Proceedings of the ASME 2010 International Mechanical Engineering Congress & Exposition
IMECE2010
November 12-18, 2010, Vancouver, British Columbia, Canada

IMECE2010-40060

DEMONSTRATION OF CONTINUOUS ELECTROWETTING ACTUATION

Corey M Lynch
University of South Florida
Tampa, FL, USA

Mehdi Khodayari
University of South Florida
Tampa, FL, USA

Alex A Volinsky
University of South Florida
Tampa, FL, USA

Nathan B Crane
University of South Florida
Tampa, FL, USA

ABSTRACT

Electrowetting is the change in apparent surface energy of a liquid in an applied electric field. It has shown great promise in diverse applications including lab-on-a-chip and electronic displays. The electrowetting response is typically considered independent of the actuation voltage polarity. This paper describes a new approach that achieves actuation in different directions for positive and negative voltage polarities using the electrochemical characteristics of aluminum electrodes. This paper presents a concept for continuous actuation of a droplet using a single electrode and DC voltage based on this effect. Initial experiments demonstrate that droplet motion is possible. Measurements of voltage drop across aluminum electrodes confirms the polarity-dependent response of the electrodes.

INTRODUCTION

Electrowetting can be defined as the phenomenon whereby the application of a difference in electrical potential (voltage) between a solid electrode and a small droplet of a partially-wetting conductive fluid (lying on the electrode) results in a decrease in the contact angle between droplet and substrate, effectively increasing substrate wettability. While the phenomenon has been studied for almost a century, in more recent years there has been a virtual explosion of research in the area as a result of the introduction of a thin dielectric layer between the electrode and electrolyte, which has the effect of limiting reactions between them and dramatically increasing the allowed voltage. This architecture (with either air, inert gas, or often an insulating oil as the 'ambient' phase) has formed the basis for most recent research in the area termed Electrowetting on Dielectric (EWOD) [1].

The applications of EWOD are diverse, from lab-on-a-chip devices [2], to micro-optic lenses and fiber optics [3, 4], to digital displays [5], and even micro motors and propulsion devices for micro-scale "pond skaters" [6, 7]. A key capability of many lab-on-a-chip and other digital microfluidic device designs is the controlled transport of discrete droplets of fluid, to and from reservoirs and reaction/testing cells. A simple and popular way to accomplish this is to use EWOD to reduce the contact angle of only a portion of the droplet. This asymmetry in droplet contact angle causes an imbalance in the net forces acting on the droplet, causing its motion. The current paradigm for EWOD droplet transport (described in more detail below) requires an entire array of independently controlled electrowetting electrodes, which must be activated/deactivated in a carefully controlled sequence [2, 8]. This paper explores a novel design for droplet transportation in which this array is replaced by a single electrode, and the direction of droplet movement is controlled by the polarity of the voltage applied. This novel behavior is accomplished by taking advantage of the unique electrochemical properties of aluminum.

The current rectification properties of aluminum surfaces has been long established, and in fact gave rise to the term "valve metal" to describe aluminum and other metals that develop stable passivating oxide layers in air at standard conditions (as they all tend to exhibit this rectifying behavior to one extent or another) [9]. Testing by the authors has demonstrated the existence of this property in thin aluminum films created by evaporation and sputtering, and characterized the durability of the response.

ALUMINUM ELECTROCHEMISTRY: THE BASIS OF BIDIRECTIONAL ELECTROWETTING

The Nernst equation could describe the relationship between the aluminum/platinum reference electrode potential difference (E) and concentrations of oxidized and reduced species ([O] and [R]), as follows:

