Flat-Shape Capacitive Sensor of Droplet Contact-Angle for Electrowetting-on-Dielectric Microfluidic Systems

Tomohiro Kodaniguchi Akira Tsuchiya Toshiyuki Inoue Keiji Kishine

Department of Electronic System Engineering
The University of Shiga Prefecture
2500, Hassaka-cho, Hikone, Shiga 522-8533 Japan
tsuchiya.a@e.usp.ac.jp

Abstract— This paper proposes a fully-electrical and flat-shape sensor for contact-angle of droplet on microfluidic systems. Contact-angle sensor that can be implemented in microfluidic system has not been developed although contact angle is an essential parameter for electrowetting-on-dielectric microfluidic systems. To realize flat-shape sensor, we employ planar-type capacitors for contact-angle estimation. By improving the estimation procedure, the proposed method covers wide range from 40 degrees to 140 degrees. We verified the proposed method by electromagnetic simulation and measurement of proof-of-concept model.

I. Introduction

Microfluidic systems are systems that handle micro-droplet and proceed experiments. According to many advantages, for example less amount of samples and parallel experiments, microfluidic systems have been employed in biomedical region and it is expected to spread to other regions, such as food, environment and so on. There are several mechanisms to handle droplet, and we focus on electrowetting-on-dielectric (EWOD) microfluidic [1]. EWOD microfluidic system control droplets by electrode array embedded at the surface of device. Electrowetting is a method to change the contact angle of droplet by electric field. This means that the contact angle is an essential parameter that determines behavior of droplets. Conventional contact-angle measurement uses camera [2] or special device [3]. Although the contact angle is a crucial characteristic for EWOD microfluidic systems, it is difficult to realize contact-angle measurement in microfluidic system. To implement in microfluidic systems, the measurement system should be small and flat shape. One of the solutions is capacitive sensor [4, 5]. However, measurement range should cover over 90 degrees because EWOD microfluidic system often uses high-repellency coating or material to make the contact angle higher.

In this paper, we improve our preliminary work [5]. Ref. [5] achieved flat-shape, however, there is a problems in the measurement range and the accuracy. The method in Ref. [5] can measure up to 90 degrees, and the accuracy gets worse around 90 degrees. We improve the estimation procedure and enlarge the measurement range to over 90 degrees. Simulation results show the proposed method achieves good agreement from 40 degrees to 140 degrees. Also, we verify a proof-of-concept (POC) model. Since the proposed method is based on static capacitance, we the POC model is scaled-up from actual device size. To obtain precise shape of liquid, we create water-containers by a 3D printer. Measurement by the POC model, the estimation achieves good accurary from 60 degrees to 120 degrees. On the other hand, the estimation error is larger than simulation, especially when the contact angle is small. The contribution of this paper is demonstration of a proof-of-concept of flat-shape contact-angle sensor.

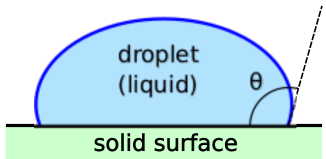

Fig. 1. Definition of contact angle.

The rest of this paper is organized as follows. Section II explains the fundamentals of contact-angle measurement. Section III describes the proposed method. Then, Section IV verifies by electromagnetic simulation and Section V shows measurement results of a POC model. Section VI summarize the discussion.

II. Droplet Contact-Angle

This section briefly explains needs of contact-angle measurement. When a droplet is on a solid surface, contact angle means the angle between the solid surface and the droplet surface. Fig. 1 shows the definition. The contact angle is determined by the surface tension of the solid surface and the droplet.

In EWOD microfluidic systems, electric field makes the contact angle smaller. Fig. 2 shows the mechanism of droplet handling. In EWOD microfluidic system, electrode array is embedded in the solid surface. We can change the pattern of high/low voltage of electrodes. That makes nonuniform electric field across the droplet. Then, the droplet shape deformed as shown in Fig. 2. Near high-low gap, electric field is strong

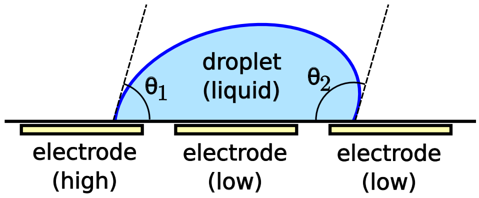

Fig. 2. Droplet deformation by electrowetting.

