Volume and Concentration Identification by Using an Electrowetting on Dielectric Device

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***Abstract*— An ultra-sensitive electrowetting on dielectric (EWOD) capacitance measurement system is proposed in this study. A 24-bit integrated circuit (IC) capacitance-to-digital (CDC) sensor is used to convert the capacitance changes caused by variations in droplet volume and concentration to digital data. A 2.3 mm by 2.3 mm printed circuit board (PCB) based electrode pair is used to sense the analog capacitance change. The capacitance of pure water and NaCl solutions are tested by the CDC system. Desktop-drawing software is used to fix the position of the droplet to obtain a small capacitance deviation of 10 fF. Result shows the CDC system can resolve the capacitance changes caused by adding 0.1 micro-liter droplets or by increasing the NaCl concentration by 1%. The digital output of the sensor is interface-friendly to microcontrollers.**

Keywords—electro-wetting; capacitance; capacitance to digital converter (CDC); printed circuit board (PCB) microfluidics

I. INTRODUCTION

Electrowetting on dielectric (EWOD) is a promising microfluidic actuation technique [1-3]. EWOD can be used to improve the throughput and the reliability of biological experiments. Small liquid droplet can be created, actuated, merged and split on a EWOD platform, so the small chemical droplet preparation can be controlled electrically instead of manually. Efforts have been taken to make electrical portion of the EWOD system more automated and intelligent. For example, a fuzzy PID control system was used to optimize droplet actuation in [4]. A real-time feedback control circuit was applied for volume-dependent droplet creation in [5]. Droplet composition and volume status monitor was employed for high efficient droplet mixing in [6]. In [7] a morphometry and velocimetry measuring system was proposed for droplet tracking. The most important part of any intelligent feedback system is the front sensing component. The accuracy and reliability of the sensed signal dominate the judgment of the backend digital signal processing system. The capacitive sensor should be sensitive to the droplet parameters, including the droplet volume, composition and position. Capacitance is one of the most sensitive parameters to subtle droplet volume and composition changes.

The droplet introduced variations in capacitance has been used to measure the speed of the droplet movement [8], to identify the composition of the dynamic droplets and to estimate the position of the droplet on the EWOD platform [9]. Most of the previous capacitance measurement techniques are based on a simple oscillator circuit [10] or a bench capacitance meter [6, 9, 11], which suffer from low resolution, low throughput and incompatible interfaces to an external digital system. In this study, an ultra-high resolution (24-bit) commercial IC (Integrated Circuit) is used to identify the volume and concentration variations of a droplet on a printed circuit board (PCB) based EWOD platform [12]. The results presented in this paper are useful for further studies of using a commercial IC CDC for intelligent control of specific biological animal tissue staining experiments.

II. MATERIALS AND METHODS

A. PCB-substrate EWOD Device

The capacitive sensor is fabricated using a standard (FR-4, glass epoxy) double-sided PCB process (Advanced Circuits, Tempe, AZ, USA). The electrodes are 2.3 mm x 2.3 mm square bare copper spaced 0.3 mm apart as seen in Fig. 1. A plastic layer (15 μm thick Saran Wrap) [12] is used as the dielectric layer for the electro-wetting device. There are two types of EWOD configurations. One is the single-plate (Fig. 2a) configuration, another one is the dual-plate configuration (Fig. 2b). In the single-plate configuration, the probes of the capacitance measurement circuit are connected between the two bottom electrodes. In the dual-plate configuration, the probes are connected between the top and the bottom electrodes. Single-plate EWOD is used in this study because it is easier to add and remove liquid between the electrodes (access is available, unimpeded, directly above the electrodes).

B. Capacitance Measurement System Design

A high resolution capacitance-to-digital converter (CDC) (AD7745, Analog Device, Inc., MA, USA) is used for the front-end capacitance measurement. The AD7745 has a resolution of 24-bits. Without using an extension circuit (in the CDC Block) shown in Fig. 3, the CDC's measurement range is 4 pF. The measurement range can be extended to 48 pF if the extension circuit is applied. (The extension circuit includes the op-amp seen in Fig. 3. Additonal details can be found on the AD7745's datasheet). AD7745 has a delta-sigma ADC to convert the analog capacitance data to digital signals, and communicate with microcontrollers through I2C serial port. The digital data is stored in three 8-bit registers before transmitting to the outside world by the I2C serial port. A 16-bit, 80-pin micro-controller (PIC24f96J, Microchip, USA) is used to receive the capacitance data from the CDC and forward to an LCD monitor for display. At the same time the same capacitance data package is sent to a PC through a UART serial communication port for a real-time display.

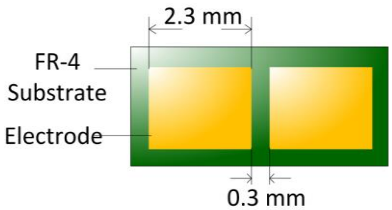

Figure 1 – Single-plate EWOD capacitance sensor.

