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Electrowetting, Applications

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Synonyms

Electrowetting on dielectric (EWOD); Electrowetting on insulator coated electrodes (EICE); Electrowetting on line electrodes (ELE); Static electrowetting; Spontaneous electrowetting

Definition

Electrowetting employs an externally applied electric field to actuate or manipulate small volumes of liquid by altering its interfacial tension and hence the macroscopic contact angle or by inducing bulk liquid motion through an interfacial electric stress. Due to the low power consumption, electrowetting therefore affords an efficient, rapid, reversible, and precise means for actuating and manipulating very small volumes of liquid in microfluidic devices without the need for mechanical components.

Overview

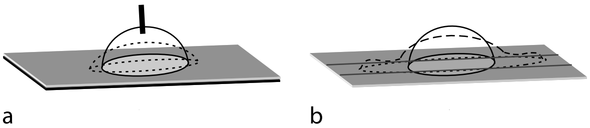
At microscale dimensions, the surface area to volume ratio, which scales as the inverse of the characteristic length scale of the system L, becomes increasingly large, thus stipulating the dominance of surface forces over body forces. This makes it extremely difficult to move and manipulate small volumes of fluid in miniaturized fluidic devices. Several schemes that exploit Marangoni (surface tension gradient) and thermocapillary (temperature gradient) stresses to control the interfacial energy and hence drop motion have been proposed. Nevertheless, these suffer from several limitations in terms of reliability, controllability, response times and compatibility.

In contrast, the use of electrokinetics has generally been heralded as the preferred method for microfluidic manipulation due to the ease/low costs of electrode fabrication given the recent advances in micro/nano-fabrication technology, the precision and controllability afforded by electric fields, and, the reliability in the absence of mechanically moving parts. Electric field driven actuation is also rapid since the limitation is usually imposed by the hydrodynamic time scale $\mu_l L/\gamma \sim 10^{-4}$ s, which is typically larger than the time scale for charge separation $\varepsilon_0\varepsilon_l/\kappa_l \sim 10^{-6}$ s; μ_l, $\varepsilon_0\varepsilon_l$ and κ_l denote the liquid viscosity, permittivity and conductivity, respectively, and γ is the interfacial tension. As such, the use of electrowetting, in which an external electric field is exploited to modify the wettability of the drop through a change in its interfacial tension or by inducing bulk motion through an interfacial stress, has become increasingly attractive as a means for microfluidic actuation and manipulation.

Yeo and Chang [1, 2] proposed that electrowetting phenomena can, in general, be classified into *static electrowetting* and *spontaneous electrowetting*, depending on the electrode configuration adopted. Static electrowetting, in which the drop sits above a planar dielectric coated plate electrode (synonymous to the configurations employed in electrowetting-on-dielectric (EWOD) or electrowetting on insulator coated electrodes (EICE); see, for example, Fig. 1a), involves the alteration of the macroscopic contact angle of the drop due to the applied electric field. It was shown in [1] through an analysis of a conducting drop that the dominant gas-phase electric field endows the drop interface with an interfacial charge and hence normal interfacial electric stress that is weakly singular towards the three-phase contact line. Nevertheless, due to the confinement of this singularity in a very small region, of the order of the dielectric coating thickness (typically microns), the interfacial stress is insufficient to result in a bulk pressure gradient in the liquid; an electric force, which can be obtained by coarse graining, simply arises at the contact line that balances the surface forces. This is shown to give rise to a modification of the macroscopic contact angle of the drop θ which obeys the Lippmann condition:

$$\cos\theta = \cos\theta_0 + \frac{\varepsilon_0\varepsilon_l V^2}{2d\gamma_{LV}}, \tag{1}$$

where θ_0 is the equilibrium contact angle in the absence of the electric field, V the applied voltage, d the dielectric coating thickness and γ_{LV} the liquid–vapor interfacial tension.



Electrowetting, Applications, Figure 1 Schematic illustration of (**a**) static electrowetting in which the applied electric field induces a macroscopic change in the contact angle, and, (**b**) spontaneous electrowetting in which a thin front-running electrowetting film is pulled out and advances ahead of the macroscopic spreading drop. The film thickness in (**b**) is not drawn to scale

Spontaneous electrowetting, on the other hand, arises when a thin front-running electrowetting film is pulled out and advances ahead of the macroscopic drop when parallel line electrodes are employed [2, 3], as shown in Fig. 1b. This has been termed electrowetting on line electrodes (ELE). In [2], the electric field in the liquid phase is dominant and gives rise to a non-singular tangential interfacial electric stress that decays away from the contact line with increasing interfacial height. This electric stress gradient consequently gives rise to a negative macroscopic pressure gradient that induces liquid flow from the bulk of the drop towards the contact line region, therefore pushing out a thin spontaneous electrowetting film ahead of the macroscopic drop, which advances with a constant contact angle self-similarly in time t as

$$x_f = 0.43 R_\mathrm{e} \left(\frac{t}{T_\mathrm{cap}} \right)^{1/3} , \tag{2}$$

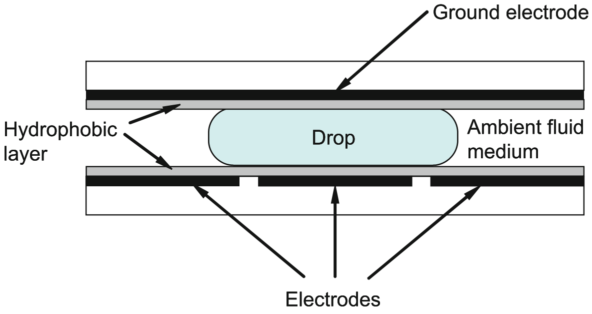
independent of drop dimension, interfacial tension or wettability; x_f is the position of the advancing front, R_e the electrode separation and

$$T_\mathrm{cap} = \frac{\pi^2 \mu_1 R_\mathrm{e}}{8 \varepsilon_0 \varepsilon_1 V^2} , \tag{3}$$

is the electrocapillary time scale.

