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Novel flexible reflective color media with electronic inks

Tim Koch[a*], Jong-Souk Yeo[a†], Zhang-Lin Zhou[b], Qin Liu[a], Jeff Mabeck[a], Gregg Combs[a], Vincent Korthuis[a], Randy Hoffman[a], Brad Benson[a] and Dick Henze[b]

[a]*Hewlett-Packard Company, 1000 NE Circle Boulevard, Corvallis, OR 97330, USA;* [b]*Hewlett-Packard Laboratories, 1501 Page Mill Road, Palo Alto, CA 94304, USA*

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A novel architecture and proprietary electronic inks were developed to provide disruptive digital-media solutions based on an electrokinetic technology platform. The flexible reflective electronic media (eMedia) was fabricated by imprinting three-dimensional microscale structures with a roll-to-roll manufacturing platform. The HP technologies enable the required attributes for eMedia, such as low power, transparency, print-quality color, continuous levels of gray, and low-cost scalability. Pixelation was also demonstrated by integrating with the prototype oxide thin-film transistor backplane, and the system architecture was further developed by stacking primary-colorant layers for color reflective-display application. The innovations described in this paper are currently being developed further for the eSkins, eSignage, and ePaper applications.

Keywords: electrokinetic; reflective; flexible; roll-to-roll; oxide TFT; stacked color system

1. Introduction

With the widespread adoption of E Ink Holdings, Inc.'s micro-encapsulated black-and-white electrophoretic display film for eBook readers, low-power reflective displays have drawn much attention from various research groups in the academia as well as industry [1]. While the black-and-white reflective-display technology has been successfully commercialized, the market is yet to see a convincing color reflective-display solution. Reflective displays are expected to provide a user interaction similar to that provided by printed paper, with the added versatility of dynamically refreshed images. Unlike the conventional transmissive or emissive display, the reflective display does not generate photons, but merely reflects ambient light as efficiently as possible to produce colorful images. Thus, the direct adoption of the conventional techniques in generating display color, such as the polarizer-based, lateral-colorant, or monochrome-plus side-by-side color filter approaches, does not lead to bright or saturated color solutions in reflective displays. In this paper, a print-like color electro-optic device is described using a novel system architecture and new electronic ink. The resulting color reflective display has the qualities needed for an electronic media designed to replace printed paper with low power, excellent viewing angle, and fast switching speed.

2. System architecture for print-like color

Low-power color reflective displays require system and electro-optic device architectures that are optically and electrically efficient. To meet these challenges, HP has adopted the approach of 'Print' rather than 'Display' in system architectures by layering subtractive colorants (CMYK) to allow every available color at every addressable pixel location. This system of electronically addressable layered colorants to achieve saturated color is similar to the subtractive primary approach adopted by the printing industry. Layered colorants in eMedia can be enabled by stacking electro-optic layers that are modulated between colored and transparent optical states. The optical and electrical performance of individual electro-optic layers is critical to the overall performance of a stacked color system.

The visual performance of a reflective display is determined by perceived contrast (ΔL^*), color gamut volume (colorfulness), tonal resolution (gray levels), spatial resolution (pixels per inch (ppi)), sensitivity to lighting and viewing angle, and switching speed performance. The choice of electro-optic switching technology determines attributes such as tonal resolution, spatial resolution, viewing angle, and switching speed performance, while the color gamut and contrast ΔL^* can depend strongly on the architectural arrangement of the system design. As the

*Corresponding author. Email: tim.koch@hp.com
†Current address. Yonsei University, 162-1 Songdo-dong, Yeonsu-gu, Incheon 406-840, Korea.

