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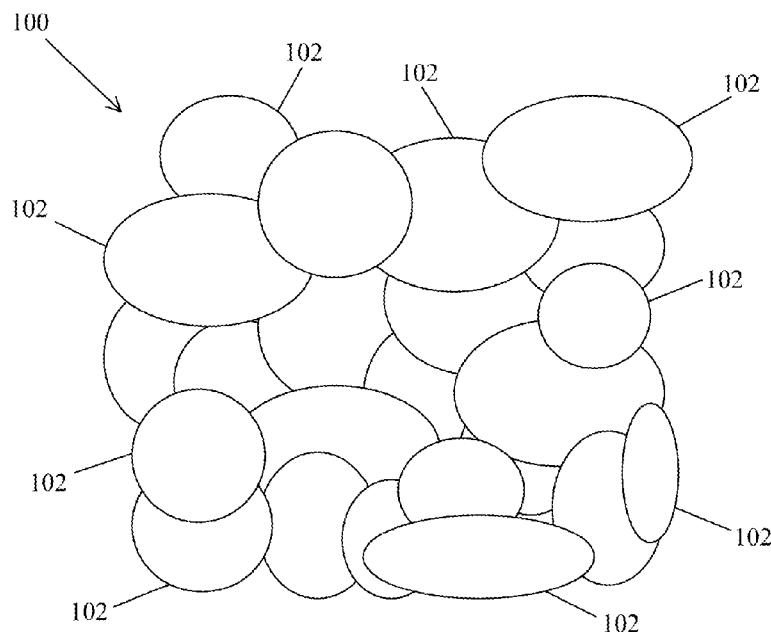


Fig. 1

[Continued on next page]

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(57) Abstract: An embodiment of a superhydrophilic nanostructure includes nanoparticles. The nanoparticles are formed into porous clusters. The porous clusters are formed into aggregate clusters. An embodiment of an article of manufacture includes the superhydrophilic nanostructure on a substrate. An embodiment of a method of fabricating a superhydrophilic nanostructure includes applying a solution that includes nanoparticles to a substrate. The substrate is heated to form aggregate clusters of porous clusters of the nanoparticles.

SUPERHYDROPHILIC NANOSTRUCTURE

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RELATED APPLICATIONS

[0001] The application claims priority to U.S. Provisional Patent Application Ser. No. 61/176,864, filed May 8, 2009, which is herein incorporated by reference in its entirety.

STATEMENT OF GOVERNMENT SUPPORT

[0002] This invention was made with government support under Contract No. DE-AC02-05CH11231 awarded by the U.S. Department of Energy. The government has certain rights in this invention.

BACKGROUND OF THE INVENTION

[0003] The present invention relates to the field of surface science and, more particularly, to the field of surface science where there is a desire to improve a hydrophilic behavior of a surface.

[0004] Fogging frequently occurs when a cold surface suddenly comes in contact with warm, moist air. Fogging scatters light and often renders the surface translucent. Fogging severity can ultimately compromise the usefulness of the transparent material and can be a dangerous condition, for example when the fogged material is a vehicle windscreen or goggle lens.

[0005] As an example, fogging of spectacle lenses made of glass or plastic occurs when water vapor in the air condenses because of the difference between the temperatures of the air and the spectacle lenses, with the result that tiny water droplets adhere to the surfaces of the spectacle lenses and irregularly reflect or refract light in a complex manner. To prevent the occurrence of such fogging, it is known to coat the surfaces of the spectacle lenses with an anti-fogging liquid such as a hydrophilic activator so that the surface tension is decreased and the generation of water droplets is thereby avoided. However, this technique suffers from a problem in that the coated anti-fogging liquid cannot remain effective for a long period of time because it evaporates or is wiped off.

[0006] Current commodity anti-fog coatings often lose effectiveness after repeated cleanings over time, and therefore require constant reapplication to ensure

their effectiveness. Numerous compositions have been proposed for anti-fog applications. For example, in U.S. Patent 6,455,142 entitled, "Anti-fog coating and coated film," Heberger et al. teach a coated polymer film that is applied to a surface and that provides an essentially streak free coated surface. Another example is U.S. Patent 5,853,896 entitled, "Water repellant agent for glass," in which Kondo et al. teach a water repellant composition for application to glass (e.g., glass windshields) where such a composition is a mixture of an organosilane and a diorganopolysiloxane. Yet another example is U.S. Patent 5,804,612 entitled, "Transparent anti-fog coating," in which Song et al. teach a transparent coating that includes a polymer, an aluminum containing crosslinker, and a surface active agent containing hydroxyl or siloxane groups.

[0007] In certain applications, such as dental mirrors, where accurate reflection of a patient's dental details is of paramount importance, and where non-toxicity is imperative, such compositions are not completely satisfactory. Nor do they provide a total solution to the anti-fogging problem. Some require lengthy curing. Some are toxic. Many will immediately dissolve and wash off from a dental mirror in the water generated by high speed drills in current use. And none provide adequate visibility for viewing details in the operative field: the proximity of a dental mirror to the tooth diffuses the reflection and obscures tooth details necessary for precise dental work.

[0008] More generally, surfaces that strongly attract (super-hydrophilic) or repel (super-hydrophobic) water are key to the two basic routes to self-cleaning, through film or droplet flow, respectively (see, R. Blossey, *Nature Materials* 2 (2003) 301). While theories established in the early 20th century (see, A.B.D. Cassie et al., *Transactions of the Faraday Society* 40 (1944) 0546; and R.N. Wenzel, *Industrial and Engineering Chemistry* 28 (1936) 988) were able to relate the wetting phenomena to general surface properties, the role of surface structures has been revisited recently after studies of a number of biological systems, e.g., lotus leaf (*Nelumbo Nucifera*), *Colocasia esculenta*, and Namib desert beetle (see, W. Barthlott et al., *Planta* 202 (1997) 1), revealed the significance of complex hierarchical microstructures to realizing extreme wetting surfaces. These studies prompted a new strategy for self-cleaning technologies based on mimicking the morphology of biological surfaces (see, L. Zhai et al., *Nano Letters* 4 (2004) 1349), although the primary goal has been to achieve super-hydrophobicity.