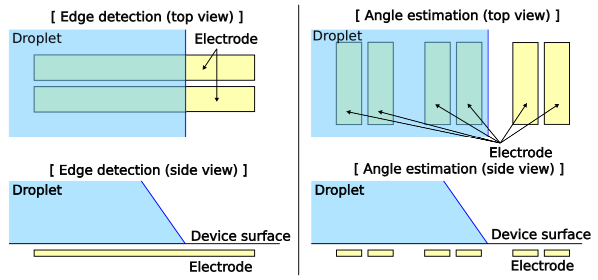

Fig. 3. Structure of capacitive sensors.

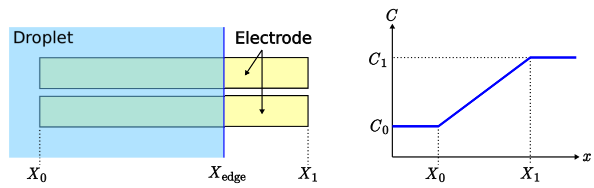

Fig. 4. Edge detection by the edge-detecting capacitor.

and the contact angle θ_1 becomes small. On the other hand, near low-low gap, the contact angle θ_2 does not change drastically. This deformation makes force to move the droplet. So, the contact angle is an essential parameter for EWOD microfluidic systems and high repellency coating or material is used to makes the contact angle higher.

Contact angle depends on the surface tension of the solid surface and the droplet. So, the contact angle is different for liquid by liquid. If the contact angle becomes small, the deformation by electric field becomes small and the droplet might fail to move. Also, degradation of the solid surface can make the contact angle smaller. This means that the contact angle may change during experiments. Thus, contact-angle monitoring system in EWOD microfluidic system is needed. However, conventional contact-angle measurement uses camera, and the contact angle is calculated from the droplet shape in the photo. It is difficult to implement such system in EWOD microfluidic systems. To tackle this challenge, our goal is developing a contact-angle sensor with following features.

- Flat-shape and small size to embed at the surface of device
- Electrical measurement
- Wide measurement range (> 90 deg. is necessary.)

III. Proposed Method

This section introduces the proposed sensor and the estimation procedure. First, the structure of the capacitive sensor proposed in our preliminary work [5]. Then, improved estimation procedure is described.

A. *Preliminary Work of Capacitive Contact-Angle Sensor*

In the preliminary work [5], we use planar capacitors to realize flat surface. Fig. 3 shows the structure of the capacitors. There are two types of capacitors, one is for edge detection, and another is for contact angle estimation.

The preliminary work [5] is based on the tangent line of a circular region around the angle-estimation capacitor. However, the method only covers less than 90-degree. Also, the method in Ref. [5] becomes inaccurate around 90-degree contact angle. The results in Ref. [5] shows that the method cannot recognize from 70-degree to 90-degree. This is crucial for microfluidic systems because EWOD microfluidic systems uses high-repellency surface and the contact angle of droplet is assumed 90-degree or higher.

B. *Estimation Procedure*

Here, we propose an improved method of contact-angle estimation. The basic idea is to use rectangular region instead of the circular region in Ref. [5]. The estimation procedure is as follows.

B.1. Edge Detection

Detecting of liquid edge by a capacitor is well-known and widely used as water-level sensor. The edge-detecting capacitor works like a capacitive water-level sensor. Fig. 4 shows the concept of edge detecting. When the capacitor is partially covered by the droplet, the capacitance between the electrodes is determined by the location of the edge. If we can assume the capacitance is proportional to the covered area, the relationship between the capacitance C and the edge location X_{edge} is

$$\frac{C - C_0}{C_1 - C_0} = \frac{X_{\text{edge}} - X_0}{X_1 - X_0}. \tag{1}$$

Thus, we can know the edge location X_{edge} from the edge-detecting capacitor.

B.2. Selecting Angle-Estimating Capacitor

To estimate the contact-angle, we have to know one more point of the droplet surface. Here, we assume that we can define a rectangular region where the liquid affects the capacitance.

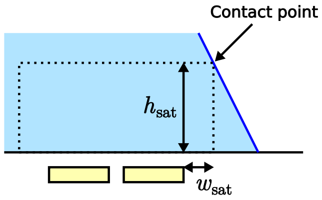

Fig. 5. A rectangular region that affects the capacitance.

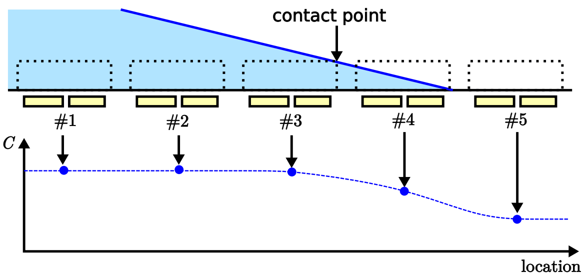

Fig. 6. A rectangular region that affects the capacitance.

