Display Technology Letters

1000:1 Contrast Ratio Transmissive Electrowetting Displays

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***Abstract*—Transmissive electrowetting display pixels are reported with ∼1000:1 contrast ratio and >50% optical transmission. This high performance is enabled by improved optical density of a black oil layer, and through use of an integrated metal reflector. The integrated metal reflector is placed such that black-oil motion self-aligns with the reflector, ensuring optimal operation of the pixel structure. The integrated reflector can also serve as a storage capacitor during active-matrix addressing. The pixels utilize new black SU-8 for the hydrophilic grid, which allows high contrast ratio in bright lighting. These high contrast electrowetting display pixels are increasingly compelling for high efficiency transmissive displays, and it is theoretically predicted that >80% transmission, <20 ms switching speed, and >1000:1 contrast ratio can be simultaneously achieved with optimized design.**

***Index Terms*—Displays, electrowetting, high contrast, transmissive.**

I. Introduction

ELECTROWETTING displays (EWDs) have been pursued primarily [1], [2] for reflective electronic paper [3]. Transmissive mode operation is also attractive because EWDs are optically highly efficient, inherently analog in grayscale response, easily provide video speed operation, and use many LCD-style fabrication processes [2], [4]. We first reported transmissive mode operation in 2005 [5], and integrated-reflector enhanced operation in 2008 [6]. However, high-contrast is required for transmissive operation [7], especially with LCD and Plasma contrast ratios well into the 1000's:1. Furthermore, the device structure must maintain high contrast in bright ambient lighting, requiring that all front-visible materials be black in color. In addition, these features must be achieved in a simple-to-fabricate and -operate pixel structure.

We report on transmissive electrowetting display pixels with ∼1000:1 contrast ratio and >50% optical transmission. These improved pixels implement several key features: higher optical density black oil; a black hydrophilic grid for contrast in bright lighting; and an integrated metal reflector which improves transmission efficiency, uniform oil motion, active-matrix compatibility, and operation speed. The integrated reflector can also be modified for transflective operation. This work theoretically predicts that transmissive EWDs can achieve >80% transmission, <20 ms switching speed, and >1000:1 contrast ratio, which is compelling for numerous display applications.

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II. Device Fabrication and Physics

A complete pixel structure is shown in Fig. 1(a), with only the backlight unit not shown since any conventional backlight unit is applicable. Pixel fabrication begins with ITO sputter deposition onto the glass substrate, followed by PECVD of 300 nm of SiN dielectric. A reflective Al electrode layer is then deposited and patterned to create transmissive apertures in each pixel. A 50 nm layer of Asahi Cytop hydrophobic fluoropolymer is then dip or spin coated, followed by baking at 180 °C. 50 nm of fluoropolymer is sufficiently thin and inherently porous that it does not effectively electrically insulate the underlying Al reflective electrode. Next, the SU-8 hydrophilic grid is applied. In order to achieve high contrast in bright ambient lighting, we collaborated with MicroChem Corp[1] on a new black-colored SU-8. The black SU-8 grid is processed similar to standard SU-8 on fluoropolymer [2], is 15 μm thick and 10 μm wide, and forms a pixel size of 150×450 μm^2. After the black SU-8 grid is applied, the array of 8500 pixels is self-assembled with black-oil and water using a process we have previously reported [8]. The dosed oil thickness is the same as the height of the black SU-8 pixel grid. The black oil is improved in optical density by using alkane oils and dyes that we have demonstrated in the past [2], but with additional solvents to boost solubility from 10% in pure alkane oil to 30%–50% in the alkane:solvent blend [9]. After dosing, a second glass substrate with an ITO electrode is used to cap the device, including edge-sealing with a UV curable epoxy.

Operation is diagrammatically and photographically shown in Fig. 1(a), (b), respectively. With no applied voltage, the water has a Young's angle of 180° which causes the oil to form a film confined within the black SU-8 grid. The oil film and integrated reflector block all light transmission, and the black SU-8 grid and oil film also prevent front light reflection (pixels appear black). Next, voltage is applied to the bottom ITO electrode (pixel electrode), while both the Al reflector and front ITO electrode are held at ground. As a result electrowetting occurs only in regions where there is no Al reflector electrode, and

[1]Black SU-8 materials were provided by G. Cernigliaro and J. Collins, MicroChem Corporation, USA.

