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Invited

Prospects for Emerging e-Paper Technologies, and a New Breakthrough in Electrofluidic Displays

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Abstract

e-Paper is now established, growing in volume despite increased competition from LCDs. The application space for e-Paper is larger than what it can currently satisfy. This presentation reviews leading technologies for satisfying monochrome, color signage, and color-video e-Paper. In addition, a recent breakthrough in electrofluidic displays will be introduced and compared to existing e-Paper.

1. Introduction

This past February, I and three industry experts published *'A Critical Review of the Present and Future Prospects for Electronic Paper'* [1] which has provided significant guidance for how we pursue development of new technologies for e-Paper. In particular it is apparent that while e-Paper is growing in commercial success, e-Paper does not yet fully satisfy the performance desired for existing and emerging applications. This presentation reviews and predicts on leading technologies for satisfying the highest performance for monochrome-video, color signage, and color-video e-Paper. In addition, a recent (and previously unpublished) breakthrough in electrofluidic displays will be introduced and compared to the existing competition in e-Paper.

This paper consists of three major sections:

(1) a review of key applications and the competition;
(2) a brief review of electrofluidic displays;
(3) introduction of a new breakthrough in electrofluidic displays, and discussion related to potential applications.

2. e-Paper for Monochrome Applications

Although development of color e-Paper tends to capture significant attention, monochrome e-Paper may continue to be the most important implementation of e-Paper. This can be argued based on two reasons. First, in full-color applications, LCD and OLED technologies will continue to dominate because they can provide brightness and color saturation even beyond high-quality printed-media, like magazines. Second, and more importantly, color printing has been around for a long time, yet monochrome print is everywhere (signage, text, etc.). Clearly, the opportunity space for improved monochrome e-Paper should not be overlooked. As shown in Tbl 1, monochrome SNAP [1] (newsprint) requires 60% white reflectivity. No commercial e-Paper technology is capable of providing this reflectance, let alone, the much higher standard of SNAP (magazine quality) at 76% white reflection. This presents a significant opportunity that could be captured by a new technology with brightness superior to the ~40% reflectance of E Ink [2]. Several technologies have the potential to commercially satisfy monochrome SNAP requirements, including in-plane electrophoretic [3], electrokinetic [4], electrofluidic [5], and electrochromic [6]. Of all of these, if monochrome video is required, electrofluidic may be the only available option. If SWOP level white reflectance is required, the only viable approaches appear to be in-plane electrophoretic, electrochromic, and possibly a new electrofluidic architecture (see last section).

3. e-Paper for Color Signage

Color e-Paper signage, including formats such as billboards are now being commercially implemented using technologies such as cholesteric liquid crystal. Advertising is a particularly important application, and at least SNAP level color performance is required. Of all technologies, only stacked 3 layer technologies based on CMY filtering (Fig. 1b) are close to the desired performance. This includes unpublished 3 layer

Table. 1 – SNAP (Specifications for Newsprint Advertising Production) and SWOP (Specifications for Web Offset Publications), adapted from [1].

	White		Black (CMY)		Cyan		Magenta		Yellow	
	L*	%R	L*	%R	L*	%R	L*	%R	L*	%R
SNAP	82	60	30	6	57	25	54	22	78	53
SWOP	90	76	19	3	57	25	48	17	85	67

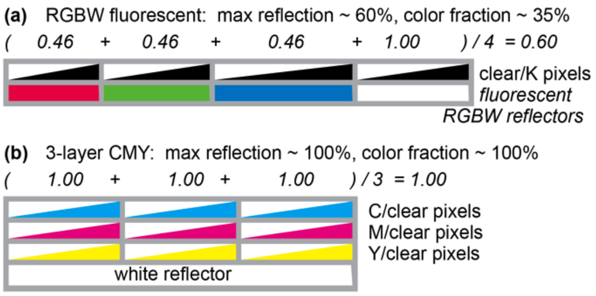

Fig. 1 – Two example color spaces, adapted from [1]. The latter (b), stacked CMY, is currently the leading approach for full color signage. The former (a) may be of increasing performance for single-layer displays.

electrokinetic [7] and Ricoh's new 3 layer electrochromic [8]. Technologies such as in-plane electrophoretic, electrowetting, and electrofluidic, in theory can perform colorant transposition with high enough compaction of the colorant to allow SNAP level color reflectance. However, no such performance has been demonstrated.

