Born as a Philips spin-off
2011: bought by Samsung
2013: bought by Amazon
2014: 5 patents filed by Amazon
2015: New color Kindle? NO
...
2018: Etulipa - Eindhoven startup company: outdoor advertising
2021   http://bits-chips.nl
"Etulipa’s next-gen electrowetting displays shine in full color"

Liquavista

Electrowetting Displays

A paper by Johan Feenstra & Rob Hayes

Electrowetting Displays

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. Fig 1(a) 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 fig 1(b) a voltage difference is applied between the electrode in the water and a sub-surface electrode present underneath the hydrophobic insulator. As a result of the voltage, the droplet spreads, i.e. the wettability of the surface increases strongly.

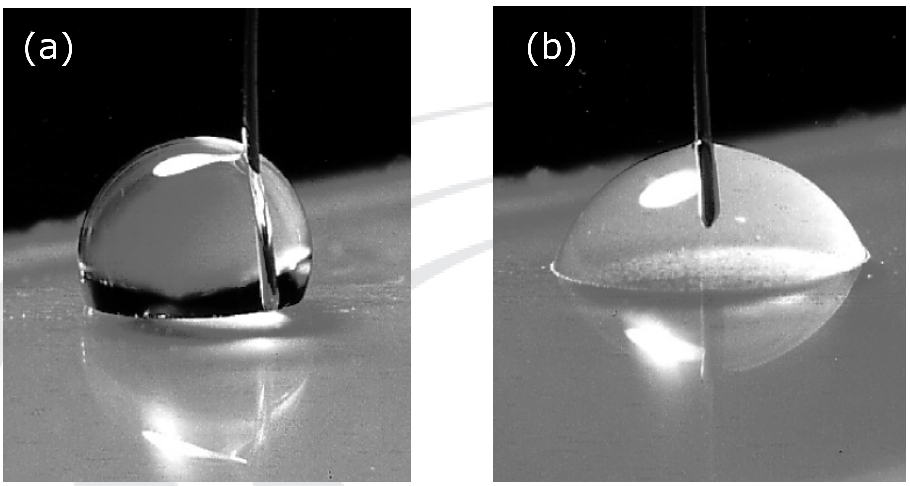

Figure 1 – water droplets on hydrophobic surface (a) without and (b) with voltage applied.

When the voltage is removed, the droplet returns to the original state indicated in figure 1(a).

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:

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

where γ_i are the respective surface tensions of the liquid/vapor, solid/vapor and solid/liquid interfaces and θ is the contact angle.

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]:

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

https://www.nobelprize.org/prizes/physics/1908/lippmann/biographical/

where ε_r and d are the dielectric constant and the thickness of the hydrophobic insulator, respectively.

The Lippman equation includes an electrostatic term that is the result of the liquid/insulator/solid capacitor being charged. Since γ_{LV}, γ_{SV} and γ_{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 utilized 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 more than 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 combines 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. This and other core patents were assigned to Liquavista, coinciding with the spin-off from Philips.

Figure 2 – Cover of the Nature edition with the first public disclosure.

3. Electrowetting display principle

In Fig. 3 the principle of a reflective Electrowetting display is shown. Figure 3(a) shows the optical stack, comprising a transparent 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. 3a) 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.

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. 3b) and exposing the underlying reflecting surface.

