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Sensors and Actuators A 141 (2008) 499–505

SENSORS AND ACTUATORS A PHYSICAL

www.elsevier.com/locate/sna

Push/pull actuation using opto-electrowetting

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Received 17 March 2007; received in revised form 25 July 2007; accepted 14 August 2007
Available online 19 August 2007

Abstract

It is shown theoretically and experimentally that opto-electrowetting may be used for both pulling and pushing liquid droplets. A theoretical analysis based on the Lippmann-equation and an electronic equivalent circuit model allows definition of a voltage and frequency range for which pushing may be achieved, a novelty in electrowetting-based actuation. Experimental confirmation of the effect demonstrates that enhanced flexibility in micro-fluidic actuation may be obtained under appropriate bias conditions.

Keywords: Opto-electrowetting; Electrowetting; Electrowetting-on-dielectrics; Liquid handling; Micro-fluidic device; Lab-on-a-chip

1. Introduction

Electrowetting allows modification of the contact angle of a liquid droplet on a surface through application of an electric field. Typically, the contact angle of a conductive or polar liquid droplet resting on a dielectric substrate is decreased by applying a bias voltage between the droplet and an electrode underneath the dielectric layer. Although long known [1], the effect has in recent years seen a renaissance of interest since it has proven of great utility for applications in optical Microsystems or droplet-based micro-fluidic systems.

In micro-optics, electrowetting has been successfully applied as a tuning mechanism for adaptive liquid lenses without any mechanically moving parts [2–4]. In these systems, the change in contact angle and curvature of a liquid droplet caused by the applied voltage is exploited to incite a change in focal length of the droplet acting as a liquid lens. This approach is sufficiently well advanced that commercial products based on it are available.

Electrowetting is also a promising actuation mechanism in droplet-based micro-fluidic systems [5] because of its ability to precisely handle small amounts of liquid. In typical systems, an array of electrodes is configured in such a manner that voltage may be applied over only a part of the droplet; the contact angle is thus reduced only in that area. The induced net force pulls the droplet towards the region over the biased electrode. This mechanism allows movement of droplets along a path defined by a pattern of individually addressable electrodes, or over arbitrary paths over an array of electrodes. Furthermore, splitting, merging and creating of droplets has been demonstrated [6], important for analytical applications.

The limitations imposed by the large number of electrodes required for droplet manipulation can be overcome by opto-electrowetting (OEW), an effect which was first presented by Chiou et al. [7,8]. By means of a photoconductive layer deposited underneath the dielectric layer, the voltage drop over the dielectric layer can be controlled by light. High electric fields over parts of a droplet may therefore be defined by light irradiation of the substrate. By using moving light patterns, liquid droplets may be moved continuously over a substrate, and even cell sorting is accessible using very simple devices [9]. All electrowetting-based systems demonstrated so far rely on a reversible decrease of the contact angle of the conductive liquid under applied voltage, resulting in a pulling force on a droplet towards the higher electric field.

We present here a theoretical analysis and experimental confirmation for the existence of optical pushing behavior in opto-electrowetting. Using an electronic equivalent circuit model, we derive the necessary experimental conditions to achieve this effect and show how the results may be used to obtain greater flexibility in opto-electrowetting-based micro-fluidic actuation.

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doi:10.1016/j.sna.2007.08.017

2. Theory

2.1. Electrowetting

The influence of electric fields on interfacial energies of liquid droplets was first described by Lippmann in 1875 [1] who investigated the interfacial energy of a mercury–electrolyte interface as a function of an applied bias voltage. He explained the observed effects by the reversible charging of the capacitance formed by the Helmholtz electric double layer formed at the interface between the liquids.

More recently, Berge [10] revived electrowetting through his idea of using an artificially generated insulating layer between a solid electrode and a conductive liquid droplet. Because of the thickness of this insulating layer, which exceeds the thickness of the Helmholtz double layer (typically a few nanometers) by several orders of magnitude, the actuation voltages in the configuration reported by Berge are significantly higher than in the work of Lippmann. This configuration is now commonly known as electrowetting-on-dielectrics (EWOD) and has become the one most frequently used.

