

# Biomimetics studies of *Salvinia molesta* for fabrication

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It has been reported that the sophisticated structure of the *Salvinia molesta* surface offered a novel mechanism for long-term air-retention. It was difficult to mimic the structure, for it was composed of complex elastic eggbeater-shaped hairs with a coating of nanoscopic hydrophobic wax crystals, except for the top of the hairs. In this work, a structure of fibres cross on a patterned paper to mimic the ability of *S. Molesta* is manufactured. The complex elastic eggbeater-shaped hairs with a coating of SU-8 photoresist can support a droplet water of 1 ml. This work offered a new simple method to mimic the properties of *S. molesta* surface.

**1. Introduction:** Superhydrophobic surface is one of the most remarkable functions in the complex multifunctional interface of biology. Owing to its potential applications in a wide range of scientific and technological areas, from coatings [1], heat transfer [2], drag reduction [3] to biological applications, [4] many researchers have focused on controlling the wettability of solid surfaces in the field of biomimetic structures [5, 6].

The contact angle is usually employed as a measure of wettability. The surface is superhydrophobic when the contact angle on the solid surface is larger than 150°. Over millions of years evolving, many biological surfaces such as lotus leaves, rice leaves, butterfly wings, water strider legs, mosquito compound eyes, and red rose petals exhibit fascinating superhydrophobicity [7]. The superhydrophobicity arises from the cooperative interactions of multiscale surface structures and chemical compositions [8–13]. On smooth extreme hydrophobic surfaces, the maximum contact angle reaches 120° [14]. Higher contact angles can only be achieved by multiscale surface structures. Lotus leaves exhibit low adhesive superhydrophobicity originating from multiscale structures with randomly distributed micropapillae covered by branch-like nanostructures. Micropapillae and branch-like nanostructures are about 59 µm in length and 120 nm in diameter, respectively [7]. The non-wetting legs of the water striders originate from the unique hierarchical micro and nanostructures on the leg's surface [10].

In contrast to those superhydrophobic biological surfaces, the leaf surfaces of the *Salvinia molesta* were composed of complex elastic eggbeater-shaped hairs with a coating of nanoscopic hydrophobic wax crystals, except for the top of the hairs [15]. The sophisticated structure of the surface offers a novel mechanism for long-term air-retention. The trichomes and waxes make *Salvinia* surface superhydrophobic to prevent the surface from wetting and have a positive effect on maintaining an air film underwater. Many researchers have paid attention to it, due to the structure's potential applications such as air-retaining and drag reduction between the water and the surface [7, 15–20]. Hunt and Bhushan [16] attempted to fabricate the *Salvinia* structure on a silicon wafer. They first developed the micropillar structure by photolithography, and then coated the structure with a hydrophobic layer of trichlorosilane. Finally, they stripped away the coating on the top by a double-sided tape. They obtained the structure to retain air. However, they used the coating to take the place of the complex structure of elastic eggbeater-shaped hairs, ignoring the function of the structure in minimising the shear stress and the frictional drag between water and the surface.

In this Letter, we try to mimic the ability of *S. molesta* using a simple method. First, we obtained the hydrophobic surface of the fibre by soaking the fibre in SU-8 and exposing to 365 nm

ultraviolet (UV) light. Second, we fabricated a pattern of micropore by standard photolithography. Finally, we manufactured the elastic eggbeater-shaped hairs structure to mimic the ability of *S. molesta*.

**2. Theory:** One of the first model to describe the effect of roughness on wetting is the Wenzel model [21]. The model describes the relationship between water, solid states, and gas, by modifying the Young's equation (2.1) [22] through introducing a surface roughness coefficient

$$\cos\theta = \frac{\gamma_{sv} - \gamma_{sl}}{\gamma_{lv}} \quad (2.1)$$

Where  $\theta$  is the Young contact angle;  $\gamma_{sv}$ ,  $\gamma_{sl}$ , and  $\gamma_{lv}$  are surface tensions at the solid/vapour, liquid/solid, and liquid/vapour interfaces, respectively. The Young's model defines the static contact angle of a droplet on a flat homogeneous solid surface. If the static contact angle is  $>90^\circ$ , the droplet cannot wet the solid; thus, the solid is hydrophobic. Wenzel introduced a roughness factor ( $r$ ) defined as the ratio between the true surface area over the apparent one (2.2)