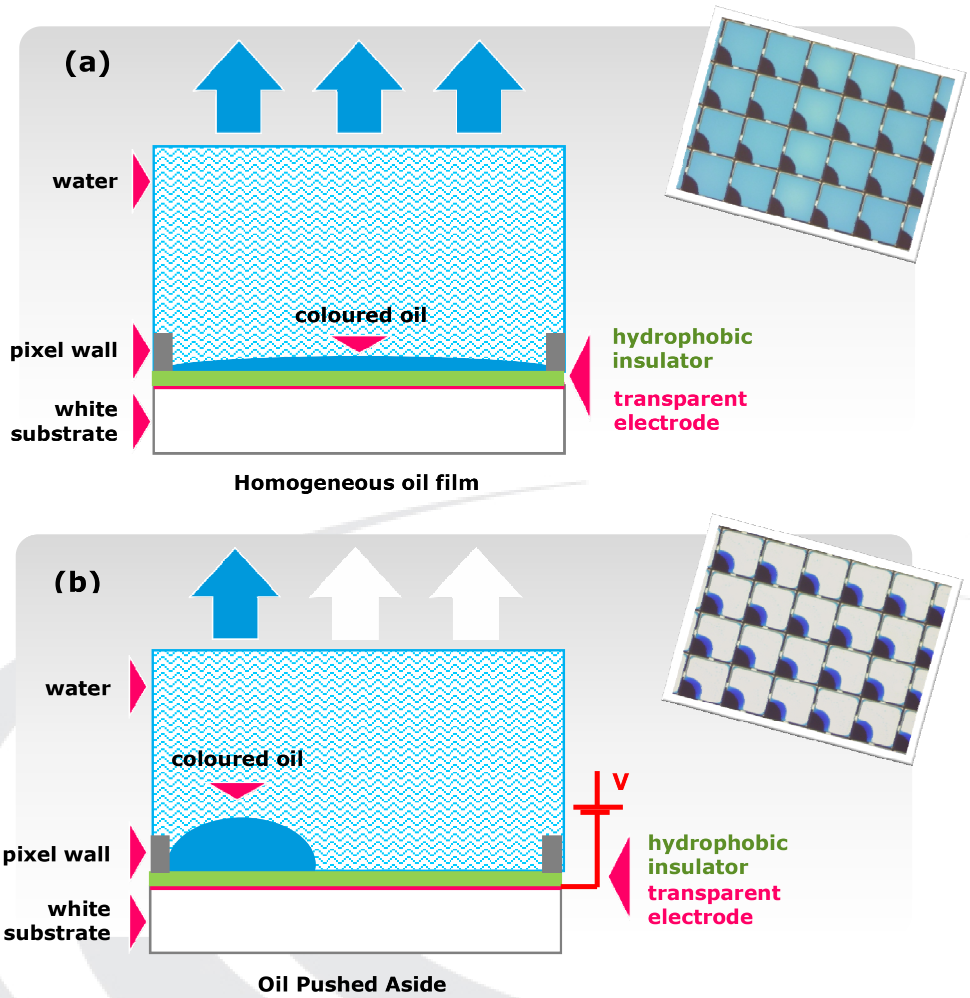

Figure 3 – Electrowetting display principle.

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 transparent on-state, provided the pixel is sufficiently small so that the eye averages the optical response. The pixel can be made reflective by adding a reflector underneath the stack or by making the electrode reflecting.

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

Available in all modes

As shown in figure 3, the electrowetting optical switch is intrinsically transparent, except for the colored oil layer. This means that the switch can be used to form the basis of transmissive, reflective and transflective displays. Hence, electrowetting displays are the only display technology other than LCD that has this versatility. This means that, in principle, the application space for electrowetting technology is as broad as it is for LCD's.

4. Full color electrowetting displays

Nearly all of the emerging 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. 4) including red, green, blue, 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].

Figure 4 – Color palette for electrowetting displays.

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 inevitably arise when the display is flexed.

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. Single-layer architecture

A low cost, full color display can be fabricated with electrowetting using an RGB color filter approach (fig. 5). In this case, 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.

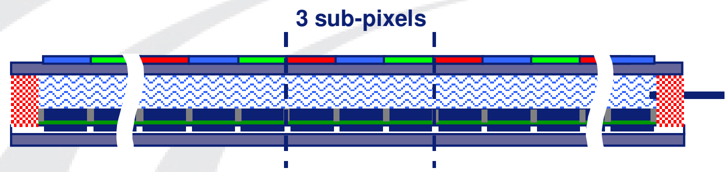

Figure 5 – Single layer architecture with black dye and RGB color filter (not to scale).

One of the biggest advantages of using this approach for achieving a color display is that the manufacturing process and flow is very similar to that used for LCD's. Compared to LCD this architecture offers an improvement of a factor of 2 in color conversion factor (CCF = theoretical light out / light in). In practice, the advantage is even larger, as the electrowetting display will have a naturally unlimited viewing angle, while LCD's typically use approaches for improving the viewing which lead to further reduction of brightness.

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 films. Also in transmissive mode electrowetting displays offer a power consumption reduction due to the increased efficiency of the optical switch.

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. 6). Having three monochrome layers ensures that all processes used for the single-layer display can be used for the three-layer display as well.

