A first demonstration and analysis of the biprimary color system for reflective displays

Sayantika Mukherjee (SID Student Member)
Nathan Smith
Mark Goulding (SID Member)
Claire Topping
Sarah Norman
Qin Liu
Laura Kramer
Senal Kularatne
Jason Heikenfeld (SID Senior Member)

Abstract **—** A new biprimary color system is demonstrated for single-layer reflective displays, capturing much of the improved color performance of multilayer displays while potentially maintaining single-layer display advantages in high resolution and faster switching. Electrophoretic pixels were operated with dual-particle complementary-colored dispersions such as green/magenta (G/M). Using simple interdigitated three-electrode architecture, four colored states (KWGM) were achieved with a preliminary contrast ratio of 10 : 1. Furthermore, biprimary ink dispersions were shown to be functional in a more advanced electrokinetic pixel structure. A full-color biprimary pixel contains three complementary subpixels (G/M, B/Y, R/C), and the requisite electrophoretic ink dispersions were also formulated and spectrally characterized in this work. Lastly, theoretical color space mapping confirms that the biprimary concept provides twice the brightness and twice the color fraction compared with the conventional RGBW subpixel approach, and that the biprimary concept can approach performance close to that of magazine print (Specifications for Web-Offset Print).

Keywords *— reflective displays, electrophoretic, electrokinetic, biprimary.*

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1 Introduction

Reflective displays, often referred to as 'electronic paper' or e-paper, have for at least a decade, been assumed to be the future technology for sunlight-readable, low-power, reduced weight, and the preferred route to achieve flexible or rollable displays.[1] In support of this assumption, video-rate e-paper technology is now achievable, including electrowetting[2,3] and Micro Electro Mechanical Systems (MEMS) technologies.[4,5] However, of the dozen or more technologies that exist, none are able to provide bright color operation without moving toward multi-layer Cyan-Magenta-Yellow (CMY) color generation, and therefore having to accept significant compromises in switching speed[6,7] or pixel resolution.[8–10] Therefore, faster switching speeds or higher pixel resolutions are typically relegated to lower-performance color systems such as side-by-side RGBW pixels, which can only display saturated color at 25% of the display area (color fraction (CF) = 25%, see Fig. 1a,b).[11] What is needed, and has not been yet demonstrated, is a color system, which merges the cost, resolution, and switching speed advantages of single-layer color-additive displays, with the improved color performance of multi-layer color subtractive displays.

Demonstrated here is a new biprimary color system[11], which provides a doubling of both color and brightness and is able to do so using a highly desirable single-layer implementation. The term 'primary' prefixed by 'bi' originates from unification of both the RGB and CMY primary color systems inside a single pixel. As shown in Figs 1c–1d, each subpixel can be dual-colored with one of the RGB primaries and its complementary color in the CMY primaries. W is achieved by clearing the colors, K by fully mixing them, and bright colors such as R achieved by activating the subpixel colors that most strongly contribute to R, for example, a display of RMY where M and Y themselves are half-red in their spectra.

The experimental demonstration in this work utilizes electrophoretic pixels and two-particle two-color ink dispersions.[12] Pixel fabrication and characterization is performed for the G/M subpixels and the potential of inks for the other sub-pixels (R/C, B/Y) are analyzed using reflection analysis. With the G/M inks and simple interdigitated three-electrode architecture, all four states of KWGM can be achieved with contrast ratios of up to 10 : 1. A more sophisticated electrokinetic pixel structure (faster, two-electrodes) is also demonstrated for the G/M ink. Lastly, a theoretical color-space analysis and display simulation is provided, which visually shows the qualitative doubling of brightness and CF as compared with the conventional RGBW approach. The predicted biprimary performance is close to that of color-quality standards for magazine print (Specifications for Web-Offset Print or SWOP). Although these are preliminary results, they confirm that biprimary pixels can be fabricated and operated under the basic fundamentals for biprimary color.

2 Biprimary experimental demonstrations

2.1 Device fabrication

In this work, both 3 and 4 electrode in-plane electrophoretic pixels were demonstrated, with the 3 electrode system

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J. Heikenfeld, S. Mukherjee, S. Kularatne are with Electrical Engineering and Computing Systems, University of Cincinnati, Cincinnati, OH, USA; e-mail: heikenjc@ucmail.uc.edu.
N. Smith, M. Goulding, C. Topping, S. Norman are with the Research and Development, Merck Chemicals Ltd., Southampton, U.K.
Q. Liu and L. Kramer are with the Hewlett-Packard, Corvallis, OR, U. S. A.
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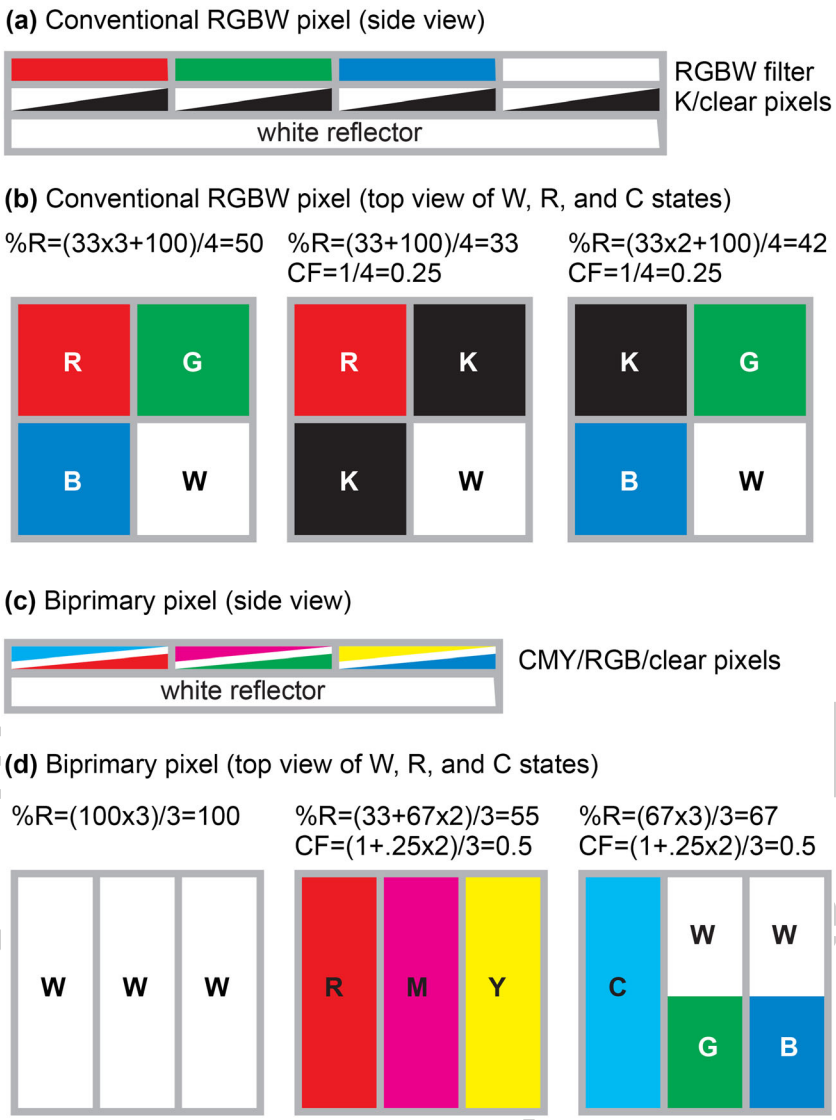


