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Electrowetting: a flexible electronic-paper technology

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A new approach to color displays promises to combine the look and feel of paper with video speed for e-paper applications on flat and pliable substrates.

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

The current main competition comes from liquid crystal display-based tablets, which use backlit transmissive displays with full color and video. Tablets have many additional capabilities beyond being e-readers. However, they consume more power and are generally bulkier and heavier than EPDs. Another approach (see Figure 1) being pursued uses electrowetting[2] (EW) to form a light valve by moving two immiscible liquids (one clear and one colored) in and out of the light path by applying an electric field. Figure 2(a) shows a schematic illustration of the EW effect in a pixel containing oil and water for zero and applied bias along with photographs of a portion of an array under corresponding conditions. EW technology has many applications, including flat-panel displays, electronic-focus lenses, 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 important, its switching speed is in the millisecond time range,[3,6] which enables video operation.

An important consideration in all display technologies is power consumption. In EW displays, several approaches for minimizing power use have been reported, including bistable,[7] multi-value stable,[8] and complementary operation.[9] Figure 2(b) shows complementary operation of EW devices under applied voltage. We have achieved a reversal of the normal two-fluid competitive (water vs. oil) EW on a dielectric by plasma

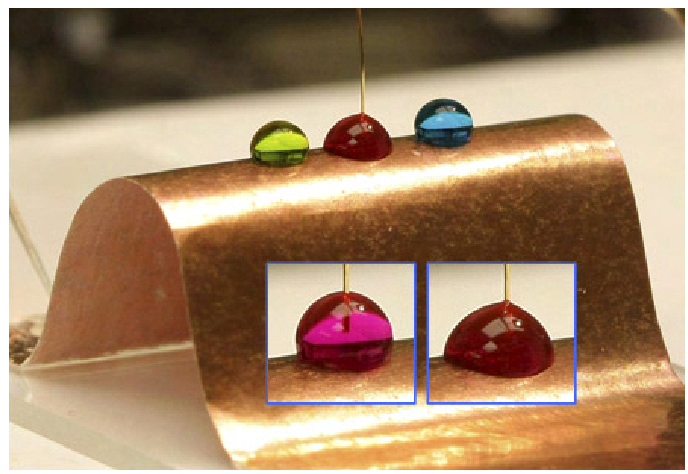

Figure 1. *Flexible electronic-paper technology.*

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 CMOS, this method can lead to low-power operation of EW devices. The ability to reverse the polarity effect of EW and to operate in bistable modes is another indication of the flexibility of this technology.

Multicolored EW displays using side-by-side subpixels 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 three subpixels. We have demonstrated[11] three-color EW pixels by stacking three color levels vertically, thus keeping the overall pixel size the same as that of each individual level. The levels can be operated independently, allowing for many color combinations (see Figure 3).

We are currently developing flexible displays on paper substrates.[12] Figure 4 shows EW action on paper bent to form a small-diameter tube. We have obtained EW switching times that are nearly as fast as those on conventional glass substrates, indicating the possibility of video-rate display operation.

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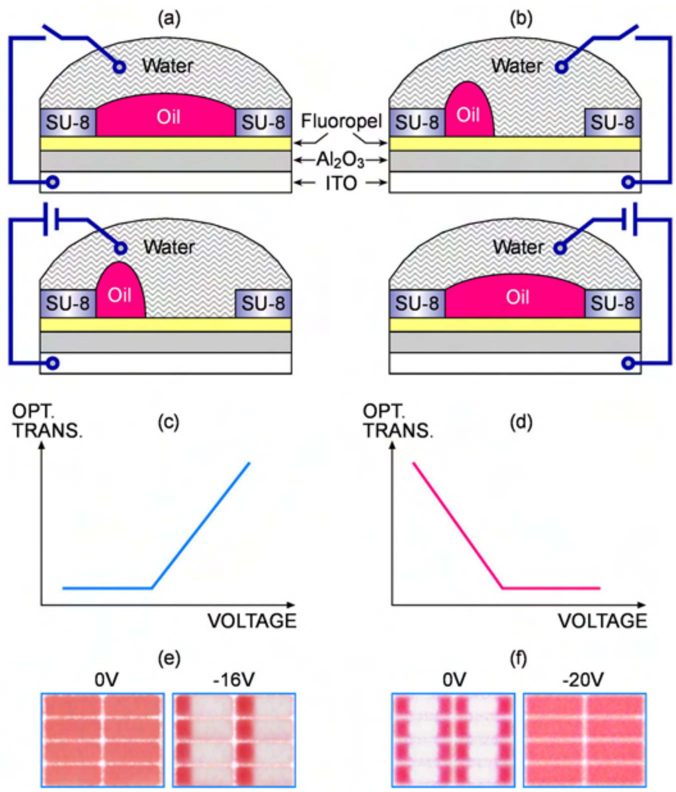

Figure 2. Operation of electrowetting (EW) devices using conventional processes (left) and a plasma/anneal EW process (right). (a, b) Device schematics under floating (or zero) and negative voltage. (c, d) Trend in optical transmission with applied voltage. (e, f) Photographs of EW arrays under zero and negative voltage. SU-8: Epoxy-based negative photoresist (MicroChem Corp.). Fluoropel: Fluoropolymer thin film. Al_2O_3: Aluminum oxide. ITO: Indium tin oxide.

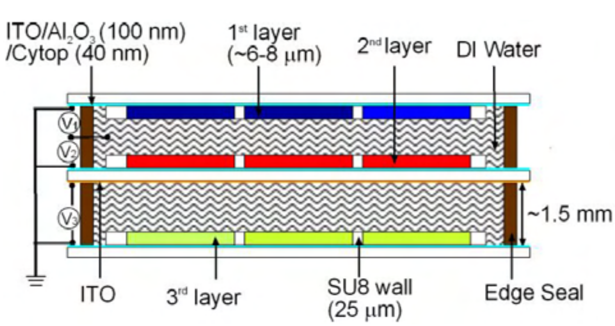

Figure 3. Three-color EW array using a vertical-stacking approach. Cytop: Fluoropolymer. DI: Distilled water. V: Voltage.

Paper is an attractive substrate material for many device applications because it is very low cost, available in almost any size (from precut to roll-to-roll) and with a variety of surface finishes, portable (lightweight and flexible), and easy to dispose of (e.g., through incineration or biodegradation). This paper-based approach is particularly suited to e-reader devices, where the ideal solution for providing the look and feel of ink on paper is to have *e-paper on paper*. As next steps, we plan to develop EW arrays on paper substrates and to determine their optimum operating conditions.

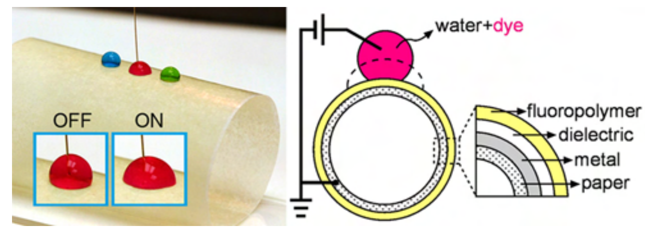

***Figure 4.** EW on paper substrate. (left) Operation on rolled paper. (right) Schematic diagram of the substrate structure.*

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