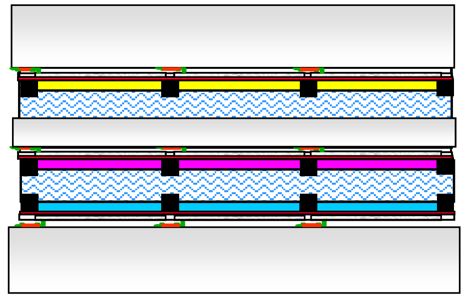

Figure 6 – triple-layer architecture with CMY dyes (not to scale).

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.

Color gamut of 3 layer structure

The three-layer structure offers one further important advantage in color rendering. In fig. 7 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.

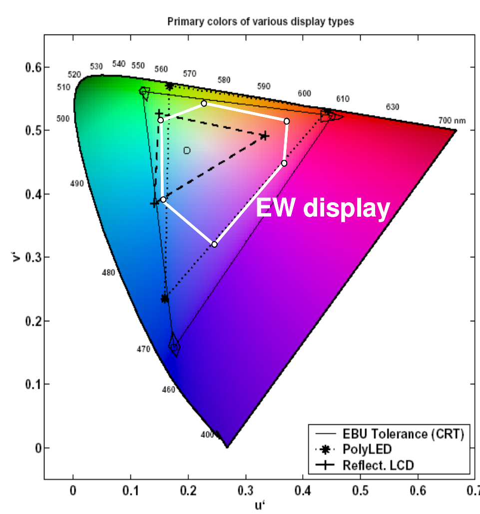

Figure 7 – Color gamut of the three-layer electrowetting architecture, compared to reflective LCD, OLED and EBU.

4.4. Display performance

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

Technology	**B/W Reflectivity**	**Color Conversion**	**Contrast-ratio**	**Viewing angle**	**Grey Scales**	**Image update**
Reflective LC	50	33	15	Limited	Analog	Video
CTLC	30	50*	10	Limited	Analog	> 1s
Electrophoretic	45	33	12	Unlimited	Limited	~ 1s
MEMS	50	33	12	Limited	PWM, Area	Video
1 layer EWD**	60	33	12	Unlimited	Analog	Video
3 layer EWD**	60	100	18	Unlimited	Analog	Video
Paper	70	100	15	Unlimited	Area	-

* assumed the practical case that either left or right-handed polarization is used.
**optical properties: in-pixel x 0.90 (accounting for losses at walls)

Table 1 – Comparison of key performance parameters for various display 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. Video speed

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

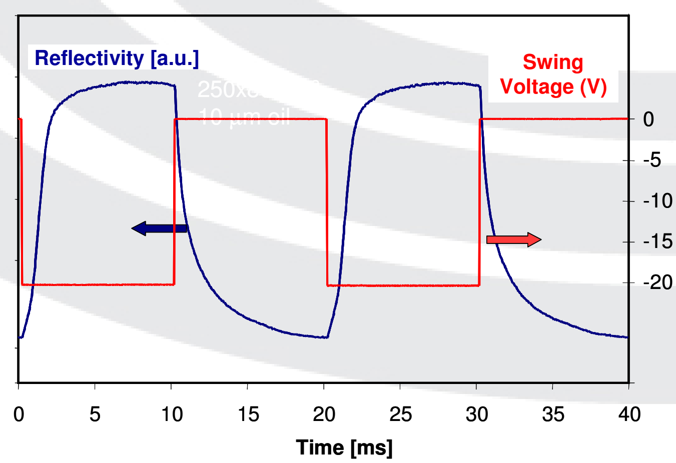

Figure 8 – Response transient of electrowetting display pixels.

Figure 8 shows the response speed of a 100-ppi sub-pixel (250x80 μm^2) upon voltage application. At t = 0, the voltage is switched on. In this case, the 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.

4.4.2. Grey scales

The electro-optic response of an electrowetting pixel with a 160-ppi resolution (160x160 μm^2) is depicted in fig. 9. The pixel white area, i.e. the area from which the oil is removed, is plotted as a function of dc voltage.

