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Directional Droplet Transportation on Microchannels

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Abstract

In recent years, anisotropic wetting surfaces have attracted wide scientific attention for both fundamental research and practical applications. Directional transportation of droplets, as an efficient method to conduct droplet motion, has attracted great interest in research and industrial fields. Nevertheless, the great challenges in its application focus on these aspects such as sample conservation, velocity, distance, precision and driving force. Very recently, some research highlights were published regarding improving the directional transportation of aqueous droplets by creating micro topological channels. The conceptually novel multi-bioinspired strategy based on structures and functions is rendering a promising candidate for practical applications. In addition, the numerical simulation and experimental verification can adjust and optimize the configuration parameters to improve the transportation capacities of the channels. This review focuses on typical and recent advances in the area of directional droplet transportation on micro channels, mainly based on micro-/nanostructures. As a result of their excellent performance in solving the aforementioned challenges, we anticipate that these works would prosperously promote the fabrication and application of directional droplet transportation.

Subject Areas

Functional Materials, Material Experiment, Surface and Intersurface of Materials

Keywords

Directional Droplet, Transportation, Superwettability, Microchannels

1. Introduction

Directional transportation of water has tremendous application potential in a number of fields such as microfluidic devices, cell screening, heat transfer, directional oil/water separation and water collection [1]. Therefore, its development has attracted broad interest for decades [1] [2]. However, the conventional methods (e.g. μPADs) have problems in conducting water, such as low velocity, short distance, low accuracy and mass loss, which lay back the application of water transportation [3] [4] [5]. What's more, due to their low slippery performance, in which solutions stick onto the surface instead of freely sliding off, external driving forces, such as gas pressure [6], light [7], UV irradiation [8], gravity [9] and magnetic [10], are required for the droplet motion. This limits the application scenarios of conventional directional transportation protocols. Herein, it is crucial to develop new directional transportation technologies that solve the problems mentioned above.

The excellent directional water transportation behavior, by contrast, can be widely observed on natural surfaces, such as plant leaves, bug wings and bird feathers [1] [7] [11] [12]. Surface characterization reveals that hydrophobic topological channels on those surfaces act as micro-sized railways and transport water droplets from one end to the other [1] [2]. Very recently, inspired by these intriguing phenomenon, the creation of slippery anisotropic channels on substrates has been reported for transportation of water droplets [3] [4] [5] [11] [13]. These channels could contain the water drops in the designed areas and conduct them directionally with excellent performances in aspects of velocity, volume range, mass conservation and driving force [14]. This work has briefly summarized recent advances in the development and application of novel directional wetting interfacial phenomena based on the utilization of unique micro-/nanostructures, and we believe that it could promote the development of directional water transportation on microchannels.

2. Directional Droplet Transportation

2.1. T-Shaped Channels

Among all natural products, the directional transportation capability of Sarracenia trichome is highlighted. The water transportation speed is tens of times faster than spider silk and cactus [13]. The mass loss of the solution during the drop migration is an obstacle in directional transportation, especially for droplet-scale sample transportation. Huang *et al.* revealed that the liquid residue is the result of a transport-velocity-dependent dynamic wetting mechanism [5]. To overcome this challenge, radially arranged Reentrant shape (T-shaped) omniphobic channels were initially fabricated on silicon substrate. After comparing two types of coating materials (rigid layer vs flexible brush), a liquid-like perfluorinated polyether (PFPE) was chosen to craft the channels (**Figure 1(a)** and **Figure 1(b)**). The fabricated substrate could directionally transport liquid with a wide range of surface tension (27.5 to 65.3 $mN \cdot m^{-1}$) without liquid residue on channels, microscopically. The transportation behavior is efficient, with the highest velocity up to 122.1 $mm \cdot s^{-1}$ for transporting N-hexadecane (C16SH), which was attributed

