MERCURY DROPLET ACTUATION USING NEW DESIGN OF ELECTRODES FOR LONG WORKING RANGE

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Abstract: This paper reports an electrowetting-based mercury droplet actuator with a long working range. The actuator uses micro pillars on the surface to reduce the wettability of a mercury droplet as well as a new design of driving electrodes, which theoretically allows an unlimited working range. A mercury droplet was actuated by 1 Hz AC driving voltage of 300 V_{p-p}. It moved step by step synchronously with the switching of driving voltage. However, the droplet was trapped at some points probably due to charge-up at the top of the micro pillars. This actually limited the working range. The observed maximum working range was ca. 200 μm, which is much longer than previous reported values.

Key words: Mercury, Droplet actuation, Electrowetting, Thermal switch

1. INTRODUCTION

A micro thermal switch is applicable for the micro heat engines [1], micro refrigerators, micro reactors etc. To date, many types of thermal switch have been proposed, e.g. one using heat pipes [2], controlling thermal conductivity by a magnetic field [3] and switching contact and noncontact state [1, 4–6].

The most important characteristic of the thermal switches is ON/OFF ratio of the thermal conductance. To obtain a high ON/OFF ratio, thermal contact resistance between two objects in ON state must be reduced. In solid-solid contact condition, however, micro and nano scale surface roughness limits real contact area, and thus increases the thermal contact resistance.

To overcome this problem, high contact pressure should be applied, or a soft intermediate layer with high thermal conductance should be used. However, it is difficult to generate high contact pressure by micro actuators, and such an intermediate layer is not readily available. Another possible solution is to use solid-liquid contact, because the liquid fills the roughness of the solid contact surface. Mercury is an ideal material for this purpose because of its high thermal conductivity in comparison with other liquid materials such as water and oil.

In addition to reducing contact resistance in ON state, thermal isolation in OFF state is also important. Longer distance between two objects leads to better thermal isolation, and thus long working range of the droplet is required. Furthermore, the long working range allows loose tolerance of the droplet diameter.

Weiss *et al.* used a mercury droplet for a thermal switch [1], and obtained the maximum ON/OFF ratio of ca. 130, which is the highest value that was ever reported for micro thermal switches. However, a large external piezoelectric actuator was used in their device, preventing miniaturization. For most of applications in micro scale, a thermal switch monolithically integrated with a micro actuator is preferred.

To date, several types of integrated mercury droplet actuator are proposed. Lee *et al.* moved a mercury droplet by electrocapillary [7]. The working range was quite large, but the actuator can be operated only in liquid (e.g. water). It was used for a micro pump, but cannot be used for a thermal switch due to thermal conduction through the liquid. Zeng *et al.* [8] and Shen *et al.* [9] used electrostatic force to move the mercury droplet vertically and laterally, respectively. However, the working range of both actuators was not sufficient for the thermal switch.

From these points of view, the purpose of this study is to demonstrate long working range mercury droplet actuation in air or vacuum by an integrated small actuator. As mentioned above, the potential application is the thermal switch, but there are other applications such as electrical switches [9], optical switches [10] and optical scanners.

2. DESIGN

2.1 Actuator surface structure

In the previous study, we fabricated an electrowetting-based mercury droplet actuator [11], and confirmed the maximum working range of ca. 230 μm, which was the longest one that was ever reported to the best of our knowledge. However, the droplet motion was not repeatable probably due to the charge-up of the actuator surface. We thought that reducing the contact area and wettability of the droplet would solve this problem, and fabricated a lot of pyramidal micro pillars on the actuator surface, as shown Fig. 1. To avoid electrical shorting, the actuator surface is

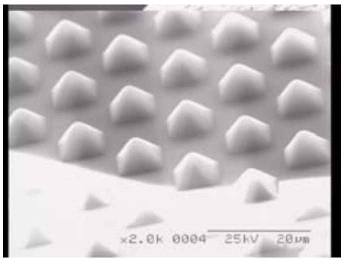

Figure 1. SEM image of micro pillars.

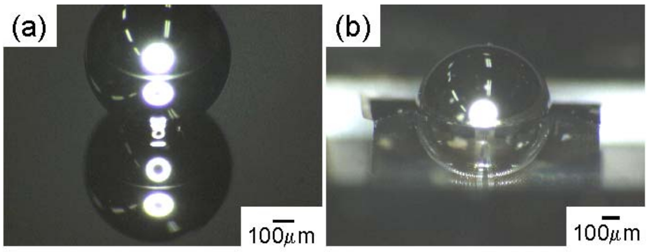

Figure 2. Mercury droplet on (a) a flat silicon dioxide and (b) micro pillars.

covered with silicon dioxide.

