Full Color Reflective Electronic Media

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Abstract

Just as HP is leading the transition to individually tailored content consumption for printed media with variable data printing from its digital presses, it is also actively pursuing full-color reflective display technologies as an electronic media in support of low-power applications for digital content consumption. A great challenge in realizing the potential of reflective electronic media is achieving vivid full colors that match or exceed the color gamut described by printing standards such as the Specifications for Newsprint Advertising Production (SNAP). Based on the principles of color printing, a stacked device design using a novel electrokinetic architecture has been proposed that offers the potential for achieving or exceeding SNAP's color gamut. Proprietary electrically addressable imaging fluids (electronic inks) have been developed to support such design. Electronic inks with CMY primary colors have been demonstrated to exceed the chroma values of SNAP in a single layer. Integrated into a stack of electro-optic layers employing HP's electrokinetic architecture, these inks have enabled a reflective full-color electronic media demonstrator built on roll-to-roll manufacturing platform with a color gamut approaching that of the SNAP standard. In this paper we report the development of full color electronic inks and demonstration of stacked full color reflective segmented and pixilated active matrix devices.

Introduction

Since the initial demonstration of the principle and construction of a reflective electrophoretic display more than 30 years ago [1], tremendous progress has been made in making electrophoretic reflective display a commercial success, for example, the rapid adoption of eBook readers using E-Ink Corporation's micro-encapsulated black and white electrophoretic display film [2]. In the digital age, individualization of content consumption, convenience and environmental consciousness of consumers continue to drive the development of electronic paper (media). In addition to being flexible, light weight, superior sunlight readability and easier on the eye, reflective electronic media that rely on ambient light for illumination and electrical field for electro-optical effects consume very little power [3] and thus are environmental friendly from the energy consumption perspective. Elimination of paper also contributes positively to the conservation of the environment. However, a great challenge in realizing the potential of reflective electronic media is achieving bright, high quality full color images. Conventional displays typically use a combination of side-by-side color elements and electro-optic layer to generate additive color (for example, RGB color filters). Since reflective display relies solely on ambient light for illumination, the image will be bright and colorful only if the incident light is reflected efficiently. Side-by-side color approaches devote portions of each pixel area to only certain colors, they inherently absorb the majority of the incident light and thus are inefficient (<50% efficiency), resulting in limited color gamut volume [3, 4]. Similarly, approaches that rely on polarized light also absorb major portion of the light and are not efficient.

At Hewlett-Packard (HP) we are approaching the challenge of generating bright, high quality reflective color images from the perspective of printing by layering subtractive colorants (CMYK) to allow every available color at every addressable pixel location. HP has been developing enabling technology platforms such as flexible roll-to-roll manufacturing platform, electrokinetic technology platform, electrically addressable imaging fluids (electronic inks), and active matrix backplanes based on transparent metal oxide TFTs (thin film transistors).

We have previously reported the development and application of HP's electrokinetic architecture and electronic inks to thin, flexible, segmented and reflective "electronic skins" (eSkins) [4, 5] as well as integration of reflective color media with transparent metal oxide TFTs [6, 7].

In this paper we report the development of full color electronic inks and demonstration of stacked full color reflective segmented and pixilated active matrix devices.

Electrokinetic Technology and Stacked Architecture

Conventional electrophoretic architectures (e.g. E-Ink's Vizplex™ film) are based on out-of-plane switching with out-of-plane optical effects, where the colorant particles are primarily moved perpendicular to the plane of the film [2]. These architectures do not allow transparent state for print-like full color. Alternative in-plane electrophoretic architectures are based on in-plane switching with in-plane optical effects, where the colorant particles are primarily moved parallel to the plane of the film [8, 9]. While the in-plane electrophoretic architectures provide a transparent state to enable stacked layers for full color displays, they are generally limited by trade-offs between clear aperture and switching speed in addition to requiring electrical cross-over of in-plane electrodes which increases manufacturing complexity. To address these issues, HP has developed a hybrid architecture adopting out-of-plane switching fields with in-plane optical effects. Response times are improved compared with in-pane electrophoretic devices by reducing the distance the colorant particles have to travel and increasing the driving force applied to the particles. A large clear aperture is achieved through a uniform distribution of dot arrays to minimize the areas where colorant particles are compacted. Since the control of the multiple electrokinetic forces leads to the compaction and spreading of colorant particles, the technology is termed “electrokinetic” media.

The novel eletrokinetic device architecture is illustrated in Figure 1a. As shown there is a transparent state when the colorant particles are compacted and a colored state when the colorant particles are spread. Shown in Figure 1b is an optical profilometric image of the imprinted media fabricated by R2R manufacturing platform.

Figure 2 depicts a schematic cross-section when the electrokinetic front plane is integrated with a metal oxide TFT back plane.

