Electrowetting Displays

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1. What is Electrowetting?

With Electrowetting a voltage is used to modify the wetting properties of a solid material. An example of such increased wettability is illustrated in the photographs of figure 1. The left hand side shows a water droplet on a hydrophobic surface. The water droplet does not like to be in contact with the surface and therefore minimizes the contact area.

In the photograph on the right hand side, a voltage difference is applied between the electrode in the water and a sub-surface electrode present underneath the hydrophobic insulator material. As a result of the voltage, the droplet spreads, i.e. the wettability of the surface increases strongly.

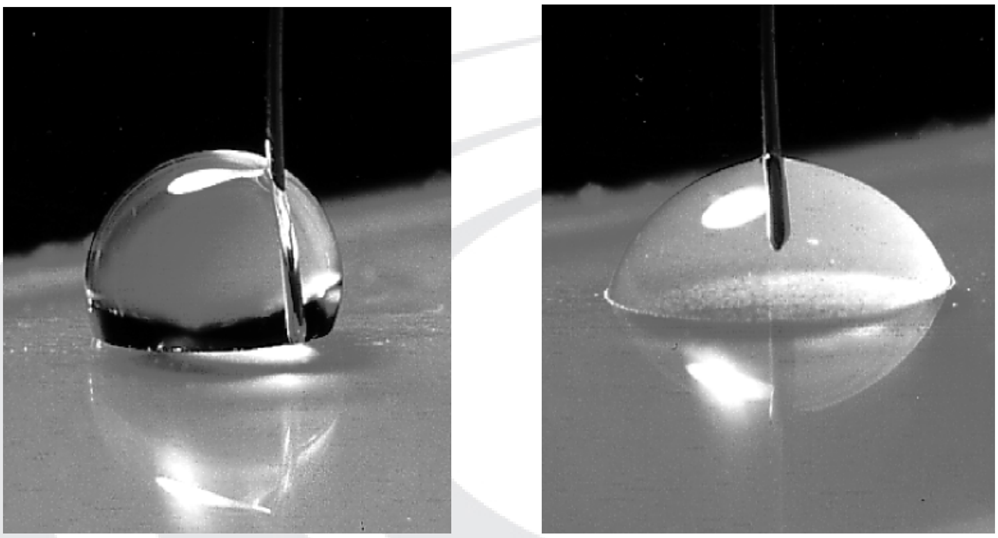

Figure 1 – water droplets on hydrophobic surface without and with voltage applied.

When the voltage is removed, the droplet returns to the original state indicated on the left hand side.

Electrowetting finds its origin in the combination of two classic and very well understood fields: interfacial chemistry and electrostatics. The starting situation where a droplet of liquid sits on a solid surface (fig. 1a) is described by the Young equation:

$$\gamma_{LV} \cos\theta = \gamma_{SV} - \gamma_{SL} \qquad (1)$$

In the case of electrowetting, an electrostatic term is added to the energy balance of the system. As a result, the droplet will adjust its shape to lower the energy of the total system as shown in fig. 1b. The final result, including the electrostatic energy, was found by Nobel Prize winner Gabriel Lippman [1]:

$$\gamma_{LV} \cos\theta = \gamma_{SV} - \gamma_{SL} + \frac{1}{2}\frac{\varepsilon_0 \varepsilon_r}{d} V^2 \qquad (2)$$

The Lippman equation includes an electrostatic term that is the result of the liquid/insulator/solid capacitor being charged. Since $_{LV}$, $_{SV}$ and $_{SL}$ are material constants, applying a voltage will increase $\cos\theta$, implying that the liquid will spread.

Rapid progress in performance of electrowetting has been achieved in the last twenty years due to improvements in materials and processing. In the last decade, electrowetting has been utilised for an increasing number of applications. These include pixelated optical filters [2], fiber optics [3], adaptive lenses [4,5], lab-on-a-chip [6] and curtain coating, in use by Kodak for about 10 years [7].

2. Electrowetting as a display technology

With Electrowetting displays, a simple optical switch is obtained by contracting a colored oil film electrically. This switch has many attractive properties that make it suitable to be used as a display, as it can combine high color brightness, video speed and low power consumption – a mix which is sought after but seldom found in a single technology.

The invention of fast switching Electrowetting displays was the subject of a Nature article published in September 2003 [8] and has been patented by Philips.