Figure 2 compares mercury droplets on a flat silicon dioxide and the micro pillars. The mercury droplet on the micro pillars is almost a complete sphere, demonstrating considerable reduction of the wettability. This effect is well known as "lotus leaf effect".

2.2 Driving electrode design

The electrode design used in our previous study [11] cannot be used for long working range actuation in conjunction with the micro pillars, because the contact area of the mercury droplet is considerably small. In this study, therefore, we newly designed the driving electrodes.

Figure 3 shows the structure of the mercury droplet actuator. The driving electrodes like a grating are embedded in an electrically and thermally insulated membrane. The pitch of the driving electrodes is identical to that of the micro pillars. Figure 4 illustrates the actuation mechanism. When the driving electrode beside the contact points is energized by AC voltage (Fig. 4 (a)), it attracts and moves the droplet by the pitch (Fig. 4 (b)). The next electrode is then energized and moves the droplet again. By repeating this step, the droplet is actuated in a long working range. In this study, the pitch and width of the driving electrodes are 20 μm and 10 μm, respectively. The total of 54 electrodes forms 6 phase electrode groups.

The actuation voltage is designed using a simplified model shown in Fig. 5. The cross-sectional shape of the mercury droplet between the micro pillars is assumed to be a circular arc. h and R in Fig. 5 represent pillar height and radius of the contact line formed by supporting four micro pillars, respectively. Considering the balance of the surface tension and electrostatic force, the maximum driving voltage that can be applied without touching the sphere and the bottom of the micro pillars is represented as

$$V = \sqrt{\frac{\sigma h^3}{\varepsilon R^2}},$$

where σ is the surface tension of the mercury, and ε is the dielectric constant of the vacuum. The maximum applicable voltage is expected to be 260 V, assuming

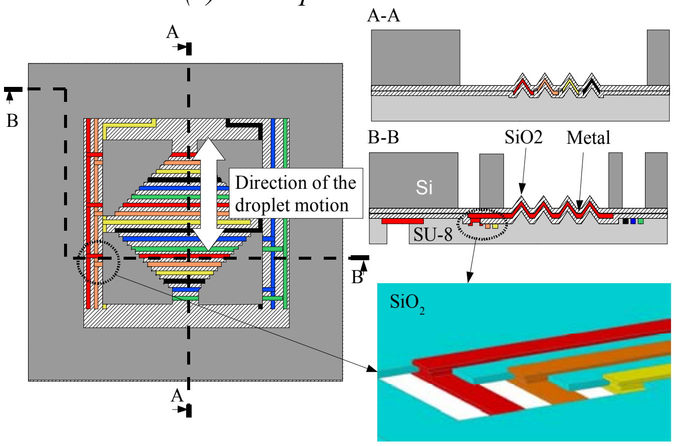

Figure 3. Structure of the mercury droplet actuator.

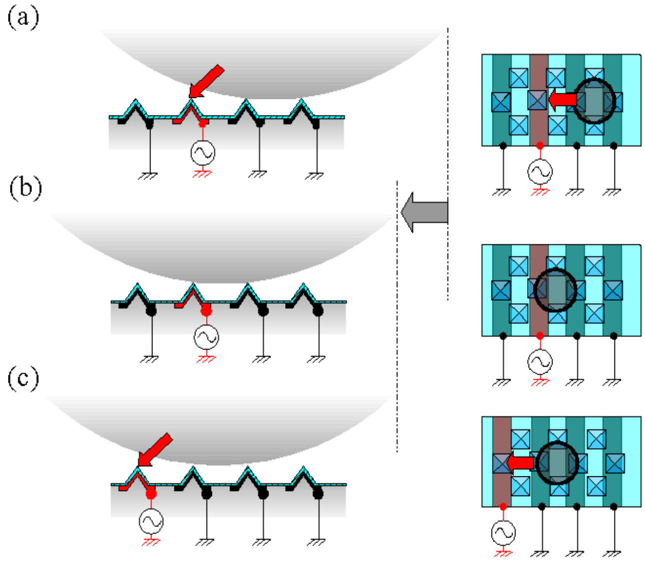

Figure 4. Droplet working mechanism: (a) An energized electrode attracts the droplet. (b) The droplet moves by a pitch of driving electrodes. (c) The next electrode is energized and attracts the droplet again.