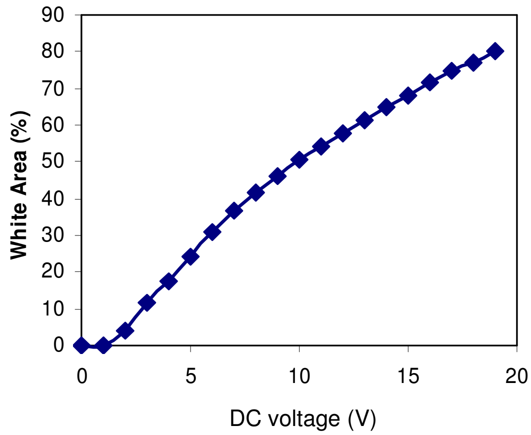

Figure 9 – Electro-optic response of 160x160 μm^2 pixels.

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

An example of 6-bit PWM grey-scale operation (i.e. 256k colors) in a 1.8” active matrix display is shown in fig. 10.

Figure 10 – 1.8” Active matrix display showing 6-bit grey-scale (256k colors) obtained by pulse width modulation.

4.4.3. Operating voltage

For high brightness operation, a dc voltage of about −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 further voltage 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 ~ 4 μm) and fluoropolymer (~0.8 μm) can be used to reduce the operating voltage. Reducing both by a factor of 2 will bring the voltage down below 10 V. Other parameters that can be used to lower the operating voltage further are the dielectric constant of the oil and fluoropolymer and the surface tension of the oil/water interface.

4.4.4. Power consumption

One of the most important advantages of reflective electrowetting displays is their very low power consumption for high color brightness. In fig. 11 we summarize the power consumption of several technologies. We have chosen to compare technologies for video-rate displays.

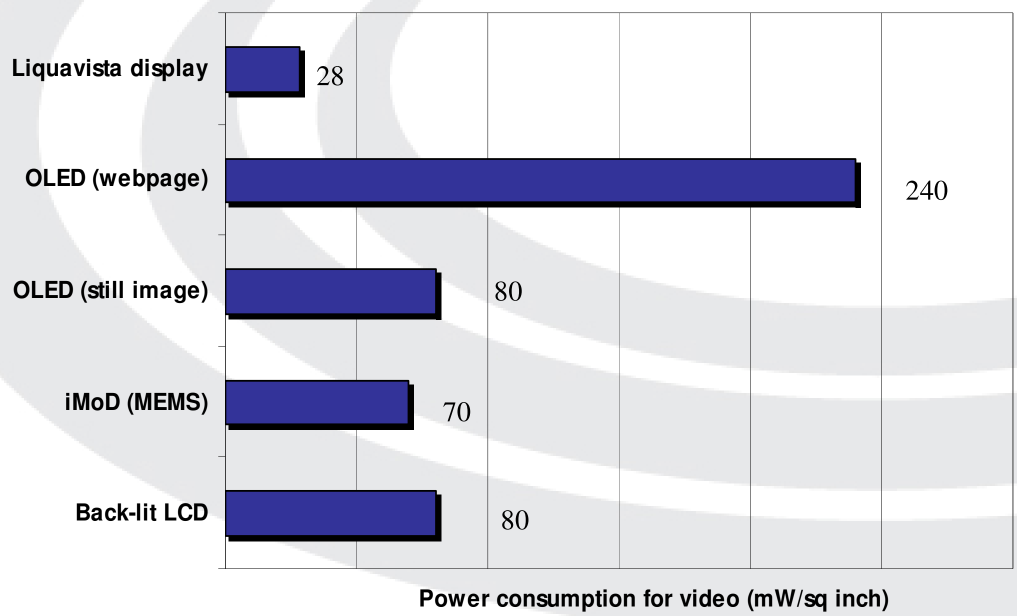

Figure 11 – Comparison of power consumption for a variety of video displays.

As the value for back-lit LCD’s we have taken a typical power consumption for a 2.5” display of around 250 mW. For AMOLED’s, the actual power consumption is dependent on the image content. Therefore, we have depicted 2 numbers for OLED’s, one showing the power consumption for web-based content and one for a typical photograph (still image). As the former contains more white, the power consumption is significantly higher. Obviously, generating light costs much energy.

For the iMoD technology, the power consumption has been determined by ab-initio calculations, assuming a 6-bit grey scale by spatial dithering and an increased frame rate, resulting in higher power consumption even though no illumination is used.
For Liquavista displays, we used the same calculations with amplitude modulated grey scales and our present voltage of about 20 V (dc). As we anticipate the driving voltage to be reduced further in the (near) future, this power consumption will be significantly reduced further. However, already with contemporary driving voltages, the power consumption is much lower than for the other technologies.