[0009] In the meantime, TiO₂ has received much recent attention as a unique photocatalyst with exciting potential for many energy and environmental applications crossing traditional disciplinary boundaries (see, e.g., X. Chen, S.S. Mao, *Chemical Reviews* 107 (2007) 2891). Since the discovery of UV light induced photocatalytic activity that can enhance its surface wettability (see, R. Wang et al., *Nature* 388 (1997) 431; and R. Wang et al., *Advanced Materials* 10 (1998) 135), TiO₂ has been extensively used in self-cleaning and related anti-pollution, anti-bacteria applications (see, I.P. Parkin et al., *Journal of Materials Chemistry* 15 (2005) 1689). However, a critical challenge of TiO₂-based techniques originates from the difficulty of sustaining the wetting behavior, though many drastic steps have been taken to overcome this challenge using, for instance, non-transparent (see, C. Pan et al., *Materials Research Bulletin* 42 (2007) 1395; and Z.Z. Gu et al., *Applied Physics Letters* 85 (2004) 5067) or composite systems (see, D. Lee et al., *Nano Letters* 6 (2006) 2305). Recent attempts of a multilayer assembly of TiO₂ nanoparticles and polyethylene glycol (see, W.Y. Gan et al., *Journal of Materials Chemistry* 17 (2007) 952; and S. Song et al., *Materials Letters* 62 (2008) 3503) showed a short-lived super-hydrophilic surface without the use of UV irradiation, for which the extreme wetting behavior collapsed after exposure to a moderate temperature. From the point of view of applications, achieving super-hydrophilic surfaces from TiO₂ while circumventing the need of external stimuli is regarded as the ultimate self-cleaning technology, in particular if the extreme wetting property could be combined with additional functionalities (see, C.W. Guo et al., *Chemphyschem* 5 (2004) 750) such as optical transparency. In fact, incorporating TiO₂ on traditional transparent substrates (e.g. glass) for low reflectance, high transmittance applications has often been challenging.

SUMMARY OF THE INVENTION

[0010] Embodiments of the present invention include a superhydrophilic nanostructure, an article of manufacture, and a method of fabricating a superhydrophilic nanostructure. An embodiment of a superhydrophilic nanostructure of the present invention includes nanoparticles. The nanoparticles are formed into porous clusters. The porous clusters are formed into aggregate clusters. An embodiment of an article of manufacture of the present invention includes the superhydrophilic nanostructure on a substrate. An embodiment of a method of fabricating a superhydrophilic nanostructure of the present invention includes

applying a solution that includes nanoparticles to a substrate. The substrate is heated to form aggregate clusters of porous clusters of the nanoparticles.

BRIEF DESCRIPTION OF THE DRAWINGS

- [0011] The present invention is described with respect to particular exemplary embodiments thereof and reference is accordingly made to the drawings in which:
- [0012] Fig. 1 illustrates an embodiment of a nanostructure of the present invention yielding superhydrophilicity;
- [0013] Fig. 2 illustrates a superhydrophilic nanostructure on a substrate in accordance with an embodiment of the present invention;
- [0014] Fig. 3 illustrates embodiments of an aggregate cluster, porous clusters, and nanoparticles in accordance of the present invention and also provides an AFM image of example of aggregate clusters of the present invention and a TEM image of example nanoparticles of the present invention;
- [0015] Figs. 4A and 4B provide time sequence photos of liquid spreading on an example treated surface of the present invention and on an untreated surface, respectively;
- [0016] Figs 5A, 5B, and 5C provide graphs of data related to liquid spreading on example treated surfaces of the present invention;
- [0017] Figs. 6A and 6B provide optical transmission and reflectance data and spectroscopic ellipsometry data, respectively, for an example treated surface of the present invention; and
- [0018] Fig. 7 is a photo that shows an anti-fogging character of an example treated surface of the present invention in comparison to an untreated surface.

DETAILED DESCRIPTION OF THE INVENTION

- [0019] Embodiments of the present invention include a superhydrophilic nanostructure, an article of manufacture, and a method of fabricating a superhydrophilic nanostructure.
- [0020] Fig. 1 illustrates a top view of an embodiment of a superhydrophilic nanostructure 100 of the present invention. The superhydrophilic nanostructure 100 includes a plurality of aggregate clusters 102. Each aggregate cluster 102 includes a plurality of porous clusters (not shown). Each porous cluster includes a plurality of nanoparticles (not shown). Shapes of the aggregate cluster when viewed from above

as illustrated in Fig. 1 may be round, oblong, rod-shaped, spindle-shaped, or other suitable shapes. The superhydrophilic nanostructure 100 may include a mixture of such shapes. According to embodiments, dimensions of the aggregate clusters 102 may be within the range of about 150 nm to 5 μm . According to other embodiments, dimensions of the aggregate clusters 102 may be within the range of about 200 nm to 5 μm .

[0021] Fig. 2 illustrates a side view of an embodiment of an article of manufacture 200. The article of manufacture 200 includes the superhydrophilic nanostructure 100 on a substrate 204. The superhydrophilic nanostructure 100 includes the plurality of aggregate clusters 102. According to embodiments, a height of the aggregate clusters 102 may vary within the range of about 150 nm to 5 μm . According to other embodiments, a height of the aggregate clusters 102 may vary within the range of about 200 nm to 5 μm .

[0022] It will be readily apparent to one skilled in the art that the substrate 204 may be a layered substrate in which layers reside on between a base substrate and the superhydrophilic nanostructure 100.

[0023] Fig. 3 illustrates a side view of an embodiment of a single aggregate cluster 102 of the present invention. The aggregate cluster includes a plurality of porous clusters 306. The porous clusters 306 may be spherically shaped, as illustrated in Fig. 3, or may have other shapes including a mixture of shapes. For example, shapes of the porous clusters 306 may be oblong, rod-shaped, spindle-shaped, or other suitable shapes. According to embodiments, dimensions of the porous clusters 306 may be within the range of 20 to 600 nm. According to other embodiments, dimensions of the porous clusters 306 may be within the range of about 50 to 600 nm.

[0024] A single porous cluster 306 is illustrated to the right of the aggregate cluster 102. The porous cluster 306 includes a plurality of nanoparticles 308. A single nanoparticle 308 is illustrated to the above left from the porous cluster 306. While shapes of the nanoparticles 308 are illustrated in Fig. 3 as spherical or quantum dot shaped, the nanoparticles 308 may have other shapes including a mixture of shapes. For example, the nanoparticles 308 may be nanorods, nanospindles, nanosheets, nanowires, nanodisks, branched nanoparticles, or other suitable nanoparticles. According to embodiments, dimensions of the nanoparticles 308 may be within the range of about 1 to 100 nm. According to other embodiments, dimensions of the nanoparticles 308 may be within the range of about 1 to 50 nm.

Typical dimensions for the aggregate cluster 102, the porous clusters 306, and the nanoparticles 308 are indicated in Fig. 3 as 200 nm, 50 nm, and 5 nm, respectively.

[0025] According to an embodiment, the nanoparticles 308 include TiO₂ nanoparticles. Such TiO₂ nanoparticles may include a dopant or dopants such as an H, N, S, C, or B dopant or a combination of such dopants.

