Invited Paper

Flexible electrowetting and electrowetting on flexible substrates

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ABSTRACT

Electrowetting (EW) technology is shown to be quite flexible in operation and able to operate on flexible substrates. Complementary ON/OFF characteristics of EW devices have been obtained through a plasma irradiation and annealing process. This enables the design of EW array operation in a reduced power mode. Examples of EW operation on flexible substrates are discussed. This includes paper, plastic and metal substrates. Prototypes of flexible EW arrays on plastic substrates are demonstrated to switch reversibly by applying a low voltage difference (20 V). The array operation is maintained even when the display is mechanically flexed. These results indicate the promise of flexible EW devices for mobile and other devices, including video rate flexible e-paper.

Keywords: electrowetting, complementary, low power, flexible substrates, displays, e-paper, e-reader

1. INTRODUCTION

Electronic readers are a rapidly growing market despite of the shortcomings of the most commonly utilized e-paper technology - electrophoretic displays[1] (EPD) - because of the very attractive functionality that they provide. The limitations of EPD technology include a slow response time (not suitable for video operation), relatively low contrast, and absence of color. On the other hand, since EPD e-readers operate using ambient light (i.e. in reflective mode) they have very low power consumption, resulting in long battery operation.

The current main competition comes from LCD-based tablets, which use back-lit transmissive displays and provide full color and video capability. Tablets have many additional capabilities beyond the e-reader function. However, they consume more power and are generally bulkier and heavier than EPD-based units.

2. ELECTROWETTING OPERATION

Another approach being pursued utilizes the electrowetting (EW) effect[2] to form a light valve by moving two immiscible liquids (one clear and the other colored) in and out of the light path through the application of an electric field. This approach is illustrated in Fig. 1a, where schematics of the EW effect in a pixel containing oil and water are shown for zero and applied bias along with photographs showing a portion of an array under corresponding conditions. EW technology has many applications, including flat panel displays, lenses with electronic focus, and microfluidic devices. The EW light valve display approach is quite versatile, allowing for reflective[3], transmissive[4,5] and even emissive[6] operation. Most importantly, its switching speed is in the millisecond time range[3,6] enabling video operation.

3. COMPLEMENTARY EW FOR LOW POWER OPERATION

An important consideration in all display technologies is power consumption. In EW displays, several approaches for minimizing power consumption have been reported, including bi-stable operation[7], multi-value stable operation[8] and complementary operation[9]. The complementary operation of EW devices under applied voltage is illustrated in Fig. 1b. We have achieved a reversal of the normal two-fluid competitive (water vs. oil) electrowetting on dielectric by plasma irradiation of the normally hydrophobic fluoropolymer followed by thermal annealing. Similar to the reduction in power dissipation obtained when nMOS and pMOS transistors are combined in complementary MOS (CMOS), this method can lead to low power operation of EW devices. The ability to reverse the polarity of the EW effect and to operate EW devices in bi-stable modes is another indication of the *flexibility* of the EW technology.

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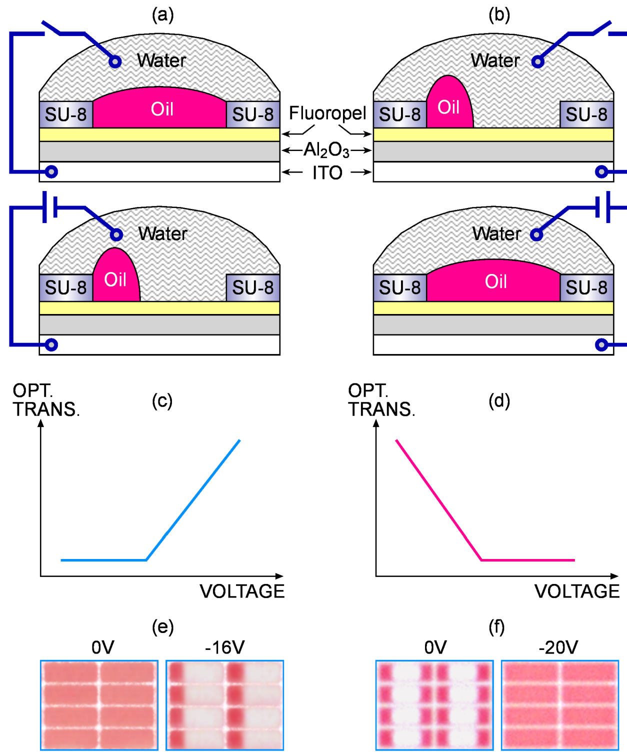

Figure 1. Operation of EW devices[9] with normal process (left column) and with plasma/anneal process (pEW – right column): (a, b) device schematics under floating (or zero) and negative voltage; (c, d) trend in optical transmission with applied voltage; (e, f) photographs of EW arrays under zero and negative voltage.