FIGURE 1 — Diagrammatic representations of RGBW and biprimary color systems, along with examples for display of the colors W, R, and C. Calculations of theoretical reflection (%R) and color-fraction are shown in (b, d).

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utilized in most of the experiments. The 3 electrode system (Fig. 2) is simpler to fabricate and increases the maximum optically active area, but unlike the 4 electrode system, it requires a clearing or 'reset' state in between color changes. There are two moving electrodes (ME1 and ME2) and one gating electrode (GE), all fabricated 'in-plane' (on the same substrate).With 4 electrodes, another gate GE2 could be added adjacent to ME2 (not shown). The electrodes are made from transparent In_2O_3:SnO_2 (ITO), patterned by wet etching and photolithography. The test device is assembled with a transparent top-plate, and the biprimary ink is dosed similar to the 1-drop filling technique used in liquid crystal display manufacturing. Once the device is assembled, the electrodes ME1, ME2, and GE are operated individually with three-way switches to enable 0, +32.5,−32.5 V DC voltage control. When tested in reflective mode, a rear reflector is required. For higher resolution pixels and to minimize light-outcoupling losses[13], the rear reflector should be as close to the pixels as possible but also separated from the pixels by a low-refractive index layer or air-gap. In this work, the rear reflectors were fabricated by coating a 25-µm thick polyethelene sheet with light-scattering (diffusing) barium sulfate powder ($BaSO_4$), mixing with a small amount of organic binder, and placing that sheet on the top of a 99.8% reflective 3-M Vikuiti™ Enhanced Specular reflector (ESR)film.

The dual particle ink dispersions, based on dyed polymer microparticles[12] used in the device are a key enabling material for the biprimary color system. It has been demonstrated by Merck (known as EMD in North America) that the particle design, color, size, charge, and surface functionality can be independently tailored with the use of suitable dyes to realize any combination of two colored particles including those from the subset of RGBCMY. Particle synthesis enables covalent combination of dye, charging components (of either sign)