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3. Electrowetting display principle

In Fig. 2 the principle of a reflective Electrowetting display is shown. Figure 2a shows the optical stack, comprising a reflecting electrode, a hydrophobic insulator, a colored oil layer and water. In a display these layers will be sandwiched between glass or polymeric substrates. In equilibrium the colored oil naturally forms a continuous film between the water and the hydrophobic insulator (fig. 2a) due to the fact that this is the lowest energy state of the system. At the typical length scales used in display (pixel sizes around or below 200 µm) the surface tension force is more than 1,000 times stronger that the gravitational force. As a result, the oil film is stable in all orientations.

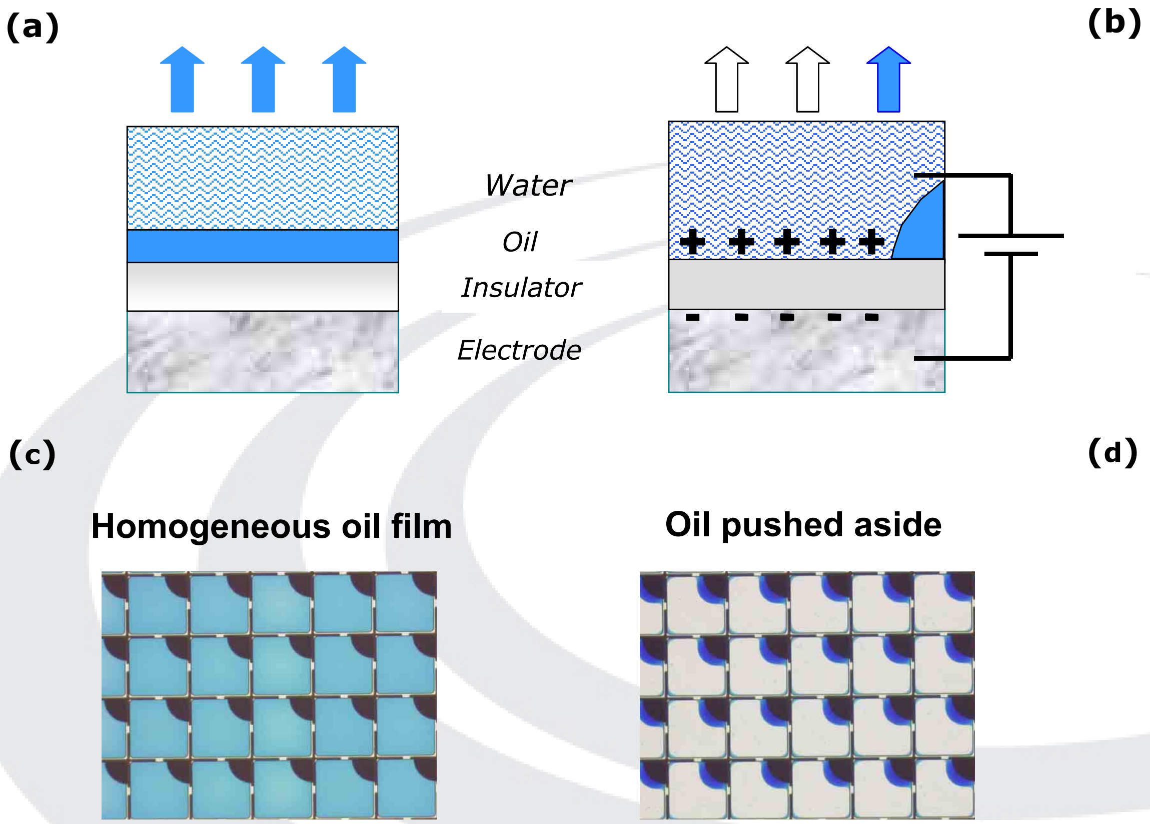


Figure 2 – Electrowetting display principle.

When a voltage difference is applied across the hydrophobic insulator, an electrostatic term is added to the energy balance and the stacked state is no longer energetically favorable. The system can lower its energy by moving the water into contact with the insulator, thereby displacing the oil (fig. 2b) and exposing the underlying reflecting surface.

The balance between electrostatic and surface tension forces determines how far the oil is moved to the side. In this way the optical properties of the stack when viewed from above can be continuously tuned between a colored off-state and a white on-state, provided the pixel is sufficiently small so that the eye averages the optical response.

