JUMPING FORCE OF COALESCING DROPLETS ON A SUPERHYDROPHOBIC SURFACE

T-V. Nguyen[1], T. Mouterde[2], H. Takahashi[1], D. Quéré[2] and I. Shimoyama[1]
[1]The University of Tokyo, Tokyo, JAPAN
[2] École Polytechnique, Paris, FRANCE

ABSTRACT

We report a method to directly measure the jumping force during the coalescence of two water droplets on a superhydrophobic surface using a MEMS-based force sensor as shown in Figure 1(a). The sensor is designed to measure the jumping force during the coalescence of two droplets whose radii are several hundred µm. The measurement results show that the maximum jumping force could be more than 10 times larger than the total weight of the merged droplet. Moreover, the impulse calculated from the measured force was on the same order with the jumping momentum of the droplet. Therefore, our sensor is a useful tool to investigate the mechanism of coalescence-induced droplet jumping.

INTRODUCTION

When two small droplets coalesce on a super-hydrophobic surface, the released energy due to the reduction of surface area can induce the jumping of the merged droplet. This phenomenon is beneficial in various applications including self-cleaning surface, water condensation and anti-fogging because it allows the removal of the droplets from the surface without requiring any external energy [1-4]. One important topic in the study of coalescence-induced droplet jumping is to predict the jumping velocity of the droplet after coalescence. In previous studies, models based on energy balance were used to analyze the jumping velocity of the merged droplet [1, 2]. However, it has been difficult to achieve a model that can precisely predict the jumping velocity because as shown in Figure 1(b), the released surface energy is converted to not only kinetic energy (jumping) but also the oscillation energy which corresponds to the vibration of the droplet caused by the coalescence. This oscillation energy cannot be easily analyzed due to the complicated shape of the droplet.

To understand the mechanism of the coalescence-induced droplet jumping, it is important to reveal the interaction force between the droplets and the surface, which plays the role of boundary condition for the motions of the droplets. During the coalescence, the vertical motion of the droplet's center of mass is determined by only gravity and the total normal force acting on the contact area between the droplets and the substrate. Therefore, if we can reveal this normal force, it is possible to obtain the jumping velocity regardless on the oscillation of the droplet.

In this study, we used a MEMS-based force sensor to directly measure the normal force during the coalescence of two water droplets on the plate of the sensor. By making the surface of the plate superhydrophobic, it is possible to induce the jumping of the merged droplet since the adhesion of the droplets to the plate becomes significantly low. Herein, we report on the design, fabrication and evaluation of the sensor. Using the fabricated sensor, we demonstrate a direct measurement of the jumping force during the coalescence of two sub-millimeter diameter droplets.

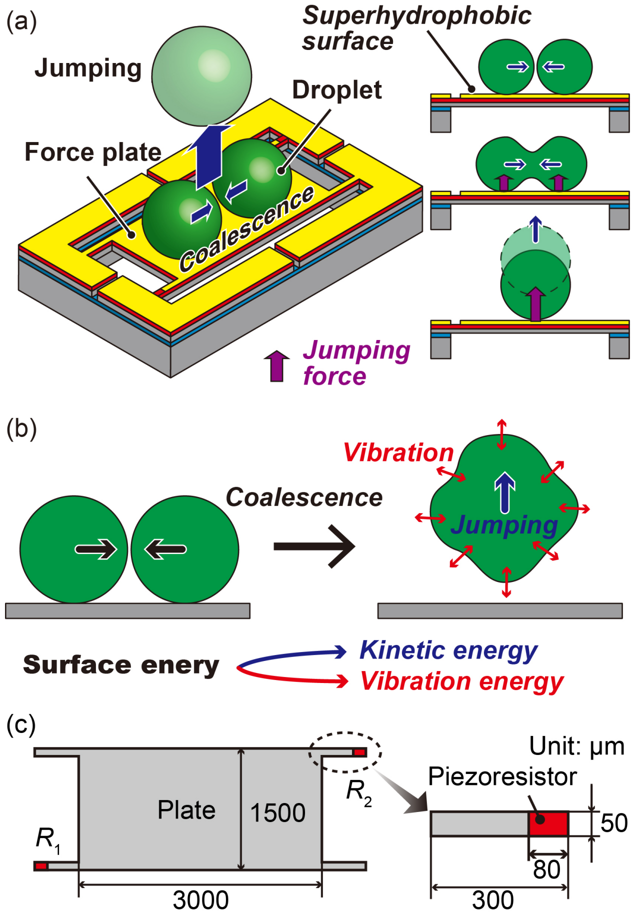

Figure 1: (a) Conceptual illustration of this study. Normal force acting on the substrate during the coalescence of two droplets is directly measured by a MEMS-based piezoresistive force sensor.
(b) Energy conversion during droplet coalescence.
(c) Design parameters of the sensor.

