

## Cross-References

- ▶ [CMOS MEMS Fabrication Technologies](#)
- ▶ [Integrated Micro-Acoustic Devices](#)
- ▶ [MEMS Packaging](#)

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## Electrostatic RF MEMS Switches

- ▶ [Capacitive MEMS Switches](#)

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## Electrothermomechanical Actuators

- ▶ [Thermal Actuators](#)

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## Electrowetting

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## Synonyms

Digital microfluidics; Droplet microfluidics;  
Electrocapillarity; Electrostatic actuation of droplets;  
Electrowetting-on-dielectric (EWOD)

## Definition

Making a surface more wetting to a liquid by applying voltages.

## Introduction

When a material (typically solid) and a liquid are in contact, the application of an electric potential between them may cause the wettability of the material to

increase, which is exhibited by a decrease of the observed contact angle. This phenomenon is called electrowetting – a term reminiscent of the more traditional electrocapillarity. In recent years, the development of various electrode and material configurations for technological applications – mostly in the rapidly expanding field of microfluidics – has given rise to additional terms such as electrowetting-on-dielectric (EWOD). Because technologies relying on the actuation of liquids by applied electrical potentials are still new, the terms used to describe such systems can be difficult to delineate. It will therefore be helpful to introduce a few terms related to electrowetting with a little bit of the history and theoretical background behind each of them. While the basic approaches to utilizing the electrowetting phenomenon to obtain physical results are presented here, applications of electrowetting to manipulate droplets or to develop devices and systems are deferred to other related entries as well as other works referenced later in this entry.

## Electrocapillarity and Electrowetting

A typical liquid (e.g., water) rises in a vertical glass capillary against gravity by the intermolecular attraction between the liquid and the inner wall of the capillary. A terminal height is reached when the gravity of the liquid column equals the attractive force or, more precisely, the vertical component of the liquid-air interfacial tension. The vertical component is larger if the liquid wets the glass surface better (e.g., the surface is clean). The degree of wetting is expressed by the contact angle  $\theta$  of the liquid on the solid surface by the Young equation:

$$\gamma \cos \theta = \gamma_{sg} - \gamma_{sl} \quad (1)$$

where  $\gamma$ ,  $\gamma_{sg}$ , and  $\gamma_{sl}$  are the interfacial energy (or interfacial tension, surface tension) between liquid and air (gas), solid and air, and solid and liquid, respectively. On the other hand, if the liquid does not wet the glass (e.g., mercury), i.e., the contact angle is greater than  $90^\circ$ , the liquid falls down in the capillary. A terminal falling depth against gravity is determined by the surface tension and the contact angle.

In 1875, Gabriel Lippmann showed that a mercury column in a glass capillary, which is dipped into an electrolyte bath, rises or falls when a voltage is applied

between the mercury and the electrolyte [1]. This experiment, which is called the Lippmann electrometer, demonstrated that the interfacial tension between the mercury and the electrolyte is a function of the electric potential across the interface. Perhaps termed originally to depict the initial experimental configuration involving a capillary tube, *electrocapillarity* nevertheless describes a general phenomenon of interfacial energy changing by electric fields.

In 1981, Beni and Hackwood [2] introduced the term *electrowetting* to describe a manifestation of electrocapillarity that occurs when the configuration of materials and electrodes is somewhat different than that of the classical Lippmann electrometer. Specifically, in the traditional electrocapillarity measurement, voltage is applied between a metallic *liquid* (i.e., mercury) and an aqueous liquid (i.e., electrolyte), while both materials are surrounded by an insulating *solid* (i.e., glass capillary). For electrowetting, on the other hand, voltage is applied between a metallic *solid* and an aqueous liquid surrounded by an insulating *fluid* (e.g., air or oil). [Figure 1](#) schematically illustrates these two phenomena, which operate under the same general principle but are distinguishable by how the materials are configured.

