Review Paper: A critical review of the present and future prospects for electronic paper

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Abstract — The commercial success of monochrome electronic paper (e-Paper) is now propelling the development of next-generation flexible, video, and color e-Paper products. Unlike the early battles in the 1980s and 1990s between transmissive and emissive display technologies, there is a extraordinary diversity of technologies vying to become the next generation of e-Paper. A critical review of all major e-Paper technologies, including a technical breakdown of the performance limitations based on device physics and commentary on possible future breakthroughs, is presented. In addition, the visual requirements for color e-Paper are provided and compared to standards used in conventional print. It is concluded that researchers have much work remaining in order to bridge the significant gap between reflective electronic displays and print-on-paper.

Keywords — *Displays, reflection, optical materials, flexible structures.*
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1 Introduction

Electronic displays have reached a remarkable state of maturity. The image quality and panel size for transmissive LCDs and emissive plasma displays are exceptional, and the resolution of displays in some mobile devices is at the limits of human perception. However, basic and applied display research is still very active, especially in pursuit of reflective electronic-paper (e-Paper) displays.[1–4] e-Paper technologies have now demonstrated near-zero-power operation, flexible or rollable form factor,[5] superior optical contrast in direct sunlight, and even panel integration with a photovoltaic power source.[6] For portable reading applications, many prefer e-Paper devices because of reduced eyestrain.[7,8] e-Paper devices typically require only a very small battery, enabling new ergonomic designs as seen in many electronic-reader products incorporating electrophoretic display technology. Other applications, such as electronic shelf-labels, benefit from low-power operation that permits 5 years of continuous operation without refreshing the batteries.

Despite these major advances, a commercial e-Paper technology with high-resolution color and gray scale comparable to printed media is still lacking. Furthermore, some of the most promising color e-Paper technologies are unable to provide the speed required for advanced touch interfaces or video media. As a result, e-Paper is far from becoming a ubiquitous replacement for paper or for supplanting LCDs in applications where power consumption and weight are a concern.

There are numerous market-strategy reports and studies that provide a roadmap for the constantly evolving competition space for e-Paper.[9,10] To date, though, there does not exist a technical review that can promote a discussion on what monochrome and color e-Paper can achieve now and how closely these technologies can match print-on-paper in the future. There are many questions to be considered. For example, are designs using two- and three-layer subtractive-color displays really a viable approach from a performance, cost, and manufacturing yield perspective? For monochrome, what is "bright enough" when considering existing newsprint and magazine standards? What is an acceptable color gamut for color e-Paper to gain acceptance?

In this paper, we critically review the present and future prospects for e-Paper. First, some aspects of the physics and common optical losses for e-Paper are presented. Next, visual requirements for color e-Paper are assessed and compared to standards used in reflective displays and conventional print. Then each e-Paper technology will be analyzed in terms of device physics and maximum optical performance. After analyzing the existing technologies, we will discuss the fundamental optics and device physics required for uncompromised e-Paper performance. Lastly, the review findings will be summarized and major technical conclusions provided.

Although this review may be used as a basic introduction or overview of e-Paper, our intent is to go far beyond a cursory summary of present technology. We aim to use an understanding of device physics to make a critical prediction on the future performance possible for each major e-Paper technology. We touch briefly on applications, market trends, and other business/industry-related issues, though these factors can be critical in determining whether a particular technology will be adopted. It will be seen that no single technology yet possesses all the features required to make

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e-Paper ubiquitous. However, several technologies have the potential to achieve low power and bright full-color e-Paper. It is our intent that this article will help direct academia and industry toward the next set of research and development initiatives for e-Paper.

2 The optics of e-Paper

2.1 Fundamental optical challenges for all e-Paper

A clear definition of e-Paper remains elusive. The most important attributes that differentiate e-Paper displays from conventional electronic displays often depends on the application. One unequivocal definition of e-Paper is that it is a reflective-display technology, requiring no internal light source. Other common properties include an appearance that is insensitive to lighting conditions and to viewing angle, lightweight, and low power.

The reflective pixels used in e-Paper present a set of optics challenges in many ways different from transmissive- or emissive-display technologies. In emissive or transmissive displays, optical inefficiency is often overcome by simply increasing the electrical power for light generation. In e-Paper, inefficient pixel optics leads directly to reduced image quality. The maximum reflective performance for a monochrome e-Paper pixel can be understood in terms of the optics of a reflective electronic pixel:

1. Light must be effectively coupled into the pixel. As shown in Fig. 1, Fresnel reflection[11] occurs off each abrupt change in refractive index (air/substrate/electrode/*etc.*). These reflections are optical losses because they are unlikely to line up with the viewer and, more importantly, they are not switchable (they do not contribute to the display image). In_2O_3:SnO_2 (ITO) has a high refractive index of $n \sim 1.8$–2.0, so both the ITO/glass and glass/air interfaces are quite reflective. A front conductive substrate can increase the reflectivity of the dark state of the display by as much as ~10%, seriously degrading the display contrast. When index matched by use of a multilayer coating, the optical loss due to ITO can be reduced to <0.5% with multilayer coatings, such as those provided by TFD, Inc.[12]

Thin-film anti-reflection layers or low-index coatings can also reduce the reflectivity at the glass/air interface to 1% or less. Recently, anti-reflective surfaces based on a "moth-eye"-type graded index have demonstrated high-performance, broadband, omni-directional anti-reflective properties[13,14] and are finding commercial applications.[15] ITO alternatives are also emerging, including nanotube[16] and nanowire[17,18] films, and Kent Displays' use of conducting polymer films that allow >97% transmission with designs that tolerate resistivities as high as 1 kΩ/□.[19]

When coupling light into the pixels, fewer layers and closely matched refractive indices are critical. Also, diffusing top layers typically reduce the amount of light coupled into the pixel through backscattering effects and by redirecting light away from the rear surface of the pixel.

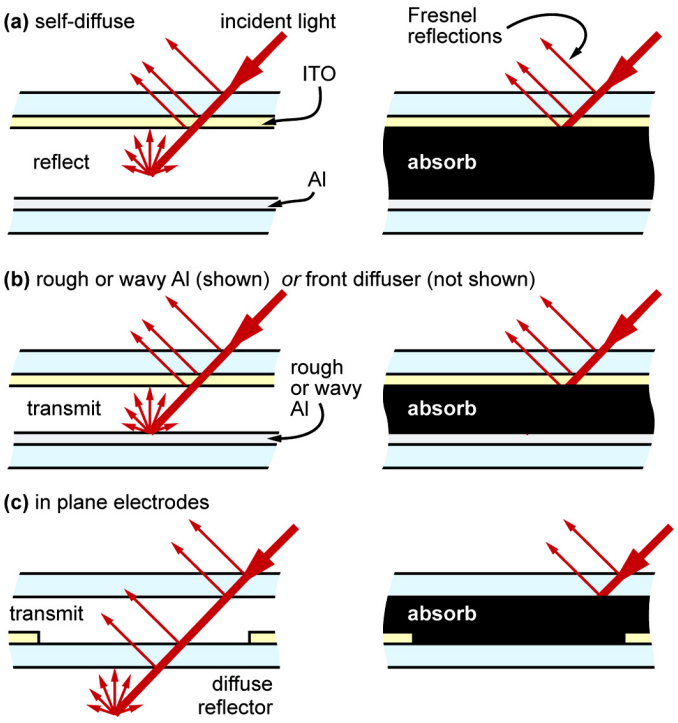


FIGURE 1 — Example reflective display pixels architectures, including techniques for creating diffuse reflection. Note, not all e-Paper technologies are represented in this figure.

2. Light must be efficiently reflected inside the pixel. A mechanism for efficient reflection is needed, and further discussion is saved for the in-depth technical reviews of e-Paper technologies. Generally, the reflection from e-Paper must be at least semi-diffuse in order to provide a paper-like experience, and it is most efficient in a reflective display to have the viewing cone broadened inside the pixel. Surface reflection can be specular, with very smooth surfaces (reflection angle being equal to the incident angle). Alternatively, the reflection can be diffuse, with rough surfaces or scattering particles (reflection with broad distribution of angles). Some surfaces exhibit a combination of specular and diffuse reflectance. A special case of diffuse reflection is a Lambertian surface with equal brightness from all viewing angles. Paper is primarily a diffuse (or Lambertian) reflector,[11] allowing use of any illumination angle. Several example mechanisms for diffusing light are shown in Fig. 1.

3. The diffusely reflected light must be outcoupled. Once the incident light is diffused, it must also be outcoupled. Some light does not escape due to total internal reflection and must be diffusely reflected again, inducing further optical loss. For example, assuming a pixel that is internally 90% reflective and of refractive index of $n \sim 1.6$, >10% of the light will be lost to inefficient outcoupling.[20] This loss is further compounded if the materials in the pixel stack exhibit even small optical absorption. An anti-reflection layer can enhance outcoupling, as can diffusing layers, although a front layer diffuser degrades the light entering the pixel, as noted earlier.

One approach to improve the apparent reflectivity of a display is to use a gain reflector as the pixel reflector. For

light entering the cell at a certain angle, the reflected light is broadened into a cone around that angle, broadening the viewing angle of the display. The ratio of specular to diffuse reflection, and the reflected distribution of light, can be controlled by the surface roughness. A gain reflector can result in a range of angles where peak brightness is enhanced. Additionally, there is the additional benefit of out-coupling more reflected light by effectively reducing the rays that can be trapped by total internal reflection.

For a gain reflector to be effective, the ambient light must have some directionality (*i.e.,* it cannot be totally diffuse), as diffuse light reflected from a gain reflector is still diffuse. These systems work best in mobile displays where the user can adjust both the illumination and viewing angles, or in situations where both the illumination and viewing angles are well defined. Gain reflection films were used in early reflective liquid-crystal displays[1] and are being adopted in current e-Paper displays depending on the application.

In general, the performance of e-Paper displays often depends on the details of lighting and the viewer. Directional lighting such a lamp or direct sun – or diffuse like a cloudy day – can lead to significant differences in performance of reflective displays. The position of the viewer and the ability to reorient the display for maximum contrast varies based on application. The most desirable performance requirements for handheld devices can be quite different from digital signage, which may lead to a preference of one e-Paper technology over another for different applications.

2.2 Types of optical switching inside an e-Paper pixel

Reflective-display pixels can be formed by various types of electro-optical switching modes. Electro-optic devices suitable for reflective displays can be categorized into four major categories of pixel architecture:

1. Vertical colorant transposition. Colorants or reflector materials are moved or rotated to the surface to control the optical state. Examples include Figs. 1(a), 4, 7, and 15.

2. Horizontal colorant transposition. Colorants are moved in or out of the light path. Examples include Figs. 1(c), 5, 6, 9, and 10. The colorant can be moved through an liquid or a colored fluid moved to provide the optical change.

3. Electro-optics. The transmission through a switching layer is modulated by altering optical scattering, interference or polarization. Examples include Figs. 11, 12, 14, and 16.

4. Electrochromic. The colorants undergo a chemical change that alters the light transmission, absorption, and/or reflection. Examples include Figs. 1(a) and 8.

2.3 Techniques for full-color generation

Full-color e-Paper can be generated by modulating light in an additive system with the primaries of red, green, and blue [RGB, Figs. 2(a)–(d)], by using a subtractive system with cyan, magenta, and yellow [CMY Figs. 2(e)–(g)], or a subtractive/additive hybrid system using both RGB and CMY primaries in a cooperative "biprimary" system [Figs. 2(h)–(j)]. The key measures of performance are white-state reflectance (W), the black-state reflectance (K), and the color gamut (which includes availability of gray scale). While the approach of a side-by-side RGB additive system has been applied successfully to transmissive and emissive displays where optical inefficiency is overcome by increased light generation, as shown in Fig. 2(a) the RGB system in e-Paper using fully saturated color filters limits the white-state reflectance to a poor value of 33%. The white-state reflectance can be boosted to a theoretical maximum of 50% by using a RGBW approach [Figs. 2(b) and 4(c)] or by desaturating the color filters. Nevertheless, reflective RGB and RGBW designs suffer from poor color fraction (CF is a new term we introduce; *i.e.,* the effective area at which a saturated color can be displayed). For example, creating a red color with RGBW limits the red color fraction to only 25% of the display area, severely limiting the color gamut and overall luminance.

There are two exceptions to this limit for an RGB additive system. Firstly, the multilayer RGB approach [Fig. 2(d)] such as that used for cholesteric liquid crystal displays (Fig. 12). Of course, stacking display layers generate additional issues of parallax, optical losses, cost, and fabrication difficulty, as will be discussed in the next paragraph. Secondly, there is a photoluminescent enhancement[21] (fluorescent) approach that is currently being developed by HP [Fig. 2(c)]. In this approach, the luminophores within the red subpixel, for example, absorb the incident light from the near-UV to green, and re-emit it as longer-wavelength red light, providing a several-fold increase in the perceived intensity of red light returned to the viewer relative to a purely reflective technology. Luminescent enhancement of blue subpixels is generally ineffective because the amount of near-UV light available to pump the blue color is usually minimal. Figure 2(c) assumes red and green photoluminescent reflectors that are 200% and 150% brighter, respectively, and therefore the blue subpixel area can be made larger. By maintaining white balance, the RGBW area percentages can be calculated as 17, 23, 35, and 25%. The cumulative effect for RGBW is to add 10% to both white reflectance and color fraction.

The subtractive CMY system can, in theory, provide excellent color saturation and brightness and requires pixels that switch between optically clear and one CMY color. Even with only two switching layers the theoretical white state is 66%, and the color fraction for a primary color such as red would be 66% [Fig. 2(e)]. A theoretically perfect white state and perfect color fraction can be achieved by stacking three CMY switching layers [Fig. 2(f)]. While stack-

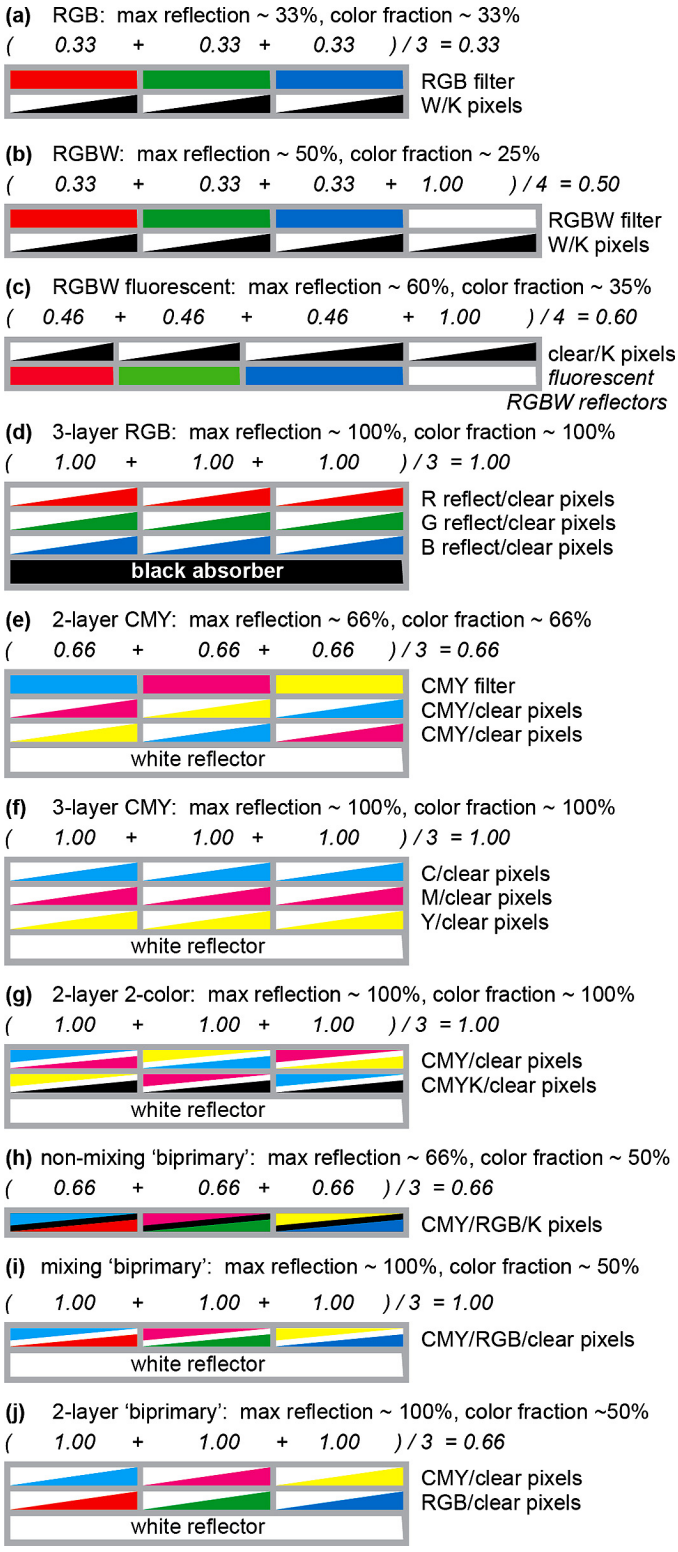


FIGURE 2 — Architectures for full-color e-Paper. Note, the maximum reflection and color fraction are not practically achievable due to optical inefficiencies. Color fraction is a new term we introduce, *i.e.,* the effective fraction of the pixel area that can display a saturated RGB. The color fractions for CMY may be different.

ing layers can dramatically expand the available color gamut for a reflective display, these approaches create additional difficulties that make stacked displays less attractive, and in some applications not even practical. As noted previously, in a two- or three-layer stack of RGB or CMY, the optical losses and contrast-reducing glare (Fig. 1) can become significant. Furthermore, with a stacked display, cost and complexity are increased, requiring additional display materials, backplanes, and drive electronics. Although subpixelation is no longer needed, pixel resolution can be limited to maintain adequate clear aperture. Clear aperture is needed to avoid both the compounding of optical losses and parallax. To avoid fatal parallax issues, the distance between the front and the rear pixel in a multilayered stack should be no larger than the pixel size,[22] which is currently difficult at pixel sizes below 200 µm (>100 ppi).

