33.3: Flexible Electrofluidic Displays Using Brilliantly Colored Pigments

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Abstract

We have developed a novel electrofluidic technology for displays that employs brilliantly colored, well-saturated pigments in solution, modulated by electrowetting physics. We discuss the operating principles of the display, and demonstrate progress in key areas needed for realizing products, including fabrication on flexible substrates and performance from -28℃ to 80℃.

1. Introduction

Reflective display technology has now reached the 'tipping point' for applications such as electronic paper, as evidenced by the recent success of the Amazon Kindle. Reflective displays utilize ambient light to illuminate the screen image and therefore provide superior energy efficiency, sunlight legibility, and reduced long-term eye-strain. Numerous technologies are vying for reflective applications such as electronic paper where high white state reflectance (R) is critical including electrophoretic[1] (e-Ink, R~40%), electrowetting[2] (Liqua-Vista, R>50%), cholesteric liquid crystal[3] (Kent Displays Inc., R~30%), electrochromic[4] (NTerra Inc., R~45%), micro-electromechanical interference[5] (Qualcomm Inc., R~25%), and liquid powder[6] (Bridgestone, R~40%). However, all of these technologies fall well short of the visual brilliance and contrast of pigments printed onto bleached-wood fiber paper (R>80%). For example, electrophoretic and liquid powder displays are fundamentally challenged by the need to place a thin white pigment layer in front of a black absorbing pigment layer. Interference modulated displays can provide brilliant reflective color at a single pixel, but creating a broadband and wide-angle white reflector is not achievable at the scales required for micro-electromechanical operation. Electrowetting displays currently provide the best white state reflectance. This is achieved by simply modulating the coverage of a colored oil film on a high-reflectance white surface. However, the colored oil typically presents the following challenges: ~20% of the viewable area is typically always occupied by the colored oil (reduced white state), dyes lack the stability and color-performance of pigments, and the colored oil is not stable in a given position without continual application of voltage (not bistable). Therefore if reflective displays are to achieve the performance of paper, it will require an all-together different approach.

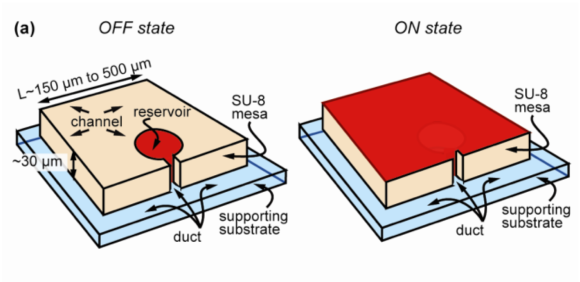
To address the lack of reflectivity and color in existing reflective technologies, we developed an electrofluidic display technology.[7] Based on electrowetting physics, this technology introduces two important advances over traditional electrowetting devices: 1) a 3D structure which increases the aperture ratio above 90%, thereby improving contrast, and 2) a pigmented colorant which provides high color saturation at minimal thickness. In this paper, we will describe the operating principles of the display, and demonstrate progress in key areas needed for realizing products, including pixel fabrication on flexible substrates and the development of fluid systems that meet environmental requirements for portable devices.

2. Methods and Results

2.1. The Electrofluidic Device

We designed and fabricated a first generation electrofluidic structure to demonstrate the device operating principles. An electrofluidic cell comprises a bottom plate with three-dimensional features, as shown in Fig. 1a, and a top plate that includes the common electrode (not shown) underneath a hydrophobic dielectric layer. The pixel structure on the bottom plate contains several important microfluidic features. First, there is a reservoir, which will hold liquid pigment dispersion in less than 5-10% of the visible area in the 'off' state. Second, a surface channel covering 80-95% of the visible area pulls the pigment dispersion from the reservoir in the 'on' state. Third, a duct enables counter-flow of a non-polar fluid (i.e. black oil) as the pigment dispersion leaves the reservoir. The bottom electrowetting plate utilizes a highly reflective electrode such as Aluminum.

The pixel is operated as follows: With no applied voltage, a net Young-Laplace pressure ($\Delta p=2\gamma/R$) causes the pigment dispersion to occupy the cavity that imparts a larger radius of curvature on the pigment dispersion. Therefore at equilibrium, the pigment dispersion occupies the reservoir and is largely hidden from view. Next, a voltage is applied between the two plates and the pigment dispersion. This induces an electromechanical pressure that exceeds the Young-Laplace pressure, and the pigment dispersion is pulled into the channel.