[0026] Applications of the superhydrophilic nanostructure 100 of the present invention include use of the superhydrophilic nanostructure 100 as self-cleaning coatings or anti-fogging coatings. Such anti-fogging coatings can be used in any setting where the condensation of water droplets on a surface is undesired, particularly where the surface is transparent. Examples of such settings include sport goggles, auto windshields, windows in public transit vehicles, windows in armored cars for law enforcement and VIP protection, solar panels, green-house enclosures, sun-wind-dust goggles, laser safety eye protective spectacles, chemical/biological protective face masks, ballistic shields for explosive ordnance disposal personnel, and vision blocks for light tactical vehicles. Further, additional applications of the present invention include spectacle lenses, cameras, lenses for various types of optical devices, dental mirrors, and windowpanes.

[0027] More generally, applications of the superhydrophilic nanostructure 100 of the present invention include self-cleaning for pollution control, self-cleaning or anti-fogging windows, self-cleaning or anti-fogging medical applications (e.g., dental mirrors), self-cleaning or anti-fogging flexible plastic film. An example of the latter is a flexible plastic film used for wrapping foods on display in a market. Because such a plastic film precludes formation of water droplets or fog on its surface, customers can see through the plastic film and easily view the product (e.g., a refrigerated or frozen food item).

[0028] An embodiment of a method of fabricating a superhydrophilic nanostructure of the present invention includes providing a solution that includes nanoparticles. The solution is applied to a substrate. The substrate is then heated to form aggregate clusters of porous clusters of the nanoparticles. In an embodiment, applying the solution to substrate includes spin casting the solution onto the substrate. Embodiments of heating of the substrate following application of the solution to the substrate include heating the substrate in an oven or furnace that has a temperature within the range of about 50 to 600 °C for a period of time within the range of about 5 minutes to 12 hours. Other embodiments of heating of the substrate include heating

the substrate in an oven or furnace that has a temperature within the range of 200 to 600 °C for a period of time within the range of about 1 to 12 hours. In yet another embodiment, the substrate is heated in an oven or furnace with a temperature of about 500 °C for about 5 hours. Heating of the substrate may be referred to as a calcination technique since heating of the substrate forms the porous clusters of nanoparticles into the aggregate clusters. That is, the superhydrophilic nanostructure of the present invention is formed in the heating or calcination step.

[0029] An embodiment of the method of fabricating the superhydrophilic nanostructure further includes forming the nanoparticles. In an embodiment, the nanoparticles are formed using an electrochemistry technique. Such a technique includes placing a pair of electrodes in an ionic solution and applying a voltage across the electrodes. This creates an ionic channel in the solution, which oxidizes the metal of the salt to form the porous clusters of the nanoparticles. In embodiments, first and second electrodes may be chosen from the pairs of Pt and Ti, Pt and Fe, Fe and Fe, Fe and Ti, and Ti and Ti electrode pairs. According to embodiments, the ionic salt solution is an aqueous solution that includes NaCl, NaF, KCl, KF, or another suitable salt. In an alternative embodiment, the porous clusters of the nanoparticles are formed using another solution chemistry approach such as a sol-gel approach.

[0030] An alternative embodiment of fabricating the superhydrophilic nanostructure of the present invention employs a physical vapor deposition technique (e.g., a laser ablation technique). Such a technique includes placing a prefabricated TiO₂ solid target material in a chamber, which may be maintained in vacuum or filled with gases, such as O₂, N₂, Ar, with pressure up to the atmospheric pressure. This target material is vaporized by an energetic beam, such as a laser beam, an electron beam, or an ion beam, the vaporized target material is deposited onto a substrate, such as a glass or a plastic sheet, forming a porous network of TiO₂ nanoclusters.

[0031] Since the discovery of extreme surface wetting phenomenon induced by ultraviolet (UV) photocatalysis, TiO₂ has become the material of choice for environmentally friendly applications such as self-cleaning and anti-contamination coatings. Nevertheless, it remains a significant challenge to realize surfaces exhibiting persistent super-hydrophilicity but without the need of external stimuli, especially UV irradiation that also degrades the wetting surface over a period of time. The present invention is a porous TiO₂ nanostructure that shows extreme super-hydrophilicity without the need of light activation, and with stability against

successive wetting-dewetting cycles. Additionally, this ultimate TiO₂ wetting surface exhibits high optical transmittance over a wavelength range from near UV to the infrared, thus enabling practical anti-fogging technologies where transparency is equally critical.

[0032] In view of the importance of surface microstructures on the extreme wetting property as reflected by many biological systems, a hierarchical porous TiO₂ surface was designed and deposited on glass substrates. The hierarchical porous TiO₂ surface possesses a self-similar morphology with roughness at three different length scales - a macroscopic roughness in the range of a few hundred nanometers and greater (i.e. the aggregate clusters 102 of Figs. 1, 2 and 3), a secondary feature with dimensions of tens of nanometers to hundreds of nanometers (i.e. the porous clusters 306 of Fig. 3), and individual TiO₂ nanoparticles with a diameter of a few nanometers (i.e. the nanoparticles 308 of Fig. 3). It has been demonstrated that the intrinsic hydrophilic property of TiO₂ combined with a hierarchical porous structure provided much desired extreme wetting behavior. In Fig. 3, a first inset 310 provides an AFM (atomic force microscopy) image of an example of an aggregate cluster and adjacent aggregate clusters. Spherical shaped objects in this image are porous clusters. In Fig. 3, a second inset 312 provides a TEM (transmission electron microscopy) image of example nanoparticles of a porous cluster.

[0033] The initial spreading stages of a water droplet on a glass coated with the self-similar porous TiO₂ and on an untreated glass surface are shown in Figs. 4A and 4B, respectively. With enhanced spreading, the water droplet penetrates into the recessed areas and spreads within a couple hundred milliseconds on the porous TiO₂ surface. As a consequence, the self-similar porous TiO₂ surface exhibits a vanishing equilibrium contact angle, whereas the contact angle for water droplets on a glass substrate is approximately 34°. Neither UV irradiation nor visible light was applied for the activation of this extreme, super-hydrophilic behavior.

[0034] Figs. 4A and 4B show dynamics of liquid spreading on self-similar porous TiO₂ and untreated surfaces, respectively. Selected images show the spreading of a 0.5 µl water droplet at the early stages after contacting with a self-similar porous TiO₂ surface, Fig. 4A and an uncoated glass substrate, Fig. 4B. The static contact angles for the TiO₂ surface and the untreated surface are 1° and 34° respectively. For the TiO₂ surface, super-hydrophilic behavior (contact angle less than 5°) is established

very fast (i.e. during the first 160 ms following the droplet deposition). Here, time zero ($t = 0$) is defined as the frame just before the drop is released on the surface.