The contact angle, θ, of a droplet sitting on a planar dielectric substrate in the EWOD configuration can be described using the so-called Lippmann-equation [10]

$$\cos(\theta) = \cos(\theta_0) + \frac{C}{2\gamma_{LG}A}V^2 = \cos(\theta_0) + \frac{\epsilon\epsilon_0}{2\gamma_{LG}t}V^2 \qquad (1)$$

where θ_0 represents the initial contact angle, ϵ the permittivity of the dielectric layer, γ_{LG} the interfacial energy between the droplet and the ambient phase, t the thickness of the dielectric layer, C the capacitance of the system, A the area covered by the droplet, and V is the voltage applied over the total capacitance. Eq. (1) is derived using the Young-equation with an additional term representing the energy stored in the capacitance formed by the droplet and the electrode under the dielectric layer. Consequently, the voltage drop over the total capacitance is that which leads to the spreading of the droplet.

Eq. (1) allows us to draw a number of conclusions concerning electrowetting and its limitations: first, due to the quadratic voltage dependence, the polarity of the bias voltage is not relevant, such that dc or ac biases may be used and secondly, only a contact angle reduction can be achieved in EWOD. In addition, we see that the driving voltage amplitude may be reduced by a low thickness and a high permittivity of the dielectric layer.

2.2. Opto-electrowetting

Recall that it is the voltage drop across the total capacitance that is responsible for the reduction of the contact angle. Thus, by introducing a variable resistance into the system and using an ac-voltage, the contact angle may be varied by changing this resistance. This effect is exploited in opto-electrowetting, in which a the variable resistance is provided by a photoconductive layer. Since photoconductive materials reduce their resistivity by about three orders of magnitudes upon illumination, a contact angle difference of 10° or more may be achieved between illuminated and dark states.

In a typical opto-electrowetting configuration, the photoconductive layer is placed underneath the dielectric layer as shown schematically in Fig. 1. The system thus consists of an electrode, the photoconductive layer, a dielectric coating, and the liquid droplet. The fabrication of these substrates is easy: only layer deposition, and no photolithography, is required.

The change of contact angle can then be used to move droplets from one position to an other. By non-uniform or partial illumination of the photoconductive layer beneath the droplet, the contact angle of the droplet changes (reduces) only on the *light* side of the droplet. The corresponding gain in interfacial energy leads to movement of the droplet towards those areas of the substrate in which the droplet has a smaller contact angle, i.e., generally in direction of the illumination. We will show below that, under certain experimental conditions, the smaller contact angle can be generated on the *dark* side of the droplet.

3. Simulation

3.1. Equivalent circuit model

The electrical and mechanical behavior of an OEW-system can modeled by representing the structure in an equivalent circuit model, as shown in Fig. 1 and adjusting the capacitance formed between the droplet and the electrode. The dielectric layer is represented by a simple capacitance C_{de} with a complex impedance $Z_{de} = 1/j\omega C_{de}$, in which ω is the angular frequency of the ac bias voltage. The photoconductive layer is modeled as a parallel combination of a capacitance C_{pc} and a resistance R_{pc}, where the latter is decreased by 3–4 orders of magnitude upon illumination due to carrier generation.

In Eq. (1) an additional term to the Young-equation was implemented representing the energy stored in the capacitor formed between the droplet and the electrode. In OEW the capacitance of the photoconductive layer has to be taken in care, too. Thus, the Lippmann-equation has to be adjusted by the total capacitance of the dielectric and the photoconductive layer. This

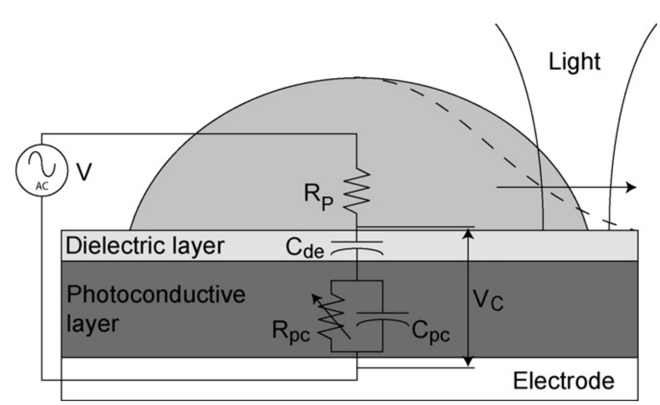

Fig. 1. Schematic view of a typical opto-electrowetting setup; the system consists of an electrode, a photoconductive layer, and a dielectric layer on which a droplet is located. By a locally varying light intensity, the droplet can be moved. Inside, the corresponding equivalent electric circuit of the system is shown.