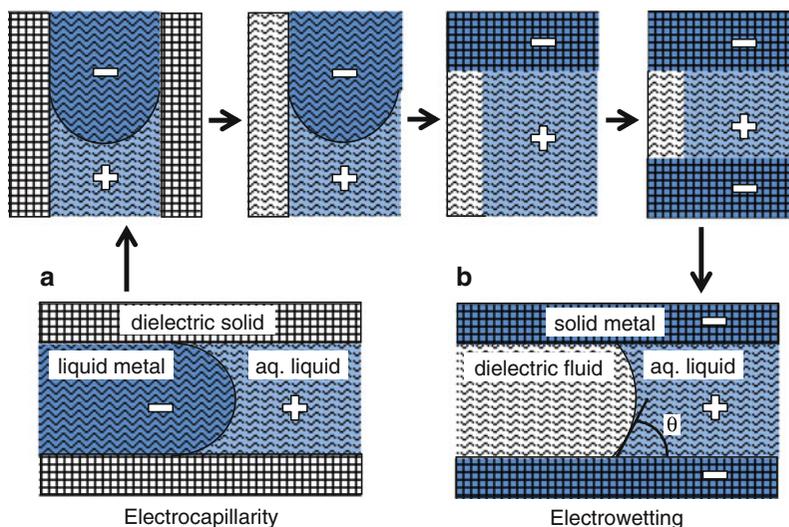
Readers may realize that, despite their apparent differences, electrocapillarity and electrowetting describe essentially the same principle. One can do a mental exercise that involves dictating phase changes of a given material. Rotate [Fig. 1a](#)  $90^\circ$  clockwise; remove the right dielectric solid and convert the left dielectric solid into a fluid (i.e., vapor or liquid); and convert the liquid metal into a flat solid metal and duplicate it at the bottom. Now one has [Fig. 1b](#). So, the two terms describe one phenomenon depending on the users' focus of interest. If the interest is a liquid column moving in a solid capillary, electrocapillarity describes the phenomenon well. If the interest is how well a liquid wets a solid surface, e.g., what is the contact angle, electrowetting is a better description.

Some readers may raise another question, however. There exists a contact angle of the liquid electrolyte on the solid surface in the electrocapillarity of [Fig. 1a](#), and there exists a column of the liquid electrolyte in a metallic capillary in the electrowetting of [Fig. 1b](#). The confusion may be avoided if one notes that the main interest should be in the interface across which the electric potential is applied. In [Fig. 1a](#), the liquid-liquid interface, across which the voltage is applied,

**Electrowetting,**

**Fig. 1** Comparison between electrocapillarity (a) and electrowetting (b), drawn to maintain the original configurations presented by Beni and Hackwood [2].

A *grid pattern* implies a solid, and a *wave pattern* implies a fluid. A *white* background implies a dielectric, and a *gray* (blue if seen in color) background implies a conductor



travels in a capillary, exhibiting capillary action. In Fig. 1b, the solid-liquid interface, across which the electric potential is applied, forms a contact angle, exhibiting wetting.

### Electrowetting and Electrowetting-On-Dielectric (EWOD)

Historically, for both the electrocapillarity and the electrowetting phenomena, the main interest was the interface between an aqueous liquid and a metal. Whether the metal was a liquid (for electrocapillarity) or a solid (for electrowetting), the electric double layer (EDL) at the interface played a critical role. Since the underlying mechanism for both phenomena was that the free interfacial energy can be modulated by increasing or decreasing the capacitive energy stored at the EDL via an electric potential across it, the mechanism would be valid only while the EDL functions as an insulating capacitor, i.e., below  $\sim 1$  V range in practice. An applied voltage above such a limit would induce electrochemical reactions, such as electrolytic gas generation, and alter the surface. In the case of electrowetting, it was difficult to induce contact angle changes large enough to be useful without degrading the surface. Promising utilities were limited to the case of a liquid metal in an electrolyte-filled capillary, e.g., [3, 4].

