LOW-VOLTAGE ELCTROSTATIC ACTUATION OF DROPLET ON THIN SUPERHYDROPHOBIC NANOTURF

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ABSTRACT

This paper reports an electrostatic actuation of droplets on a NanoTurf surface. By employing the nanostructured layer instead of a flat and smooth dielectric, both a large driving force and low friction are achieved, presenting a droplet operation at a lower driving voltage compared with general electrowetting-on-dielectric (EWOD) configurations. The dielectric NanoTurf layer is formed on electrodes by using laser interference lithography. With a contact angle of ~170° and its hysteresis of ~5° on syperhydrophobic NanoTurf, water droplets are actuated at ~24 V, much lower than general EWOD.

1. INTRODUCTION

Driving droplets with electric potential has gained significant popularity for its simplicity in microfabrication and low power consumption, helping the birth of "digital microfluidics". Although much lower than the voltages used in early years (> 200 V), the typical range today (40–80 V in air, i.e., on dry surface) still imposes some difficulties in system development. Analyzing the mechanisms from the fundamental level, we report a method to lower the voltage by incorporating superhydrophobic NanoTurf technology [1, 2].

Despite the variation (direct electrostatic [3], electrowetting [4], dielectrophoretic [5]), most known voltage-driving mechanisms actuate a droplet squeezed between two plates with the following equation, which can be simply derived from the electrostatic energy of the system:

$$F_d = \frac{\varepsilon}{4}\frac{w}{t}V^2, \tag{1}$$

where F_d is the driving force, ε is the permittivity of the dielectric layer, w is the droplet width, t is the thickness of the dielectric layer (or distance between electrode and liquid), and V is the applied voltage. Droplets move when the actuation force is greater than the resistance (friction). Static friction, determining the driving voltage needed in most cases, is mainly caused by the contact angle hysteresis and may be expressed as (e.g., [6]):

$$F_f = 2\gamma w(\cos\theta_{adv} - \cos\theta_{rec}), \tag{2}$$

$$\approx -4\gamma w \sin(\theta_c)\sin\left(\frac{\Delta\theta}{2}\right), \tag{3}$$

where F_f is the friction force of the droplet, γ is the surface tension at the liquid-air interface, θ_{adv} and θ_{rec} are advancing and receding contact angles, θ_c is the static contact angle, and $\Delta\theta$ is the contact angle hysteresis ($\theta_{adv} - \theta_{rec}$).

To increase the driving force for a given voltage, a thinner dielectric with a higher permittivity is desired [7]. To decrease the resistance against the droplet movement, on the other hand, we propose a superhydrophobic surface, which usually exhibits a very small contact angle hysteresis. The superhydrophobicity can be obtained by hydrophobic textured surfaces. However, the reported superhydrophobic structures [3, 8] are taller (i.e., thicker) than the dielectric thin films used for most voltage-based droplet-driving methods [3, 4, 5, 7], resulting in a higher driving voltage.

To lower the driving voltage, one cannot simply fabricate the surface structures as short (i.e., thin) as possible. If one made the surface structures too short, the menisci would be pulled down by electrostatic attraction, failing the superhydrophobicity, which requires the droplet

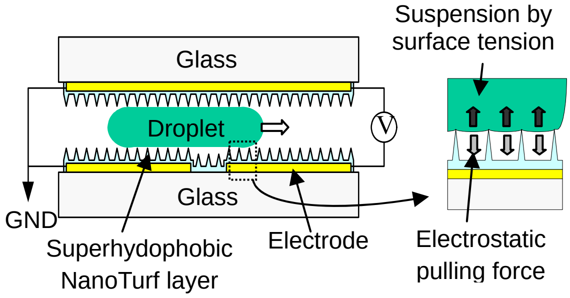

Figure 1. Proposed electrostatic actuation on hydrophobic NanoTurf surface.

staying on top of the structures, as illustrated in Figure 1. To keep the menisci suspended under the electrostatic pull down, one can decrease the distance between the structures (i.e., periodicity) to a sufficiently small amount, because capillary force is inversely proportional to the distance. The menisci remain stable against disturbances in most practical cases when the periodicity is reduced down to submicrometers, which was the main motivation of NanoTurf technology in the first place [2].