4. MULTI-COLOR EW DISPLAYS

Multicolored EW displays using side-by-side sub-pixels and thin film filters are now commercially available[10]. However, the side-by-side approach limits the ultimate resolution because a full color pixel requires 3 sub-pixels. The vertical stack approach contains all 3 colors in a multi-layer structure, as shown in Fig. 2. The main advantages and challenges of these two approaches to full-color EW displays are summarized in Table 1.

Table 1. Advantages and challenges of full-color integration approaches in EW displays: horizontal integration (single level plus color filter) vs. vertical integration (multi-layer stack).

Single Layer + Filter Approach	**Multi Layer Vertical Stack Approach**
(+) Simple EW structure	(-) Multi-layer Alignment
(-)Needs Filter Alignment	(-) Drive Electronics
(-)Lower Brightness	(+) Higher Brightness
(-) Reduced Resolution	(+) Higher Resolution

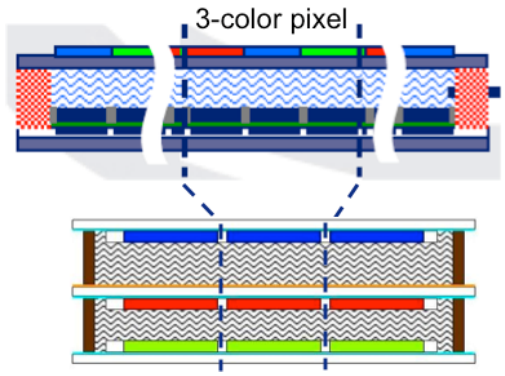

Figure 2. Implementation of three-color EW displays using the side-by-side filter approach (top) and the multi-layer vertical stack approach (bottom).

We have demonstrated[11] three color EW pixels by stacking 3 color levels vertically, therefore keeping the overall pixel size the same as that of each individual level. As shown in Fig. 3, each level can be operated independently allowing for many color combinations.

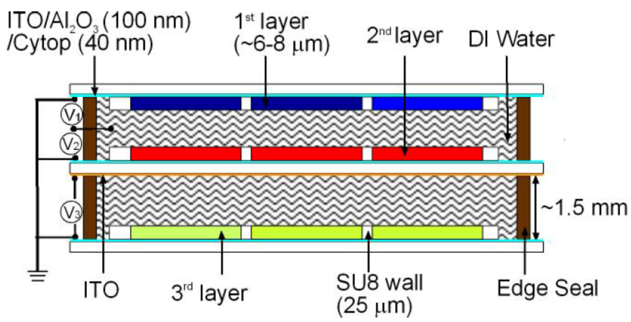

Figure 3. Three-color EW array using the vertical stack approach[11].

Pixel switching in an EW array is illustrated in Fig. 4. In this example, a 45×21 array with pixel dimensions of 300×900μm is shown switching from closed to open under applied bias.

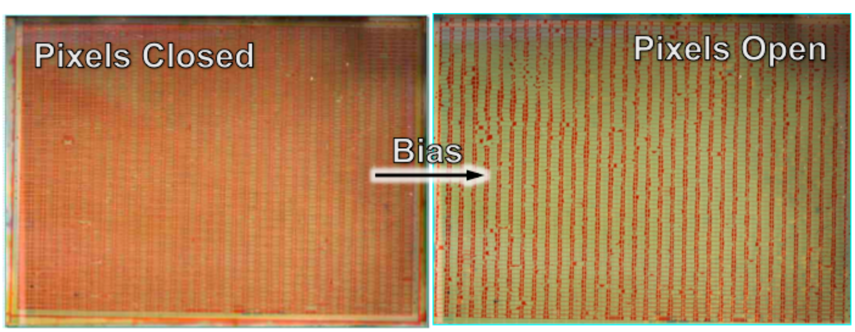

Figure 4. Switching of EW array with 45×21 pixels under applied bias.

The switching speeds of the blue, green and red levels in a vertical stack multi-color EW array are shown in Fig. 5. The times to switch from fully closed to 80% of the maximum open area level for a bias of 12V are 5.8, 9.8 and 10.4 ms for the blue, green and red levels, respectively. These characteristics demonstrate that the EW vertical structure has the potential to produce attractive video-speed color reflective electronic paper devices.