Basic Methodology

The majority of effort in developing applications based on electrowetting has largely centered on static electrowetting processes. As a result, the motion is essentially in the form of discrete steps rather than a single continuous process as in spontaneous electrowetting. In general, these static electrowetting schemes for moving and manipulating individual drops in open systems have collectively been described by the term *digital microfluidics* in order to provide a distinction to microfluidics systems involving continuous flow within closed microchannels. Less common is the use of the synonymous term *flatland microfluidics*. Although digital microfluidics is perhaps not particularly useful for continuous flow analysis, and particularly that involving larger liquid volumes, discrete drop microfluidics allows the possibility of scalability and reconfiguration such that analyses can be carried out in similar fashion to traditional benchtop protocols [4]. Besides, drops are often useful as carriers for biological entities and hence different biological agents can be transported separately in different drops without coming into contact with the other providing the drops never meet. Digital microfluidics also has the advantage of minimizing the amount of liquid required as well as the contact between the liquid and solid surface. The latter is crucial in applications, most commonly those that involve biomolecules, in which surface adsorption is undesirable [5]. Protein adsorption is commonly due to electrostatic interactions and the degree to which it occurs is dependent on the charge, polarity on the protein as well as the applied voltage [6]. The open system also eliminates the attenuation of detection signals through channel walls although it is prone to contamination and evaporation. A possibility to circumvent the problem due to evaporation is to house the system within an oil medium, which has been found to also suppress adsorption.



Electrowetting, Applications, Figure 2 Schematic depiction of a typical static electrowetting setup for drop actuation in a microfluidic device

Practical static electrowetting schemes typically involve the use of a patterned array of multiple electrodes, each of which can be individually controlled, as shown in Fig. 2; note that the use of a wire electrode in contact with the drop in the usual EWOD/EICE setup in Fig. 1a is impractical due to the moving drop. The drop should also span across two electrodes at any one time to facilitate continual discrete motion [7]; the smallest liquid volume that can be manipulated is therefore constrained by the electrode size. The activation and subsequent deactivation of an applied potential across one electrode in the array and the ground electrode (top electrode plate in Fig. 1), then allows the drop to march forward discretely towards the next electrode in the array sequence which is then subsequently activated (and then deactivated again) to translate it forward to yet the next electrode. The programming of a sequential logic scheme for the activation/deactivation of individual electrodes then allows the drop to be translated in a desired direction. Increasingly complex control schemes have since been proposed to perform more complicated and sophisticated tasks such as drop splitting, recombination and mixing. This therefore allows applications in widespread areas, although efforts have largely concentrated around two major areas, i. e. microfluidic Lab-on-a-Chip devices as micro total analysis systems (µTAS) and electro-optic devices.

