# 10.2: Electrofluidic Displays: Multi-stability and Display Technology Progress

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## Abstract

*Electrofluidic displays have been demonstrated with multi-stable states that enable on, off, or grey-scaled pixel states with zero holding power. We demonstrate operating principles and characterize optical, electrical and environmental performance. We also report other electrofluidic developments including device operation from -30°C to 70°C and 30 millisecond switching speeds at 25°C.*

## 1. Introduction

Through much of the last decade, transmissive liquid crystal displays replaced reflective and transflective display technology in the portable electronics market. In the last several years, however, electronic books enabled by electrophoretic display technology have created an entirely new market segment for reflective displays. Reflective displays have rebounded.

Reflective displays utilize ambient light to illuminate the screen, thereby providing superior energy efficiency, sunlight readability, and reading comfort. The key performance attributes for reflective displays are brightness, contrast (especially under high ambient illumination), and color. Of these, the brightness and contrast are determined by the diffuse reflectivity of the display white and black states. Electrophoretic technology has demonstrated market- accepted levels of diffuse reflectivity ($R_{white}$~ 40%, $R_{black}$ ~ 4%), but these values fall short of the performance of conventional newspapers ($R_{white}$ ~ 60%, $R_{black}$~6%, Contrast~ 10:1), as dictated by the Specifications for Newsprint Advertising Production (SNAP). In fact, the black and white performance of a majority of reflective technologies vying for a niche in reflective displays falls short of conventional newspapers in white performance.[1] The back and white requirements for magazine printing are even more stringent ($R_{white}$~ 76%, $R_{black}$~ 2.7%).

More importantly, the future uptake of reflective technologies will be determined by their color performance. Printed media has the advantage of stacking pigments to produce an entire area full of a single color. For example, a newspaper stacks magenta and yellow pigments to produce a red shade over the entire area. To date, stacked color layers have not been adapted to high resolution electronic paper due to challenges of cost, parallax and optical loss (although electrokinetic, electrowetting, electrofluidic and cholesteric technologies might be suitable for large pixels). As a result, the RGBW color filter method has been employed. The reflection of a color like red is then reduced to 25% of the visible area, which when coupled with the 40% reflectivity of example ePaper technology, results in a red color with only ~15-20% of what is achievable with conventional printed media. Moreover, the 4% off-state reflectivity of the other 3 subpixels tends to wash out the color saturation further. In short, color ePaper performance currently falls substantially below printed media.

To address the white reflectivity, contrast, and color in existing reflective technologies, we developed electrofluidic display technology. Electrofluidic pixels, due to their high intrinsic reflectivity of 60-70%, offer a much higher starting point for the white state and color reflectivity performance. In addition, the black state provided by pigments provides for better color saturation with an RGBW color filter format.

The University of Cincinnati co-authors have reported several new electrofluidic concepts over the past two years.[2,3] Gamma Dynamics, in partnership with the University of Cincinnati, has reported breakthroughs and milestones specific to commercializing these concepts as displays.[4] Here we report on a new pixel structure with multi-stable states, enabling zero power displays with grayscale capability. We describe the operating principles of the display, and demonstrate progress in key areas needed for realizing products, including scaling the pixel size to that of eBook Readers, improving the pixel fill factor, and characterizing display properties such as bistability. Using the previously-described electrofluidic 'spring' pixel structure,[4] we also report on prototype displays, and then the use of these displays to demonstrate the operating temperature range for the modules and fluids, and the response time of the pixels.

## 2. Methods and Results

### 2.1. Multi-stable Pixels

We have developed a new electrofluidic pixel structure that is 'bistable' and multi-stable, thereby allowing a grayscale image to be retained with zero power. We designed and fabricated a first generation structure to demonstrate the device operating principles, as first described in Applied Physics Letters.[3] We have since created display modules incorporating next generation structures with improved pixel density (to 100 μm x 300 μm), fill factor, white reflectivity, contrast, and overall optical performance.

The device structure, shown in figure 1a, comprises two channels. The viewer-side channel is bounded by the top plate glass, index-matched ITO, and hydrophobic dielectric on the top, and a platform of thick-film epoxy-based resist on the bottom, with an overlying metal layer. This metal layer makes direct electrical connection to the polar fluid. The viewer-side channel is connected to the back-side channel by pores that allow the polar and non-polar fluids to travel between channels. The back-side channel is bounded by the bottom plate glass, electrical conductor, and hydrophobic dielectric on one side, and the thick film resist on the other side. Note that the entire device fabrication sequence is performed at low temperatures compatible with PEN and PET flexible substrates.