C. Capacitance Measurement

The capacitances of pure water and NaCl solutions were tested on the EWOD platform. The capacitance of the droplet is volume and concentration dependent. A 0.5 μL (the pippette has a dispensing range of 0.5 μL to 10 μL in steps of 0.1 μL) droplet is added directly on the top of the two electrodes. Only the first 10 measurements were recorded since the small droplet will evaporate in 5 minutes. When varying the volume of the droplet an additional 0.5 μL droplet was added vertically to the center of the droplet by a pippette. The reason we keep the same direction and angle when adding the droplet is that the sensor is very sensitive. Adding the droplet from different angles will cause the droplet to change shapes resulting in tens of femto Farads' variation in the measured capacitance.

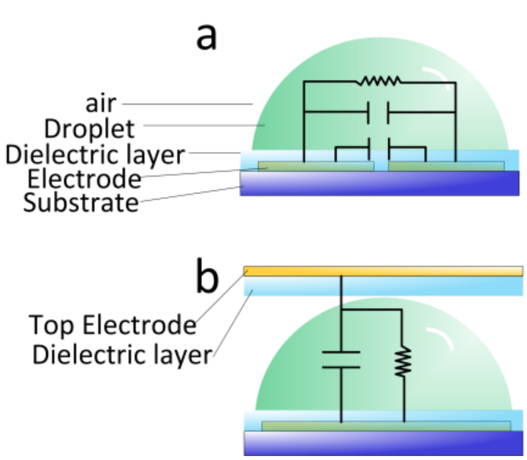

Figure 2 – a) Single-plate and b) dual-plate configuration.

To test the capacitance of various NaCl concentration on the EWOD platform, droplets of the same volume but different concentration are added and removed from the electrodes. Because the position deviation will cause errors when depositing the droplets manually, a fixed position for the droplet in each measurement is required. A microscope is used to fix the droplet position in this measurement (Fig. 4). Digital Microscope Suite 2.0 (a real-time video capture software, Celestron, LLC.) is used to show the real-time video on a PC. Desktop drawing software, Epic Pen, is used to draw the contours of the droplets directly on the captured video. The standard contour is created when the first droplet is deposited onto the electrode as seen in Fig. 4. The red contour will stay on the screen while the video continues to operate in real-time. This ensures that the following droplets are in the same position. Droplets with different concentrations are then fit into the contour before reading the measurement value.

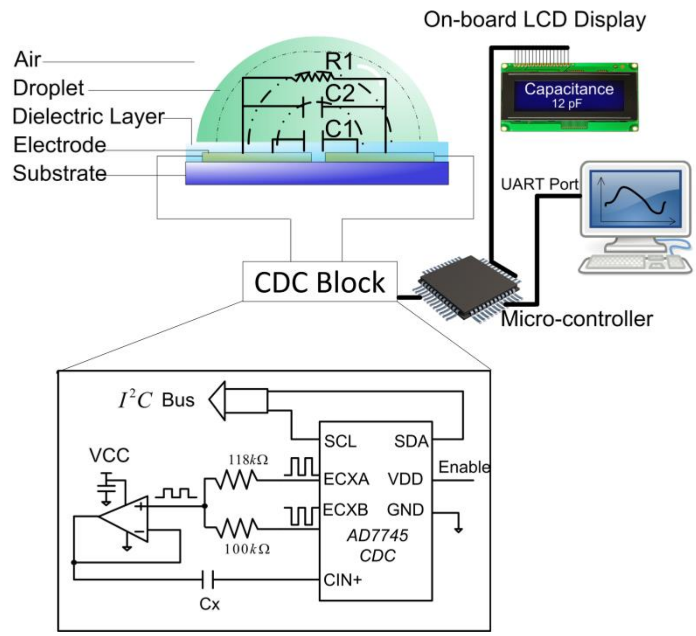

Figure 3 – Diagram of the CDC system

The PCB-based EWOD substrate has 9 electrode pairs. But in this study, only the first electrode pair is used for the capacitance measurement. The other electrodes are used for actuating, merging and spliting the droplets by applying a modulating high-voltage signal. The experiemental results of this work were reported in [12].

III. Results

As seen in Fig. 5 the capacitance changes dramatically with the volume of the droplet. The change in capacitance slows down when the droplet is larger than 3.5 μL. The electrode pair starts to be totally covered when the droplet is larger than 3.5 μL. Without a varying covered area, only the droplet's volume is affecting the capacitance. With a fixed position, the CDC sensor can resolve capacitance changes by 0.1 μL variation in volume (Fig. 5, see the small embedded illustration).