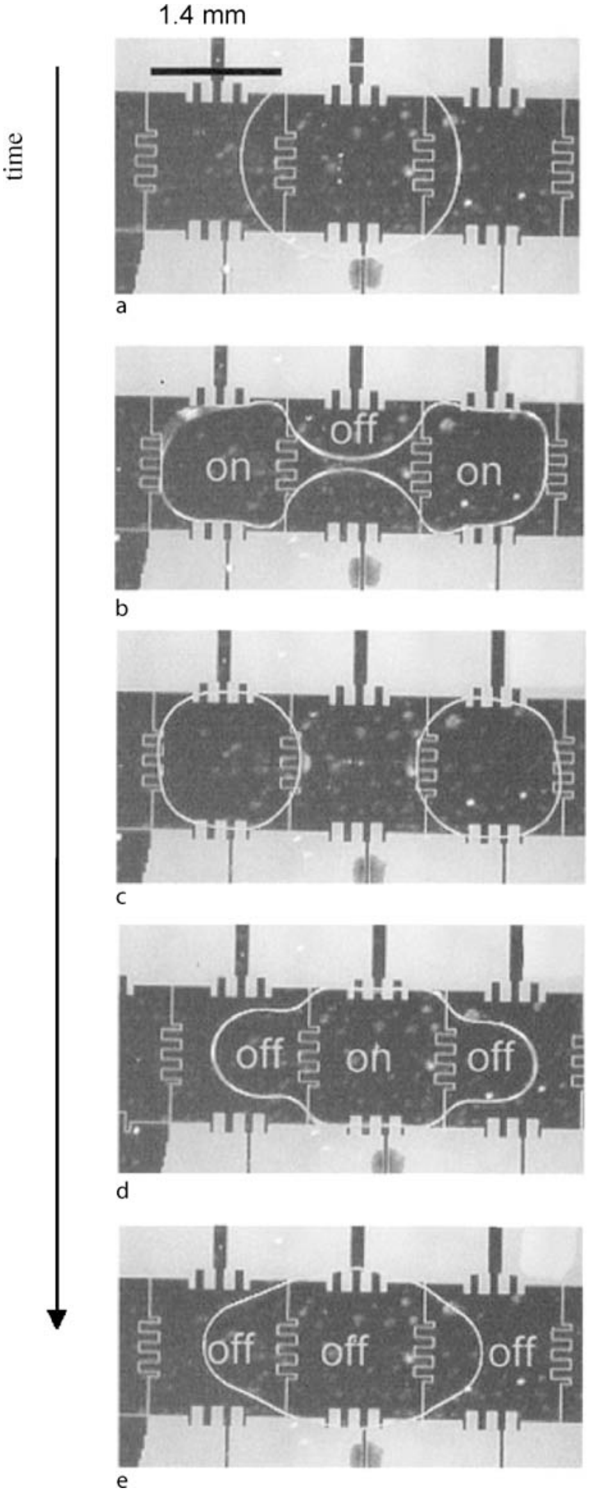
Key Research Findings

Microfluidic Components for Lab-on-a-Chip Devices

Electrowetting is most commonly used in Lab-on-a-Chip devices for microfluidic actuation and manipulation. In a typical system, very small amounts of analytes are metered into drops which are then transported, for example, to a reaction chamber where they are merged for the reaction to occur. Successive reactions can also be performed by merging drops containing intermediate reaction products. Parallel manipulation or detection can also be carried out by splitting the drop into smaller droplets [4]. All of these drop operations, namely, metering, translation, merging and splitting, can be carried out using static electrowetting schemes.

Early work on static electrowetting for these microfluidic applications focused on these individual tasks separately. These initial efforts were concentrated on driving a conductive drop through an open channel using electrowetting. The setup is similar to that shown in Fig. 2. The channel however is required to be open for positioning of the drop within, which required a fair amount of precision, and the filling of the medium around the drop; the channel could later be closed by employing a cover slip. Lee and Kim [8] employed a liquid metal drop surrounded by a liquid electrolyte medium. In this case, however, the electrodes were positioned at the end of channel instead of comprising the top and bottom plates. Although they termed their setup *continuous electrowetting*, the use of electric fields to change the macroscopic liquid metal–electrolyte contact angle is more akin to the classical electrocapillary experiments [1]. In any case, however, their work culminated in one of the first demonstrations of drop transport in a miniaturized fabricated device. An extension of this work is the fabrication of a 2 mm circular loop track along the periphery of which several electrodes are embedded in order to drive the drop around the track at rotation speeds up to 420 rpm with an operating voltage of 2.8 V. A similar demonstration is reported in Pollack et al. [7] with electrolyte drops within an air or oil medium. Drop translation with speeds over several cm/s were obtained with applied voltages of 1 – 100 V.

Elegant protocols for drop metering, splitting and merging were later proposed by Cho et al. [9]. The drop splitting process is illustrated in the image sequences given by Figs. 3a–3c. Of vital importance in order for the drop to split is the necking (negative radius of curvature at the neck position R_n) and rupture (when the drop radius of curvature at its ends, which is proportional to the drop size and roughly commensurate with the electrode width R_t, become equal, i. e. $R_n = -R_t$) processes, which can be caused by removal of the voltage on the middle elec-

