Reversible switching between superhydrophobic states on a hierarchically structured surface

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Nature offers exciting examples for functional wetting properties based on superhydrophobicity, such as the self-cleaning surfaces on plant leaves and trapped air on immersed insect surfaces allowing underwater breathing. They inspire biomimetic approaches in science and technology. Superhydrophobicity relies on the Cassie wetting state where air is trapped within the surface topography. Pressure can trigger an irreversible transition from the Cassie state to the Wenzel state with no trapped air—this transition is usually detrimental for nonwetting functionality and is to be avoided. Here we present a new type of reversible, localized and instantaneous transition between two Cassie wetting states, enabled by two-level (dual-scale) topography of a superhydrophobic surface, that allows writing, erasing, rewriting and storing of optically displayed information in plastrons related to different length scales.

Results

Superhydrophobic surfaces with two-level topography were constructed from silicon wafers patterned with a square array (pitch 20 μm) of cylindrical microposts (diameter 10 μm, height 5 or 10 μm) that are further coated with silicone nanofilaments (24–26). The nanofilaments are themselves superhydrophobic (advancing and receding contact angles of planar coating 170°/145°±5°), which is necessary for a stable nano-Cassie state. Submerging the hierarchical surface in water leads to the formation of a plastron in the micro-Cassie state. A local switching to the nano-Cassie state can be induced by “writing” with a jet of water (see Fig. 1B). The dynamic pressure of the jet gives rise to Laplace pressure (pressure difference between water and plastron) that pushes the water between the microposts, causing a localized and immediate transition. Calculations predict a transition Laplace pressure of 6.9 kPa (see SI Text). Yet, even a large pressure will not cause a transition to the Wenzel state due to the high stability of the plastron within the nanofilaments. An optical micrograph of a nano-Cassie/micro-Cassie boundary is shown in Fig. 24.

Unlike the Wenzel to Cassie transition, the nano-Cassie to micro-Cassie transition involves only a low kinetic barrier due to the small amount of wetted solid in the nano-Cassie state. In fact, the micro-Cassie state is energetically more stable than the nano-Cassie state (see SI Text). We were able to restore the wetting states on a hierarchical superhydrophobic surface immersed in water. The states arise from the two topographical levels on the surface: a pattern of silicon microposts and a superhydrophobic nanofilament coating grown on the microtopography (Fig. 1B). In one wetting state the plastron occupies the space between the microposts—we call this state the micro-Cassie state as the plastron has micron-scale dimensions. In the other state the space between the posts is mostly filled with water but air still remains in the nanofilament layer, which is only hundreds of nanometers thick. Because of this thin plastron, the state is also of the Cassie type because the water-solid contact area fraction is small. This state is called the nano-Cassie state, accordingly. We will show that the wetting states can be locally and reversibly switched by using a nozzle to cause pressure-driven transitions (Fig. 1B).


Conflict of interest statement: T.V., C.B., P.A., and R.H.A.R. have filed a patent on the technology discussed in this paper.

This article is a PNAS Direct Submission. Freely available online through the PNAS open access option.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1204328109/-/DCSupplemental.
micro-Cassie state by a reverse writing process: local negative Laplace pressure was built between water and the plastron by sucking water with the needle close to the surface, causing the plastron to fill the space between the posts once again (see Fig. 1B). According to our calculations (SI Text) the nano-Cassie state becomes unstable at a Laplace pressure between $-5.0$ kPa and $-1.3$ kPa. The local transitions do not alter the pressure of the plastron because a gas reservoir (like an air bubble on the surface shown in Fig. 3A) will store and release air as needed.

For comparison with the hierarchical topography, we also fabricated a superhydrophobic surface with single-level topography (see Fig. 1A) by coating a micropatterned silicon surface with a hydrophobic fluoroalkylsilane monolayer (advancing and receding contact angles of coating on flat surface $118^\circ/102^\circ \pm 3^\circ$) instead of nanofilaments. The plastron on an immersed single-level surface is in the Cassie state, and the water jet writing technique shown in Fig. 1A can be used to cause a local Cassie-Wenzel transition, which is irreversible.