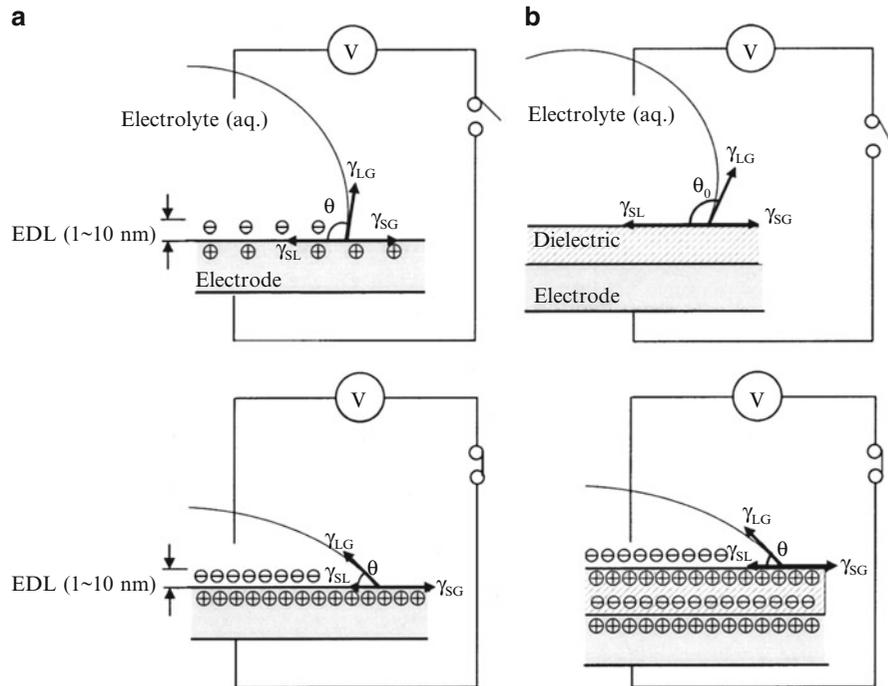
Building on the findings of Minnema et al. [5], in 1993 Berge [6] reported that it is possible to perform

electrowetting on a dielectric material when it is placed (as a solid film) between the liquid and the electrode. In a nutshell, the dielectric film functions as the primary energy-storing capacitor, thereby serving the same function as the EDL in conventional electrowetting. Since it required a very high voltage for electrowetting to be noticeable on an insulator, it is fitting that the first such observation was made during investigations of “water trees” (degradation structure grown in a polymer due to humidity and an electric field) in high-voltage cables [5]. Several kV were commonly used in the early reports. Since reducing the operating voltage range was simply a matter of making the dielectric layer thinner and of higher quality materials, the thin-film techniques of microelectromechanical systems (MEMS) played a timely role in helping experimenters reduce the dielectric thickness from the millimeter range [5, 6] to the micrometer range [7]. To distinguish it from the conventional practice of electrowetting on a metal surface and because it provided unprecedented viability for practical applications, Lee [8] and Moon et al. [7] named this new material configuration electrowetting-on-dielectric (EWOD). Figure 2 compares EWOD with conventional electrowetting.

Although a significantly higher voltage is necessary to charge the dielectric capacitor of EWOD than the EDL of electrowetting in order to obtain the same degree of wetting, much higher voltages can be applied to the dielectric for additional wetting. In other words, a larger contact angle change can be achieved with EWOD by allowing high voltages, whereas

**Electrowetting,**

**Fig. 2** Electrowetting and EWOD [7]. **(a)** Illustration of conventional electrowetting. *Top:* With no external voltage applied, charges are distributed at the electrode-electrolyte interface, forming an EDL. *Bottom:* With an external voltage applied, charge density at EDL changes, and the contact angle decrease or increase. **(b)** Illustration of EWOD. *Top:* With no external voltage applied, there is little charge accumulation at the interface. *Bottom:* With an external voltage applied, charge accumulates at the interfaces, and the contact angle  $\theta$  decreases



