High reflectivity electrofluidic pixels with zero-power grayscale operation

S. Yang, K. Zhou, E. Kreit, and J. Heikenfeld

Novel Devices Laboratory, School of Electronics and Computing Systems, University of Cincinnati, Cincinnati, Ohio 45221, USA

Gamma Dynamics, Cincinnati, Ohio 45221, USA

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Electrofluidic display pixels are demonstrated with zero-power grayscale operation for 3 months and with >70% reflectance. The color of the pixel is changed as electrowetting moves the pigment dispersion between a top and bottom channel. When voltage is removed, a near zero Laplace pressure and a hysteresis pressure of 0.11 kN/m² stabilizes the position. For 450 μm pixels, an electromechanical pressure of 1.4 kN/m² moves the pigment dispersion at a speed of ~2650 μm/s. The predicted switching speed for ~150 μm pixels is consistent with video rate operation (20 ms). The geometrically sophisticated pixel structure is fabricated with only simple photolithography and wet chemical processing. © 2010 American Institute of Physics. [doi:10.1063/1.3494552]

Electronic paper (e-paper) is now a commercial reality, mainly due to advances in electrophoretic technology. Most e-paper products are currently monochrome with ~40% white state reflectance. Significant work remains provide full color e-paper that is comparable in brightness to conventional printed media. In addition to bright color, it is highly desirable to implement pixels that retain their image even without electrical power (grayscale-stable). Grayscale-stable operation is also beneficial in terms of display longevity: a grayscale-stable display that switches in 30 ms, and is updated once every 60 s, is only operating for a total of 50 h during 100 000 h of continuous use. A relatively newer e-paper technology, electrowetting (EW) displays have now demonstrated video and ~20–30% full color reflectance but require constant electrical power for grayscale operation. A variation in EW displays, termed “droplet-driven” displays has shown bistable and bright monochrome operation but the pixels are very large and only two grayscale states have been shown. Recently, yet another EW variant, the electrofluidic display (EFD), was reported to provide video speed, high pixel resolution, and the potential for bright color due to the use of pigment dispersions similar to those found in inkjet printing. However, like EW displays, constant electrical power is required to hold an image. Reported herein is the first of two methods now in development for creating EFDs that can hold a grayscale image without any electrical power. Also detailed with this report, is a simple fabrication technique for creating geometrically sophisticated fluidic pixels, which may be of broader value to other display and microfluidics researchers.

The grayscale-stable EFD pixel construction is illustrated in Fig. 1(a). A polymer film (Parylene or SU-8) was deposited onto In₂O₃:SnO₂ coated glass to make a bottom EW substrate. SU-8 is particularly useful because it acts as a dielectric and it also promotes adhesion of the next polymer layers. Onto the bottom EW substrate, a DuPont PerMX dry film photosensit (20 μm) was hot-roll laminated (85 °C, 40 psi, 1 fpm), photolithographically exposed, and developed to form a bottom grid of 450×150 μm² cells with 30 μm grid width. Next, a middle PerMX film was then laminated onto the bottom grids and patterned with 130×60 μm² and 130×20 μm² vias at the ends of the pixel cell. Al was vacuum deposited onto the middle PerMX layer, serving as an optical reflector and a ground electrode. The vias through the middle PerMX layer form an overhang, so no patterning of the Al was required to electrically separ-
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rate Al on the middle PerMX and bottom substrate surfaces. A top PerMX layer was then added in a grid geometry similar to the bottom PerMX. However, as shown in the scanning electron microscopy (SEM) photograph of Fig. 2, the top PerMX grid was discontinuous, to allow self-assembled dosing of pigment dispersion and oil liquids. Before liquid dosing, all featured carried by the bottom substrate were conformally dip-coated with Cytonix Fluoropel 1601 V fluropolymer. After fluropolymer coating and self-assembled liquid dosing, the device was sealed with a transparent top EW plate similar to that used in conventional EFDs.

Grayscale-stable EFD pixel operation involves a competition between Laplace pressure, hysterisis, and electromechanical pressure. All surfaces of the completed pixels are uniformly hydrophobic. Therefore, Young’s angle for the pigment dispersion in oil is ~180° and the vertical radius of meniscus curvature in the top (R_T) and bottom channels (R_B) is half of the 20 μm channel height (~h/2, Fig. 3). Because h is much smaller than the channel width, the Laplace pressure with no voltage (∆p_0) can therefore be approximated as ∆p_0 = 2γ_c/h (N/m^2), where γ_c is the interfacial tension N/m between the electrically conducting pigment dispersion and the electrically insulating oil. The top and bottom channel heights are nearly identical, and therefore the Laplace pressure for the pigment dispersion does not change with fluid position. Also, contact angle hysteresis induces a threshold pressure that along with neutral Laplace pressure, stabilizes the positions of the fluids [Fig. 3(a)].