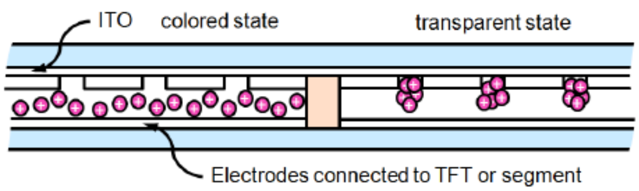

Figure 1a *Schematics of Novel Electrokinetic Device Architecture: Colored and Transparent state.*

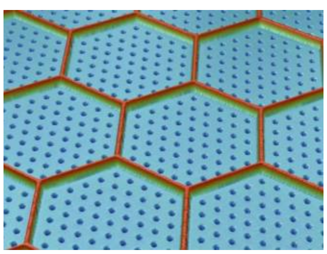

Figure 1b *Optical Profilometric Image of Imprinted Media*

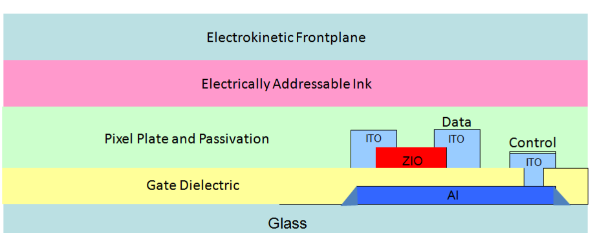

Figure 2 *Schematics Cross-Section of Integrated Front and Back Plane*

Colored Electronic Inks

Leveraging HP”s several successful encompassing digital printing technologies, we have developed electrically addressable imaging fluids (electronic inks) that are suitable for the novel electrokinetic architectures.

As illustrated in Figure 3, a typical electronic ink contains non-polar carrier fluids, colorant particles, dispersants and charge directors. Typical non-polar carrier fluids are hydrocarbons that possess fairly high boiling point, high resistivity and low dielectric constant. At HP, we have used pigment particles as the colorant particles. These particles are suspended and charged in the carrier fluids by dispersants and charge directors. Charging mechanisms have been hypothesized to include acid-base interactions between the particle surfaces and surfactants, adsorption of ionic species, and competitive adsorption of oppositely charged micelles [10, 11, 12, 13].

We have previously reported black and white electronic media based on electrokinetic technology platform that are relatively fast switching (<500ms) and have reflectance of greater than 60% with contrast ratio of 30:1. Low power holding of transparent state (<1 $\mu W/cm^2$ at ~5V) and grey scale of more than 3 bits has also been demonstrated previously [7]. We have since developed the full color capability which includes electronically addressable imaging fluids (electronic ink) with three primary subtractive colors: C, M, and Y.

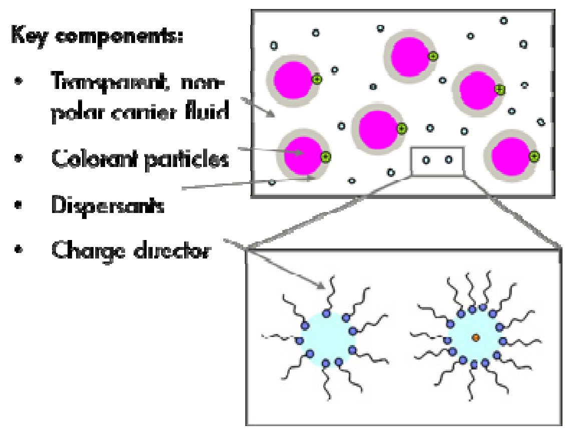

Figure 3 *Schematic of HP’s Proprietary Electronic Ink*

These electronic inks are incorporated into the electrokinetic architectures to generate reflective display elements. Figure 4 shows optical images of the three primary colorant (CMY) electronic inks in individual electrokinetic devices in the colored state (a) as well as the transparent state (b) respectively. Without an applied voltage, the pigment particles are spread uniformly and the display element is in the colored state. Under a bias, the pigment particles are compacted into the dot-patterned cavities yielding a transparent state for the display element. These individual devices are characterized in color and compared with Specifications for Newsprint Advertising Production (SNAP). For reflective color devices, printing standards (designed for reflective images) are preferable to conventional display standards (designed for emissive/transmissive images) for evaluating image quality. SNAP are standards used for newspaper ad inserts in the printing industry and are well known to advertisers. Significantly SNAP requires ~57% peak reflectivity which cannot be achieved by color filter or polarization approaches that are <50% efficient. In addition, it is also important to consider the complete color gamut achievable.

(a) Colored state (b) Transparent State

***Figure 4** Microscopic Images of Electrokinetic Devices in Colored and Transparent State Respectively*

Chromaticity measurements are conducted using i1 Basic Pro from X-Rite Incorporated with D50 illumination and 2º observer. The results for individual device of each color using 99% Reflective Lambertion reflective standard from LabSphere are summarized in Table 1 along with corresponding values from SNAP. The measured values are both brighter and more colorful than SNAP. The switching speeds of these devices are relatively fast (<500ms).