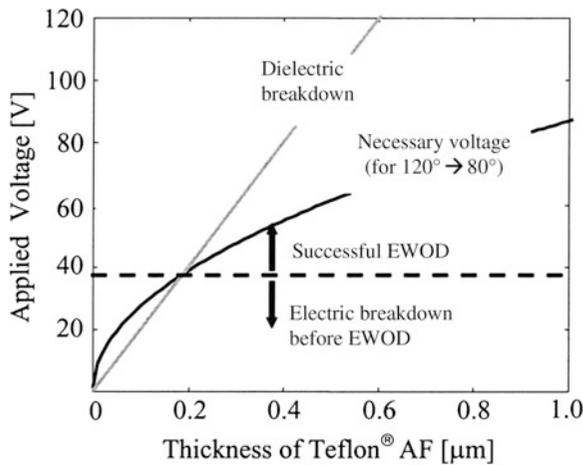
conventional electrowetting is severely limited by the small breakdown voltage of the EDL. Figure 3 explains the trade-off between dielectric thickness and operating voltage in EWOD, and why it is advantageous to use EWOD (compared to conventional electrowetting) despite the relatively high voltages that are needed. The thick solid curve in the figure shows that the voltage required to induce a specified increase in wetting (i.e., a reduction of contact angle  $\Delta\theta$ ) is proportional to the square root of the thickness of the dielectric layer for a given dielectric material (Teflon AF is assumed in the figure), while the thin solid straight line shows that the breakdown voltage of the dielectric layer is proportional to the thickness. For successful operation, the electrowetting voltage should be smaller than the breakdown voltage. Although the required voltage continues to increase with the dielectric thickness, the margin of safety increases as well.

Despite the higher operation voltages, e.g., 15–80 V in air or 10–50 V immersed in oil in present experimental reports, EWOD is preferred over electrowetting on a conductor (which uses less than 2 V) in most cases. One may lower the voltage requirements of EWOD without sacrificing the electrowetting effect by coating the dielectric with a very thin layer of a very hydrophobic material. This strategy works by reducing the contact angle hysteresis, thereby enabling

the contact lines (and thus droplets as well) to move more easily. A wide variety of droplet-medium combinations can be manipulated with EWOD, e.g., water in air, water in oil, oil-encapsulated water in air, oil in air, gas in water, etc. To learn more about the fundamentals of electrowetting and EWOD, readers are encouraged to consult [10].

**Theories and Equations**

The phenomenon of electrowetting can be interpreted (or understood) thermodynamically as well as electro-mechanically. In the thermodynamic interpretation, assuming conventional electrowetting, the electrical energy accumulated at the solid-liquid interface,  $cV^2/2$  (where  $c$  is the capacitance per area of the EDL and  $V$  the voltage across it), decreases the interfacial energy. For EWOD, the interpretation is slightly modified: the electrical energy accumulated in between the electrode and the liquid,  $cV^2/2$ , where  $c$  is the capacitance per area and  $V$  the voltage applied between them, makes the interfacial energy between the solid surface and the liquid decrease. The interfacial energy is exhibited as the contact angle of the liquid on the solid surface  $\theta$ , which is easily measurable; as the solid-liquid interfacial energy decreases, so



**Electrowetting, Fig. 3** Electrowetting voltage and dielectric thickness [7]. The *thick solid line* represents the voltage required to obtain a certain degree of wetting (drawn for a contact angle reduction from  $120^\circ$  to  $80^\circ$  – enough reduction to slide a water droplet on many nonwetting solid surfaces in air) with Teflon AF as the sole dielectric, and the *thin solid line* represents the breakdown voltage for the same dielectric layer. A desired wettability increase is possible only where the electrowetting curve (the parabolic curve) stays safely below the *breakdown line* (the *straight line*). In other words, the dielectric should be thicker than where the two lines cross ( $\sim 0.2 \mu$  in the figure), as marked “Successful EWOD.” If a smaller degree of wetting (e.g., moving a droplet on a solid surface coated with or immersed in oil) were acceptable, the corresponding electrowetting curve would be drawn lower, allowing lower voltages and thinner dielectrics. For conventional electrowetting, in contrast, the electrowetting curve would be drawn much lower than the EWOD curve in the figure due to the huge capacitance of the EDL (typically only several nanometers thick). Only  $\sim 1$  V was used to induce enough wetting ( $70^\circ$ – $40^\circ$  to rough estimations) on gold to draw water in air environment [9]. However, that 1 V, which was the minimum needed to move the interface, was the maximum that could be applied before severe electrolysis. With no margin of safety, the actuation was not reversible