2. DESIGN

Figure 1 shows a schematic side view of the proposed scheme. Unlike the existing voltage-driven mechanisms, the liquid lies on top of the needle-like structures, sliding by electrostatic attraction. The operation voltage can be lowered by (1) reducing the friction and (2) increasing the force for a given voltage. The former is possible if the surface is superhydrophobic and the latter if the gap (t) between the droplet and the imbedded electrode is very small. We propose that a combination of the above is possible if one utilizes NanoTurf, where the densely (nanoscale) populated sharp needles cover a large area [1, 2].

The driving voltage can be estimated from equations (1) and (2) for a given NanoTurf height and contact angle. The horizontal straight lines in Figure 2 depict friction forces for various contact angles and contact angle hysteresis, and the curved lines depict driving forces for a given gap between the electrode and the droplet. By adopting a superhydrophobic surface (typically θ_c = 170º, $\Delta\theta$ = 5º) with a NanoTurf height of 0.25 μm on 0.25 μm-thick SiO_2, we can expect 17.5 V of operation voltage. In comparison, a well-constructed EWOD device using 0.5 μm of silicon dioxide (relative permittivity $\varepsilon_r \cong 3.8$) coated with hydrophobic Cytop (typically θ_c = 112º, $\Delta\theta$ = 13º) would require almost 43 V.

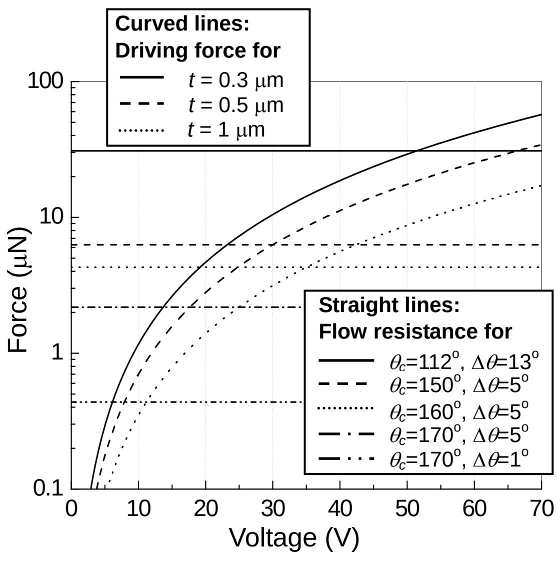

Figure 2. Force estimation on NanoTurf. Curved lines are electrostatic driving force for various NanoTurf heights. Horizontal straight lines are flow resistance for various contact angle (θ_c) and hysteresis ($\Delta\theta$).

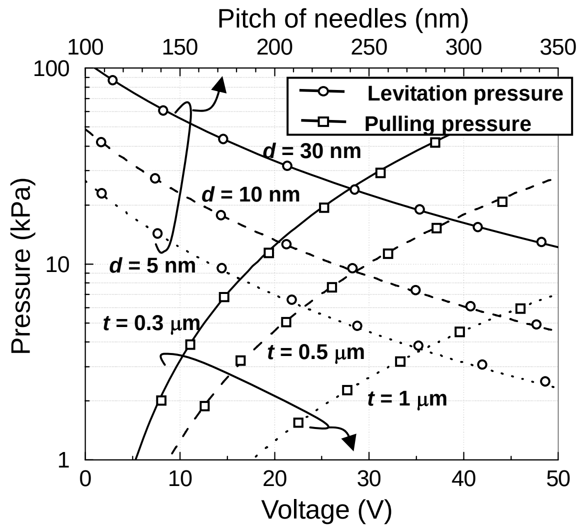

Figure 3. Maximum meniscus-suspension pressure (circular dots) for pitch of needles and electrostatic pulling pressure (rectangular dots) for applied voltage.