Application of an electric field between the top plate and the center electrode draws the polar fluid to the viewer channel. Application of an electric field between the bottom plate and the center electrode draws the polar fluid to the bottom channel. The two channels have nearly the same geometries, so the there is neutral Laplace pressure when the voltage is removed. That, combined with contact angle hysteresis, stabilizes the position of the fluids in the absence of applied voltage. Additionally, driving the devices at intermediate voltage levels creates stable grayscale states (% black area), as shown in Figure 1b.

The prototype device shown in Figure 1c demonstrates the cells in operation switching a black-pigmented polar fluid between the viewer-side and the back-side channels. In the device, the pixel walls are transparent, but recent designs include black walls that greatly enhance dark-state contrast. Newer device structures also increase the white-state reflectivity.

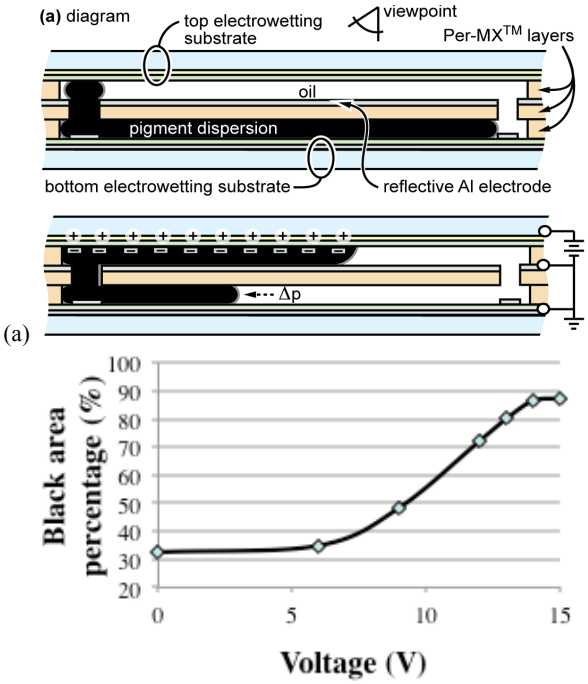



**Fig. 1. Innovative multilayer pixel structure fabricated using only simple photolithography (a), a multi-stable grayscale level vs. voltage curve (b), and black fluid pixels in operation, fabricated in a 100 µm x 300 µm pixel size (c).**

To demonstrate bistability, the device was photographed over time. The device was switched once per day to the opposite state, and photographed again. Data for 11 days of switching is shown in figure 2. The pixels are clearly both bistable and switchable.

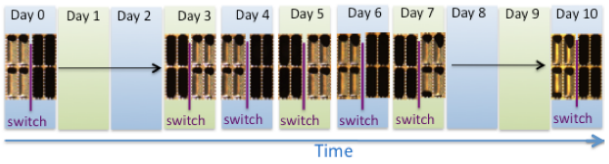



**Fig. 2. Repetitive switching between bi-stable states. The pixels were switched and held until the next business day, with starting and ending state pictures captured above.**

## 2.2. Electrofluidic "Spring" Pixel

The electrofluidic 'Spring' pixel structure, shown in Figure 3, was previously reported in the SID '10 Proceedings. Since this publication, we have fabricated complete display modules with these pixels (Fig 4a). We have also implemented an improved optical stack, including index-matched ITO and improved diffuser technology resulting in improved white state reflectivity and contrast. The black fluid, contained in a 4 µm channel, is optically dense. A spectra of the fluid alone in a 4 µm thick channel, bounded by a glass top-plate with index-matched ITO on the inside, and a 94% reflective back-side, is optically dense enough to capture > 99% of the incident light, excluding the 3 to 4 % reflected at the top surface glass-to-air interface (Fig. 4b).

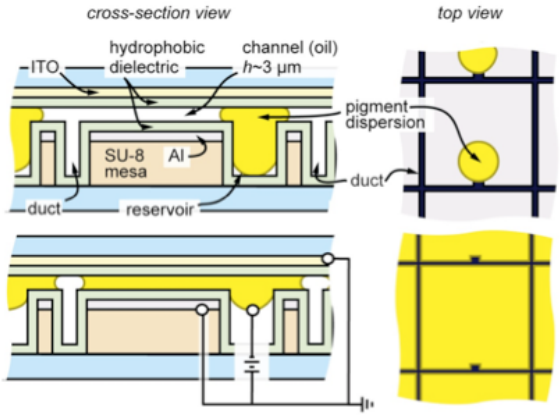



**Figure 3. Cross-sectional and top-down views of an electrofluidic 'spring' pixel. With no voltage applied, the pigmented fluid (yellow) resides in a reservoir (top schematics). With applied voltage, the fluid moves into the channel, expressing the color of the pigment on the surface (bottom schematics).**

The 'electrofluidic spring' pixels are designed for fast switching speeds. The fluid must move laterally across the pixel, but unlike lateral electrophoretic technology, where particles must move through a liquid, for electrofluidic displays, the entire fluid body moves as one unit, making it much faster. The time to switch a pixel from 'off' to 'on' is determined primarily by the distance the fluid travels, the viscosity of the fluid, and the surface energy parameters of the fluid. To date, we have demonstrated a 19 to 24

millisecond response times (as defined in the VESA Flat Panel Display Measurement and Metrology Standard) in 150 µm x 150 µm pixels at room temperature using black-pigment dispersions (Figure 5). This response time is certainly adequate for animation, web-browsing, and lower frame rate video. We expect continued improvements as we further optimize the fluids.