Table 1 Lightness and Chroma Values for Single Layer CMY

Particle Color	Lightness (L*)		Chroma (c*)	
	SNAP	Measured	SNAP	Measured
Cyan	56.58	63.9	35.32	63.9
Magenta	52.69	55.9	44.15	70.1
Yellow	76.57	89.4	54.87	71.9

Integrated Full Color Devices

The single devices of three primary colors made from imprinted electrokinetic media and segmented electrodes on plastic films are integrated into a stacked segmented full color device. Figure 5 (a) and (b) are snapshots of the video captured when the device (75mmx75mm in view area) is switched to demonstrate a variety of the colors achieved as compared with a SNAP card around the device. Chromaticity measurements of this stacked device are plotted against the SNAP values and a modeled color performance based on a commercial black and white device with a modeled color filter along with values for single layer devices (Figure 6). HP's full color reflective e-media exceeded the chroma of SNAP in majority of the color space and is far superior to that from a black and white device with modeled RGBW color filters. The white state and composite black state has a lightness difference of 41.6 with 32.1% and 3.4% in reflectance respectively, yielding a contrast ratio of 9.4:1. This value compares favorably to the contrast ratio of 6.8:1 from the modeled performance using a modeled color filter with a conventional black and white device. The difference in chroma between the single layers and that of the stacked device represents the potential for improvement in color performance of the stacked device.

(a) One State with SNAP Card (b) Another State with SNAP Card

***Figure 5** Video Snapshot of a Stacked Segmented Full Color Device (75mmx75mm) with SNAP Card around the Device*

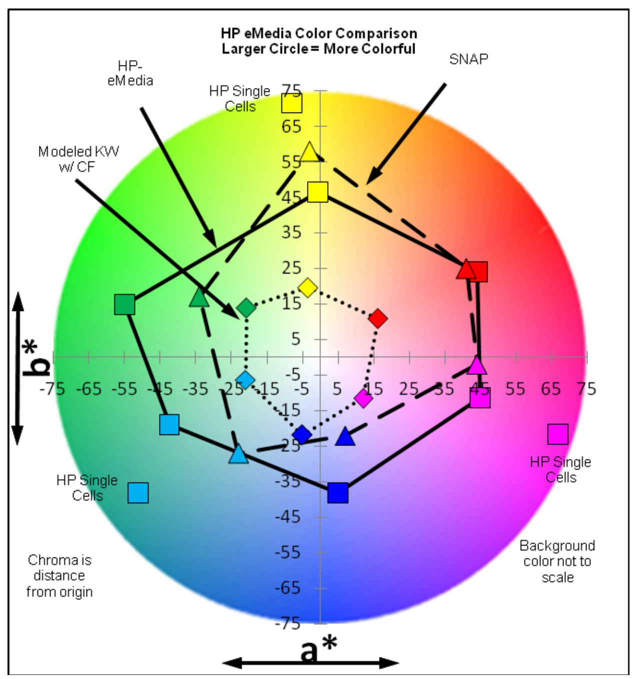

***Figure 6** HP Full Color Segmented eMedia Color in Comparison with SNAP and a Modeled KW Device with Color Filter*

The electrokinetic frontplane and electronic inks have also been integrated with transparent active matrix backplanes of metal oxide TFTs and stacked to yield a full color pixelated device (Figure 7). Pixels in this device are approximately 500µm by 500µm which is determined by the dimensions of the active matrix backplane. There are 16384 pixels (128x128) in each backplane with 65mmx65mm viewing area. Improvement in yield and optimization in the TFT backplane as well as stacking are expected to enhance the optical performance.

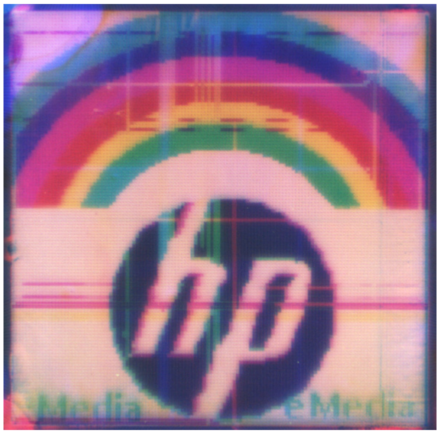

Figure 7 *HP Full Color Active Matrix eMedia (65mmx65mm)*

Conclusions

World class full color segmented and pixelated electronic media have been demonstrated. The chromaticity of these devices are approaching and in some area exceeding that of SNAP printing standard. The full color electronic medias are enabled by HP proprietary electronically addressable color imaging fluids and novel electrokinetic architectures that can be layered. These devices can be processed through roll-to-roll manufacturing and can be driven by active matrix backplanes. These reflective, low power, full color, print-like media will lead to eco-friendly, bright, full color and flexible e-paper/e-media applications in conventional printing and new markets.

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Author Biography

Qin Liu received her Ph.D. in Mat. Eng. Sci. from Virginia Tech (1992). She has being engaged in research and development on polymeric materials, formulations, processes and applications first at Novartis and then at Hewlett Packard for the last 19 years. Her experiences span textiles, contact lenses, thermal inkjet printing, fuel cells, and flexible displays. She is currently a member of the technical staff developing full color electronic media.