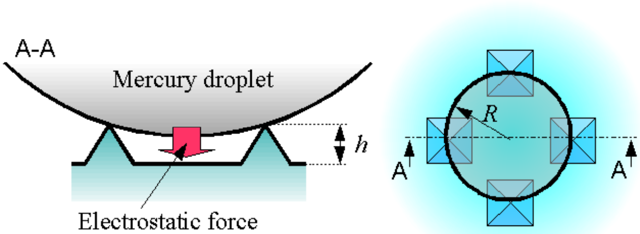

Figure 5. Diagram for estimating the maximum driving voltage.

that h is 5 μm and R is 10 μm.

3. FABRICATION

Figure 6 shows the fabrication process of the mercury droplet actuator. Silicon dioxide is thermally grown on a silicon substrate and etched partly by BHF (buffered hydrofluoric acid) using a photoresist mask. Using the patterned silicon dioxide as an etching mask, silicon is anisotropically etched by TMAH (tetra methyl ammonium hydroxide) to form pyramidal shape pits. After that, all silicon dioxide is etched by BHF, and then new silicon dioxide is thermally grown. Gold and chrome are deposited on it and partially etched away using a photoresist mask to form the driving electrodes. Further on it, silicon dioxide is deposited by PECVD.

Electrical contact via holes are formed in the silicon dioxide layer by BHF, and interconnecting metal electrodes are formed in a manner similar to that for the driving electrodes. After that, thick photosensitive polymer (SU-8) is spin-deposited and patterned. Silicon dioxide on the other side is partly removed by BHF to make etching windows, and silicon is etched by DRIE (deep reactive ion etching) to release a suspended SiO_2/SU-8 composite membrane. Finally, a mercury droplet is formed and placed using a micro syringe. The diameter of the droplet is approximately 400 μm.

4. EVALUATION

4.1 Experimental setup

Figure 7 shows experimental apparatus. The fabricated device is placed in a transparent acrylic chamber to prevent mercury vapour from diffusing to the ambient. AC voltage is used for driving to avoid the charge-up of the silicon dioxide. Each electrode is connected to a switch, being turned on in order. The motion of the mercury droplet is observed by a microscope with a CCD camera placed above the acrylic chamber.

4.2 Experimental result

The driving voltage was set at 300 V_{p-p}, i.e. 150 V in amplitude, which is smaller than the limit value calculated in Section 2.2. The experimental apparatus was not equipped with a droplet position sensor, and thus the switching frequency of the driving electrode is set at 1 Hz, which might be slow enough for the droplet not to step out.

Figure 8 shows an example of actuation results. The mercury droplet moved step by step synchronously with the switching of driving voltage. However, the droplet was trapped at some points.

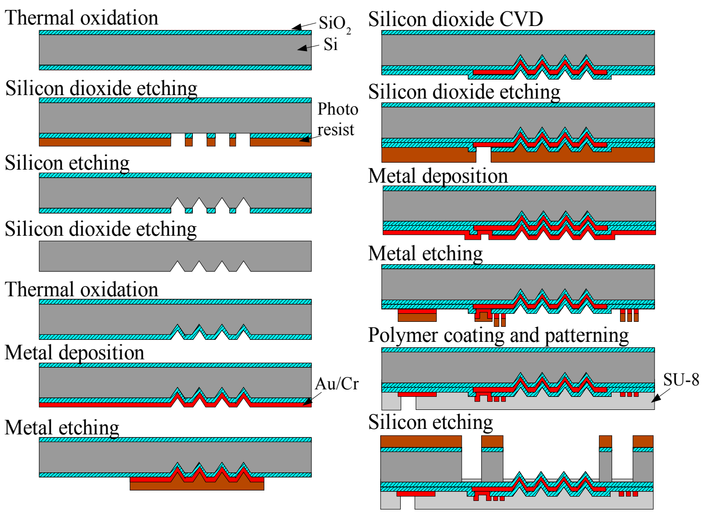

Figure 6. Fabrication process.

