Bidirectional electrowetting actuation with voltage polarity dependence

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This work presents an electrowetting system in which the actuation direction depends on the polarity of the applied voltage. Since electrowetting response depends on the voltage squared, it is typically independent of voltage sign to first order. However, the introduction of an electrochemical diode into the equivalent electrical circuit permits polarity-dependent behavior. Electrochemical diodes were created by making holes in the dielectric. The aluminum electrodes passivate and prevent current flow in one direction, creating diodelike electrical behavior with high breakdown voltage. The resulting actuation forces were directly measured and are of comparable magnitude for both actuation directions. © *2010 American Institute of Physics*. [doi:10.1063/1.3353990]

Electrowetting, the change in apparent surface energy with applied electric field,[1] has been widely investigated as a potential tool for manipulating liquids at miniature scales with applications including digital microfluidics, cooling, electronic displays, and focusing lenses.[1–5] Most applications use electrowetting on dielectric (EWOD) configuration in which a dielectric layer separates the fluid droplet from the electrodes to reduce electrochemical reactions. If a voltage is selectively applied on just one side of the droplet, the effective surface energy locally decreases where the voltage is applied and the droplet moves in the lower energy direction. The most common electrical configuration relies on a grounded droplet where the ground may be located on the substrate.[6] However, it is possible to use a floating droplet configuration in which the droplet is positioned across two electrodes.[7] Both configurations can be modeled using lumped parameter electrical circuits (Fig. 1).

Below saturation, the contact angle (θ) will depend on the liquid wetting angle without voltage applied (θ_0) and the voltage (V) between the substrate electrode and the droplet. These can then be related to the thickness (δ) and permittivity ($\varepsilon_0, \varepsilon_R$) of the dielectric layer as follows:

$$\cos\,\theta_1 = \cos\,\theta_o + \varepsilon_o \varepsilon_r V^2 / 2\gamma_{lv}\delta. \quad (1)$$

While many electrowetting configurations require a series of sequentially activated electrodes,[2,8] others use photoconductors[9] or photovoltaic generation of voltage[10] to manipulate droplets. This work reports on an alternative arrangement in which the actuation direction depends on voltage polarity. While polarity differences[11] and frequency dependence[12] have been used to achieve bidirectional droplet actuation, the actuation force in these methods is much smaller in one direction than the other. The present approach can achieve full reversal of the actuation force direction and magnitude with voltage polarity changes.

This simplified actuation can be achieved by introducing a diodelike element into the electrical circuit in parallel with one or both of the capacitors as illustrated in Fig. 1 (bottom). Ideally, this diode-element shorts the droplet on the side of the lower potential electrode so that the entire voltage drop is across the dielectric over the opposite electrode. This creates an energy imbalance that moves the droplet toward the higher potential. If the voltage polarity is reversed, the direction of actuation will reverse as well. While typical semiconductor diodes would undergo breakdown under common electrowetting voltages (20–100 V), diodelike behavior can also be achieved via electrochemical effects as in electrolytic capacitors.[13]

EWOD substrates with aluminum electrodes and 2.1 μm thick Cytop dielectric layers were prepared as described previously.[14] Defects in the dielectric layer were introduced by creating a single scratch in the Cytop coating with a probe tip on a micropositioner. Typically, the damaged Cytop region was 150 μm long by 70 μm wide at its largest extent. A 50 μl droplet of 1 mM NaCl solution was placed over the scratched area and voltage was applied to a tungsten probe placed in the droplet while the aluminum electrode was grounded. Figure 2 shows the I-V characteristics of the droplet/scratch/substrate circuit for three different scratches. The irregular size of the Cytop holes produces a variation in the I-V profiles, but they consistently show diodelike current behavior with very low currents when the electrode has a higher potential than the electrolyte. After testing (Fig. 2 inset), the aluminum was etched away some distance beyond the scratch in the Cytop coating.