$$\cos\theta^* = r \cos\theta \quad (2.2)$$

where  $\theta$  is the Young contact angle on a smooth surface and  $\theta^*$  is the real measured contact angle;  $r$  is the roughness ratio defined as the ratio between the actual and projected areas. The model shows that the roughness factor enhances the solid surface energy. However, the Wenzel model cannot explain the phenomenon of extremely high contact angles. Cassie and Baxter [23] examined the relationship between chemical surface heterogeneity and wettability in their fundamental work on extreme water repellency and make the conclusion that extreme water repellency is caused by air being enclosed between the surface structures of a rough surface (2.3)

$$\cos\theta^* = -1 + \phi_s(\cos\theta + 1) \quad (2.3)$$

where  $\theta$  is the Young contact angle on a smooth surface,  $\theta^*$  is the real measured contact angle, and  $\phi_s$  is the solid fraction in contact with the water.

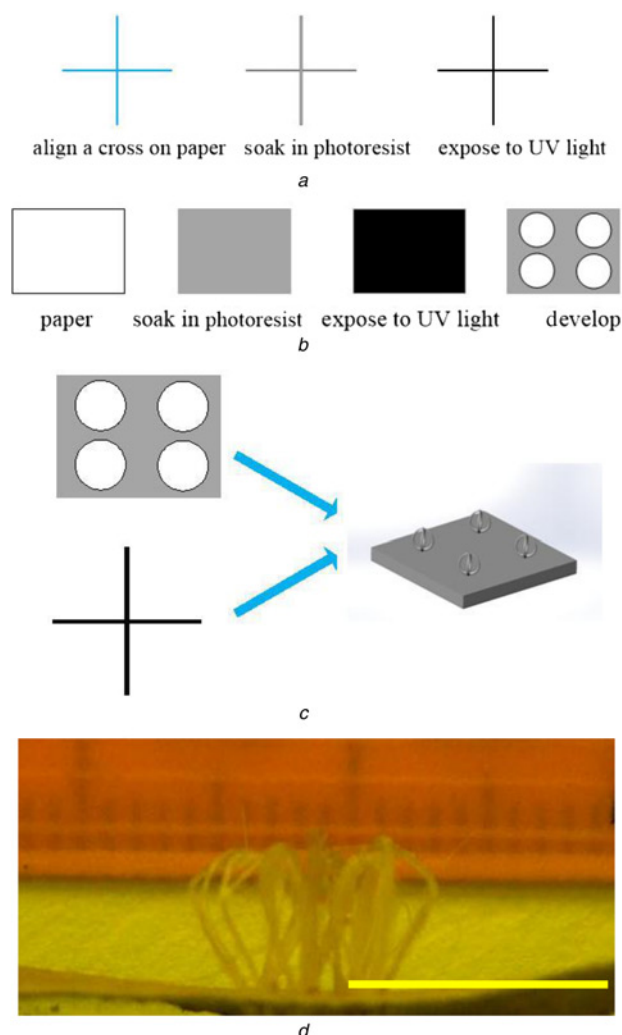
According to the structure of *S. molesta*, it effectively reduces the area of the liquid–solid interface and increases the area of the liquid–air interface, which increase superhydrophobic by reducing the  $\phi_s$  and minimise the shear stress and the frictional drag between water and the surface. In addition, the top surface of the *Salvinia* structure with hydrophilic patches considerably enhances

the air-retaining property. So it is important to fabricate the similar structure to mimic the ability of *S. molesta*.

### 3. Materials and method

**3.1 Materials:** A negative photoresist SU-8 2010 (MicroChem Corp. Newton, MA). Whatman chromatography paper #1 ( $20.0 \times 20.0 \text{ cm}^2$ , General Electric Company (GE) Healthcare Worldwide Pudong Shanghai, China). Fibre with diameter 20  $\mu\text{m}$  is stripped from the optical fibres with diameter 125  $\mu\text{m}$  (Quanzhou Anpon Company, China). A positive photoresist EPG 533. A microscope (Nikon eclipse LV100, Japan).

**3.2 Method:** The manufactured process can be seen in Fig. 1a. There are three procedures. First, two fibres were put on the surface of the paper as a pattern of cross. Following this, we put the pattern into the SU-8 liquid for 3 seconds and then removed it. A layer of SU-8 liquid was coated on the pattern. Then, the pattern was baked at  $95^\circ\text{C}$  for 5 min to remove the cyclopentanone in the SU-8 formula. After that the photoresist and the pattern were exposed to UV light with wavelength of 365 nm for 30 s (ABM, Inc.). After exposed, the pattern was baked a second time at  $95^\circ\text{C}$  for 5 min.



