities 24. If this occurs, the liquid will be drawn into space 34, and collapse over the asperities, destroying the ultraphobic character of the surface. The value of D_1 represents a critical asperity height (Z_c), and is determinable according to the following formula:

$$D_1 = Z_c = \frac{d\left(1 - \cos\left(\theta_{a,0} + \omega - 180^\circ\right)\right)}{2\sin\left(\theta_{a,0} + \omega - 180^\circ\right)}, \qquad (12)$$

where (d) is the distance between adjacent asperities, ω is the asperity rise angle, and $\theta_{a,0}$ is the experimentally measured true advancing contact angle of the liquid on the asperity material. The height (z) of asperities 24 must be at least equal to, and is preferably greater than, critical asperity height (Z_c).

Although in Figs. 1d-3 the asperity rise angle ω is 90 degrees, other asperity geometries are possible. For example, ω may be an acute angle as depicted in Fig. 9 or an obtuse angle as depicted in Fig. 10. Generally, it is preferred that ω be between 80 and 130 degrees.

It will also be appreciated that a wide variety of asperity shapes and arrangements are possible within the scope of the present invention. For example, asperities may be polyhedral, cylindrical as depicted in Figs. 11-12, cylindroid, or any other suitable three dimensional shape. In addition, various strategies may be utilized to maximize contact line density of the asperities. As depicted in Figs. 14 and 15, the asperities 24 may be formed with a base portion 38 and a head portion 40. The larger perimeter of head portion 40 at top edge 30 increases the contact line density of the surface. Also, features such as recesses 42 may be formed in the asperities 24 as depicted in Fig. 16 to increase the perimeter at top edge 30, thereby increasing contact line density. The asperities may also be cavities formed in the substrate.

The asperities may be arranged in a rectangular array as discussed above, in a polygonal array such as the hexagonal array depicted in Figs. 4-5, or a circular or ovoid arrangement. The asperities may also be randomly distributed so long as the critical contact line density is maintained, although such a random arrangement may have less predictable ultraphobic properties, and is therefore less preferred. In such a random arrangement of asperities, the critical contact line density and other relevant parameters may be conceptualized as averages for the surface. In the table of Fig. 13, formulas for calculating contact line densities for various other asperity shapes and arrangements are listed.

Generally, the substrate material may be any material upon which micro or nano scale asperities may be suitably formed and which is suitable for use in the processing environment in which the carrier is used. The asperities may be formed directly in the substrate material itself, or in one or more layers of other material deposited on the substrate material, by photolithography or any of a variety of suitable methods. A photolithography method that may be suitable for forming micro/nanoscale asperities is disclosed in PCT Patent Application Publication WO 02/084340, hereby fully incorporated herein by reference.

Other methods that may be suitable for forming asperities of the desired shape and spacing include nanomachining as disclosed in U.S. Patent Application Publication No. 2002/00334879, microstamping as disclosed in U.S. Patent No. 5,725,788, microcontact printing as disclosed in U.S. Patent No. 5,900,160, self-assembled metal colloid monolayers, as disclosed in U.S. Patent 5,609,907, microstamping as disclosed in U.S. Patent No. 6,444,254, atomic force microscopy nanomachining as disclosed in U.S. Patent 5,252,835, nanomachining as disclosed in U.S. Patent No. 6,403,388, sol-gel molding as disclosed in U.S. Patent No. 6,530,554, self-assembled monolayer directed patterning of surfaces, as disclosed in U.S. Patent No. 6,518,168, chemical etching as disclosed in U.S. Patent No. 6,541,389, or sol-gel stamping as disclosed in U.S. Patent Application Publication No. 2003/0047822, all of which are hereby fully incorporated herein by reference. Carbon nanotube structures may also be usable to form the desired asperity geometries. Examples of carbon nanotube structures are disclosed in U.S. Patent Application Publication Nos. 2002/0098135 and 2002/0136683, also hereby fully incorporated herein by reference. Also, suitable asperity structures may be formed using known methods of printing with colloidal inks. Of course, it will be appreciated that any other method by which micro/nanoscale asperities may be formed with the requisite degree of precision may also be used.