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conventional-printed-media advertisers are accustomed to standards such as Specifications for Newsprint Advertising Production (SNAP) for newspaper ad inserts and Specifications for Web Offset Publications (SWOP) for magazines and other high-quality printing, the performance of color reflective eMedia should be evaluated based on these standards for eMedia, so it could be regarded as a viable replacement for printed paper. Meeting SNAP requires 60% white-state reflectivity (82 lightness L^*), a value that many existing color reflective technologies utilizing polarization effects or side-by-side color filters have difficulty achieving due to fundamental technology limitations. Figure 1 shows how brightness and contrast compare for printing and various reflective-display technologies. Inkjet printing and the magazine SWOP standard have very high brightness and contrast, so they appear in the upper-righthand corner with high white-state and low dark-state lightness values. The HP technology presented herein is predicted to meet or exceed the SNAP printing standards using a system of layered colorants. White-state lightness meeting SNAP from monochrome devices was demonstrated and will be continually improved for full-color application [2].

3. Novel electrokinetic architecture

To achieve low power for mobility, a good viewing angle for paper-like experience, and rich color with ambient lighting, HP has developed a novel electro-optic device with optically transparent and colored states using hybrid architecture adopting out-of-plane switching fields with in-plane optical effects and proprietary electronic inks of primary subtractive colorants. In contrast, the conventional electrophoretic architectures (e.g. E Ink Pearl Imaging 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 by applying electric fields primarily perpendicular to the plane of the film [3]. These conventional architectures do not enable transparency and thus do not allow stacked architecture to produce print-like color. Alternative in-plane