To study in detail the shape of the water-air interface in the micro-Cassie and nano-Cassie states we introduced a new laser scanning confocal imaging technique that makes use of fluorescent polymer nanoparticles dispersed in the water. Two confocal scanning modes are combined: reflection of 633-nm-wavelength laser light and fluorescence from the nanoparticles that are excited with a 543-nm-wavelength laser light. The reflection signal provides information on topography while the fluorescent nanoparticles help to differentiate water from air. Fig. 2B shows a series of micrographs of the boundary between nano-Cassie and micro-Cassie regions, focused 15, 10, 5 and 0 μm above the substrate. The fluorescence image shows that, while the space between the posts in the micro-Cassie region is filled with air, in the nano-Cassie region water occupies most of the space except the filament layer, as depicted in the schematic picture in Fig. 2B.

The interference fringes in the reflectance images—caused by interference between reflections from the water-air interface and the air-silicon interface at the bottom—reveal the shape of the water-air interface. The vertical distance between two intensity maxima corresponds to a half of the wavelength of the laser light, 317 nm. The interface starts to curve downwards about 30 μm from the boundary between the micro-Cassie and nano-Cassie states with the slope increasing close to the boundary.

Although water fills most of the space between the posts in the nano-Cassie state, the “coronae” surrounding the posts in the microscope images in Fig. 2 suggest that micrometer-sized pockets of air still remain around the bases of the posts (see also Figs. S1 and S2). Indeed, theoretical considerations (see SI Text) show that small air pockets are expected to remain in the corners between the posts and the bottom if the advancing contact angle of the nanopattern is greater than 135°. Negative Laplace pressure is shown (SI Text) to destabilize the air pockets, ultimately inducing transition to micro-Cassie state.

Fig. 3A shows a sample with two-level topography and another with single-level topography in water. The sample with two-level topography is mostly in the micro-Cassie state but has regions, made in the shape of letters (“2 TIER”), which are in the nano-Cassie state. These regions appear remarkably bright due to intense light scattering. In fact, nano-Cassie regions exhibit an order of magnitude stronger scattering intensity than micro-

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**Fig. 1.** Wetting states and transitions between them on surfaces with different topographies. (A) With single-level topography, positive Laplace pressure causes a transition from the Cassie to the Wenzel state. The transition involves wetting of the whole solid surface and is irreversible in most cases. (B) Hierarchical topography. Nanofilaments suppress the transition to the Wenzel state and positive Laplace pressure will cause a transition to the nano-Cassie state instead, where wetted solid area remains small due to the plastron in the nanofilament layer. This transition can be reversed by negative Laplace pressure. Constant pressure in the plastron is maintained by a gas reservoir such as a macroscopic bubble on the edge of the surface. Scale bar in the scanning electron micrographs is 10 μm (in the inset, 500 nm). The post height in the micrographs is 5 μm.
Cassie regions, leading to substantial optical contrast (see Fig. S3). The scattering is caused by the curved interface between water and the air pockets around the bases of the posts that cause reflections to a wide range of angles (see Fig. S2). Unlike nano-Cassie regions, Wenzel regions on single-level topography (letters “1 TIER” in Fig. 3A) do not scatter much due to the absence of a water-air interface.

The difference in terms of wettability between the nano-Cassie and the Wenzel state is demonstrated in Fig. 3B, which shows the samples from Fig. 3A after water has been drained out. A thin film of water stays on the Wenzel regions on the single-level surfaces and assembles into droplets, while the two-level surfaces emerge completely dry: this is because the nano-Cassie state is nonwetting whereas Wenzel is wetting.

Fig. 3C confirms that although the nanofilament layer is just hundreds of nanometers thick and thus the nano-Cassie plastron is very thin, air can still flow through it to form a micro-Cassie region inside a larger nano-Cassie region.