In some applications, particularly where the carrier will not be subjected to high fluid pressures or where the surface is intended to repel droplets of liquid that may precipitate or condense on the surface, ultraphobic surface 20 may be formed with a coating of polymer material applied using known chemical vapor deposition techniques. For example, a thin layer of PFA, PTFE, or other polymer material may be applied to the polycarbonate surfaces of a carrier using gas phase polymerization. The resulting ultraphobic surface 20 will be generally characterized by randomly shaped and arranged asperities formed in the PFA material, and will be ultraphobic at low fluid pressures.

In another embodiment for low fluid pressure applications, a fractal ultraphobic surface may be formed as a layer of material on the substrate. In one such embodiment, a layer of alkylketene dimer (AKD) or similar material may be melted or poured on the polymer substrate and allowed to harden in a nitrogen gas atmosphere. One suitable method for forming an AKD surface is more fully described by T. Onda, et.al., in an article entitled "Super Water Repellant Fractal Surfaces", Langmuir, Volume 12, Number 9, May 1, 1996, at page 2125, which article is fully incorporated herein by reference.

In another embodiment suitable for low fluid pressure applications, polymer material, such as polypropylene, may be dissolved in a solvent, such as p-xylene. A quantity of non-solvent such as methyl ethyl ketone may be added to the solution, and the solution deposited on the carrier substrate. When the solvent is evaporated, a porous, gel-like ultraphobic surface structure will result.

In each of the above polymer layers, the resulting surface will be generally characterized by randomly shaped and arranged micrometer scale asperities. Although the actual contact line density and critical contact line density values for such surfaces are difficult to determine due to the variations in individual asperities, these surfaces will exhibit ultraphobic properties if the contact line density value for the surface equals or exceeds the critical contact line density for the surface. For such surfaces, the actual contact line density will necessarily be an average value for the surface due to the variability of dimensions and geometry of individual asperities. In addition, asperity rise angle ω in equations 9 and 11 should be an average value for the surface.

The present invention may be embodied in other specific forms without departing from the spirit or essential attributes thereof, and it is, therefore, desired that the present embodiment be considered in all respects as illustrative and not restrictive.

CLAIMS

What is claimed is:

1. A tray carrier for articles comprising:

a body having a substrate portion with a surface, at least a portion of said surface having a multiplicity of substantially uniformly shaped asperities thereon to form an ultraphobic surface, each asperity having a common asperity rise angle relative to the substrate portion, the asperities positioned so that the ultraphobic surface defines a contact line density measured in meters of contact line per square meter of surface area equal to or greater than a contact line density value "Λ_L" determined according to the formula:

$$\Lambda_L = \frac{-P}{\gamma \cos\left(\theta_{a,0} + \omega - 90^\circ\right)}$$

where γ is the surface tension of a liquid in contact with the surface in Newtons per meter, $\theta_{a,0}$ is the experimentally measured true advancing contact angle of the liquid on the asperity material in degrees, ω is the asperity rise angle in degrees, and P is a predetermined liquid pressure value in kilograms per meter, wherein the ultraphobic surface exhibits a liquid-solid-gas interface with the liquid at liquid pressures up to and including the predetermined liquid pressure value.