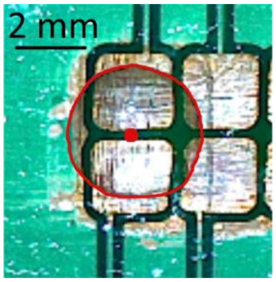

Figure – 4 A capture of the EWOD electrodes and a 3.5 μL droplet bridges the electrode pair. The droplet is marked by a red contour in the figure. When the contour is created, the following droplets should be fit in to the contour frame to ensure an unchanged droplet position.

As can be seen in Fig. 5 pure water has a larger dielectric constant than saline solutions, so the saline solution droplet has a lower capacitance than the water droplet. The deviations of the droplet capacitance measurement is small (around 10 fF, reduced by almost 10 times by using Epic Pen to fix the position and the shape of the droplets).

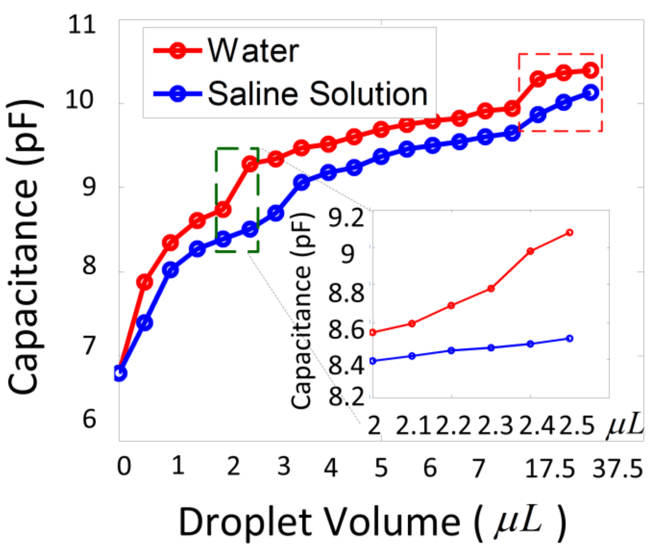

Figure 5 – Comparison of the capacitance with various droplet volume (0.5 μL in step). The green dashed square marks the selected volume range, 2 μL – 2.5 μL, for a 0.1 μL (minimum unit of the pipette) step measurement. The data marked by a red dashed square in the right corner is obtained by 17.5 μL, 27.5 and 37.5 μL. The rest of the data are from 0 μL to 7.5 μL, with a step of 0.5 μL.

A 1% concentration step is selected for the capacitance versus droplet concentration experiment, Fig. 6. The deviation of the measurement is about 10 fF. The CDC cannot resolve concentration changes smaller than 1%. The dielectric constant decreases when there are more ions dissociated, so as shown in Fig. 6, the capacitance decreases when the concentration increases.

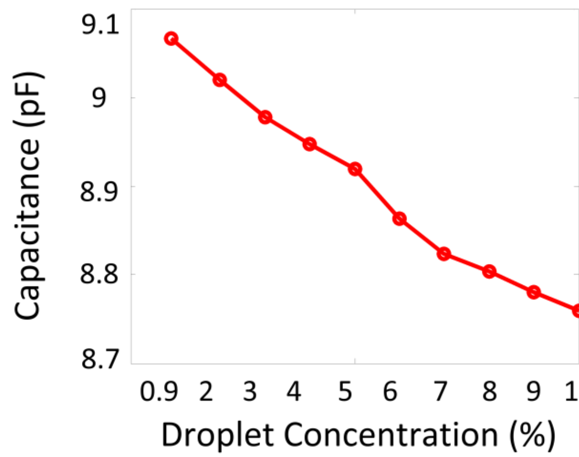

Figure 6 – Capacitance changes with different NaCl concentrations.

IV. CONCLUSION

A commercial high resolution CDC is used in an EWOD device for capacitance measurement. The applications of using high resolution capacitance sensor in microfluidics are numerous. For example, controlling the droplet creation and merging in an EWOD system [5, 6] and detecting the droplet position for an EWOD-based H&E [13] or immuno-histochemistry staining experiments.

The CDC used in this system is an all-in-one IC. Digital data can be directly read out from the I2C communication port by a microcontroller and a PC. By using the extension circuit (Fig. 3, CDC block), the measurement range can reach 48 pF. The theoretical resolution of the CDC is 4 fF. In the real measurement, the CDC system can resolve 0.1 μL changes in volume and 1% changes in concentration. If the position of the droplet is fixed, the capacitance deviation is around 10 fF.

A PCB-based EWOD device has several advantages over the platforms fabricated in a clean room. It has a lower cost and it can provide a fast fabricating technique for biologists who do not have clean room facilities. A larger EWOD array with distributed CDC sensors can be used to create a high throughput, intelligent microfluidic system. The capacitance sensor proposed in this study can improve the automation of some specific biological experiments. The data presented in this study may be an important reference for further studies towards the automation of animal tissue staining experiments.

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