4.4.5. Environmental parameters

Switching stability

We run an extended lifetime and reliability program according to industry standards in order to test and predict the performance of displays in the field.

For the electrowetting pixels, a negative dc-voltage is used. Individual displays have been switched more than several hundred 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. Also other important characteristics, including switching speed, high color brightness and white area are unaltered during switching.

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.

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. The use of combinations of inert materials results in a long shelf lifetime.

The classes of dyes we use have been chosen for their stability in typical outdoor environments. As a result, bleaching is not an issue for present displays. Each new dye is only used in our displays after passing accelerated testing with a high intensity lamp according to industry standards.

5. Display addressing

5.1 Segmented displays

With the large variety of colors illustrated above (see fig. 4), 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 advertisement. In the case of segmented displays, the addressing can be done with commercially available STN-type driver ICs.

Segmented Liquavista displays exhibit several unique new features that provide significantly more design freedom than conventional displays, which are explained below.

Selective Fill and Vivid color range

One of these unique features is the ability to *selectively fill* the display with colored oil, by our patented filling process. Making use of the hydrophobic/hydrophilic patterning of the surface, the colored oil can be positioned in a pre-determined shape. As a result, the display already shows an image in the off-state. For example, the images of the fish in the display shown in the upper part of Figure 12 are created by using Selective Fill. Thanks to the strength of the surface tension forces, an unlimited variability in shape can be used, including very sharp corners, rounded edges and small internal patterns.

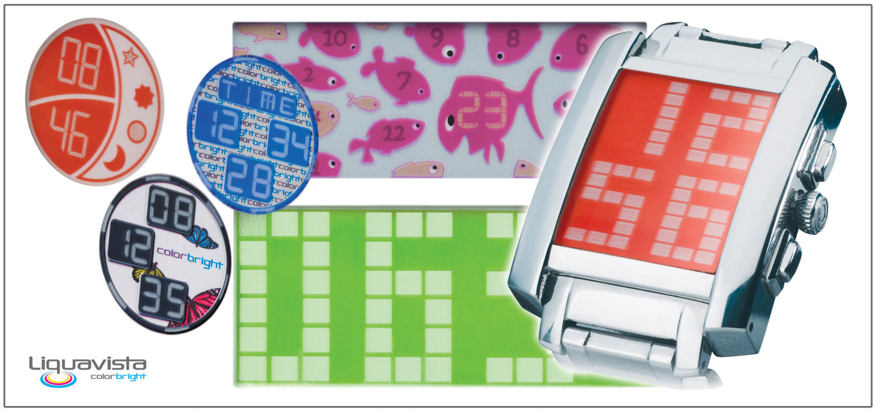

Figure 12 - Examples of segmented Liquavista displays illustrating the large design freedom.

Combined with a large variety of bright colors, this creates a display that can have a strong design impact when used in many applications: watches, consumer electronics, decorative displays, etc.

Reflector patterning and Reveal

In the case of Selective Fill, part of the display has no colored oil present in the optical path and is therefore fully transparent in these areas. As a result the reflector is fully exposed and can show a background containing patterns, logos or images. For example, the display shown in the lower left corner of Fig. 12 has the Liquavista logo and the butterflies printed on the reflector.

This is illustrated further in fig. 13 which shows the simple architecture of a segmented Liquavista display. In the upper left corner of the display model shown in Fig. 13, segmented electrodes are used to show numerical information on a reflector that is partly colored. In the bottom part of the display, we illustrate a feature called *Reveal*. When activated, the segment reveals the underlying effects of the reflector design, in this case the number 6.

This creates strong opportunities for further product differentiation.

Figure 13 - Display model, showing the switching segment layer and the reflector separately, illustrating the large design freedom.

5.2 Active Matrix Addressing

For a high resolution, video-speed display active matrix addressing is generally used. Presently, the operating voltage required for a high brightness optical state is about −20 V. These voltages can easily be accommodated by commercially available active matrix backplanes, as illustrated by the display shown in fig. 14.

Figure 14 – 1,8" full color active matrix 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 and color on a flexible, paper-like display in the foreseeable future.

