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Solid/liquid interfacial friction and slip behaviors on roughness surface under applied voltage

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ABSTRACT

The solid/liquid interfacial friction and slip behaviors on roughness surface under applied voltage were studied. Results showed that the slip behaviors of droplets on roughness surface in the unstable region cannot fit by electrowetting equation. The slip distance and directions mainly depended on difference between right and left friction force at the triple contact line, which were caused by the asymmetric roughness of the solid surface. Moreover, microstructures with various heights were used to control the solid/liquid slip behaviors. Results indicated that when the ridges of scratch far higher than surface roughness of the hydrophobic surface, the slip distance increased and slip direction can be controlled. The findings have potential applications in oriented driving of droplets by electric field.

1. Introduction

Oriented driving microdroplet on a solid surface has attracted much attention in recent years because of its wide application in lab-on-a-chip [1,2], inkjet printing [3,4], and DNA microarrays [5,6]. Traditionally, oriented driving of microfluidics was done by combination of micropumps, microvalves and microchannels [2]. By intermittently switching on and off the microvalves and micropumps, individual droplets can be obtained and actuated according to requirements [7–9]. However, because the actuation systems were composed of complex mechanical devices, the reliabilities were restricted by the development of miniaturization and integration. Consequently, all kinds of new approaches were proposed to manipulate microdroplet, such as magnetic actuation technology [10,11], optofluidic technology [12,13] and electrowetting on dielectric (EWOD) technology [14,15]. For magnetic-induced and light-induced actuation technologies, magnetic-sensing and photosensitive particles should be added to the droplets to control the movement [10,12]. These particles may contaminate droplets and were difficult to remove. Conversely, by changing the effective solid/liquid interface tension through electric field, EWOD technology can be used to generate and actuate droplets accurately [16,17]. Due to without mechanical devices, EWOD technology has several advantages, such as non-polluting, real-time actuation, fast response, long-term stability and reliability [18,19]. Consequently, EWOD technologies are considered as one of the most potential technologies to actuate microdroplets.

A typical EWOD system composed of a substrate, droplet and a power supply, as shown in Fig. 1a. When voltage was applied between the droplet and substrate, the shape of the droplet changed with the increase of the applied voltage. Therefore, droplets can be actuated by array electrodes by EWOD system [20]. In order to actuate droplet accurately, solid/liquid interfacial behaviors under applied voltage have attracted considerable attention [21–25]. Previous studies were mainly concentrated on the deformation process of droplet [26], low voltage actuation [19]. and sliding friction behaviors [27]. These studies indicated that the solid/liquid interfacial behaviors were associated with surface roughness, which cause additional friction force at the triple contact line [27]. For a real surface, surface defects and surface roughness are unavoidable. Consequently, it is necessary to study the interfacial friction of droplet on a roughness surface to actuate droplets efficiently.

In this paper, the variations of contact angle and triple contact line before and after slipping in the unstable region were characterized by contact angle meter. Moreover, the slip distance and slip direction of droplet under direct voltage were studied. Next, a nano-scratch was utilized to make microstructures to control the slip behavior of droplet. In addition, the interfacial friction of droplet on a roughness surface was discussed using balance of forces at the triple contact line. The findings in this paper may be helpful to extend the wetting theory of droplet under direct voltage and has potential applications in oriented driving of

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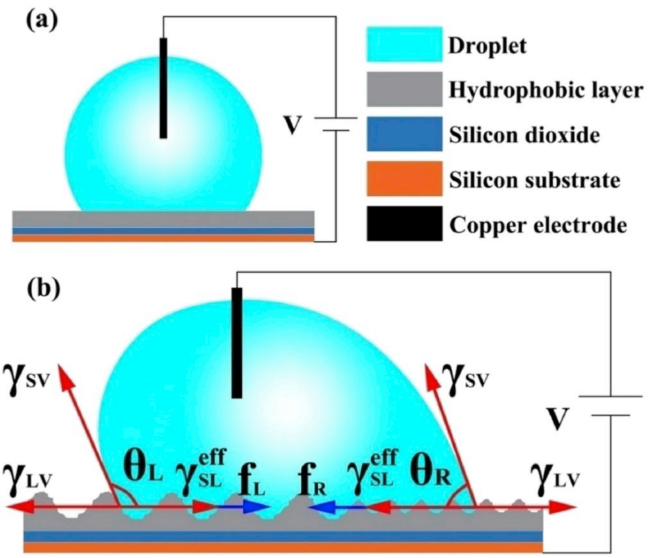

Fig. 1. Schematic of the electrowetting system and forces at the triple contact line. (a) schematic diagram of the experimental method. (b) schematic of the balance of forces at triple contact line on an inhomogeneous surface under applied voltage.

droplets by electric field.