For portable high-resolution stacked displays, video is also a challenge because active-matrix driving is often required, and the optical losses associated with even a transparent active matrix can be significant as the pixel size (clear aperture) is reduced. A more-detailed discussion of the optical losses for active-matrix driving is provided in Sec. 3.3, *Electronic Design Principles for e-Paper.* Even with these limitations, a prototype of the reflective three-layer guest-host liquid-crystal display by Toshiba has demonstrated good performance over a limited viewing angle: 43% reflectance in the white state, contrast ratio of 5.3, 240 × 160 pixels in 300-µm size, >85% clear aperture for each of three TFT arrays, and fabricated on a <400-µm-thick substrate.[23,24]

There is one further stacked CMY approach shown in Fig. 2(g), which requires only two layers, but does require two CMY or CMYK colors in each pixel.[25] While Fig. 2(g) shows all possible combinations of dual colorant inks, actual implementation can use one CMY in the first layer and the remaining two of CMY in the second layer. The approach is theoretically attractive if two colorants inside each layer can be independently controlled.

Some interesting alternate options open up with a hybrid (additive and subtractive) color system using both RGB and CMY primaries in a cooperative "bi-primary" system.[26] The bi-primary system of Figs. 2(h) and 2(i) is single layered and the pixel must switch between two colors (one CMY and one complimentary RGB color) and obtain black by mixing the primaries or by using a third black colorant. Consider the creation of a "red" color as an example. The pixel would display RMY for a reflectance of 55% (33% from R and 67% from each M and Y). Regarding color fraction, R contributes 100% and M&Y 25% each. The color fraction for M&Y is 25% because each is comprised of half R (50% CF) but also a non-red color (B, G) which reduces their color fraction by a factor of two. Two-layer operation [Fig. 2(j)] is also possible with performance equal to that for single-layer operation [Fig. 2(i)]. However, single-layer operation is typically preferred for video and high resolution. Further details on bi-primary are reported elsewhere.[26] In summary, bi-primary can be a single layer and in theory can double the white reflectance and color fraction compared to that of single-layer RGBW.

It is possible to apply image-processing algorithms to improve the appearance of color reflective displays. Such processing adjusts the image data to account for the performance of the display or the presence of white subpixels, leading to an improved image. Subpixel-rendering algorithms that improve the perceived resolution of the display are also of value because these approaches can generate images that are perceived at an increased resolution compared to conventional color-filter layouts.[28,29]

3 Visual and electronic standards

The title of this article includes the term e-Paper, which is the most popular term used to describe numerous forms of reflective-display technology. Defining standards for e-Paper produces a challenge, as there are well-established, but distinct, standards for electronic displays and for print. Since one of the goals of this review is to connect these areas, visual standards are provided for *both* electronic displays (subsection 3.1) and conventional paper printing (subsection 3.2). We also discuss in this section some electronic design principles for e-Paper (subsection 3.3). Many e-Paper technologies exhibit desirable optical performance, but not all can be electrically driven using the electrical addressing techniques in current use for LCD panels. Modifications to backplane devices and processes can be costly, and often impedes market entry for new technologies. In addition the low-cost driver chips for the pixelated device may or may not match the industry-available chips (requiring costly modifications or the use of high-cost general-purpose ICs).

3.1 Visual standards for reflective displays

In conventional electronic-display technologies, many groups rely on the flat-panel display measurement (FPDM) standards, first published by VESA[30] and now in the process of being updated by the International Committee on Display Metrology.[31] The FPDM standard covers a wide range of display parameters, including luminance, contrast, color gamut, white-point and gray-scale accuracy, resolution, response time, viewing-angle performance, uniformity, power consumption, and many others. While it is natural to draw on these well-established metrics in the evaluation of electronic-paper technologies, actual performance in the field is complicated for reflective displays. For many reflective display technologies, the appearance of the display depends on the exact luminance (position and distribution of the apparatus providing the illumination) and on the viewing angle of the user (receiving detector with optics) due to many of the issues we have already highlighted.[32,33] To provide a reasonable characterization, both specular and diffuse reflectance should be measured.[32,34] Appropriate ambient lighting conditions must also be considered, such as daylight readability and contrast, in a continued effort to define reflective-display standards.[35,36] We note with some irony that an important characteristic of print-on-paper is the insensitivity of the image appearance to lighting and viewing conditions, so that the historical difficulty in characterizing reflective displays illustrates how un-paper-like many of them have been.

3.2 Standards for printing

Since e-Paper technologies aim to reproduce the appearance of print-on-paper, it is also useful to consider standards developed in the digital printing industry. Digital printing is a common experience in today's world and the color reproduction possible with most digital ink-jet and laser printers can meet or exceed the quality of the historical analog print media such as newspapers, books, and magazines. Many of the new e-Paper technologies aspire to reproduce the visual experience of conventional printed media such as newspapers. Therefore, a review of the printed-media color capability can serve as a reference point for reflective-display technology and related applications.

One of the key requirements for good color reproduction is the ability to achieve a high brightness or white state as well as a dark state which can be measured in terms of L^*, the lightness measurement of *CIE 1976* ($L^*a^*b^*$) *color space* or *CIELAB color space*.[37,38] L^* measurements closely match human perception of lightness, whereas reflectivity measures the amount of photons reflective from a given surface (and is not linear with the human visual system). For all but very dark lighting situations, L^* is proportional to the cubic-root of reflective light.

In the printing industry for newspaper and magazines, standards have been developed to ensure consistent color reproduction across the industry. Consistent color reproduction is valuable to the advertisers who expect the ads to reproduce the correct color each and every time a page is printed. For example, the color "Coke Red" is defined to be a specified color of red by the Coca-Cola Company. Advertisers are accustomed to standards such as SNAP standard[39] (Specifications for Newsprint Advertising Production) used for newspaper ad inserts, and the SWOP standard[40] (Specifications for Web Offset Publications) used for magazines and other high-quality printing. For e-Paper to become a viable replacement for printed paper, its performance must be put into the context of the metrics used by the printing industry. In this review, we describe in detail these print standards to e-Paper performance for the first time.

As detailed in Table 1, SNAP aims for a paper surface with an L^* value of 82 (~60% peak reflectivity) while SWOP expects an L^* value of at least 90 (~76% peak reflectivity). These results assume a D50 source of light. It is noteworthy that the black or dark levels of the SNAP color-printing standard are at $L^* = 30$ or $R = 6.2\%$ which gives a contrast $\Delta L^* = 52$ or a %R contrast of ~10:1. To meet or exceed newspaper printing, both specification of light and dark must be achieved. A contrast ratio exceeding 10:1 should not imply that newspaper standards can be met without reference to the L^* specifications. It is interesting to note that

TABLE 1 — SNAP and SWOP standards: (a) comparison to % reflectivity; (b) details for SNAP; (c) details for SWOP.

(a)

	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

(b) SNAP details (ISO 13655, 2 degree observer, D50 illuminant, 0/45)

	White (paper)	Black (CMY stack)	Black (K ink only)	Cyan	Magenta	Yellow	Red (MY stack)	Green (CY stack)	Blue (CM stack)
L*	82	30	36	57	54	78	52	53	41
a*	0		1	-23	44	-3	41	-34	7
b*	3		4	-27	-2	58	25	17	-22

(c) SWOP details (Grade #5 paper, 2 degree observer, D50 illuminant, 0/45)

	White (paper)	Black (CMY stack)	Black (K ink only)	Cyan	Magenta	Yellow	Red (MY stack)	Green (CY stack)	Blue (CM stack)
L*	90	25	19	57	48	85	47	52	27
a*	0	0	1	-38	70	-6	64	-61	19
b*	4	0	1	-41	-4	85	43	27	-42

some of the reflectance and L^* values for SWOP colors are lower than SNAP. This is not due to poorer color; rather, it is representative of the requirement for more saturated colors in SWOP.

Traditional paper media is assumed to have a very wide viewing angle easily exceeding 170° because most paper surfaces exhibit Lambertian reflectance. The situation for e-Paper is more complicated. Some e-Paper technologies have wide viewing angles (*i.e.*, no dramatic loss of contrast or color gamut at large viewing angles), though all suffer somewhat from specular reflectance from the front sheet of the display cell.

The color gamut for reflective technology should also be considered, not just the peak reflectivity of the white state. Figure 3 compares the color-gamut volumes of the SNAP standard, SWOP standard, and a conventional LCD notebook display, both measured in a typical indoor office environment (ambient luminance level = 300 lux) and in a typical outdoor environment on an overcast day (ambient luminance level = 3000 lux). As shown in Fig. 3, there is a dramatic reduction in both the perceived contrast and color-gamut volume of the LCD when viewed outdoors, where as the print color gamut does not change significantly between these two light environments.[41] Full sunlight can be in excess of 30,000 lux, and the disparity between paper, e-Paper, and conventional LCD performance can be dramatic in outdoor lighting.

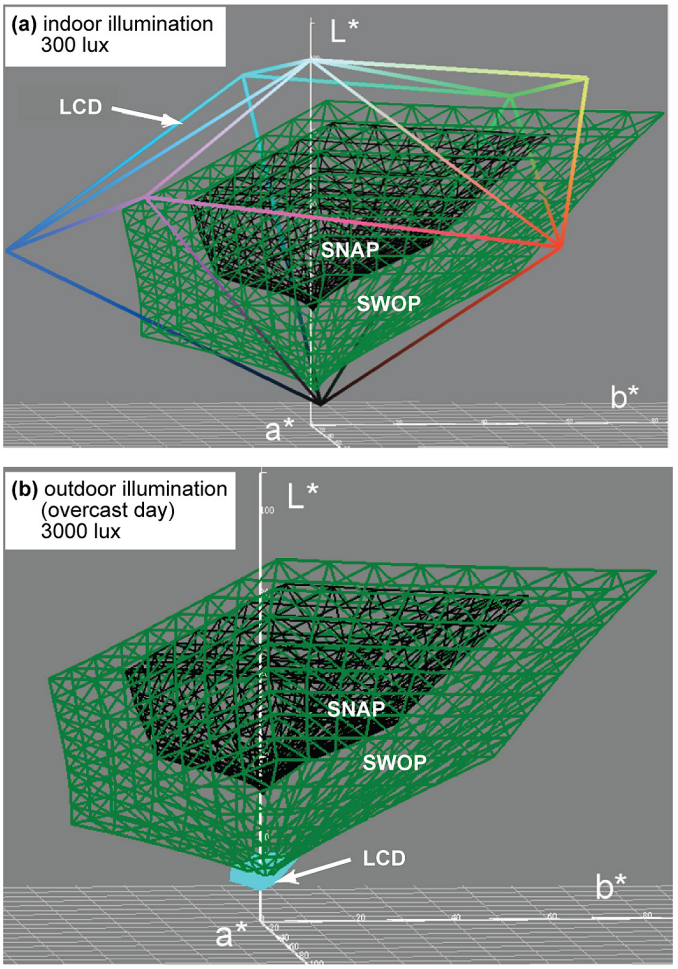


FIGURE 3 — Color gamut volumes[41] of the SNAP standard, SWOP standard, and a conventional LCD notebook display, both measured in a typical indoor office environment (ambient luminance level = 300 lux) and in a typical outdoor environment on an overcast day (ambient luminance level = 3000 lux).

Some transmissive/emissive display manufacturers attempt to use "% of NTSC" as a standard to evaluate e-Paper displays. This metric addresses only color purity of the RGB primaries, ignoring luminance and display performance in bright ambient lighting conditions. "% NTSC" is therefore an inadequate metric for evaluating e-Paper performance.

For applications such as electronic signage, where advertisers will expect their ads to be perceived the same as conventional printed media with similar color gamut independent of viewing angle, it will be critical that e-Paper technology approach or meet paper standards. For other applications such as e-Readers, the need for wide viewing angle is not as great and therefore not all the attributes of paper are required.

In this review, the various technologies under consideration have attributes that aim to meet paper-like specification in some capability of performance, but not in others. The goals for paper-like performance are understood, but developers of current e-Paper technologies often have specific applications in mind, and do not treat all paper-like attributes as equally important.

3.3 Electronic design principles for e-Paper

Nearly all high-information-content displays require arrayed pixels that are driven using a matrix of row and column electrodes; using passive-matrix, control-grid, or active-matrix designs. For passive-matrix (PM) addressing, row and column electrodes are built onto the opposing cell faces and the display is scanned with voltage one row at a time. Not all display technologies can support passive addressing, which is limited to technologies that show a sharp threshold voltage for a transition, and/or a large hysteresis loop. The resolution and frame rate for a passive-matrix display is often limited by cross-talk between pixels, and the rate that an individual line can be addressed and switched. Passive addressing often requires a higher voltage drive compared to the voltage required to switch a single pixel, but the ready availability of high-voltage drivers makes possible amplitudes of several tens of volts at a pixel. Passive-matrix displays are typically less capable of high-resolution and video-rate performance, compared to active-matrix designs.

Active-matrix (AM) drive relies on the presence of a thin-film transistor (TFT) at each pixel. Row electrodes are connected to each transistor gate in that row, while column electrodes are connected to the pixel electrode through the TFT. The display is scanned one row at a time by applying a voltage signal to the row electrode, and thus to the gates connected to that line. Voltage or charge from the column electrodes is coupled through the activated TFT source to the pixel connected to the TFT drain. When the row electrode is de-activated, the TFT is de-activated and the pixel is electrically insulated from the column electrodes. The supplied voltage or charge can continue to hold the pixel at a given state by the inherent capacitance of a pixel or with the addition of a dedicated storage capacitor. Active-matrix addressing can support a range of voltages, with practical upper limits typically in the range of 30–40 V.[42]

Most AMLCD backplanes have an optical efficiency (aperture) of 55–65% based on transistors using amorphous-silicon (a-Si) TFTs and opaque capacitors, though designs of up to 80% aperture ratio have been demonstrated.[43] In e-Paper devices that do not rely on horizontal colorant transposition, the transistors are usually behind the reflective pixels, and the active pixel area can be quite high. Aperture ratios of over 92% have been demonstrated in reflective devices.[44]

Recently, the emergence of transparent and/or smaller-area TFTs based on organic materials or metal-oxides[45] has spurred interest in applying active matrix to stacked displays [Figs. 2(d)–2(g) and 2(j)]. The significant mobility improvement of metal oxide TFTs over a-Si TFTs allows for a much smaller TFT area.[46] In addition, metal oxide transistors can have an optical transparency of 70–80% whereas the a-Si devices must be masked to prevent a photo-generated transistor response in the a-Si TFT. In theory, a backplane with 150 ppi (170-μm pixel size) can potentially provide a clear aperture of 94% if the TFT area is $10 \times 15\ \mu m^2$ and the row and column electrodes are 5 μm in width.