(b) latest generation ~100 DPI prototype, ~10,000 pixels

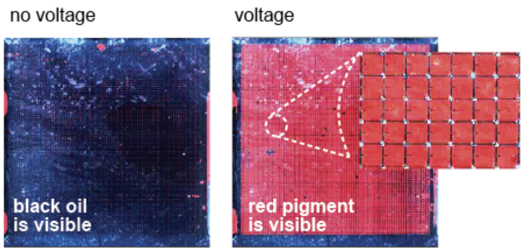


Figure 1. Schematic of an electrofluidic cell structure without the top plate (a). Switching a 10,000 pixel device from black to red. (b)

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Prototype devices in Figures 1a and 2 show the cells in operation. To achieve high contrast ratio, black oil has been used in the device. This device features a 300 µm pixel cell dimension, 10um pixel spacing, and a reservoir area which is ~10% of pixel visible area. With this design, the maximum contrast ratio which can be achieved on this device is ~9:1. By decreasing the reservoir area to 5% of pixel area, the contrast ratio can be expected to reach ~20:1. There is no voltage penalty for reducing the reservoir area; the drive voltage is the same.

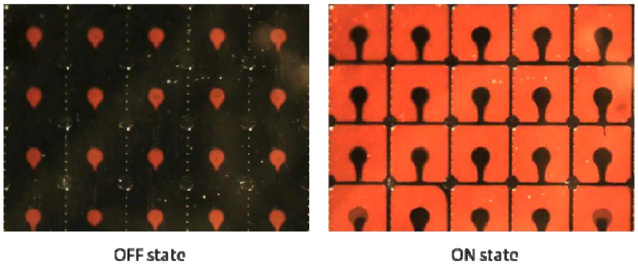

Figure 2. Close-up of switching electrofluidics pixels using a red pigment dispersion and black oil.

2.2. Flexible Electrofluidics

Electrofluidic pixels are particularly well suited for flexible display applications for several reasons. First, the pigment is sandwiched between two substrates with periodic spacers support a cell gap of a few micrometers. The spacers prevent changes in the cell gap during flexure, providing consistent device performance. Next, the layers can be thin (< 100 um including substrates) enabling a small bend radius. Finally, electrofluidic devices can be fabricated with flexible materials at low processing temperatures

The devices demonstrated in Figures 1 and 2 were fabricated on glass substrates using low temperature processes. The entire process can be implemented with temperatures as low as ~100-120°C and is therefore compatible with both glass and flexible plastic substrates. We recently transferred these processes to a 125 µm thick polymer backplane (both PET and PEN), shown in figure 3. In the simplest embodiment, the mesa structure was photolithographically patterned onto the PET bottom substrate to create the reservoirs and ducts. Next, an Al electrode was vacuum-deposited and patterned to provide a highly reflective backplane and cell pixelation. A dielectric layer and a hydrophobic layer were deposited over the aluminum. For the top plate, ITO and the dielectric and hydrophobic layers were deposited onto the substrate. The highest temperature process during fabrication occurred at the hydrophobic layer deposition step. We kept the temperature considerably lower than that of our glass substrate recipe (>160ºC) and found that the resulting contact angles for water on the hydrophobic layer were equal to those for samples processed at higher temperatures. The array of pixels was dosed with oil and the pigment dispersion. The dosing used a self-assembly approach[8] that in this work was based on capillary forces.

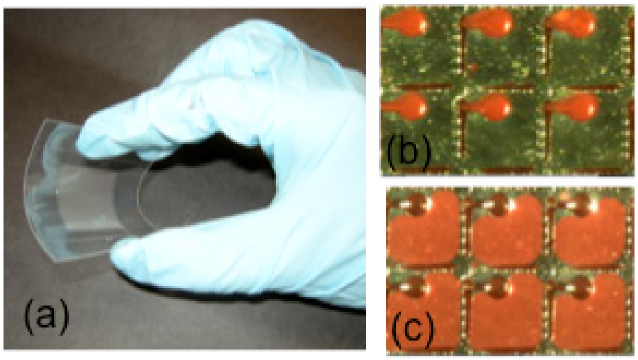

Figure 3. The electrofluidic 3D structure fabricated on a PET backplane (a), with pixels in the 'off' (b) and 'on' (c) states.