does the contact angle. By combining this energy equation with the Young equation and following the thermodynamic principle of energy minimization, the electrowetting equation (often called Lippmann-Young Equation) can be derived and written as follows:

$$\cos \theta = \cos \theta_0 + \frac{cV^2}{2\gamma} \quad (2)$$

where  $\theta_0$  is the contact angle when there are no charges at the solid-liquid interface, i.e., no EDL exists, and  $\gamma$  is liquid-fluid (air being a fluid in Eq. 1) interfacial

energy. The fluid may be a gas or a liquid that is immiscible with the liquid of interest, to which voltage is applied. For EWOD, where the specific capacitance can be obtained from the dielectric properties as  $c = \epsilon/d$  ( $\epsilon$  is the permittivity, and  $d$  is the thickness of the dielectric),  $\theta_0$  coincides with the contact angle at no applied voltage, i.e., the Young angle, as the EDL has a negligible effect in this case. Considering the wide range of dielectric materials (i.e., representing a wide range of permittivities) and different liquid-fluid combinations used, it is convenient to define the second term on the right side of the equation as:

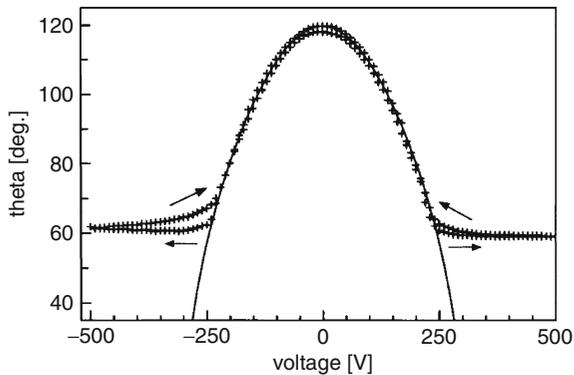
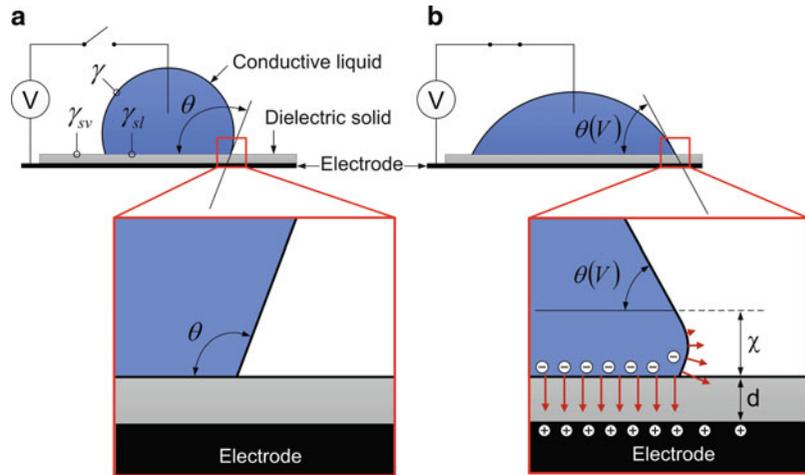
$$E_w = \frac{cV^2}{2\gamma} \quad (3)$$

The dimensionless Electrowetting Number  $E_w$ , defined as Eq. 3, expresses the importance of electrical energy relative to the free energy at the liquid-fluid interface. The liquid-fluid interface can be liquid-gas, liquid-vapor, or liquid-liquid if immiscible liquids. Although a liquid-air system is considered a standard in this essay, liquid-liquid systems of aqueous solution and oil are found in many electrowetting devices.

