

Electrowetting

and

Digital Microfluidics

Different driving forces become pertinent in microscale systems in contrast to their macroscale counterparts to drive fluids.

Surface tension force

Important in microscale domain owing to the fact that the surface to volume ratio increases significantly in microscale.

The control of surfaces and surface energies is one of the most important challenges both in microtechnology in general as well as in microfluidics. For liquid droplets of sub-millimetre dimensions, capillary forces dominate.

The control of interfacial energies (both liquid–vapour and solid–liquid interfaces) has therefore become an important strategy for manipulating droplets at surfaces.

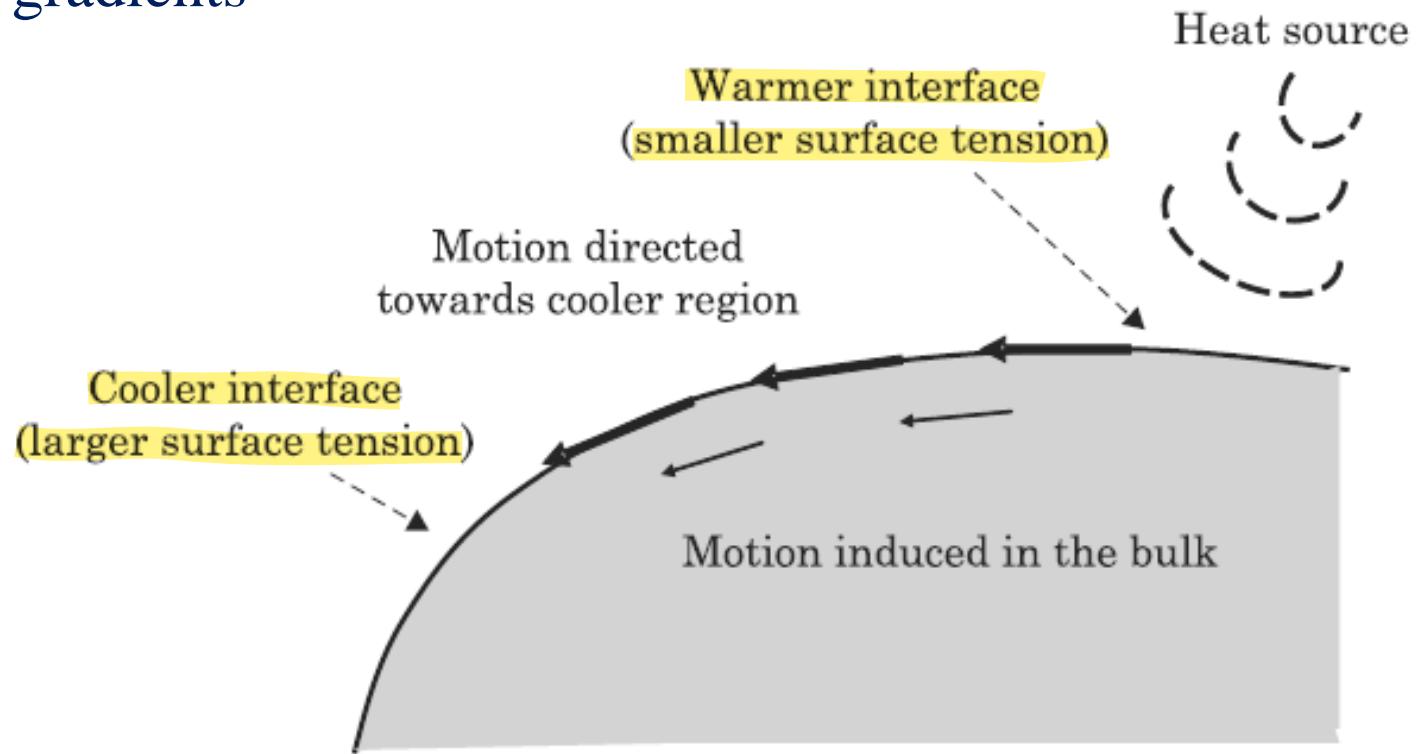
Precise manipulation of droplets in the micrometer scale.

Four fundamental fluidic operations (creating, transporting, cutting, and merging) with droplets are utilized to digitize droplet- based fluidic system which has evolved into a new microfluidics paradigm

Digital Microfluidics

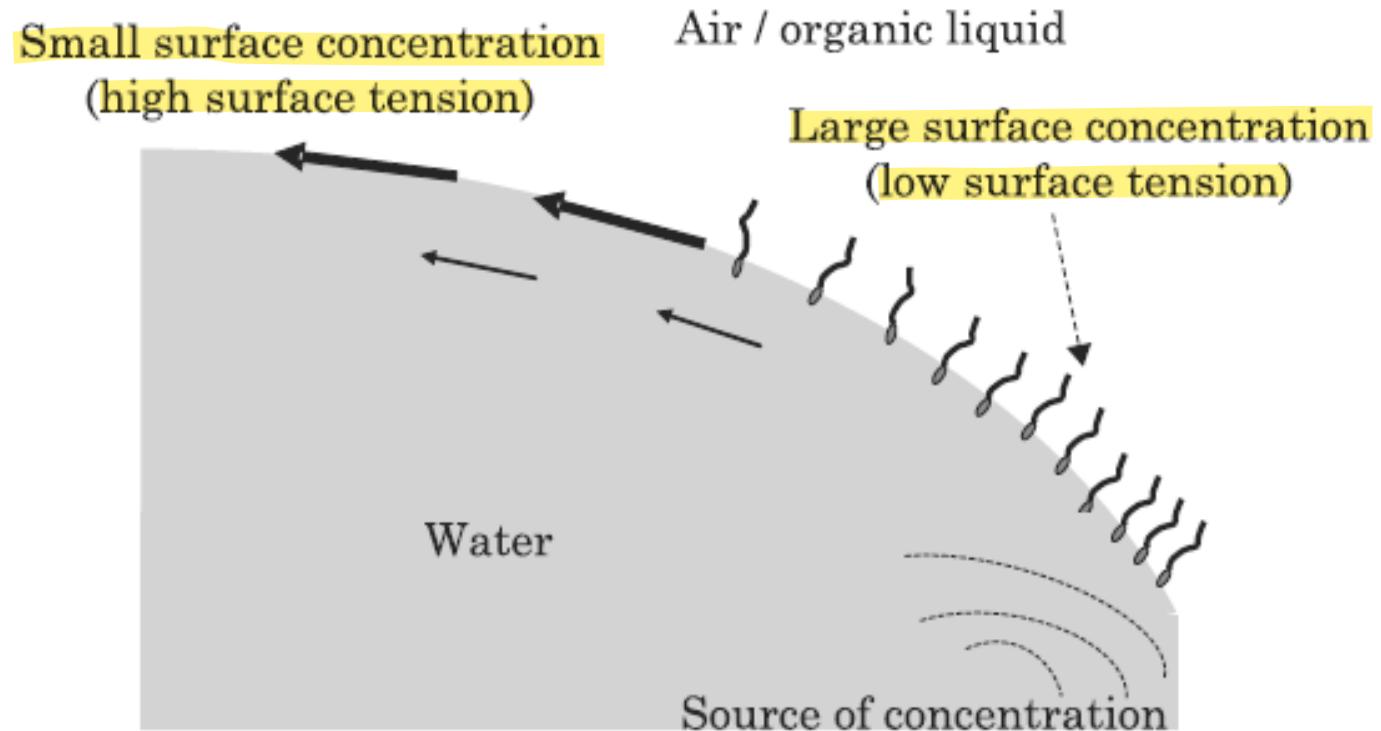
Ways to influence the interfaces

Temperature gradients



Interface motion induced by a thermal gradient between two regions of the surface. The interface motion propagates into the bulk due to viscous forces.

Gradients in the concentration of surfactants across droplets



Gives rise to gradients in interfacial energies, mainly at the liquid–vapour interface, and thus produce forces that can propel droplets making use of the thermocapillary and Marangoni effects.

Marangoni convection occurs if the variation of the surface tension force dominates the viscosity forces.

A dimensionless number—the Marangoni number (thermal)—determines the strength of the convective motion

$$Ma = \frac{\Delta\gamma R}{\rho v \alpha}$$

where R is the radius of the spherical cap, ρ the density of the liquid, v the kinematic viscosity, α the thermal diffusivity, and $\Delta\gamma$ the variation of surface tension on the interface.

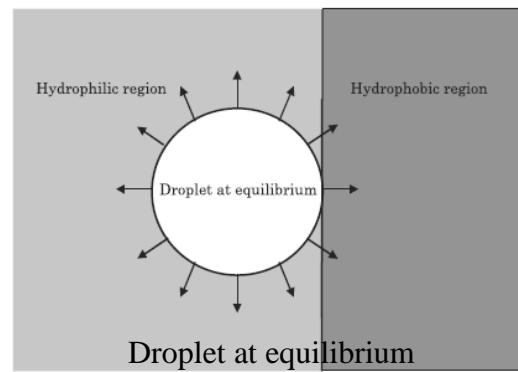
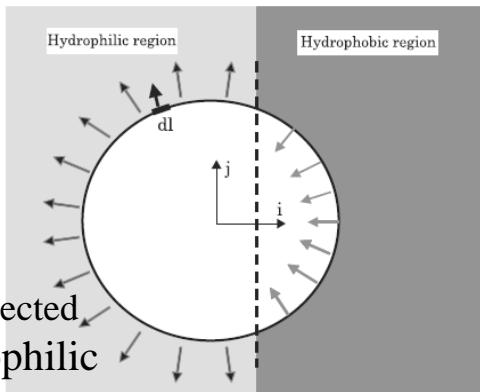
The Marangoni number represents the ratio between the tangential stress and the viscosity.

Drops Moving by Capillarity

At the microscopic scale there are other forces to move fluids that are not efficient at the macroscopic scale. These forces are electro-osmosis and capillarity. In particular capillarity is widely used for actuating droplets.

