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Electrowetting of a droplet under an AC Electric Fields

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교류 전압 하에서의 액적의 전기습윤현상

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Abstract

Electrowetting is prevailing for its various applicability on lap-on-a-chip, and MEMS devices, such as a pump, lens, micro-actuator in the micro-TAS technology. In the usual electrowetting, an AC power is preferred to DC practically. The AC electric field delays the contact angle-saturation, decreases the hysterisis, and is more stable in the view point of dielectric strength. But researches for AC electric field on electrowetting have not been reported very much yet. The different effect of AC on the electrowetting system, especially the effect of a frequency needs to be understood more concretely. In this work, the usual system for electrowetting, water droplet on the dielectric coated electrode (EWOD) is analyzed. Experimental study on the response of contact angles on input frequencies is performed. The simple circuit-model for EWOD system is considered to explain the experimental results. For more concrete understanding, the system is analyzed numerically, where simple AC-conduction model is used. Wetting tensions are analyzed under various input frequency to excavate the experimental results for the responses of the system on input frequencies.

1. Introduction

Electrowetting, the wettability change of liquid on the solid substrate by an external electric field, is prevailing due to the various applicability[1]. Commonly in any implemented system, conductive fluid confined on hydrophobic dielectric coated electrode is under an external electric field. Typically, two types of sources for electric fields are used the DC (Direct Current) and the AC (Alternating Current). In usual electrowetting system, the AC power is preferred to the DC for practical reasons. The AC electric field delays the contact angle-saturation, decreases the effect of the hysterisis including the prevention for permanent adsorption of charged species[2]. In addition, the AC is more stable in the point of dielectric strength.

Jones et al.[3]-[5] have reported the effect of the frequency on the electrowetting through experiments. They analyzed the systems using equivalent circuit with lumped parameter such as capacitance and conductance But, for the system such as a semi-circular droplet on the substrate, it may have some problem to be modeled using lumped parameters. And it can give more clear understanding to illustrate the concrete distribution of the electric force with respect to the input frequency. Therefore, in this work, the typical system for electrowetting, conductive droplet on the dielectric coated electrode is considered (Figure 1). The responses of the contact angle are obtained experimentally corresponding to various input frequencies. For more concrete understanding, the system is analyzed numerically. Wetting tensions are calculated with respect to various input frequencies to excavate the experimental results for the responses of the system on input frequencies.

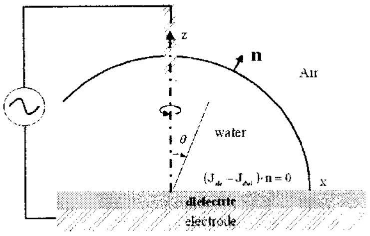

Figure 1. System for simulation

2. Numerical analysis

Figure 1 shows the computational domain. Let us consider a droplet on a dielectric-coated electrode, being immersed in another fluid (such as air) (see Figure 1). A cross-section of half the spherical droplet shown in Figure 1 can be imagined to rotate normal to the page. This assumption can be appropriate to a droplet with a diameter less than one millimeter usually. In the analysis, liquid droplet is assumed to be an leaky dielectric with isotropic electrical properties. Based on these assumptions, the system can be represented by an AC-conduction problem. Therefore, for the quasi-electrostatic field, using complex potential($\varphi = \varphi_r + j\varphi_i$), the Maxwell equations and charge conservation equation can cooperate to give the governing equations[6].

$$\begin{aligned} \nabla\cdot(\sigma\nabla\varphi_r) - \nabla\cdot(\omega\varepsilon\nabla\varphi_i) &= 0 \\ \nabla\cdot(\sigma\nabla\varphi_i) + \nabla\cdot(\omega\varepsilon\nabla\varphi_r) &= 0 \qquad (1) \end{aligned}$$

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Each one can be solved by the successive iteration numerically part by part. (using the package, CFD-ACE+, ESI-soft.). From the distribution of the electric potential and the electric field, the electrowetting tension (electric force per unit length along the three phase contact line, W_{el}) can be obtained from the integration of Maxwell stress tensor.