**Discussion**

We wish to emphasize that the two wetting states can be thought of as bistable logic states to store binary data. For example, the surface could be divided into an array of dots that represent bits. Also, the optical contrast between the states suggests that such an array of bits could be used for a bistable reflective display. To demonstrate repeated write/erase cycles, we present in Fig. 3D a series of photographs of a group of five nano-Cassie dots. The dot in the center is repeatedly erased and rewritten. Furthermore, to verify stability and reversibility even after prolonged storage, a pattern was written on a surface and inspected after 30 days. The pattern was found to be unchanged and still erasable.

Apart from data storage or display applications, we also envision uses in microfluidics. While the micro-Cassie state is expected to have a large slip length (5), the nano-Cassie state most likely involves little slip regardless of the plastron, as water between the microposts is unlikely to flow well. The
micro-Cassie/nano-Cassie transition could enable dynamical creation of configurable flow barriers or fast-flowing channels.

To summarize, we demonstrated reversible bistable switching between two Cassie-type wetting states on a hierarchical superhydrophobic surface and used a novel confocal microscopy technique based on dye-labeled nanoparticles for imaging the plasmon. A localized writing/erasing procedure was used for instant switching of wetting state, enabling storage of binary data, and a substantial scattering intensity contrast between the states allows optical reading of information. We believe the result opens a new perspective to wetting-functionalized surfaces as reversibly configurable information-carrying media.

Materials and Methods

Silicon Micropatterning. Microposts were fabricated on (100) silicon wafers. A UV-lithography step defined the patterns of the microposts to a 500 nm thick layer of AZ1505 photoresist (Clariant). Subsequently, cryogenic deep reactive ion etching (Oxford Instruments, Plasmalab 100) was used to etch the microposts in silicon. (temperature ~120 °C, inductively coupled plasma power 1 000 W, capacitively coupled plasma power 3 W, pressure 10 mTorr, SF6 flow 40 scm, O2 flow 6 scm). The etch rate was measured to be 2.0–2.5 μm/min. After etching, the remaining photoresist was removed in acetone.

Deposition of Nanofilament and Fluoroalkylsilane Coatings. For nanofilament deposition, patterned silicon samples were kept in oxygen plasma (plasma power 65 W, pressure 70 mTorr, O2 flow 60 sccm) and then exposed to SF6/O2 mixture (plasma power 65 W, pressure 70 mTorr, SF6 flow 5 sccm). Fluoroalkylsilane coatings were made in a similar manner by placing to a glass reaction vessel (volume ca. 1 L) which was flushed with humidified argon (relative humidity 30%). After flushing, the gas inlet and outlet were closed and ca. 100 μl of methyltrichlorosilane (Sigma-Aldrich, 99%) was injected with a syringe through a silicone septum into a Teflon cup inside the vessel. After at least 14 hours the samples were taken out and rinsed with deionized water. Fluoroalkylsilane coatings were made in a similar manner except the vessel was flushed with dry argon and CF3(CF2)i(CH2)nSiCl2 precusor (ABCR, 97%) was used (injected amount was ca. 30 μl).

ACKNOWLEDGMENTS. The authors are grateful for financial support by Nokia Research Center, Academy of Finland (projects 253949 and 256206), the Finnish Funding Agency for Technology and Innovation, and the Medical Research Council (Career Development Award to K.F.). This work made use of the Aalto University Nanomicroscopy Center premises.