1. Drop Moving Over a Transition of Wettability

Resulting force directed towards the hydrophilic region



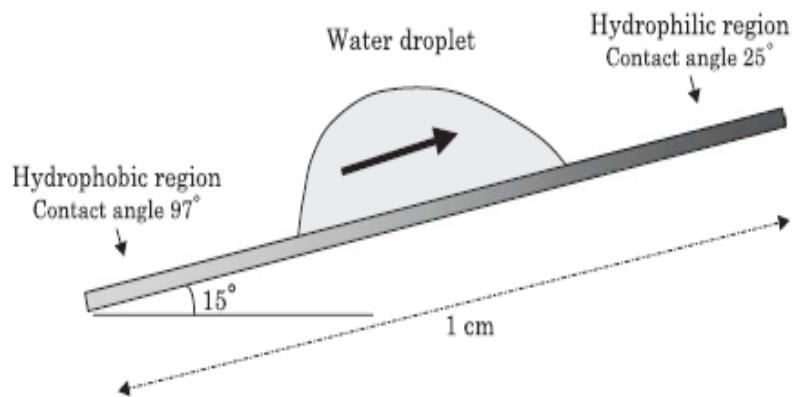
If L_1 and L_2 are the contact lines in the hydrophilic and hydrophobic planes, and θ_1 and θ_2 the contact angles, the force acting on the drop is

$$\begin{aligned} F_x &= \int_{L_1} (\gamma_{SG} - \gamma_{SL})_1 (\vec{i} \cdot d\vec{l}) - \int_{L_1} (\gamma_{SG} - \gamma_{SL})_2 (\vec{i} \cdot d\vec{l}) \\ &= \int_{L_1} \gamma_{LG} \cos \theta_1 (\vec{i} \cdot d\vec{l}) - \int_{L_2} \gamma_{LG} \cos \theta_2 (\vec{i} \cdot d\vec{l}) < 0. \end{aligned}$$

2. Drop Moving Uphill

Capillary forces may be sufficient to make micro-drops move upwards on an inclined plane.

M.K. Chaudhury and G.M. Whitesides, “How to make water run uphill,” *Science*, Vol. 256, pp. 1539–1541, 1992.



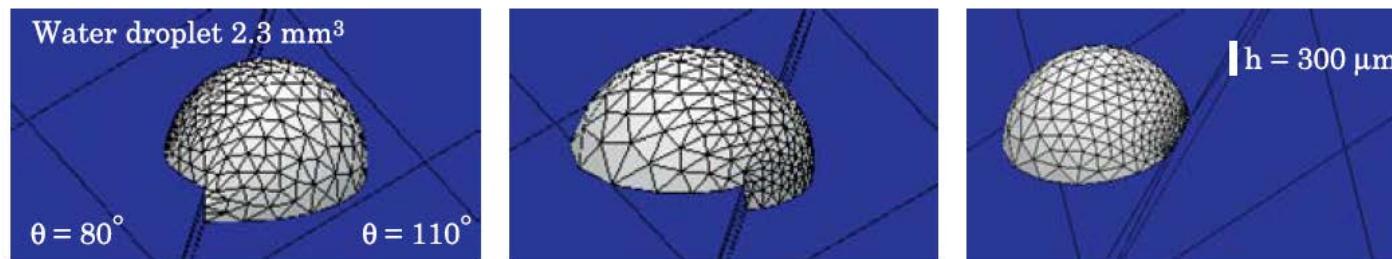
The required gradient in surface free energy was generated on a polished silicon wafer by exposing it to the diffusing front of a vapor of decyltrichlorosilane,

The average velocity is approximately 1 to 2 mm/s

A drop moves uphill towards the more hydrophilic region.

3. Drop Moving up a Step

A micro-drop of water is initially located on a step at the boundary of a hydrophilic region (on top of the step) and a hydrophobic region (at the base of the step). The drop progressively moves towards the hydrophilic region, even if this region is located at a higher level (simulation result)

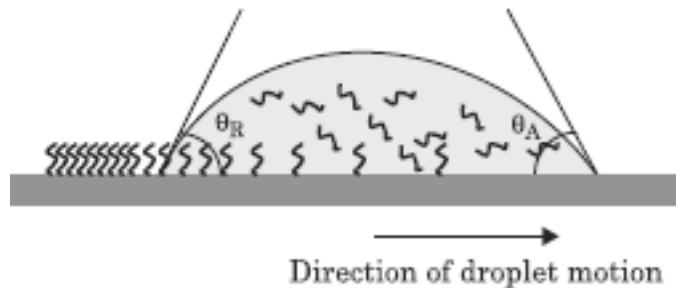
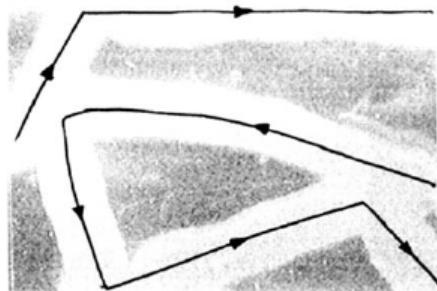


Motion of a drop up a step towards the hydrophilic plane (simulation)

4. Drop Moving Over a Gradient of Surface Concentration of Surfactant

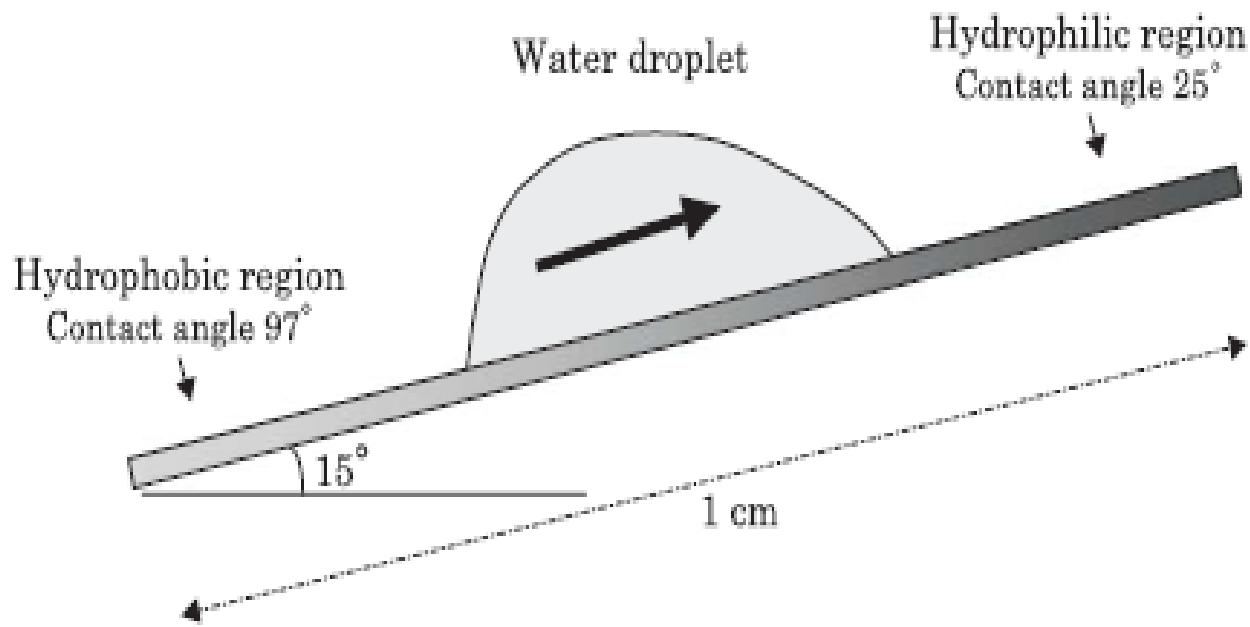
Chemical reactions between the liquid of the droplet and the substrate can create droplet motion. A droplet of n-alkanes containing silane molecules is placed on a hydrophilic surface. Silane molecules form dense grafted monolayers on silicon or glass, rendering the surface hydrophobic.

If such a droplet is deposited on a glass surface and pushed with a pipette, then the droplet continues to move on the substrate. It moves in nearly linear segments and changes its direction each time it encounters a hydrophobic barrier. The droplet cannot cross its own tracks.



The advancing contact line has a hydrophilic Young contact angle. Molecules of silane concentrate at the vicinity of the receding contact line and form a hydrophobic layer.

Chemical and topographical structuring of surfaces - local wettability

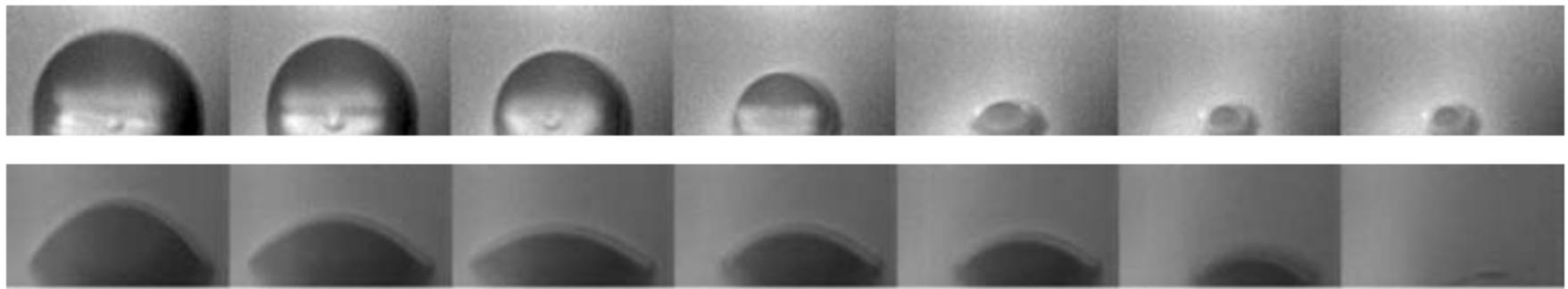


The main disadvantage of chemical and topographical patterns is their **static nature**, which prevents active control of the liquids.

Examples of the role of the interface/contact line

Evaporation of sessile droplets

It has been observed experimentally that wetting and non-wetting droplets do not evaporate in the same way.



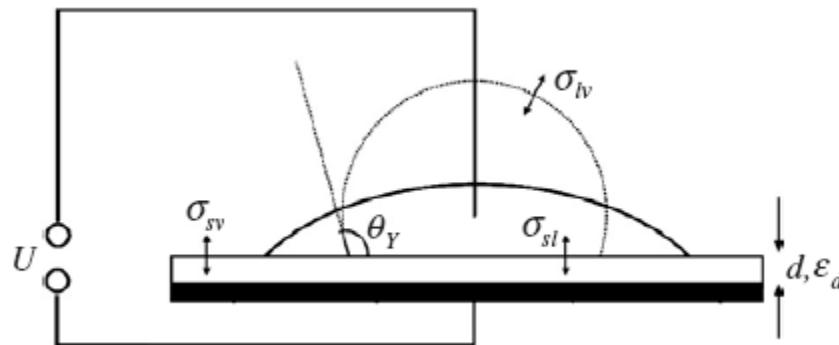
Water Droplet on hydrophobic (top) and hydrophilic (bottom) surfaces

In the case of a non-wetting droplet, it is the **contact angle that remains constant (CCA)**, the contact radius decreases gradually.

In the case of a wetting droplet the **contact radius remains constant (CCR)** during the evaporation process, the contact angle decreases gradually. It is as if the contact line was pinned on the initial contact line.