Another design consideration for NanoTurf is the periodicity (i.e., density) of nano needles. To levitate the liquid on top of NanoTurf against the electrostatic pulling down, the nano needles should be positioned dense enough to exert enough suspension by surface tension. The electrostatic pulling pressure and levitation pressure are roughly estimated by equations (4) and (5), respectively, and drawn in Figure 3.

$$P_{pull} = \frac{1}{8}\frac{\varepsilon_{eff} V^2}{t^2}, \tag{4}$$

$$P_{lev} = \gamma \cos\theta_c \frac{\pi d}{s^2 - 0.25\pi d^2}, \tag{5}$$

where ε_{eff} is the effective permittivity of double layers of NanoTurf ($\varepsilon_r \cong 1$) and SiO_2 ($\varepsilon_r \cong 3.8$), t is the distance between liquid and electrode, d is the diameter of the nano needle tip and s is the pitch of the needles. For a NanoTurf height of 0.25 μm on top of 0.25 μm-thick SiO_2 ($\varepsilon_{eff} \cong 2.5$), the pulling pressure at 30 V is about 10 kPa, which can be

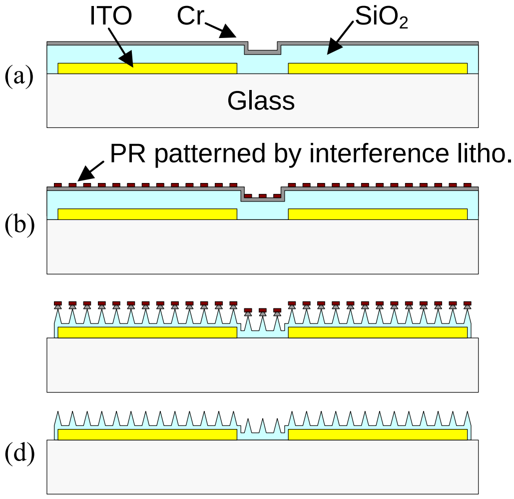

Figure 4. Fabrication Process. (a) ITO patterning. SiO_2 and Cr deposition.. (b) PR nano patterning using laser interference lithography. (c) Cr and SiO_2 etch. (d) Masking materials removal and SAM coating.

overcome by suspension pressure by surface tension if the pitch is less than 230 nm (assuming needle diameter d = 10 nm). In this work, the NanoTurf is designed to have a pitch of 200 nm.

3. FABRICATION

Figure 4 shows the fabrication process: (a) ITO (as electrode) was deposited on a glass wafer and patterned only on the bottom plate. Then PECVD SiO_2 and Cr were deposited. (b) Next, photoresist (PR) was nano-patterned by interference lithography [9]. (c) After patterning Cr by wet etching, SiO_2 was etched in ICP-RIE to form NanoTurfs. (d) After removing PR and Cr, a perfluorodecyltrichlorosilane (FDTS) hydrophobic self-assembled monolayer (SAM) was coated. (e) Finally, the two plates with NanoTurf are placed parallel by a spacer, squeezing a droplet in

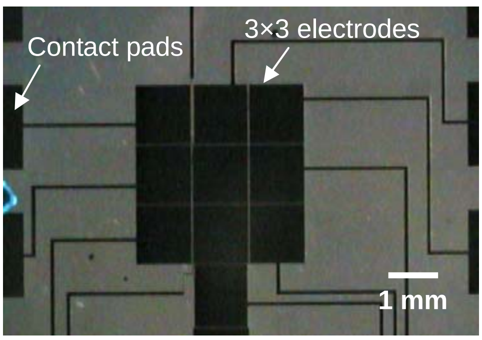

Figure 5. Fabricated device.

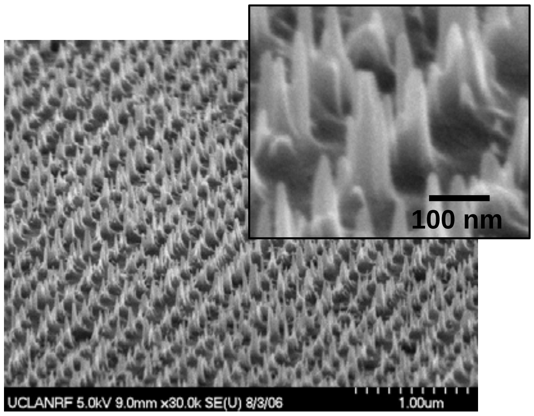

Figure 6. NanoTurf structure made of silicon dioxide.

between. Figure 5 shows the fabricated device with 3×3 electrodes. The NanoTurfs were successfully formed with a height of ~170 nm, a pitch of ~200 nm, and a tip diameter of ~30 nm (Figure 6).