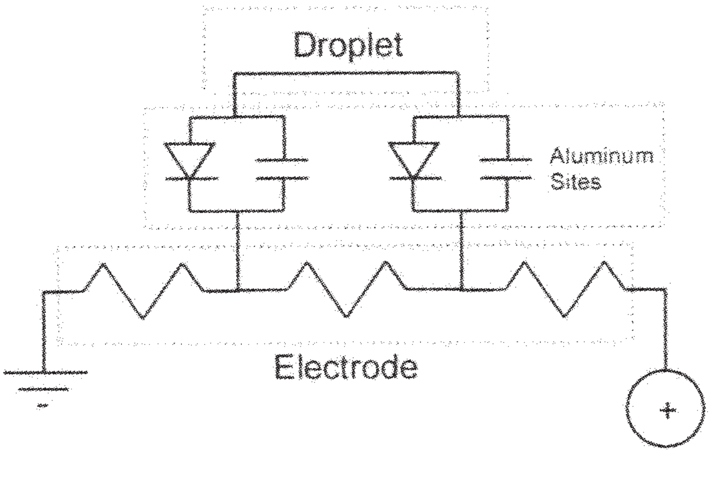

FIGURE 5 EQUIVALENT CIRCUIT OF POLARITY-DEPENDENT ELECTROWETTING SETUP. THE POSITIVE SITE IS REVERSE-BIASED, AND RESISTS CURRENT FLOW, WHILE THE NEGATIVE SITE IS FORWARD-BIASED AND ALLOWS CURRENT FLOW

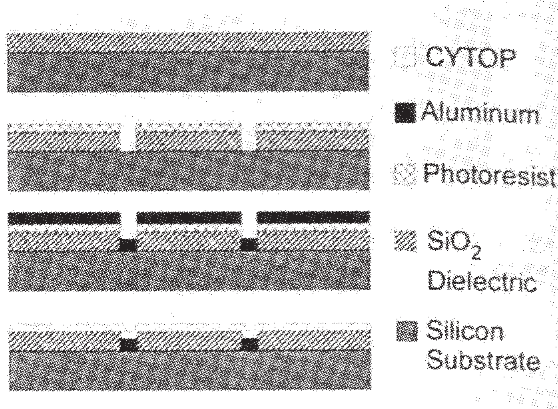

FIGURE 6 CONSTRUCTION TECHNIQUE FOR ELECTROWETTING DEVICE. *TOP:* Si SUBSTRATE WITH SiO_2 DIELECTRIC LAYER. *TOP MIDDLE:* PHOTORESIST LAYER AFTER PATTERNING AND ETCHING. *BOTTOM MIDDLE:* ALUMINUM LAYER APPLIED BY ELECTRON BEAM DEPOSITION. *BOTTOM:* PHOTORESIST IS REMOVED IN LIFTOFF PROCEDURE ALONG WITH UNWANTED ALUMINUM, LEAVING ALUMINUM LAYER IN PREVIOUSLY PATTERNED HOLES IN DIELECTRIC LAYER. ENTIRE TOP SURFACE IS GIVEN CYTOP SURFACE TREATMENT

anodic site becomes cathodic (hence allowing current flow and removing the potential difference between it and the droplet). The contact angle of the leading edge of the droplet will thus always be reduced, while the trailing edge will remain at its natural contact angle. The design serves not only to illustrate a method of creating single-electrode continuous droplet movement, but also one in which the polarity of voltage applied determines the system behavior, namely the direction of droplet movement (towards positive voltage).

EXPERIMENTAL VERIFICATION

The test setup featured here uses a high-resistivity (300-500 Ω·cm) silicon wafer substrate as the electrode. Atop this a thermally grown SiO_2 layer (480 nm) is used as the main dielectric. Standard photolithography techniques are used to pattern and etch holes in the silica. After etching, the entire wafer is coated with 300 nm of evaporated aluminum. The photoresist and (and above-lying aluminum) are then removed in a liftoff technique leaving aluminum present only where there had been holes patterned in the dielectric layer. The entire wafer was then layered with a spin-coat of 180 nm of CYTOP to increase the hydrophobicity of the surface (see Figure 6).