The photographs in fig. 2c and d show a typical oil retraction obtained for a group of pixels with a size of 160x160 μm^2. The photograph in fig. 3d confirms the 80% white area required for a 70% in-pixel color reflectivity. Part of the electrode is omitted in the upper right corner of each pixel to control the oil motion [9]. In fig 2c and d. the control of oil motion strongly improves pixel-to-pixel homogeneity and hence the display uniformity.

4. Full color electrowetting displays

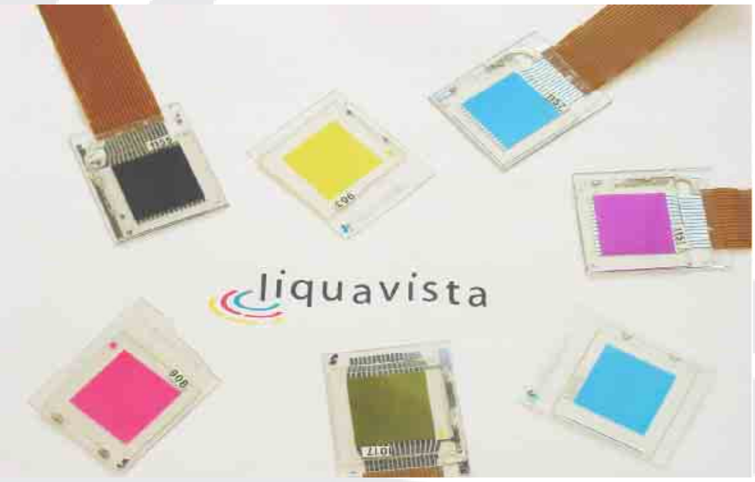
Nearly all of the emerging reflective display technologies use RGB segmentation to realize color, constituting an intrinsic loss of 2/3 of the incoming light. For the most commonly used display technology, LCD, an additional 50% of the light is lost due to the presence of polarizers. With the exception of electrowetting displays, generating high brightness color is a strong limitation of all contemporary display technologies including the ones in development.

4.1. Color palette

The materials used in Electrowetting displays are very simple: two pieces of glass or plastic and water and oil in between. In addition, an essential ingredient to complete the display is the dye that is dissolved in the oil.

The choice of dye determines the color of the display, in particular in the off-state where the oil covers the entire pixel. This implies that a wide range of colors can be achieved with the electrowetting technology simply by varying the color of the dye.

A wide variety of colors (see fig. 3) including cyan, magenta, yellow and black have already been demonstrated. The ample knowledge available in the dye industry allows for a nearly unlimited choice in color, using dyes that have proven to be very stable under lighting conditions typically encountered in outdoor environments [10].



4.2. Cell-gap

The total cell gap of this structure can be as small as 25 µm. The size of the cell-gap does not affect the optical performance of the display, provided it is sufficiently thick to avoid the oil touching the top plate in the switched state. This stems from the fact that the thickness *d* given in eq. (2) is the thickness of the insulator, not the cell-gap: the electric field is applied across the dielectric and not across the entire cell-gap.

The insensitivity to cell-gap thickness is highly advantageous when the electrowetting technology is used in flexible displays, since cell-gap thickness variations is one of the most important difficulties that occurs upon flexing the display.

4.3. Display Architectures

Because of its intrinsic nature as a colored light switch, electrowetting allows for a variety of display architectures with improved color brightness. Of these, two are discussed below as they represent the extremes of architectural possibilities. All show low power and video rate switching.

4.3.1. One-layer architecture

A low cost, full color display can be fabricated with electrowetting using an RGB color filter approach (fig. 4). In this case, a black-colored oil is required as an absorbing switch. Compared to MEMS or CTLC based approaches, electrowetting offers the same performance in a simpler, lower cost structure.

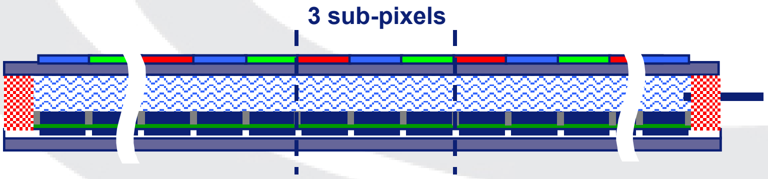


Figure 4 – single layer architecture with black dye and RGB color filter (not to scale).