Electrocapillarity, the basis of modern electrowetting, was first described in detail in 1875 by Gabriel Lippmann.

the capillary depression of mercury in contact with electrolyte solutions could be varied by applying a voltage between the mercury and electrolyte



Generic electrowetting set-up. Partially wetting liquid droplet at zero voltage (dashed) and at high voltage (solid).

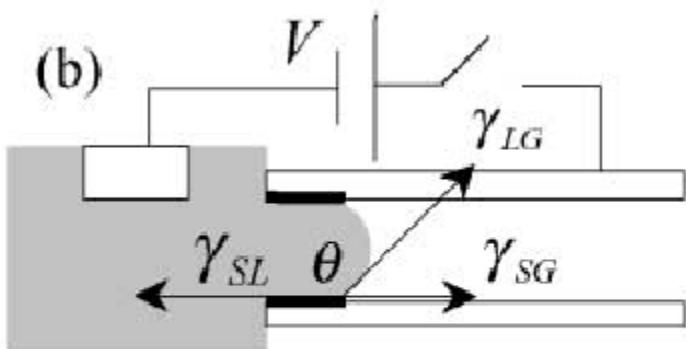
Electrowetting (EW) has proven to be very successful:

Contact angle variations of several tens of degrees are routinely achieved.

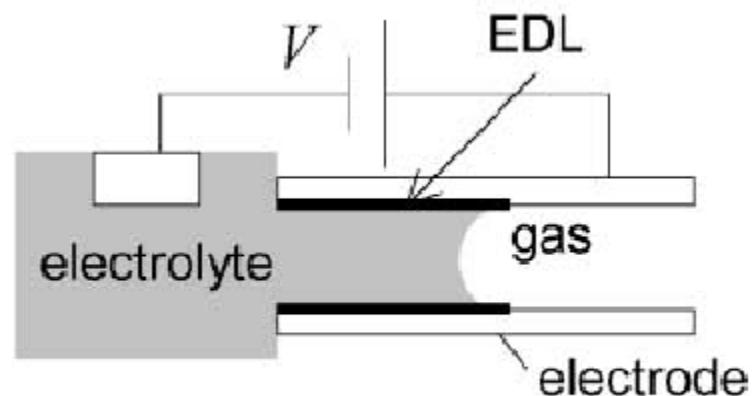
Electrowetting (EW)

In EW an electrical double layer (EDL) is formed between the electrode and aqueous solution that is between 1 nm and 10 nm thick.

Applying a voltage difference may cause a hydrophobic surface to behave like a hydrophilic one. The electric energy counterbalances the free surface energy and lowers the surface tension γ_{SL} .



hydrophobic: retracting



hydrophilic: advancing

Switching speeds are limited (typically to several milliseconds) by the hydrodynamic response of the droplet rather than the actual switching of the equilibrium value of the contact angle.

Excellent stability without noticeable degradation

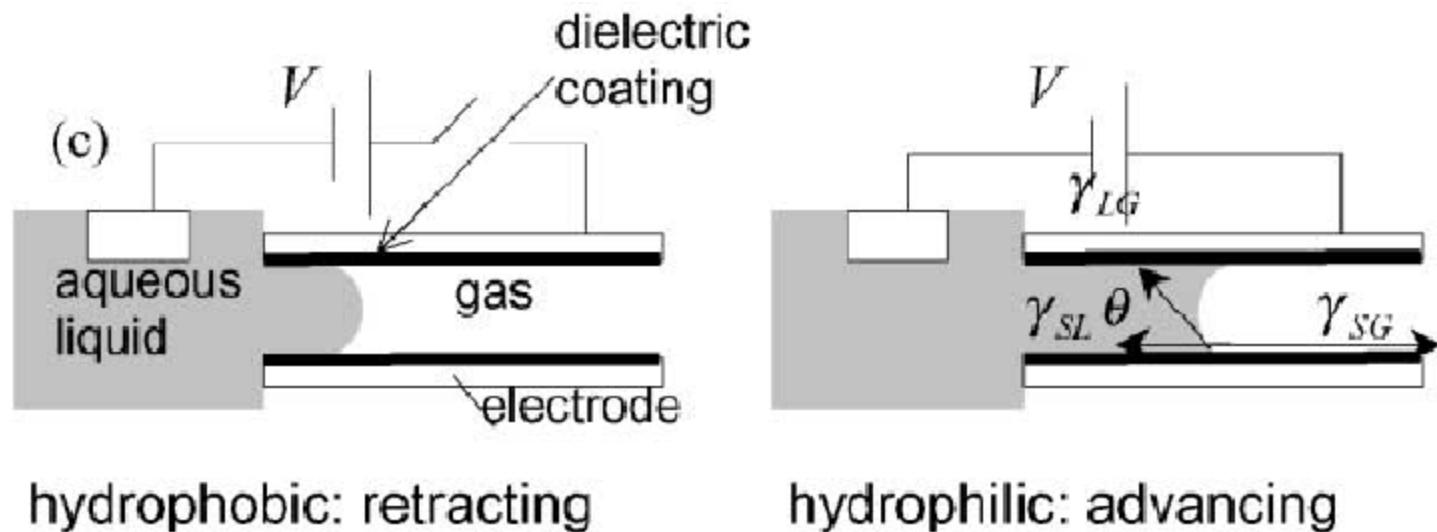
Nowadays, droplets can be moved along freely programmable paths on surfaces; they can be split, merged, and mixed with a high degree of flexibility.

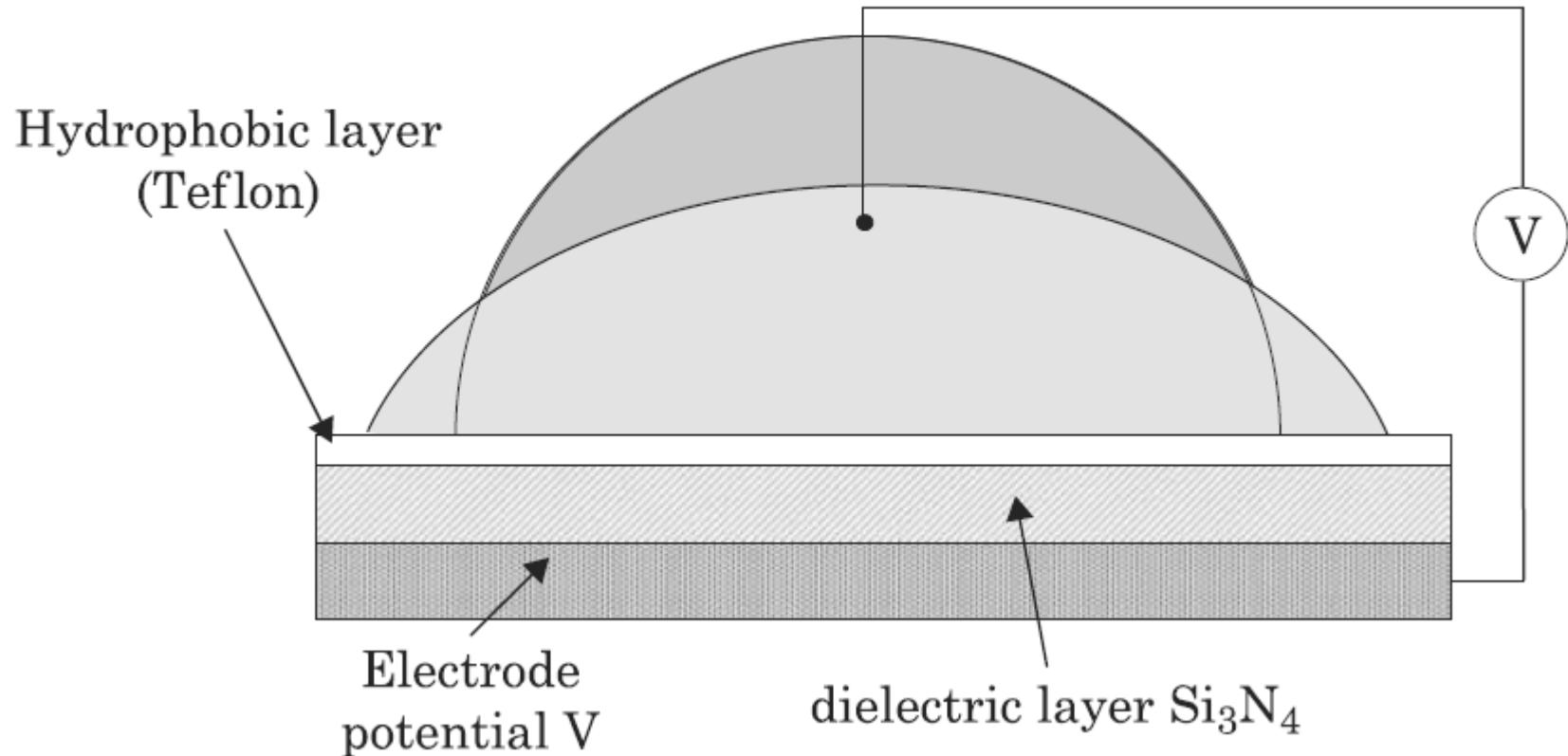
However, electrolysis start within a few milli-volts to make EW difficult to use for practical applications.

Electrowetting-on-dielectric (EWOD)

Berge in the early 1990 introduced the idea of using a thin insulating layer to separate the conductive liquid from the metallic electrode in order to eliminate the problem of electrolysis - **Electrowetting on dielectric (EWOD).**

In EWOD there is no electric double layer, but the change in the energy balance takes place in the hydrophobic dielectric layer; A Teflon layer, $0.8 \mu\text{m}$ thick was used as the dielectric. Lee, J., Moon, H., Fowler, J., Schoellhammer, T., and Kim, C.-J. (2002). Electrowetting and electrowetting-on-dielectric for microscale liquid handling. *Sens. Actuators, A*, 95:259–268.





EWOD

Electrowetting: basics to applications

Electrowetting has become one of the most widely used tools for manipulating tiny amounts of liquids on surfaces.

Applications range from ‘lab-on-a-chip’ devices to adjustable lenses and new kinds of electronic displays.

Issues

Fundamental and applied aspects.

Basic electrowetting equation,

Origin of the electrostatic forces that induce both contact angle reduction and the motion of entire droplets.

Issues – contd.

