Pinhole Effect Investigation in Electrowetting Dielectrics by Current Density Measurements

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Abstract. In this paper, we use current density measurement as an important diagnostic method to study the reliability of electrowetting devices. The current density distribution data is closely related to the early detection of malfunctions or failures in the devices. Here we use segmented cell technology to investigate the current density distributions in the top substrate to determine the initiation of dielectric breakdown. The current density measurements are further used to determine the signature of pinhole formation in the dielectric film. Different behavior is observed for dielectric failure under DC and AC voltages, and a sudden current change associated with vaporization of water is assumed to trigger the failure of the device.

1. Introduction

Electrowetting is a versatile tool to actuate liquid droplets in microfluidics because it enables control over fluid shape and flow by electrical signals alone. A popular microfluidic scheme using electrowetting is called ‘digital microfluidics (DMF)’ in which individual droplets are created from a reservoir and independently manipulated over a planar electrode array. Because of their flexibility and reconfigurability, DMF chips have been used in a wide range of lab-on-a-chip applications [1-3], demonstrating the potential of digital microfluidics as a miniature platform for biochemical applications.

In 1857, G. Lippmann observed a change in the capillary rise of mercury in the presence of electric charges, and advanced the principle of electro-capillarity as described by an equation which is now called the Lippmann law. This equation provides the principle of electrowetting. After that, many researchers have developed techniques that harness electrowetting effect for liquid actuation at scales below the capillary length $\lambda_c = \sqrt{\gamma/\rho g}$, where $\gamma$ is the liquid surface tension, $\rho$ is liquid density, and $g$ is gravitational acceleration. For water, the capillary length is about 2-3 mm. Apart from droplet actuation, electrowetting effect is used in variable-focus liquid lenses [4,5], optical displays [6, 7], mirrors [8], electrical[9] and thermal [10] switches, a tensiometer [11], rheometers [12] and many digital (droplet) microfluidic devices for bioanalysis.

A typical electrowetting-based microfluidic device consists of two parallel plates as shown in Figure 1. Droplets sandwiched between parallel plates can be manipulated by selectively applying voltage to an array of electrodes (here on the bottom). In this EW-based liquid microactuator, two types of insulating materials are used for device operation: a dielectric material to provide capacitance between the liquid and conductor, and a hydrophobic coating at the interface of liquid and insulator.
The dielectric and hydrophobic layers could be the same material, but this demands a rather rare combination of favorable electrical, mechanical and chemical properties.

![Figure 1](image_url) *Figure 1*. Cross-section of a parallel plate device to manipulate liquid droplets by electrowetting.

A popular term to describe the configuration in which a dielectric layer is introduced to separate the working liquid and actuation electrodes is Electrowetting-on-dielectric (EWOD). Despite the much higher voltage needed, EWOD is the preferred arrangement for most droplet actuation applications. The dielectric films prevent the working fluids from electrolysis, thereby allowing a much higher electric field before an electrical leakage or breakdown. And by coating a thin layer of hydrophobic material, the contact angle hysteresis is reduced and thus the working fluids move easily. In EWOD devices, much of the applied voltage is sustained by the dielectric layer, so the electric field distribution and associated electrowetting forces are linked primarily to the thickness and physical properties of the dielectric.

Generally, high dielectric constant and dielectric strength for the dielectric layer are important for maximizing the liquid actuation force. [13] For commercialization of EWOD based devices, the reliability of these devices becomes the most important issue. The failure of an EWOD based microactuator is mainly caused by dielectric breakdown, i.e., observation of bubbles or leakage current is considered to be the sign of negative result. In order to achieve a better understanding of the electrochemical processes in dielectric films and to investigate effects of operating conditions on the device failure, we use a current density distribution mapping technique to study the homogeneity of current distribution, and the results are consecutively used to investigate pinhole failures of the film and to determine their signatures in the current density distributions. This study aims at early detection of effective film thinning to avoid the resulting failure of the devices by adapting operation conditions.

2. **Experimental**

The test chip consists of two parallel substrates with the droplet sandwiched in between. A metal electrode is patterned on the bottom substrate, on top of which we coat a dielectric layer and a hydrophobic layer. The top substrate is a PCB board with current collector segments, and we also coat a hydrophobic layer on top of this substrate. We fabricate the bottom substrate on a glass plate and the size of the bottom electrode is 1 mm* 1 mm. In the fabrication process, the glass substrate cleaned with acetone and isopropanol was first sputtered with a 300 nm Au film. Then the Au film was patterned into an electrode by standard lithography process and wet etching. Subsequently, a Parylene layer was coated on top of the glass plate. The Parylene surface was then coated with a 100 nm Teflon-AF layer to finish the process of the bottom plate. A PCB board coated with Teflon-AF film was used as the top plate and connected to the bottom plate by proper spacers.
A segmented PCB plate with 25 segments for the single 1mm electrode was used in this experiment. The schematic of the segment in the PCB is shown in Figure 2. The current collector segments of the measuring board are gold plated to decrease the contact resistance and to avoid corrosion. The sensing wires on the segmented plate are connected to a data acquisition unit consisting of a multiplexer and a digital millimeter. The measurement setup works independently from the electric load unit and the voltage control system.