Compared to LCD this architecture offers an improvement of a factor of 2 in color conversion factor (CCF = theoretical light out / light in).

In addition, in reflective mode, the electrowetting display offers a strong improvement in power consumption with respect to emissive technologies due to the absence of a backlight. The absence of the backlight also results in a significant cost reduction, which will be reduced further by the omission of optical enhancement layers. Finally, the single layer architecture has the clear advantage of being visible in a large variety of lighting conditions, ranging from indoor to outdoor environments.

4.3.2. Three-layer architecture

A strong improvement in optical performance is obtained when three monochrome layers are placed on top of each other (see fig. 5). Having three monochrome layers ensures that all processes used for the single-layer display can be used for the three-layer display as well. This includes the oil dosing process that is performed on individual displays, after which the displays are assembled and aligned with standard equipment.

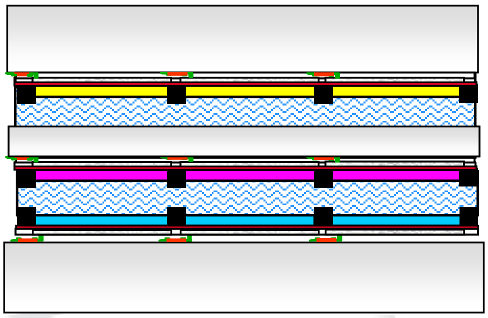


Figure 5 – triple-layer architecture with CMY dyes (not to scale).

The second layer is introduced on the bottom of the middle substrate, opposite the first oil layer. Surface tension ensures that this state is stable in time. The third oil layer is positioned on a third substrate in the stack. Each layer can be switched independently.

This configuration has several additional advantages. Most importantly, the CCF is increased with respect to the single layer structure with a factor of 3, since any color can be generated anywhere on the display surface, i.e. sub-pixelation is no longer required. In this architecture no color filter is required, yielding a further cost reduction. The cost of the display is now dominated by the presence of 3 driving substrates, which can be either segmented or matrix driven.

For mobile displays, the cost is expected to be comparable to a transflective LCD. The improvement of the CCF by a factor of 6 compared to LCD renders a paper-like optical performance. As a result, the reflective electrowetting display can be used under all conditions in which people can use paper, ranging from very dimly-lit rooms to bright day-light conditions.

4.4. *Full color display performance*

Table 1 compares the properties of the 3-layer electrowetting architecture with competing technologies. For reference, we have included the properties of paper.

Technology	**B/W Reflectivity**	**Color Conversion**	**Contrast**	**Viewing angle**	**Switching speed (ms)**
Reflective LC	50	33	15	Limited	15
CTLC	30	100	10	Limited	50
Electrophoretic	55	33	12	Good	150
MEMS	50	33	12	Limited	<10
Electrowetting*	60	100	15	Good	<10
Paper	70	100	15	Good	-

* optical properties: in-pixel x 0.90 (accounting for losses at walls)

Table 1 – Comparison of key performance parameters for various reflective technologies.

Table 1 illustrates that the electrowetting technology offers a unique combination of paper-like optical performance with rapid switching speeds, allowing for video-content to be shown.

4.4.1. Color gamut

The three-layer structure offers one further important advantage in color rendering. In fig. 6 the color gamut of an electrowetting display is compared to that of reflective LCDs. The EBU standard color gamut is shown as well.

The full color response of a display is determined by its color gamut and the brightness, which are intimately related. LCDs could expand their color gamut by absorbing more light, but obviously this will reduce the brightness.

In the case of the electrowetting display, a much larger color gamut is obtained at the high brightness discussed previously. Further improvement on optical spectra is expected to expand the color gamut even further approaching the gamut of emissive technologies such as OLEDs.