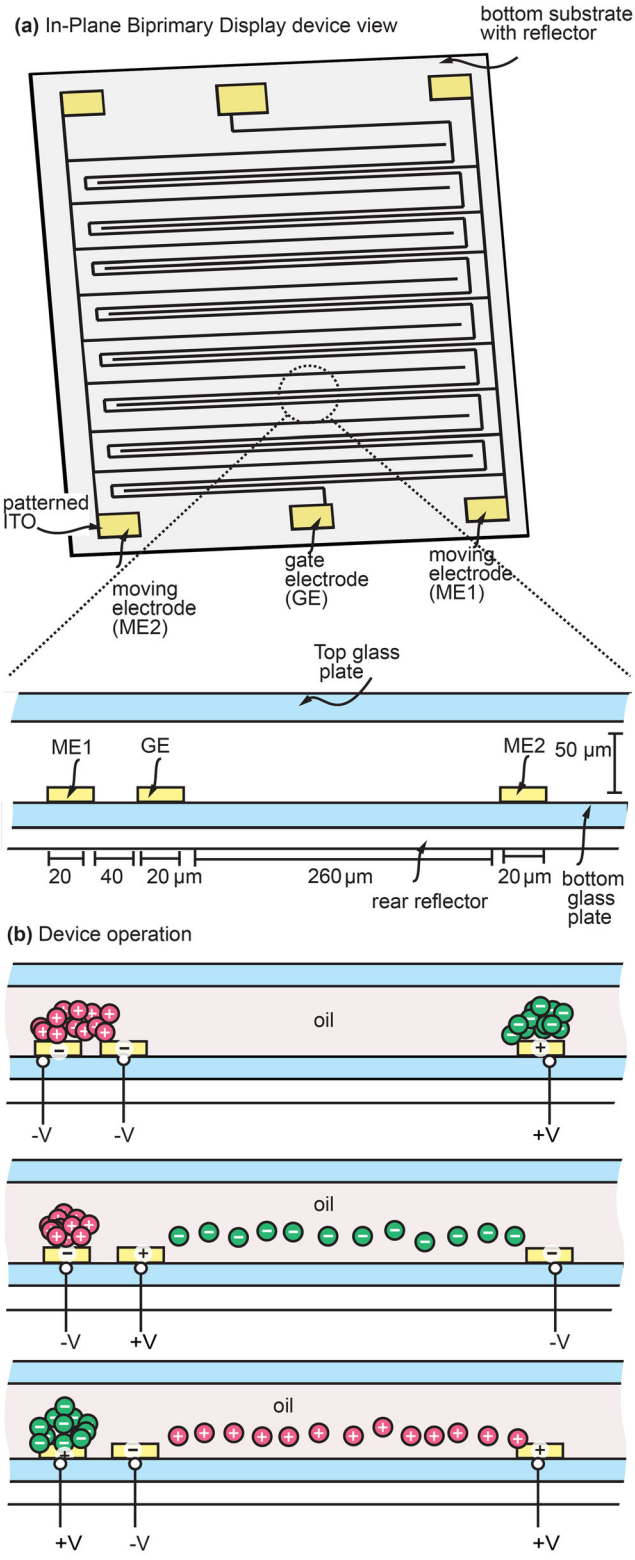


FIGURE 2 — (a) Characterization device layout and (b) Device operation for W, G, and M states.

and a steric stabilizing surface modification. By controlling the synthetic conditions, size is accurately controlled, to yield dispersions in hydrocarbon oils. The particle sizes typically range from 60–1000 nm, and in this work, the green particles are negatively charged, whereas the magenta particles are positively charged. Electrophoretic mobilities for the particles were measured and reported in a later section of this paper.

2.2 Operation

In-plane electrophoretic displays work on the principle of using an electric field to move charged pigment particles towards or away from the viewable area in each pixel (colorant transposition). The operation of the biprimary color dispersions are illustrated in Fig. 2 and photographs of K, W, G, and M states are provided in Fig. 3. Using pulse-width modulation of particle spreading or other techniques, grayscale can be achieved[14] but was not demonstrated in this work. In this work, each of the colored states was achieved using fully colored or cleared states. The voltage sequences were as follows:

Black state (K): Firstly, the pigments are all compacted onto electrodes by setting ME1 = +32.5 V and ME2 = −32.5 V (with a net potential difference of 65 V) and GE = +32.5 V. Next, all the electrode polarities are reversed for a duration of ~7 s to spread the pigment particles (incomplete movement across the

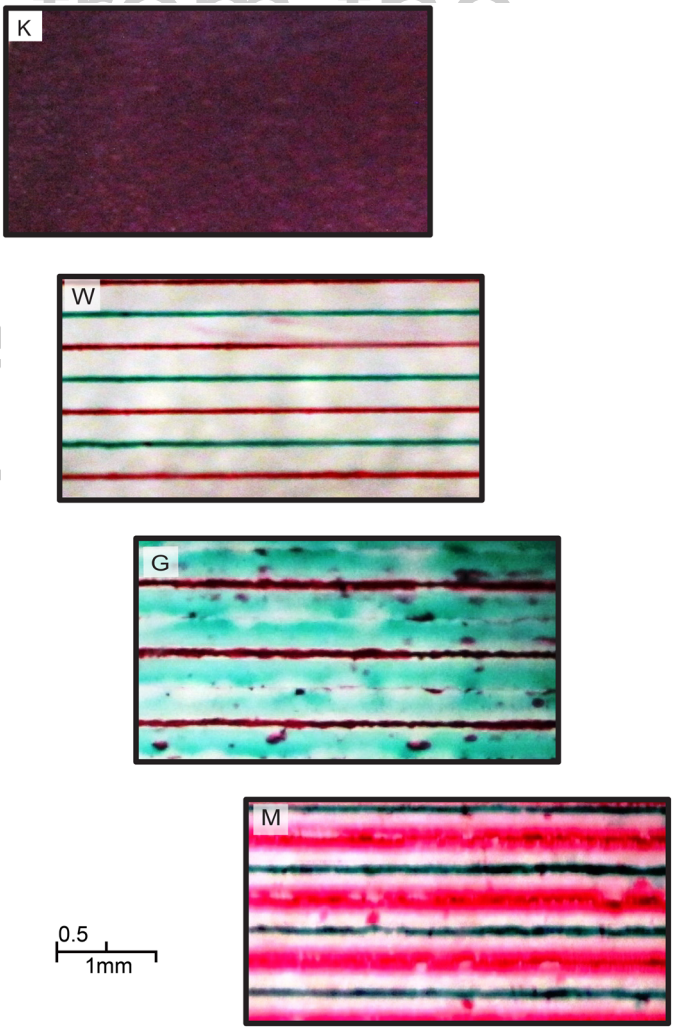


FIGURE 3 — Photographs of demonstrated K/W/G/M states.

pixel) then voltages are removed allowing the particles to remain in a fully mixed (black) state.

White state (W)*:* Next, the voltage is applied as shown in Fig. 2b with ME1 = −32.5 V, ME2 = +32.5 V, GE = −32.5 V, and the pigments are compacted onto the electrodes, revealing the white reflector at the background.

Green state (G): After obtaining W, voltages are set as ME1 = −32.5 V, ME2 = −32.5 V, and the GE electrode is switched to +32.5 V, which (1) confines the M pigment compacted on ME1; and (2) spreads the G pigment across the viewable area. After ~10 s, the G spread state is achieved, and the voltage between ME1 and GE is then set to a value of 10 V to sustain M compaction on ME1, and 0 V between GE and ME2 to sustain the spread of G pigment.

Magenta state (M): M is obtained by again first setting the W state, and using the opposite polarities as were described earlier for setting the G state.

The diffused spectral reflectance data of these states were measured and are plotted in Fig. 4. Biprimary switching behavior is seen in the plots, but is also non-ideal in spectral performance as the G pigment does not fully suppress M reflection and M pigment likewise does not fully suppress G reflection. These particle dispersions utilize typical dyed polymer microparticles from Merck and are not optimized for biprimary operation. Therefore, improvements in maximum reflection, color reflection, and in black states are all expected in future work (discussed in greater detail in Section 3.1).