Limitations of the electrowetting equation

Failure of the electrowetting equation, namely the saturation of the contact angle at high voltage,

The dynamics of electrowetting

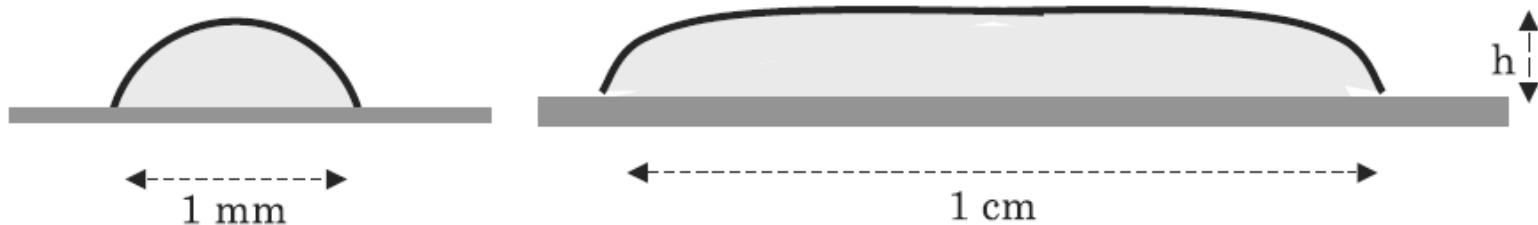
Overview of commercial applications

Theoretical background

Basic aspects of wetting

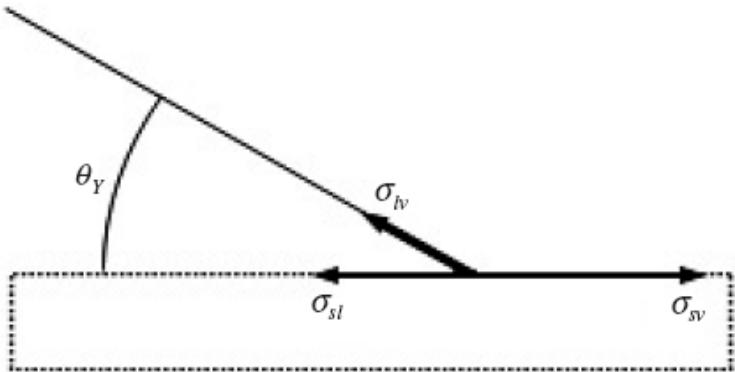
In electrowetting, one is generically dealing with droplets (typical size of the order of 1 mm or less) of partially wetting liquids (aqueous salt solutions) on planar solid substrates.

Bond number $Bo = \sqrt{g \Delta \rho R^2 / \sigma_{lv}}$ measures the strength of gravity with respect to surface tension.



If $Bo < 1$, the strength of gravity is neglected and the behavior of the droplets is determined by surface tension alone.

The free energy F of a droplet is a function of the droplet shape.



Force balance at the contact line

The free energy F of a droplet is the sum of the areas A_i of the interfaces between the three phases, weighted by the respective interfacial energies, i.e. σ_{sv} , σ_{sl} , and σ_{lv} :

$$F = F_{if} = \sum_i A_i \sigma_i - \lambda V \quad (1)$$

λ is equal to the pressure drop across the liquid–vapour interface.

Minimization of Eq. (1) leads to the following condition that any equilibrium liquid morphology has to fulfill -

Laplace Equation

$$\Delta P = \sigma_{lv} \left(\frac{1}{r_1} + \frac{1}{r_2} \right) = \sigma_{lv} K \quad (2)$$

$$\textbf{Young Equation} \quad \cos \theta_Y = \frac{\sigma_{sv} - \sigma_{sl}}{\sigma_{lv}} \quad (3)$$

relates Young's equilibrium contact angle to the interfacial energies

Both equations are approximations intended for mesoscopic scales.

Electrowetting theory for homogeneous substrates

The thermodynamic and electrochemical approach - Lippmann's derivation
- direct metal – electrolyte interfaces

Upon applying a voltage dU , an electric double layer builds up spontaneously at the solid–liquid interface consisting of charges on the metal surface on one hand and of a cloud of oppositely charged counter-ions on the liquid side of the interface.

Since the accumulation is a spontaneous process, it leads to a reduction of the (effective) interfacial tension, σ_{eff}

$$d\sigma_{sl}^{eff} = -\rho_{sl} dU \quad (4)$$

$\rho_{sl} = \rho_{sl}(U)$ is the surface charge density of the counter-ions, U = applied voltage

The voltage dependence of σ_{sl}^{eff} is calculated by integrating this equation

Simplifying assumption - the counter-ions are all located at a fixed distance d_H (*of the order of a few nanometres*) from the surface (**Helmholtz model**).

In this case, the double layer has a fixed capacitance per unit area,

$$C_H = \frac{\epsilon_0 \epsilon_1}{d_H} \quad C_H = \rho / U$$

Where ϵ_1 is the dielectric constant of the liquid. γ_{SL}^{eff} denotes the effective surface tension at the liquid–solid interface

$$\gamma_{SL}^{\text{eff}}(U) = \gamma_{SL} - \int_{U_{pzc}}^U C_H U dU = \gamma_{SL} - \frac{\epsilon_0 \epsilon_1}{2d_H} (U)^2 \quad (5)$$

U_{pzc} is the potential (difference) of zero charge and approximated to zero.

Mercury surfaces—like those of most other materials—acquire a spontaneous charge when immersed into electrolyte solutions at zero voltage. The voltage required to compensate for this spontaneous charging is U_{pzc}

$$\gamma_{LG} \cos \theta = \gamma_{SG} - \gamma_{SL}$$

Young's law applied successively at zero potential and at potential V can be written

$$\gamma_{SG} - \gamma_{SL} = \gamma_{LG} \cos \theta_0$$

$$\gamma_{SG} - \gamma_{SL}^{\text{eff}}(V) = \gamma_{LG} \cos \theta$$

where θ, θ_0 are respectively the actuated and non-actuated contact angles.

$\gamma_{LG} \cos \theta = \gamma_{SG} - \gamma_{SL}$
This equation for γ_{sl}^{eff} is inserted into Young's equation.

For an electrolyte droplet placed directly on an electrode surface one can find (U_{pzc} approximated to zero)

$$\cos \theta = \cos \theta_Y + \frac{\epsilon_0 \epsilon_1}{2d_H \sigma_{lv}} (U)^2 \quad (6)$$

θ_Y - equilibrium contact angle at zero applied voltage, ϵ_0 - permittivity of free space, ϵ_1 - dielectric constant of the insulating layer, σ_{lv} - surface tension between the liquid and the vapor, and U the applied voltage

For typical values of d_H (2 nm), ϵ_1 (81), and σ_{lv} (0.072 mJ m⁻²) the ratio on the rhs of equation is on the order of 1 V⁻².

The contact angle thus decreases rapidly upon the application of a voltage.

This equation is only applicable within a voltage range below the onset of electrolytic processes, i.e. typically up to a few hundred millivolts.

Modern applications of electrowetting usually circumvent this problem by introducing a thin dielectric film, which insulates the droplet from the electrode.

In EWOD, the electric double layer builds up at the insulator–droplet interface.

Since the insulator thickness d is usually much larger than d_H , the total capacitance of the system is reduced tremendously.

The system may be described as two capacitors in series, namely the solid–insulator interface (capacitance c_H) and the dielectric layer with

$$c_d = \frac{\epsilon_0 \epsilon_d}{d}$$

ϵ_d is the dielectric constant of the insulator.

Since $c_d \ll c_H$, **the total capacitance per unit area $c \approx c_d$.**

With this approximation, the finite penetration of the electric field into the liquid, is neglected (liquid treated as a perfect conductor) and the voltage drop occurs within the dielectric layer.

Equation (5) is replaced by

$$\sigma_{sl}^{eff}(U) = \sigma_{sl} - \frac{\epsilon_0 \epsilon_d}{2d} U^2 \quad (7)$$

It is assumed that the surface of the insulating layer does not give rise to spontaneous adsorption of charge in the absence of an applied voltage, i.e. $U_{pzc} = 0$.

In this equation the entire dielectric layer is considered part of one effective solid–liquid interface with a thickness of the order of d , typically $O(1 \mu m)$.

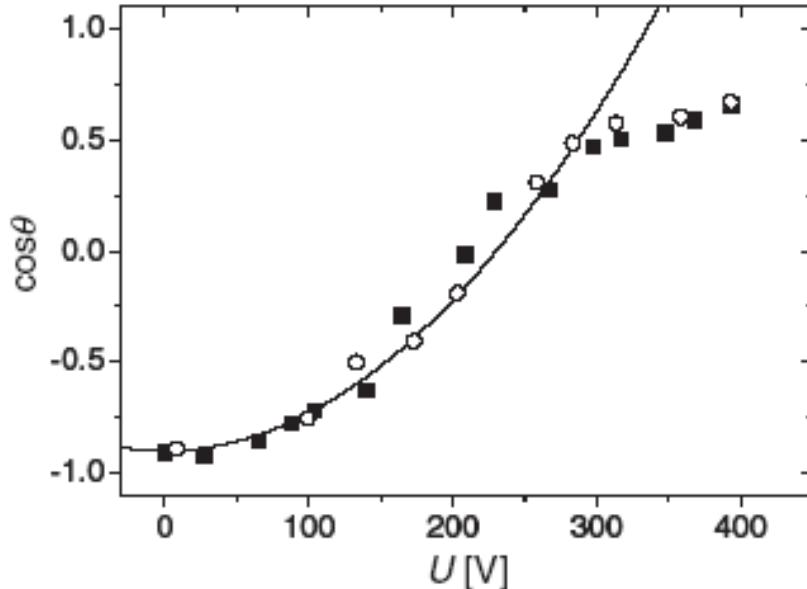
Combining Eq. (7) with Eq. (3), the basic equation for EWOD is obtained

$$\cos \theta = \cos \theta_Y + \frac{\epsilon_0 \epsilon_d}{2 d \sigma_{lv}} U^2 = \cos \theta_Y + \eta \quad (8)$$

$\eta = \frac{\epsilon_0 \epsilon_d}{2 d \sigma_{lv}} U^2$ is the **dimensionless electrowetting number** which measures the strength of the electrostatic energy compared to surface tension.

The ratio in the middle of Eq. (8) is typically four to six orders of magnitude smaller than that in Eq. (6), $\frac{\epsilon_0 \epsilon_1}{2 d_H \sigma_{lv}}$ depending on the properties of the insulating layer.

Consequently, the voltage required to achieve a substantial contact angle decrease in EWOD is much higher.



Contact angle versus applied voltage for a glycerol–salt (NaCl) water droplet.

Filled (open) symbols: increasing (decreasing) voltage.

Solid line: parabolic fit according to Eq. (8)

Equation (8) is found to hold as long as the voltage is not too high.