2. The tray carrier of claim 1, wherein the body has a plurality of pockets, each pocket adapted to receive a component.

3. The carrier of claim 1, wherein the asperities are projections.

4. The carrier of claim 3, wherein the asperities are polyhedrally shaped.

5. The carrier of claim 3, wherein each asperity has a generally square transverse cross-section.

6. The carrier of claim 3, wherein the asperities are cylindrical or cylindroidally shaped.

7. The carrier of claim 1, wherein the asperities are cavities formed in the substrate.

8. The carrier of claim 1, wherein the asperities are positioned in a substantially uniform array.

9. The carrier of claim 8, wherein the asperities are positioned in a rectangular array.

10. The carrier of claim 1, wherein the asperities have a substantially uniform asperity height relative to the substrate portion, and wherein the asperity height is greater than a critical asperity height value "Z_c" in meters determined according to the formula:

$$Z_c = \frac{d\left(1 - \cos\left(\theta_{a,0} + \omega - 180^\circ\right)\right)}{2\sin\left(\theta_{a,0} + \omega - 180^\circ\right)}$$

where d is the distance in meters between adjacent asperities, $\theta_{a,0}$ is the experimentally measured true advancing contact angle of the liquid on the asperity material in degrees, and ω is the asperity rise angle in degrees.

11. A process of making a tray carrier with an ultraphobic surface portion, the process comprising:

providing a tray carrier including a substrate having an outer surface; and

forming a multiplicity of substantially uniformly shaped asperities on the outer surface of the substrate, each asperity having a common asperity rise angle relative to the substrate portion, the asperities positioned so that the surface has a contact line density measured in meters of contact line per square meter of surface area equal to or greater than a contact line density value "Λ_L" determined according to the formula:

$$\Lambda_L = \frac{-P}{\gamma \cos\left(\theta_{a,0} + \omega - 90^\circ\right)}$$

where γ is the surface tension of a liquid in contact with the surface in Newtons per meter, $\theta_{a,0}$ is the experimentally measured true advancing contact angle of the liquid on the asperity material in degrees, ω is the asperity rise angle in degrees, and P is a predetermined liquid pressure value in kilograms per meter, wherein the ultraphobic surface exhibits a liquid-solid-gas interface with the liquid at liquid pressures up to and including the predetermined liquid pressure value.

12. The process of claim 11, wherein the asperities are formed by photolithography.

13. The process of claim 11, wherein the asperities are formed by a process selected from the group consisting of nanomachining, microstamping, microcontact printing, self-assembling metal colloid monolayers, atomic force microscopy nanomachining, sol-gel molding, self-assembled monolayer directed patterning, chemical etching, sol-gel stamping, printing with colloidal inks, and disposing a layer of parallel carbon nanotubes on the substrate.

14. A process for producing a tray carrier having a surface with ultraphobic properties at liquid pressures up to a predetermined pressure value, the process comprising:

selecting an asperity rise angle;

determining a critical contact line density "Λ_L" value according to the formula:

$$\Lambda_L = \frac{-P}{\gamma \cos\left(\theta_{a,0} + \omega - 90^\circ\right)}$$

where P is the predetermined pressure value, γ is the surface tension of the liquid, $\theta_{a,0}$ is the experimentally measured true advancing contact angle of the liquid on the asperity material in degrees, and ω is the asperity rise angle;

providing a carrier with a substrate portion; and

forming a multiplicity of projecting asperities on the substrate portion so that the surface has an actual contact line density equal to or greater than the critical contact line density.

15. The process of claim 14, wherein the asperities are formed using photolithography.

16. The process of claim 14, wherein the asperities are formed using wherein the asperities are formed using nanomachining, microstamping, microcontact printing, self-assembling metal colloid monolayers, atomic force microscopy nanomachining, sol-gel molding, self-assembled monolayer directed patterning, chemical etching, sol-gel stamping, printing with colloidal inks, or by disposing a layer of parallel carbon nanotubes on the substrate.

17. The process of claim 14, further comprising the step of selecting a geometrical shape for the asperities.

18. The process of claim 14, further comprising the step of selecting an array pattern for the asperities.

19. The process of claim 14, further comprising the steps of selecting at least one dimension for the asperities and determining at least one other dimension for the asperities using an equation for contact line density.

