# Modeling for Droplet Manipulation Based on "L-DEP on Electret"

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In a novel low-voltage electrostatic droplet manipulation method called liquid dielectrophoresis on electret (L-DEPOE), liquid molecules are polarized in the non-uniform electric field produced by the electret film, leading to net electrostatic forces which can drive the liquid to move. A dielectric droplet can move between two electrodes by switching an external capacitor using 5 V driven relays. The prototype is micro fabricated with 18 μm-thick corona charged parylene-C as the electret, hexadecane ($C_{16}H_{34}$) as the dielectric liquid, and ITO as the transparent electrodes. A RC circuit model is developed to obtain system potential distributions under proper initial conditions. The Maxwell stress tensor method is used to calculate the electrostatic force, and damping forces including viscous drag and contact angle hsysteresis (CAH) force are analysed in the hydrodynamic domain. A numerical computation for droplet motion traces based on the RC model and force analysis is performed and compared with the experimental results.

**Keywords** : liquid dielectrophoresis, droplet manipulation, microfluidics, Maxwell stress tensor, contact angle hysteresis

## 1. Introduction

Both electrowetting on dielectrics (EWOD) and liquid dielectrophoresis (L-DEP) attract much attention for the manipulation of micro droplets[1,2], but they usually need high driving voltage. We proposed a novel droplet manipulation method called "L-DEP on Electret (L-DEPOE)"[3]. By using electret as the voltage source, a droplet switching between two electrodes has been successfully demostrated with a low driving voltage.

The cross-sectional view of a L-DEPOE is shown in Fig. 1. A ~4 pL n-hexadecane ($C_{16}H_{34}$) dielectric droplet is placed between a top electret film and two bottom electrodes, separated by a 55 μm-thick SU-8 wall. 300 nm-thick ITO is used as transparent electrodes, and 5 μm-thick parylene-C is used as the dielectric coating. We found that parylene-C can be used as electret material with good charge stability in liquid environment. The surface potential for 18 μm-thick parylene electret is around –1200 V.

When a ~4 pF external capacitor is connected to either of the bottom electrodes, the droplet will leave the connected electrode to other. By operating a 5 V driven relay, the droplet can switch between two bottom electrodes.

## 2. Circuit Model

The L-DEPOE device can be modeled with a RC circuit model, as shown in Fig. 2. Liquid and the relay are modeled with resistors, respectively $R_2$, $R_3$ and $R$. Let $\sigma$ and $C$ are respectively the surface charge density of electret and the external capacitor. $C_{e1}$~$C_{e4}$ and $C_{b1}$~$C_{b4}$ represent equivalent capacitances of the electret and dielectric coating, and $C_1$, $C_4$ and $C_2$, $C_3$ are respectively capacitances corresponding to the air and liquid medium between the electret surface and the bottom electrode. All

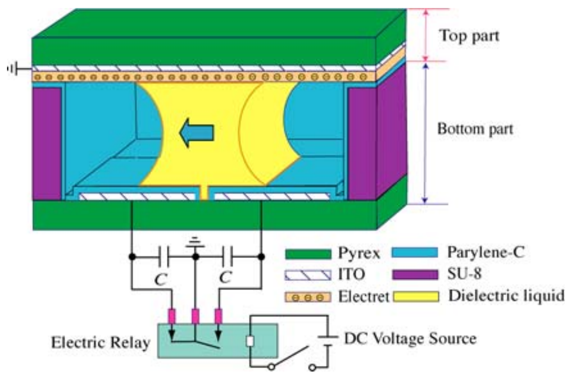


Figure 1. Structure of a L-DEPOE device.

capacitors are functions of the length $x$ occupied by the droplet on the right electrode. Voltages for these capacitors $V_{e1}$~$V_{e4}$, $V_1$~$V_4$, $V_{b1}$~$V_{b4}$ can be calculated as the following procedure.

By applying the Gauss's law to the left electret surface, we get

$$\varepsilon \frac{V}{h} - \varepsilon_e \frac{V_{e1}}{s} = \frac{\sigma}{\varepsilon_0} \quad (1)$$

$$\varepsilon_d \frac{V_{b2}}{d} - \varepsilon_e \frac{V_{e2}}{s} = \frac{\sigma}{\varepsilon_0} \quad (2)$$

where $\varepsilon_e$, $\varepsilon_d$, $\varepsilon$ and $\varepsilon_r$ are relative permittivity respectively for electret, the dielectric coating, air, and liquid, while $\varepsilon_0$ is the permittivity of vacuum. Parameters $s$, $d$ and $h$ are the thickness of the electret , the dielectric coating and the gap height.