2.3 Electrophoretic mobility and speed

Electrophoretic mobility for the dual-particle green-magenta dispersion ink was tested in a simple two interdigitated electrode test cell (ME1 and ME2 only, no GE, Fig. 2). These electrodes are 20 µm wide and were spaced at 300 µm distance from each other, and the applied voltage was 70 V. The apparent electrophoretic mobility of the particles was then calculated using ImageJ analysis of video of the moving particles. The speed of the particles was measured every 50 µm distance, and the electrophoretic mobility constant (μ) is calculated using the common formula:

$$\mu = \frac{v}{E}\,(\mathrm{cm^2/V\text{-}s})$$

Where v is the velocity of the particles and E is the applied electric field. The plot in Fig. 5 shows the trend of electrophoretic mobility of both the green and magenta particles. Two important observations can be made. Firstly, the average mobilities are in the range of 3 to 6×10^{-6} cm^2/V-s range, which is an order of magnitude lower than the best electrophoretic dispersions in existing commercial products. Achieving mid 10^{-5} cm^2/V-s mobilities, which is 10 times the calculated mobility value, and small electrode spacings (~tens of µm) is essential if near-video speed switching is to be achieved (tens of ms). Secondly, as can be seen in Fig. 5, the velocity of the particles is not constant, and therefore the apparent mobility changes. The apparent mobility decreases as particles get closer to their final destination electrode, implying that the particles provide some repulsive force as they accumulate and start to internally screen the applied electric field.[15] This effect is important, because when scaling the pixels to higher resolutions, the switching speeds will be slower than that predicted by the maximum mobility. Based on the data in Fig. 5, with each 50 µm distance decrease in electrode pitch, there is roughly a reduction of ~20% in the electrophoretic mobility.

2.4 Electrokinetic pixel demonstration

The green-magenta dual particle dispersion was also tested in an electrokinetic device (EKD) structure provided by Hewlett-Packard (HP) Corp.[8–10] The device cross-sectional structure is illustrated in Fig. 6. The bottom plate of the device assembly consists of a sheet Indium Tin Oxide (ITO) electrode, onto which hexagonal pixel structures are formed. The regular hexagonal pixels have an array of pits. The top plate is a transparent glass plate with a whole area ITO coating, kept at a channel

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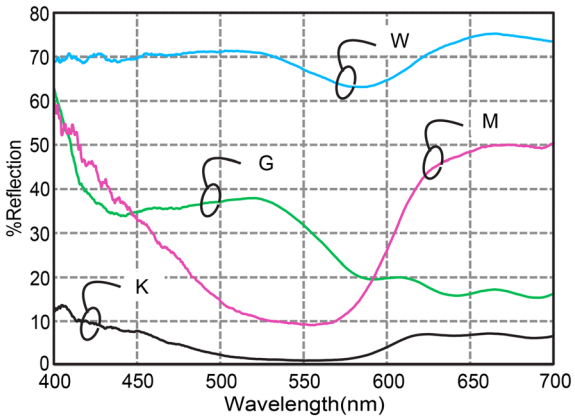


FIGURE 4 — Reflection spectra obtained in the device for K, W, G, and M modes of Figs 2 and 3.

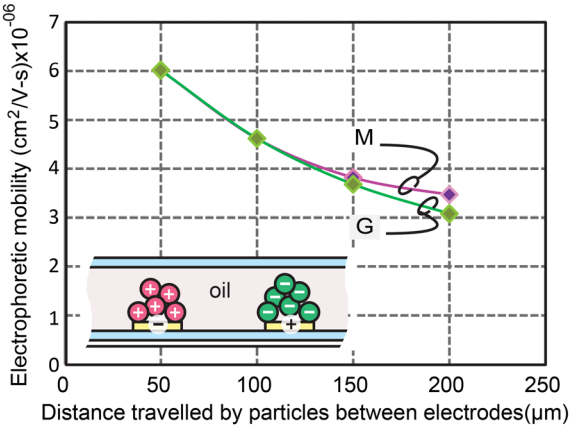


FIGURE 5 — Plot of Electrophoretic mobility versus distance traveled by color particles between electrodes.