The diodelike behavior is caused by the formation of a passive aluminat coating when the aluminum electrodes have

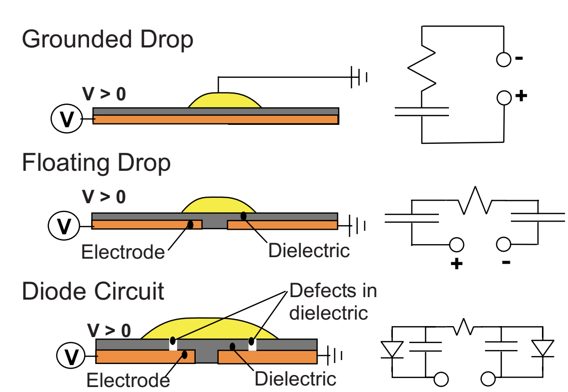

FIG. 1. (Color online) Illustration of the equivalent lumped parameter circuit models for (top) grounded and (center) floating droplets. Bottom: possible implementation of a diode circuit through dielectric holes and its equivalent circuit.

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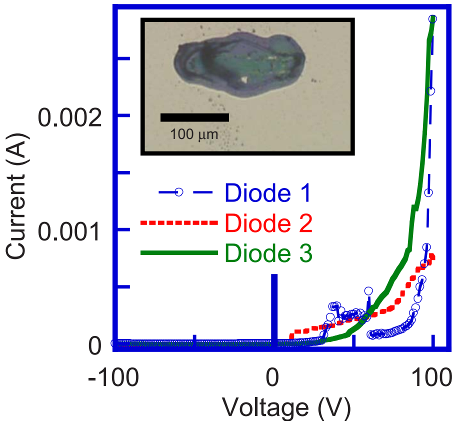

FIG. 2. (Color online) I-V curves demonstrating diodelike behavior of aluminum electrodes. Inset: picture of the scratched region after testing.

a higher electrical potential than the electrolyte ($V<0$ in Fig. 2). When the potential is reversed, a current readily passes through the NaCl solution/aluminum interface.[15] Thus, each hole in the dielectric becomes an electrochemical diode but based on passivation rather than transport limits.[16,17] The resulting circuit permits voltage polarity-dependent force response because most of the voltage drop occurs across the electrode with the higher electrical potential. The force acts toward this electrode. The steady state current is limited because the two aluminum electrodes always have opposite polarities relative to the electrolyte so that one is always passivated.[13]

The electrowetting response was measured using the electrowetting force technique of Crane *et al.*[14] (Fig. 3) in which a flat glass plate (9×9 mm^2) is positioned over two electrodes with a NaCl solution droplet wetting the plate. The force applied to the plate can be related to the electrowetting response. The resulting force (F_y) is parallel to the substrate and perpendicular to the electrode boundary due to an applied voltage (V), given by

$$F_y = -\varepsilon_0 \varepsilon_r s V_{\mathrm{tot}}^2 y/(s-g)\delta, \tag{2}$$

$$F_y = \pm \varepsilon_0 \varepsilon_r s^2 V^2/(s-g)\delta, \tag{3}$$

for the floating and grounded droplets, respectively. Here, "s" is the width of the glass plate, "y" is the offset of the plate center from the electrode gap, and "g" is the gap width. Substrates were produced as for the electrochemical diode experiments, except the aluminum was patterned to create two electrodes. Typical test parameters were ($g=0.5$ mm, $s=9.0$ mm, and $y=-3.0$ mm). In this case, no dielectric holes

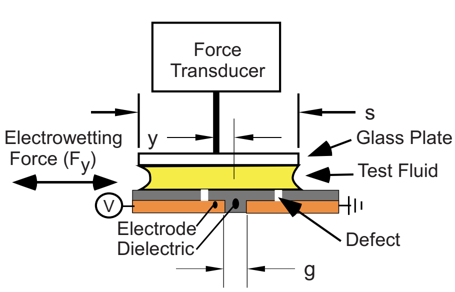

FIG. 3. (Color online) Arrangement for measuring electrowetting actuation forces. Droplet transfers the electrowetting actuation force to the nanoindenter transducer through the wetted glass plate.