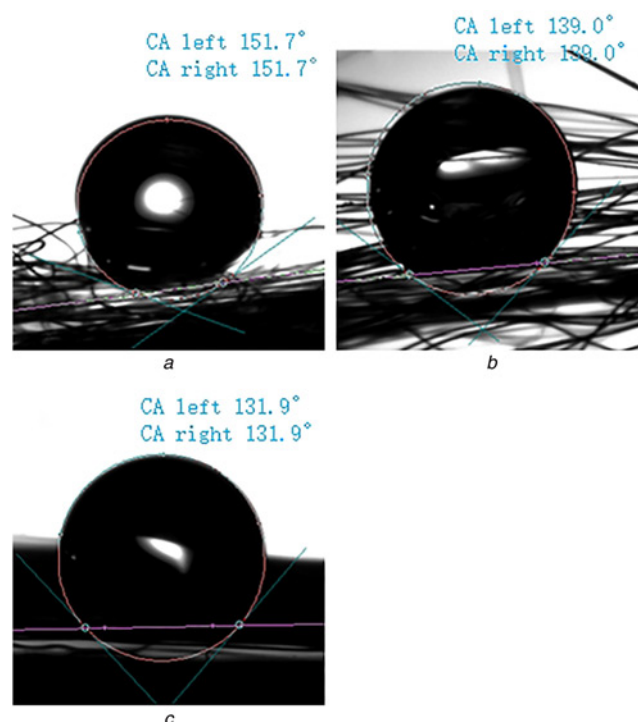
**Fig. 1** Process of fabricating the elastic eggbeater-shaped hairs structures  
a Changing the surface property of fibre by covering a layer of SU-8  
b Fabricating the patterned paper using the standard lithography  
c Fabricating process of elastic eggbeater-shaped hairs structures on the patterned paper  
d Elastic eggbeater-shaped hairs structures on the patterned paper. The scale is 1 cm

Second, the pattern of the paper was produced as follows (Fig. 1b): we soaked the paper into the positive photoresist for 1 min and baked for 5 min at  $95^\circ\text{C}$  in the dry oven. Then, the paper was exposed to UV light for 30 s (ABM, Inc.) through a photomask and developed in a photoresist developer. After that, patterned microholes were obtained by wiping off the excess paper using ultrasonic cleaner.

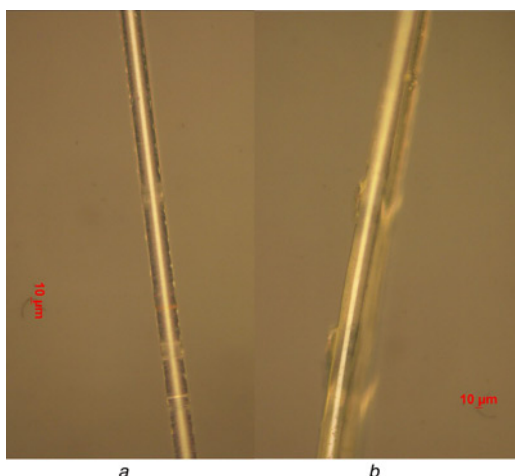
Third, the structure of elastic eggbeater-shaped hairs was fabricated by fibres going through the hole (Fig. 1c). In Fig. 1c, the cross of the fibres has four endpoints. When all the endpoints go through the same hole, the fibres would form eggbeater-shaped hairs due to the elasticity of the fibres. The scale of the structures on the Salvinia surface is several hundreds of micrometres. However, it was difficult to manufacture them by hand and we can only make structures with the scale of several millimetres (as shown in Fig. 1d). We believe that the smaller and more sophisticated structures can be made by the mechanical method. Those structures will have the properties of long-term air retention.

**4. Results and discussion:** To understand the contact angle changing induced by the changing of the contact area between solid fibre and liquid droplet, we measured three contact angles in different contact area between solid fibre and liquid droplet by contact angle meter (Dataphysics, German). As shown in Fig. 2, the three contact angles were measured in the same conditions: the fibres were manufactured in the same bath; the water was acquired at one time; the contact angle is measured in the same temperature ( $25^\circ\text{C}$ ) and humidity (65% relative humidity (RH)). Then, a droplet of 5  $\mu\text{l}$  water was put on the fibres. Water droplets formed a nearly perfect sphere on the fibres. In Fig. 2a, the droplet was supported by several fibres and the contact angle can reach to  $151.7^\circ$ . In Figs. 2b and c, the droplet was supported by more fibres, so the contact angle can reach  $139^\circ$  and  $131.9^\circ$ . So we can come to the conclusion that the high contact angle is due to the decreased contact area between solid fibre and liquid droplet.