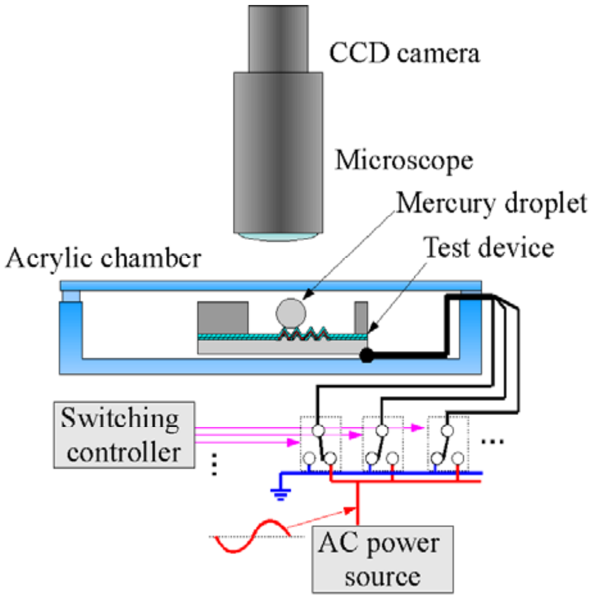

Figure 7. Experimental apparatus.

Sometimes, the droplet could escape from the trapped point in several trial runs. If the trapping force probably due to charge-up was stronger than the actuation force, however, it only oscillated around the trapped point. Actually, this limited the maximum working range of the droplet. The observed maximum working range was ca. 200 μm.

5. DISCUSSION

Theoretically, the proposed method of mercury droplet actuation allows unlimited working range. However, the actual working range was limited by the trapping of the droplet probably due to the charge-up at the top of the micro pillars. The silicon dioxide surface which once contacted mercury could be charged up by contact electrification as reported in Ref.

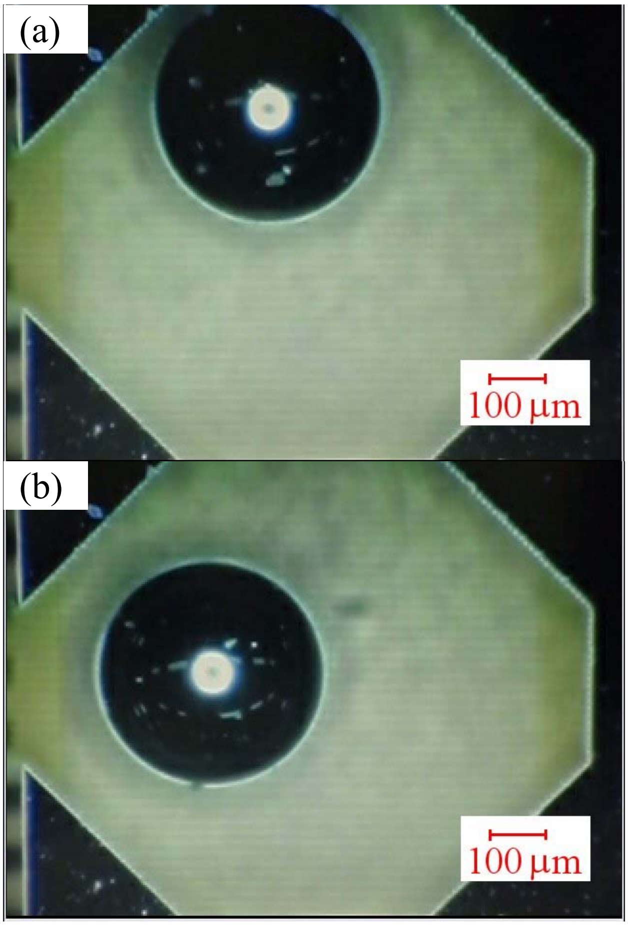

Figure 8. Actuation result: (a) Initial state, (b) Final state, in which the droplet was trapped.

[12]. To avoid this charge-up problem, coating the actuator surface with a semi-insulating film such as silicon-rich silicon dioxide can be effective.

Another problem is weak actuation force. This is serious especially for the application to thermal switches, because the actuation force must be large enough to detach the mercury droplet from thermal transfer walls. At the present, therefore, the developed actuator should be used for such applications that the mercury droplet needs not to touch the sidewalls, for example, optical switches.

6. CONCLUSION

An electrowetting-based mercury droplet actuator with a long working range was designed, fabricated and tested. The actuator uses micro pillars on the surface to reduce the wettability of a mercury droplet as well as a new design of driving electrodes, which theoretically allows an unlimited working range.

A mercury droplet of 400 µm in diameter was actuated by 1 Hz AC driving voltage of 300 $V_{p\text{-}p}$. It moved step by step synchronously with the switching of driving voltage. However, the droplet was trapped at some points probably due to charge-up at the top of the micro pillars by contact electrification. This actually limited the working range, which was ca. 200 µm in this study. The charge-up problem will be solved by coating the actuator surface with a semi-insulating film such as silicon-rich silicon dioxide.

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