[0035] The spreading of a liquid on a solid surface is generally described by the Tanner power law (see, G. McHale et al., *Physical Review Letters* 93 (2004) 036102), which predicts a decrease in the contact angle (θ) with time (t) from droplet deposition, $\theta \propto (t_0+t)^{-n}$, where t_0 is a constant. Fig. 5A provides contact angle variation as a function of time for porous TiO₂ layers of 200 nm (sample A) and 400 nm (sample B) in thickness, which shows the early stage, time-dependent behavior of the contact angle for water deposited on self-similar porous TiO₂ surfaces. The solid lines in Fig. 5A (and Figs. 5B and 5C) are fittings of the measured data to the power law. The power coefficient, n , increases with the thickness of the self-similar porous TiO₂, suggesting that an increase in the thickness of the porous TiO₂ layer leads to more efficient liquid spreading. Fig. 5B provides a graph of spreading of a water droplet on a self-similar porous TiO₂ surface in the x and y directions (parallel and vertical to the surface). There is a preferential spreading across the surface with an average velocity of ~ 0.3 cm/s, followed by sinking of the water droplet into the porous layer.

[0036] The stability of the self-similar porous TiO₂ surface was tested by studying their response against successive wetting–dewetting cycles. The change in the contact angle with time for an increasing number of wetting–dewetting cycles is shown in Fig. 5C. The power law dependence remains essentially unaltered for more than 20 successive wetting cycles. Adsorption of hydrocarbons from the ambient on the TiO₂ surface has often been reported to cause increase of the contact angle. The negligible variation in the time-dependent behavior of the vanishing contact angle suggests that the self-similar porous TiO₂ surface is resistance against surface contamination.

[0037] The observed extreme wetting phenomenon can be interpreted under the framework of Wenzel model (see, R.N. Wenzel, *Industrial and Engineering Chemistry* 28 (1936) 988), according to which surface roughness acts to enhance the wettability of an initially hydrophilic flat surface. In a homogeneous wetting regime where the liquid completely penetrates in the entire surface, the apparent contact angle, θ , is given by, $\cos\theta = r \cos\theta_0$, where r is the ratio of the unfolded surface to the apparent area of contact under the droplet, and θ_0 is the contact angle on a flat surface of the same nature (Young's contact angle). Since r is always greater than unity, the

contact angle will decrease for an otherwise hydrophilic ($\theta_0 < 90^\circ$) surface. For self-similar layers such as a self-similar porous TiO₂ surface where $\theta_0 = 50-70^\circ$ for flat TiO₂ (see, R. Wang et al., *Nature* 388 (1997) 431; and N. Stevens et al., *Langmuir* 19 (2003) 3272), the increase of the overall roughness due to the multiple length scales leads to ever increasing r , thus facilitating a completely wetted surface ($\theta \sim 0^\circ$).

[0038] In addition to the extreme wetting behavior that is favorable for self-cleaning and anti-contamination technologies, the self-similar porous TiO₂ surface exhibits optical transparency that makes them ideal for anti-fogging applications. Fig. 6A compares the transmittance and reflectance spectra of a glass substrate coated with a self-similar porous TiO₂ surface, to the spectra of an untreated glass substrate. The optical transparency remains essentially unaffected by coating a self-similar porous TiO₂ surface. A transmittance over 90% and reflectance between 6 and 8% are obtained in the 300-2500 nm wavelength range for the porous TiO₂ coated glass.

[0039] Spectroscopic ellipsometry measurements of a self-similar porous TiO₂ coated glass were carried out at an angle of incidence of 70° in the wavelength range of 375-830 nm. The measured Δ (Delta) and Ψ (Psi) data were fitted using the Bruggeman effective-medium theory, EMT (see, M. Mosaddeq-ur-Rahman et al., *Journal of Applied Physics* 88 (2000) 4634), as shown in Fig. 6B. The effective dielectric function was calculated by taking into account the existence a porous TiO₂ layer on a glass substrate, and the porosity was estimated to be $\sim 70\%$. The EMT model extracts the refractive index of the self-similar porous TiO₂ layer as a function of wavelength, shown in the inset of Fig. 6B, where the refractive index has a value 1.40 ± 0.04 in the visible wavelength range, which is significantly lower than that (~ 2.7) of bulk TiO₂.

[0040] To demonstrate the anti-fogging potential enabled by optical transparency combined with the super-hydrophilic nature of the self-similar porous TiO₂, an untreated glass slide and a self-similar porous TiO₂ coated slide were placed in a freezer at a temperature of approximately -15°C , followed by exposure to the humid air. Fig. 7 shows the anti-fogging property of a glass slide (left) next to the TiO₂ coated slide (right). In the latter case, the letter sequence "LBNL" can be clearly resolved as the result of efficient spreading of water droplets to form a uniform film. On the other hand, since the untreated glass surface has poor wettability, moisture condenses on its surface as discrete droplets, causing light scattering and obscuring of

the letter sequence under the untreated glass surface. It is also noted that the coated surfaces exhibit the ability to prevent dewetting; a coated glass surface remains fully wet after immersion in water, and this state is maintained until water evaporates.

[0041] Experimental:

[0042] Anatase TiO₂ nanoparticles were synthesized by a sol-gel process. The sol-gel process included forming an aqueous solution that included a Ti precursor and an acid or base. In some examples, the solution also included an alcohol. In some examples, the solution also included a surfactant. In most examples, the resulting solution was stirred for a period of time. The solution was then heated or calcinated to obtain the anatase TiO₂ nanoparticles. In a first example, the aqueous solution included titanium propoxide, ethanol, HCl, and F 127 surfactant. Molar concentrations were 1:40:0.5:0.005, but can be 1:(10-500):(0.001-10):(0.00001-10). The solution was stirred for 24 hours and then calcinated in a furnace at 500 °C for 5 hours. In a second example, the aqueous solution included titanium chloride, methanol, NaOH, and Triton X 100 surfactant. Molar concentrations were 1:40:0.2:0.02, but can be 1:(10-500):(0.01-10):(0.0001-10). The solution was stirred for 1 hour and then calcinated in a furnace at 300 °C for 2 hours. In a third example, the aqueous solution included titanium butoxide and HF and H₂O. Molar concentrations were 1:10:10, but can be 1:(0.01-10):(1-100). The solution was heated to 180 °C for 24 hours. In a fourth example, the aqueous solution included titanium dioxide fine powder (P25), HCl, and NaCl. Molar concentrations were 1:0.1:0.05, but can be 1:(0.0001-10):(0.0005-1). The solution was stirred for 24 hours and then calcinated in a furnace at 500 °C for 24 hours. Alternatives for the Ti precursor include titanium alkoxide and other suitable Ti precursors. Alternatives for the alcohol include propanol and other suitable alcohols. Alternatives for the acid include nitric acid and other suitable acids. Alternatives for the base include KOH and other suitable bases. Alternatives for the surfactant include P 125 and other suitable surfactants.