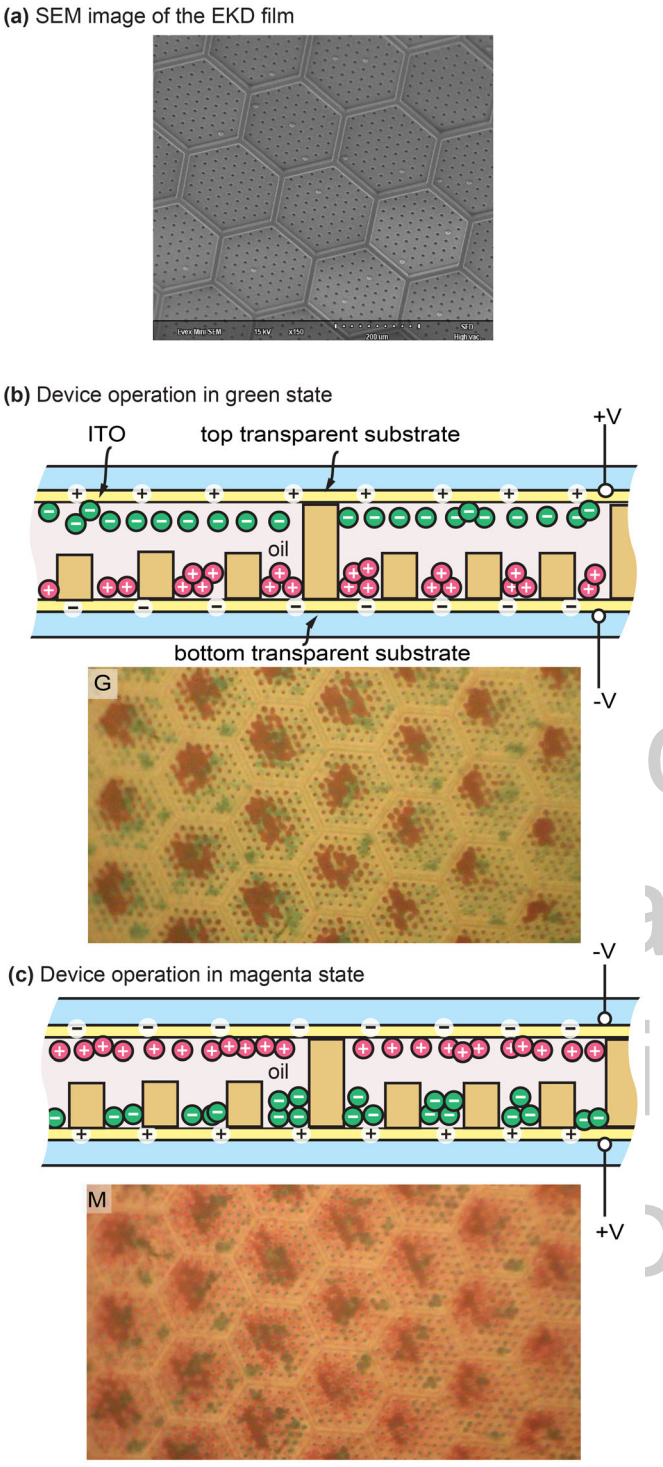


FIGURE 6 — (a) SEM of HP's electrokinetic device structure. (b,c) Side-view diagrams and top-view photographs of device operation in green and magenta states.

height equal to the side walls of the hexagonal pixels. Exact dimensions are proprietary to HP. Figure 6(a) shows an Scanning Electron Microscopy (SEM) image of this EKD pixel, which is fabricated by a roll-to-roll manufacturing platform.

The principle of operation for electrokinetic pixels includes both an out-of-plane (vertical) and an in-plane (horizontal)

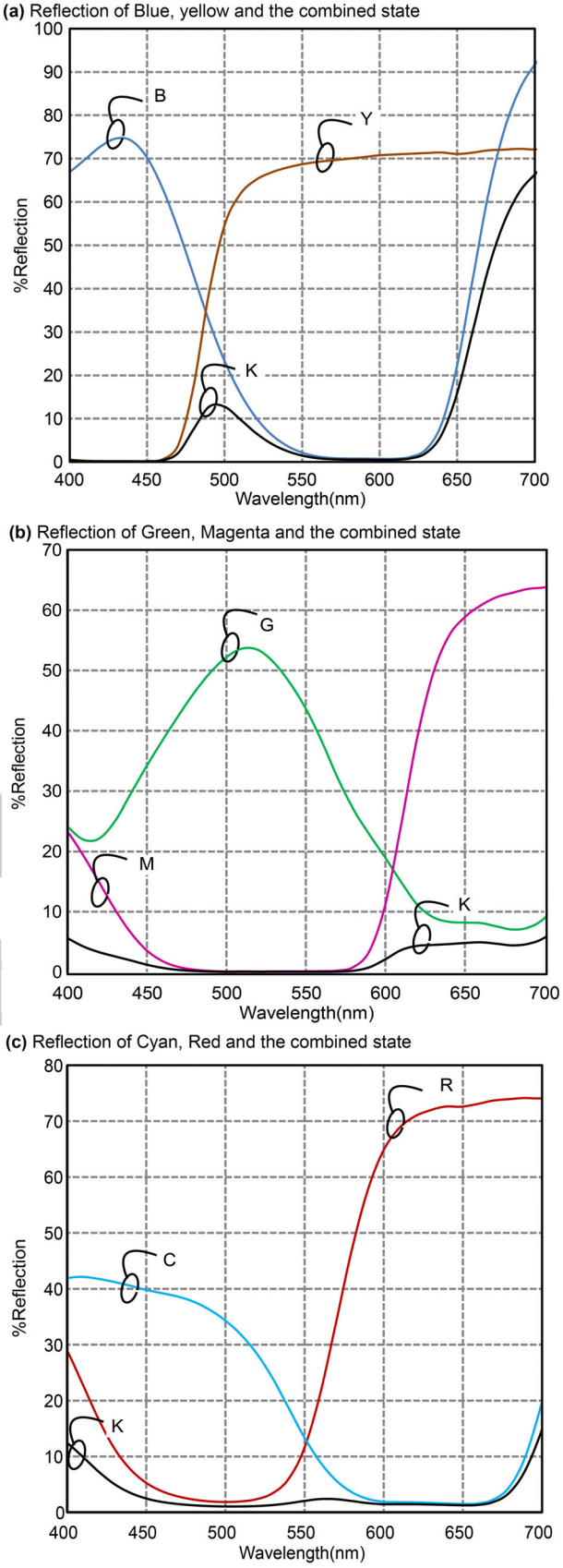


FIGURE 7 — Reflection spectra of (a) B-Y-K, (b) G-M-K, and (c) C-R-K (actual measurements of individual colored inks only and the K spectra are calculated by simply multiplying the measured data).