2. Materials and methods

2.1. Sample preparation

Conductive silicon wafers coated with a 300 nm silicon oxide layer were used as the ground electrode (SSPP, Siltronic, Germany). In order to minimize contact angle hysteresis, the silicon oxide surface was hydrophobic treated with a Teflon emulsion (Teflon AF1600, Dupont, USA). The Teflon emulsion was spinning on the silicon oxide surface using a spin processor (KW4A, Beijing Saidekai Co., China) at 500 rpm for 20 s and 3000 rpm for 30 s respectively. After heating at 200 °C for 2 h, the hydrophobic layer with ~2 μm thick was obtained. The water contact angles of the specimens were approximately 130°.

2.2. Electrowetting parameters measurement

The schematic diagram of electrowetting is shown in Fig. 1. The silicon wafer of the specimen was connected to the negative electrode of a power supply (PSW250–4.5, GuWei, China). Next, a 10 μL droplet was placed on the surface of specimen and a copper wire with diamond of 100 μm was inserted inside the droplet. And then the copper wire was connected to the positive electrode of the power supply. An applied voltage ranged from 0 to 200 V with incremental velocity of 1 V/s was provided. The voltage resolution of the power supply is 0.1% ± 10 mV. The variations of contact angles of droplet with applied voltage were obtained using a contact angle meter (DSA30E, KRUSS, Germany). For the contact angle meter, the measurement resolution is 0.01° and 0.01 mm. Consequently, the lengths of triple contact line under different applied voltages were recorded by DSA contact angle analysis software (DSA30E, KRUSS, Germany). In order to study the effect of ion concentration on the slip behaviors of droplet under applied voltage, sodium chloride solution (NaCl) with different concentrations (0 mol/l, 1 mol/l and 2 mol/l) were used.

2.3. Morphology of the hydrophobic layer

Considering the solid/liquid friction behaviors of droplet were closely associated with the morphology of specimens, the topographies of the hydrophobic layer were acquired by white light scanning profilometry (MFT-3000, Rtec, USA). The Z axis resolution of the white light scanning profilometry is 0.1 nm, and X & Y axis resolution is 1 μm. To study the effect of roughness on solid/liquid friction, moreover, a nano-scratch tester (G200, Keysight, USA) was used to make microstructures on the hydrophobic surface. During processing, a conical diamond tip with a radius of 1.8 μm was used and scratches were performed under 5 μN–30 μN respectively. Moreover, the scratch length for each scratch was 5 mm at a velocity of 5 μm/s. The topographies of the scratch profiles were acquired by white light scanning profilometry. All experiments were performed under atmospheric conditions at room temperature.

3. Results

3.1. Slip behaviors before saturation

The variation of contact angle and the length of triple contact line with applied voltage were shown in Fig. 2. Obviously, the contact angle and triple contact line curves can be divided into four regions, namely, Istatic region, IIsliding region, III unstable region and Ⅳ saturated region. In the static region, the contact angle decreased slightly while triple contact line remained constant. In the sliding region, the contact angle decreased and contact line increased with increasing of applied voltage. In the saturated region, the contact angle and triple contact line almost kept constant with increasing of voltage. It was noted that an unstable region exist before saturation. In this region, the variation of contact angle and triple contact line cannot fit by electrowetting equation. As shown in Fig. 2, sharply stick-slip behaviors of droplet can be observed before saturation. As shown in the inset of Fig. 2, the contact angle suddenly increased and triple contact line decreased respectively when the droplet slid from point A to point B. The difference of contact angle (DCA) and triple contact line (DCL) between point A and point B were summarized in Table 1. It was found that the DCA and DCL were independent on the concentrations of NaCl.

3.2. Slip distance and directions

For a homogenous surface, the variation of contact angle and triple contact line were axisymmetric. Theoretically, droplets changed symmetrically with applied voltage along a symmetrical axis (green dotted line), as shown in Fig. 3. As mentioned above, droplet slipped from one equilibrium state to other equilibrium state before saturation for a rough surface. So slip toward left and right of the droplet can be observed. Moreover, the slip behaviors of droplets were overlooked by a camera, as shown in Fig. 4. The photo of the droplet before and after slip is shown in Fig. 4b. The schematic diagram of the droplet before and after sliding is shown in Fig. 4c. 50 repeated experiments were done on a batch of specimens. Results showed that the slip directions of droplets under applied voltage were uncertainly. As shown in Fig. 4d, slip toward east (E), south (S), west (W), north (N) and other directions can be observed. The number of times in different directions was summarized in Table 2. Where E, S, W, and N represent the direction of east, south, west and north respectively. And the NW, NE, SW, SE represents the direction northwest, northeast, southwest and southeast respectively. According to the data in Table 2, it can be deduced that the slip directions were uncertain. The distance between the axes before and after slipping was termed as slip distance (SD). Results showed that the average SD of droplet was approximately 0.4 mm for the surface with a roughness of Ra 53.9 ± 16.9 nm, as shown in Table 1. Moreover, there were no significant differences of the SD among three different solutions.

The dynamic responses of droplet with increase of applied voltage are shown in Fig. 3. The average contact angle θ, left contact angle θ_L and right contact angle θ_R for a droplet were showed under the photograph. It was found that the difference between θ_L and θ_R (DLR) was less than 1° for an homogenous surface under applied voltage. However, the