Beyond a certain system dependent threshold voltage, however, the contact angle has always been found to become independent of the applied voltage -

- Contact angle saturation phenomenon

After some initial contact angle decrease, even very large external voltages fail to achieve full wetting, i.e., zero contact angle. It is often perceived that this saturation phenomenon is a device-related imperfection that could be remedied through better engineering.

Interestingly, the basic physics of the phenomenon has not been fully clarified. Several rather disconnected hypotheses have been advanced such as charge trapping, gas ionization in the vicinity of the contact line, contact line instability, droplet resistance, and the zero interfacial tension criterion.

At high voltage, the contact angle has always been found to saturate.

In particular, no voltage-induced transition from partial to complete wetting has ever been observed. (On the basis of equation (8), such a transition would be expected to occur at

$$U_{spread} = (2\sigma_{lv}d(1 - \cos \theta_Y)/(\varepsilon_0\varepsilon_d))^{(1/2)} .$$

Instead, θ adopts a saturation value θ_{sat} varying between 30° and 80° , depending on the system

Contact angle saturation is still not well understood.

Digital microfluidics refers to describe two different technologies —

- **an open system** - droplet position is controlled by actuating electrodes arranged in a two-dimensional array
- **confined system** - droplets are manipulated inside microchannels.

These systems enable the miniaturization of reactions by compartmentalizing reactions in droplets of nanoliter to microliter volumes.

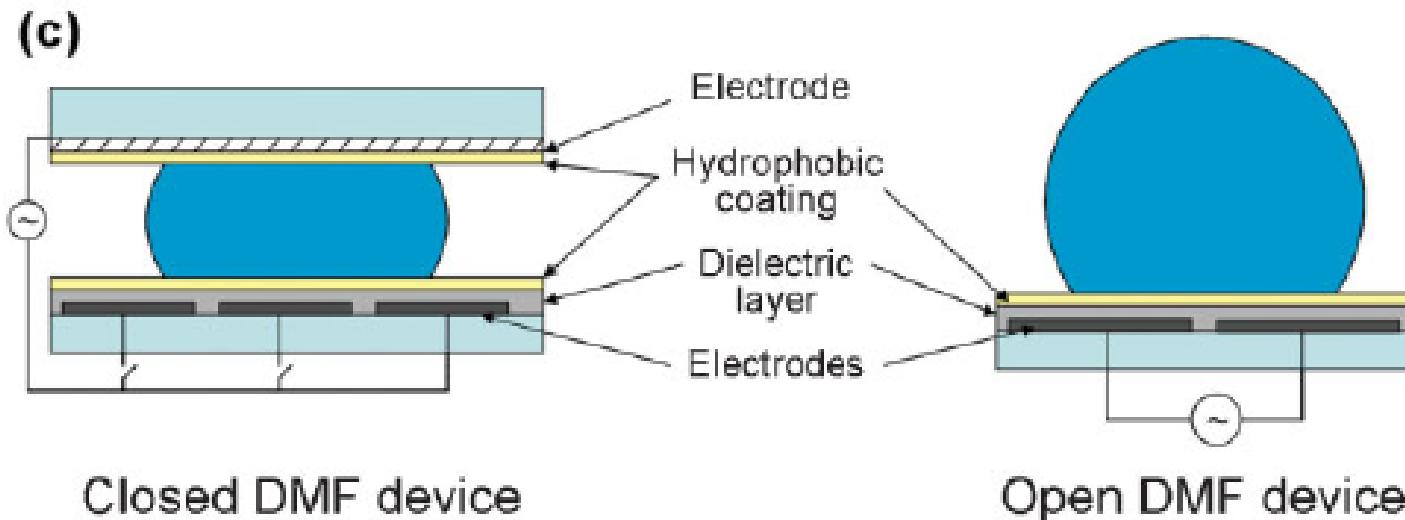
Compartmentalization in droplets provides rapid mixing of reagents, control of the timing of reactions, control of interfacial properties, and the ability to synthesize and transport solid reagents and products.

Droplet-based microfluidics can help to enhance and accelerate chemical and biochemical screening, protein crystallization, enzymatic kinetics, assays.

DMF is typically implemented in one of two different configurations –

The **closed format** (also known as the two-plate format), in which droplets are sandwiched between two substrates patterned with electrodes (the substrates house driving and ground electrodes, respectively).

The **open format** (also known as the single-plate format), in which droplets are placed on top of a single substrate, housing both actuation and ground electrodes.



In both configurations, **an insulating layer of a dielectric material** is deposited on top of the actuation electrodes, to limit current and prevent electrolysis.

Typically, the insulating layer is covered by an **additional hydrophobic coating**, which reduces droplet-sticking to the surface.

Closed DMF devices are best suited for a **wide range of droplet operations** – dispensing, moving, splitting, and merging are all feasible.

Open DMF devices are typically not efficient for splitting and dispensing; however, the open format facilitates **fast sample and reagent mixing**, the capacity to move large droplets, and better access to samples for external detectors.

Additionally, **evaporation rates are higher in open-format devices**, which may be advantageous or inconvenient, depending on the application.

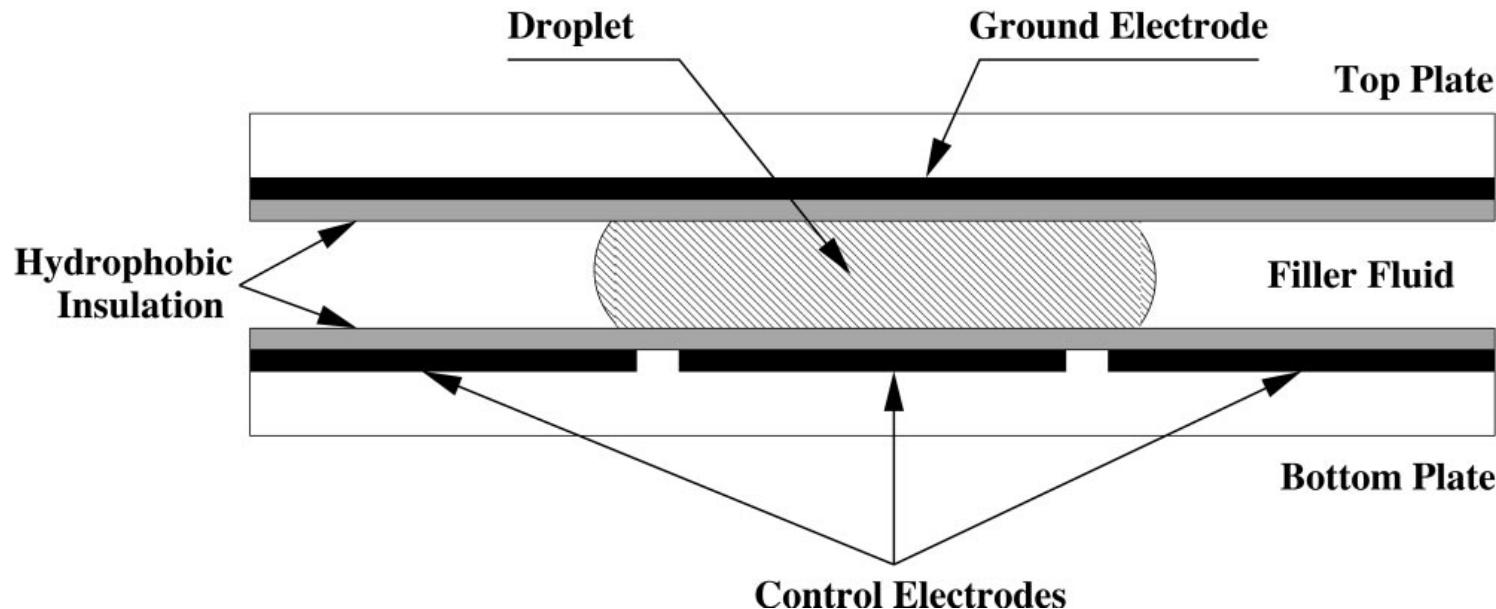
Liquid motion could only be achieved above some **threshold voltage**.

This observation is attributed to contact angle hysteresis: droplet motion can only set in when the contact angle on the leading edge of the droplet exceeds the local advancing contact angle.

Reynolds numbers of electrowetting-induced flows are rather low.

With typical velocities of the order of $v \approx 10^{-2} - 10^{-1} \text{ m s}^{-1}$ and droplet sizes of $R \approx 10^{-3} \text{ m}$ or less, one obtains $Re = \rho v R / \mu \approx 100$ for water and even smaller values for more viscous liquids. Hence, the flow is usually laminar.

Within the range of validity of the electrowetting equation EW-induced motion is analogous to the motion of droplets on chemically heterogeneous substrates,



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.

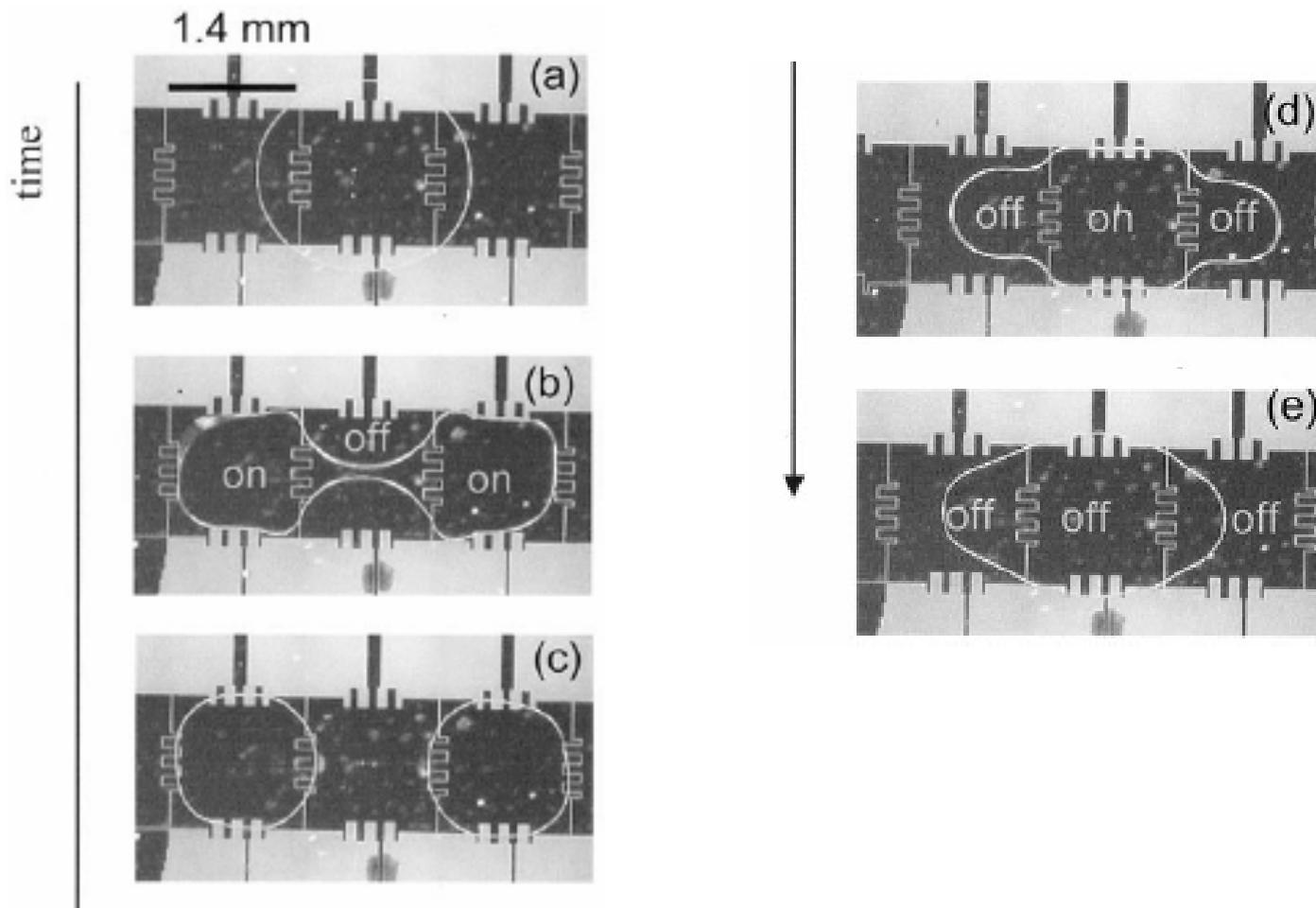
The system geometry and droplet volume are controlled such that the footprint of the droplet overlaps at least two adjacent control electrodes while also making contact to the upper ground electrode.