The importance of EWOD over conventional electrowetting and the growing view of the phenomenon as a physical force have led some researchers to the electromechanical interpretation of electrowetting, as summarized in Fig. 4. Considering the interfaces close to the solid-liquid-fluid triple point as illustrated in Fig. 4b, one can see that the applied voltage produces normal electrostatic forces on the solid-liquid interface. Also, the fringe electric field on the liquid-fluid interface near the triple point exerts electrostatic traction normal to the liquid-fluid boundary right above the contact point (i.e., within  $\chi$  in the figure), resulting in a net force parallel to the solid surface and causing droplet spreading. These electrostatic forces deform the liquid-fluid interface very close (sub-micron range in most practical cases) to the triple point, and this deformation reduces the slope of the interface away from the region. This reduced slope is the contact angle apparent to the observer. This pure electromechanical interpretation of electrowetting was made by theoretical derivations, e.g., [11, 12], and observed in experiments [13]. Under the electromechanical view, the electrowetting force is not infinitely concentrated at the contact point.

### Electrowetting,

**Fig. 4** Electromechanical interpretation of electrowetting, illustrated for EWOD [10]. (a) With no voltage applied, the contact angle of a liquid is the Young angle. (b) With voltage  $V$  applied, the contact angle decreases by electrowetting. In the figure magnifying the area of solid-liquid-fluid triple point,  $\chi$  is on the order of the dielectric thickness  $d$ , which is on the order of  $1\ \mu\text{m}$  in many EWOD devices



**Electrowetting, Fig. 5** A typical electrowetting curve [14] follows the electrowetting equation (Eq. 2) until the electrowetting effect saturates at high voltages (Reprinted with permission from American Chemical Society)

### Electrowetting Curve

Since the electrowetting equation (Eq. 2), derived by both the thermodynamic and the electromechanical approaches, matches the experiments quite well in most cases, it plays an important role in understanding the phenomenon and performing research and development for applications. An example is shown in Fig. 5, which also reveals an important limitation: contact angle saturation. When the voltage is applied above a certain limit, a further increase of voltage does not decrease the contact angle anymore, e.g., not below  $60^\circ$  in Fig. 5. Instead, excessively high voltages only bring about detrimental effects, such as the liquid-fluid interface becoming unstable and ejecting small

droplets. Contact angle saturation is one of the most common sources of frustration for those engaged in research and development involving electrowetting. Despite its importance, however, the origin of saturation is still not well understood.

### Summary

While explaining electrowetting, other closely related terms (electrocapillarity and EWOD) have also been described. Based on the same fundamental concept of electric potential affecting the interfacial energy, each portrays the electrowetting phenomenon in a somewhat different material configuration. Depending on the user's interest, one configuration may be more convenient than others, although EWOD is by far the most widely used configuration today. Basic theories of electrowetting have been presented through the conventional thermodynamic interpretation as well as the relatively new electromechanical interpretation, both of which result in the same electrowetting equation. The electrowetting equation is very useful as experimental data usually match the electrowetting curve. Today electrowetting is used in a wide range of applications including optical, biomedical, and even electronic.

### Cross-References

► [Dielectrophoresis](#)

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## Electrowetting-on-Dielectric (EWOD)

- ▶ [Electrowetting](#)

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## Energy-Level Alignment

- ▶ [Electrode–Organic Interface Physics](#)

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## Engineered Nanoparticles

- ▶ [Physicochemical Properties of Nanoparticles in Relation with Toxicity](#)

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## Environmental Impact

- ▶ [Fate of Manufactured Nanoparticles in Aqueous Environment](#)

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## Environmental Toxicology

- ▶ [Ecotoxicity of Inorganic Nanoparticles: From Unicellular Organisms to Invertebrates](#)

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## Epiretinal Implant

- ▶ [Artificial Retina: Focus on Clinical and Fabrication Considerations](#)
- ▶ [Epiretinal Prosthesis](#)

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## Epiretinal Prosthesis

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## Synonyms

[Epiretinal implant](#); [Retinal prosthesis](#)

## Definition

Epiretinal prosthesis refers to the device designed to restore partial vision for the blind people by stimulating the retina through electrodes on the retina surface.