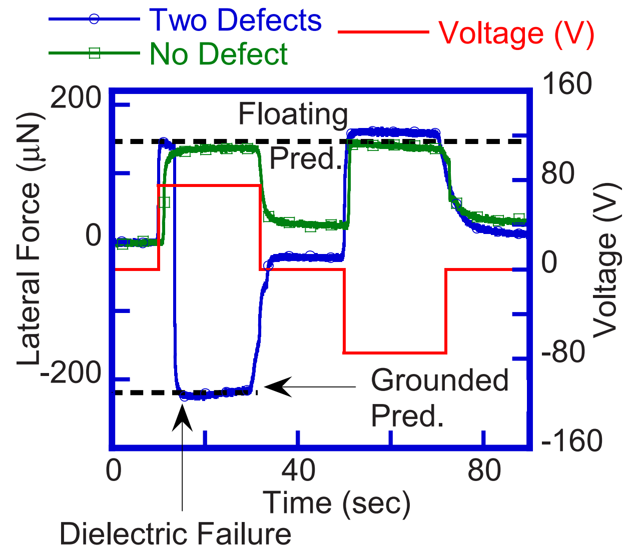

FIG. 4. (Color online) Electrowetting force measurements showing force transition with dielectric failure on one side. Force magnitudes agree with analytical predictions.

were intentionally made. However, in many test cases, etching of the aluminum layer was visible after testing. We believe this is due to local dielectric breakdown and/or small pores in the dielectric layer.[18] Without these defects, the force was independent of the voltage polarity with a magnitude comparable to the predictions of Eq. (2) (Fig. 4, "No Defect"). However, several different behaviors are possible with defects. A defect over just one electrode could switch between floating droplet and grounded droplet forces with applied voltage polarity change. Depending on which electrode has the defect, the force direction may or may not switch. Figure 4 shows a sample in which the dielectric failed during testing on the high voltage side. At dielectric failure, the force switches from floating droplet to grounded droplet mode and its direction reverses. When the voltage polarity switches, the force returns to the grounded droplet force value and its direction reverses again. If defects occur over both electrodes, the force direction changes with the

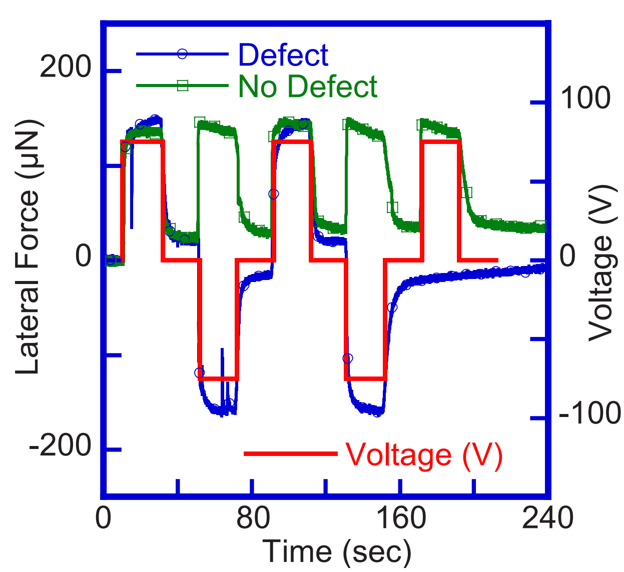

FIG. 5. (Color online) Force response for the sample with a defect on both sides of the dielectric gap compared to the no defect case.

voltage polarity and the force magnitude is the same in both directions (Fig. 5). Ideally, the force magnitude is given by Eq. (2) but leakage currents in the electrochemical diodes produce a voltage drop that decreases the electrowetting force.

The introduction of voltage polarity dependence enables new actuation behavior. Polarity dependent actuation could be used to develop analog actuation systems for precise positioning of individual droplets or bidirectional force actuators. Continuous droplet motion with dc voltage could be achieved if a series of diode elements were introduced at appropriate intervals over an electrode. The incorporation of diodes into other electrowetting configurations may enable other valuable performance characteristics as well.

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