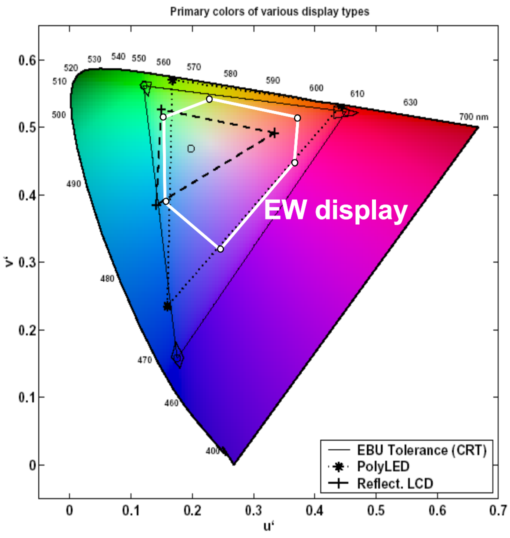


Figure 6 – Color gamut of the three-layer electrowetting architecture, compared to reflective LC, OLED and EBU.

The 3-layer structure, in which subtractive colors are positioned on top of each other, strongly resembles the approach used in printing of color paper. The larger color gamut is very attractive, in particular for mobile devices where color rendering is rather poor using contemporary displays.

4.4.2. Video speed

With electrowetting liquids can be moved very rapidly. As a result, it is possible to show video-content on an electrowetting reflective display for pixels smaller than about 500 m in size [11].

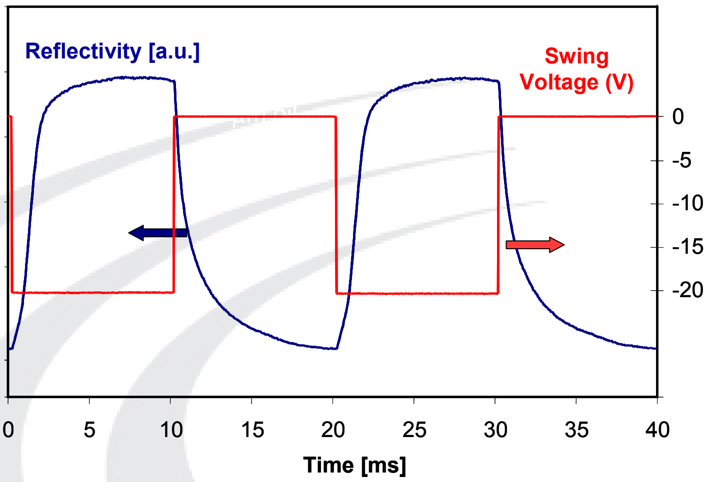


Figure 7 – response transient of electrowetting display pixels.

Figure 7 shows the response speed of a 100-ppi sub-pixel (250x80 m^2) upon voltage application. At t = 0, the voltage is switched on. In this case, the swing voltage required for a switch to the high brightness state is about –20 V. The on-switch occurs very fast; showing a response time of about 3 ms. A commonly used definition of the response time is the time it takes for the pixel to reach 90% of the final value.

After 10 ms, the voltage is switched off, and the pixel relaxes to its original state. The response time for the off-switch is around 9 ms. Clearly the on- and off response times are sufficiently fast to be able to show video content on an electrowetting display.

4.4.3. Grey scale

The electro-optic response of an electrowetting pixel with a 160-ppi resolution (160x160 m^2) is depicted in fig. 8. The pixel white area, i.e. the area from which the oil is removed, is plotted as a function of swing voltage.

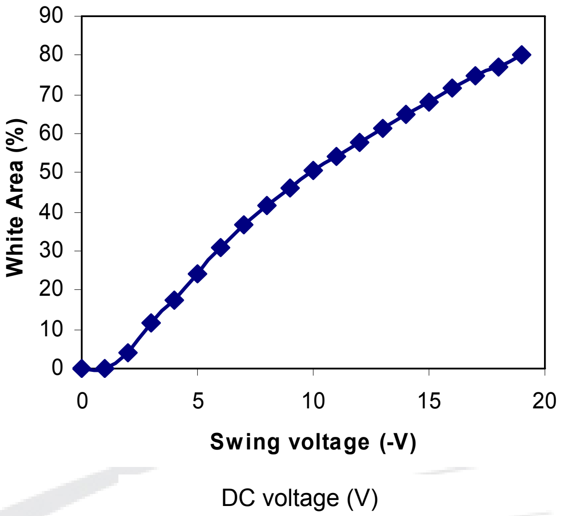


Figure 8 – Electro-optic response of 160 ppi

The electro-optic response shows a small threshold voltage before displacement of the oil film commences. The white area shows a steady increase upon increasing voltage. The in-pixel reflectivity is proportional to the white area and can be as high as 70% for a white area of 80%. All intermediate optical states are stable, implying that analogue, voltage-controlled grey-scales can be realized.