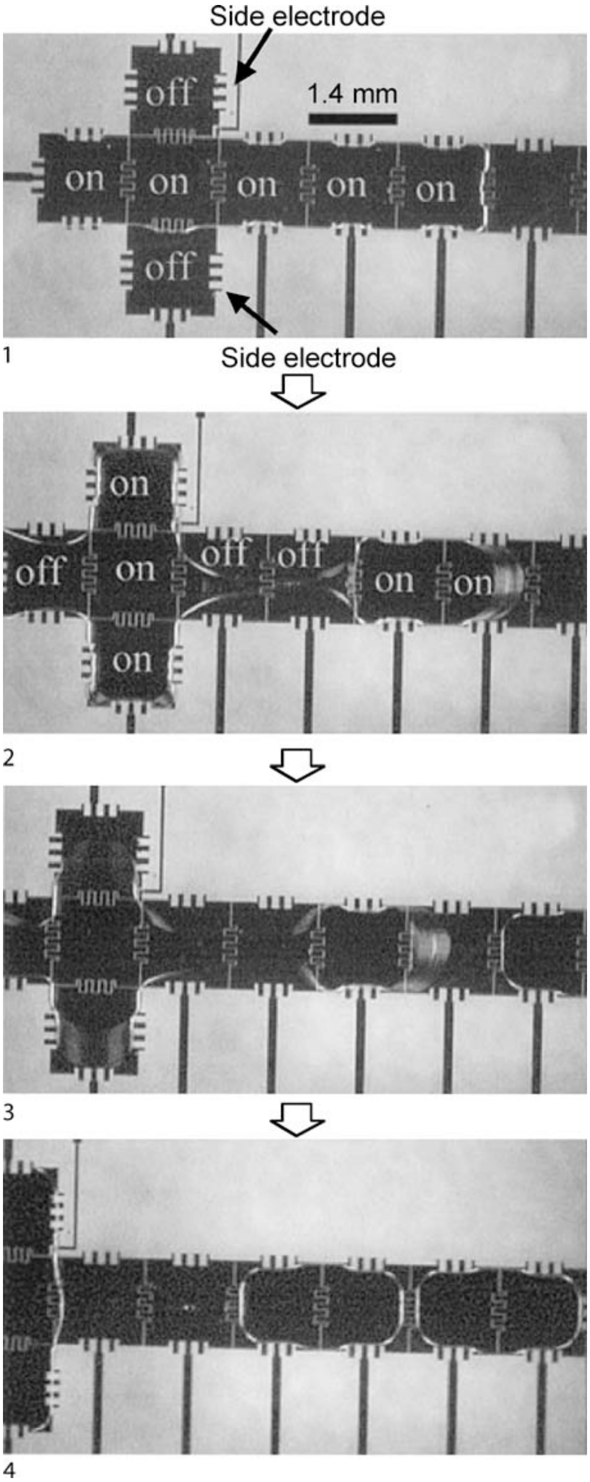


Electrowetting, Applications, Figure 3 Drop surgery by programmable static electrowetting protocols. The voltage on and voltage off states of individual electrodes are indicated. Images (**a**), (**b**) and (**c**) depict drop splitting whereas images (**c**), (**d**) and (**e**) show drop merging (from [9]) trodes. For necking to occur, however, the ratio of the channel height to the drop radius of curvature at its ends h/R_t needs to be below a critical value; this critical value itself increases as the ratio $|R_n|/R_t$ increases [9].

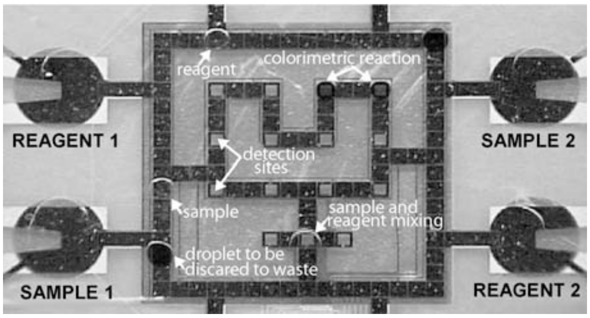
The procedure for drop metering from a reservoir is related to the drop splitting process. Again, this is facilitated by smaller channel heights and smaller drop reservoirs. Figure 4 shows the drop metering process; lateral electrode arrays are required to hold the drop reservoir in position whilst the electrodes ahead of the reservoir are activated in order to pull a drop out from the reservoir. By turning off the electrodes in the middle, necking occurs to split the drop from the reservoir. For the entire reservoir to be drained, however, the surface of the reservoir must be rendered hydrophobic [9]. The merging of drops, on the other hand, can be carried out by translating the drops together such that coalescence occurs by removing the voltage on the electrodes beneath the drops and activating the electrode between the drops [9]. This is shown in Figs. 3d and 3e.

Other microfluidic components have also been developed using static electrowetting. An electrowetting-actuated valve was proposed by Cheng & Hsiung [10]. A hydrophobic layer comprising plasma-modified poly(tetrafluoroethylene) was coated onto the channel to prevent through-flow; the plasma modification served to reduce the hydrophobicity of the poly(tetrafluoroethylene) slightly so that upon modification of the advancing liquid meniscus contact angle via an electric field, through-flow can be obtained.

Electrowetting-based platforms have also been proposed as a convenient means for driving micro-mixing of discrete drops of different chemicals. The simplest form of such mixing is to adopt a passive scheme in which two drops are translated together and merged by electrowetting using the procedures described above. However, it is also possible to induce active mixing after the coalescence event in order to reduce the mixing time. A straightforward way is to oscillate the merged drop between two or more electrodes in a linear arrangement at a fixed frequency. Paik et al. [11] observed that the mixing times decreased with increasing number of electrodes and the switching frequency (inverse of the time that the drop is present on one electrode), both of which increases the complexity of the flow recirculation within the drop. Electrowetting-driven mixing of ionic liquids containing different reagents was investigated by Dubois et al. [12]. These ionic liquids which have negligible vapor pressure are environmentally-friendly alternatives to the volatile organic solvents commonly used in chemical synthesis which are subject to evaporation problems in open microfluidic systems and problems due to oil/solvent miscibility and cross-contamination when the



Electrowetting, Applications, Figure 4 Drop dispensing or metering from a reservoir using static electrowetting schemes (from [9])



Electrowetting, Applications, Figure 5 Electrowetting based integrated microfluidic device for glucose assays (from [15])

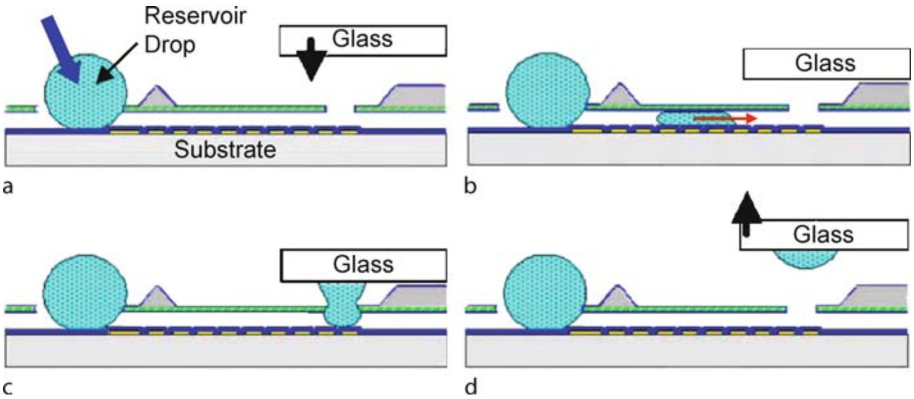
drop analysis carried out under an oil layer to minimize evaporation.