For display technologies that do not inherently support conventional AM or PM drive schemes, the addition of a third electrode to form a control structure can enable matrix addressing. An early example of a control grid enabling a matrix drive of a vertical electrophoretic display (EPD) was reported by Dalisa *et al.* in 1977.[47]

4 Critical review of e-Paper technologies

4.1 Selection criteria

In this short review, it is possible to cover only a subset of all e-Paper technologies. As selection criteria, we required that each technology be currently in development by at least one commercial entity and have the potential of replacing or enhancing applications currently served by electronic displays or by print.

4.2 Conventional (vertical) electrophoretic

History, Maturity: A vertical electrophoretic display (EPD) consists of charged particles moving either towards or away from the viewer in response to an electric field. Electrophoretic displays have a long history. Ota *et al.* first reported[48] in 1973 a display comprised of pigments suspended in a color oil, where DC voltage brought the pigments to the front of the cell (generating the pigment color) or drove them to the back of the cell (generating the dye color). Despite intensive development by a number of laboratories for nearly a decade, several problems such as pigment flocculation remained unresolved. Commercialization was further slowed with the rapid success of passive-matrix LCDs, and work levels remained low for two decades. Then, in the late 90s, Jacobson and co-workers demonstrated the first example of a microencapsulated EPD at MIT.[49] Subsequent work at E Ink Corp. led to dramatic improvements in performance,[50–52] and the subsequent availability of active-matrix backplanes led to the commercial EPDs now ubiquitous in e-Readers.

Construction, materials, and physics: Today, the dominant vertical electrophoretic display cells are manufactured by E Ink Corp., using black and white pigments in a microencapsulated and electrically insulating oil. The basic operating principles of this two-particle microencapsulated EPD[53] are shown in Fig. 4. When a DC voltage is applied to a pixel, the black and the white particles are driven to opposite faces of the pixel, each attracted to a particular charge. The pigments tend to form a solid layer across the face of the microcapsule, with the pigment in the front of the cell hiding the pigment in the back. Continuous gray scale can be achieved by only partially driving the pigments across the cell gap. The particle movement is driven by an impulse (field × time) so that to first order the response time of the cell is given by $d^2/\mu V$, where V is the applied voltage, μ is the electrophoretic mobility of the particle, and d is the cell gap. While this simple equation implies simple behav-

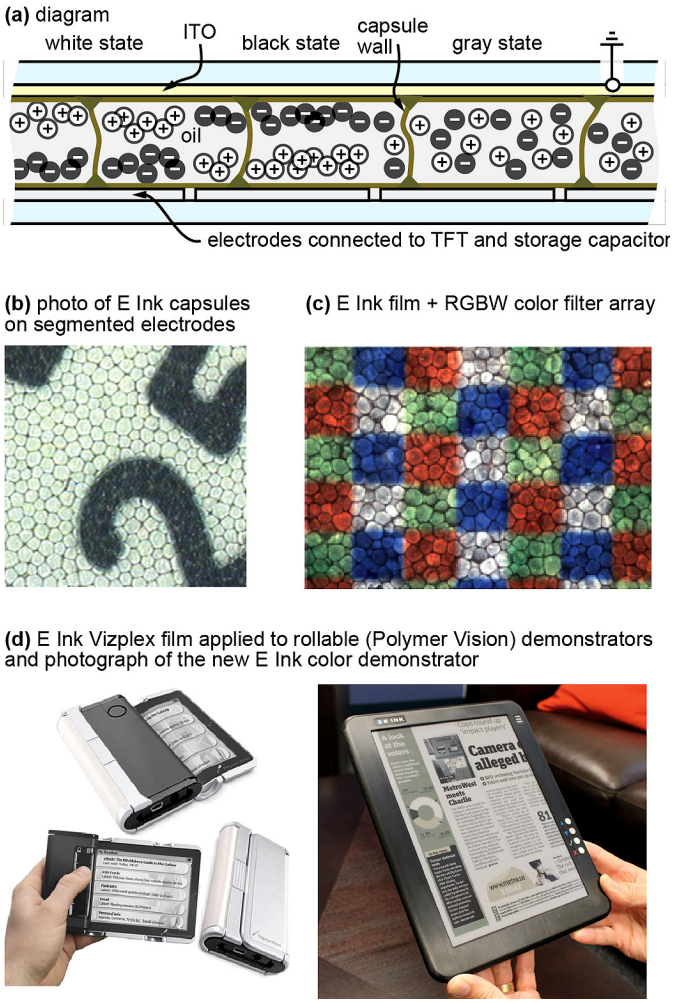


FIGURE 4 — Vertical electrophoretic e-Paper (a) diagrams, (b) pixel photos, (c) color filter application, and (d) rollable and color-display demonstrations.

ior, the situation is far more complex. Each particle is surrounded by its own cloud of counter-ions, experiences nonlinear interactions between the pigments and with the bounding surfaces (including a weak attractive force that provides the bistability behavior), and undergoes complex hydrodynamic flow. While EPDs have historically had the reputation of being slow, a cell with a 30-msec cell response at 15-V operation has been reported.[54]

Electrical addressing and gray scale: To change the image in an EPD, an impulse signal of a single polarity determines the final state of the pixel. As a practical matter, EPD's require the periodic application of a reverse impulse signal. If a net DC voltage builds up across the EPD cell, then not only does this affect the switching behavior, but can lead to irreversible electrochemical damage of the EPD cell. Another complication is that when driven to gray scales, the different switching history of different pixels can lead to different distribution of particles within the fluid, which leads to optical non-unformities across pixels. The easiest way to prevent this behavior is to apply one or more reset pulses that drive the pigments to a uniform state, though such pulses lead to an often-undesired flicker between image frames.

High-resolution images require accurate gray scale, and EPDs present significant challenges. The cell gaps in EPDs are relatively large (in the range of 15–30 μm[55]), so that at small pixel sizes the fringe fields from one pixel can affect neighboring pixel signals. The signal required to drive a pixel to a particular gray level also depends strongly on the internal state of the pigments within the microcapsules, which in turn depends on the switching history of the pixel. Direct gray–gray switching leads to the growth of non-identical distributions of particles and charges in pixels that are supposed to have the same gray level. Significant work has been performed on developing drive schemes that enable accurate gray-scale switching while minimizing flicker.[56] Commercial products now routinely achieve 16 gray levels with flicker between image updates, and 256 gray levels have been demonstrated through performing image processing to develop halftones in a 16-level display.[57]

While in principle it is possible to use combinations of colored pigments to generate full color, these approaches have not yet been successful in generating color approaching print-on-paper in actual displays.[58,59] The most successful implementation of color displays to date has used a black and white particle EPD with a RGBW color filter [Figs. 2(b) and 4(c)]. The use of a white subpixel enables a brighter white state, at the cost of desaturating colors. This approach appears preferable to the alternative of using either desaturated RGB or CMY filters, which tend to give dark, muddled white states and poorly saturated colors.

Enhancement of color images has also been attained through the use of image processing, which enables neighboring subpixels to interact to produce a color image that appears to be more saturated.[27] Color-rendering algorithms with custom color filters (such as RGBW with added blue and white subpixels) have been studied as a means to providing a more satisfactory color image.[60]

Vertical EPD displays are bistable, in that they maintain a gray-scale image for long periods of time after removal of the driving signal. Power consumption for a display will be dominated by how rapidly the display is updated. In an electronic book, the display may be updated only every minute, so that power consumption is quite small.[61] Of course, rapid switching (such as rendering video) will increase the power consumption substantially.

Fabrication/environmental: The fabrication of the E Ink two-particle microencapsulated EPD involves several steps.[62] The pigments must be treated chemically to generate the desired charge, but to also resist irreversible agglomeration. After dispersed into oil, this slurry is microencapsulated, then the microcapsules are blended with a polymer and coated as a single layer on a transparent conductive sheet. It is highly advantageous if the microcapsules are somewhat deformable to maximize the amount of film area that is able to show an optical switching effect. After drying, this film is laminated to a release sheet for transport or stor-

TABLE 2 — Summary of performance and other key factors for monochrome e-Paper technologies. References for data can be found in the associated sections in the article.

	Electrophoretic (commercial)	Electrophoretic (R&D)	In-Plane Electrophoretic	Electrokinetic	Liquid Powder	Electrochromic	Electrowetting	Electrofluidic	IMOD (MEMS)	Cholesteric LC	PDLC (scattering)	Reflective LC w/ Polar.
%R for White or Color	40% W	>48% W	70% W	60% W	30% W	>50% W	55% W	70% W	45% C	30%-35% C	50% W	39% W
%R for Black	4%	<6%	6%	2%	3%	-	3-5%	5%	4%	6%	5%	2%
Contrast Ratio	10:1	>8:1	>10:1	30:1	8:1	-	10-15:1	-	15:1	6:1	10:1	20:1
Lambertian	yes	yes	yes	yes	yes	yes	partial	yes	no	partial	no	partial
Mono SNAP/SWOP	-	maybe SNAP	SNAP	SNAP	-	-	maybe SNAP	SNAP	SNAP	-	maybe SNAP	-
Voltage (V)	15	-	~10	5-40	30-70	~1	15-20	10-20	5-10	<4 (lab); 25-40 (products)	5	10-30
Bistable	yes	yes	no	no	yes	hours	no	yes	yes	yes	no (yes with matix)	Yes
Switching Speed (msec)	100's	30	~1000	100's	0.2	~msec	10	10's	0.01's	500-700/ frame	100	1 msec/line
Matrix Drive	AM	AM	AM / PM	AM	PM	PM	AM	AM / PM	PM	PM	AM	PM
Gray-Scale Approach	Pulse	Pulse	Analog or Pulse	Pulse	multi-write	-	Analog	Pulse	Spatial/ Temporal	Pulse	Analog	Halftone
Gray-Scale Bit Level	4	16	>3	>3	2	-	4	2	6	4	1	1
Neutral White Point	yes	yes	yes	yes	yes	possible	yes	yes	yes	no	yes	possible
Lifetime	good	-	unproven	unproven	good / ltd.	ltd. / unproven	unproven	unproven	good	good	good	great
Power (static image)	none	none	very low	very low	none	very low	moderate	none	very low	none	low	moderate
Power (video)	low	low	n/a	n/a	low	very high	high	high	high	moderate	moderate	low
Years In Development	12	-	3+	2+	10	40	10	3	20+	18	25+	10
Maturity	many products	R&D	AM & PM demo	AM demo	ESL product / large PM	smart card products	AM demo	segment demo	PM products	PM products	AM prototypes	Products

age. To fabricate a high-resolution cell, the release sheet is removed and the film is laminated to the active-matrix backplane. With a production history of many years and millions of displays, the E Ink system has achieved a good level of reproducibility and durability. E Ink reports[63] that the operating temperature range of its displays is 0–50°C, and the storage temperature range is –25–70°C.

SiPix Imaging has pioneered an alternative construction for EPD cells, using an embossed polymer matrix to contain the fluid, rather than microcapsules.[64] This technology, coined MicroCup, shows many of the attractive characteristics of the microencapsulated EPD, though the SiPix technology has relied primarily, to date, on white pigment dispersed in a black-dyed oil. The reflectivity of single particle/dye EPD tends to be inferior to the optics of the two-particle system (33% reflectivity with 9:1 contrast ratio at 30-V operation[65]). SiPix and collaborators have demonstrated numerous high-resolution prototypes on rigid and flexible backplanes, as well as many direct drive prototypes.[66]

Outlook: EPDs using the E Ink technology have achieved a reasonable maturity, with millions of devices shipped. Current commercial specifications claim a white state of 40%, a contrast of 10:1, and 16 gray levels. Display sizes and resolutions range from 9.7 in. (1200 × 825, 150 dpi) through 5 in. (800 × 600, 200 dpi). Display response time is reported as <1 sec for full-gray-scale images, but the displays also offer a 1-bit 250-msec mode.[63] Chunghwa Picture Tubes has demonstrated 6 in. (800 × 600, 167 dpi) and 8 in. (1024 × 768, 160 dpi) microencapsulated active-matrix EPDs with a reported reflectivity of 48%, contrast ratio of 8:1, and 16 gray levels.[67] Table 2 provides information regarding the optical properties demonstrated for these displays.

Today, when most people think about e-Paper, they are considering products containing the EPD technology of E Ink. This technology, along with the product capabilities introduced by the Amazon Kindle and its competitors, has established e-Books as a viable product category, with e-Paper as the preferred technology for immersion reading. The technology continues to advance, becoming higher performance, more reliable, and lower in cost.

Success breeds competition, though, and it is likely that the e-Paper product area will evolve rapidly over the next few years. Costs for these devices will continue to decrease

with increased volumes, creating an additional barrier for competing technologies. The first commercial color EPD product, with a 9.68-in. diagonal, was announced by Hanvon in November 2010 for introduction in China. Still, video capability with gray scale remains a major unsolved challenge for vertical EPDs. If demand for color and video in e-Paper products becomes high, and vertical EPD technology cannot respond adequately, then the current dominance of vertical EPD devices could very well be eroded.

4.3 Horizontal (in-plane) electrophoretic

History, maturity: Horizontal EPD displays operate through the lateral movement of pigments across a pixel. In-plane electrophoretic displays were reported by IBM and Canon in 2000.[68,69] For in-plane electrophoretic displays, the colorant particles absorb light when distributed across the pixel to produce a dark (or colored) pixel state. In the light (or cleared) pixel state, the particles are collected into a laterally small area of the pixel allowing light to be transmitted through the pixel, exposing a reflector underneath. Canon reported an active-matrix in-plane electrophoretic display of 200 ppi in 2002.[70] More recently, Philips reported pixelated displays without an active matrix using one or two charged colorants through the use of a gate (control) electrode within each pixel.[71] With the ability to achieve a clear or light-transparent state, multiple layers can be stacked with subtractive colorants to achieve bright, color electronic paper [Figs. 2(e)–2(g)]. Examples of in-plane electrophoretic displays are shown in Fig. 5 from Philips.

Construction, materials, and physics: Construction of the in-plane electrophoretic devices is similar to other electrophoretic devices and differs in the placement of the electrodes, which typically uses ITO or metal lines within the pixel cells or thin metal on the vertical edges of the pixel cells. The devices use the same thin films as used for LCDs with the exception of a spacer or cell wall material that is used to define the pixels and maintain the fluidic gap. Most of these devices use a photosensitive polymer film that can be patterned to the desired cell geometries.

The key material in these devices is the colorant fluid, which contains charged colorant particles in a dielectric liquid that can be spread or collected on electrodes within the cell. The charge particles can be similar to the type of particles used for vertical electrophoretic displays. However, the colorant particles and fluid must be designed to prevent light scattering, thereby allowing effective stacking of the colorant layers. The physics of in-plane devices is governed by similar physics as vertical EPD devices. Critical parameters such as fluid viscosity, effective charge on particles, and electrical field strength must be optimized to create an effective display.

Optical performance: The advantage of stacked in-plane electrophoretic is the ability to create highly saturated colors compared to the devices that use color filters or side-by-side colorants. In addition, the viewing angle is excellent like all electrophoretic-based displays. Single-color devices with black particles and a white reflector have demonstrated 70% white reflectance,[72] >10:1 contrast ratios, or even >70:1 with larger geometries.[73] The devices depend on optimizing the clear-state aperture and the colorant spread state.