In addition to amplitude modulation (AM), electrowetting displays can also be addressed with pulse width modulation (PWM) to realize grey scales.

An example of this type of grey-scale operation is shown in fig. 9. On the left hand side, a photograph of the display in the off-state is shown. The photograph on the right hand side shows 15 line segments addressed with PWM, resulting in a 4-bit grey scale demonstration. Both methods have advantages and disadvantages, but the flexibility that electrowetting displays can use either of the two, or a combination of both provides an excellent grey scale capability.

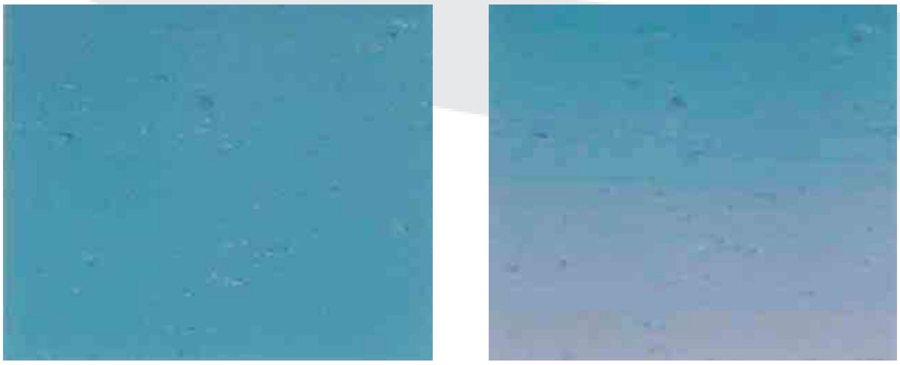


Figure 9 – 4-bit grey-scale obtained by pulse width modulation

4.4.4. Operating voltage

For high brightness operation, a dc swing voltage of about -15 to –20 V is typically used. Material and processing improvements have enabled a strong voltage reduction over the last few years [12], since earlier applications were operating around 200V [2,5,6].

Parameters for voltage reduction

From the electrostatic term in eq. (2) it can be understood which system properties can be used for this further reduction. Most importantly, reducing the thickness of the dielectric will lower the operating voltage. Before oil motion commences, the dielectric comprises both oil and fluoropolymer.

Hence, both the thickness of the oil film (presently ~ 6 m) and fluoropolymer (~0.8 m) can be used to reduce the swing voltage. Reducing both by a factor of 2 will bring the swing voltage down below 10 V. Other parameters that can be used to lower the operating voltage further are the dielectric constant of oil and fluoropolymer and the surface tension of the oil/water interface.

4.4.5. Power consumption

One of the most important advantages of reflective electrowetting displays is their very low power consumption for high color brightness. In fig. 10 we summarize the power consumption of several technologies, both existing and in development. We have chosen to compare technologies for video-rate displays, as this is largest part of the available market. Hence we have not included technologies that are unable to show video-content in the comparison.