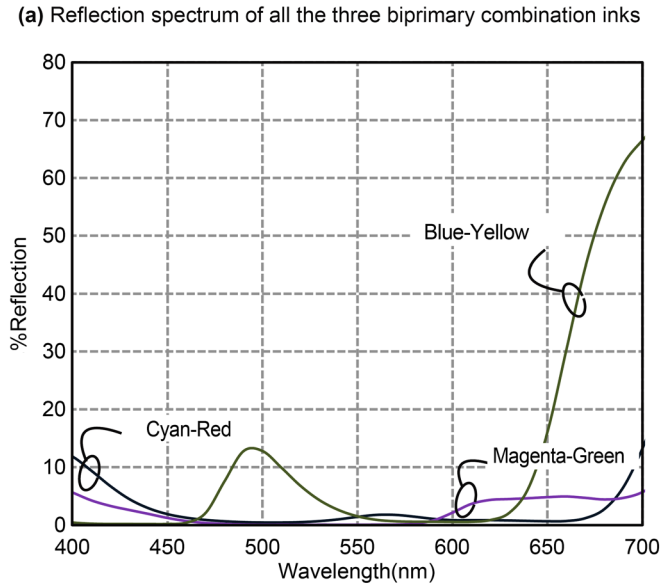


FIGURE 8 — (a) Comparison between reflection spectra of the K states of C-R, B-Y, G-M inks and, (b) Luminous reflectivity (%R × l m/w) of those same inks.

movement of the pigment particles. The electrokinetic effect can hence be called a hybrid between in-plane and vertical electrophoretic effects.

The electrokinetic device was driven with 20 V. Less voltage is needed compared with the in-plane electrode devices (Figs 2 and 3) because the distance between the electrodes is >10× smaller. Two colored states were demonstrated as follows.

Green state (G): To obtain G, the bottom plate is switched to −10 V, and the top plate set to +10 V, which pulls the M pigment down and compacts it in the micropits, and which pulls up and spreads the G pigment.

Magenta state (M)*:* To display M, the bottom plate is switched to +10 V, and top plate switched to –10 V, which compacts the G pigment and spreads the M pigment.

The switching time of the dual-particle dual-color dispersions in the EKD pixels was found to be ~700 ms, which compares well to the HP's single-color ink, which switches <500 ms. The color performance is lacking, as the dispersions are not yet optimized for EKD operation. These results do show that biprimary EKD operation is possible. However, for color grayscale to be achieved, a gating electrode will need to be added to the pixel structure. There could be some applications that do not require a gating electrode. For example, consider a blue-yellow dispersion utilized for simple

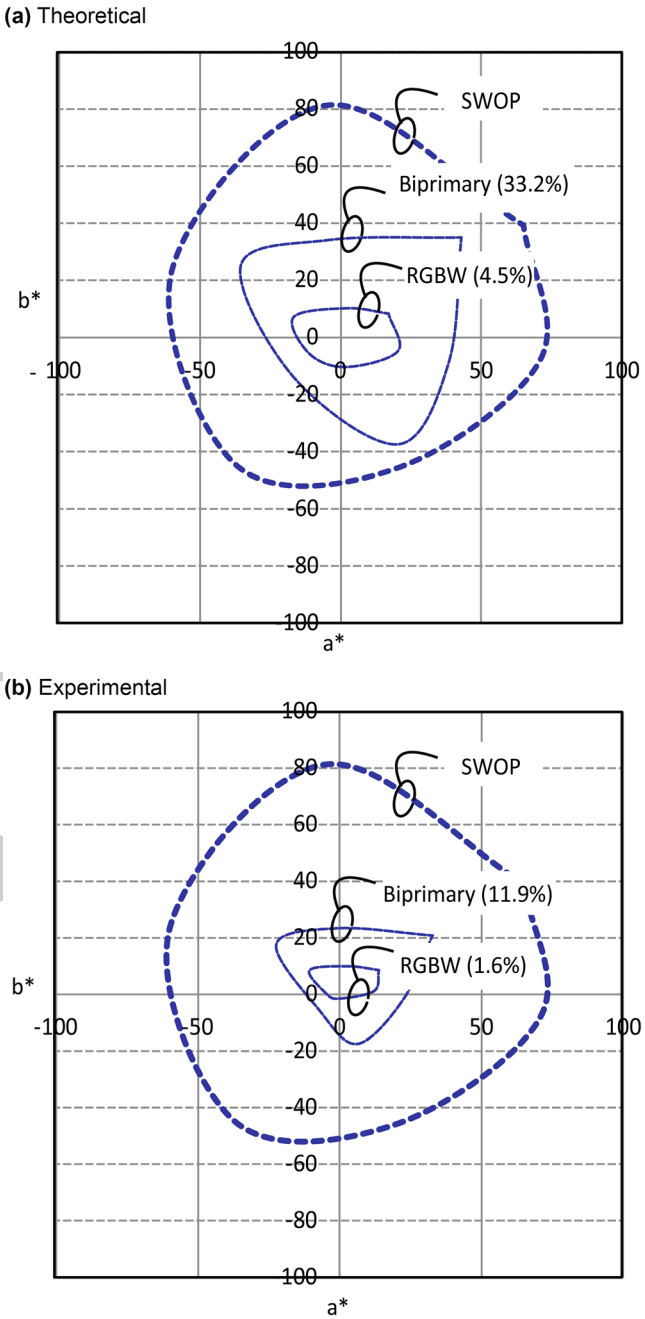


FIGURE 9 — (a) Theoretical plot of biprimary versus RGBW, (b) 'Experimental' plot of biprimary versus RGBW. The % area of Specifications for Web-Offset Print covered by biprimary and RGBW is calculated and added in each plot in the parenthesis.