A compound surface is formed which consists of a few solid portions and enclosed air. Considering to Cassie and Baxter, it is



**Fig. 2** Water contact angles of fibre surface  
a Water contact angle on several fibres  
b and c Water contact angle on the surface formed by more fibres

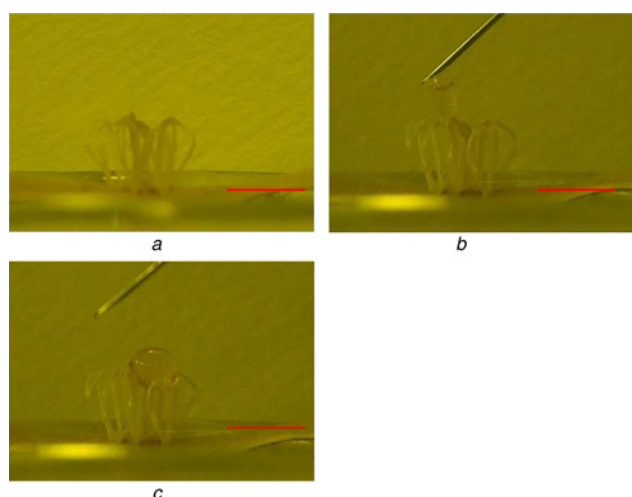


**Fig. 3** Microfibre imaged by the microscope with enlargement factor of 200  
 a Fibre before soaked in SU-8 2010  
 b Fibre after soaked in SU-8 2010. The scale is 10 µm

important that the extreme water repellent is caused by roughness and air being enclosed between the surface structures of a rough surface. For the maximum contact angle can only reach 120° on the smooth extreme hydrophobic surfaces [14]. To achieve higher contact angles, it is necessary to increase the surface roughness and the air being enclosed between the surface structures. The smaller the part of the solid in contact with the liquid, the more the contact angle trends toward 180°. In Fig. 2, the contact angles decrease due to the increasing of the part of the solid in contact with water.

As shown in Fig. 3a, the surface of the fibre is smooth. So the fibre has poor hydrophobic property. After the fibre was soaked in the SU-8 and exposed to the UV light, the surface of the fibre is covered by the SU-8. The SU-8 layer has good hydrophobic property. On the surface of the SU-8 layer, there are many heaves. The exit of the heaves will increase the contact angle by reducing the solid fraction in contact with the water  $\phi_s$ . The larger contact angle will minimise the shear stress and the frictional drag between the water and the surface.

The result shows that the contact angle can reach 150° on the fibre covered by SU-8. The fibres can be used to fabricate the



**Fig. 4** The process that the 1 ml droplet water formed sphere on the structures  
 a Structure of elastic eggbeater-shaped hairs fabricating by hand  
 b Process that water broke away from the syringe needle and formed a nearly perfect sphere  
 c Droplet of 1 ml water formed a nearly perfect sphere on the structures. The scale is 1 cm

elastic eggbeater-shaped hairs. Three structures of elastic eggbeater-shaped hairs were fabricated on the patterned paper (Fig. 3a). Though the scales of the structures have reached several millimetres, the structure can also support water droplet. As shown in Fig. 4c, a droplet of 1 ml water formed a nearly perfect sphere on the structures. Fig. 3b shows the process that water broke away from the syringe needle and formed a nearly perfect sphere. The result shows that the structures not only have the hydrophobic property but also have better adhere property.

**5. Conclusion:** To summarise, this Letter offered a new easy fabrication and lower-cost method to mimic the properties of the elastic eggbeater-shaped hairs. First, we achieved fibres cross-structure with the water repellent by covering a coating of SU-8 photoresist on the fibres surface. Then, a patterned paper was manufactured by the standard lithography. Finally, the elastic eggbeater-shaped hairs were fabricated on the patterned paper. The structures with the scale of several millimetre can support a water droplet of 1 ml. They cannot achieve the properties of long-term air-retention, due to the rough structures made by hand. We believe that the more sophisticated structures can obtain the properties of long-term air-retention, when the structures are made by mechanical.

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## 7 References

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