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Electrowetting-based actuation of liquid droplets for microfluidic applications

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A microactuator for rapid manipulation of discrete microdroplets is presented. Microactuation is accomplished by direct electrical control of the surface tension through two sets of opposing planar electrodes fabricated on glass. A prototype device consisting of a linear array of seven electrodes at 1.5 mm pitch was fabricated and tested. Droplets (0.7–1.0 μl) of 100 mM KCl solution were successfully transferred between adjacent electrodes at voltages of 40–80 V. Repeatable transport of droplets at electrode switching rates of up to 20 Hz and average velocities of 30 mm/s have been demonstrated. This speed represents a nearly 100-fold increase over previously demonstrated electrical methods for the transport of droplets on solid surfaces. © *2000 American Institute of Physics.* [S0003-6951(00)01237-7]

We report here rapid actuation of discrete liquid droplets based upon direct electrical control of their surface tension. Controlled transfer of droplets at high rates under low voltages offers numerous advantages over current continuous flow and electrokinetic flow technologies. Direct manipulation of discrete droplets enables integrated microfluidic systems to be realized without the use of conventional pumps, valves, or channels. Such systems are flexible, efficient, and capable of performing complex and highly parallel microfluidic processing.

Several methods for manipulating microdroplets have been proposed including the use of structured surfaces,[1] thermocapillarity,[2,3] electrochemical effects,[4] and electrostatic actuation.[5] We present here an electrostatic method for manipulating discrete microdroplets which is based upon direct electrical control of the surface tension, a phenomenon known as electrowetting.[6–10] This method requires no moving parts or fixed channels, is self-contained, consumes little power, and imposes minimal constraints upon the fluid being pumped.

The electrowetting microactuator is presented schematically in Fig. 1. A droplet of polarizable and conductive liquid is sandwiched between two sets of planar electrodes. The upper plate consists of a single continuous ground electrode, while the bottom plate consists of an array of independently addressable control electrodes. Both electrode surfaces are covered by a thin layer of hydrophobic insulation. The system geometry and droplet volume are controlled such that the footprint of the droplet overlaps at least two adjacent control electrodes while also making contact to the upper ground electrode. The surrounding medium may be either air or an immiscible fluid such as silicone oil to prevent evaporation of the droplet.

Initially all electrodes are grounded and the contact angle everywhere is the equilibrium contact angle of the droplet. When an electrical potential is applied to a control electrode underneath the droplet, a layer of charge builds up at the interface between the droplet and the energized electrode resulting in a local reduction of the interfacial energy γ_{SL}. Since the solid insulator controls the capacitance between the droplet and the electrode the effect does not depend on the electrolyte's specific space-charge effects as did earlier uninsulated electrode implementations.[10]

The voltage dependence of the interfacial energy reduction is described by[8]

$$\gamma_{SL}(V) = \gamma_{SL}(0) - \frac{\varepsilon}{2d} V^2, \quad (1)$$

where ε is the permittivity of the insulator, d is the thickness of the insulator, and V is the applied potential. The change in γ_{SL} acts through Young's equation to reduce the contact angle at the interface between the droplet and the energized electrode. If a portion of the droplet also overlaps a grounded electrode, the droplet meniscus is deformed asymmetrically and a pressure gradient is established between the ends of the droplet which results in bulk flow towards the energized electrode.

A prototype device consisting of a single linear array of seven interdigitated control electrodes at a pitch of 1.5 mm was fabricated and tested. The control electrodes were formed by patterning a 2000-Å-thick layer of chrome on glass using standard microfabrication techniques. The chips

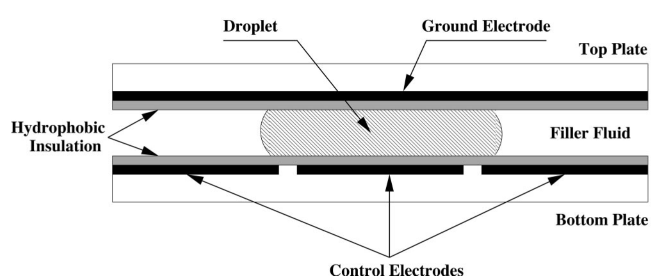

FIG. 1. Schematic cross-section of the electrowetting microactuator.