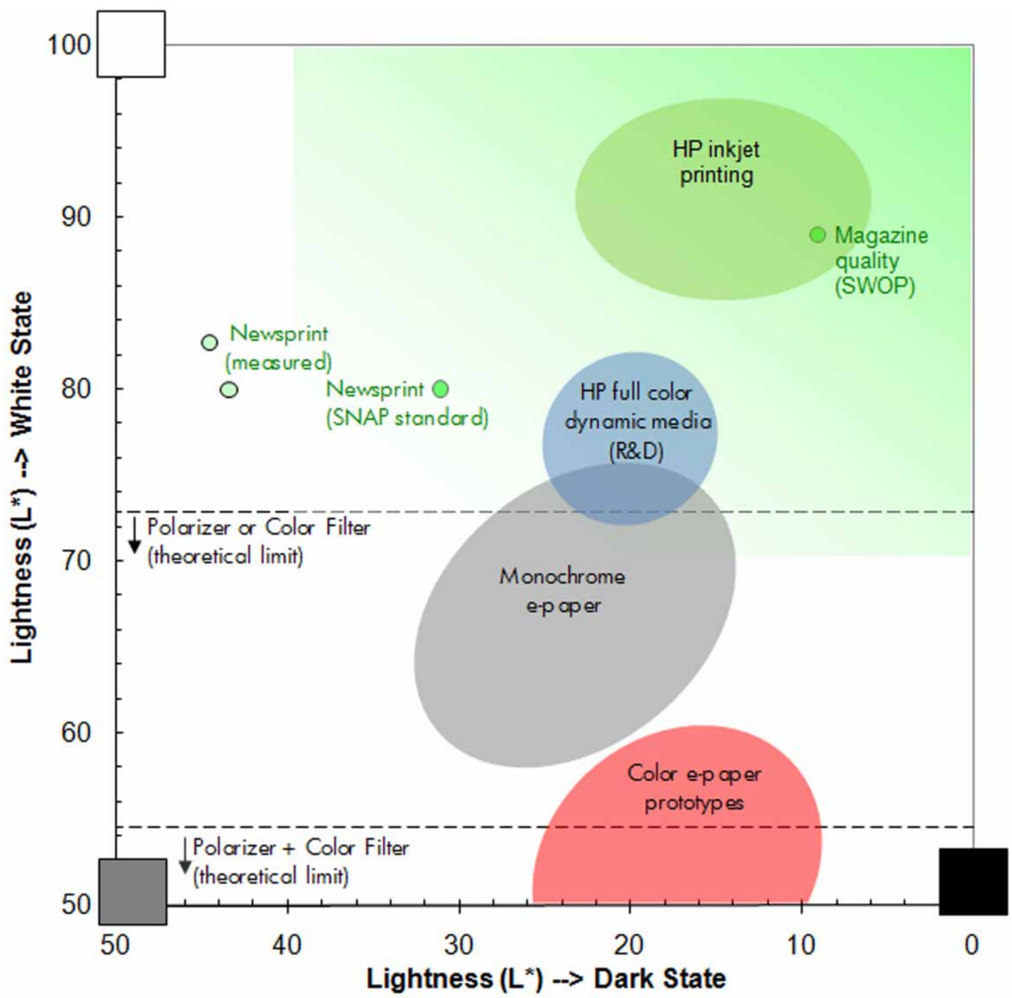

Figure 1. Brightness and contrast comparison of the print and reflective-display technologies.

electrophoretic architectures based on in-plane switching with in-plane optical effects have been shown by IBM, Philips, and others [4,5], where the colorant particles are primarily moved parallel to the plane of the film by applying electric fields primarily parallel to the plane of the film. While the in-plane electrophoretic architectures provide a transparent state that enables stacked layers for full-color displays, they are generally limited by the trade-offs between clear aperture and switching speed, and they also require electrical crossovers of in-plane electrodes, which increase the manufacturing complexity. In contrast, the hybrid architecture presented herein allows transparency in the clear state by introducing a uniform distribution of dot arrays that allow more localized particle compaction inside the pixel. This hybrid architecture 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, (3) optical loss is minimized by compaction of pigment in two-dimensional arrays of recessed dots in the dielectric layer on top of a transparent conductor. Figure 2 shows the schematics of this novel device architecture with (a) the spread and compacted states of nanoscale colorant particles and microscopic images of the cells of this architecture in (b) a colored state and (c) a transparent state. As the control of multiple electrokinetic forces leads to the compaction of charged colorants, the technology is termed 'electrokinetic' media. Without an applied voltage, the colorant particles are spread uniformly within a cell, and the display element is in the colored state. Under a bias condition that enables the compaction of colorant particles into dot-patterned cavities, the display element produces a transparent state. The example shown here with cyan ink demonstrates high optical transparency ($\sim$80%) at a low bias ($<$15 V), with relatively fast switching ($<$300 ms).

4. Design of electrically addressable inks

A high-performance electronic ink should exhibit good optical density, high mobility for fast switching speed, high cycle switching endurance, environmental stability, and low toxicity. Stable, charged colorant particle suspensions require at least the following four components: (1) colorant particle; (2) carrier fluid; (3) dispersant; and (4) charge director. The colorant particle provides the color and can participate in the charging. The key considerations are the particle size, surface functional groups, dispersibility, hue, chroma, and lightness. The carrier fluid acts as a vehicle for dispersing the pigment, as well as a low-dielectric-constant medium. The dispersant provides steric stabilization of the colorant particles to prevent particle aggregation. The charge director enables charging of the particles and carries countercharges. The counterions are stabilized by reverse micelles composed of the charge director. Various charging mechanisms have been described elsewhere [6,7]. Through systematic studies of the key components, magenta, black, cyan, yellow, and white electronic inks were formulated. Figure 3 shows the results of the formulation of primary subtractive colorant inks (a) in their colored states and (b) in their transparent states.

5. Roll-to-roll manufacturing

A set of roll-to-roll (R2R) processing capabilities for making fine-scale circuitry and physical features on plastic substrates that are compatible with the needs of reflective displays was also developed [8]. The processes are scalable to large web widths, and the fine features enable high-density circuits and future integration with more complex passive and active elements. These R2R processes, which utilize imprint lithography and related techniques as key patterning steps, also offer significant cost advantages compared with the conventional photolithographic processes. The custom equipment set that was used here is capable of continuous processing of webs with widths ranging from under 0.15 m up to 0.3 m. The tool set currently enables the unit processes of coating, imprinting, plasma treatment, electrolytic and electroless plating, and laser micromachining. The patterns that are produced can have features with minimum width dimensions of less than 5 μm, a submicron edge definition, and up to 30 cm product lengths. This low-cost R2R manufacturing platform was applied to fabricate the flexible electrokinetic reflective frontplane described herein. A photolithographically prepared master substrate was used to fabricate a flexible stamp. The stamp material must have sufficient modulus and strength as well as low surface energy for clean release from the embossing resin and master. The stamp and imprint processes use proprietary resin materials to allow the replication of multilevel three-dimensional patterns down the web continuously. Critical thickness control of coated resin is required, as well as critical viscosity, to fill the cavity features of the stamp. Figure 4 shows a particular tool for imprinting from a set