4. EXPERIMENT

Figure 7 shows a droplet on the fabricated device, open and squeezed. The contact angle was measured at 169º. The angles when droplets start to slide were measured by a simple tilting experiment with 5 μL off water droplets. The sliding angle on a single plate was 3º, corresponding to ~5.5º of the contact angle hysteresis, much smaller than that on flat Cytop surfaces (13º). Using this value, the driving force is expected to be ~17.5 V from Figure 2 with a 0.5 μm gap between the liquid and the electrode in our design. The sliding angle of the droplet squeezed between two plates was measured at ~30º, representing the friction force of ~2.55 μN and an estimated threshold voltage of about 16 V from Eq. (3), which corresponds well with the single-plate analysis.

First, we ran actuation tests of a droplet on a single plate, similar to the previous reports [3] and [8]. The droplet was placed on top of a fabricated device, and an actuation signal was applied

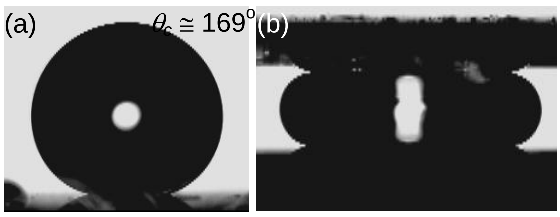

Figure 7. (a) Water droplet on NanoTurf. (b) Droplet between two NanoTurf plates.

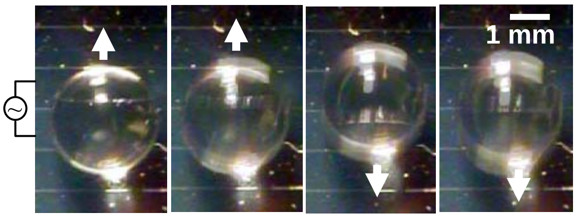

Figure 8. A sequence of pictures showing an oscillatory droplet on superhydrophobic bottom plate with no cover (at 10 V_{rms}, 10 Hz).

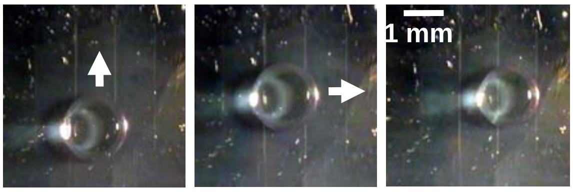

Figure 9. A sequence of pictures showing a translational droplet between two superhydrophobic surfaces (at 24V_{rms}, 10 Hz).

between the two electrodes below the droplet (Figure 8). The oscillation motion of the droplet was observed at 10 V_{rms} (sinusoidal signal of 10 Hz), which is much lower compared with hydrophobic textured surfaces.

Next, we ran actuation tests of a droplet between two plates. The bottom plate has patterned electrodes, and the top plate has a blank ground electrode, as shown in Figure 1. We applied 100 Hz sinusoidal signals with various amplitudes. The droplet started to move at 20 V_{rms} and was transported to the next electrodes (i.e., continuous sliding obtained) at 24 V_{rms}. In comparison, the droplet was estimated by equations (1) and (2) to start moving at 17.5 V.

5. CONCLUSIONS

In an attempt to reduce the operation voltages of most voltage-driven droplet actuation mechanisms including EWOD, we introduced dielectric NanoTurf in place of a flat dielectric layer to cover the driving electrodes. Because of the large contact angle and very small contact angle hysteresis, the friction of a droplet on a superhydrophobic NanoTurf surface is much smaller. By making the NanoTurf height (i.e., thickness) small, the electrostatic driving force was kept high for a voltage. The small pitch of densely-populated needles on the NanoTurf allowed the surface tension to resist against the menisci collapsing by electrostatic pulling-down. By combining the low friction and the effective driving on the thin NanoTurf covering electrodes, the driving voltage was significantly reduced (43 V → 25 V). The proposed scheme is expected to widen the application areas of droplet-based digital microfluidics by lowering the voltage requirement.

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