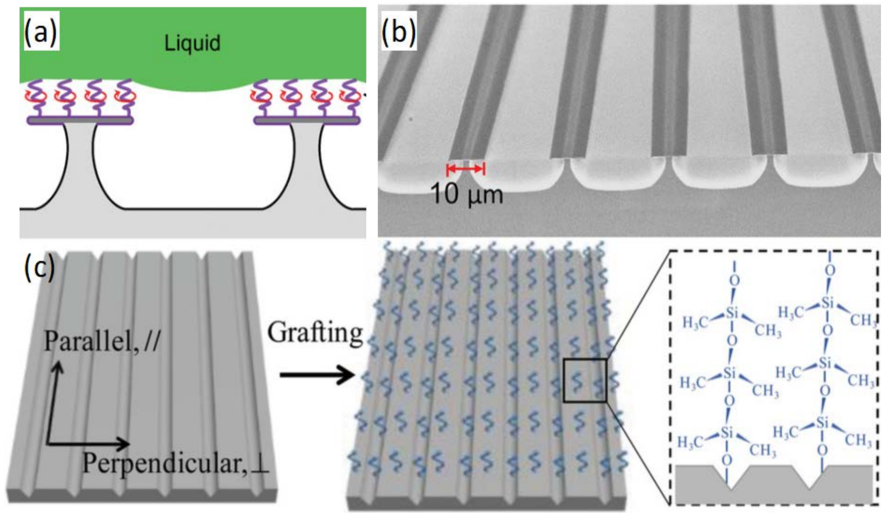

Figure 1. (a) schematic illustration of liquid on "T"-shaped slant microwall assays grafted with liquid-like brushes; (b) SEM image of the "T"-shape reentry channels; (c) Schematic illustration of abraded channels grafted with liquid-like PDMS and the chemical structure of the formed liquid-like PDMS brushes (right side). Reproduced with permission from *ref.* 4 and 5; copyright 2019 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim and 2020 Wiley-VCH GmbH.

to lower contact angle hysteresis and superamphiphobicity created by T-shaped channels. And similarly, the recent study also fabricated the directional transportation substrates by grafting the liquid-like polymers on microchannels [4]. Initially, the silicon wafer was abraded using different diamond lapping films. It was found that the larger lapping size of films corresponds to better wetting performance (higher water contact angles and lower sliding angles). Then, liquid-like Polydimethylsiloxane (PDMS) brushes were coated onto the prepared silicon substrates. This fabricated substrate has an excellent anisotropic omniphobic sliding property that could resist droplets with surface tensions lower than 37.7 $mN \cdot m^{-1}$, and a long shelf life of up to 240 days (**Figure 1(c)**).

2.2. L-Shaped Channels

Moreover, high-resolution scanning electron microscope (SEM) images showed that the surface of Sarracenia trichome was covered with parallel hierarchical ribs. Based on the results of this finding, Chen *et al.* proposed that pre-wetted thin water film inside base channels could be attributed to the ultra-fast water transportation property. By mimicking this morphology, the researchers fabricated hierarchical microchannels on glass slides with lithography technology. Transport distance on fabricated substrates will increase with the increasing number of ribs (NA), inclined angle of ribs (2θG), and number ratio of high/low ribs (**Figure 2(a)** and **Figure 2(b)**). It was demonstrated that the water transportation speed on a pre-wetted substrate could be about four-fold faster than that on a dry substates (~3.8 $mm \cdot s^{-1}$ vs. ~0.9 $mm \cdot s^{-1}$), which verified that pre-wetted channels could increase the transportation speed. Afterward Wu *et al.* increased