Supporting Information

Verho et al. 10.1073/pnas.1204328109

SI Text

Energetics of the Micro-Cassie to Nano-Cassie Transition. Calculating the free energy difference of the micro-Cassie and nano-Cassie states is no different from calculating the Cassie-Wenzel transition energy for a single level topography, except that the equilibrium (Cassie-Baxter) contact angle of the nanofilaments has to be taken as the Young’s contact angle of the microposts. The free energy change during the transition is

\[ \Delta G = (\gamma_d - \gamma_s) \Delta A_d + \gamma \Delta A_l. \]  

[S1]

where \( \Delta A_d \) is the increase of solid-liquid contact area and \( \Delta A_l \) is the change of liquid-air interfacial area. \( \gamma, \gamma_d, \) and \( \gamma_s \) are the liquid-air, solid-air and liquid-solid interfacial tensions, respectively. Using \( A_b \) as the area of the bottom in a unit cell and \( 2\pi r_p h \) as the area of the post sidewalls, we arrive at, using the Young’s equation \( \cos \theta_{y} = (\gamma - \gamma_d) / \gamma 
\]

\[ \Delta G = \gamma (- \cos \theta_{y} (A_b + 2\pi r_p h) - A_b). \]  

[S2]

The micro-Cassie state is energetically favorable if \( \Delta G > 0 \). This is the case if

\[ \cos \theta_{y} < - \frac{A_b}{A_b + 2\pi r_p h}. \]  

[S3]

For the micropattern discussed in this study, with a post height of 5 \( \mu \)m, the inequality is satisfied with \( \theta_{y} \) larger than 132°. The equilibrium contact angle of the nanofilament coating is clearly larger than this, which implies that the micro-Cassie is the lower energy state.

Micro-Cassie to Nano-Cassie Transition. By a force balance consideration, we can calculate the critical Laplace pressure \( \Delta p_c \) for the micro-Cassie to nano-Cassie transition. The transition occurs when the meniscus depins from the edges of the posts and moves toward the bottom (see Fig. S1A). We proceed under the assumption that the shape of the meniscus around each post is approximately identical across the area under the water jet, which is reasonable because the diameter of the water jet is much larger than the size scale of the micropattern. The downward force per unit cell exerted on the meniscus by the Laplace pressure is

\[ F_{lp} = A_b \Delta p. \]  

[S4]

where \( \Delta p \) is the Laplace pressure. The balancing upward force caused by surface tension at the edges of the posts has the value

\[ F_{\gamma} = -2\pi r_p \gamma \cos \theta, \]  

[S5]

where \( \theta \) is the contact angle that the meniscus makes with the sidewall of the post. In equilibrium \( F_{\gamma} = F_{lp} \). The forces are largest when \( \theta \) equals the advancing contact angle of the sidewalls \( \theta_{A} \) (the advancing contact angle of the nanofilament coating). The Laplace pressure is then

\[ \Delta p_{c} = - \frac{2\pi r_p}{A_b} \gamma \cos \theta_{A}. \]  

[S6]

The advancing contact angle of the nanofilament coating is roughly 170°, which gives \( \Delta p_{c} = 6.9 \) kPa. For comparison, for single level topography with a fluorinated coating with an advancing angle of 120° one gets \( \Delta p_{c} = 3.5 \) kPa.

Axisymmetric Meniscus Shape. Consider the microscopic meniscus on the sidewall of a micropost shown in Fig. S1B. Assuming cylindrical symmetry, we write the vertical force balance for the part of the meniscus indicated in the figure. The surface tension on the contact line acts to pull the meniscus upwards, while the Laplace pressure \( \Delta p \) and the surface tension at \( r \) tend to push the meniscus toward the bottom. The force balance reads

\[ \pi (r^2 - r_p^2) \Delta p + 2 \pi r_p \gamma \cos \theta + 2 \pi r \gamma \sin \alpha = 0, \]  

[S7]

where \( r_p \) is the post radius and \( \gamma \) is the surface tension. The sine of \( \alpha \) can be expressed in terms of the derivative \( dz/dr \) as

\[ \sin \alpha = \left( 1 + \frac{1}{(dz/dr)^2} \right)^{-\frac{1}{2}}. \]  

[S8]

Inserting [S8] into [S7] yields

\[ \frac{dz}{dr} = \left[ \left( \frac{r}{r_p \cos \theta + \frac{\gamma}{\pi} (r^2 - r_p^2)} \right)^{\frac{1}{2}} - 1 \right]^{-1}. \]  

[S9]

This result will be used below. In addition, we remark that this equation can also be used to calculate approximate shapes of the meniscus close to the micro-Cassie to nano-Cassie transition, although in reality the shape will not be perfectly axisymmetric.