These various drop actuation and manipulation schemes and microfluidic components have been integrated into more complex devices to perform multiple chip based tasks. Pollack et al. [13] employed a combination of electrowetting-driven microfluidic components for drop dispensing, actuation and merging/splitting to discriminate alleles with single base pair variations on an integrated polymerase chain reaction (PCR) microchip. Srinivasan et al. [14] developed an electrowetting-based microfluidic chip platform to perform glucose detection via colorimetric enzyme kinetics. The glucose assay consisted of three steps, namely, dispensing, mixing and detection; dispensing was carried out by manual pipetting, drop translation leading up to mixing by electrowetting and detection by measuring the absorbance signal corresponding to the color change in the system subsequent to an enzymatic reaction.

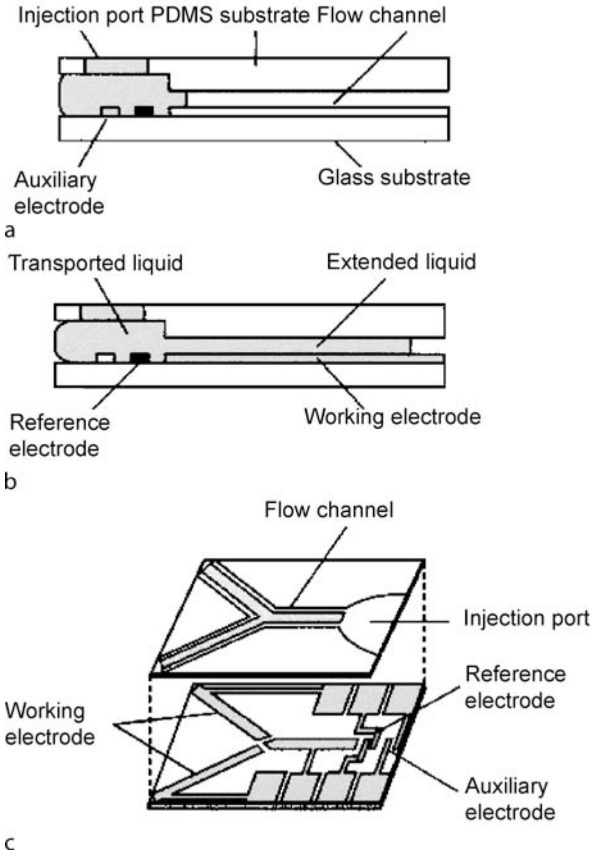
A more complex and integrated prototype miniaturized medical diagnostic platform based on electrowetting, as shown in Fig. 5, was engineered by Srinivasan et al. [15], in which it was confirmed that electrowetting actuation can be carried out, at least in principle, reliably and with a high degree of reproducibility on physiological liquid samples such as a whole blood, saliva, sweat, plasma, serum and urine. Biocompatibility issues, and, in particular, the problem of protein adsorption was discussed, in which it was found that a thin oil film wetting the hydrophobic substrate to avoid direct drop/surface contact led to suppression of the undesirable adsorption effects.

The highly programmable and controllable handling of individual drops using electrowetting lends itself conveniently to various microarray technologies. One example is the possibility of microfluidic chip multistep synthesis or multiplex reactions for high throughput combinatorial drug screening [16]. Another example is the preparation of drop arrays for matrix assisted laser desorption/ionization (MALDI) mass spectrometry proteomic analysis [17].

A way of spotting these microarray patterns onto a substrate is proposed by Yi and Kim [18] who drew out a drop from a liquid reservoir, transported it through a hydrophobic channel by electrowetting to a location where it can be deposited by capillarity onto the desired hydrophilic substrate, as shown in Fig. 6. They termed this as *soft printing* because biological materials contained within a liquid drop acting as a carrier can be spotted on a substrate without requiring solid to solid contact or drop ejection, for example, mechanical spotting or ink-jet printing, which are associated with problems such as splashing and spreading that lead to non-uniformities in the spot shape and size. Multiple spots can be achieved with multiple orifices at



Electrowetting, Applications, Figure 6 Illustration of the *soft printing* process. (**a**) Loading of the sample and approach of the glass plate on which the drop is desired to be spotted. (**b**) Drop dispensing and drop translation to the orifice by electrowetting. (**c**) Drop contact with the glass plate through the orifice. (**d**) Glass plate lift off and adhesion of the drop due to capillarity (from [18])



Electrowetting, Applications, Figure 7 Experimental setup of the *microchannel-like* flow type electrowetting device of Satoh et al. [19]. Panels (**a**) and (**b**) are cross-sectional views of the electrode and flow channel geometry, and, panel (**c**) shows the architecture of the device (from [19])

predetermined locations, the size of the spots being controlled by the metered drop volume.