2.3. Environmental Performance

Electrofluidic displays must meet established environmental requirements for products such as storage temperature and operating temperature. This is especially true for flexible displays, which tend to encounter problems at temperature extremes. Pigment dispersion stability in our polar fluid is the key for obtaining a wide environmental range. We have demonstrated that our pigment dispersions are stable over a wide temperature range. Moreover, they can survive storage without degradation of their electrowetting response from -28°C to 80°C (the widest range investigated).

The pigment dispersion samples used for the stability tests were blended with silicone oil, the ambient in our device. Three samples of the pigment/silicone oil mixture were stored at (-28)°C, 20°C and 80°C respectively for 24 hours. Wetting angle vs. voltage measurements were performed immediately after removal from the extreme environments for these three samples in silicone oil. For these measurements, a droplet of pigment dispersion was placed into silicone oil on a top of the top plate structure (described earlier) and contacted with a metal probe. The response of wetting angle vs. applied voltage was video recorded by camera (Figure 4). As we can see from figure, there is no difference between the samples stored at different temperature. The initial Young's angle is ~160°. Under the voltage of 50V, the wetting angle reaches saturation region, and the saturation wetting angle is ~60°. After removing the voltage, the droplet wetting angle jumps back to ~160°, demonstrating that our pigment

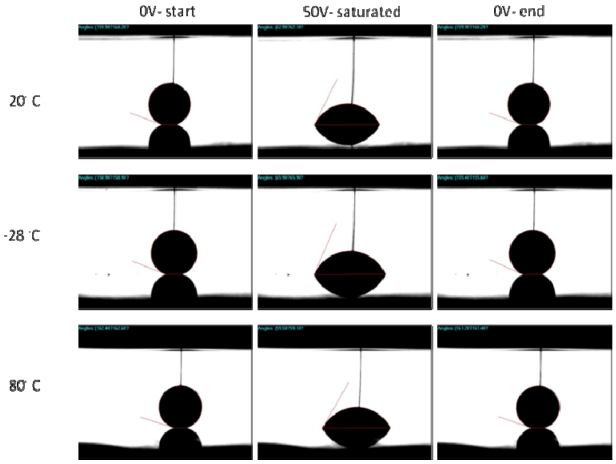

Figure 4. Stability of the pigment dispersion over temperature. There is no change in behavior after storage at various temperatures.

dispersion performs without change after storage between -28°C and 80°C.

In addition to measurements over storage range, we also measured the electrowetting performance of the pigment dispersions at temperature in silicone oil ambient. We observed satisfactory electrowetting performance for device operation over the entire measured temperature range (-20^{o}C to 50^{o}C). Examples of electrowetting modulation are shown in Figure 5 at operating temperature extremes.

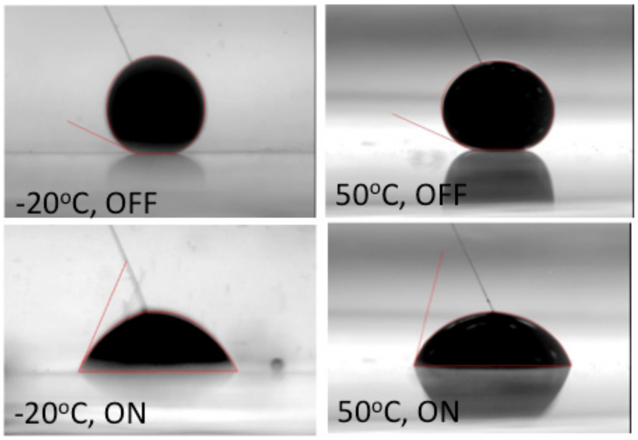

Figure 5. Electrowetting actuation of a drop of pigmented fluid on a hydrophobic surface at –20^{o}C and 50^{o}C.

3. Conclusions

Electrofluidic displays offer improved reflectivity and color saturation over other electronic paper technologies. They can be fabricated at low processing temperatures (< 120^{o}C) making them suitable for flexible displays using plastic substrates. We have demonstrated operating electrofluidic display pixels fabricated on flexible plastic substrates at low temperatures. We have also demonstrated the development of pixel fluids that withstand the temperature extremes required for commercializing products.

4. Acknowledgements

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