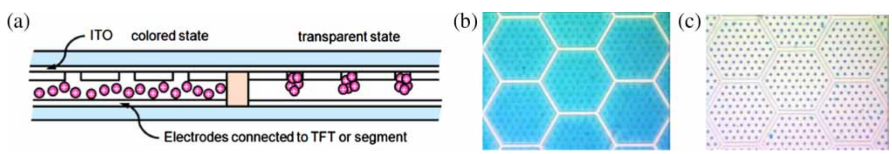

Figure 2. Schematics of the novel device architecture: (a) spread and compacted states, (b) colored spread state, and (c) transparent compacted state.

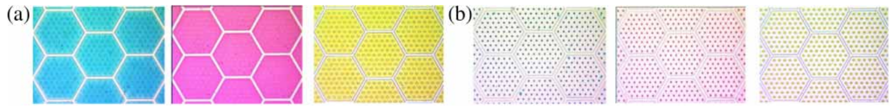

Figure 3. Micrographs of the device architecture with subtractive primary-colorant inks in the spread and compacted states: (a) colored spread state and (b) transparent compacted state.

of R2R process capabilities (a) and an optical profilometric image of the imprinted media (b) fabricated by the R2R manufacturing platform. The figure shows fine-scale multilevel embossing capability at a high yield on a flexible substrate.

6. Grayscale and pixelation

For the frontplane technology to provide full-color display, grayscale addressing capability is critical. In the electrokinetic architecture, each display element that contains electrically addressable inks can be driven with direct addressing or active-matrix addressing to produce continuous levels of gray. The out-of-plane switching geometry allows the control of colorants in the spread and compacted states, and grayscales can be achieved by controlling the specific concentration of colorant particles in the visible region of the display element. The electrokinetic frontplane technology is capable of producing greater than 4-bit gray levels. In Figure 5, eight levels are shown, using directly driven segments along with their respective images. Figure 5 also shows the dynamic transition from one grayscale level to another, allowing continuous dynamic driving without having to reset the colorant particles from a clear or saturated state.

The out-of-plane electrode geometry used in our frontplane architecture provides compatibility with active-matrix backplane control. HP is developing an active-matrix backplane technology based on transparent metal oxide thin-film transistors (TFTs) that are compatible with existing glass (AMLCD) fabs and that are capable of eventual migration to a R2R manufacturing process [9]. One of the key challenges to achieving a pixelated bright-color reflective device using a stacked architecture is the need to minimize the light absorption through the electronic elements within the optical stack. The recently developed amorphous metal oxide transistors, which have high electron mobility, can be used to improve the overall optical aperture significantly. Due to the high mobility of the transistor, its dimensions can be proportionally downscaled, thus reducing its optical impact to a level of optical loss acceptable for a stacked device. Metal oxide semiconductors, such as indium gallium zinc oxide and zinc tin oxide, have a large electronic bandgap (∼3–3.5 eV). The transistor can thus be made optically transparent, thereby further decreasing the optical loss due to the backplane circuitry. The flexible frontplane media and oxide TFT backplane were integrated by laminating the flexible frontplane onto the backplane array with electrically addressable ink fluid between the two layers. To modulate the optical state of each pixel, the transparent pixel plate electrodes are selectively activated through the TFT array, while the top electrode is maintained at a fixed reference bias. A full-scale and microscopic image of a few pixels from the integrated active-matrix electrokinetic-display prototype is shown in Figure 6. A 1024-pixel (32 rows × 32 columns) prototype backplane was used to demonstrate the integration feasibility of an active-matrix pixelated color reflective display. Although some backplane-related yield loss and the nonuniformity of the TFT array can be seen in the integrated devices shown in Figure 6, the results demonstrate the successful pixelation of the electrokinetic frontplane media through active-matrix backplane control. The pixels shown in Figure 6 are approximately 750 μm square (limited here by the dimensions of the active-matrix backplane; the effective resolution of the frontplane can exceed 300 ppi as each cell can be made down to a single microcavity).