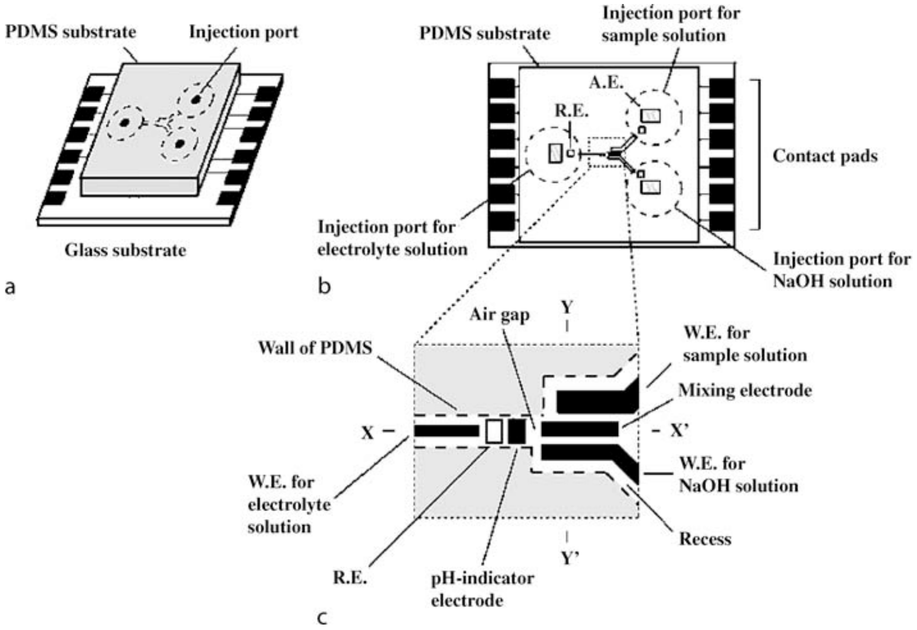
We briefly mention an attempt to employ electrowetting to drive *microchannel-like* flow as opposed to individual drop translation by using arrays of elongated electrodes (Fig. 7) instead of the short electrode array shown in Fig. 2 [19]. Their setup consisted of a large reservoir, from which a liquid meniscus advances, much like the electrocapillary-driven height-of-rise experiments between two vertically oriented electrode plates [20]. However, by adopting horizontal channels, gravity is eliminated allowing the meniscus to advance much easier. The advancement of the meniscus front, however, remains discrete unlike true continuous microchannel flow, for example driven by electroosmosis. This is due to the need to sequentially activate successive electrodes, as in all static electrowetting schemes. The setup was subsequently extended to allow for two converging flow channels such that mixing could occur [21]. An additional electrode was employed where the two flows converged, as shown in Fig. 8. Upon activation, this mixing electrode causes both fluids to wet the area above it in order to drive the mixing. An ammonium detection component was also integrated into the device by introducing a third channel that drove an electrolyte solution towards the mixing area (Fig. 8c), which is separated from the electrolyte by an air gap. Ammonia gas released due to the mixing then diffuses across this air gap and into the electrolyte solution, thus increasing its pH, which is subsequently detected by a pH indicator electrode.

Electrowetting has also been proposed for inducing rapid reversible switching of the lateral position of a liquid stream flanked by two side gas streams in a microfluidic channel, as depicted in Fig. 9 [22]. By careful alignment of the electrodes housed under the microchannel substrate, fluid streams can be merged or split using this method. This is potentially useful in the control and sorting of two-phase microfluidic flows. Another potential application for this flow switching technique is for generating parallel and sequential lamination between streams for micro-mixing without requiring complex fabricated geometries.

Electro-Optical Applications

Static electrowetting techniques are also extremely attractive for many electro-optical devices. Electrowetting was first employed in these applications for the dynamic and latchable tuning of optical waveguides [23, 24]. In these fiber optic applications, electrowetting is employed to alter the amount by which a conducting fluid (the choice of which is contingent on its viscosity being sufficiently low and its refractive index being greater than that of the fiber) housed in an insulating lubricant medium surrounds a section of an optical fiber stripped of its coating which runs through the fluidic channel loop; the loop allows fluid recirculation to eliminate back pressure. This voltage adjustable overlapping then modifies the transmission characteristics of the fiber due to electromagnetic field leakage of the cladding resonance modes, obtained with the aid of in-fiber gratings, into the fluid. Mach et al. [22] reported attenuation beyond 45 dB across both narrow and broad bands at 10^{-3} s order switching speeds; the insertion losses, attributed to mechanical coupling between the fiber and the light source and spectrum analyzer with the use of a fusion splice, were observed to be approximately 2 – 3 dB.

The ability to alter the interfacial shape of the drop via the application of an external electric field thus allows it to be used as an adaptive liquid lens whose focal length can be flexibly, reversibly and accurately adjusted via manipulation of the drop shape. The optical microcell consisted of two density-matched immiscible liquids (low conduc-

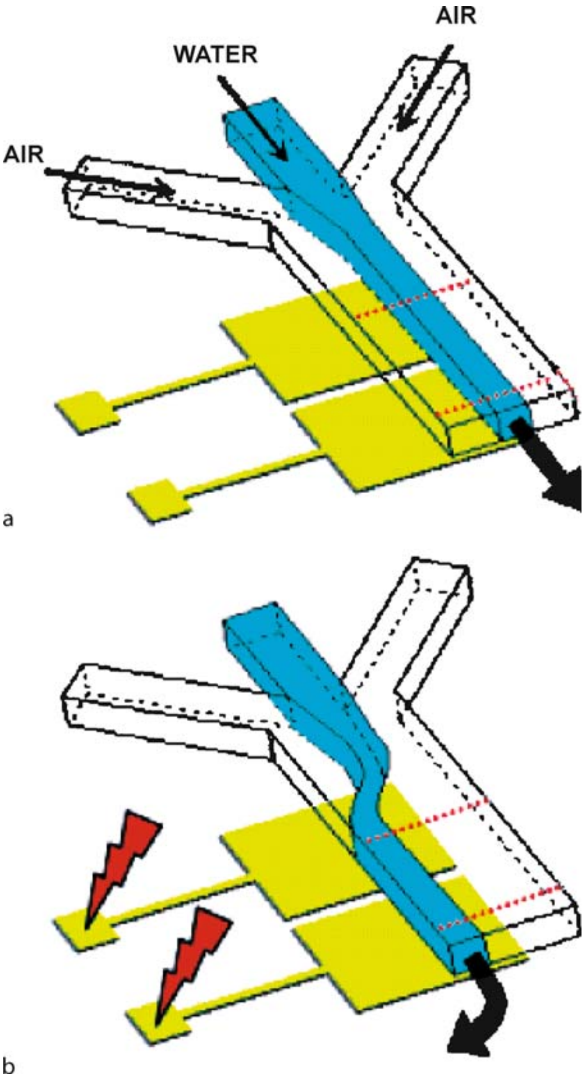


Electrowetting, Applications, Figure 8 Experimental setup of a miniaturized device which incorporates microfluidic actuation, mixing and sensing by electrowetting. Panel (**a**) shows the geometry of the channels and electrodes. Panel (**b**) shows the plan view of the device. Panel (**c**) is a magnification of the mixing and sensing chambers in which ammonia is detected (from [16])