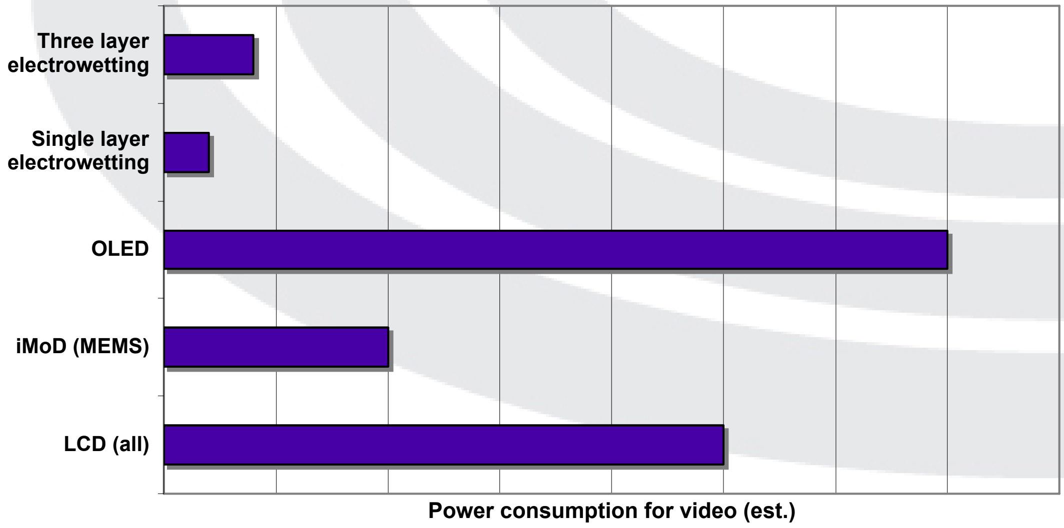


Figure 10 – Comparison of power consumption for a variety of video displays.

The most striking difference is between the reflective technologies and the transmissive and emissive technologies. For LCDs and OLEDs the power performance of typical displays that are on the market are indicated. Obviously, generating light costs much energy: in a typical LCD, the backlight consumes about 90% of the total power budget and the total power consumption of OLEDs is even higher.

Making use of ambient light therefore results in a reduction of display power consumption by a factor of 8 to 10. The difference between the single layer electrowetting display and the iMoD, which have similar optical performance, is caused by the different grey scale methods. Analog grey scaling results in the lowest power consumption, while time modulation as used for the MEMS display requires a significantly higher frame rate. The three-layer structure with a much-improved optical performance has slightly higher power consumption than the single-layer one due to the increase in length of the wiring and an increased parasitic capacitance.

4.4.6. Environmental parameters

Switching stability

For the electrowetting pixels, a negative dc-voltage is used. Individual displays have been switched more than 100 million times between 0 and high voltage, with no visible deterioration of the switching behavior, i.e. no image sticking or retention, a problem often encountered with LC displays.

This illustrates that charging problems are negligible at these operating conditions. The insensitivity to charging is mainly due to the fluoropolymer insulator, which is an extremely inert material. Also other important characteristics, including switching speed, high color brightness and white area are unaltered during switching.

Operating range

Varying the liquids allows for adjusting the display to the appropriate temperature range. The material system currently in use is able to sustain a temperature range larger than –30 and 80 C, sufficient for most consumer applications. The most important requirement for the liquids is that one should be polar whereas the other liquid is non-polar.

A low surface tension between the polar and non-polar liquid is desired, to ensure a good stability of the oil film in the off-state. A further requirement for the non-polar liquid is that is should be a good solvent for colored dyes. As surface tension is an important parameter for the operation of the display, contamination should be avoided, also on the long term. The use of combinations of inert materials results in a long shelf lifetime.

The class of dyes used have been chosen for their stability in typical outdoor environments. As a result, bleaching is not an issue for present displays. Each new dye used in the display undergoes accelerated testing with a high intensity lamp to determine its light stability. In extreme environments, including a UV-filter in the display can circumvent bleaching.

5. Display addressing

5.1 Segmented displays

With the large variety of colors illustrated above (see fig. 3), electrowetting displays are very interesting for use in segmented displays. The "colorability", or ease with which one can apply different colors provides a design feature that cannot be achieved with existing technologies. This means that electrowetting displays can make a difference in many applications where segmented displays are used, including watches, signage and point-of-purchase advertising.

As an example, a photograph of watch-type display is shown in fig. 11. In the case of segmented displays, the addressing can be done with commercially available STN-type driver ICs. The three-layer architecture is possible with segmented displays as well. With this structure, high brightness colors can be produced at any area of the display.

Figure 11 – electrowetting watch type display. Note colored appearance.

5.2 Passive Matrix Addressing

The electro-optic curve for the electrowetting display can be tuned by varying the pixel parameters. It is believed that tuning these parameters can ultimately provide a curve that is suitable for passive matrix driving. Passive matrix addressing would allow for a relatively simple backplane structure with no active elements, and therefore a significantly lower cost price. Furthermore, the easier manufacturing required for passive matrix addressed displays provides a better fit with a future generation of displays that are expected to be manufactured in a roll-to-roll type fashion, shifting cheaper display forward on the product roadmap.

5.3 Active Matrix Addressing

For a high resolution, video-speed display active matrix addressing is generally used. Presently, the swing voltages required for a high brightness optical state are about –15 to –20 V. These voltages can easily be accommodated by commercially available active matrix backplanes, as illustrated by the display shown in fig. 12. This display was manufactured on commercially available backplane provided to us by the Philips foundry in Kobe, Japan.