7. Demonstration of the stacked reflective display

This frontplane technology was applied to the very thin and flexible color electronic-skin prototypes shown in Figure 7(a)–(c), as well as to the pixelated color reflective

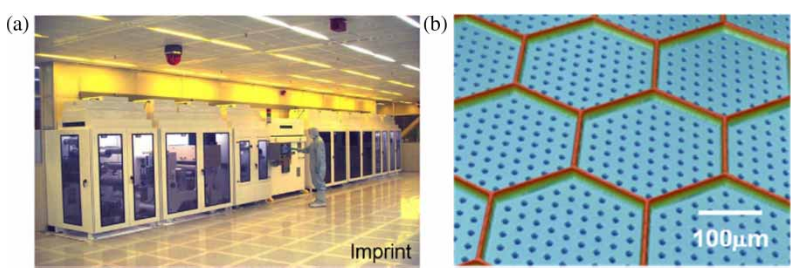

Figure 4. (a) R2R process equipment for imprinting. (b) Optical profilometric image of imprinted media.

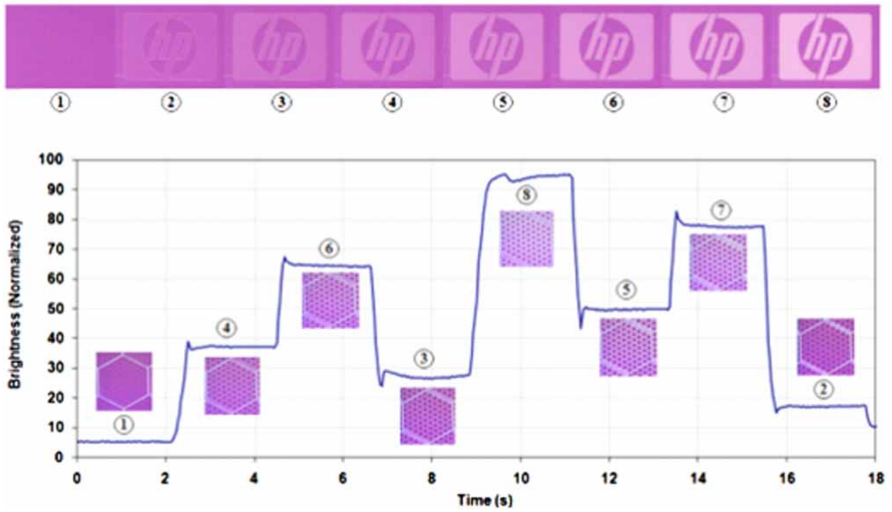

Figure 5. Dynamic driving for grayscale continuously addressed and held flat at eight levels and their respective microscopic images.

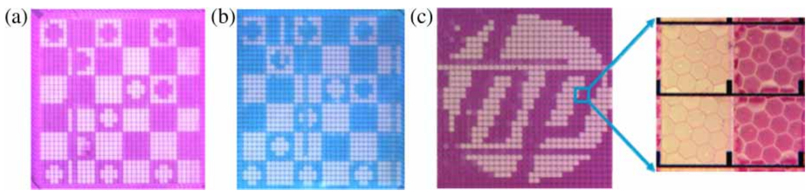

Figure 6. Integration of the front and back planes with (a) magenta ink, (b) cyan ink, and (c) macroscopic and microscopic images.