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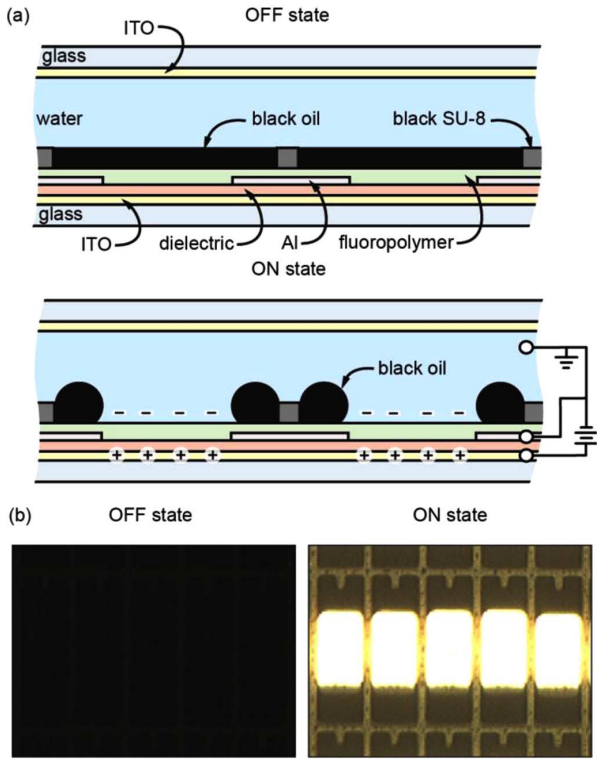


Fig. 1. (a) Diagram of a high contrast transmissive EWD pixel with an integrated Al layer reflector; (b) photos of the transmissive EWD pixels in the OFF and ON states. The OFF state photo in (a) is taken in conventional 300 lux lighting and also reveals the low front reflectance of the pixel.

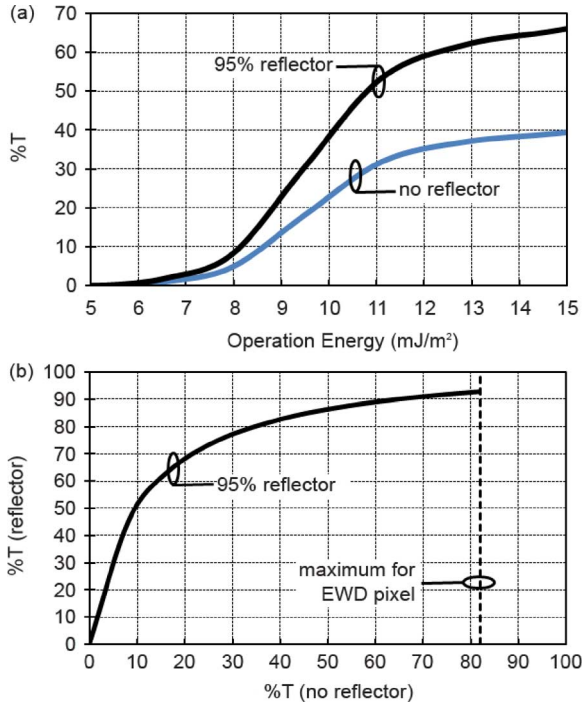


Fig. 2. (a) Pixel transmission versus. pixel energy with reflector area equal to 47% (black line). (b) Theoretical transmission plots for several pixel apertures as calculated using theory from [6] with the reflector area equal to the oil area.

the oil self-aligns over the Al reflector electrode. This movement of the oil comprises two steps: first the water is electromechanically forced to the hydrophobic fluoropolymer surface (similar to spinodal dewetting [10]). Second, a horizontal electromechanical force results from the fringing electric field at the three-phase oil/water/fluoropolymer interface, and this force drives the oil onto the Al reflector. When voltage is removed or reduced the system reverses itself, as driven by surface tension forces. Intermediate locations (grayscale) for the oil can be selected with analog voltage control [1], [2]. With an optimized pixel architecture, the switching speed is currently measured at <8 ms and 30 ms for ON and OFF switching, respectively, to $>90\%$ or $<10\%$ of the maximum transmission.

III. Pixel Results

Pixels were characterized by measuring the transmission through pixels without backlight recycling of light (Fig. 2(a) blue line). The pixel transmission theoretically predicted with backlight recycling was also provided in Fig. 2(a) (black line) and Fig. 2(b). The optics and theory behind use of an integrated reflector (backlight recycling) can be found in our previous work [6]. The effective ON state transmission is plotted vs. the pixel operation energy $((CV)^2/2)$. This is more representative than voltage, because electrowetting is driven by electromechanical force that overcomes surface tension (mN/m, or mJ/m^2) [2]. Therefore a variety of dielectrics and voltages (1s to 10s of V) can be used to provide the pixel response shown in Fig. 2(a), with the pixel energy being the same. Most typically, 15–20 V is required for electrowetting pixels [3]. The raw transmission is 40% at 15 mJ/m^2, which includes 15% Fresnel reflection loss at various film interfaces. The maximum transmissive area is therefore $>50\%$ for this work. Also shown is Fig. 2(a) is the potential transmission with a 95% average of an integrated-reflector and backlight reflectance ($\sim$90% Al reflector, $\sim$99% backlight reflectance using 3M ESR film or similar reflector). This will boost the transmission by 66%. It is important to note, that when a reflective backlight is used (not this work), the actual transmission value will be higher because a portion of the 15% Fresnel reflected loss will also be recycled.