[0043] Sol-gel synthesized anatase TiO₂ nanoparticles dispersed in water were spin-coated on plain soda lime glass slides (Gold Seal) to form porous TiO₂ nanoparticle coatings. The resulting films were subsequently calcinated at 500 °C for 5 hours. Surface topographical images of the samples were obtained using a Hitachi (S-4300SE/N) Field Emission SEM, a Veeco Nanoscope III Atomic Force Microscope (AFM) in tapping mode, and a Philips CM200/FEG TEM. X-Ray

Diffraction (Siemens D-500 diffractometer) was applied to define the composition and crystallinity of the samples. Statistical analysis of the surface features was performed by using the WSXM software.

[0044] The spreading behavior of water droplets in contact with the resulting structures was studied through dynamic contact angle measurements. Water droplets (resistivity of 18.1 M Ω , surface tension of 72.8 mN/m at 20 °C) were gently deposited on the TiO₂ surfaces with the use of a microliter pipette, and a CCD camera lens array system was used in order to record video images of the droplet profiles at a 60 Hz frame rate. The water droplets had a volume of 0.5-3.0 μ l (diameter of 0.49-0.89 mm) and contact angle measurements were performed at an environment with relative humidity of 80%. For antifogging experiments, both un-coated and TiO₂ coated glass slides were placed in a freezer at a temperature of -15 °C for 1 hour and subsequently exposed to the humid laboratory air.

[0045] The transmittance and reflectance of the coated samples were measured using a UV-Vis spectrophotometer (Perkin-Elmer, Lambda 900) equipped with an integrating sphere. A FilmTek 3000 spectroscopic ellipsometer was used for determining the refractive index of the fabricated TiO₂ films.

[0046] Conclusion:

[0047] Inspired by the hierarchical microstructures existing in a number of biological systems, we self-similar porous TiO₂ surfaces that exhibit stable super-hydrophilic wetting behavior without the need of UV light activation were fabricated. In fact, no light was applied in this study, which suggests that there is no need of conventional photocatalytic reactions, nor the requirement of an enhancing agent, to induce super-hydrophilicity in TiO₂. The self-similar porous TiO₂ surface achieved here also shows favorable optical response with high visible transparency, which, in combination with super-hydrophilicity, makes affordable self-cleaning windows and anti-fogging coatings closer to reality.

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[0049] It is noted that as used herein and in the appended claims, the singular forms "a", "and", and "the" include plural referents unless the context clearly dictates otherwise.

[0050] The foregoing detailed description of the present invention is provided for the purposes of illustration and is not intended to be exhaustive or to limit the invention to the embodiments disclosed. Accordingly, the scope of the present invention is defined by the appended claims.

What is claimed is:

1. A superhydrophilic nanostructure comprising:
nanoparticles;
the nanoparticles formed into porous clusters; and
the porous clusters formed into aggregate clusters.
2. An article of manufacture comprising:
a substrate; and
a superhydrophilic nanostructure on at least a portion of a surface of the
substrate, the superhydrophilic nanostructure comprising;
nanoparticles;
the nanoparticles formed into porous clusters; and
the porous clusters formed into aggregate clusters.
3. The article of manufacture of claim 2 wherein the nanoparticles comprise titanium
dioxide.
4. The article of manufacture of claim 3 wherein the nanoparticles further comprise
a dopant.
5. The article of manufacture of claim 4 wherein the dopant is selected from the
group consisting of H, N, S, C, B, and a combination thereof.
6. The article of manufacture of claim 2 wherein the nanoparticles have dimensions
within the range of about 1 to 100 nm.
7. The article of manufacture of claim 6 wherein the nanoparticles have dimensions
within the range of about 1 to 50 nm.
8. The article of manufacture of claim 2 wherein the porous clusters have

dimensions within the range of about 20 to 600 nm.

9. The article of manufacture of claim 8 wherein the porous clusters have dimensions within the range of about 50 to 600 nm.
10. The article of manufacture of claim 2 wherein the aggregate clusters have dimensions within the range of about 150 nm to 5 μm .
11. The article of manufacture of claim 2 wherein the aggregate clusters have dimensions within the range of about 200 nm to 5 μm .
12. A method of fabricating a superhydrophilic nanostructure comprising:
applying a solution that includes nanoparticles to a substrate; and
heating the substrate to form aggregate clusters, each of the aggregate clusters comprising porous clusters of the nanoparticles.
13. The method of claim 12 further comprising forming the nanoparticles.
14. The method of claim 13 wherein forming the nanoparticles comprises forming the nanoparticles using an electrochemistry technique.
15. The method of claim 13 wherein forming the nanoparticles comprises forming the nanoparticles using a sol-gel technique.
16. The method of claim 12 wherein applying the solution to the substrate comprises spin casting the solution onto the substrate.

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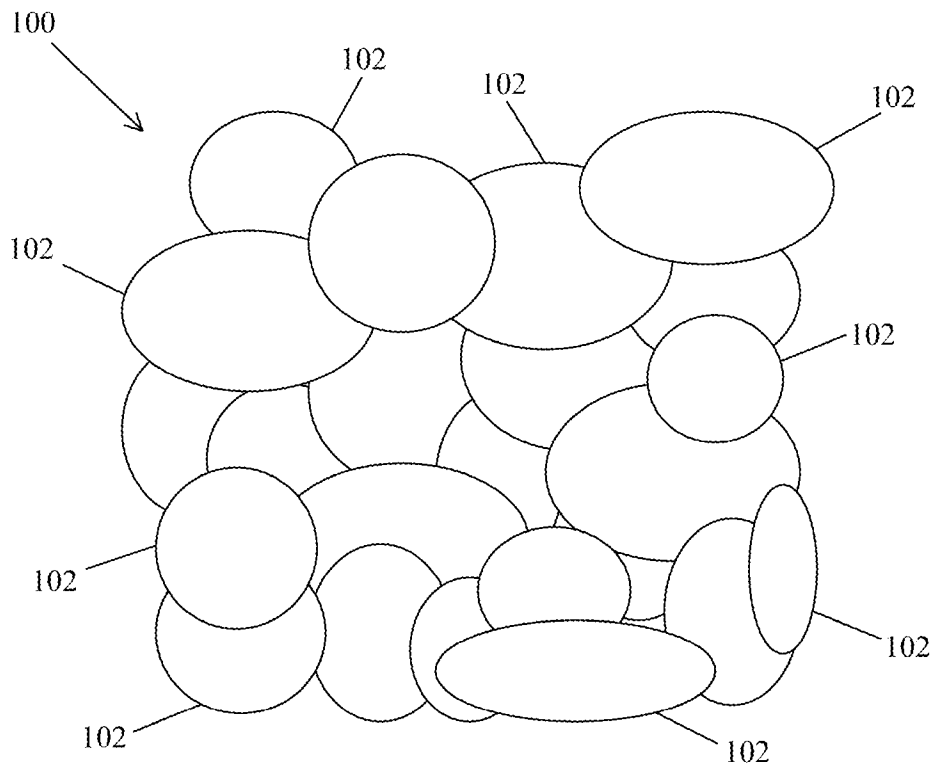