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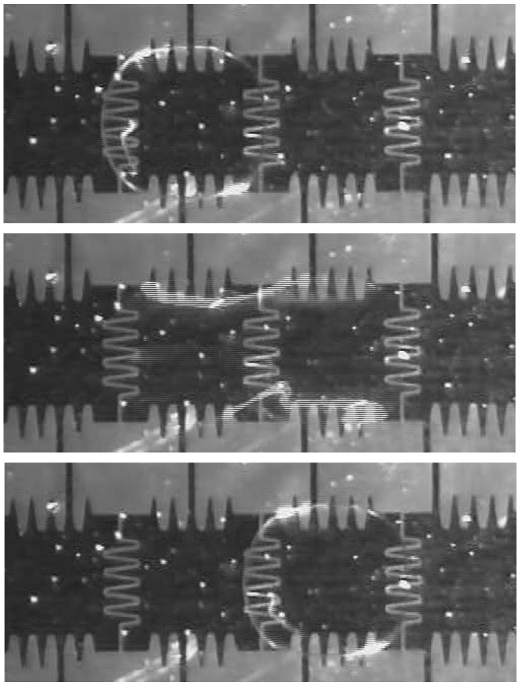

FIG. 2. Video frames of a moving droplet at 33 ms intervals. View is from the top looking through the ITO ground electrode. In the first frame 80 V is applied to the electrode underneath the droplet while adjacent electrodes are grounded. In the second and third frames the 80 V potential has been switched to the electrode to the right and the droplet follows.

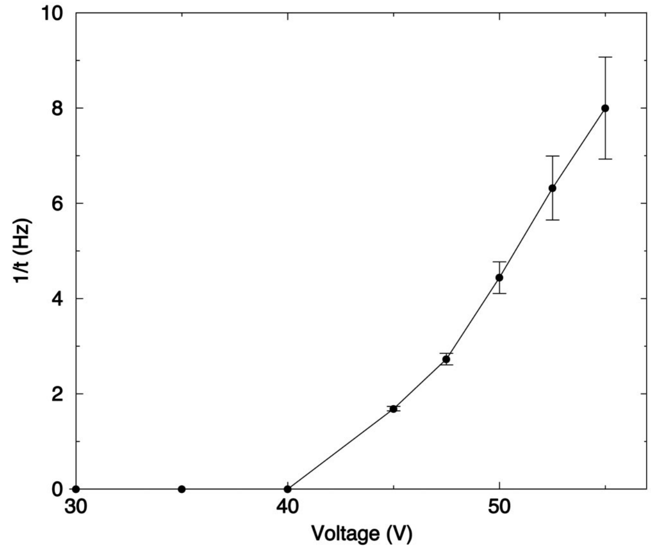

FIG. 3. Maximum switching rate $1/t_{tr}$ of a 1.5-mm-diam droplet as a function of applied voltage. No movement was observed for $V<35$ while between 35 and 40 V the droplet moved but failed to reach the next electrode. For $V>55$ droplet movement was too rapid to be measured reliably by video techniques. Error bars represent the sensitivity of the measurement to a single-frame variation.

were then coated with 7000 Å of Parylene C followed by approximately 2000 Å of Teflon AF 1600. The ground electrode consisted of a plate of glass coated with a conducting layer ($R_S<20\,\Omega$/square) of transparent indium–tin–oxide (ITO). A thin (~500 Å) layer of Teflon AF 1600 was also applied to the ground electrode. The thin Teflon coating on the ground electrode served to hydrophobize the surface, but was not presumed to be insulative. After coating with Teflon, both surfaces had a contact angle of 104° with water.

Droplets (0.7–1.0 μl) of 100 mM KCl were dispensed onto the array using a pipet and the top plate was positioned to provide a gap of 0.3 mm between the opposing electrodes. A customized clamp with spring-loaded contact pins was used to make connections to the bond pads. A computer was used to control a custom-built electronic interface which was capable of independently switching each output between ground and the voltage output of a 120 V dc power supply.

A droplet was initially placed on the center of a grounded electrode and the potential on the adjacent electrode was increased until motion was observed. Typically 30–40 V were required to initiate movement of the droplet. Once this threshold was exceeded, movement was both rapid and repeatable. We believe that contact angle hysteresis is the mechanism responsible for this threshold effect. Three successive video frames (30 frames/s) of a moving droplet at 80 V of applied potential are shown in Fig. 2. These frames were captured from a sequence during which a droplet was moved repeatedly back and forth across all four electrodes at a switching frequency of 15 Hz.

We define the transit time t_{tr} of the droplet as the time required for the droplet to reach the far edge of the adjacent electrode following the application of the potential. The transit time thus represents the minimum amount of time that must be allowed between successive transfers and $1/t_{tr}$ is the maximum switching rate for continuous transfer of a droplet. The maximum switching rate as a function of voltage is plotted in Fig. 3, where t_{tr} was determined by counting recorded video frames of a moving droplet.

Sustained droplet transport over 1000's of cycles at switching rates of up to 20 Hz has been demonstrated. This rate corresponds to an average droplet velocity of 3.0 cm/s which is nearly 100 times faster than a previously reported method for electrical manipulation of droplets.[5] Comparable velocities cannot be obtained in thermocapillary systems because (for water) the required temperature difference between the ends of the drop exceeds 100 °C.[3] These results demonstrate the feasibility of electrowetting as an actuation mechanism for droplet-based microfluidic systems. We expect that this design could be extended to arbitrarily large two-dimensional arrays to allow precise and independent control over large numbers of droplets and to serve as a general platform for microfluidic processing.

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