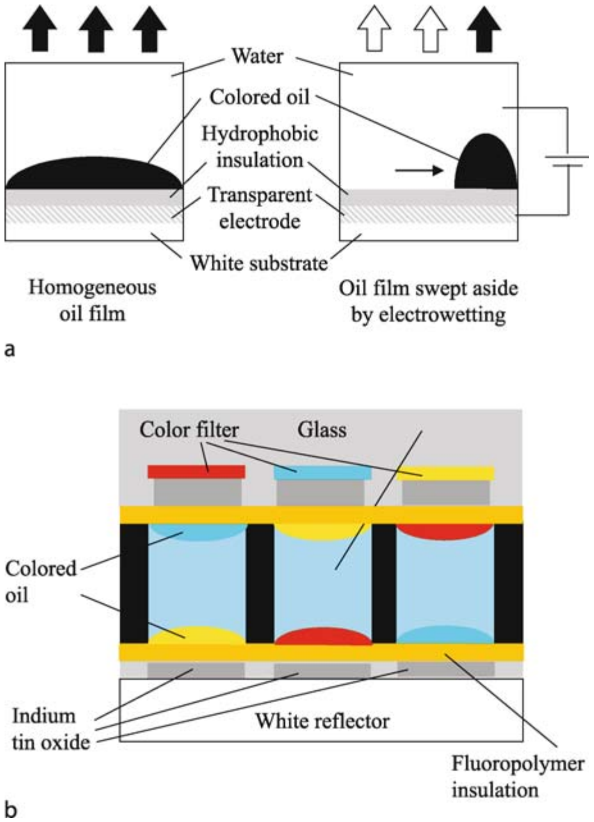
tivity non-polar organic liquid drop under a conducting aqueous solution) to eliminate gravitational effects on the interfacial shape. As a consequence of the contact angle dependence on the applied voltage, the focal length and refractive power is also a function of the voltage. Berge and Peseux [25] observed very short response times which thus allowed the lens to be switched rapidly at typical frequencies of order $10^2 - 10^3$ Hz. This switching frequency is dependent on the liquid viscosity; liquids with low viscosity resulted in excessive oscillation prior to obtaining an equilibrium shape whereas extremely viscous liquids led to overdamping and hence slow response times. This variable focusing technology was later developed for specific applications such as mobile phone cameras [26] although other applications such as optical modulators and amplifiers are also envisaged [27]. Photopolymeric conductive liquid drops can also be used in order to solidify the drop and hence retain its drop interfacial shape in a fixed position through exposure to ultraviolet irradiation [28].

Another interesting electro-optical application that has been developed using static electrowetting is in display technology. This idea was initially proposed in the 1980s by Beni and Hackwood [29] although a demonstrable prototype concept was only produced in 2003 by Hayes and Feenstra [30]. The principle is illustrated in Fig. 10a. A dyed oil drop under a transparent aqueous solution is confined within a cell that represents a single pixel in the reflective display; the cell is placed atop a white substrate. A hydrophobic layer is coated at the bottom of the cell such that in the absence of an applied potential, the oil forms a thin equilibrium layer covering the entire cell area. Upon application of the electric field, however, the contact angle increases and the oil film retracts to form a drop in the corner of the cell. The extent to which the drop retracts is thus dependent on the applied voltage. The 250 μm^2 pixels are also believed to be sufficiently small such that an area average is only apparent to the observer; the retracted spot should therefore go unnoticed. The pixel can thus be switched between the colored (voltage on) and transparent (voltage off) states rapidly, the switching speed, typically milliseconds, depending on pixel size and the thickness and physical properties of the oil film [31], being sufficiently fast for current display applications, such as video graphics and electronic paper.

An electrowetting colored display was also demonstrated by subdividing the pixel cell into three subcells, as shown in Fig. 10b, above each of which a different color filter is placed. An additional oil layer/drop is included in each pixel, this time on the top of the cell, the interfacial shape of which can be altered independently of the bottom layer through the application of a potential between the aqueous phase and the top electrode. Hayes and Feenstra [30] reported that the brightness (in terms of intrinsic reflec-



Electrowetting, Applications, Figure 9 Electrowetting activated liquid stream switching in two-phase microflows. (**a**) No applied voltage. (**b**) Voltage applied (from [22])



Electrowetting, Applications, Figure 10 (**a**) Principle of electrowetting display technology. The left images show the spreading of the homogeneous colored oil film across the entire pixel cell when no voltage is applied. The right images show the retraction of the oil drop to the corner of the pixel cell upon application of a voltage. (**b**) Principle of a color electrowetting display showing the division of the pixel cell into three subcompartments, each with two active layers. Different color filters are placed above each subcompartment (from [30])

tivity) of their full color display was approximately four times that of liquid crystal displays.