The light recycling can become even more powerful with use of high efficiency (multilayer) reflectors, or by increasing the open aperture for transmission. Electrowetting pixels can typically achieve a maximum of $\sim$80% open aperture. As shown in Fig. 2(b), excluding Fresnel losses this could lead to a very high effective pixel transmission of $>90\%$ with 95% reflectors. This backlight recycling is similar to that used by Pixtronix in MEMs based transmissive pixels [11], but it can be speculated that electrowetting pixels are simpler to fabricate [3].

The pixel ON/OFF transmission (contrast ratio) was measured across the visible spectrum. As shown in Fig. 3, a $\sim$ 1000:1 contrast ratio was achieved. This contrast ratio is measured at the 0 mJ/m^2 and 15 mJ/m^2 pixel energies (40% transmission). With backlight recycling and the integrated reflector, the contrast ratio would be even higher. Also provided in Fig. 3 are colored dashed lines with the intensities of LEDs of different wavelengths; useful because of the growing importance of LED backlights. The acheived contrast ratio is fully suitable for nearly all display applications. It is apparent that if a thicker grid layer was used, the black oil would be thicker, and even

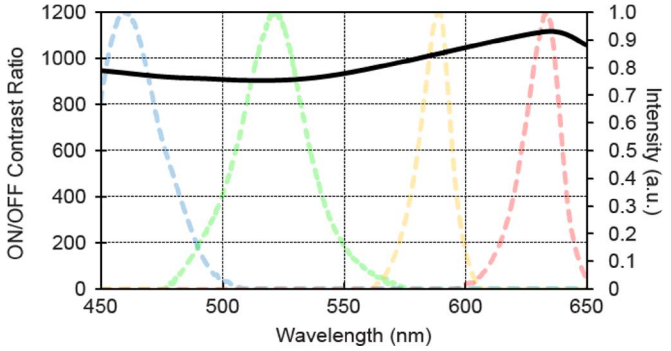


Fig. 3. Experimentally measured contrast ratio versus wavelength (15 μm thick oil). For reference, intensity spectrums of different wavelength LEDs are shown.

higher contrast ratios could be achieved. However, given tradeoffs in voltage, switching speed, and maximum transmission, thinner oil layers are desirable. 15 μm thick black oil may not be required with improved dye formulations, and it is suspected that further improved dyes may already be in use by companies such as LiquaVista. As we have shown previously, thinner oil layers would also allow scaling of the pixels to higher resolution [8]. Even if the pixel electrode must remain large, the pixel electrode can simultaneously operate multiple smaller sub-pixels covering the pixel electrode. Smaller sub-pixels easily satisfy video speed requirements ($\sim$10 ms) [3]. The pixel dimensions reported herein are satisfactory for television resolution, but not for laptop or cell-phone use. Using materials similar to that used herein, we have previously demonstrated in 2007, high resolution pixels ($<$100 μm) operating at 15 V with a conventional active matrix TFT backplane.

IV. Additional Benefits of the Integrated Reflector

The integrated reflector boosts pixel transmission through light recycling (see previous Section III) but also has several other significant benefits. Firstly, as mentioned in Section II, motion of the oil is automatically aligned to the integrated reflector because the reflector is has the same voltage applied to the electrowetting water. Secondly, the integrated reflector can boost switching speed by optically masking the slowest portion of the oil motion. Electrowetting pixels operate somewhat like compressing and decompressing of a spring (analogous to surface tension). When the pixel switching is close to equilibrium, the electromechanical and surface-tension forces are nearly in balance, and the force completing the oil movement becomes vanishingly weak (slow). Therefore, implementing an integrated reflector that masks the oil motion at the extremes of oil motion (flat film, spherical cap) will substantially increase switching speed. Pixels currently measure at switching speeds of 30 ms, which can certainly be further optimized and improved to $<$20 ms, especially as pixel size is reduced.

The last benefit provided by the integrated reflector is for active-matrix addressing using arrayed thin-film-transistors (TFTs). During active matrix addressing TFTs are only activated for a time period of $1/(\text{rows} \times \text{frame rate})$ seconds. If the TFT activation time is only microseconds, and the oil uncovers the high capacitance pixel structure in milliseconds, then the TFT will not be able to fully charge the pixel to its desired optical state. The integrated Al reflector allows a storage capacitance for the pixel, which can be fully charged by the TFT (is not dependent on the time for oil to uncover the pixel surface). Referring back to Fig. 2(a), a pixel transmission of $>$65% can be achieved for 50% oil uncovering of the pixel (95% reflector). In this example, the pixel and storage capacitance would be equal, allowing improved compatibility with standard active-matrix drive circuitry.

V. Summary

In summary, the first 1000:1 contrast ratio transmissive EWD pixels have been demonstrated by making use of improved black oil while simultaneously achieving $<$30 ms switching speed, and $<$20 V operation. The transmission and contrast ratio can be even higher with proper integration of a high efficiency backlight and the integrated Al reflector. New black SU-8 materials have also been implemented for the pixel grid layer to ensure high contrast in bright lighting. EWDs are becoming increasingly compelling for transmissive display applications.

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