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.

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 uninsulated electrode implementations.

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.



Sequential images of successful cutting and merging of droplets at 25 V
(gap size $d = 70 \mu\text{m}$, electrode is 1.4 mm x 1.4 mm, volume is 0.2 μl).

One of the substrates contains the patterned electrodes for liquid actuation.

The other substrate consists of a homogeneous electrode that provides electrical contact to the droplet(s) independently of its (their) position.

- transparent ITO layer on a glass substrate, covered with a thin hydrophobic layer that gives rise to a large contact angle and weak contact angle hysteresis but does not prevent electrical contact.

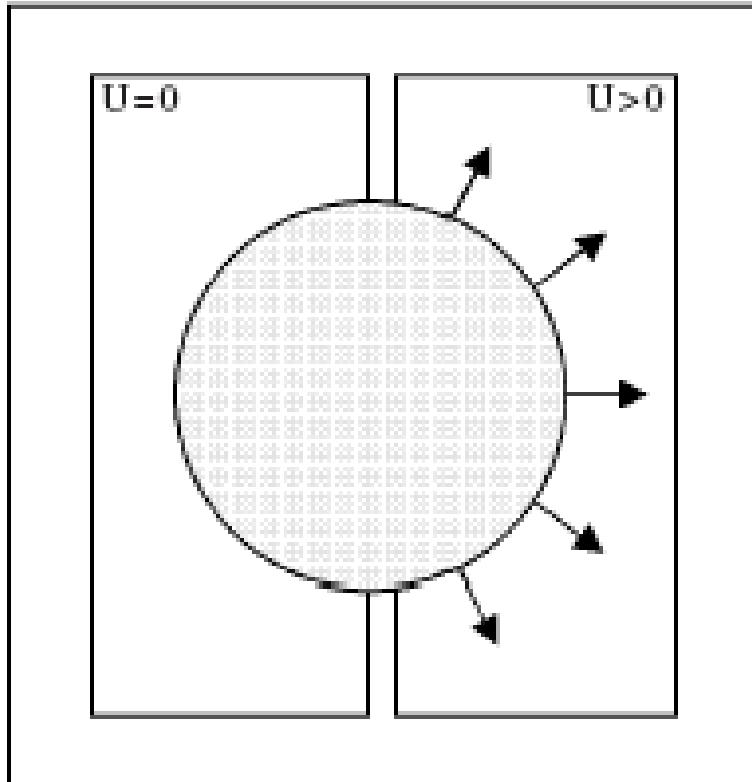
Droplet actuation- droplet edges must overlap with at least two adjacent electrodes.

With substrate separations of 100–500 μm and electrode sizes of the order of 1 mm, this means **typical droplet volumes of 0.1–1 μl** .

Routine tasks e.g., moving, merging, mixing, and splitting of droplets

Dynamic aspects of electrowetting

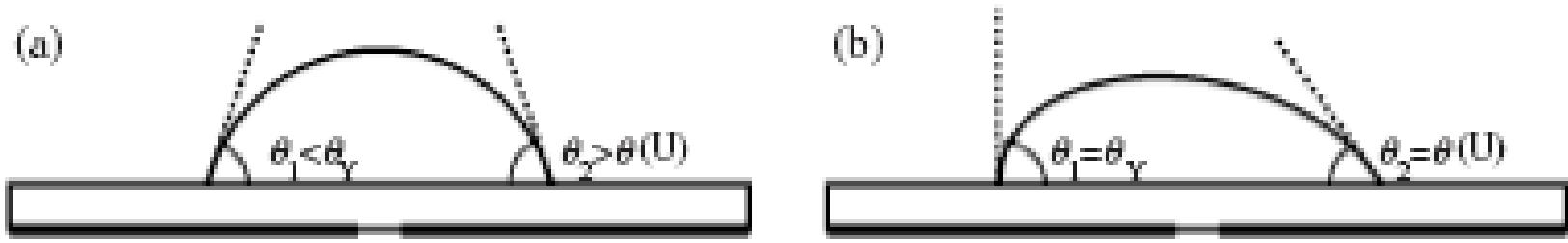
For many practical applications, the dynamic response of the liquid is of interest



Top view of a droplet partially overlapping with an **activated (right)** and a **deactivated (left)** electrode. Arrows indicate the force acting on the contact line.

The contact angle assumes a time and speed dependent value which is determined by local dissipative processes and flow fields at the vicinity of the TCL.

On the other hand, the entire droplet also responds on a global scale, e.g. by a translation of its centre of mass.



Side view of imbalanced droplets partially overlapping with a **deactivated (left) and with an activated (right) electrode**. (a) Droplet dominated by contact line friction; (b) droplet dominated by bulk viscous dissipation.

There are several contributions to the net force which oppose the motion.

If the dissipation is dominated by **contact line friction**, the **pressure within the droplet equilibrates quickly** and the **droplet retains its spherical cap shape** but with a **time dependent dynamic contact angle θ_d**

If bulk viscous effects dominate, the contact angle assumes its local equilibrium angle everywhere along the contact line. As a result, the drop shape is non-spherical and a hydrodynamic pressure gradient arises and drives fluid flow within the droplet.

In most practical situations, an intermediate behaviour is expected.

By considering the static mechanical equilibrium, the bubble driving force produced by electrowetting actuation may be approximated as follows:

$$F_{Driving} = 2\gamma w \sin\left(\frac{\theta_R + \theta_L}{2}\right) (\cos\theta_R - \cos\theta_L)$$

where γ is the interfacial tension between the liquid and the bubble, and w is the width of the bubble base that linearly scales with the radius R of the bubble.

Here, the contact angle θ_R of the bubble is modulated by electrowetting actuation and decreases from the equilibrium contact angle θ_e with a large span (generally $\sim 40^\circ$).

$$F_{Driving} = 2\gamma w \sin\left(\frac{\theta_R + \theta_L}{2}\right) (\cos\theta_R - \cos\theta_L)$$

Therefore, the sine term can be roughly approximated to the sine of the equilibrium contact angle θ_e , whereas the difference in the cosines increases as the contact angle θ_R for the bubble is decreased by electrowetting modulation.

Based on these relationships, it can be concluded that the maximum driving force can be achieved when the equilibrium contact angle is close to 90° and the contact angle modulation is maximized by electrowetting actuation.

This force can be in the micro Newton range.

Contact Line Friction

As the droplet moves along the path of decreasing hydrophobicity (due to electrowetting, for example), dynamic wetting can be visualized as the displacement of the three phase contact line from one location to another.

The advancement of the three phase contact line leads to dissipation of energy at the molecular level and is commonly known as the three phase contact line friction force.

Contact Line Friction

Theoretical Model

The instantaneous velocity of the droplet on surface can be evaluated by analyzing the surface tension gradient inspired driving force and the resistive forces acting on the drop, namely the hydrodynamic and the three phase contact line forces.

A force balance on the moving droplet results in the following equation,

$$m \frac{dU}{dt} = F_{driving} - [F_h + F_{cl}]_{resistive}$$

where m is the mass of the moving droplet; F_h = hydrodynamic force; and F_{cl} = three-phase **contact line friction force**.

The droplet also experiences a drag force if it is encapsulated by a filler medium. However, this drag force is found to be insignificant when compared to the other resistive forces and is neglected.

The driving force acting on the droplet is given as,

$$F_{driving} = 2R(t)\gamma g(\theta)$$

where

$$g(\theta) = \int_0^{\pi/2} [\cos(\theta)_a - \cos(\theta)_r] \cos \phi d\phi$$

$R(t)$ is the radius of the footprint of the drop and γ is the liquid–gas interfacial tension.

A wedge approximation to the Stokes flow condition analysis was used to predict the hydrodynamic force exerted by the solid surface on the liquid drop as,

$$F_h = [8\mu R(t) f(\theta, \varepsilon) U]$$

U is the instantaneous velocity of the drop; θ is the dynamic contact angle of the drop, and $\varepsilon = L_s/R$ where L_s is the slip length, $O(1\text{nm})$.

The three phase contact line friction force can be expressed as,

$$F_{cl} = 2P(t)\zeta U$$

where $P(t)$ is the droplet perimeter length and ζ is the coefficient of the contact line friction

Therefore, the governing equation for droplet movement can be expressed as

$$m \frac{dU}{dt} = 2R(t)\gamma g(\theta) - [8\mu R(t)f(\theta, \varepsilon) + 4\pi R(t)\zeta]U$$

This equation can be integrated to obtain the expression for U , with ζ being the only unknown.