DESIGN AND FABRICATION

The sensor consists of a plate and four supporting beams as shown in Figure 1 (a). The sensing principle of the sensor is based on the piezoresistive effect [5-8]. Two of the four beams have a piezoresistor formed at their roots and the normal force acting on the plate is calculated from the fractional resistance changes of these piezoresistors. The design parameters of the sensor are shown in Figure 1 (c). The measurement target in this study is the coalescence of droplets whose diameters are smaller than 1 mm. Therefore, the size of the plate was designed to be 3 mm length and 1.5 mm width on which two droplets can be deposited. The length and width of the beam are 300 µm

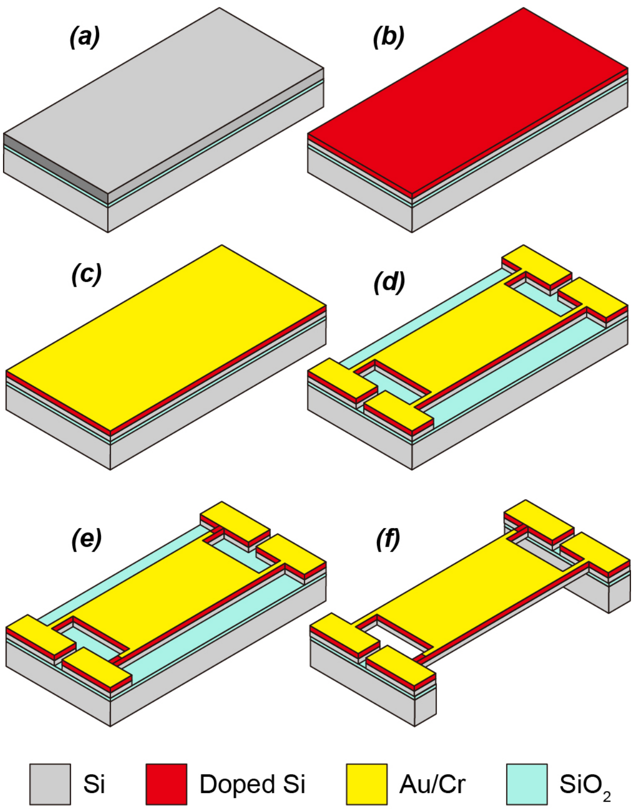

Figure 2: Fabrication process of the sensor.

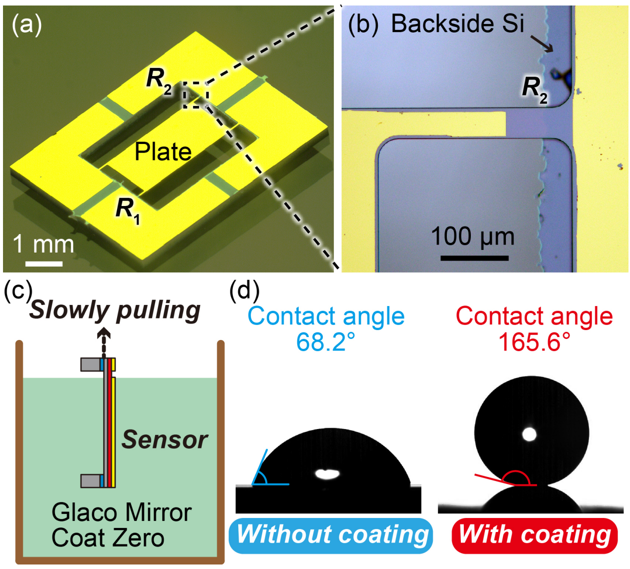

Figure 3: (a) Photograph of the fabricated sensor. (b) Zoomed-in view of a piezoresistor. (c) Superhydrophobic coating of the sensor surface. (d) Effect of the coating on the contact angle of a droplet on the sensor surface.

and 50 μm, respectively. The thicknesses of the plate and the beams are both 5 μm. Moreover, the length of the piezoresistor was designed to be 80 μm as depicted in Figure 1 (c).