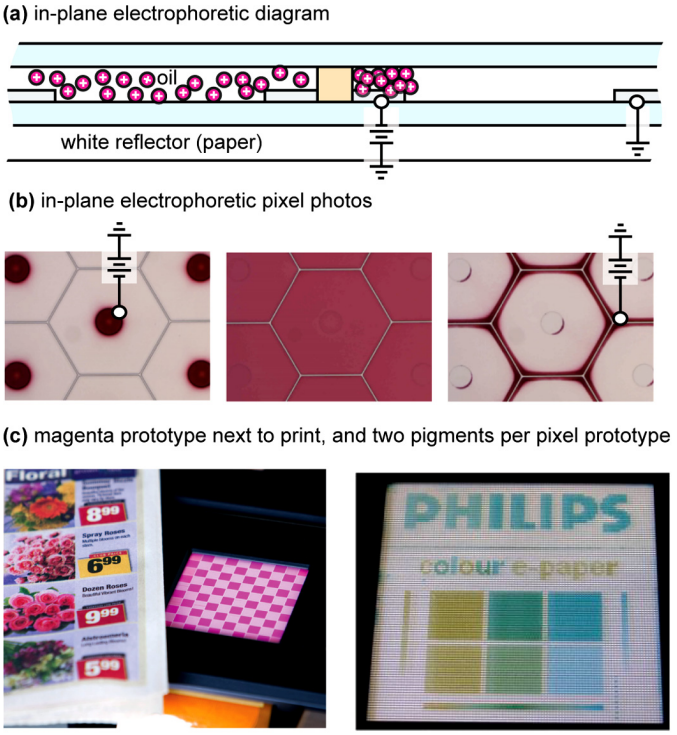


FIGURE 5 — Horizontal (in-plane) electrophoretic technology: (a) simple pixel diagram, (b) pixel photos, (c) monochrome and color demonstrator units.[73]

One of the trade-offs for overall device performance is between the speed of the device and the clear-state transparency. Larger geometries allow higher transparency, but at the expense of slower switching times due to the quadratic dependency on distance travelled of the colorant particles (*e.g.*, the same $d^2/\mu V$ dependence as vertical EPDs).

Electrical addressing and gray scale: Gray scale is achieved by controlling the amount of colorant that is released from the collected area into the larger pixel area through the use of a separate gate (control) electrode creating a threshold for passive-matrix addressing. Also, a built-in gray scale was shown by Phillips by using multiple electrodes.[73] Even without a bistability state, the hold state for in-plane devices generally requires very low voltage, thus suitable for low-power applications but not zero-power applications. The voltage required for in-plane displays can vary from a few volts to hundreds of volts, depending on the fluid characteristics and the cell geometries (*e.g.*, pixel resolution), as well as the speed requirements. Higher voltages generate larger fields, leading to faster switching displays.

Fabrication/environmental: In-plane devices have used glass or plastic as a substrate material. The complexity of the required processing is dependent on whether the

design requires an active-matrix backplane, or requires a gate (control) electrode and an additional metal level, as in the Philips approach.

Outlook: Electrophoretic-based displays are now common (e-Readers) based on vertical switching. Given the color limitation of out-of-plane (vertical) switching, in-plane (horizontal) devices remain an attractive alternative. In-plane displays may find a product space where the demand for print-like color is required; for example, electronic signage and/or electronic skins on the outside of electronic devices. Personal-use devices such as eReaders are possible with this technology by balancing color and resolution of the final device.

4.4 Electrokinetic

History, maturity: A new approach to electrophoretic displays, coined electrokinetic technology by Koch and co-workers at Hewlett-Packard, was first reported at SID 2009.[41] Since this time, HP had demonstrated fully functional and flexible segmented e-skin modules that were fabricated using roll-to-roll manufacturing. Yeo and co-workers at HP have more recently demonstrated in 2010 both gray scale and pixelation with an active-matrix backplane.[74]

Construction, materials, and physics: Electrokinetic displays are a hybrid vertical and horizontal (in-plane) electrophoretic technology. As shown in Fig. 6, micro-pits allow more localized particle compaction inside the pixel. This has several distinct advantages: (1) switching speed is improved by effectively reducing the electrode gap (higher electric field, shorter distance for particles to travel); (2) electrode misalignment is allowed because of the localized particle compaction. Since the control of multiple electrokinetic forces leads to the compaction of colorant particles, the technology is termed "electrokinetic" media.[74] The colored state (spread particles) is stable at zero voltage, and similar to in-plane electrophoretics, the clear state can be maintained with a low power holding voltage. The colorant fluid has similar requirements as in-plane electrophoretic technology.

Optical performance: HP has demonstrated reflectance larger than 60% (brightness $L^* > 80$) with a contrast ratio of 30:1 (black particles over a white reflector of $L^* \sim 96$).[74] To provide print-like color, HP has proposed stacking of layered colorants similar to Figs. 2(f) and 2(g). The color-stack approach requires a highly transparent backplane. It should be noted that unlike in-plane electrophoretics, electrokinetics places two transparent electrodes in the light path for each pixel layer. Therefore, low-loss index-matched ITO films or comparable transparent conductors are needed to maximize the optical performance in single- or stacked-layer devices. Since each cell can be made down to a single micro-pit, frontplane architecture can allow high resolution. So, the maximum resolution is limited by the requirements for transparent backplanes and stacking as discussed in subsection 3.3.

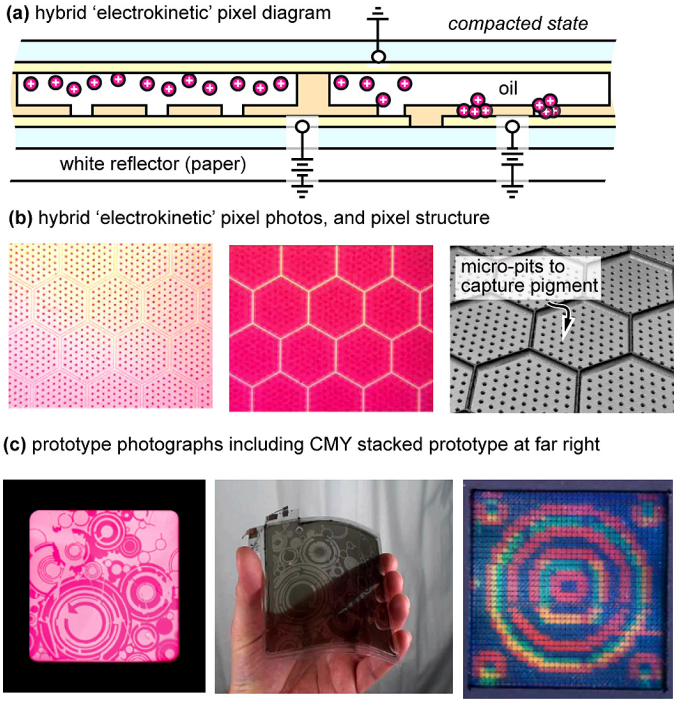


FIGURE 6 — Hybrid electrophoretic e-Paper (HP "electrokinetic"): (a) diagrams, (b) pixel photos, and (c, d) prototype demonstration.[74,75]

Electrical addressing and gray scale: Electrokinetic display-driving voltages vary from 5 to 40 V, depending on the switching time required. A switching speed of <300 msec has been reported at 15-V operation.[75] The transparent state can be maintained with a low-power holding voltage (<50 $\mu W/cm^2$ at <15 V typical). Gray scale has been demonstrated by modulating the pulse width or pulse amplitude to control the specific concentration of colorant particles in the pixel. Continuous dynamic driving to transition from one gray level to another has been shown for eight gray levels without having to reset the colorant particles.[74] Figure 6(c) shows segmented monochrome prototypes and a 35×35-pixel color display using three-layer CMY stacking. For the stacked prototype, each layer is integrated with a transparent oxide TFT backplane of 750-µm pixel size.[46,75]

Fabrication/environmental: Low-cost roll-to-roll manufacturing has been used to create the prototypes shown in Fig. 6(c). A photolithographically prepared and flexible master stamp is used to microreplicate the multi-level pixel geometry. This flexible frontplane was laminated with the ink onto a segmented or active-matrix backplane. Environmental performance is expected to be comparable to other electrophoretic approaches.

Outlook: In summary, the hybrid electrokinetic architecture benefits from both out-of-plane electrical switching and in-plane optical effects. The technology has progressed at an extremely rapid pace, demonstrating within 2–3 years time roll-to-roll manufacturing and three-layer CMY active-matrix operation. With low power and print-like color, electrokinetic reflective electronic media may provide new platforms for electronic-signage applications.

4.5 Liquid powder

History, maturity: Quick-response liquid powder displays (QR-LPD®) were first presented at SID 2003 by a collaborative team at Kyushu University and Bridgestone Corp.[76] Bridgestone is now leading the commercialization with numerous partners including Hitachi and Delta Electronics, and field trials of dot-matrix electronic shelf-labels have begun with Pricer. Flexible full-color prototypes have been shown, and rigid monochrome customer evaluation kits are available up to 21 in. on the diagonal and up to ~150 ppi.

Construction, materials, and physics: As shown in Fig. 7(a), QR-LPD moves particles rapidly across a ~50-μm vertical gap containing only gas. As a result, pixel switching speed is very rapid at ~0.2 msec. Pigment particles can be held in a bistable fashion at the top or bottom plate of a pixel by Van der Waals forces and electrode polarization. However, separating the charged pigments from each other and the electrodes requires significant force (unlike liquid-dispersed pigments in electrophoretic displays), and the dielectric constant of air is low. As a result, display-operating voltages are high, typically on the order of 40–70 V.[77]

Optical performance: Liquid powder suffers from brightness challenges compared to the best vertical EPDs, and in standard diffuse lighting provides a monochrome white state in the range of 25–30% and a black state of ~3% for an 8:1 contrast ratio.[77] The dominant factor is limited thickness and therefore reflection from the white pigment layer (dominant loss mechanism). By displaying a dry layer of pigment, the technology achieves paper-like appearance with no dependence on view or illumination angle.

Electrical addressing and gray scale: The voltage required for liquid-powder displays (40–70 V) is higher than required by with conventional active matrix (<15 V). Fortunately, these displays can be passively addressed, so that high-voltage TFT arrays are not necessary to achieve high resolutions. The fast pixel response time (0.2 msec) allows a passive-matrix refresh rate for a UXGA panel (1200 rows) of 0.2 × 1200 or ~240 msec. Bridgestone has developed an ultra-thin, flexible Si wafer drive circuit that has been integrated with a flexible liquid-powder display and could lead to locally refreshed (faster) update.[77] With infinite bistability, power consumption is a non-issue for static images. Gray-scale generation is somewhat like that used for cholesteric displays, requiring a reset to white or black, followed by a multiple write sequence that slows the panel refresh time. Although numerous gray-scale images are featured in publications and in demonstrations, the only published gray-scale data is four gray levels.[78] A custom driver circuit has enabled for pen input (*i.e.*, locally updating a set of pixels without refreshing the entire screen).

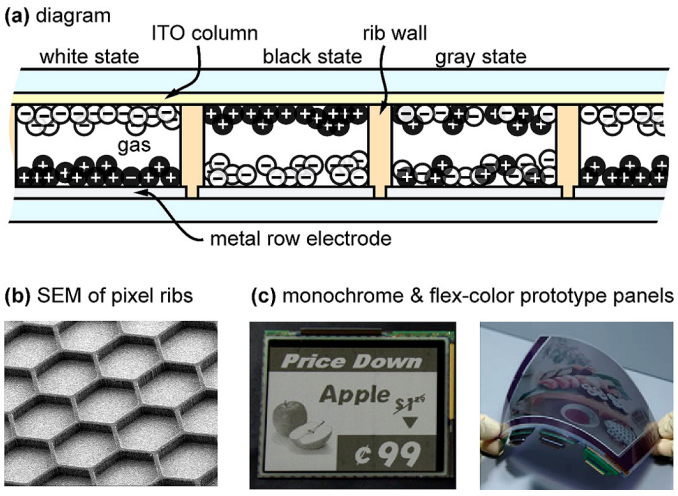


FIGURE 7 — Liquid-powder display: (a) diagrams, (b) SEM of pixel ribs, and (c) monochrome and color-prototype demonstrations.

Fabrication/environmental: Bridgestone developed a flexible and low-cost roll-to-roll process for forming the pixel structures.[79] The available evaluation kits specify an environmental range of –30 to +40°C operating and <70°C storage for <96 hours. Other issues such as lifetime and the effects of humidity (flexible modules) are not known. During switching, particles reach speeds of 40 km/hour,[80] and particle or electrode degradation could limit the available number of switching cycles.

Outlook: To summarize, liquid powder provides a relatively fast-update passive-matrix bistable paper-like display. Liquid powder is currently the only technology to demonstrate this unique combination of capabilities in a fully functional demo unit. Monochrome color is limited in applicability, however, and full color is more challenged considering the additional optical losses and reduced color gamut caused by RGBW color filtering [Fig. 2(b)].

4.6 Electrochromic

History, maturity: Electrochromism is more than 30 years old[81] and is currently used in high-volume commercial products such as smart windows and rear-view mirrors. Early participants in electrochromic display development include Sony, Fujitsu, Alpine Polyvision, and Rockwell, and more recently by Acreo, NTERA, Aveso, and Samsung. A short yet comprehensive review of electrochromic is impossible due to an enormous variety of chemistries and performance. Instead, only a select few research and commercialization efforts will be discussed. All the commercialization efforts are monochrome-only [Figs. 8(b) and 8(c)] with stacked CMY[82] color mainly in the lab stage [Fig. 8(d)]. The first products are targeted at applications well suited to electrochromics. Aveso and DZ Card Intl. released in October of 2009 a six-digit alphanumeric smart card with a 2-year battery life. NTERA announced in July of 2009 a similar commercialization pursuit with GSI Technologies.

Construction, materials, and physics: The device diagram shown in Fig. 8(a) is greatly overly simplified. The construction of electrochromic displays varies widely, but for this review we will only describe one particular system. Displays developed by NTERA consist of several stacked porous layers. The front-most layer is a porous semicon-

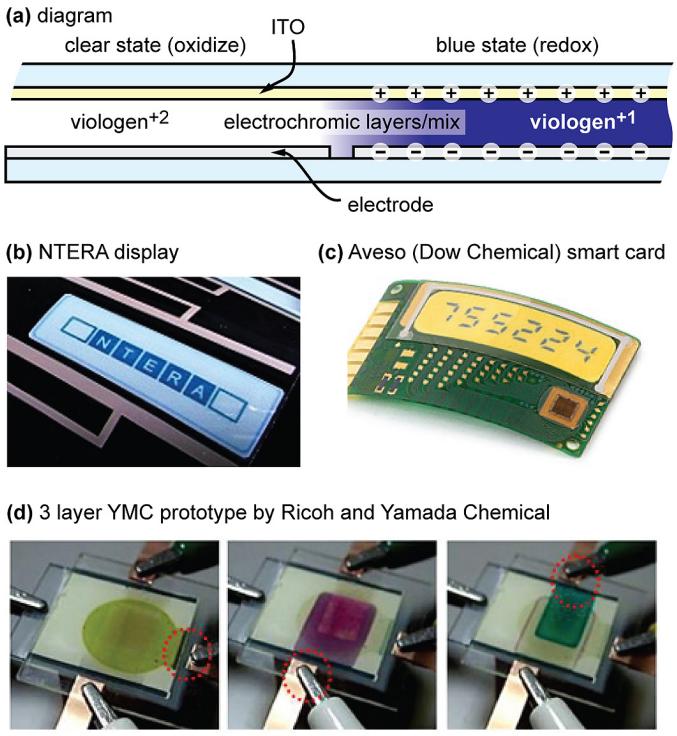


FIGURE 8 — Electrochromic technology: (a) simplified device structure diagram, most approaches require more layers than that shown in the diagram; (b, c) NTERA and Aveso monochrome modules; (d) proof of concept for three-layer CMY stacking.[82]

ducting oxide layer with irreversibly chemisorbed viologen molecules on all surfaces. The rear electrode is a simple conductive carbon layer. A porous, insulating, and white reflector film is placed close behind the front electrode, and a second film in front of the rear electrode helps maintain charge balance across the cell. A signal of ~1 V is utilized to oxidize (bleach) or reduce (color) the viologen layer in tens to hundreds of milliseconds,[83] depending on device construction. The film stack forms a simple, yet leaky, capacitor, so the device slowly loses its image by discharging over a couple of hours unless a holding voltage is maintained. Segmented displays can be very low cost with use of mainly printing fabrication and can be fabricated directly on a paper substrate. The entire display stack of printed films can be as thin as 25 µm thick, but this completed device of course will be much thicker based on the choice of substrate materials.