Fig. 1

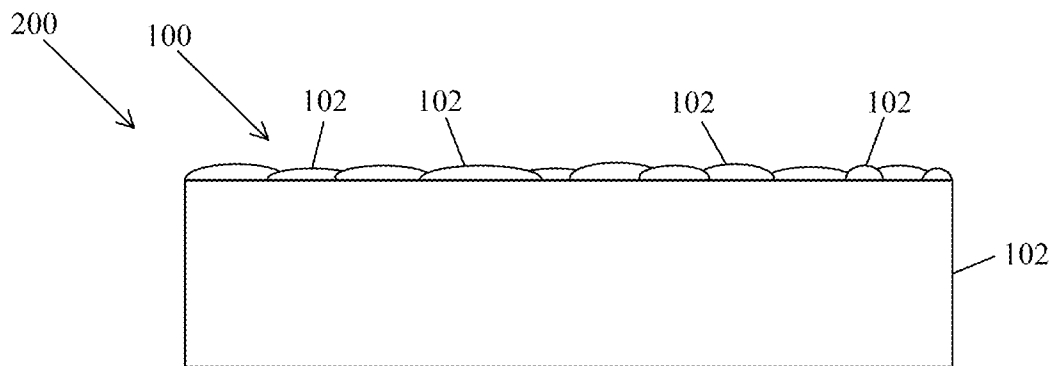


Fig. 2

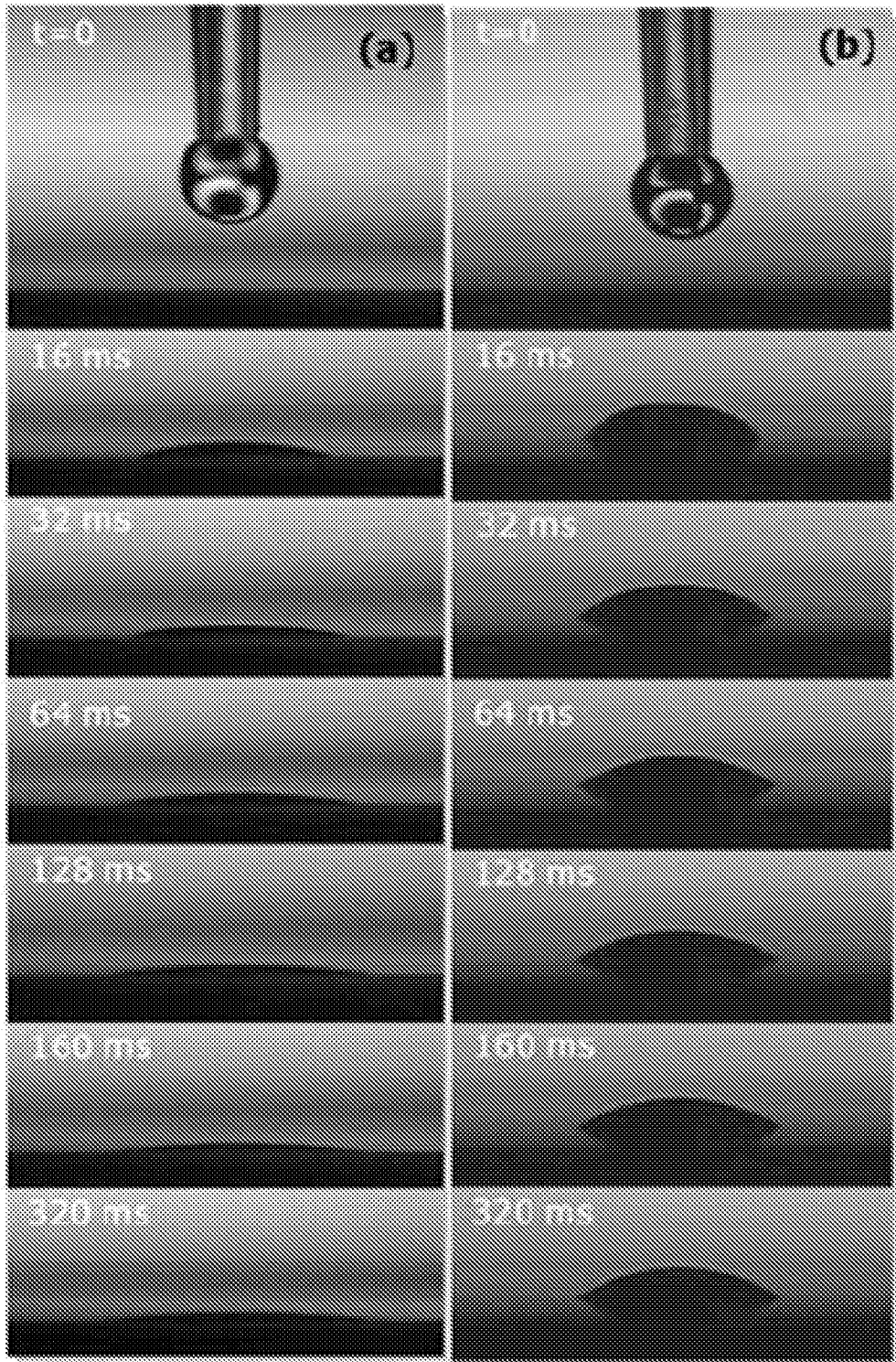


Fig. 4A

Fig. 4B

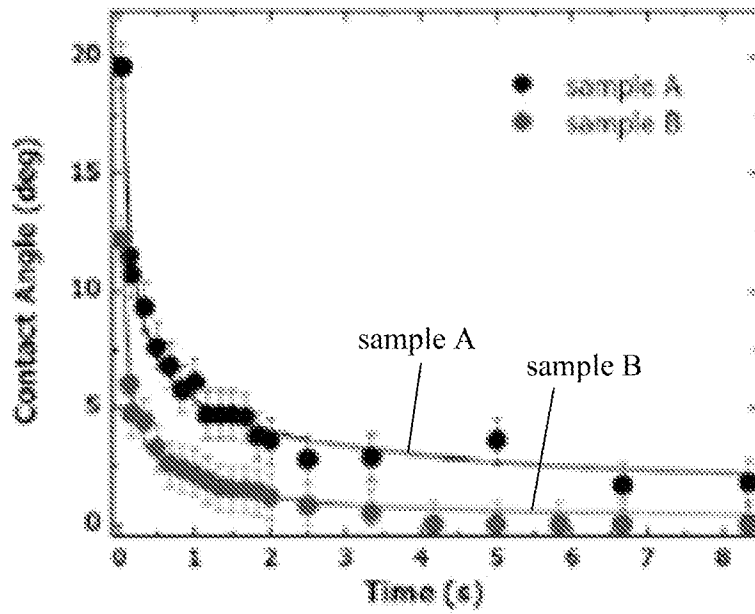


Fig. 5A

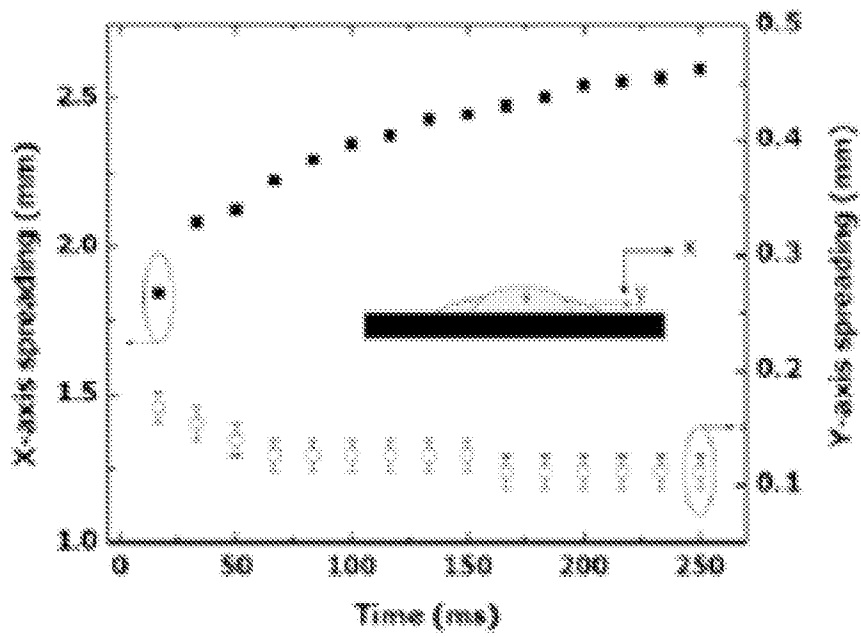


Fig. 5B

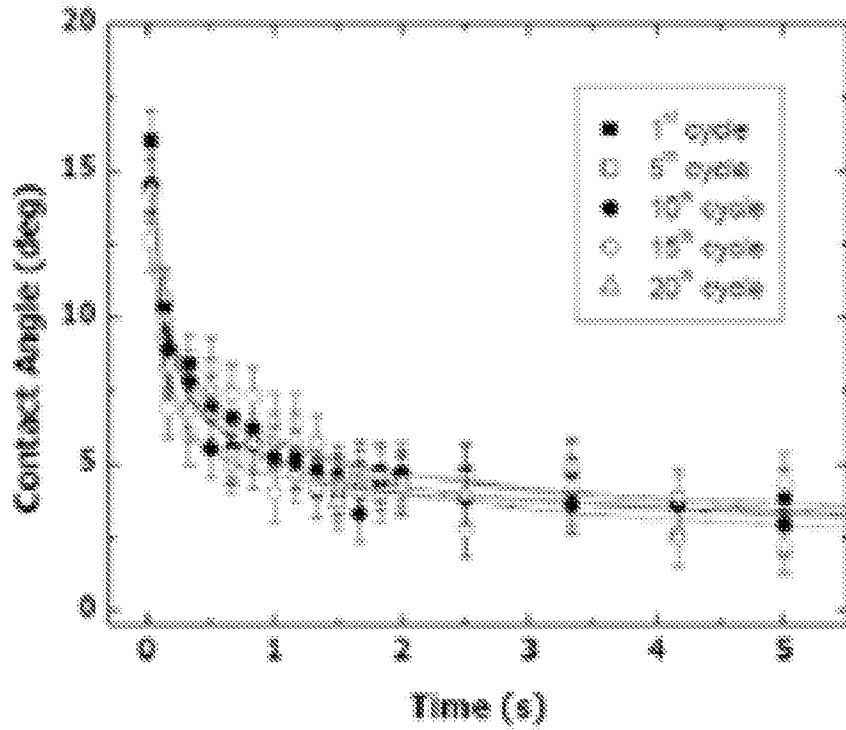


Fig. 5C

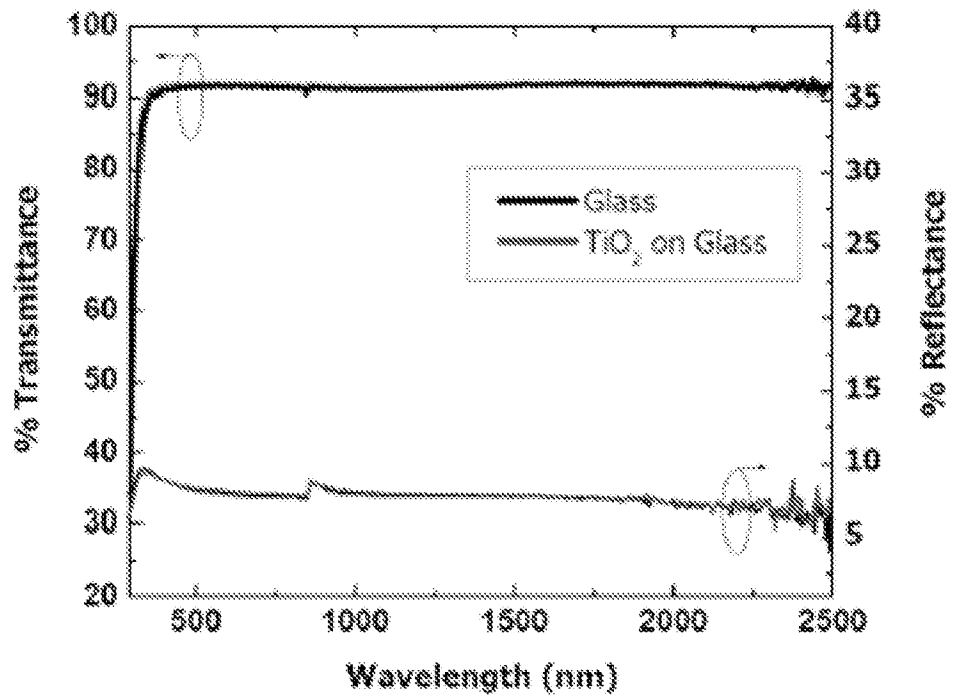


Fig. 6A

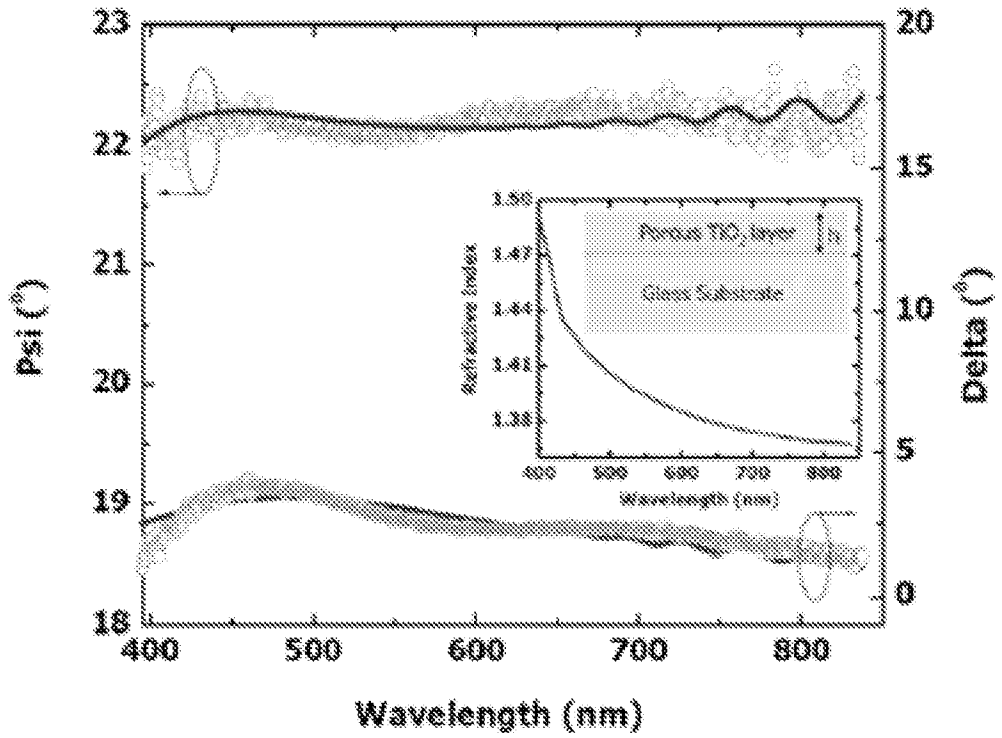
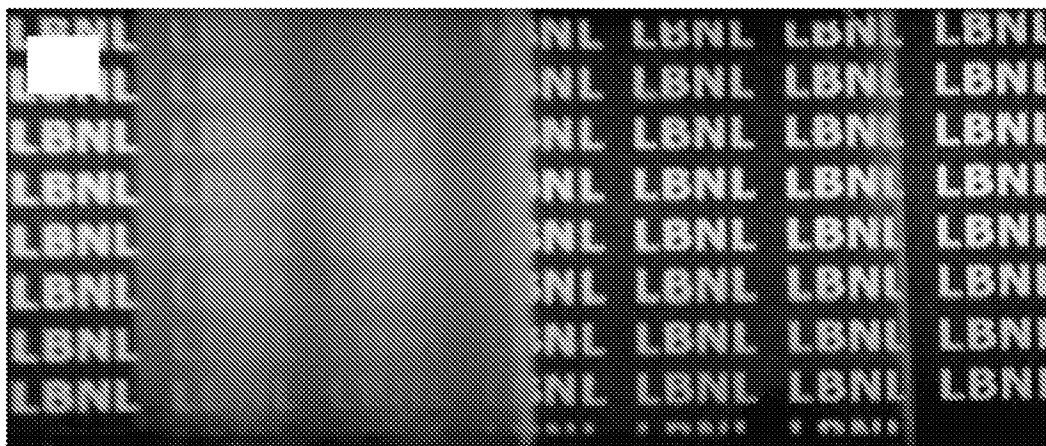


Fig. 6B



Glass TiO₂ on glass

Fig. 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 10/33927

A. CLASSIFICATION OF SUBJECT MATTER
 IPC(8) - B82B 1/00; B82B 3/00; B05D 3/00 (2010.01)
 USPC - 977/700; 427/2.1
 According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC- B82B 1/00; B82B 3/00; B05D 3/00 (2010.01)
 USPC- 977/700; 427/2.1

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