Initial testing of the above device has shown the predicted behavior, namely continuous droplet movement in the direction of positive voltage (Figure 7). Testing was carried out on test arrays constructed as described above. The ambient phase used was n-Hexadecane 99% (Alfa Aesar) to reduce droplet hysteresis, and the electrolyte droplet consisted of $BMIMPF_6$ (Acros Organics), an ionic-phase fluid. Continuous movement on the order of 2-2.5 cm was observed, with actuation voltage on the order of 300 V. Droplet velocity ranged from 2.9 to 3.3 mm/s with velocity decreasing with each subsequent trial on the same test array, likely as a result of degradation of the aluminum sites (as discussed above) and/or dielectric layer. The actuation force was of sufficient magnitude to cause splitting of the droplet when individual sites had become sufficiently degraded to cause "anchoring" of some portion of the drop above it, as can be seen in FIGURE 8. The relatively high voltage necessary poses the problem of observed degradation of the surface of the device (and hence its performance) over the course of several trials. Further development utilizing thinner dielectric and surface treatment layers, and different (higher permittivity) dielectrics is in progress to devise a system with lower actuation voltages and more repeatable performance.

CONCLUSIONS

While the diode-like properties of aluminum surfaces has long been known, the application presented here is novel. By utilizing the ability to rectify current, the aluminum sites allow for a capacitance build-up under only a portion of a droplet, resulting in geometrically asymmetric electrowetting. Most current designs for electrowetting droplet transportation feature a large array of individual electrodes, which add difficulty to manufacturing and system control processes. By patterning an array of aluminum sites along a single high resistivity electrode it has been shown that continuous droplet movement can be achieved. While preliminary testing has demonstrated the fundamental validity of the design, further work is needed to decrease operating voltages, and increase device durability.

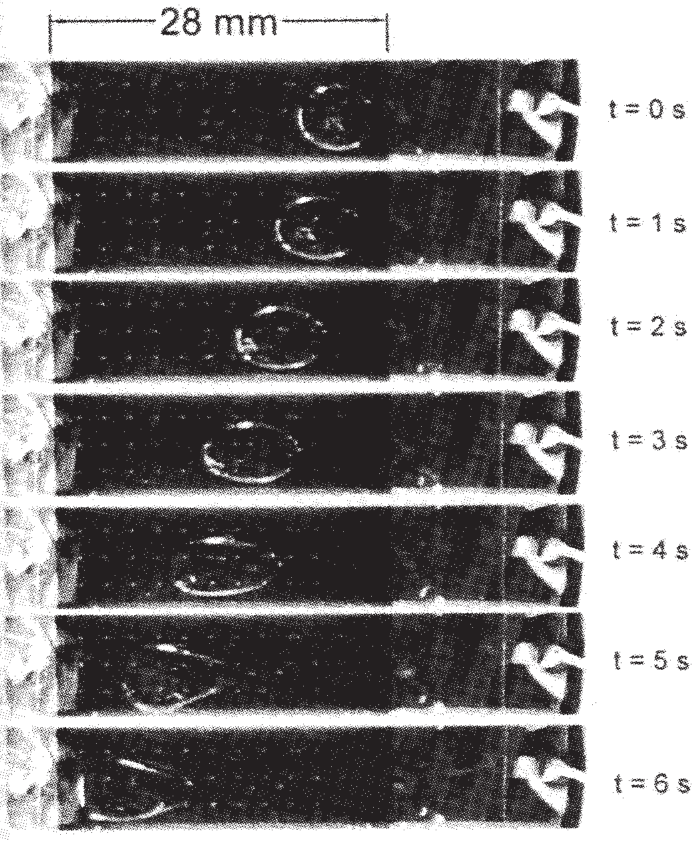

FIGURE 7 CONTINUOUS DROPLET MOTION ACROSS TEST STRIP. THE VOLTAGE IS APPLIED WITH THE LEFT-HAND SIDE OF THE STRIP POSITIVELY CHARGED.