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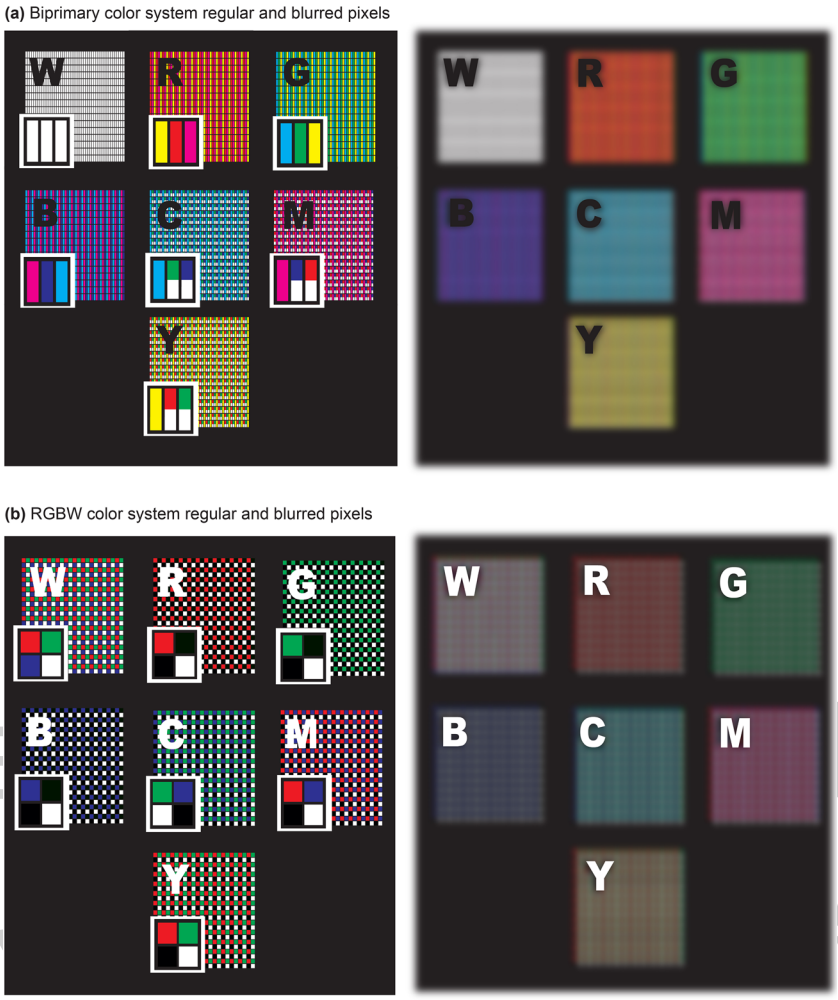


FIGURE 10 — (a) Drawings of biprimary pixels and (b) RGBW pixels. All pixels include 20% pixel dead area. The blurred images shown at right are to simulate visible appearance and color-perception at a distance by the naked eye.

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signage, and capable of displaying blue, yellow, or black, using only a single pixel structure and only two electrode contacts per pixel.

3 Biprimary color-space predictions

3.1 Predicted spectra for full color operation

In this work, G/M pixels were fully characterized, and other dual-particle dual-color dispersions also are available to satisfy the remaining C/R and B/Y sub-pixels in a biprimary display. These particles have similar mobilities, so the performance parameter of greatest interest is their spectral performance: if the spectral transmittance of the pigments is known, then the reflectance of the display is the product of the white background reflectance and the pigment transmittance squared.

Figure 7 lists the reflection spectrum data (specular excluded) for each biprimary combination. In each plot, the two colors are measured for their reflection individually in a 50 µm channel between two glass slides, and the K state is obtained by calculating the reflection of the combined state using the following equation where X and X' are the two complementary colors,

$$\%R_K = \frac{\%R_X \times \%R_{X'}}{100}$$

Again, the particles are not optimized for biprimary operation and the maximum reflection values are below what is theoretically possible due to the spectral absorbance of the pigments, spatial distribution of the pigments and the total internal reflection at the display surface.

Of particular interest in the spectral data is the black state. Strong black inks that are not based on carbon-black typically require five or more colorants (dyes, pigments) to achieve uniform light absorption across the visible spectrum. Therefore, as expected and as can be seen in Fig. 7, there are small portions of the reflection spectrum, which limit the black state for the preliminary two-colored particle dispersions of this work. Figure 8 provides a comparative analysis of the

theoretical K states of all the three biprimary pairs (C/R, M/G, B/Y), and their 'luminous reflectivity' obtained by multiplying the %R with the phototopic lumen/watt equivalent for each wavelength.[16] This is a better measure than just raw-reflectivity and reveals that the blue-yellow dispersion would exhibit the poorest black-state as perceived in terms of brightness by the human-eye.

3.2 Color space comparison: biprimary versus RGBW

Figure 1 explains the theoretical color fraction (CF) and reflectance of W, R, and C and also demonstrates the sub-pixel colors for each color compared with the RGBW. As calculated in Fig. 1, the biprimary colors theoretically boost the reflectance and the CF by approximately a factor of 2. CF is a simple term for use in comparing color systems.[1] A more colorimetric comparison is provided in the plot in Fig. 9 showing a 2D a*b* plot for the artificial pixel layouts provided in Fig. 10. For each color shown in Fig. 10a, a zoom-in inset diagram is shown for the three sub-pixels comprising a single biprimary color pixel. It is important to note that the artificial pixel layouts in Fig. 10a include black space amounting to 20% of the area, in order to mimic a reasonable fill factor for a real pixel. The pixels in Fig. 10 are provided in as drawn form and also provided in blurred format (Adobe Photoshop, Gaussian Blurr 9.0) to mimic visual appearance at a normal viewing distance. Figure 10b also shows RGBW pixels for comparison.

Firstly, for the data in Fig. 9a, the theoretical La*b* data points were directly extracted from the digital image files of Fig. 10 using digital color meter. The gamut area has been calculated for SWOP, biprimary, and RGBW for both the plots using the following equation[17]:

$$A = \frac{1}{2}\left|(a_1^* - a_2^*)(b_1^* + b_2^*) + (a_2^* - a_3^*)(b_2^* + b_3^*)\ldots.(a_6^* - a_1^*)(b_6^* + b_1^*)\right|$$

As can be seen, and also from the numerical calculation, the theoretical performance is ~33% of the SWOP area for the biprimary, whereas the RGBW is found to be 4.5% of the SWOP area.