QUASI-STABILITY

The power consumption can be reduced further, by running the display at a much reduced frame rate. This can be done, thanks to the low leakage current and the stability of the voltage residing on the pixel - even when it is addressed less frequently - as well as thanks to the dc-driving and the absence of drift of the electro-optical curve during operation. We call this feature *Quasi-stability*. Quasi-stability results in ultra-low power consumption, comparable even to bi-stable displays for situations where the display is not updated for several seconds. Moreover, while it is difficult to have video-speed switching and a competitive number of grey-scales in bi-stable displays, these properties are maintained in a quasi-stable Liquavista display.

The combination of quasi-stability while having full video-speed and grey scale capability also provides interesting options, such as showing video images on part of the display, while having static content on the rest. Using *selective pixel addressing*, i.e. only update those pixels that require updating, a further reduction of power consumption can be realized.

6. Manufacturing processes

The process flow for manufacturing an electrowetting display is shown in fig. 15.

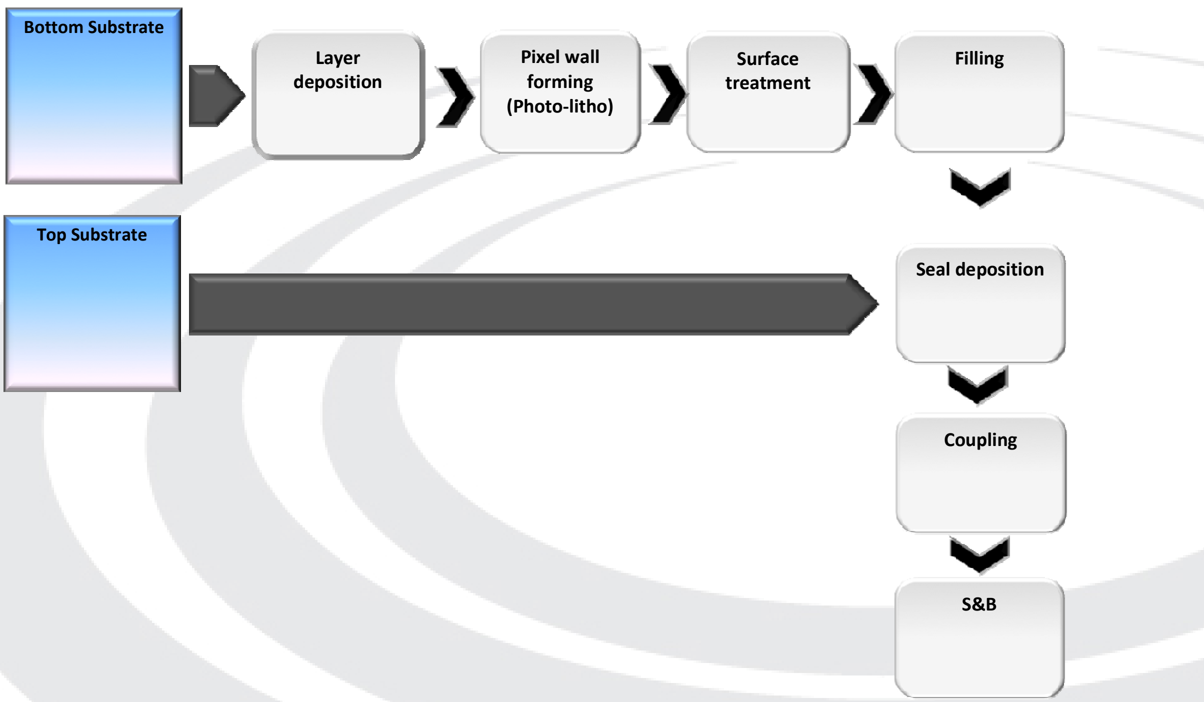

Figure 15 – Process flow for manufacturing electrowetting displays.

As the bottom substrate any type of substrate can be used, ranging from structured ITO-coated glass for segmented displays to active matrix substrates for high resolution, pixelated displays to even flexible substrates.

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 off-state. Photolithographic walls form the pixel structure 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 cover substrate to provide the electrical contact to the water.

As can be seen, electrowetting display processing consists of standard technologies of which nearly all are used in existing LCD display manufacturing facilities. This means that for current players in the industry, electrowetting displays offer a great opportunity to commercialize strongly improved displays with a relatively low investment.

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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