The fabrication process of the sensor is shown in Figure 2. The details of the fabrication process can be found elsewhere [9]. The sensor was fabricated from a silicon-on-insulator wafer (SOI, thickness: 5/2/300 μm). A piezoresistive layer was formed on the device layer of the SOI by rapid thermal diffusion [10]. Then, Cr and Au

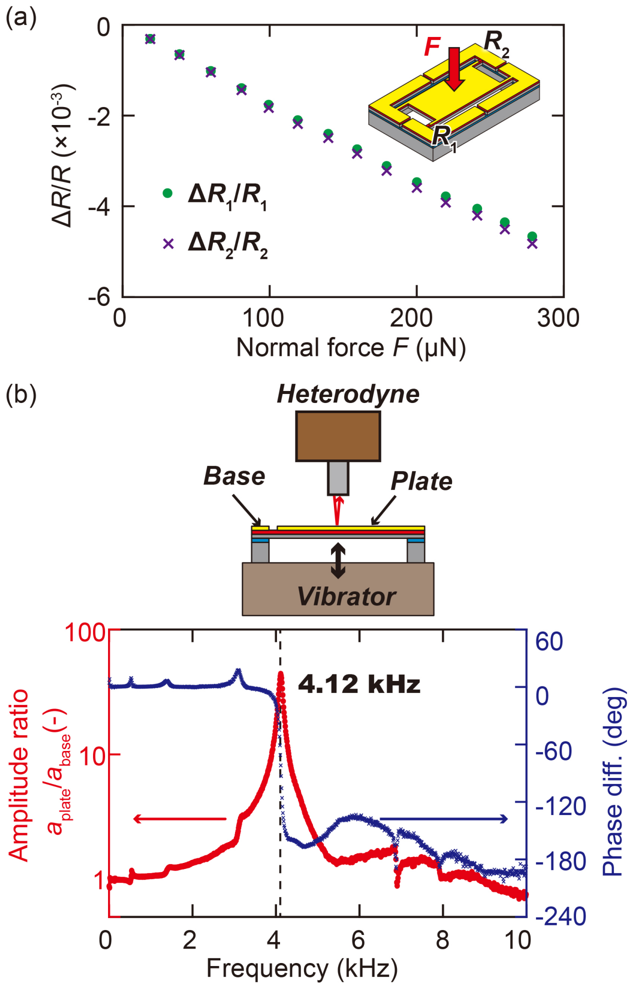

Figure 4: Calibration and measurement of the frequency response of the sensor.

layers with thicknesses of 5 and 50 nm were deposited on the piezoresistive layer. The plate was formed by patterning the Au/Cr layers and etching the device silicon layer using DRIE. Next, the piezoresitors were formed by the second patterning of the Au/Cr layers. Finally, the handle silicon layer was etched and the sensor was released after etching the box layer using HF vapor.

Photographs of the fabricated sensor chip and a piezoresistor are shown in Figure 3 (a) and (b), respectively. The fabricated sensor was dipped in a commercial superhydrophobic coating solution (Glaco Mirror Coat "Zero", Soft 99 Co., Japan) as shown in Figure 3 (c). After removing the sensor from the solution, the sensor was baked at 150 degree Celsius inside an oven for one hour. After the coating, the sensor surface became superhydrophobic as the contact angle of a water droplet deposited on the sensor surface was approximately 167°, as shown in Figure 3 (d).

EXPERIMENTS AND RESULTS

Sensor evaluation

The fabricated sensor was calibrated using a setup reported previously [11]. The normal force applied to the sensor surface was measured using a commercial load cell (LVS-5GA, Kyowa Electronic Instruments, Japan). The calibration result is shown in Figure 4 (a). The fractional resistance changes of both the piezoresistors R_1 and R_2 were linear with the applied force. The proportional coefficients between $\Delta R_1/R_1$, $\Delta R_2/R_2$ and the applied force were 1.70×10^{-5} and 1.77×10^{-5} (μN^{-1}), respectively. Because our measurement circuit is able to detect a fractional resistance change of less than 10^{-5} (-), the sensing resolution of the sensor design is less than 1 μN, which corresponds to the weight of ~0.1 μL water droplet (diameter: ~0.6 mm).

The frequency characteristic of the sensor response was also measured using a setup shown in Figure 4 (b). Vibration was applied to the sensor using a mini-shaker (Type 4810, Brüel & Kjær Inc., Denmark). The frequency of the sensor was swept from 10 Hz to 10 kHz and the vibration amplitude of the plate surface and that of the base were measured using a heterodyne. The measurement results shown in the graph indicate that the first resonant frequency of the sensor was approximately 4.12 kHz. Because the coalescence of two μL-sized droplets occurs during several milliseconds as shown later in the next section, the fabricated sensor is suitable for the measurement target.