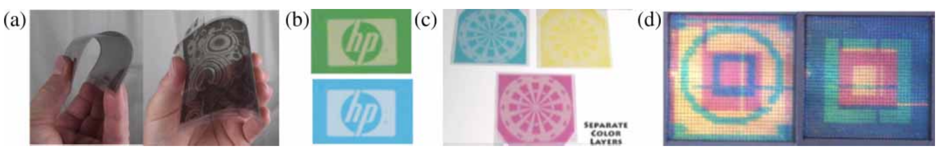

Figure 7. (a, b, and c) Thin, flexible color reflective electronic-media prototypes. (d) Three-layer stacked color reflective display.

display shown in Figure 7(d). The electronic-skin examples herein provide an effective resolution (>100 ppi) for a frontplane with a transparent state at a low holding power, for color reflective media ($<50\,\mu$W/cm^2 at <15 V typical). Figure 7(c) shows the segmented prototypes with each primary colorant, and Figure 7(d) shows an image of the *world's first electronic-ink-based pixelated stacked color reflective display* using a three-layer cyan/magenta/yellow stack, each layer integrated with a prototype oxide TFT backplane. This architecture also allows an optional backlit transmissive mode using semitransparent reflectors, under low- or no-ambient-light conditions. The stacked color reflective-display devices measured with gain reflectors, which also help suppress the total internal-reflection loss, have 33% reflectivity or $L^* \sim 65$. The modeling herein indicates that white-state reflectance will provide >60% if the interfaces are index matched and the top surface is antireflection coated for the efficient coupling of the incoming light. The HP technology is thus predicted to approach the SNAP printing standards. This full-color capability will enable a level of image quality that is critical to the extension of the market and business opportunities for electronic paper technology.

8. Conclusion

A novel hybrid architecture for reflective color electronic media has been demonstrated that combines out-of-plane switching with in-plane optical effects providing an excellent transparent state with relatively fast switching capability. A bright full-color reflective display was created by stacking three layers of pixelated colorants of the subtractive primaries CMY. Based on optical modeling, the HP's reflective color eMedia technology is predicted to approach the color gamut and brightness of the SNAP printing standard. Future integration of HP's R2R-compatible frontplane and backplane technologies will demonstrate a scalable platform for low power, transparent, print-like media that creates a path towards eco-friendly, bright, full-color, flexible eMedia.

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References

[1] J. Heikenfeld, P. Drzaic, J.S. Yeo, and T. Koch, J. Soc. Info. Display **19**, 129 (2011).

[2] J.S. Yeo, Z.L. Zhou, T. Emery, G. Combs, V. Korthuis, J. Mabeck, R. Hoffman, T. Koch, and D. Henze, SID Symp. Dig. **41**, 1041 (2010).

[3] B. Comiskey, J.D. Albert, H. Yoshizawa, and J. Jacobson, Nature **394**, 253 (1998).

[4] S. Swanson, M.W. Hart, and J.G. Gordon II, SID Symp. Dig. **31**, 29 (2000).

[5] K.-M.H. Lenssen, P.J. Baesjou, F.P.M. Budzelaar, M.H.W.M. van Delden, S.J. Roosendaal, L.W.G. Stofmeel, A.R.M. Verschueren, J.J. van Glabbeek, J.T.M. Osenga, and R.M. Schuurbiers, SID Symp. Dig. **39**, 685 (2008).

[6] G.S. Robert, R. Sanchez, R. Kemp, T. Wood, and P. Bartlett, Langmuir **24**, 6530 (2008).

[7] I.D. Morrison, Colloids Surf. A Physicochem. Eng. Aspects **71**, 1 (1993).

[8] T. Koch, D. Hill, M. Delos-Reyes, J. Mabeck, J.-S. Yeo, J. Stellbrink, D. Henze, and Z.-L. Zhou, SID Symp. Dig. **40**, 738 (2009).

[9] R. Hoffman, T. Emery, B. Yeh, T. Koch, and W. Jackson, SID Symp. Dig. **40**, 288–291 (2009).