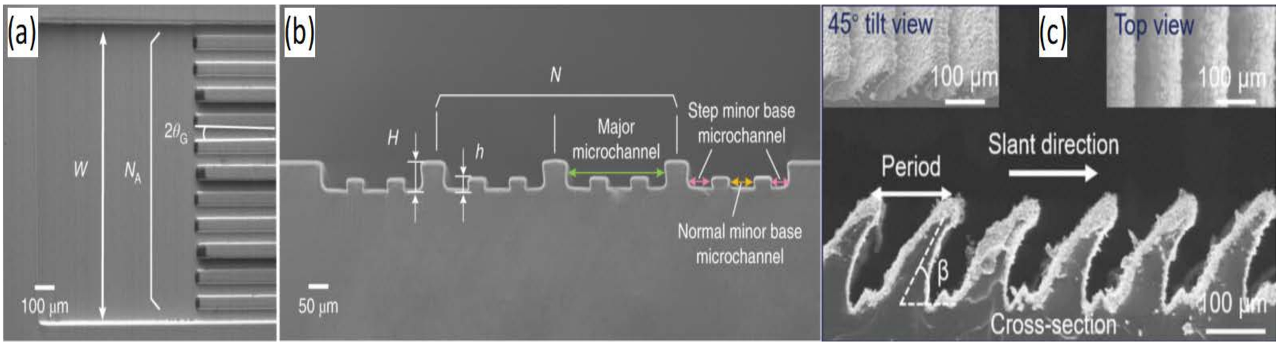

Figure 2. (a) and (b) are SEM images of microchannels designed by Chen *et al.*, where W = 1500 μm, NA is the total number of ribs, 2θG is the inclined angle of two neighboring ribs, H = 50 μm and h = 20 μm; (c) is the cross-section image of slant microwall channels. Reproduced with permission from *ref.* 13 and 14; copyright 2022 Springer Nature and 2020 Wiley-VCH GmbH.

the speed of drop transportation up to 22.86 mms^{-1} on silicon wafer constructed with parallel L-shaped slanted microwall channels, which were created by femtosecond laser oblique ablation (**Figure 2(c)**). The high transportation speed and large volume ranges of droplets ($V_{Max}/V_{Min} \approx 100$) could be achieved with the help of horizontal vibration [13] [15].

2.3. Topological Microchannels

Very recently, to improve the precision of channels during water transportation, Yang *et al.* created the three-dimensional topological slippery liquid-infused porous surfaces (SLIPS) on copper substates using laser milling, as **Figure 3** shown [3]. The surface is finished by infusing the surface with silicon oil and forming a uniform lubricating layer. It was shown that the sliding resistance anisotropy of the resulting substrate is 27 times greater than that of natural rice leaves. With mere gravity force, this type of substrate can be used efficiently and precisely transport droplets. The velocity of transportation is five times higher than the conventional substrates. Also, water droplets could move freely across the surface without mass loss. It is worth highlighting that inspired by the beak of shorebirds, wedged-shape channels were also created to transport water droplet without external forces (including gravity). It can transport water droplets for a distance of up to 12 mm, which is sufficient for microfluidic applications.

2.4. Microspine Chips

It could be predicted that more micro railway-based directional water transportation methods will be created in the near future. To solve multiple challenges in this field, different strategies could be combined together, for instance, combining wedged-shaped channels (*ref.* 3) and hierarchical microchannel strategy applied in *ref.* 14 (high and low ribs) to self-transport longer and faster. For other strategies, the transportation could be applied to liquids with a lower surface by treating specific topography (e.g. doubly re-entry channels for transporting hydrofluoric acid solutions [15] [16]), or simplify the substrate design by using sand paper to scratch the polymer surface (such as polycarbonate, and so on).