Fig. 5 shows the rectangular region of the angle-estimating capacitor. The height of the region is h_{sat} from the device surface, and the width is $2w_{sat}$ wider than the width of the electrodes. As shown in Fig. 3, the angle-estimating capacitors are aligned as array. Fig. 6 shows the capacitance of each capacitor. When the rectangular region is filled by liquid (capacitors #1 and #2), the capacitance saturates. On the other hands, the rectangular region includes air, the capacitance value becomes smaller (capacitors #4 and #5). The capacitor #3 is at the border between the location where the capacitance saturates and the location where the capacitance starts decreasing. In this case, we can expect the rectangular region of the capacitor #3 contacts to the surface of the droplet. The location of the selected capacitor is known. The parameters h_{sat} and w_{sat} can be obtained by electromagnetic simulation. Thus, we can estimate the contact point. We will verify the assumption in Section IV.

B.3. Contact-Angle Estimation

After finding a suitable capacitor, we can estimate the contact angle by simple trigonometric function. Fig. 7 shows the positional relation obtained by Step B.1 and Step B.2. From Fig. 7, the contact angle θ is expressed as follows.

$$\theta = \begin{cases} \tan^{-1}(h_{sat}/\Delta X) & (\theta < 90 \text{ deg.}) \\ 180 - \tan^{-1}(h_{sat}/\Delta X) & (\theta > 90 \text{ deg.}) \end{cases} \quad (2)$$

IV. Verification by Electromagnetic Simulation

This section verifies the proposed method by a static 3D electromagnetic simulator [6]. A key point of the proposed

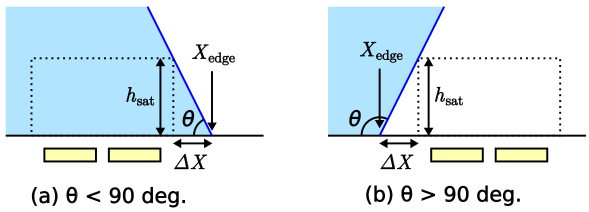

Fig. 7. Contact-angle estimation.

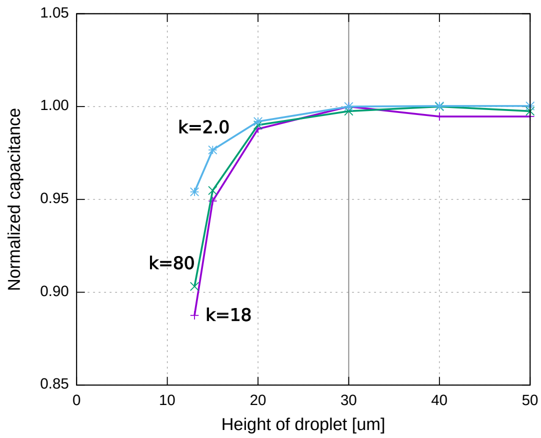

Fig. 8. Verification of the capacitance saturation by the thickness of droplet.

method is the assumption in Step B.2. Fig. 8 shows the capacitance versus the thickness of the droplet. To evaluate the impact of the permittivity, the relative permittivity is varied from 2.0 (oil) to 80 (water). The capacitance is normalized by the capacitance value when the thickness h is large. As shown in Fig. 8, the capacitance saturates at $h = 30\ \mu$m and the saturation thickness is independent on the relative permittivity. Also, the verification about the width is shown in Fig. 9. When the relative permittivity k is from 18 (alcohol) to 80, the capacitance saturates at $w = 6\ \mu$m. When $k = 2.0$, the saturation width w_{sat} becomes 8 μm. The saturation width w_{sat} depends on the relative permittivity, however we can assume that w_{sat} is constant from $k = 18$ (alcohol) to $k = 80$ (water).

Now, we verify the contact angle estimation by simulation results. We select an angle-estimating capacitor which has 99% of the saturated capacitance. From the results of Figs. 8 and 9, we set the saturation thickness h_{sat} and the saturation width w_{sat} to 30 μm and 6 μm, respectively. Fig. 10 shows the estimation results. The estimation matches well in all contact-angle range. Even the relative permittivity changes, the estimation error is within the range from −12% to +15%. Therefore, the proposed method can estimate the contact angle in wide range of the contact angle and the relative permittivity.