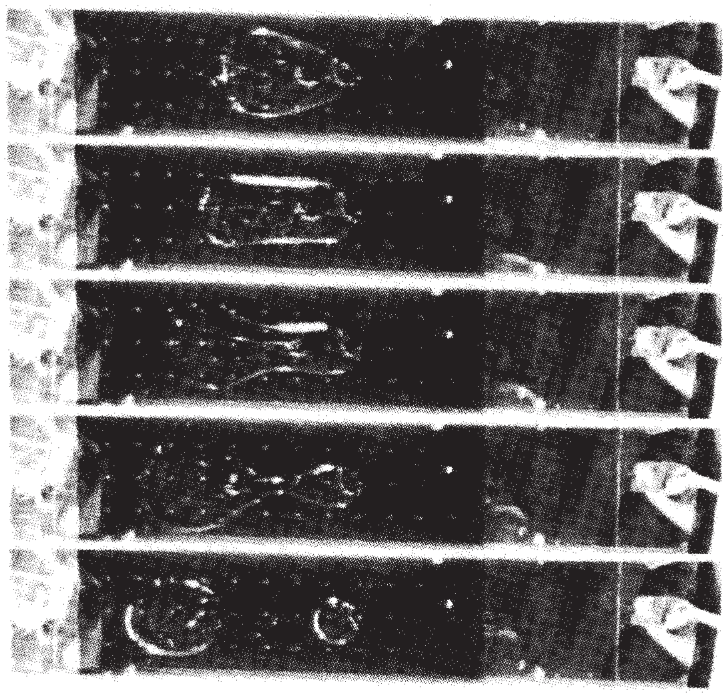

FIGURE 8 DEMONSTRATION OF DROPLET SPLITTING, ILLUSTRATING MAGNITUDE OF ACTUATION FORCE. NOTE PORTION OF DROPLET ANCHORED TO DEGRADED ALUMINUM SITE. TIME INTERVAL BETWEEN ALL IMAGES IS 1 SECOND.

ACKNOWLEDGMENTS

Nathan B. Crane would like to acknowledge support from NACE International. Alex A. Volinsky would like to acknowledge NSF support under CMMI-0600266 grant.

REFERENCES

[1] Mugele, F., 2005, "Electrowetting: From Basics to Applications," Journal of Physics.Condensed Matter, **17**(28) pp. R705.

[2] Junghoon, L., 2002, "Electrowetting and Electrowetting-on-Dielectric for Microscale Liquid Handling," Sensors and Actuators.A, Physical, **95**(2) pp. 259.

[3] Berge, B., 2000, "Variable Focal Lens Controlled by an External Voltage: An Application of Electrowetting," The European Physical Journal.E, Soft Matter, **3**(2) pp. 159.

[4] Mach, P., 2002, "Dynamic Tuning of Optical Waveguides with Electrowetting Pumps and Recirculating Fluid Channels," Applied Physics Letters, **81**(2) pp. 202.

[5] Kaige, S., 2008, "Reflective display device based on electrowetting," pp. 4.

[6] Mita, Y., 2009, "Demonstration of a Wireless Driven MEMS Pond Skater that Uses EWOD Technology," Solid-State Electronics, **53**(7) pp. 798.

[7] Takei, A., 2007, "Liquid motor driven by electrowetting," pp. 42.

[8] Cho, S., 2003, "Creating, Transporting, Cutting, and Merging Liquid Droplets by Electrowetting-Based Actuation for Digital Microfluidic Circuits," Journal of Microelectromechanical Systems, **12**(1) pp. 70.

[9] Young, L., 1961, "Anodic oxide films," Academic Press, London, New York, pp. 377.

[10] Crane, N., Volinsky, A., Mishra, P., 2010, "Bidirectional Electrowetting Actuation with Voltage Polarity Dependence," Applied Physics Letters, **96**(10) pp. 104103.

[11] Shih-Kang, F., 2007, "Asymmetric Electrowetting-Moving Droplets by a Square Wave," Lab on a Chip, **7**(10) pp. 1330.