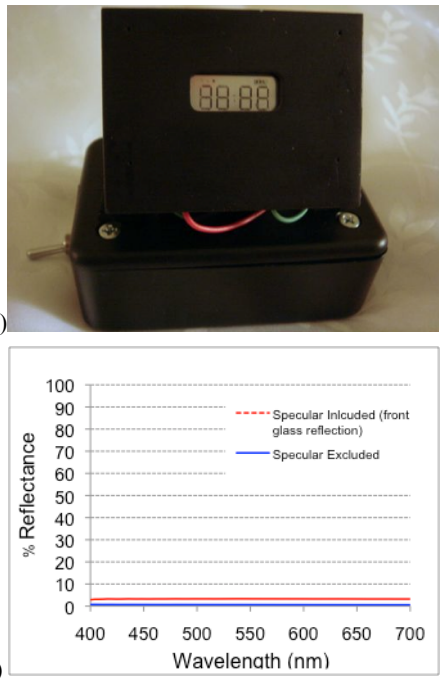



**Fig. 4. A watch-sized demonstrator display module using the 'electrofluidic spring' pixel structure (a), and the optical density of the black fluid (b).**

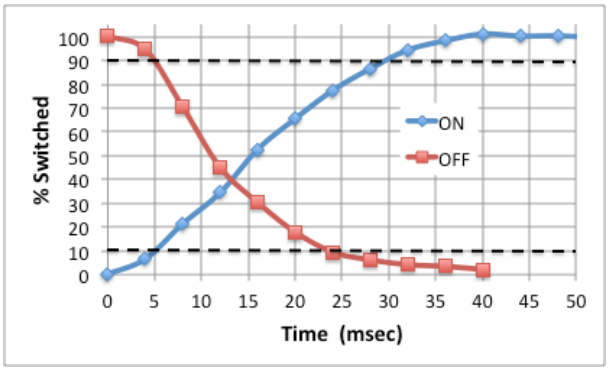



**Figure 5. The response time curves of a 150 mm x 150 micrometer electrofluidic pixel with black pigmented fluid having an optical density as shown in figure 4b.**

## 2.3. Environmental Performance

Electrofluidic displays must meet established environmental requirements for products such as storage temperature and operating temperature. Pigment dispersion stability in our polar fluid is the key for obtaining a wide environmental range. First, we tested the fluid during 25 days of simulated solar exposure and found no deleterious effects on either electrical behavior or coloration. Next, we fabricated sealed 'electrofluidic spring' display modules with the black pigment dispersion and oil system used in the multi-stable devices in Figures 1,2,and 4. As can be seen in figure 6, the device operates from -30°C to 70°C.

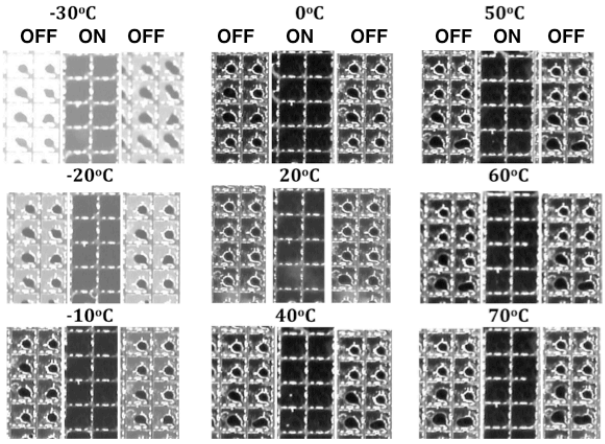



**Figure 6. Operation of display pixels over a temperature range of -30°C to 70°C. (The reduced contrast at -20°C and below is due to condensation on the camera lens.)**

## 3. Conclusions

We have demonstrated electrofluidic display pixels that are multi-stable, holding their states for as long as we have tested. The states are held in place by Laplace pressure, and are not disturbed by shaking or mechanical vibration. We have also demonstrated display modules with pixel fluids operating over temperature extremes required for commercializing products and with response times required for numerous video-rate applications.

## 4. Acknowledgements

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## 5. References

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