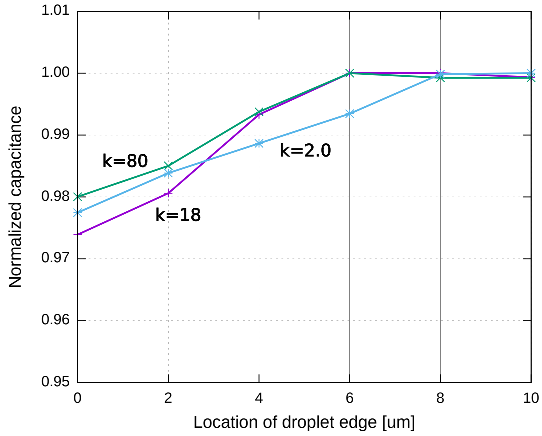

Fig. 9. Verification of the capacitance saturation by the width of the droplet.

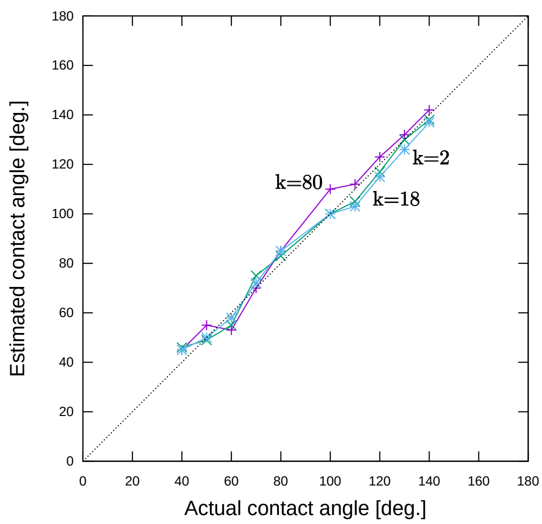

Fig. 10. Verification of estimated contact angle (simulation).

V. Verification by Proof-of-Concept Model Measurement

In this section, we verify the proposed method by measurement. Since it is difficult to realize droplets with various contact angle, we created a proof-of-concept (POC) model by a 3D-printer.

A. *Scaled-Model for Measurement*

To verify the proposed method by measurement, we have to prepare droplets with various contact angle. However, to obtain higher contact angle, very high-repellency coating or material is needed. Also, it is difficult to set the contact angle precisely. Thus, we created a POC-model shown in Fig. 11. 5-mm wide and 0.07 mm thick copper tapes are used as electrodes. The spacing between the electrodes is 1 mm. On the electrodes, we put a container to determine the shape of liquid. The dimension of the container is shown in Fig. 11. We created

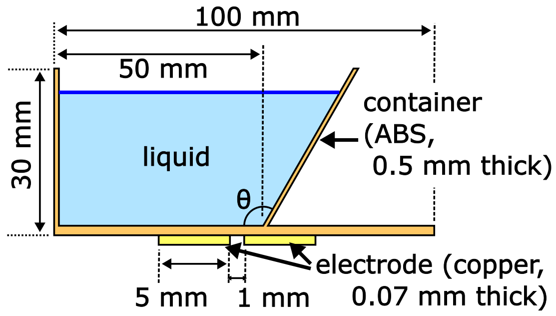

Fig. 11. Proof-of-concept-model for measurement (cross-section).

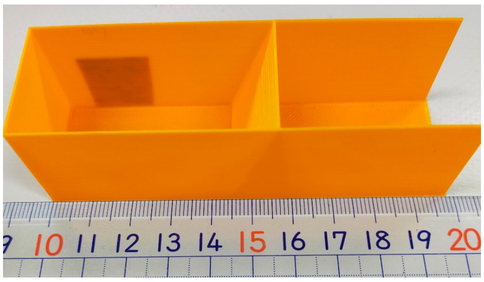

Fig. 12. Photo of liquid container created by a 3D-printer.

containers with various angle θ by a 3D printer. The containers mimic various contact angle of droplet. The material of the containers is ABS. To minimize the effect of the ABS wall, the thickness of the wall is 0.5 mm, the minimum thickness by the 3D printer. Fig. 12 shows a photo of a container. Since the container is much larger than actual droplet, the electrodes are also scaled up to 5-mm width. The scaled-model reproduces phenomena in actual size, because the proposed method is based on the static capacitance of the electrode. We measured the edge-detecting/angle-estimating capacitors by a desktop LCR meter (HIOKI IM3536). The liquid in the container is water.

B. *Measurement Results*

First, we verify the accuracy of the edge detection. Fig. 13 shows the estimated edge location by the edge-detecting capacitor. Both high contact angle (120 deg.) and low contact angle (45 deg.), the estimation matches the actual edge location, however the estimation error becomes larger in the case of 45 degrees.