$$W_{\mathrm{el}} = \frac{\int_{\partial\Omega} (\mathbf{T}_A - \mathbf{T}_W)\cdot \mathbf{n} \cdot \mathbf{e}_x \mathrm{ds}}{2\pi R} \tag{2}$$

n is the outward unit normal vector to the droplet surface (See Figure 1). R is the radius of the droplet, $\mathbf{T}_A$ and $\mathbf{T}_W$ is the Maxwell stress tensor in the air and the water phase respectively. The Maxwell stress tensor (**T**) is, for the constant electric permittivity, ε , as following.

$$\mathbf{T} = \varepsilon\mathbf{E}\mathbf{E} - \frac{1}{2}\varepsilon E^2 \mathbf{I} \tag{3}$$

E is the electric field, $E=|\mathbf{E}|$, **I** is the second order isotropic tensor. It is noted that all electric fields are the root-mean-values, which denotes that the quantities obtained from eqs 5 and 6 are all time-averaged values.

3. Results and Discussions

Potential distribution was obtained in the high and low frequency. Figure 2 shows the distribution of the real part of the complex potential. $\Delta\varphi_{rms}$=143V.

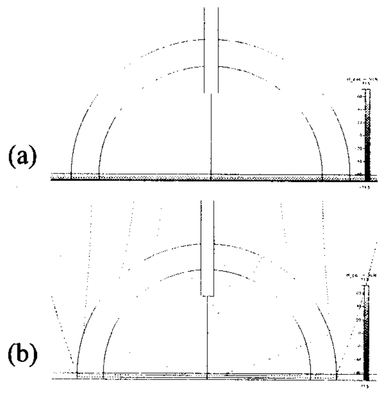

Figure 2. Potential contours (a) 0Hz (b) 100MHz
($\varphi_{top} = 71.5V$, $\varphi_{bottom} = -71.5V$)

In figure 2, Potential contours are represented for both limiting situations - low frequency and high frequency region. The domain was divided into two region for force calculation. The material properties for calculation are in table 1. σ and ϵ_r is electric conductivity and dielectric constant for each material respectively.

	Liquid	Air	Dielectric
$\sigma(S/m)$	2.4×10^{-6}	3.45×10^{-14}	1.25×10^{-18}
ϵ_r	78.5	1	2.7

Table 1. Electric properties for Numerical calculation

Time averaged wetting tension was calculated form the potential results. As mentioned, the force decreases as the input frequency increases. For low frequency, conductive liquid can behave as a perfect conductor due to sufficient time for ions or electrons to correspond with the change in polarity of the external potential. But, for high frequency, there is not enough time. Liquid can be regarded as a dielectric. Potential drop through the liquid. The electric field is hardly concentrated at the contact point. The wetting tension decreases (Figure 3).

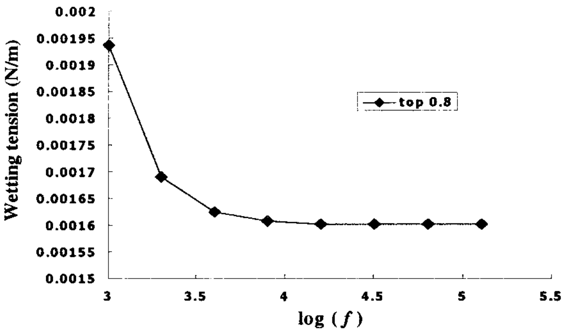

Figure 3. Electrowetting tension corresponding to frequency

Contact angle was measured by using image analysis for similar (not exactly matching) system to be simulated.

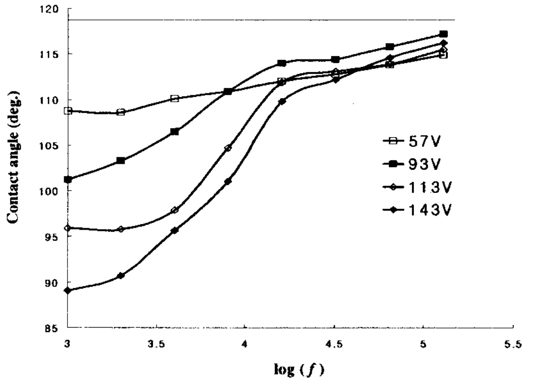

Figure 4. Contact angle corresponding to frequencies and input rms voltages (Horizontal line measns the angle without electric field.

For the same reason, the contact angle response can be understood. The driving force for electrowetting decreases as the frequency increases, then the deformation of liquid droplet becomes smaller.

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