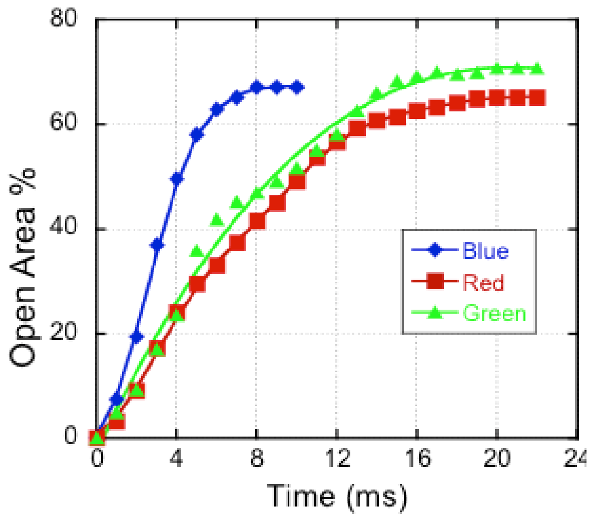

Figure 5. Open area as a function of time for each level in a multi-color vertical stack array[11].

5. EW ON FLEXIBLE SUBSTRATES

Flexible displays are expected to play an increasing role in many applications, from newspaper-like displays to packaging, specialized clothing, etc. We are currently developing flexible displays that utilize the attractive properties of EW technology on substrates made of flexible materials (cf. paper, metal, plastic).

In many ways, paper is an attractive substrate material for many device applications: very low cost, available in almost any size (from pre-cut to roll-to-roll) and with many surface finishes, portable (light weight and flexible), easy to dispose of (incineration, biodegradable). This is particularly true for e-reader devices, where the ideal solution for providing the look-and-feel of ink on paper is to have *e-paper on paper*.

A demonstration of EW action on a paper substrate is shown in Fig. 6, where the paper is bent to form a small diameter tube. We have measured[12] EW switching times on paper are nearly as fast as those on conventional glass substrates, indicating the possibility of video rate display operation.

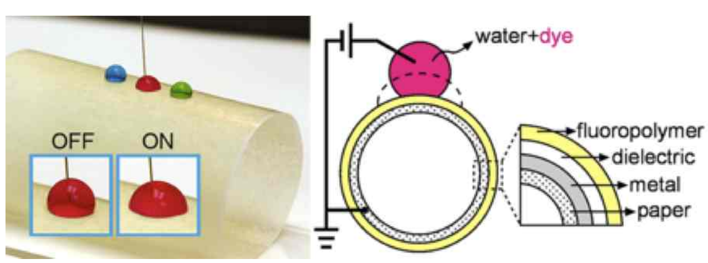

Figure 6. EW on a rolled paper substrate[12].

A flexible EW display array is shown in Fig. 7.The array specifications (45×21 array with 300×900 μm^2 pixels) are the same as the ones for the array shown in Fig. 4, except that in this case the substrate is a flexible plastic material (PET). The device is photographed while being manually flexed. The left and right photographs show the array at zero voltage (OFF state – oil covering pixels) and -20 V voltage (ON state – oil displaced), respectively. The array is fully operational in both OFF and ON states, while being bent in a curved shape. The EW reflective display specifications are maintained even when the display is mechanically flexed.

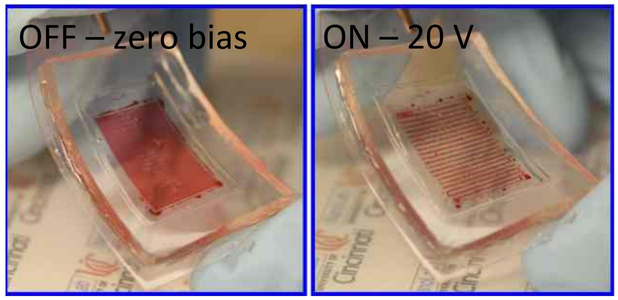

Figure 7. EW array on a flexible plastic substrate.

SUMMARY AND CONCLUSIONS

The reverse EW obtained from plasma irradiation and annealing has led to the possibility of complementary operation of EW arrays, which has the potential of reducing the power requirements for many portable applications. The operation of EW structures on several types of flexible substrates (paper, plastic and metal) has been demonstrated, indicating the feasibility of using these substrates as a cheap and flexible option for EW-based e-paper displays. Their relatively fast switching speed (of the order of a few tens of milliseconds) is very promising for video display applications. This is particularly true for e-reader devices, where the ideal solution for providing the look-and-feel of ink on paper is to have *e-paper on paper*. EW display prototypes on plastic substrates have been to shown to operate when the units are mechanically flexed.

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