Optical performance: NTERA can achieve a white reflectance >50% that is paper like in viewing and illumination angle, with a dark blue state of ~5:1 contrast ratio.[84] Experimental electrochromic devices have exhibited white reflectance as high as 90%.[85] In the colored states, most systems provide poorly saturated color compared to standard RGB or CMY pigments. NTERA claims to be working on red and orange capability.[86] A stacked CMY color system is the proposed approach for full color,[82] with sample photographs shown in Fig. 8(d). To date, compelling prototype demonstrations have not yet been shown for stacked electrochromic.

Electrical addressing and gray scale: Electrochromic devices are current driven, so active-matrix addressing requires non-standard TFT circuits, and the update time for active-matrix addressing is slow.[87] Passive-matrix addressing is also viable,[85,88] but even with pixel switching speeds of 1 msec the display update is 1 sec for 1000 rows, and the lack of true bistability requires an occasional image refresh. Power consumption is rarely reported, so we calculate approximate power consumption using parameters of write time and the electrochromic efficiency (cm^2/C). Assuming ~150 cm^2/C,[84] and an e-Reader screen of 300 cm^2, a single 1-V screen refresh requires 2 J of energy. At 30-Hz refresh the power consumption would require 60 W (60 A), which explains why video operation is unlikely. Gray scale is not challenging in theory, as it is possible to partially switch areas of pixels and achieve intermediate gray levels. Nevertheless, few actual examples of electrochromic gray-scale displays have been demonstrated.

Fabrication/environmental: The manufacturing processes for electrochromic rely primarily, if not entirely, on printing techniques, and so should enable low fabrication costs. Aveso claims compatibility with industry-standard fabrication equipment for smart cards, capable of hot-roll lamination at 130°C, providing a ready pathway to that application. Using accelerated lifetime testing, NTERA estimates 10-year lifetime and more than 40 million switching cycles for its commercially deployed products on glass substrates, though such lifetime has yet to be demonstrated. Even with long-lifetime operation, however, differential aging can severely degrade image performance, as the appearance of neighboring pixels changes due to different switching histories. Aveso commercial modules are specified with an operating range of 0–50°C.

Outlook: In summary, electrochromic displays represent an e-Paper product capable of high white brightness and simple construction. Claims of low cost are now justified as direct-drive electrochromic displays start to appear in smart-card products. Electrochromic displays face a much greater challenge as they attempt to move beyond simple segmented displays and into low-cost and gray-scale applications such as e-Readers. Electrochromic displays may also find difficulty competing where monochrome color customization is needed (an area where pigment transposition technologies excel). Still, some of the demonstrated white states are extremely impressive, with some of the highest reflectivities reported for e-Paper displays. It is fair to say, though, that there still remains a sizeable gap between the theoretical performance possible with electrochromic displays and the actual capabilities of working displays.

4.7 Electrowetting

History, maturity: Electrowetting displays were first reported in 2003 by Philips research by Hayes and Feenstra,[89] as an offshoot of a large electrowetting program for lenses and other devices. In 2006, the Philips spinout Liquavista was

formed to lead commercialization. At SID 2010, Liquavista unveiled an 8.5-in. XGA full-color active-matrix display [Fig. 9(c)], integrated with a Texas Instruments mobile electronics platform, which is now available as a customer development kit. Other published prototyping efforts have been reported by the University of Cincinnati, Industrial Technology Research Institute of Taiwan, and Motorola.[90]

Construction, materials, and physics: As shown in Fig. 9(a), electrowetting pixels are an open-cell structure where a dyed-oil is transposed between a film covering a hydrophobic dielectric (no voltage) and partial sphere reduced to 20–30% of the pixel area (voltage). A rapid switching speed (~10 msec) was demonstrated for >100 ppi pixels, though at lower resolutions the display should be slower since the oil film has to move a larger distance. Generally, electrowetting pixels respond quickly because over the same length scale it is typically 100× faster to move the fluid with colorant inside as opposed to electrophoretic where you move the colorant through the fluid itself. The pixels are not inherently bistable, though the power required to hold a pixel at a particular state is lower than the power to switch into that state. For a given operating voltage, the aspect ratio of the oil must be constant and therefore for >100 ppi pixels the oil film is only 3–4 μm thick. Consequently, Liquavista has made significant investment in oil-soluble dye development to meet pixel resolution requirements, including collaboration with Mitsubishi Chemical.

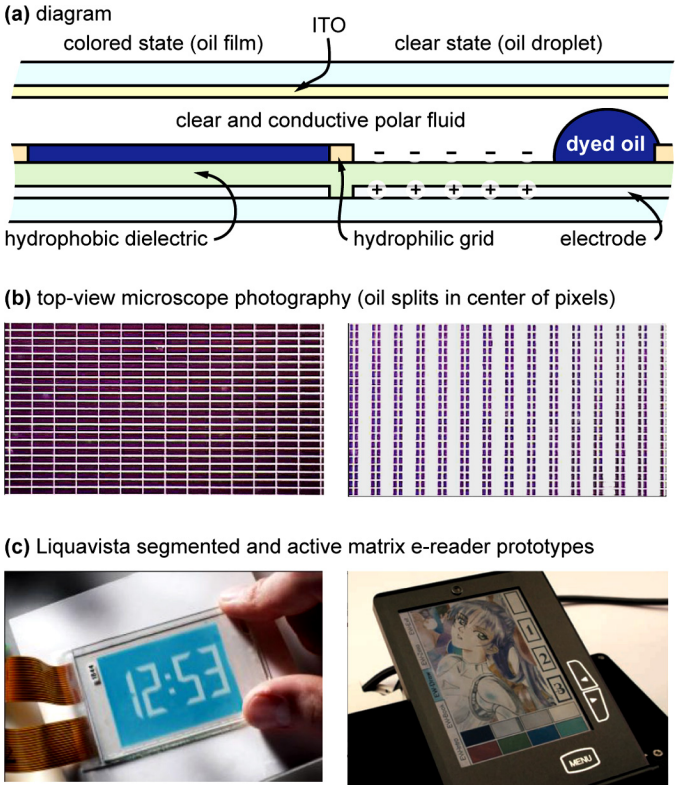


FIGURE 9 — Electrowetting technology: (a) device structure diagram; (b) top view photos of pixel switching; (c) segmented monochrome and active-matrix color prototypes.

Optical performance: The reflectance inside a pixel can be as high as 70% and is proportional to the white area (typically 80% maximum). Active-matrix prototypes currently exhibit ~40% monochrome reflectance, and with RGBW color filtering [Fig. 2(b)] the current full-color prototypes exhibit ~20% white reflectance. Contrast ratios are good, in the range of 10–15:1. Monochrome and color reflectance are claimed to reach 55% and 25–30% with commercial design rules.[91] The reflector in a Liquavista display is currently a metal electrode and requires a diffuser, at the cost of some contrast ratio and light out-coupling (subsection 2.1).

Electrical addressing and gray scale: The voltage used for electrowetting displays is currently 20 V and is expected to decrease further in order to comply with conventional TFTs. The pixel gray-scale response is gradual and greater than analog (> eight gray amplitude levels published,[92] 4–6-bit gray scale claimed for prototypes, but unpublished). Because the dyed-oil is electrically insulating, however, the pixel electrical capacitance is proportional to the area where oil is removed. In active-matrix designs, the charge cycle is only tens of microseconds per row, the oil switching speed around 10 msec, and therefore a robust storage capacitor or special TFT drive configuration is needed to fully uncover the oil within a single video frame. The pixel capacitance is high (the hydrophobic dielectric is ~10× thinner than the cell gap in liquid-crystal displays), and the dielectric requires AC voltage to prevent long-term charge injection/migration in the dielectric. In response, Liquavista has developed frame rates as low as ~1 Hz when the display provides a static image. Passive addressing has not been demonstrated, to date, in electrowetting displays.

Fabrication/environmental: Liquavista claims a low-cost manufacturing process because very little tooling in a conventional LCD fabrication lines needs to be changed. Nevertheless, the only detailed publication on fabrication and materials for electrowetting displays is for the modules collaboratively developed by the University of Cincinnati, ITRI, and Motorola.[90] Historically, the biggest manufacturing challenge for low-voltage electrowetting devices has been the dielectric layer.[93] Even the smallest of pore or other defective pathways in a dielectric can cause eventual electrical failure with a liquid electrode, which may be why Liquavista now refers to their dielectric as a "barrier" layer. Dielectric failure could be the foremost issue in long-term reliability because electrowetting pixels require constant application of voltage. Liquavista claims, however, that it will be able to meet reliability requirements, using lifetime tests that are standard for LCDs. Although environmental range has not been reported, the addition of salts or antifreeze to the conductive polar liquid might allow a temperature range similar to Varioptic electrowetting lenses[94] (–40–85°C storage, –20–60°C operating).

Outlook: Electrowetting display technology, and current Liquavista commercial focus, points to full-color video (e-Readers/Tablets) as its distinguishing feature. If low-cost

manufacturing is achieved, then electrowetting might gain commercial advantage over the similarly competitive but potentially more costly technology: Qualcomm mirasol (MEMS) discussed in section 4.9. Transflective operation is also possible by using field-sequential color for transmissive mode of electrowetting displays, opening another potential design feature.[95] Regarding potential breakthroughs on the horizon, two-layer subtractive CMY color [Fig. 2(e)] is something Liquavista has suggested in the past.[96] Because electrowetting displays are not bistable, stacked electrowetting displays will require highly transparent active-matrix backplanes. Additionally, a 4 × 200 × 200 µm oil layer has a height of 32 µm when it compressed to a hemisphere shape. Therefore, a two-layer stacked display may be satisfactory with respect to parallax, but three-layer stacked is unlikely except for low resolution.

Alternate approach: Horizontal "droplet driven": There is an alternate droplet-driven electrowetting approach in development by Advanced Display Technology GmbH (ADT). ADT moves a colored droplet between two adjacent microreplicated pixel reservoirs.[97] The system is binary and stable without voltage. Thus far, only slow switching (hundreds of milliseconds to seconds) dot indicators or arrays of switchable dots have been demonstrated. The color saturation and reflectivity are fully paper-like, but the technology focus thus far has been for simple ON/OFF indicator applications and will not be reviewed in detail since the technology is not yet compelling for high-information content displays.

4.8 Electrofluidic

History, maturity: Another display technology based on the movement of colored fluids, coined electrofluidic displays, were first reported by the University of Cincinnati in 2009[98] and is now commercially pursued by the 2009 spin-out Gamma Dynamics. In 2010, ~150 ppi and segment-driven clock displays were fabricated at the U.S. Army Flexible Display Center (Phoenix), but were only privately shown at SID 2010. Gamma Dynamics is currently working with Polymer Vision on joint development for rollable electrofluidic displays.

Construction, materials, and physics: Two basic types of electrofluidic pixels, ranging from ~20 to 70 µm thick, are shown in Figs. 10(a) and 10(b). Both constructions use two electrowetting plates, but use the nomenclature "electrofluidic" because there is a net liquid flow through microfluidic cavities. In Fig. 10(a), voltage pulls a pigment dispersion into a viewable channel in ~20–40 msec, displacing a black dyed oil (colored state). Similar to electrowetting, moving colorant with the fluid is ~100× faster than moving colorant through the fluid (electrophoretic). When the voltage is removed, surface tension drives the fluid back into an optically masked reservoir (black state). The more recently demonstrated[99] device of Fig. 10(b) 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 gray-scale states with no holding voltage.

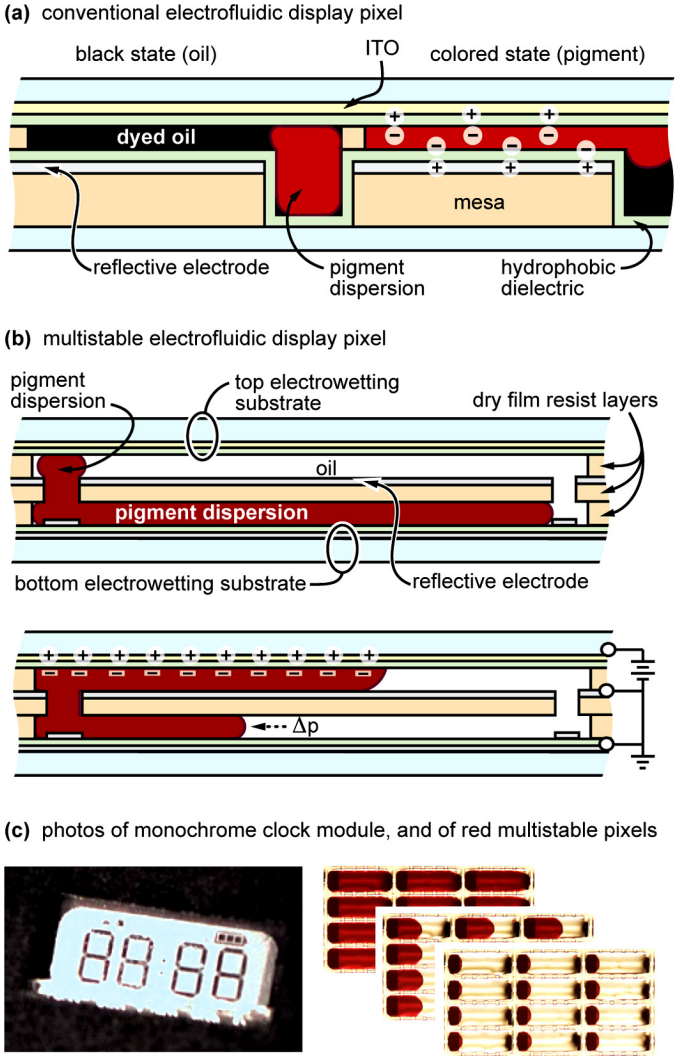


FIGURE 10 — Electrofluidic technology: (a) conventional device structure diagram; (b) newer bistable device structure diagram; (c) photos a monochrome clock module and zoom in photo of red multistable pixels.

Optical performance: The measured white-state reflectance is 75%, but without black-matrix around the pixel border. With a black matrix the white reflectance is predicted to be ~72%.[99] The optical losses are due to Fresnel reflection off the front substrate and films, the 90% Al reflector electrode, pixel border, and the opening to the reservoir. The colored pigment dispersions, developed by Sun Chemical, provide paper-like viewing angles. Full-color operation will currently require RGBW color filtering [Fig. 2(b)], but it is theoretically possible to use the bi-primary color system of Fig. 2(h) using two reservoirs with two pigment dispersions and black oil.

Electrical addressing and gray scale: While 12-V operation has been demonstrated, electrofluidic displays exhibit variable capacitance challenge similar to that described

for active-matrix electrowetting displays. The bistable approach does open the door to passive-matrix addressing. Five-level gray-scale operation has been shown for the bistable pixel using pulse width modulation. Recently, a technique for electrofluidic gray-scale reset states was published,[100] which is necessary if the bistable approach is to avoid the full-screen "reset" or flicker used in conventional electrophoretic displays.