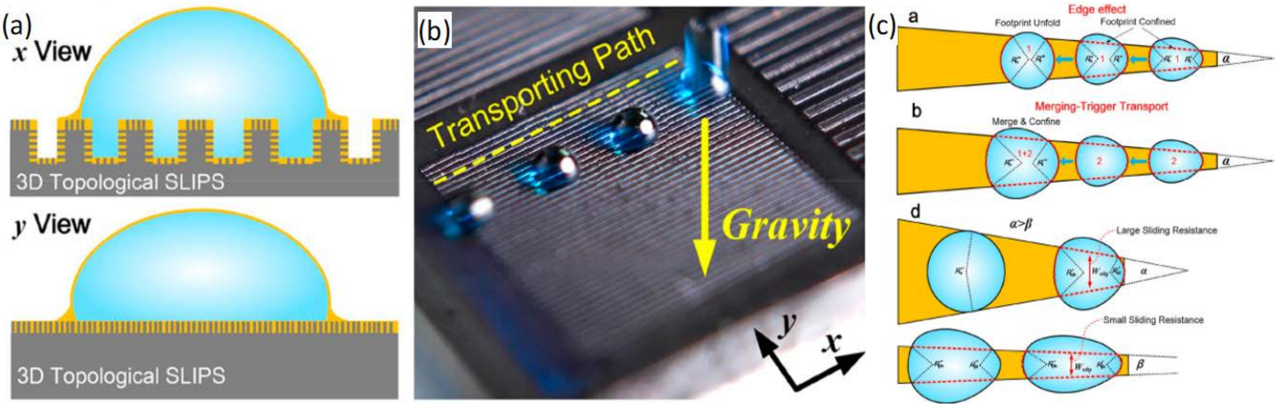

Figure 3. schematic illustration of the cross section of fabricated hierarchical anisotropic microchannels (a) and image of directional water transportation behavior on the substrate (b); (c) is schematic illustration of self-driven droplet transpiration on wedge-shaped microchannels. Reproduced with permission from *ref.* 3; copyright 2021, American Chemical Society.

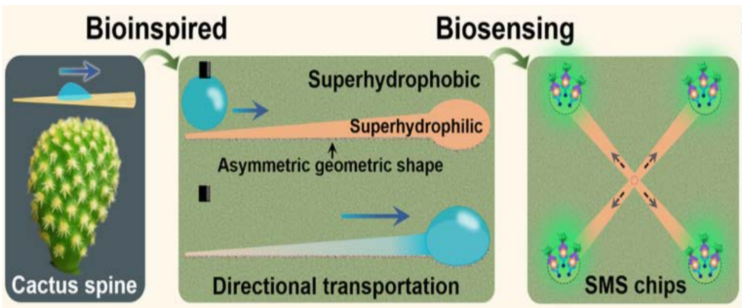

Figure 4. Directional droplet transportation on the superwettable microspine (SMS) chip, inspired by the water-collecting phenomenon on the cactus spine. Reproduced with permission from *ref.* 18; copyright 2020, American Chemical Society.

Inspired by cactus, Chen et al fabricated nanomaterial-based superwettable microspine (SMS) chips, as shown in **Figure 4** [17]. The gradient of the Laplace pressure arising from the geometric asymmetry of the SMS chip can dominate the directional transportation of the droplet, and the superhydrophilicity of the nanomaterial-based microspine can also contribute to the droplet self-transportation. It was demonstrated that the droplet moves faster by increasing wedged channel angle. Such chips are able to transport droplet longer, faster and without external forces, which greatly increases hydrophobicity.

3. Conclusions

In this review, recent advances in the development and application of novel directional wetting interfacial phenomena based on the utilization of unique micro-/nanostructures have been briefly summarized. In order to achieve the expected directional wetting phenomena, the micro-/nanostructures on the directional wetting surfaces should be controlled within a suitable range. If the droplet volume is too large or small to interact with different kinds of directional wetting surfaces, the ideal directional wetting behavior cannot be realized [18]. The conceptually novel multi-bioinspired strategy based on structures and functions is rendering a promising candidate for practical applications [19]. In addition, the numerical simulation and experimental verification can adjust and optimize the configuration parameters to improve the transportation capacities of the channels.

The trend of development relating to directional wetting may mean increasing growth in the areas of the design, preparation, and application of more complicated and subtle multifunctional directional wetting surfaces [20] [21]. As great advances are achieved, it is expected that directional wetting surfaces will be applied in many fields, and we anticipate their contributions to the energy, environmental, biological, analysis and medical domains, and other fields.

Ethical Compliance

There is no research conducted on animals or humans.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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