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Introduction of a New Disruptive Display Technology in the Existing Display Manufacturing Infrastructure

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ABSTRACT

We have been using e-paper for 15 years now, and its uses and markets are now well known. Development of e-paper markets is slow to non-existent, mainly due to the fact e-paper displays distinctly lack (saturated) color and speed. Consequence is, that e-paper has very limited access to existing markets, and occupies a niche in the display market.

Availability of full color and video will open up markets which are not accessible now, and will even create new ones. But alignment with existing display infrastructure is a condition for success.

1 INTRODUCTION

Introducing a new display technology in the market of today is a difficult challenge. The world has several world-class display technologies, some older than others, but all of them with considerable volume, and available at low cost. Any new technology has to compete with the properties already realized, and has to find the balance between niche-market advantages and volume cost. With the introduction of a new player in the display field, this needs to be prominent in the roadmap. The factors of importance are:

- Choice of technology
- TFT substrate
- Architectural process
- Dyes and optics
- Finishing and assembly

2 ELECTROFLUIDIC DISPLAY PRINCIPLE

The only technology capable of providing a real challenge for the mainstream displays is the electrowetting principle. It has extensively been discussed that video speed, high color gamut and high reflectance can be realized [1,2,3,4]. Electrowetting displays are based on the properties of hydrophobic surfaces that can be changed to hydrophilic by the presence of an electric field.

This property is then used to control the position of a dyed, non-polar fluid in the pixel of a display. The dyed fluid can be made to cover the pixel area, or contract into the corner of a pixel (figure 1). This way, an optical shutter can be realized, in the color of the dye applied. This can be a black / white shutter for monochrome e-paper or (in combination with a color filter) RGB color e-paper, or it can be used to modulate the printing primaries cyan, magenta and yellow and create a layered color display. In case of simple displays, the substrate can be a simple, passive electrode plate, but if more complex, higher resolution panels are targeted, an active matrix (TFT) substrate is necessary.

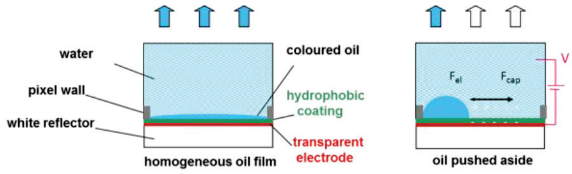

Figure 1: The electrowetting display principle

The basic display architecture will be described in more detail below.

3 ELECTROFLUIDIC DISPLAY ARCHITECTURE

3.1 The TFT substrate

Usually, the TFT substrate is the most complex and most expensive component of a display. Developments for LCD have significantly reduced the cost of individual panels, but designing a purpose built TFT panel even for LCD still is an expensive exercise, and the cost of the new design has to be compensated by significant sales volumes.

Moreover, if a different architecture is required, development becomes virtually impossible, since not only is it necessary to make a new design, also new elements have to be introduced and tested. All this work will then have to be amortized in sales volume which simply isn't present in niche market products.

In this respect, it's a good thing that electrofluidic displays can make use of tried and tested TFT backplanes, with architectures identical to LCD architecture, and no new elements are needed. The end-product of an a-Si or oxide-TFT LCD factory can be used for electro-fluidic front-end manufacturing without modification.

3.2 Electrofluidic front-end

Front-end manufacturing can be seen as construction of the pixel-scaffolding that will be used to construct the fluid switch.

The Liquid Light manufacturing line accepts G2.5 mother glass (400 x 500 nm), and manufactures the base structure in an automated production line (figure 2).

Figure 2: In-house manufacturing infrastructure

Firstly, the main insulator, intended to minimize DC current, is applied. Following that, the surface of the insulator is coated with a fluoropolymer, providing the engine for the electro-wetting effect.

On top of the fluoropolymer, a pixel wall grid is constructed, the pixel wall height being a function of the pixel size (small pixel needs a thin switch, and hence a low pixel wall).

On the counter-plate, lithographic spacers are formed, in order to maintain the correct glass spacing.

3.3 Electrofluidic back-end

Once the “scaffolding” is complete, the display can be finished. This means each pixel has to be filled with the correct amount of colored, hydrophobic liquid (“oil”). And following this, the remainder of the display cavity has to be filled with a larger quantity of a colorless, hydrophilic liquid (“water”). This is a critical part of the display, and will determine to a large extent the electro-optical properties. Key elements are:

- Dyes
- Filling rate
- Support structures

Those will be described separately

<u>Dyes</u>

Modulation of light takes place by the use of dyes dissolved in a hydrophobic liquid. Because the hydrophobic properties of the oil have to be maintained as much as possible, the dye concentration can not exceed a certain level. This also means, the dyes need to have extremely high extinction coefficients. Taking into account a typical pixel is around 100 – 200 um in size, and the corresponding oil thickness is 3 – 5 um, even very high extinction dyes can not attenuate sufficient light in a single pass. This makes the system suitable for reflective displays, not so much transmissive. Liquid Light has its own dye synthesis facilities, providing an important lead over commercial dyes (figure 3).