1" active matrix driven electrowetting displays are now routinely fabricated. These displays have around 14,000 pixels with a resolution of 170 ppi. By controlling the oil motion such that the final position of the oil overlaps with the position of the TFT, no further reduction of active area is expected in the case of active matrix driving compared to direct-driven or passive matrix displays.

Figure 12 – Active matrix addressed electrowetting display. The logo at the bottom off the figure is printed on paper to illustrate the reflective performance of the electrowetting display

The roadmap towards lower voltages presented above ensures that the operating voltage will sufficiently low at the time of product introduction to use conventional driver IC's.

The present requirements of electrowetting frontplanes are close to the current performance of flexible/organic backplanes [13,14]. Combined with the insensitivity of the optical performance to cell-gap variations, this makes electrowetting very suitable to be combined with such substrates. In addition, since electrowetting provides video-speed switching, it is the sole technology that can deliver video content on a flexible, paper-like display in the foreseeable future.

6. Manufacturing processes

A side view of a single-layer monochrome multi-pixel display prototype is depicted below.

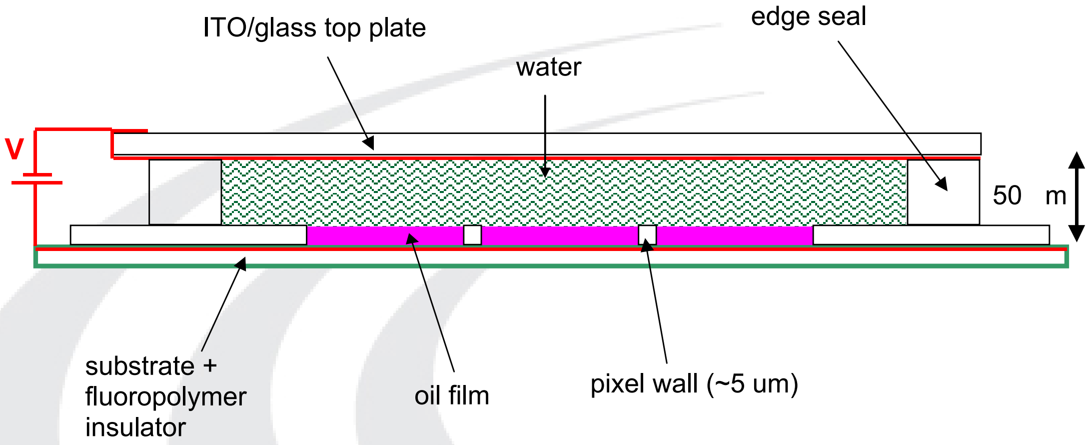


Figure 13 – Monochrome, single layer display configuration (not to scale).

A wide variety of substrates can be used, ranging from structured aluminum-coated glass for direct-driven or segmented displays to active matrix substrates for a high resolution, pixelated display.

On the substrate a sub-micron thick amorphous fluoropolymer layer is coated. The strong hydrophobic nature of this layer ensures the spreading of the oil film in the field-off state. Photolithographic walls form the pixel structure and an outer seal contains the water. The design of the pixel walls and the hydrophobic layer at the bottom of the pixels forms a pixel array that can be filled rapidly by simply dosing across the surface

The height of the pixel walls plays an essential role in determining the amount of oil that self-assembles inside the pixels. This height, determined during a standard photolithographic process is very uniform across the surface, resulting in a uniform electro-optic response.

The water, forming a continuous phase throughout the display, acts as the common electrode. After the liquids have been applied the display is closed by an ITO-coated top plate to provide the electrical contact to the water.

Electrowetting display processing consists of standard technologies of which nearly all are used in existing LCD display manufacturing facilities.

The simplicity of manufacturing also has great prospects for future generation electrowetting displays that could be manufactured in a roll-to-roll fashion. Such an approach will lead to strong cost advantages that will reshape the display industry.

7. Summary

Electrowetting displays have very favorable optical properties, combining a paper-like performance with video-speed switching speed and are manufactured using common processes. This implies that electrowetting displays present a disruptive technology from the user experience point of view, while not disrupting the existing LCD display value chain, including backplanes, components and system manufacturing.

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