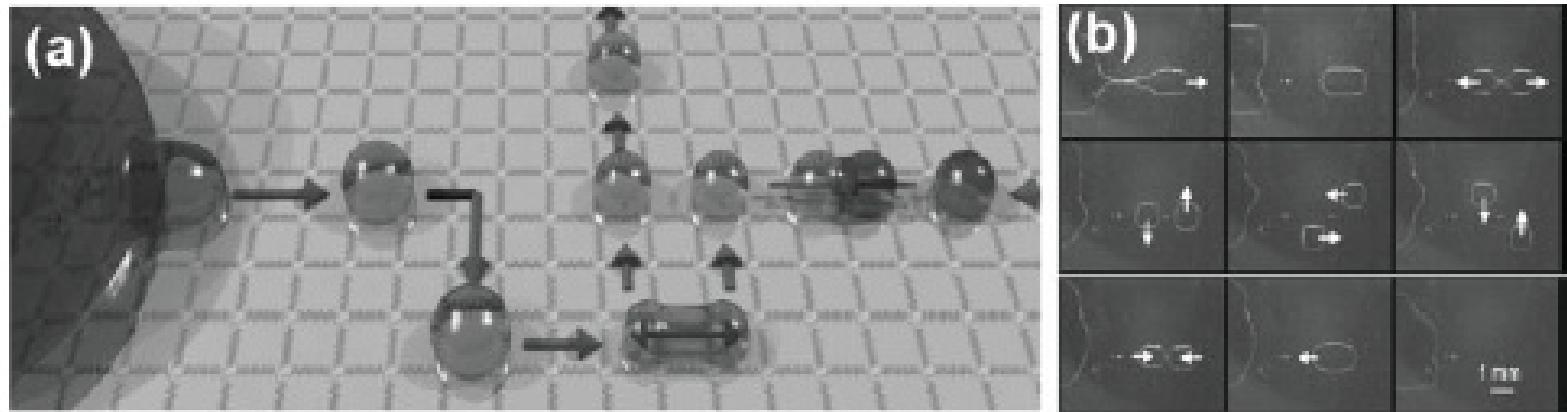
For a given solid–liquid system, there is no definitive way of predicting the values of ζ (responsible for the dynamic wetting behavior) from independently measured quantities and must be evaluated in situ for each simulation/experiment.

The values of ζ as reported in the literature vary considerably from 0.000089 Pa·s for molecular dynamics simulations of dynamic wetting behavior of liquid to 738000 Pa·s for melting of metal and oxides on molybdenum.

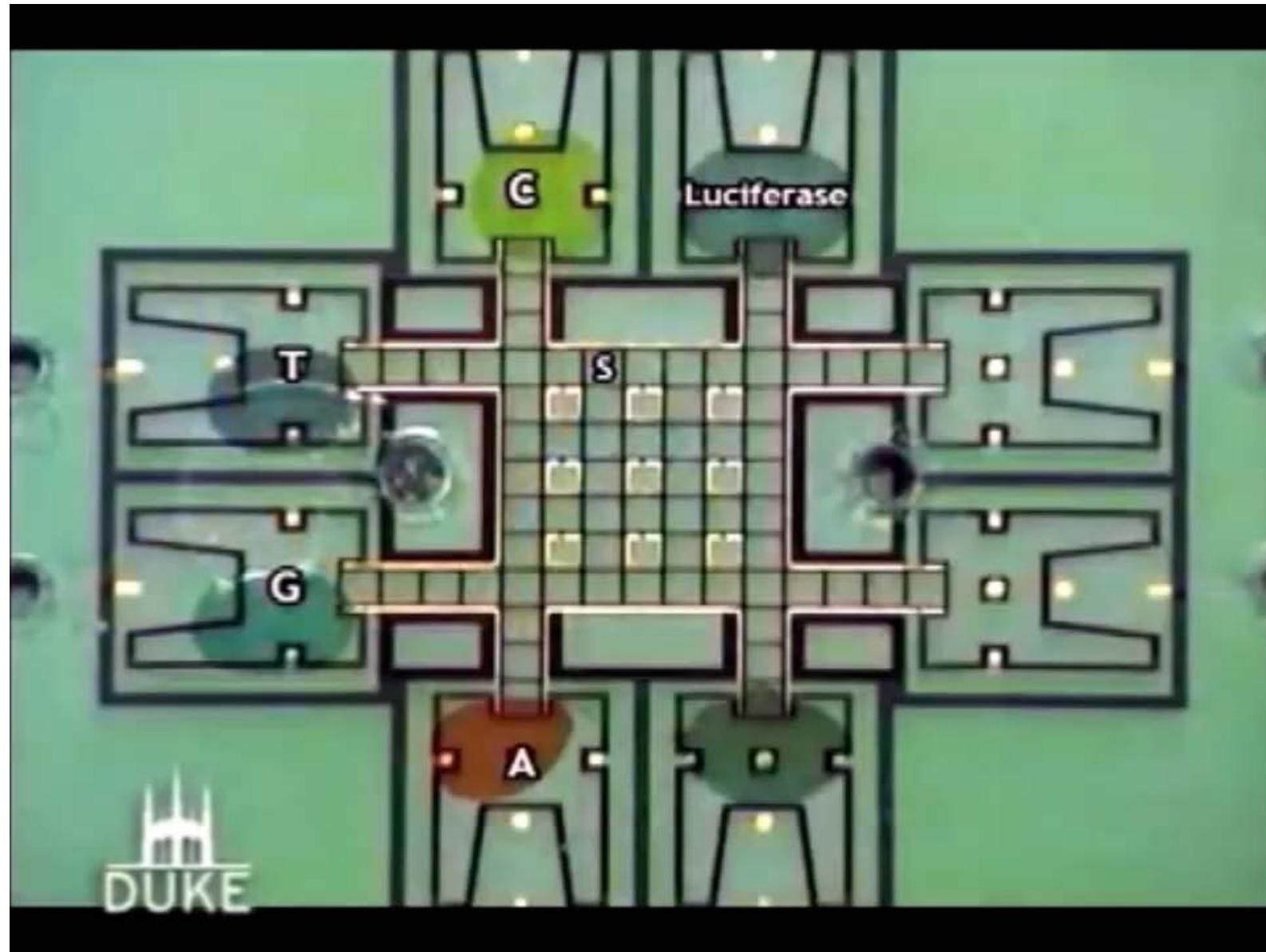
Digital Revolution In Microfluidics

In digital microfluidics (DMF), discrete droplets are manipulated by applying electrical fields to an array of electrodes.

In contrast to microchannels, in DMF each sample and reagent is individually addressable, which facilitates exquisite control over chemical reactions.



The DMF paradigm. a) Schematic and b) pictures from a movie depicting the four principle DMF processes: dispensing, moving, splitting, and merging.



Complex surfaces and droplet morphologies

- *Morphological transitions on structured surfaces*

- e.g. hydrophobic surface (e.g. $\theta = 180^\circ$) with a stripe of variable wettability.

For moderate wettability contrasts, there is only one stable morphology, which is a droplet slightly stretched along the stripe.

- *Patterned electrodes*

- multilayer substrates with various patterned electrodes separated by dielectric layers

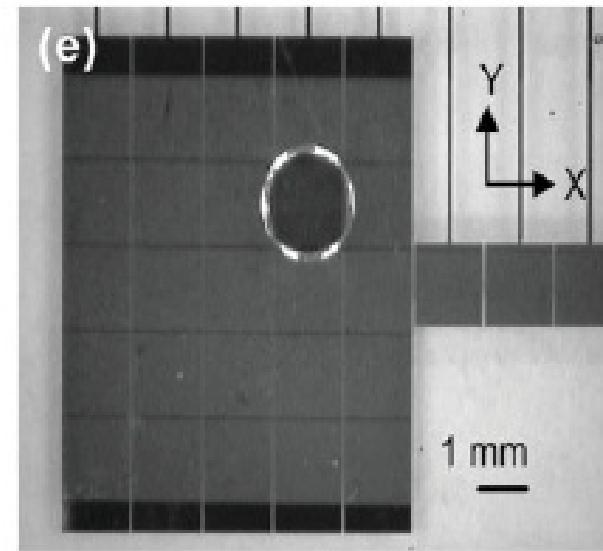
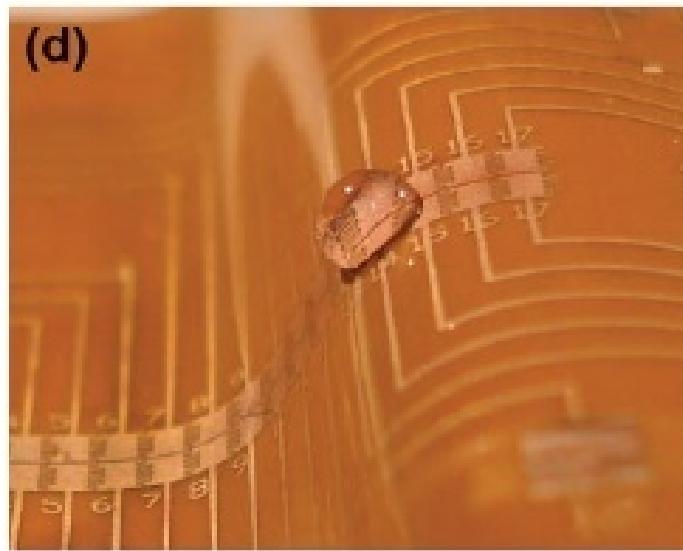
- *Topographically patterned surfaces*

- Superhydrophobicity and hydrophilicity are amongst the most spectacular consequences of surface roughness

Secondly, droplets serve as discrete microvessels, in which reactions can be carried out without cross-talk between samples or reagents.

DMF is inherently an array-based technique, good match for array-based biochemical applications.

DMF devices are straightforward to use, and are reconfigurable for any desired combination of droplet operations.



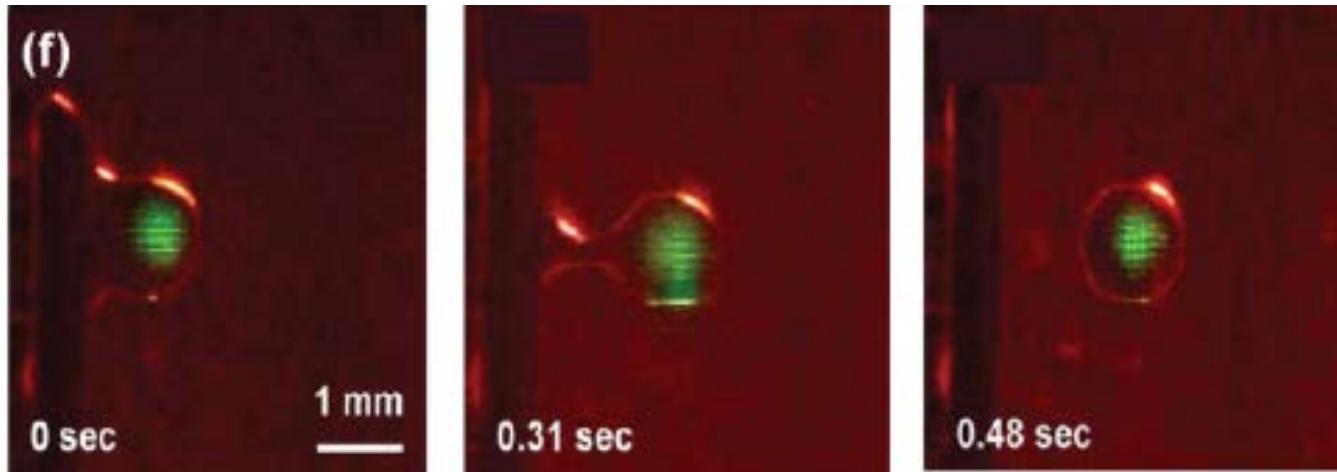
d) Picture of an ATDA (all-terrain droplet actuation) device, capable of manipulating droplets on flexible substrates. e) Picture of a DMF device powered by a cross reference electrode array.