Air Pockets at the Bases of the Posts. During a Cassie-Wenzel transition, the water immediately wets the bottom of the micropattern once it makes contact with it. However, in the case of two level topography (micro-Cassie/nano-Cassie transition) the bottom and the sidewalls are coated with superhydrophobic nanofilaments which have a very high advancing contact angle. In this case, there remain ring-shaped air pockets around the bases of the posts (a micrograph is shown in Fig. S2).

Fig. S1C depicts the situation. After the transition to nano-Cassie state, while the pressure is still on, the contact angle at the post sidewall and at the bottom equals \( \theta_{A} \). Applying Eq. S7 with \( \alpha = \theta_{A} \) and \( \theta = \theta_{A} \) we get

\[ r = \frac{\gamma}{\Delta p} \left[ -\sin \theta_{A} + \sqrt{\sin^2 \theta_{A} - \frac{r_p \Delta p}{\gamma} \left( 2 \cos \theta_{A} - \frac{r_p \Delta p}{\gamma} \right)} \right]. \]  

[S10]

which gives the width of the air pocket as \( r - r_p \). For \( \Delta p = 7 \) kPa, i.e., just enough to cause a transition to nano-Cassie state, the width of the air pockets would be 4.6 \( \mu \)m (with \( r_p = 5 \) \( \mu \)m and \( \theta_A = 170° \)). We can thus see that a larger pressure is needed to wet most of the bottom (Fig. S1D shows the shape of the air pocket with \( \Delta p = 10 \) kPa). The pocket width always has a finite value with any \( \Delta p \), so at least in theory there always remains an air pocket. On the other hand, we can see from Eq. S7 that with \( \Delta p \geq 0 \) one must have \( \cos \theta < -\sin \theta \) (i.e., \( \theta_A < 135° \)) for an air pocket to exist. Therefore air pockets will not be found on single level topographies.

When Laplace pressure is removed, the air pocket assumes a zero curvature shape (see Fig. S1D for an example). The receding contact angle \( \theta_{R} \) of the nanocoating dictates the minimum width
the pocket must have in the final state. Using [S7] with \( \Delta p = 0 \), we find

\[
 r_{\text{min}} = -\frac{\cos \theta_R}{\sin \theta_R} r_p. \tag{S11}
\]

If \( r_{\text{min}} \) is large enough, the air pockets of adjacent posts coalesce and the nano-Cassie state becomes unstable. This will happen if

\[
\cos \theta_R \leq -\left( \frac{r_p^2}{(L/2)^2 + 1} \right)^{\frac{1}{2}}, \tag{S12}
\]

where \( L \) is the pitch of the micropattern. For the geometry used in this study we find that the air pockets coalesce for receding angles more than 153.4°. In other words, too hydrophobic a nanopattern leads to an unstable nano-Cassie state.

**Negative Laplace Pressure and Reverse Transition.** When a negative Laplace pressure is produced by suction, the air pockets at the bases of the posts begin to expand, governed by the magnitude of \( \Delta p \) and \( \theta_R \). An example shape is shown in Fig. S1D. The width of the air pocket is determined by equation similar to [S10]:

\[
 r = \frac{\gamma}{\Delta p} \left[ -\sin \theta_R \pm \sqrt{\sin^2 \theta_R - \frac{r_p^2 \Delta p}{\gamma} \left( 2 \cos \theta_R - \frac{r_p \Delta p}{\gamma} \right)} \right]. \tag{S13}
\]

Of the two solutions the one corresponding to a minus sign can be deemed unphysical because with \( \Delta p \to 0^- \) we would have \( r \to \infty \). The physical solution (corresponding to plus sign) is consistent with [S11] with \( \Delta p = 0 \) and increases with decreasing pressure. However, a negative enough pressure renders the determinant (expression under square root) negative, restricting the maximum size of the air pocket.