To move the pigment dispersion, a voltage is applied to either the top or the bottom EW substrates. As illustrated in Fig. 3, EW (Ref. 5) causes the contact angle to reduce from Young’s angle θ_y to the electrowetted contact angle θ_e according to the EW equation: \[ \cos θ_y = (\gamma_d - \gamma_c)/\gamma_i + CV^2/2γ_i, \]
where C is the capacitance per unit area of the EW dielectric, γ is the interfacial tension between the conducting pigment dispersion (c), insulating oil (i) and the dielectric (d), and V is the applied dc or ac rms voltage. The contact angle reduction results in an increase in R_T or R_B according to \[ R = −h/(\cos θ_y + \cos θ_e). \]
Therefore, the pressure with voltage acting on the pigment dispersion in the top or bottom channel can be simplified to
\[ \Delta p_v = (2γ_c - CV^2)/h. \] (1)

Now, as illustrated in Figs. 3(b) and 3(c), an imbalanced pressure between the top and bottom channel can cause the pigment dispersion to move to the channel with lower pressure (greater V, larger R). Applying equivalent voltages on both substrates, or removing all voltages, would stabilize the pigment dispersion (stop movement), as illustrated in Figs. 3(d) and 3(a), respectively. Demonstration of stable positioning of the pigment dispersion in several grayscale positions is shown in the photographs of Fig. 1(b).

Equation (1) is a static model only. During movement of the pigment dispersion, there are two additional pressures that must be considered. First, there is the well-known effect of contact angle hysteresis. As shown in Fig. 4, a threshold pressure of ~0.11 kN/m^2 is required to begin to move the pigment dispersion. To achieve this threshold pressure, voltages for tested dielectrics include ~25 V for ~5 μm SU-8 (ε_r = 3.2), ~8.4 V for 300 nm of Parylene HT (Ref. 8) (ε_r = 2.2), and ~3.3 V for 150 nm of Si3N4 (ε_r = 7). If this threshold is dominated by contact angle hysteresis, then there is ~7° of hysteresis due to dielectric roughness, dielectric charge injection, and/or other pixel imperfections. This hysteresis pressure reduces the driving pressure, and slows device switching speed. However, some level of hysteresis pressure is absolutely essential for stable positioning of the pigment dispersion, because the top and bottom channel heights can never be perfectly equal.

During movement of the pigment dispersion, in addition to hysteresis pressure there is another pressure that slows the pixel operating speed. There is a dissipative force per unit length f_d (Newton per meter), which mainly consists of fluid drag and channel wall shear. This dissipative force results in a dissipative pressure calculated by \[ f_d = 0.5πR_f hw, \] where w is the channel width, h is the channel height, and R_f is the drag coefficient. To sum up all three effects, the electrostatic pressure, ∆p_v, hysteresis pressure, ∆p_h, and dissipative pressure, ∆p_d, are calculated as
\[ \Delta p_{total} = \Delta p_v + \Delta p_h + \Delta p_d. \]

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Liquid crystal-based bistable reflective displays are currently being pursued as an alternative to the e-paper technology. These displays are expected to offer contrast enhancing improvements, the theoretical white state reflectance can be very high. Assuming viscosities and interfacial surface tensions are unoptimized for the devices reported herein. Therefore device scaling and optimized materials should easily satisfy video speed requirements. Also reported herein. Therefore device scaling and optimized materials should easily satisfy video speed requirements.

The bistable EFD pixels exhibit a bright reflectance. Unlike a conventional EFD device, the pigment dispersion can be hidden in the bottom channel, and the optical loss associated with a fully visible reservoir is reduced. Plotted in Fig. 5 are the maximum and minimum reflections with use of a red pigment dispersion. The measured white state reflectance is as high as 75% in the visible light region. This is comparable to the reflectance of conventional white paper. Currently, the dark state reflectance is ~25%, resulting in a limited contrast ratio. The contrast ratio can be substantially improved by implementation of antireflection coatings on the front glass, with use of index-matched In2O3:SnO2, by using a black colored material in place of the top PerMX layer, or by patterning the Al reflector such that it does not create reflective area in the interpixel space. Even with these contrast enhancing improvements, the theoretical white state reflectance can be very high. Assuming viscosities and interfacial surface tensions are unoptimized for the devices reported herein. Therefore device scaling and optimized materials should easily satisfy video speed requirements.

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