![Segmented PCB plate for current density distribution measurement.](image)

**Figure 2.** Segmented PCB plate for current density distribution measurement.

![Plots of segmented and global current density distribution.](image)

**Figure 3.** Plots of segmented and global current density distribution.

3. **Results and discussion**

In all voltage application measurements, a DI water droplet was placed between top and bottom substrates, and the droplet was large enough to cover the entire electrode area. There are several test methods for measuring the breakdown parameters depending on the way the stress voltage or stress current are applied. In our experiments we used the voltage ramp technique. The voltage is ramped with a constant ramp rate while the current through the insulator is being measured. When there is breakdown the current jumps to a high level and passes a pre-set current limit. The value of the voltage at which this happens is defined as the breakdown voltage.

Figure 3 shows the plots of global current density versus voltage as well as locally resolved currents for selected segments for the same experiment. In this measurement the thickness of the Parylene layer was 3 μm, and the voltage applied was DC positive.
From Figure 3 we can observe that at low voltage operation conditions, the global current density gradually increase. After the applied voltage exceeds a threshold value, the current density starts to increase abruptly, indicating the complete failure of the device function. The voltage dependences of segments B1, B2, C1, E4, and D5 during the same period are also displayed. It is found that the current density of the segments exhibit different current values. The current densities can reach exceptionally high values in some segments such as B1 and B2, while the current densities in E4 and D5 remain almost unchanged. This observation can be interpreted as indicative of a spreading membrane leakage: the leakage first started at the B1 segment and then appeared in B2, and furthermore, leakages in C1 and other segments gradually appeared, which were all located at the boundary of B1. But the segments far away from B1 showed no leakage.

The device was disassembled to explore the degradation mechanism by SEM. Figure 4 shows the optical image of the electrode and morphology of the dielectric layer. It is evident that the electrode has been damaged and cracks appeared near the degraded part, more pronounced is the appearance of pinholes in the dielectric layer. Considering the malfunction of the device, it is assumed that these structural changes may lead to the current leakage and device failure.

![Figure 4. Surface morphologies of the bottom electrode. (a) Optical image of the electrode. (b) SEM image of the dielectric layer.](image)

![Figure 5. (a) Breakdown voltage as a function of dielectric layer thickness under DC voltages. (b) Breakdown voltage as a function of voltage frequencies under AC voltages. (At 3 μm dielectric layer thickness.)](image)
We have measured the breakdown voltage under both positive and negative DC polarities for different film thicknesses. The breakdown voltage results are shown in Figure 5a. As can be seen, the breakdown voltage increases directly with film thickness, and positive polarity always shows a higher breakdown voltage than negative polarity. This polarity dependence can be explained by the internal field of the dielectric layer. [14] During its preparation process, the film is likely to form gradients in the positive and negative charges, this built-in internal field results in the polarity dependence of the breakdown voltage.

Because AC voltage is more widely used in electrowetting devices [15], we also tested AC breakdown voltages under different frequencies as shown in Figure 5b. The breakdown voltage increases directly with applied voltage frequency. This is because EWOD droplets have finite conductivity, the electrical field formed within the liquid as a response to the applied actuation voltage is a function of the actuation frequency. At low frequencies, the internal field is low, and EWOD forces are localized to the contact line. At high frequencies the electric field lines penetrate the liquid, so that the electromechanical response of liquid at high frequency is equivalent to the case of an insulating liquid. As a result, more voltage drop occurs within the liquid at high frequencies, and the effective voltage applied to the dielectric layer is greatly reduced. At high frequencies, the response of liquid under AC voltage is recognized as liquid dielectrophoresis.

4. Conclusions
In this paper, we use the method of segmented current density measurement as an important tool to study the reliability of electrowetting devices. The current density distribution data is closely related to the early detection of malfunctions or failures in the devices. The device failure was closely related to the signature of pinhole formation in the dielectric film. Different behavior is observed for dielectric failure under DC and AC voltages, the experimental results showed that the breakdown voltage depends on DC voltage polarity, and this polarity dependence is closely related to the thickness of the dielectric film. When AC voltage was applied, the breakdown voltage increased directly with voltage frequency. The frequency dependence is caused by the dielectric response of liquid at high frequencies.

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