Other Applications

Various other applications based on static electrowetting have also been suggested. For example, Welters and Fokkink [32] propose that the spreading of drops due to static electrowetting is useful for temporary adhesion enhancement (e. g. in the drying of paint) or as a fast capillary switch. Prins et al. [20] demonstrated the use of electrically-induced capillary height-of-rise for the individual filling and draining of an array of vertical capillary channels. They demonstrated this by adding CsCl into the aqueous solution, which has the capability of absorbing X-rays, therefore presenting the capability of the device as a tunable optical filter, which can be exploited for X-ray shielding.

Applications Based on Spontaneous Electrowetting

Compared to static electrowetting, spontaneous electrowetting research is still in its infancy stages. Nevertheless, the technology holds substantial promise to be exploited in various microfluidic applications. The premise of generating a thin spontaneous front-running electrowetting film ahead of a macroscopic spreading drop using parallel line electrodes fabricated onto a hydrophobic substrate was first reported by Jones et al. [3] as a possible mechanism for microfluidic actuation. With slight modification of the electrodes at predetermined locations downstream, Jones et al. showed the possibility of creating nanodrops at these locations upon removal of the electric field, upon which the film ruptures and dewets due to capillary instabilities [3].

Future Directions for Research

Given that electrowetting is now moderately well understood, the main thrust in this area of research has been in the development of microfluidic and electro-optical devices based on the technology. There are one or two electrowetting driven electro-optical devices now within reach of commercial product development stage. Nevertheless, there are several technical challenges that have to be addressed before most electrowetting based devices can be translated from laboratory bench type devices to that close to commercial realization. An important limitation is contact angle saturation at high voltages; at present there is no general consensus on why this arises. Joule heating is a problem that needs to be overcome, in particular, for microdevices. In addition, a reduction in typical magnitudes in the applied voltage to obtain the desired response will make electrowetting more attractive for integration into real microfluidic devices.

Cross References

- ► Digital Microfluidics
- ► Droplet Dispensing
- ► Electrocapillary
- ► Electrowetting
- ► Electrowetting and Droplets
- ► Interfacial Electrokinetic Flow
- ► Surface Tension, Capillarity and Contact Angle
- ► Wetting and Spreading

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Electrowetting on Dielectric (EWOD)

- ► Digital Microfluidics
- ► Electrowetting
- ► Electrowetting, Applications
- ► Electrowetting and Droplets

Electrowetting and Droplets

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Synonyms

Droplet microfluidics; Electrowetting on dielectric (EWOD); Electrowetting on insulator coated electrodes (EICE)

Definition

Electrowetting is the electrostatically-induced decrease of the liquid contact angle at a contact line formed at the intersection of a liquid, solid, and a third fluid that can be a gas or immiscible liquid. The contact angle is measured within the droplet between the solid surface and the fluid–fluid interface. It ranges from 0 for complete wetting to 180 degrees for non-wetting. As applied to droplets, electrowetting can be used to spread droplets, change the shape of droplets, induce shape-mode oscillations, split droplets, move droplets across the surface, and merge and mix droplets.

Overview

Electrostatic manipulation of droplets has been utilized for ink-jet printing, ESI mass-spectrometry and flow cytometry applications. In contrast to these droplet-in-air applications, electrowetting involves the electrostatic manipulation of droplets attached to solid surfaces. Applications that utilize this method include micro-optofluidic manipulations of droplets to serve as electrically-controlled zoom lenses [1, 5] and as shutters or color filters for flat panel displays [4]. Another application is in performing biological and chemical assays by manipulating sample and reagent droplets using electrowetting [9, 10]. Thus, electrowetting of droplets on surfaces is viewed as a method that may provide a Lab-on-a-Chip (LOC) platform to replace the use of pipettes, glass beakers, tubes, pneumatic and piezoelectric automated dispensers, as well as standard (as defined by Society for Biomolecular Screening (SBS)) wells and plates in the laboratory.

The focus of this entry is on some unique physical characteristics of electrowetting applied to droplets. In particular, electrowetting-induced droplet shape changes, mixing, and droplet translation are discussed and some novel results involving shape-mode oscillations with and without simultaneous droplet translation are presented.

Basic Methodology

Shape Changes

Electrowetting can be used to manipulate the curvature of a droplet immersed in an immiscible fluid. As described by researchers from Varioptic [1] and Philips [5], this change in curvature can provide a lens with a variable focal length. Varioptic (www.varioptic.com) reports that zoom lenses and autofocus lenses for cameras and video cameras used in cell phones, scanners, printers, barcode readers and other applications are being developed using electrowetting to adjust the curvature of the meniscus between two fluids. The engineering of a system of this type, an example of which is shown in Fig. 1, requires that fluids be selected with appropriate optical properties, appropriate temperature dependence of the refractive indices and viscosities appropriate to provide rapid response and stability of the meniscus shape. If the viscosity is too low, a change in the contact angle will cause a time-decaying oscillation of the shape corresponding to underdamped motion. However, if the viscosities are too large, the system may respond in an overdamped manner that relaxes too slowly to be acceptable for use as an adjustable lens.

Another application of electrowetting control of droplet shapes is within a pixel of a flat panel display. As described by researchers from Liquavista, a VC-backed spin-out company from Philips, electrowetting can be used to spread water over a pixel to displace colored oil into a corner of the pixel [4]. With an array of pixels of this type, a flat panel video display can be generated as shown in Fig. 2. This approach is well-suited to monochrome displays and triplet sub-pixelation can be used to gener-