With a negative \( \Delta p \), the air pocket can be destabilized by two ways. First, the determinant in Eq. S13 may become negative implying that no stable solution exist. This occurs with pressures lower than

\[
\Delta p_{c,1} = \frac{\gamma}{r_p} \left( \cos \theta_R - \sqrt{2 \cos^2 \theta_R - 1} \right). \tag{S14}
\]

However, if the air pockets grow large enough to coalesce before \( \Delta p_{c,1} \) is reached, they become unstable at a pressure less negative than \( \Delta p_{c,1} \). Depending on \( \theta_R \), this will happen if the radius corresponding to \( \Delta p_{c,1} \) is larger than \( L/2 \). The receding angle value \( \theta_R^* \) for which \( r = L/2 \) at \( \Delta p_{c,1} \) is given by the equation

\[
\sin \theta_R^* = \frac{L/2}{r_p} \left( \cos \theta_R - \sqrt{2 \cos^2 \theta_R - 1} \right). \tag{S15}
\]

With \( \theta_R > \theta_R^* \), the air pockets will coalesce at the Laplace pressure

\[
\Delta p_{c,2} = \frac{2 \gamma}{r_p} \frac{L/2}{r_p} \sin \theta_R + \cos \theta_R - \frac{L/2}{r_p} \left( \frac{L/2}{r_p} \right)^2 - 1. \tag{S16}
\]

The actual critical pressure for the nano-Cassie to micro-Cassie transition can thus be written as

\[
\Delta p_c = \begin{cases} 
\Delta p_{c,1} & \text{if } \theta_R < \theta_R^* \\
\Delta p_{c,2} & \text{if } \theta_R > \theta_R^* 
\end{cases} \tag{S17}
\]

\( \Delta p_c \) depends strongly on \( \theta_R \) and obviously goes to zero when equality in [S12] applies. In this study, \( \Delta p_c \) ranges between -5.0 kPa and -1.3 kPa (corresponding to \( \theta_R = 145 \pm 5^\circ \)).

**Fig. S1.** Microscopic meniscus shape. (A) Deformation of the meniscus under Laplace pressure. The surface tension counters the force caused by pressure. (B) Schematic representation of Eq. S7 in SI Text. (C) An air pocket at the base of a post. (D) Air pocket shapes calculated by integrating Eq. S9. From Left to Right: \( \Delta p = 10 \) kPa, the state after the water has been pushed between the posts by pressure (\( \theta_A = 170^\circ \)); \( \Delta p = 0 \), the pressure has been released; \( \Delta p = -3 \) kPa, negative pressure is generated by suction (\( \theta_R = 145^\circ \)).
Fig. S2. An optical micrograph of a micro-Cassie/nano-Cassie boundary. The sample is tilted by 22° so that horizontal water-air interfaces do not reflect incident light to the objective. Consequently interfaces with a nonhorizontal slope appear brightest. Due to this, the air pockets at the bases of the posts are shown clearly. It is also obvious that the nano-Cassie region is much brighter overall due reflections from the interfaces between the air pockets and water. Because of the tilt and the shallow depth of field of the objective, only one row of posts is in focus in the image.

Fig. S3. Light scattering contrast. Solid lines: the light scattering intensity ratio \( \frac{I_{\text{nano-Cassie}}}{I_{\text{micro-Cassie}}} \) as a function of wavelength (blue curve measured with a tungsten light source, green curve measured with a mercury-vapor light source). Dotted line: eye sensitivity (photopic function, source: http://www.cvrl.org/lumindex.htm). In the range where eye is sensitive the nano-Cassie state scatters 8–14 times more than the micro-Cassie state.

Fig. S4. Original confocal microscopy data without noise removal or contrast adjustment. Images were taken every 1 μm, but only every other image is shown here to conserve space. Conventional reflectivity scan is shown on the Left, while fluorescence signal from nanoparticles is shown in the Right.