The blurred pixels were also used to generate 'experimental data' in Fig. 9b, as follows. Blurred pixels were printed with a HP Color Laserjet CP4525 color printer, onto general white printer paper (80% reflectivity). This provided an example of color-optimized pigments, which at some point could also be duplicated in biprimary pixels. This example also used a conventional reflector of only 80%, and more sophisticated gain reflectors[18] could boost the performance even further. The printed pixels were then measured using a Minolta CS-100A colorimeter and a D_{65} illuminant. Although this 'experimentally' measured color-space is reduced from the theoretical one, it still comprises a larger fraction of the SWOP color space than the RGBW, and the superiority to RGBW color is also clear.

4 Conclusion

We have successfully demonstrated here the use of a biprimary color system with G/M dual particle dispersions in both an in-plane electrophoretic pixel and in an EKD pixel architecture. The results are preliminary, with the main areas of future development being creation of ink dispersions optimized for biprimary operation. Theoretical color-space analysis was also performed, and reveals the potential improvement to be realized as compared with conventional RGBW operation. The results are commercially compelling, as they are achieved with a single-layer technology capable of combining manufacturability, excellent color performance, and potential for high resolution and faster switching speeds.

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Sayantika Mukherjee received her BTech in Electronics and Instrumentation engineering from West Bengal University of Technology, India, in the year 2011. She is currently working towards her PhD degree in Electrical Engineering from the University of Cincinnati, Cincinnati, Ohio. Her research interests are microfluidics, reflective display device physics and device fabrication.



Nathan Smith studied Chemistry at the University of Bath, England, and joined Merck Chemicals Ltd in 2001 as an Organic Chemist. After several years developing molecules and mixtures for LC display applications, Nathan joined Mark Goulding in setting up the Electrophoretic Display activities in the UK in 2008. Since November 2013, Nathan was appointed R&D Project Leader within the Technology Scouting & Feasibility-EU group, responsible for the technical development of feasibility studies based on new technologies (Europe).



Mark Goulding studied chemistry at Kingston Polytechnic and the University of Southampton, achieving a PhD in the synthesis & characterisation of nematic liquid crystals, under the supervision of Professor Geoffrey Luckhurst. Mark has over 20 years of R&D and management expertise in R&D of materials for displays, with broad expertise in Liquid Crystal (LC), Organic Light Emitting Diode (OLED), Electrophoretic Display (EPD), and other materials classes. Since November 2013, Mark was appointed Head of Technology Scouting & Feasibility-EU for Merck's Performance Materials division, Business Unit Advanced Technologies. Additionally, Mark is a member of the Materials Division of the Royal Society of Chemistry and a member and panel chair of the UK Research Councils Peer Review College.



Claire Topping studied chemistry at the University of Southampton, England; graduating with an MChem in 2006. She joined Merck soon after, working as an organic chemist synthesizing new molecules for Liquid Crystal Displays and Films. She moved on to small molecule synthesis and scale up for Organic Electronics for one year, before joining the Electrophoretic Displays team in 2010, working on R&D. Her main focus has been non-aqueous dispersion, incorporation of dyes into polymer particles, and working with pigments and light stability. In November 2013, she became part of the new Technology Scouting and Feasibility-EU group, continuing to work on particle synthesis and development of new technologies.



Sarah Norman studied for an MChem in Chemistry followed by a PhD in Medicinal Chemistry at the University of Reading. In 2008, Sarah moved to Queen's University Belfast as a Postdoctoral Research Fellow as part of the QUILL research group. In 2012, as part of a Knowledge Transfer Secondment Scheme, Sarah joined Merck Chemicals Ltd as part of the Electrophoretic Displays team where she helps develop new materials for display applications.



Qin Liu received her PhD in Material Science and Engineering from Virginia Tech (1992). She has been engaged in research and development on polymeric materials, formulations, processes, and applications first at Novartis and then at Hewlett-Packard for the last 22 years. Her experiences span from textiles, contact lenses, thermal inkjet printing, fuel cells, and flexible displays. She is currently a member of the technical staff developing inkjet inks.



Laura Kramer received her BS degree in Material Science and Engineering from MIT (1991) and her PhD degree in Material Science and Engineering from Cornell University (1996). Since joining Hewlett-Packard in 1996, she has held a variety of research and development positions in technical areas including ink delivery systems, printed electronics, 3D printing, and paper-like displays. She is currently managing the ink and supplies team in the Specialty Printing Systems division.



Senal D. Kularatne is currently working towards a BS degree at the University of Cincinnati in Computer Engineering. He worked at the Novel Devices Lab at the University of Cincinnati as an undergraduate research Co-Op. His research interests are logic, concurrency and parallelism, object-oriented technology, and visual programming.



Jason Heikenfeld received the BS and PhD degrees from the University of Cincinnati in 1998 and 2001, respectively. In 2001–2005, Dr Heikenfeld co-founded and served as principal scientist at Extreme Photonix Corp. In 2005, he returned to the University of Cincinnati as a Professor in the Department of Electrical Engineering and Computing Systems. Dr Heikenfeld's university laboratory, The Novel Devices Laboratory www.ece.uc.edu/devices, is currently engaged in electrofluidic device research for biosensors, beam steering, lab-on-chip, displays, and electronic paper. He has been awarded NSF CAREER and is both an AFOSR and Sigma Xi Young Investigator. Dr Heikenfeld has now launched his second company, Gamma Dynamics, which is pursuing commercialization of color e-Readers that look as good as conventional printed media. Dr Heikenfeld is a Senior member of the Institute for Electrical and Electronics Engineers, a Senior member of the Society for Information Display, and a member of SPIE, a member of ASEE, and a Fellow of the National Academy of Inventors. In addition to his scholarly work, Dr Heikenfeld has lead the creation of programs and coursework at the University of Cincinnati that foster innovation, entrepreneurship, and an understanding of the profound change that technology can have on society.

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