IPC- B82B 1/00; B82B 3/00; B05D 3/00 (2010.01)
 USPC- 977/700; 427/2.1 (keyword delimited) Patents and NPL

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

PubWest (US Pat, PgPub, EPO, JPO: classification, keyword), GoogleScholar;
 search terms used: high, super, ultra, ultimate, hydrophilic, nanoparticle, particulate, cluster, aggregate, agglomerate, grouped, pore, porous, porosity

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	SONG et al., "Preparation of Transparent Particulate MoO ₃ /TiO ₂ and WO ₃ /TiO ₂ Films and Their Photocatalytic Properties." Chemistry of Materials; Vol. 13, pp 2349-2355, 23 June 2001 (23.06.2001), entire document especially pp 2351-2353	1-16
Y	US 2008/0248263 A1 (KOBIRIN) 09 October 2008 (09.10.2008), para [0010], [0019], [0020]	1-16
Y	AEGERTER et al., "Coatings made by sol-gel and chemical nanotechnology." Journal of Sol-Gel Science and Technology, Vol. 47, pp. 203-23605; June 2008 (05.06.2008), entire document especially pages 231-232	4, 5
A	HEGDE et al., "Two step sol-gel processing of TEOS based hydrophobic silica aerogels using trimethylethoxysilane as a co-precursor." Journal of Porous Materials, Vol. 14, pp. 165-171; 26 January 2007 (26.01.2007), entire document	1-16
A	US 2006/0068447 A1 (BANERJEE et al.) 30 March 2006 (30.03.2006), entire document	1-16

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* Special categories of cited documents:

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

09 June 2010 (09.06.2010)

Date of mailing of the international search report

09 JUL 2010

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