Fabrication/environmental: 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.[101] The bistable module has a complex 3-D structure, but the structure is formed using simple PCB-style dry-film photoresist process co-developed with DuPont. Similar to electrowetting displays, the biggest fabrication challenge may be in electrowetting dielectric reliability. The bistable approach might circumvent this issue (*e.g.*, >1000× less time with voltage for a 40-msec image update every 60 sec). Although prototype environmental specs are not available, the oil and pigment dispersion fluids exhibit a 24-hour storage range of –28°C–+80°C. The same fluids show an operating range of –20°C–+50°.[101]

Outlook: Electrofluidic displays are the newest technology reviewed in this report, and not much information is available. Bistable electrofluidic displays may be able to compete in higher-brightness color operation if the competition is electrophoretic (E Ink) and MEMS (mirasol). Unproven, but possible, is the use of the electrofluidic architecture to hide colorant better than electrowetting displays. Additionally, future achievement of a true bi-primary color system can, in theory, provide a bright full-color e-Paper video in a single-layer system (allowing high-resolution active-matrix drive).

4.9 MEMS (electromechanical interference modulation)

History, maturity: Interference modulation displays use a microelectromechanical system (MEMS) for modulating light with an optically resonant cavity similar to a Fabry–Perot etalon. The technology was first reported at SID 1997 by Miles.[102,103] Qualcomm has recently commercialized the interferometric modulation (iMoD) displays under the trade name mirasol®. Full-color video prototypes of 5.7 in. on the diagonal for an XGA screen with touch (capacitive and optical) were shown at SID 2010.[104]

Construction, materials, and physics: As shown in Fig. 11, the construction of the MEMS device uses a self-supporting deformable reflective membrane and a thin-film stack tuned to a specific color and reflectance state. Each defined membrane area has two states of reflection: (1) the "open" state that allows the constructive interference to occur reflecting a set wavelength of color or (2) the "collapsed" state that only allows UV light reflection beyond the visible range.[105] The color states are divided into RGB areas. The gap distances are all on the order of hundreds of nanometers or less as dictated by the required interference modulation of a given color. One of the key construction challenges is the need to maintain very tight control of the thin-film layers across the display areas to ensure the correct color performance.

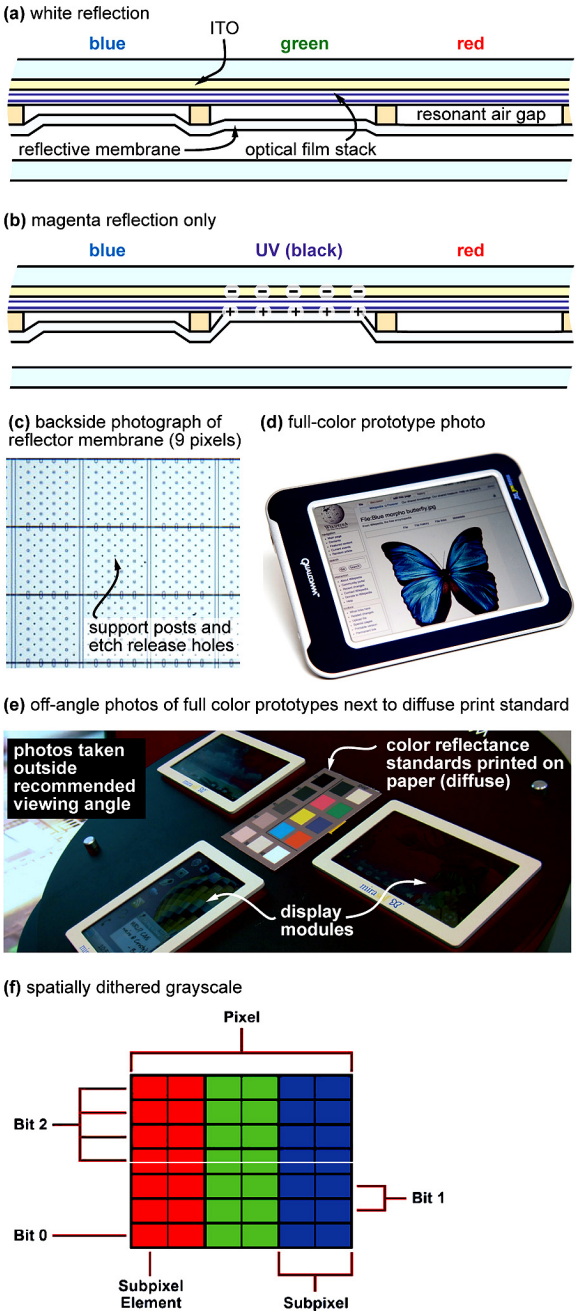


FIGURE 11 — Qualcomm MEMS "mirasol" technology: (a, b) pixel operation diagram; (c) backside zoom-in photos of pixel; (d) full-color prototype at recommended view angle; (e) full-color prototype outside the recommended viewing angle; (f) diagram of technique for spatially dithered gray scale.

Optical performance: The overall optical performance of a colored mirasol device is constrained by the total light reflected by each area, limiting reflectance of the color device because each area only reflects a single color. The

reported design uses RGB striped pixels. RGBY designs have been made and reported.[106] The color gamut of a simulated RGBY array is ~27% of the sRGB specifications and provides an increase in contrast of 16% over RGB. Other physical factors in the device construction of the MEMS array combine with the color architecture to result in an overall reflectance of ~23% (demonstrated at Display Week 2010).

The mirasol technology will be best suited to personal viewing devices such as e-Readers, smart phones, and tablets, in which the user can adjust the viewing conditions readily, and where color and video response is highly desirable. A challenge for this technology is the dependence of display optics on viewing and illumination angle – the color and contrast can be altered due to the nonconstructive interference of light when light reflects at angles away from the surface normal [Fig. 11(e)]. The viewing-angle limitation, and fabrication complexity (*i.e.,* cost), probably precludes scaling to a large-area display without tiling modules.

Electrical addressing and gray scale: Gray scale is achieved by dividing each color area into subpixels that can be individually controlled for different amounts of light reflection per pixel (spatially dithered) [Fig. 11(f)]. In addition, time-based gray scale can be achieved since each subpixel can be rapidly sequenced between the open and closed states. The combination of spatial and temporal methods allows the mirasol devices to achieve 64 levels of gray scale per color.

The voltage required for mirasol displays (~5–10 V) is within conventional driver technology used for LCDs. The use of spatial dithering for gray scale requires more drive modules and interconnects than required for the same resolution LCD, though. Drive frequency will also be higher compared to LCDs due to the need to temporally dither the subpixels for improved gray scale. The combination of spatial and temporal gray scale means that the low-power latched state cannot support the same levels of gray scale that the higher-power driven state can achieve. The device is not inherently bistable like some e-Paper technologies, but the device can be effectively bistable by using a very-low-power holding voltage on each membrane.

Fabrication/environmental: Fabrication of the mirasol devices is accomplished using conventional LCD glass-factory equipment. The primary challenge is fabricating large-area MEMS devices with high yields, a manufacturing target that is unique to these displays. The majority of materials in the mirasol device are similar to the layers used in construction of the standard LCD backplane electronics. Because the materials used in the MEMS device are mainly metal oxide conductors and inorganic dielectrics, the operating temperature range of the mirasol displays should be extremely wide. One unique requirement of the MEMS device is the need to maintain a good vacuum level in the cell gap to allow the membrane to move freely. A desiccant layer is used in the device to remove gas species that can diffuse through the layers over time. Because of the complexity of the MEMS structure and the use of inorganic dielectrics it is unlikely that this technology can be processed on flexible substrates. On January 6, 2011, Qualcomm announced a $975M investment in a Taiwan production factory that is expected to be operational in 2012.

Outlook: The mirasol displays are the fastest-switching reflective devices on the market today. This inherent advantage makes them well-suited for applications that require video capability. The reflectance capability is limited to <33% due to the side-by-side color architecture. The other optical limitation is the limited viewing angle due to the very nature of the physics required to produce the color capability of the display. Colored mirasol displays are best suited for small single-user display applications such as e-Readers, smart phones, or other hand-held devices such as GPS or gaming devices where the user can control the angle of viewing to maximize the optical contrast.

4.10 Cholesteric liquid-crystal displays

History, maturity: Workers at Kent State University and Kent Displays, Inc., have pioneered the use of cholesteric liquid crystals in large-area and in high-resolution displays. Yang *et al.*[107,108] first demonstrated that simple voltage sequences can be used to reversibly switch a cholesteric liquid crystal between a colored reflective state and a transparent state. By placing such a pixel in front of a black absorbing surface, a viewer will either see a colored pixel (from the reflective liquid crystal) or a dark state (from the transparent liquid crystal in front of a black absorber). Since the displays are bistable, they can retain an image with zero power for years.

Cholesteric displays of one sort or another have been available for sale for over 10 years by Kent Displays, but continue to serve as an area of active development. New capabilities being developed include high-resolution tablets (Fujitsu), microencapsulated cholesteric films for flexible displays, electronic skins, rewritable pressure-addressed (Kent Displays), and large-area full-color near-video-rate displays for billboards (Magink), several of which are shown in Figs. 12(d)–(f).

Construction, materials, and physics: Cholesteric liquid crystals are a class of nematic liquid crystal. Like most nematic liquid crystals used in displays, the molecules are long and rod-like, and tend to show long-range order in the direction of the long axis of the molecule. The distinguishing characteristics of a cholesteric liquid crystal are that the molecular orientation naturally wants to twist, so that the orientation of the long axes of the molecules trace out helical domains. Cholesteric liquid crystals also exhibit textures, which depend on the orientation of these helical domains. In the planar structure, the helical structure persists over long distances through the cell and is oriented with the helical axis perpendicular to the cell plane. The planar texture strongly reflects light of a particular wavelength (similar to Bragg reflection), depending on the pitch (spacing of the helix repeat distance). The color reflected depends on how

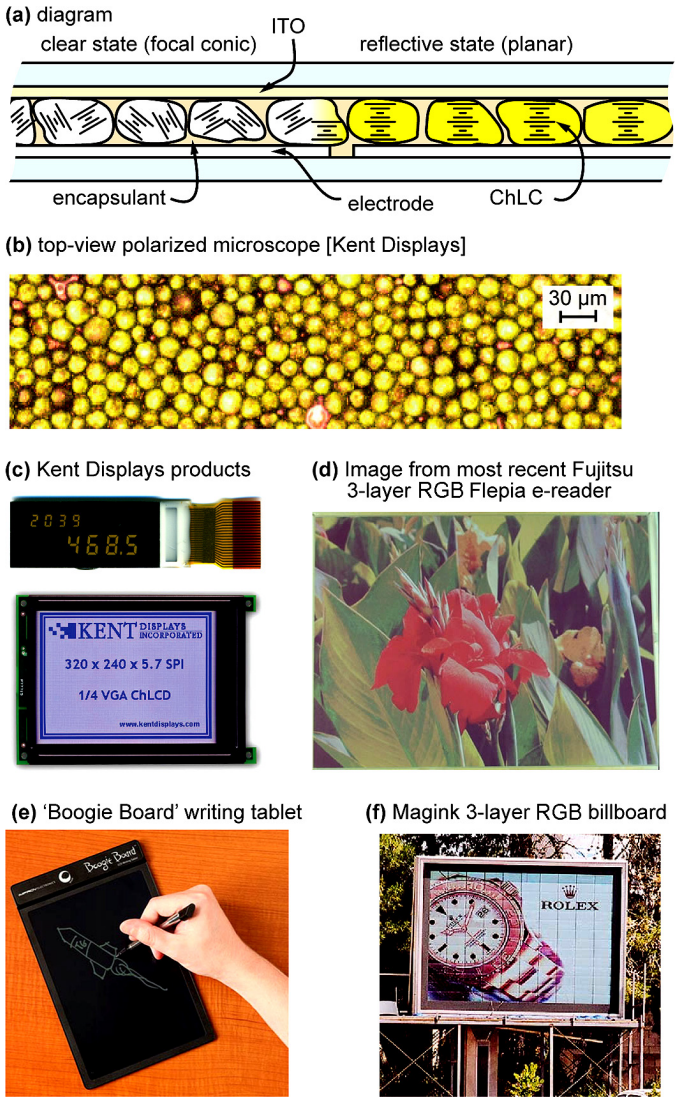


FIGURE 12 — Cholesteric liquid-crystal displays: (a) single-layer device diagram; (b) top-view microscope photos of cholesteric capsules; (c–f) photos of commercial display modules including single-layer monochrome, three-layer color, single pressure-driven layer writing tablet, and tiled three-layer color billboard.

tightly the cholesteric helix is wound and can be set by the chemical structure to reflect red, green, or blue light. If the helical structures are only uniform on a small-length scale and form multiple orientations (domains) with the cell, then the transparent focal-conic structure results.

Both the planar and focal-conic textures can be made stable so that the optical response of the liquid crystal remains fixed. Yang *et al.*[107,108] determined that a display device could be constructed by switching individual pixels between the focal-conic and planar states. This switching is accomplished by applying a strong enough field to unwind the cholesteric helix (putting it into a nematic-like homeotropic state), and then controlling how quickly the helix snaps back as the voltage is removed. A cholesteric liquid crystal can be microencapsulated and still retain this general behavior [Fig. 12(a)]. Microencapsulated cholesteric liquid-crystal films have been demonstrated as ultra-flexible cloth-like displays,[109] or multi-color electronic skins integrated into curved plastic packages.[110]

Optical performance: The planar texture of a cholesteric liquid crystal will reflect one particular circular polarization over a certain wavelength range. This means, at best, only 50% of the incident light can be returned by a single pixel.[111] Overall reflectivity is also reduced since the reflectivity is peaked at a central wavelength in each band. Full-color operation is typically achieved by stacking red, green, and blue panels, and individually switching each layer.[112] The achievable color gamut depends on the quality of the liquid-crystal alignment, on the display illumination conditions, and the effect of specular reflections off the multiple interfaces in the display stack. The quality of green and blue colors can be reasonably good, but the physics of liquid crystals often results in a desaturated red. Dyes or filters are sometimes used in conjunction with the cells to improve color saturation.[113,114]

Currently, the Fujitsu specifies that its FLEPia e-Reader (BGR stacked cells) product possesses a 33% reflectivity and greater than 6:1 contrast ratio.[115] Coates has reported that the Magink tiled cholesteric billboard (9-mm pixels), under optimal lighting conditions, can provide a white reflectance in the range of 30–32% and a contrast ratio up to 40:1.[116]

Electrical addressing and gray scale: The voltage necessary to unwind the cholesteric helix tends to be over 10 V, though a recent paper reports developing a cholesteric material that requires less than 4 V for addressing.[117] This unwinding process has a strong threshold, so cholesteric displays can readily be passively addressed. One early challenge for cholesteric displays is that it can take over 10 msec for a stable texture to form, so that line-by-line addressing of a display becomes quite slow. A major breakthrough was made by a group at Kent State, who discovered that it was only necessary to control a short, critical time during the evolution of the cholesteric texture.[118] This behavior enabled the development of pipeline-addressing algorithms, which address multiple lines at once and results in dramatically faster display updates.[119,120] Fujitsu specifies that its FLEPia reader can update a 1024 × 768 (XGA) image in 0.7 sec.[121]

These pipeline-addressing schemes are still too slow for video-rate addressing, but it is possible to achieve faster speeds by either using an active-matrix panel, or direct drive schemes, to separate the panel into several sections that are addressed simultaneously. It is also possible to switch directly between the transparent homeotropic and colored planar textures, giving up passive addressing but dramatically increasing the response time. Magink has publically demonstrated color video images and claims a 60-frame/sec update speeds for its RGB-stacked cholesteric billboard displays over a range near ambient temperatures.[122]

Pressure will also disrupt the cholesteric texture and can convert a transparent focal-conic structure (which appears dark in front of a black background) to a brighter reflective

planar texture. This effect is used by Kent Displays in a pressure-sensitive tablet [Fig. 12(e)], in which a stable image is written with a stylus and the film reset by a short voltage pulse.[123]

Fabrication/environmental: Glass-based cholesteric cells can be built using conventional liquid-crystal-display fabrication techniques. Plastic-based cells can be built on a roll-to-roll basis with microencapsulated or polymer-dispersed cholesteric liquid crystals. Due to their long history, the environmental stability of cholesteric displays is similar to other types of LCDs. Performance at different temperatures is a concern for most LCDs, so compensation circuitry, heaters, and fans are necessary for outdoor usage. Most often, the power demands of controlling temperature and providing additional light for outdoor night use dominate the power budget of the display.