Figure 3: Some examples of synthesized dyes

<u>Filling percentage</u>

In the ideal case, the surface of the oil film in the pixel would be perfectly flat. However, with most of the filling methods, the pixel will show some kind of meniscus, depending on the ration of the pixel wall height vs. pixel size, making the center of the pixel thinner than the edge. Another critical parameter contained in the pixel wall height vs. pixel size is the “closing” of the pixel: If the pixel becomes too large relative to its pixel wall height, the advancing contact angle of the “oil” is not high enough to replace the water, and an open area in the center of the pixel will result. (figure 4)

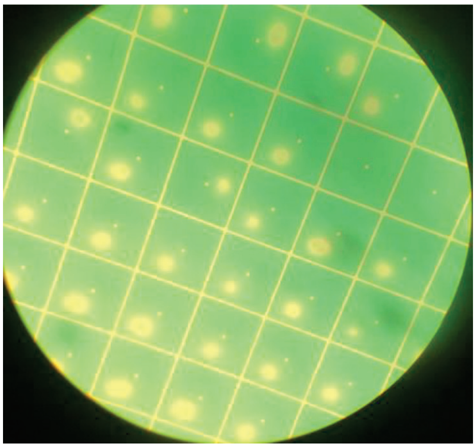

Figure 4: Example of under-filled pixels

<u>Pixel support structures</u>

In order to direct the oil flow through the pixel, it’s necessary to direct the opening process. In a normal, square pixel, the opening will typically occur in the pixel center, and progress towards the edge, leaving 4 droplets of oil in the corners. Since this isn't the energetically most favorable state, the smaller corner droplets will shrink because oil will flow through the edge capillaries to the larger corner droplets, where the surface tension is lower. So ideally, the pixel should open in one corner, an the oil should contract into the opposite corner.

Filling

The next step is filing the pixel cavities with oil and water. Although this sounds easy, it is by no means. The "oil" will stay in the pixel because the surface of the pixel is hydrophobic. However, if the oil comes in contact with water, in the presence of air, suddenly there is a more preferred "hydrophobic" surface available: The water-air interface. The oil will flow into this interface and move out of the pixel, leaving the pixel virtually empty.

In order to avoid this, in the early days the plate was submerged in water, and oil was injected into the cavity pixel by pixel. Unfortunately, this isn't a suitable process for production since it is extremely time-consuming.

To improve this, a new method was designed, filing the oil while drawing a dry plate into a water volume, via a meniscus formed by a small and well controlled volume of oil.

This works better, but still has a number of drawbacks. Firstly, the drawing process has to be slow (~15 minutes per plate), and secondly, the method is extremely sensitive to vibration.

Another way that could be used is the "co-extrusion" of water and oil, where both liquids are dispensed in a cavity formed directly above the pixels, which has the advantage that other "water" liquids could be used. However the disadvantage of speed and sensitivity to variations remains.

Finally, there is a way where the oil is first dispensed in the pixels (by carding or (inkjet) printing), after which the oil is frozen and submerged in the water phase. This way the oil can not leave the pixel cavity, and the method is fast and insensitive to speed and vibration.

4 DRIVING

Once the cell is filled and closed, the display can be driven much like an LCD. There is a choice between AC and DC voltage, which basically doesn't make much difference except for driving power and to some extent reliability. The opening of the pixel is proportional to the applied voltage, and reproducing grayscales is identical to LCD driving.

Apart from controlling grey levels, the applied voltage, and voltage slew rate, have influence on the opening dynamics of the pixel [5]. The voltage has to be carefully controlled in order to maintain a reproducible opening kinetics

The EFD pixel is not bi-stable, but because of the (required) high pixel resistance, once the voltage is applied to a pixel, it can be retained for minutes. This means the power required for retaining an image is very small, typically only the power required to scan the panel once a minute. This leads to a microwatt / cm2 power for still images, and only slightly higher for video.

5 RESULTS

Using the processes mentioned above, demonstration panels have been produced, showing low resolution (passive) displays as well as active matrix demonstrations. Results are encouraging, and show wide color gamut displays with acceptable reflectance, much better than the usual RGB solutions (figure 5).

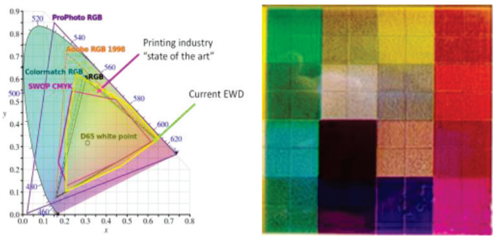

Figure 5: Achievable color gamut

Reflectance of more than 40% can be reached, while achieving >80% NTSC color gamut. While these figures are impressive by themselves, the display can switch in milliseconds, and is capable of displaying analog grey levels ("millions of colors"). First video rate prototypes greyscale and color are under construction (figure 6).

Figure 6: prototype video rate greyscale e-paper

6 CONCLUSION

Electrofluidic displays can be produced using standard TFT panel processing, combined with proprietary and cost effective front- and back-end processing. The resulting display provides good contrast and color gamut, while providing video speed (figure 7). This unique combination of properties makes it the most important technology in development for reflective displays, challenging current e-paper displays and opening new markets for reflective displays.

Figure 7: Examples of electrofluidic prototypes

7 ACKNOWLEDGEMENTS

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