20. The process of claim 14, further comprising the step of determining a critical asperity height value "Z_c" in meters according to the formula:

$$Z_c = \frac{d\left(1 - \cos\left(\theta_{a,0} + \omega - 180^\circ\right)\right)}{2\sin\left(\theta_{a,0} + \omega - 180^\circ\right)}$$

where d is the distance in meters between adjacent asperities, $\theta_{a,0}$ is the true advancing contact angle of the liquid on the surface in degrees, and ω is the asperity rise angle in degrees.

21. A tray carrier for articles comprising:

a body having a substrate and a polymer outer layer on the substrate, the outer layer having a surface with a multiplicity of asperities thereon forming an ultraphobic surface for contacting a liquid, the asperities distributed so that the surface has an average contact line density equal to or greater than a critical contact line density value, and wherein the ultraphobic surface exhibits a liquid-solid-gas interface with the liquid at liquid pressures up to and including a predetermined liquid pressure value.

22. The carrier of claim 21, wherein the critical contact line density value "Λ_L" is determined according to the formula:

$$\Lambda_L = \frac{-P}{\gamma\cos\left(\theta_{a,0} + \omega - 90^\circ\right)}$$

where γ is the surface tension of a liquid in contact with the surface in Newtons per meter, $\theta_{a,0}$ is the experimentally measured true advancing contact angle of the liquid on the asperity material in degrees, ω is the asperity rise angle in degrees, and P is the predetermined liquid pressure value in kilograms per meter.

23. The carrier of claim 21, wherein the liquid contacting the surface is in the form of droplets, and the critical contact line density "Λ_L" is determined according to the formula:

$$\Lambda_L = \frac{-\rho g (V)^{\frac{1}{3}} \left(\left(\frac{(1-\cos\theta_a)}{\sin\theta_a} \right) \left(3 + \left(\frac{(1-\cos\theta_a)}{\sin\theta_a} \right)^2 \right) \right)^{\frac{2}{3}}}{(36\pi)^{\frac{1}{3}} \gamma \cos\left(\theta_{a,0} + \omega - 90^\circ\right)},$$

where V is the volume of the droplet in cubic meters, g is the density (ρ) of the liquid in kilograms per cubic meter, (g) is the acceleration due to gravity in meters per second squared, (h) is the depth of the liquid in meters, (γ) is the surface tension of the liquid in Newtons per meter, ω is the average rise angle of the side of the asperities relative to the substrate in degrees, θ_a is the apparent advancing contact angle of the droplet on the surface, and ($\theta_{a,0}$) is the experimentally measured true advancing contact angle of the liquid on the asperity material in degrees.

24. The carrier of claim 21, wherein the polymer outer layer includes a fluoropolymer.

25. The carrier of claim 21, wherein the polymer outer layer includes alkylketene dimer.

26. A process of making a tray carrier with an ultraphobic surface portion, the process comprising:

providing a tray carrier including a substrate having an outer surface; and

forming the ultraphobic surface portion by depositing a layer of polymer material on the outer surface using a chemical vapor deposition process, the layer of polymer material having an outer surface with a multiplicity of asperities, the asperities distributed so that the ultraphobic surface has a contact line density measured in meters of contact line per square meter of surface area equal to or greater than a critical contact line density value, wherein the ultraphobic surface exhibits a liquid-solid-gas interface with the liquid at liquid pressures up to and including a predetermined liquid pressure value.

27. The process of claim 26, wherein the critical contact line density value "Λ_L" is determined according to the formula:

$$\Lambda_L = \frac{-P}{\gamma \cos\left(\theta_{a,0} + \omega - 90^\circ\right)}$$

where γ is the surface tension of a liquid in contact with the surface in Newtons per meter, $\theta_{a,0}$ is the experimentally measured true advancing contact angle of the liquid on the asperity material in degrees, ω is the asperity rise angle in degrees, and P is the predetermined liquid pressure value in kilograms per meter.