Outlook: The optical performance of cholesteric LCDs tends to be somewhat poorer than other types of electronic paper, though Fujitsu has recently announced a major improvement in brightness and gamut.[115] More so than other technologies, cholesteric displays have seen usage in a variety of different form factors, such as signs, electronic skins, indicators, and rewriteable tablets. The future success of cholesteric LCDs most likely depends on identifying the unique applications for these unusual materials, as it does on competing with other e-Paper technologies in mainstream applications.

4.11 Other reflective liquid-crystal displays

Conventional reflective polarizer-based liquid crystal: Since backlit AMLCD technology is so strongly established, reflective AMLCDs would seem like a natural competitor to other e-Paper technologies. To date, though, reflective polarizer-based LCDs have not had much commercial success. Common wisdom states that the polarizer in an AMLCD absorbs too much light to serve as the basis for electronic paper, and the dim greenish visual performance of many reflective supertwisted-nematic (STN) displays has also worked against the perception of polarizer-based liquid crystals.

Not so obvious, though, is the fact that until recently there has been very little market interest in reflective high-resolution displays so that this area has not attracted much development. Many people are surprised to learn that a properly constructed single-polarizer reflective LCD can have a white reflectivity of over 40%,[124] and neutrally colored white states.[125] The optical losses associated with achieving 40% reflection are shown in Fig. 13. It is also possible to use dichroic dyes or scattering-type displays to build bright, colorful displays. Add in some innovative cell designs, and some strong contenders emerge from the ranks of liquid-crystal devices. Since many of these cells can be fabricated using established fabs, and operate at video rates, LCDs remain an intriguing alternative to other device modes. Wu and Yang[1] provide a detailed look at many

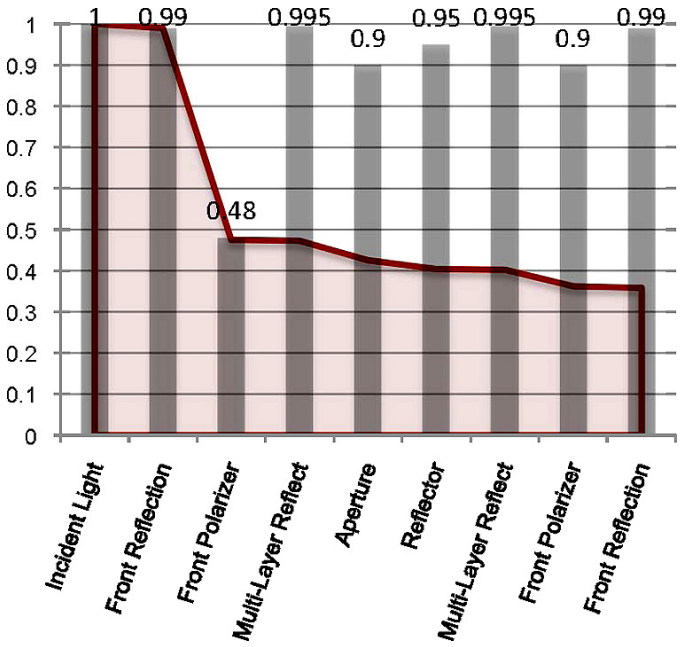


FIGURE 13 — Optical losses for a high efficiency TN-LC module (optimal materials), figure adapted from Grupp.[124]

reflective LCD technologies; here, we provide an updated perspective of several types of these displays (Fig. 14).

Guest-host liquid-crystal displays: Some of the earliest LCDs relied on the guest-host effect for optical switching. In these cells, the liquid crystals are blended with dichroic dyes, which have absorbance properties that depend on the orientation of the dye.[126] Guest-host systems are able to switch between dark and light states simply by changing the orientation of the liquid crystal (and therefore the dye) without the use of polarizers.

As mentioned earlier, Toshiba has demonstrated a three-level reflective guest-host display, which consists of stacked magenta, cyan, and yellow layers.[23] This 3.4-in. display, with three active-matrix layers, demonstrated 240 × 160 resolution at a 0.3-mm pixel pitch, with a white-state reflectivity of 43% and a contrast ratio of 5.3.

Zenith bistable: The Zenithally Bistable Display (ZBD) consists of a liquid-crystal cell in which one or both surfaces are covered by a grating.[127] This display can be passively addressed and is bistable. Switching occurs by driving the display to a homeotropic state using a DC voltage, relying on coupling to flexoelectric modes of the LC-on-grating structure.[128] The displays can be quite fast and are bistable, though the switching through the homeotropic state induces a flicker that makes video-rate switching problematic. ZBD Corp. has developed some high-brightness low-power displays aimed at shelf labels [Fig. 14(b)]. The group has also reported tuning the LCD-cell parameters to operate in the first maximum, which provides a superior white color compared to first-minimum displays.[125]

Polymer dispersed liquid crystal (PDLC): PDLC devices were the focus of intense development activity for nearly a decade starting in the mid-1980s. These devices consist of micron-sized domains of nematic liquid crystal

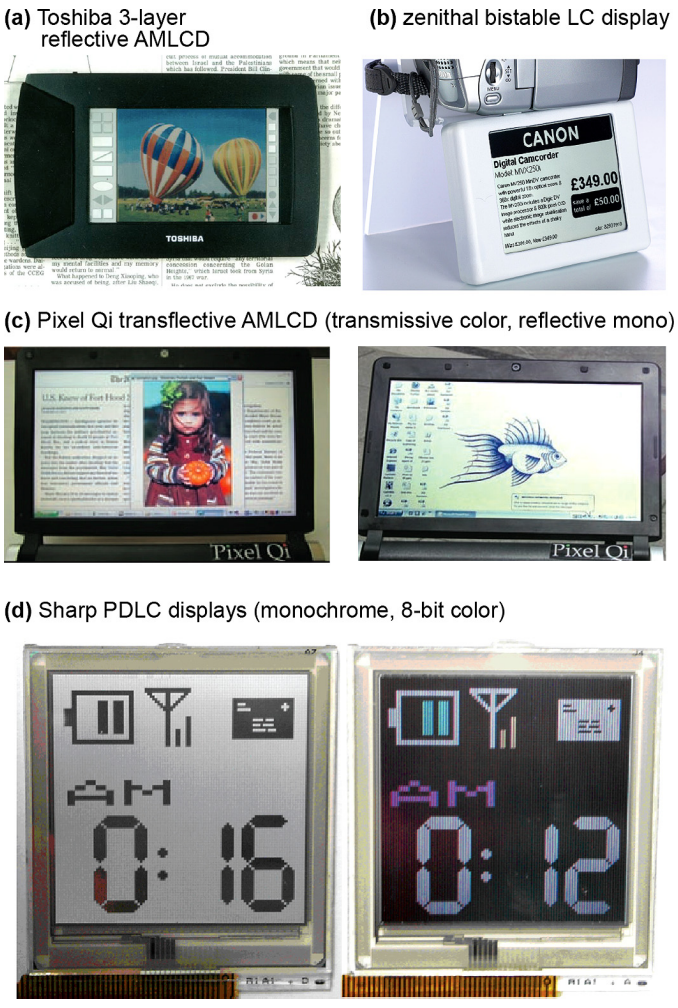


FIGURE 14 — Photographs of several demonstrations of reflective liquid-crystal displays. There is a diverse set of technologies, each with different performance strengths, and this figure only captures a small subset. It should be noted that the color image in (c) is for backlit transmissive mode.

dispersed in a polymer film.[3] Scattering-mode devices switch between a clear and a turbid (diffusing) state and have recently been used to produce low-power active-matrix reflective displays[129,130] [Fig. 14(d)]. Additionally, it is possible to incorporate a dichroic dye into some types of PDLC systems and produce a device that is highly absorbing and scattering in the low-voltage state, but weakly absorbing and transparent in the high-voltage state.[131] Fluorescent back reflectors have been used to provide enhanced brightness in area-color displays with a guest-host PDLC.[132] Such guest-host systems have been used to make large-area signs[133] and active-matrix displays.[134,135] Advantages of PDLC systems include continuous gray scale, fast switching, compatibility with many active-matrix backplane technologies, and compatibility with flexible substrates.

Surface-stabilized nematic displays: Durand and co-workers discovered in 1997 that a bistable LCD could be built using a particular type of surface treatment.[136] These displays rely on the reversible change of the surface alignment of an LC cell with voltage pulses, which enables either passive or active addressing in a polarizer-based display. Coined the BiNem display, this technology has been under steady development by the Nemoptic Corporation. In 2010, Osterman reported an active-matrix bistable display with 31% reflectivity, 10:1 contrast ratio, and a neutral white point.[137]

Outlook: The growth in interest in e-Paper applications has caused many laboratories to take another look at LCDs as an alternative to the currently dominant electrophoretic displays. While no solution is perfect, many liquid-crystal devices show reasonable performance in reflective mode. Since fabrication compatibility and cost are major drivers in the acceptance of new technologies, e-Paper devices based on liquid crystals will certainly be introduced for some types of applications.

4.12 Transflective liquid-crystal displays

Transflective LCDs possess a cell structure in which a portion of a pixel transmits light from a backlight, and the rest of the cell is reflective, using conventional nematic liquid-crystal switching modes.[138] While popular in many mobile displays, the reflective performance of colored transflective displays is usually modest, with white reflectivities of <11% being reported for RGBW designs.[139] A color-sequential transflective design has been proposed with a white reflectivity of 25% in the color reflective mode, indicating that substantial improvements can be made in principle through minimizing the transmissive aperture for each subpixel.[140]

Pixel Qi has made a major conceptual change in designing a transflective cell in which the reflective mode is monochrome, but the backlit mode is color. In this way, the color filters in the cell cover only a small area of the pixel, enabling the reflective state to remain relatively bright. Additionally, when color is desirable, then the display operates similarly to a conventional backlit AMLCD [Fig. 14(c), left]. This hybrid model of a display that is sometimes a monochrome e-Paper and sometimes color backlit display, is currently unique in the e-Paper realm. First products from Pixel Qi are scheduled to appear soon, at the time of writing this paper. Specifications indicate a 10.1-in. panel that in reflective mode will have a resolution of 3072 × 600, and a 27% reflective white state.

The benefits of video-rate operation, color on demand, and LCD fab compatibility are touted as the strong points for the technology. It remains to be seen how well the mode-switching behavior will work in real-life usage. Additionally, there is not currently a path towards high-quality reflective color using the Pixel Qi design, other than placing color filters over the reflective portions of the display, with the subsequent reduction in reflectivity.

4.13 Electromagnetic (EMD²) displays

The company Tred Displays is quietly developing a technology they label as an "Electromagnetic Display" (EMD²).

TRED's EMD[2] technology (Fig. 15) uses magnetic composite fibers coated with a white colorant on one side of the fiber and a black colorant on the other. Similar to conventional magnets, the fibers self-align due to their magnetic poles. The fibers are therefore bistable and can be flipped if an electromagnetic field is applied that is greater than the magnetic field stabilizing the fibers. The electromagnetic field is applied using inductors formed in a multi-layered printed-circuit board.

TRED claims switching speeds as fast at 50 msec, but the current density required to achieve this speed is not publicly available. According to J. Caruso of TRED, "A TRED display of four numerals (two superior, two inferior at a size of 17 × 9 in.) is approximately 5 mm thick, weighs less than 2 pounds, and 8 AA batteries could provide adequate energy for the display to run for about a year, when changing the image once or twice a day."[141] The company also claims ~80% white state. The TRED display is likely paper-like in viewing and illumination angle dependence. It is unclear based on available information if the technology can achieve high resolution or can be multiplexed to any degree, important requirements for many applications. The overall cost of the display will also be a consideration, including any reliance on nonstandard electronic drivers.

4.14 Photonic crystal displays

Photonic crystals refer to a class of structures that consist of periodic nanostructures with a spacing that interacts with the propagation of electromagnetic waves. Based on the spacing of the nanostructures, certain energy bands are allowed or forbidden for propagation, which can lead to the selective transmission or reflection of light. Dynamically changing the spacing of the nanostructures can change these propagation properties, leading to the modulation necessary to build a display. The term photonic crystal in displays is usually associated with three-dimensional periodic lattices, and the previously described MEMS interferometry (Sec. 1) is a special one-dimensional case of a photonic crystal.

Currently, there are two different photonic-crystal-based modulation approaches in development. Opalux is fabricating electrically color-tunable photonic crystals by embedding the lattices of 200-nm-diameter silica beads within an expandable electroactive polymer, which they call Photonic Ink or P-Ink.[142] Opalux has demonstrated bistable P-Ink with a reflectance >50% and switching speed ~0.1 sec.[143] The company has not described the viewing-angle dependence of their technology; photonic-crystal structures that possess highly regular crystal structures can show sharp dependences on illumination and viewing angles.

The company Nanobrick is developing systems that control the inter-particle distance of SiO_x-encapsulated metal nanoparticles (20–30 wt.%) in electrophoretic colloidal suspension.[144] These photonic crystal structures respond to signals of a few volts, shifting the reflected color through a continuous range as the average spacing changes. This enables full-spectrum tunability using a single electro-optic layer without requiring individual primary-color subpixels to generate color. It appears that the electrophoresis tends to randomize the structure somewhat, leading to reasonably wide viewing angles. Nanobrick has demonstrated a Color Tunable Photonic Crystal Display (CPD) with angle-independent optical responses (0–40°) using quasi-amorphous photonic pixels with response time <50 msec.[145]

While single-layer color tuning is a unique capability of the photonic-crystal approaches, the technology focus thus far has been limited to unit pixel or simple segments and still needs refinement in terms of the white state, reflectance *vs.* illumination condition, and demonstration with matrix addressing. Even though, in theory, colors such as red can be displayed at all pixels, white is still challenged

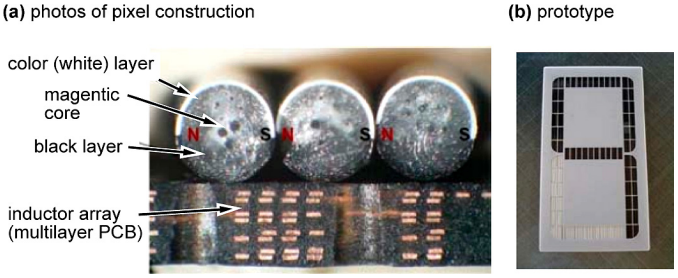


FIGURE 15 — Electromagnetic display: (a) cross-sectional photo with labels, (b) photo of a 9-in.-tall alphanumeric prototype.

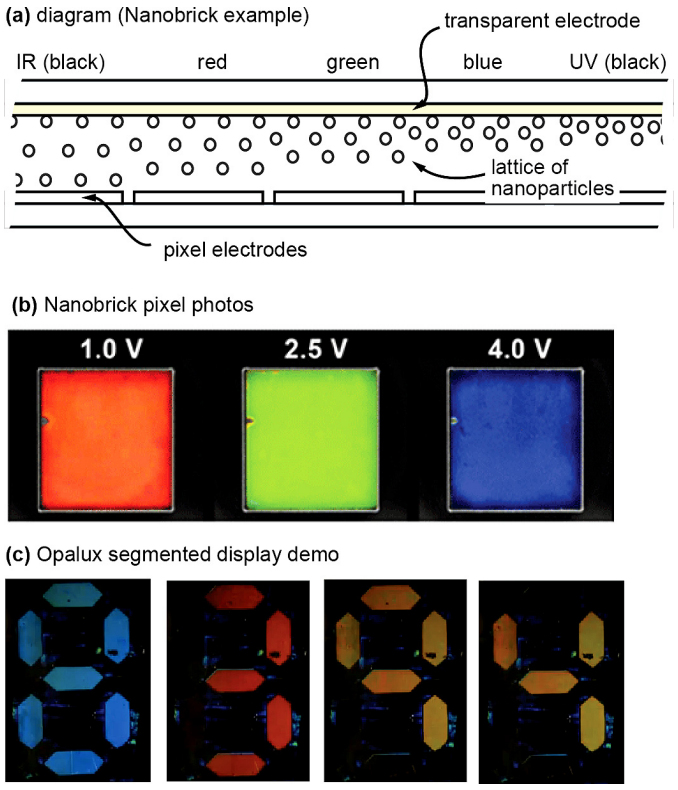


FIGURE 16 — Photonic crystal display: (a) diagram (Nanobrick example): (b) Nanobrick pixel photos; (c) Opalux segmented display demo.

because white will likely require additive display of side-by-side RGB pixels [similar to Fig. 2(b)]. Additionally, since pixels currently do not possess inherent gray scale, that means gray scale at the display level will require halftoning approaches.