4. Color Video

Video rate operation is historically challenging for e-Paper devices. Before talking about color-video, just looking for video capable e-Paper reduces the current competition to electrowetting [9], MEMs [10], and electrofluidic [5], and possibly more traditional types of liquid crystal. It is a fair assumption that high-resolution color-video will be a single-layer technology, and maybe in the future two-layer aligned and stacked for electrowetting or electrofluidic. MEMs currently is fundamentally limited in increasing its white state reflectance because MEMS pixels only generate a single color (like R, G, or B). Electrowetting and electrofluidic, in single-layer format, would at best use a color system like that shown in Fig. 1a, and initially would use a simpler traditional RGBW approach similar that used in color E Ink displays (electrophoretic). For color-video, the competition is currently similar, and the next critical advances could be in making fast, but very high reflectance white/black modulating pixel. Another critical advance might be to provide a technology that can simply be laminated onto an active matrix back-plane, similar to that achieved with E Ink's electrophoretic imaging films.

5. Electrofluidic Displays

Similar to electrowetting, electrofluidic displays are based on the movement of colored fluids [9]. The technology was first reported by the University of Cincinnati in 2009 and is now commercially pursued by Gamma Dynamics. Two basic types of electrofluidic pixels, ranging from ~20-70 µm thick, are shown Fig. 2a and 2b. Both constructions use two electrowetting plates, but use the nomenclature 'electrofluidic' because there is a net liquid flow through microfluidic cavities. In the most advanced devices, the reflective electrode is diffuse (white state) and the pigment dispersion is black. In Fig. 2a, voltage pulls a pigment dispersion into a viewable channel in ~20-40 ms, displacing an oil (black state) [5]. Like electrowetting, moving colorant with the fluid is ~100X faster than moving colorant through the fluid (electrophoretic). When the voltage is removed, surface tension drives the fluid back into an optically masked reservoir (white state). Grayscale can be set using one or more techniques, some analog, some digital in nature. The more recently [10] demonstrated device of Fig. 2b achieves bistable operation by using a viewable channel and hidden reservoir that are equal in geometry, thereby balancing the forces associated with surface tension. This is the first electrowetting or electrofluidic device capable of creating indefinitely stable grayscale states with no holding voltage. While 12 V operation has been demonstrated for active matrix addressing, the bistable approach does open the door to passive-matrix addressing.

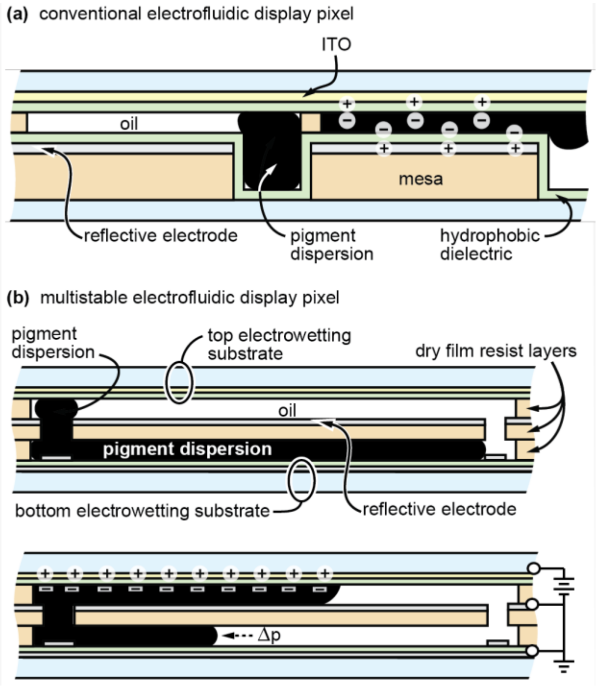

Fig. 2 – Example electrofluidic architectures that have been previously demonstrated [5, 10].