According to the principle of charge conservation,

$$C_1 V_1 = C_{b1} V_{b1} \quad (3)$$

With the Kirchhoff's second and first laws, we have

$$V_{e1}+V_1+V_{b1}+V_C=0 \quad (4)$$

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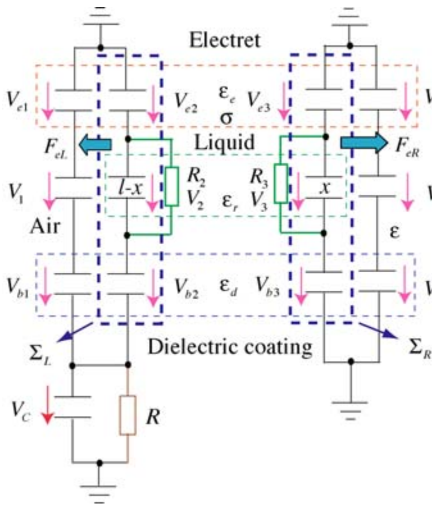


Figure 2. Circuit model of the L-DEPOE device.

$$V_{e2}+V_2+V_{b2}+V_C=0 \quad (5)$$

$$C_2\frac{\partial V_2}{\partial t}+\frac{V_2}{R_2}=C_{e2}\frac{\partial V_{e2}}{\partial t} \quad (6)$$

$$C_{b1}\frac{\partial V_{b1}}{\partial t}+C_{b2}\frac{\partial V_{b2}}{\partial t}=C\frac{\partial V_C}{\partial t}+\frac{V_C}{R} \quad (7)$$

Similarly we can formulate equations for the right side. From Eqs. (1)~(5), $V_{e1}$, $V_1$, $V_{b1}$, $V_{e2}$ and $V_{b2}$ can be obtained as functions of $V_2$ and $V_C$. Note that $V_2$ and $V_C$ contain time-dependant variable $x$, thus by combining Eq. (6), (7) with droplet dynamic equation Eq. (12), all time-dependant potential values can be numerically solved under the initial boundary condition, in which both bottom electrodes are grounded and 3 resistors are removed.

## 3. Force Analysis

Driving force can be directly calculated using the Maxwell stress tensor method[4]. In Fig. 2, by choosing close surfaces $\Sigma_L$ and $\Sigma_R$ for the droplet, potential differences yield Maxwell stress along the two surfaces, and the driving force on the droplet is

$$F_e=F_{eL}+F_{eR}=\varepsilon_e w\left(V_{e2}^2+V_{e4}^2-V_{e1}^2-V_{e3}^2\right)/2s+ w\left(\varepsilon_r V_2^2+\varepsilon V_4^2-\varepsilon V_1^2-\varepsilon_r V_3^2\right)/2h+\varepsilon_d w\left(V_{d2}^2+V_{d4}^2-V_{d1}^2-V_{d3}^2\right)/2d \quad (8)$$

where $w$ is the width of the droplet.

Since the Reynolds number $R_e$<<1, and the capillary number $C_a<10^{-3}$, one can conclude that surface tension is dominant, and inertial force can be ignored. Thus, we assume the viscous drag $F_\mu$ and the contact angle hysteresis (CAH) force $F_\theta$ as the damping forces. The droplet is assumed to have a 2D Poiseulle velocity profile, yielding

$$F_\mu \approx -\frac{12\mu w l}{h}\frac{dx}{dt} \quad (9)$$

where $\mu$ and $l$ are respectively viscosity and length of the droplet.

CAH can be divided into two parts: cricitcal CAH $\Delta\theta_{cr}$ when the droplet begin to move and dynamical CAH $\Delta\theta_d$. According to the molecular kinetic theory (MKT)[5], contact line friction caused by $\Delta\theta_d$ can be simply determined by the following correlation with a contact line friction factor $\zeta$:

$$F_\zeta \approx -2w\bullet\zeta\frac{dx}{dt} \quad (10)$$

Thus, $F_\theta$ can be expressed as the sum of a threshold force $F_{th}$ and the contact line friction:

$$F_\theta = F_{th}+F_\zeta \quad (11)$$

When the driving force $F_e$ is large enough to overcome $F_{th}$, the droplet motion begins. After some time, $F_e$ may decrease and become smaller than $F_{th}$, so that the droplet stops. The droplet motion is described as the following equations:

$$m\frac{d^2x}{dt^2}=F_e+F_\mu+F_\theta \quad (12)$$

where $m$ is the mass of the droplet.

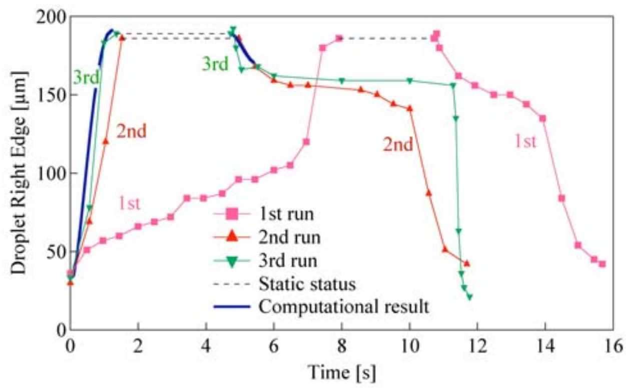


Figure 3. Computation and experimental results of the droplet motion

## 4. Calculation Result

With given device parameters, droplet position $x$ can be calculated as shown in Fig. 3. Three switching processes are performed in sequence. The first one obviously deviates from the other two, most likely due to the different wetting properties of contacting surfaces. With the fitting parameter $\zeta=3$, the computational result is in accordance with the data for the 2nd and 3rd runs. However, the experimentally observed two-segment traces on the right side cannot be reproduced. This somewhat strange phenomenon needs more investigations.

## 5. Conclusion

A model for L-DEPOE is developed considering the current leakage in the droplet and the contact line friction force.

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