5 Discussion

In this section, we will first summarize and discuss monochrome and then color e-Paper performance. The visual performance of e-Paper is determined by perceived contrast (ΔL^*), color gamut volume (colorfulness), tonal resolution (gray levels), spatial resolution (ppi), sensitivity to lighting and viewing angle, and electrical and switching performance. It is not prudent to cover all these topics in the discussion section, since such details are found in the technology sections. The two biggest performance attributes, reflectance and color gamut, will be comparatively discussed according to what capabilities have actually been achieved in display products and prototypes, and not just theoretical estimates.

There is not, and it is not likely that there will be, a single e-Paper technology that satisfies the requirements across all applications. However, several example e-Paper applications can be selected and competitive technology solutions matched. In the second half of this discussion section, five significant case studies will be discussed: e-Readers, e-labels, multimedia, billboards, and flexible/rollable. These applications are unique and have fairly clear performance requirements. As a result, e-Paper attributes beyond reflectance and color gamut must be discussed.

5.1 Summary of the monochrome e-Paper landscape

Table 2 provides a snapshot of the current monochrome performance of a number of e-Paper technologies. Monochrome e-Paper performance is critically important to understand, considering that so much conventional print is also monochrome. One observation that stands out immediately is that nearly all technologies struggle to reach monochrome SNAP requirements ($R \sim 60\%$). Beyond SNAP, only electrochromic[85] and in-plane electrophoretic technology has shown the possibility to reach monochrome SWOP ($R \sim 76\%$), and as discussed earlier both of these technologies have other issues that have prevented wide-spread commercialization. Also a challenge, the preferred color choice for most monochrome applications will be black and white (as is the case for current print). There are several technologies with good color reflectance, but currently poorer black/white performance (a "C" is noted next to their %R in Table 2). These technologies include: IMOD (MEMS) and cholesteric liquid crystal. Furthermore, electrochromic reports R&D results of bright white/black, but most products are only white/blue and well below SWOP performance. It is clear at this time that e-Paper with SWOP level white/black operation remains commercially unsolved.

The possibility exists that SNAP and SWOP standards could become less relevant with continued change-over from print to digital e-Paper media. After all, the Amazon Kindle does not even achieve SNAP, but has proven compelling for many consumers. Therefore, SNAP and SWOP should not be seen as absolute requirements for readable e-Paper, but rather goals to strive for. For some products, consumer perception of display brightness on the sales shelf will determine which product is purchased. Therefore, just being "readable" is not enough to maintain long-term competitiveness. Also, as monochrome e-Paper technologies reach SWOP, they will directly compete in appearance with monochrome backlit-LCDs, LEDs, or OLEDs. In conclusion, even though monochrome e-Paper is now widely available, improved monochrome performance seems worthy of significant R&D investment.

5.2 Summary of color e-Paper landscape

Color e-Paper remains largely unproven, except for commercialization of three-layer cholesteric e-Readers (Fujitsu FLEPia) and billboards (Magink). Current prototypes have color performance far below backlit LCDs. Examining Table 3, no technology is close to SNAP color performance in white reflectance, and those relying on RGBW color-filtering exhibit poor color gamut. Still, these displays offer other benefits (low power operation and sunlight viewing, just to name two) that backlit displays cannot currently match.

The pursuit of bright and saturated color presents the largest R&D challenge for e-Paper. It is impossible to discuss improved color without strongly considering color systems (Fig. 2). Several new color products (electrophoretic, electrowetting, and MEMS) are targeted for commercialization in 2011. All of these new products will use side-by-side RGBW or RGB color. This approach will provide perception of color, although colors will be highly muted. Still, limitations remain. Even if a perfect monochrome technology meeting SWOP performance (100% white and 0% black states) is developed and RGBW color filtering added, the color gamut will still be poor. Photoluminescent enhancement [Fig. 2(c)] may boost brightness and color gamut, but at the theoretical limit still cannot provide SNAP quality color.

To achieve uncompromised color, theory requires multiple colors available in the same pixel area (*e.g.*, three-layer e-Paper is required). Both the stacked color systems of Fig. 2(d) (RGB additive) and Fig. 2(f) (CMY subtractive) are equally compelling in possible performance. However, currently the only option for RGB additive is cholesteric liquid-crystal technology for which performance is far from SNAP/SWOP. We are not aware of any other credible approaches for additive RGB. As such, three-layer CMY appears to have the biggest potential gain in the pursuit of uncompromised color. Optically, the most promising technologies for stacked color e-Paper appears to be those using

TABLE 3 — Summary of performance and other key factors for color e-Paper technologies. References for data can be found in the associated sections in the article. Some of the technologies have not demonstrated color operation, so only calculated data can be provided. This data is purposely shown in a separate row.

	Electrophoretic (R&D)	In-Plane Electrophoretic	Electrokinetic	Liquid Powder	Electrochromic	Electrowetting	Electrofluidic	IMOD (MEMS)	Cholesteric	PDLC (guest host)	Reflective LC w/ Polar.
Color Schemes (from Fig. 2)	2b	2e,f,g	2e,f,g	2b	2a,2f	2b,e,j	2b,f,h	2a	2a,d	2a	2b
White %R (Theory*)	24%	-	-	15%	-	27%	35%	33%	50%	30%	>25%
White %R (Prototype)	22%	-	-	-	-	20% (2b)	-	23% (2a)	33%	18%	11%
Color Gamut (Theory)	poor	good	good	poor	uncertain	poor / good	poor / good	fair/poor	good	fair	poor
Color Gamut (Prototype)	poor	good	good	poor	unproven	unproven	unproven	poor	poor (e-Reader) good (signage)	poor	poor
Color SNAP/SWOP	No	maybe SNAP	maybe SNAP	No	maybe SNAP	maybe SNAP	maybe SNAP	No	No	No	No
Contrast Ratio	-	-	-	-	-	-	-	<8:1	40:1 (signage) 7:1 (e-Reader)	4:1	14:1
Lambertian	yes	yes	yes	yes	yes	partial	yes	no	no	partial	no
Frame Rate (Hz)	10 or less	>1	unkown	slow	slow	video	video, unproven	video	1-2 (PM) 30 (DD)	video	video
Matrix Drive	AM	PM	AM	PM	PM	AM	AM	PM	PM	AM	AM
Gray-Scale Approach	Pulse	Analog or Pulse	Pulse	multi-write	-	Analog	Pulse	Spatial/ Temporal	Pulse (PM) Analog (DD)	Analog	Analog
Gray-Scale Bit Level	4			-	-	-	-	6 bit	5		16
Maturity	AM demo	PM demo	AM demo	PM demo	no demo	AM demo	no demo	PM demo	product	AM demo	product

* Calculated as shown in Fig. 2, using the monochrome reflectance listed in Table 1

horizontal colorant transposition (in-plane electrophoretic, electrokinetic, electrowetting, and electrofluidic). However, horizontal colorant transposition is still commercially unproven even in single-layer form. Also, the optical losses are severely compounded in stacked displays, and all aspects of the pixel must be improved.

In applications where cost must be low, speed must be fast, and/or high resolution is needed, three-layer stacked systems may not be viable. For this reason, color e-Paper that is better than RGBW, but not still true color, might find some application space. In theory, a near doubling of the brightness and color-fraction can be achieved using a two-layer stacked system or single-layer co-operative systems such as bi-primary.[26] These color systems and technologies might move close to several aspects of color SNAP.

5.3 Brief application case studies

e-Readers are currently enjoying robust commercial success, after years of tepid market interest in both LCD- and EPD-based devices. The breakthrough event was the introduction of the Amazon Kindle, which was the first e-Reader to achieve a high level of commercial success. Unlike previous e-Readers, the Kindle made available a vast library of content, provided access to this content in a convenient wireless form, and displayed this content with a paper-like (EPD) display. Continued improvement in the device performance, dramatic reductions in price, the rise of competitors, and market acceptance of single-function reading devices has made e-Readers an established product category.

The future of e-Readers continues to evolve, though, as the functionality of mobile devices continues to evolve. Tablets and smart phones using conventional LCD or OLED technologies are adding e-Reader functions, and e-Readers are being launched with LCD technologies, competing through super-low cost or the availability of color and video. The future of the e-Reader discussion seems to unavoidably connect to the broader area of mobile-device content delivery, which will be discussed later in this section.

e-labels are a second application to consider. This term can be applied broadly to include indicator scales such as memory on USB flash drives, simple clock/timing information readouts on appliances, flexible electronic skins, and toys. A highly attractive e-label market is electronic shelf labels (ESLs) for digital display and update of pricing in stores. ESLs are a great example where the combination of low power and the desire for a print-like appearance enables monochrome e-Paper to excel over back-lit LCDs. A practical ESL must consume so little power that multiple-year battery lifetime is achieved, be highly readable in a store environment, and have sufficient pixel count, size, resolution, and form factor to provide the information needed on a shelf label. This market is mainly enabled by providing cost savings to the store over time, trading off the extra costs of the displays against the labor savings in manual updates of product pricing at the shelf. So, only inherently low-cost technologies can meet the needs of this market.

Mobile-device content delivery is a huge and therefore attractive target for many e-Paper technologies. The primary attractiveness of e-Paper is low power operation and sunlight viewing, two issues always of concern in mobile devices. e-Paper adoption in these applications has been held back by the need for high resolution, good color, and video-rate operation with gray scale. Of the technologies reviewed here, the list of candidate technologies dwindles quickly to reflective liquid crystal, liquid powder, electrowetting, electrofluidic, electrokinetic, and MEMS. Since color e-Paper is always dimmer than its monochrome version, only technologies with high inherent brightness can overcome the reduction in reflectivity that is inevitable in moving from monochrome to color operation. Based on current performance, polarizer-based reflective liquid-crystal and liquid-powder technologies are weak candidates. The remaining contest is between MEMS, electrowetting, electrofluidic, or stacked liquid-crystal technologies. At the present time, major questions for MEMS regard manufacturing yield and cost, and whether <25% reflectance and narrow viewing/illumination angle are acceptable to consumers in a mobile environment. Electrowetting color performance is similar to MEMS, and simpler manufacturing may provide a significant advantage over MEMS. Electrofluidic technology has the potential to provide a greater reflective aperture for pixels, and therefore achieve a visually appealing color for multimedia, but such performance is unproven at this time. Stacked LCDs suffer from fabrication complexity, and the lack of compelling reflective color LCDs, despite the dominance of LCD technology, speaks poorly.

It is interesting to note that during video operation many e-Paper technologies consume significant power, which reduces the power-savings advantage compared to backlit or emissive displays. As a result, e-Paper applications may be best suited for devices where a mix of video and still images are commonly used. Lastly, we note that the success of purely reflective multimedia will also be affected by progress in bright transflective (*e.g.,* Liquavista electrowetting, Pixel Qi LCD) and non-liquid-crystal transmissive technologies (*e.g.,* Pixtronix *etc.*) or by advances in battery technology, making low-power operation less important.

Billboards are unique from most other e-Paper applications in several ways: (1) the pixels can be very large, (2) having a front-side illumination source at night is easily achieved, (3) color performance is critical since the customer is often an advertiser, (4) the high price of LED-based billboards means a lower-cost electronic equivalent display is attractive, (5) the application is inevitably outdoors, requiring exceptional durability and wide-temperature-range performance. For color billboards, three-layer (RGB) cholesteric liquid crystal is being deployed by Magink with limited reflectance (<35%) and near-video-rate switching. We note that digital signage is a rapidly growing area, and the bright-light viewability of e-Paper will be attractive even for many indoor applications. At this time, improved technology for billboards and large signage might come from three-layer (CMY) horizontal colorant transposition (in-plane electrophoretic, electrokinentic, electrowetting, electrofluidic). By going to large pixels, optical loss at pixel borders and TFTs is nearly eliminated. Understanding the optical losses in stacked displays is quite complex, and it is uncertain at this time if colorant transposition can be compelling for billboards.

Flexible/rollable presents an opportunity that some e-Paper technologies are well-positioned to serve. PolymerVision has determined[5] that using proven display materials and substrates, a rollable electrophoretic display with a <0.5-cm bend radius must be at most 100 μm thick to avoid mechanical degradation over time. Many applications for rollable will require active-matrix addressing to allow large portable multi-media screens that can be compacted (rolled, folded) for storage in a pocket. Assuming 25 μm for each of the two substrates and 10 μm for an organic active-matrix backplane, only 40 μm is left for the active pixel layer. The need for thinness, and creation of color without layer stacking, immediately eliminates the competition to technologies like electrophoretic/electrokinetic, liquid crystal, and electrofluidic. Also, because of thinness, color systems (and color gamut) are therefore limited to RGBW or single-layer bi-primary. The need for video may further limit the technology options to electrofluidic. The first rollable products from PolymerVision are expected to utilize conventional electrophoretic technology, and currently PolymerVision and Gamma Dynamics are jointly pursing rollable electrofluidic displays.

6 Summary

Despite the commercial success of flat-panel displays, serious shortcomings exist in mobile devices and in sunlight-viewable applications. Numerous e-Paper technologies have been developed that surpass conventional LCDs in sunlight viewability and in low-power consumption. It is exciting to note advances in rollable active-matrix backplanes, flexible

packaging and electronic components, flexible power sources, and even solar-power integration into displays. The development of these varied technologies make the dream of a flexible, wireless, and connector-free e-Paper device fully conceivable. While devices like these are quite exciting, we are still some time away from true full-scale commercialization.

Beyond much of the hype, monochrome e-Paper will continue to create new applications and grow in existing applications such as e-Readers and electronic shelf labels. In monochrome mode, no single technology is compelling enough to satisfy all applications, so even if electrophoretic displays continue to dominate, other technologies will likely succeed on a smaller scale. Meanwhile, full compatibility with the applications driving growth in mobile displays requires commercially compelling color e-Paper. In this review, we connect the conventional print-based color requirements such as SNAP and SWOP to e-Paper displays, demonstrating that e-Paper performance still has a long way to go before it serves as a truly paperlike medium.

SNAP requirements are a realistic near-term target for e-Paper performance, with SWOP serving as a long-term goal. Today, in low or dark ambient lighting, transmissive and emissive displays exceed the color gamut of SNAP and SWOP print, and often oversaturate colors. Considering that most real-world surfaces are colored with pigments offering capability equal or lesser to those used in SWOP printing, properly shown real-world images on any display technology need not exceed the color gamut of SWOP.

The competitive technology space is changing rapidly. Several liquid-crystal technologies are now being revisited as other technologies struggle to meet all of the demands for application in the marketplace. Price for products using electrophoretic are dropping rapidly. Major investments in technologies such as MEMS and electrowetting are aiming to create the first credible color-video e-Paper products. Electrophoretic and electrowetting have seen the addition of holes or reservoirs to aid colorant compaction, branching into electrokinetic and electrofluidic displays, respectively. No technology is staying still, and we expect that the e-Paper field will continue to evolve.

It is a unique time for the area of e-Paper, with an unusually large number of competing technologies, which will likely reduce in the coming years. It was our goal in this review to highlight a need for further investment in e-Paper research and development. It is also our goal that researchers leverage visual standards such as SNAP and SWOP to benchmark performance, and closely consider the potentially dominant influence of color system choice on the future of color e-Paper. Lastly, it was our goal to provide much needed insight into the true strengths, weaknesses, and future potential for e-Paper technologies.

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