Electrofluidic devices require fabrication toolsets similar to electrowetting displays, with the added cost of one more electrowetting dielectric and thick-film photoresist instead of a thin film. Flexible modules have been fabricated and demonstrated. The bistable module has a complex 3D structure, but the structure is

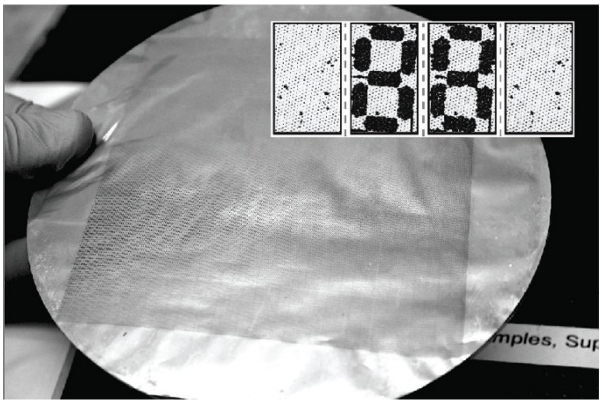

Fig. 3 – Photographs of new electrofluidic film and inset of segmented electrode demonstration at 25 PPI.

formed using simple PCB-style dry-film photoresist (Per-MX) process co-developed with DuPont. Although prototype environmental specs are not available, the oil and pigment dispersion fluids exhibit a 24 hour storage range of -28 °C to +80°C. The same fluids show an operating range of -20 °C to +50°.

6. A New Breakthrough in Electrofluidic Displays

Here we introduce a new breakthrough in electrofluidic displays. This new approach realizes several major advances compared to conventional electrofluidic and electrowetting displays:

(1) conventional electrofluidic and electrowetting displays require monolithic and aligned fabrication of the pixel structures onto the driving substrate - *this new breakthrough allows fabrication using a non-aligned laminated film similar to e-Ink, which is desired by many manufacturers.*

(2) conventional electrofluidic and electrowetting displays require pixel borders, which causes optical loss especially when scaling pixels to high resolution – *this new breakthrough has no pixel borders and can display a colored pigment dispersion across several pixels, or a fraction of one pixel.*

In addition, this new breakthrough in electrofluidic displays is bistable, and fast in switching (25 PPI pixels already switch at <60 ms). Fig. 3 shows a photo of one of the example 25 PPI films and the inset shows a segmented electrode sequential demonstration in the white / colored with voltage / colored with no-voltage / and white states of switching. Table 2 details the switching performance vs. pixel resolution. The demonstrated diffuse white reflectance is already very high and is close to 70% (Fig. 4). The film contains a highly engineered microfluidic structure for moving a pigment dispersion similar to Fig. 2, but is able to merge and split pigment dispersions between pixels as well (no pixel borders). Development of the film has required advanced understanding of fluid mechanics, which once understood, allow the fabrication of the film to be simple and low cost. This new breakthrough in electrofluidic displays might provide both a lower cost and a higher performance (white state, speed) alternative to E Ink technology.

Tbl. 2 - Scaled Parameters of the New Electrofluidic Imaging Film (* demonstrated, rest are calculations).

Pixel Density (PPI)	25*	100	1000
Fluid Reserves Pitch (μm)	508	127	12.7
Channel Height (μm)	50.8	12.7	1.27
Switching Speed (ms)	30	7.5	very fast
Film Thickness (μm)	15	10	5

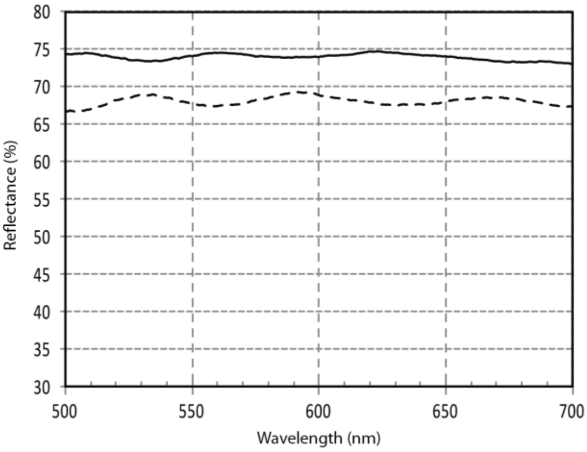

Fig. 4 – Measured reflectance for the new type of non-aligned and film-based electrofluidic display. The dotted line is the specular excluded reflection. This device is non-optimized and significantly higher reflectance values are expected.

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