Measurement of the coalescence induced jumping force

Using the fabricated sensor, we demonstrate the measurement of the jumping force during the coalescence of two water droplets. The droplets were deposited on the sensor surface using a glass needle connected to a syringe pump. The diameters of the droplets were ~1.08 mm and 0.78 mm. To make two droplets coalesce, we gently dragged the small droplet toward the big one using the glass needle. A high speed camera (FASTCAM SA-X, Photron Inc., Japan) was used to capture the motion of the droplets during the coalescence.

The images obtained from the high speed camera are shown in Figure 5 (a) and the measured normal force is shown in Figure 5 (b). Here the positive direction of normal force is defined to be the same with gravity. Initially, the value of the normal force was positive due to the weight of the droplet. The coalescence of two droplet started at t = ~3 ms, immediately followed by the occurrence of capillary waves travelling on the surfaces of droplets. At t = ~4 ms, two droplets temporarily took off from the plate as the contact areas were detached by the capillary waves and the normal force became zero. As the motion of the droplets were redirected into vertical direction, the merged droplet became into contact with the plate again and the normal force started to increase. The maximum value of the normal force F_{max} = ~101 μN was reached at t = ~5.3 ms. This maximum normal force was approximately 11 times larger than the total weight of two droplets. From t = ~6.7 ms, the merged droplet started to jump from the surface. Before the detachment of the droplet, the normal force became slightly negative due to the adhesion of the liquid to the surface.

From the images of the high speed camera, the jumping velocity was estimated to be ~4.7 mm/s, and the corresponding jumping momentum was ~0.044 μNs. On the other hand, the impulse incorporating with the normal force could be obtained as the integration of the measured force subtracted by the weight of the merged droplet. The calculated impulse was 0.065 μNs, which was on the same order with the jumping momentum of the merged droplet.

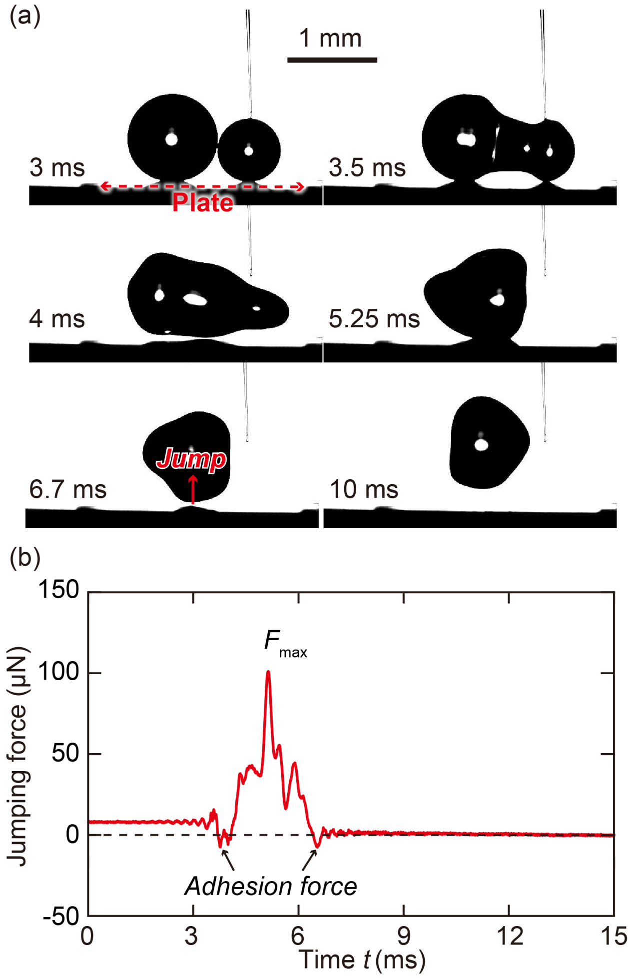

Figure 5: (a) Images of the high speed camera showing the coalescence of two water droplets. (b) Jumping force during the coalescence.

CONCLUSION

In conclusion, we have proposed a method to directly measure the jumping force during the coalescence of water droplets on a superhydrophobic surface. The measurement was realized by using a MEMS-based force plate whose surface was made superhydrophobic. We reported the design, fabrication and evaluation of the sensor. Finally, using the fabricated sensor, we demonstrate the measurement of normal force during the coalescence-induced jumping of two small water droplets. We confirmed that the impulse calculated from the measured force was in the same order with the jumping momentum of the droplet obtained from the high speed camera. Therefore, the proposed method is useful to investigate the coalescence-induced droplet jumping on superhydrophobic surfaces.

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CONTACT

*T.V. Nguyen, tel: +81-3-58416318;
vinh@leopard.t.u-tokyo.ac.jp