DMF devices are typically fabricated in a clean-room facility using conventional techniques, such as photolithography and etching.

Electrodes are formed from substrates common to such facilities (e.g., chromium, gold, indium-tin oxide (ITO), and doped polysilicon).

The **insulating dielectric layer** - vapor deposition (parylene, amorphous fluoropolymers, and silicon nitride), thermal growth (silicon oxide), or spin-coating (PDMS or SU-8).

The **hydrophobic coating** - spin-coating a thin layer of Teflon-AF.



*Series of pictures from a video (left-to-right) depicting droplet dispensing on an **optically driven** DMF device.*

While many DMF devices are used to actuate droplets in air, another common technique uses **droplets suspended in oil**, which prevents evaporation and reduces the voltages required for droplet actuation.

Fouling by a variety of bio-fluids containing high concentrations of potential surface-fouling molecules, including blood, serum, plasma, urine, saliva, sweat, and tear **could be minimized** by suspending droplets in an immiscible oil.

Oil-immersed systems have **drawbacks**,

- requirement of gaskets or other structures to contain the oil bath,
- liquid–liquid extraction of analytes into the surrounding oil,
- the incompatibility with oil-miscible liquids (e.g, organic solvents),
- the incompatibility with assays requiring drying droplets onto the device surface.

Biological Applications of Digital Microfluidics

DNA Extraction, Repair, and Amplification- Handling, purifying, detecting, and characterizing samples of DNA - genome research

Proteomics and Enzyme Assays - drug development, prepare peptide and protein samples for matrix assisted laser desorption/ionization mass spectrometry

Cell Assays Cell-based assays have been a popular target for miniaturization, as the reagents and other materials are often prohibitively expensive.

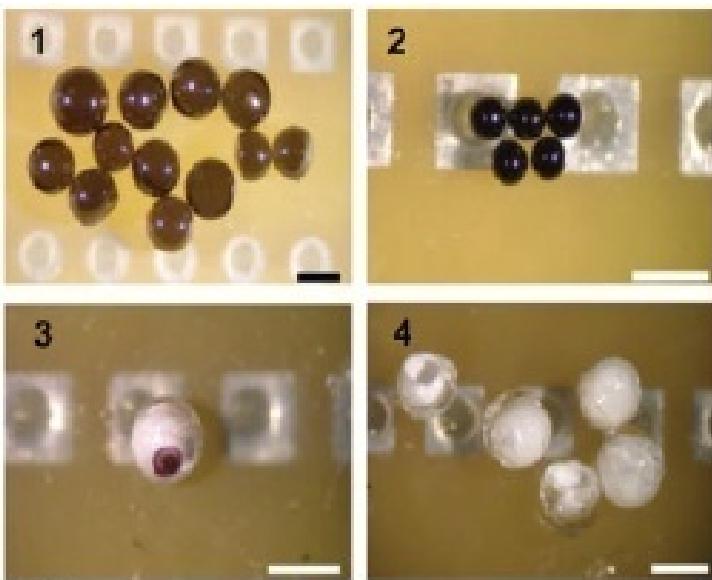
Immunoassays to detect analytes in biological samples with high selectivity.

Optical applications

Microlenses - Liquid lenses are flexible. Their curvature and hence their focal length can be tuned by adjusting their shape. This can be achieved by changing the contact angle of sessile droplets via electrowetting. This allows for the design of optical systems with variable focal length that can be addressed purely electrically,

Fibre optics **Display technology** - electrowetting-based reflective display

Particle Synthesis



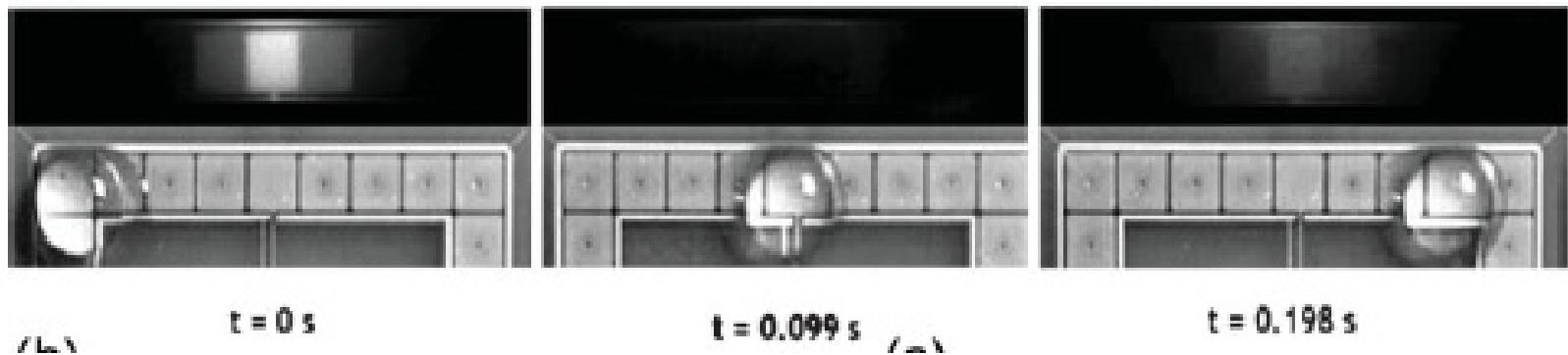
Particles being synthesized using DMF.

Conductive gold/SU-8 particles (1), semiconducting polypyrrole particles (2), “eyeball” microbeads (3), and “cups”, formed by drying water droplets that were originally encapsulated in latex (4). Scale bars: 1 mm.

Electronics Cooling

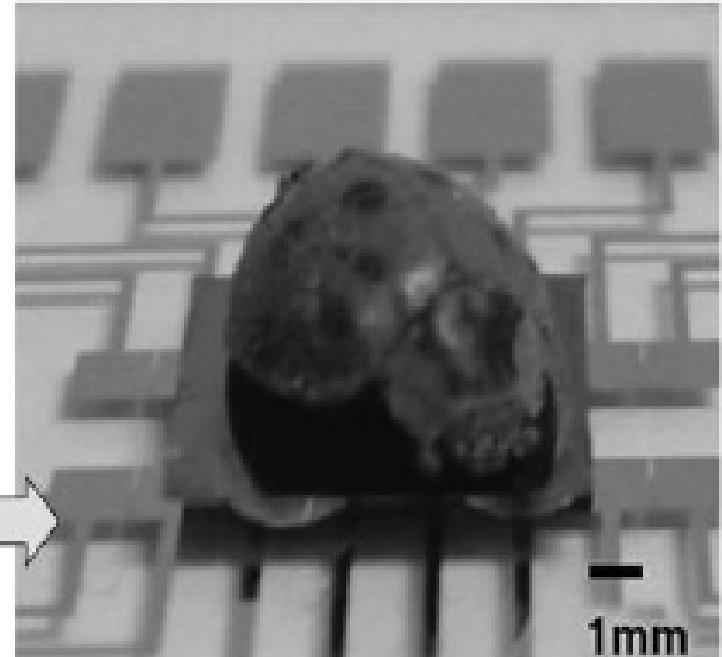
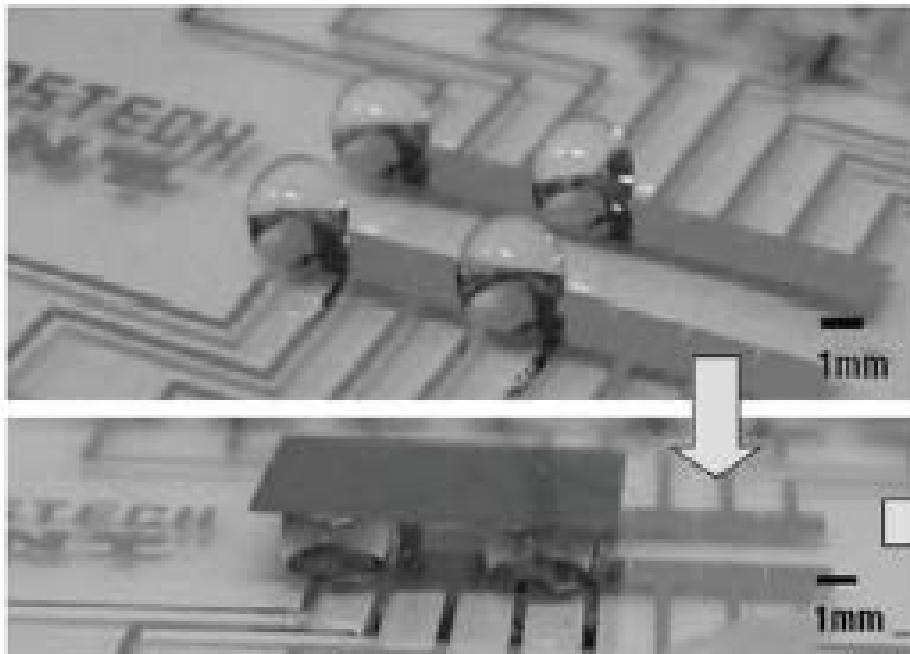
Microchannels have been applied to electronics cooling, and have been shown to be capable of achieving cooling rates as high as 100W/cm^2 may not be sufficient to cool local hot spots on integrated circuits (300W/cm^2).

DMF seems well suited for this application, as droplets can be moved directly to hot spots, by-passing the regions not requiring cooling.



Pictures depicting the use of DMF to cool an artificial hot spot (an imbedded microheater). The top half of each frame shows an infrared image of the hot spot (white - hot); the temperature drops significantly during and after the droplet passes over it.





Pictures of a microbelt conveyer system based on DMF;

A lady bug carried on a silicon wafer supported by four droplets.

Sens. Actuators A 2006, 130–131, 537.



Small is the next
big thing