Then, we evaluated contact-angle estimation. Fig. 14 shows the estimation results from the measured capacitance. The estimation works when the contact angle is large. When the contact angle is low, the estimation is not monotonic. We guess that the error cause is the container of the water. In this experiment, the thickness of the wall and the bottom is 0.5 mm. However, the wall and the bottom are not perfect plane, and the thickness has fluctuation. Also, the wall may affect edge

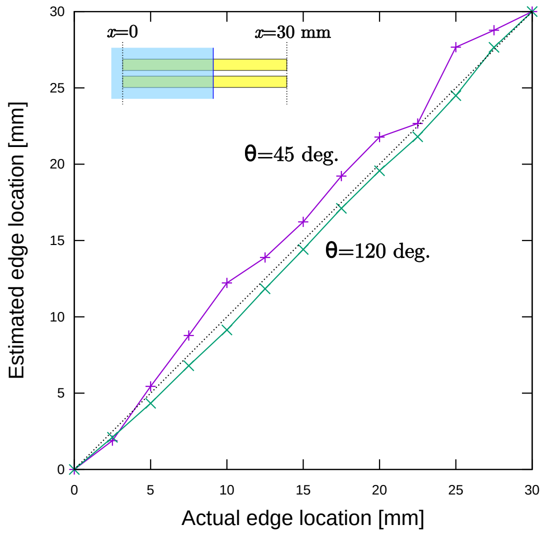

Fig. 13. Edge location estimation (measurement).

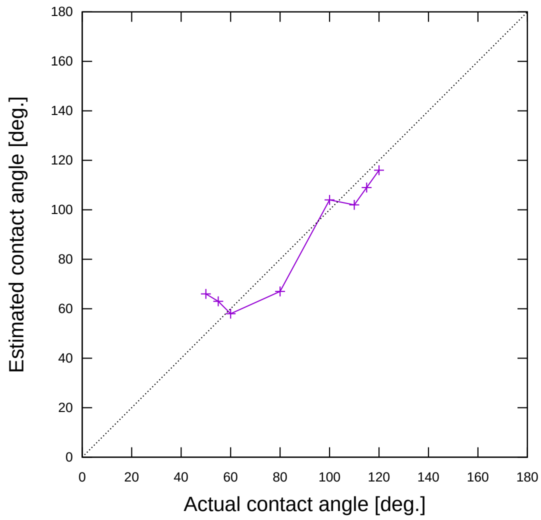

Fig. 14. Contact-angle estimation (measurement).

estimation. As shown in Fig. 13, error in edge estimation becomes large when the contact angle is small. Clarifying the error cause is our future work.

VI. Conclusion

We proposed a contact-angle estimation by fully-electrical and flat-shape sensor. For EWOD microfluidic systems, contact angle of droplet is a crucial parameter. Thus, contact-angle sensor which can be embedded in EWOD microfluidic system helps identification of droplet, control optimization, contamination prediction, self-test of coating degradation, and so on. This paper proposed a capacitive sensor consists of planar-type capacitors. By improving estimation procedure, the proposed method covers over 90-degree contact angle. We verify the proposed method by electromagnetic simulation and measurement of POC-model. Clarifying error cause and optimizing the structure of capacitors are our future work.

References

[1] L. Li, W. Kang, and D. Ye, "A Contact Angle Measurement Method for the Droplets in EWOD-based Chips," in *IEEE International Conference on Nano/Micro Engineered and Molecular Systems*, Jan. 2007, pp. 1071–1075.

[2] Z. Zeng, K. Zhang, W. Wang, W. Xu, and J. Zhou, "Portable Electrowetting Digital Microfluidics Analysis Platform for Chemiluminescence Sensing," *IEEE Sensors Journal*, vol. 16, no. 11, pp. 4531–4536, Jun. 2016.

[3] B. Murray and S. Narayanan, "The Role of Wettability on the Response of a Quartz crystal Microbalance Loaded with a Sessile Droplet," *Scientific RepoRtS*, vol. 9, no. 17289, Nov 2019.

[4] S. Choi and J. Lee, "Electrowetting interfacial tension measurement system," in *IEEE SENSORS*, Nov. 2015, pp. 1–3.

[5] A. Tsuchiya, T. Inoue, and K. Kishine, "Capacitive Sensor for Contact Angle Estimation of Droplet on Microfluidic Chip," in *2019 IEEE Asia-Pacific Microwave Conference (APMC)*, 2019, pp. 1584–1586.

[6] Ansys, *Q3D Extractor*, 2021.