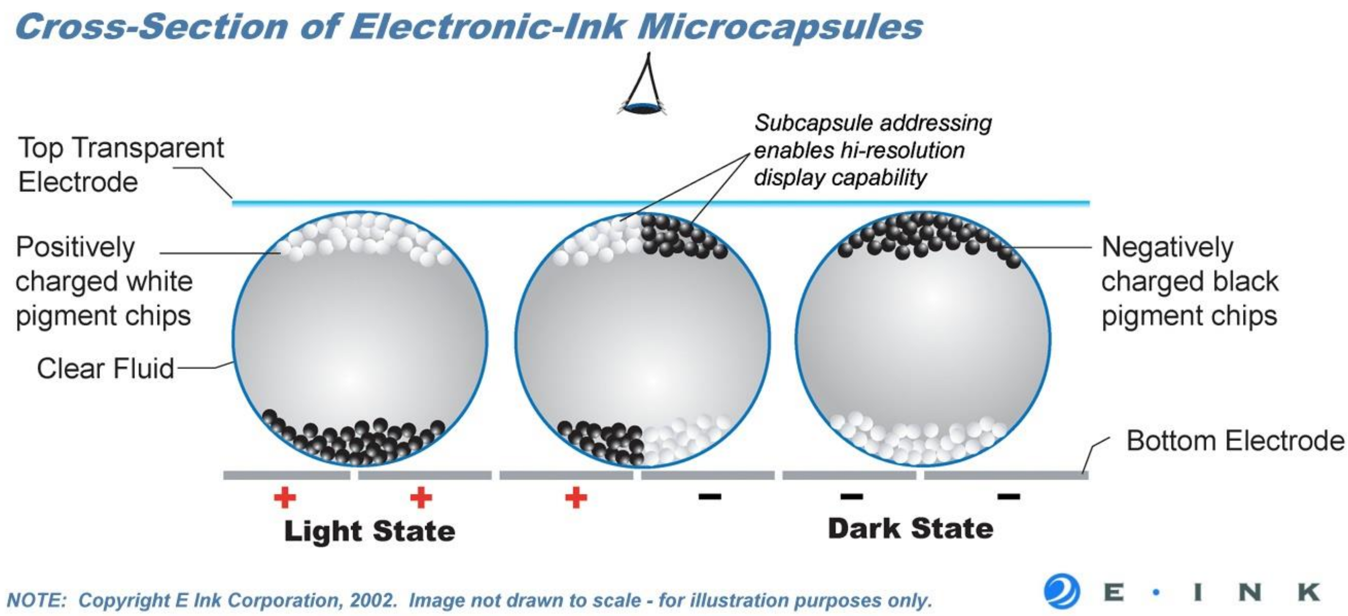
Electronic Ink

E Ink is the inventor of several novel types of electrophoretic ink, often called electronic ink. When laminated to a plastic film, and then adhered to electronics, it creates an Electronic Paper Display (EPD). It's so much like paper, it utilizes the same pigments used in the printing industry today.

Two Pigment Ink System

The two pigment electronic ink system is made up of millions of tiny microcapsules, each about the diameter of a human hair (100µm). Each microcapsule contains positively charged white particles (TiO2) and negatively charged black particles (carbon black) suspended in a clear fluid. When a positive or negative electric field is applied, corresponding particles move to the top of the microcapsule where they become visible to the viewer. This makes the surface appear white or black at that spot.



E Ink Pearl™

E Ink Pearl™ gives eReaders a contrast ratio close to that of a paperback book. Pearl's 16 levels of grey produce the sharpest rendering of images with smooth tones and rich detail. E Ink Pearl offers update times ranging from 50-250ms. In addition, E Ink Pearl supports localized animation for more enticing advertising content for eNewspaper or eMagazines and a richer educational experience in eTextbooks.

E Ink Pearl modules consist of a TFT (thin film transistor), Ink layer and Protective Sheet. In addition, product designers can include a touch solution. E Ink currently offers digitizer and capacitive touch solutions. Digitizer touch technology utilizes a stylus to update the display, with the touch sensor sitting under the TFT. Capacitive touch technology utilizes finger swipes, and is placed on top of the display module. E Ink's touch solutions will not affect the reflectivity of the display.

Three Pigment Ink System

E Ink also offers a 3-pigment (b+w+red or b+w+yellow) ink system in a microcup structure. This ink was engineered specifically for Electronic Shelf Labels (ESL). It works similarly to the dual pigment system, in that a charge is applied to the pigments, and to a top and bottom electrode to facilitate movement.

Advanced Color ePaper (ACeP)

In 2016 E Ink showcased a multi-pigment ink system, Advanced Color ePaper (ACeP). ACeP achieves a full color gamut using only colored pigments. Color is achieved by having all the colored pigments in every pixel, removing the need for a color filter array.

A Full-Color Electrophoretic Display†

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Abstract

Full color electrophoretic displays utilizing colored particles, no color filter array, and a single TFT array backplane have been demonstrated for the first time. A full color gamut including all eight primary colors has been achieved with a single layer of electrophoretic fluid addressed with voltages compatible with commercially demonstrated TFT backplanes. Displays have been made with incorporation of the electrophoretic fluid into both Microcup® and microcapsule structures.

Author Keywords

E Ink; Microcup®; microcapsules; electrophoretic display; full color; Advanced Color ePaper; ACeP

1. Introduction

For many years researchers have been seeking a reflective display technology that reproduces the appearance of printed paper – with high reflectivity and high contrast over a full range of viewing angles – while at the same time providing an image that is stable when the display is not driven. Black and white electrophoretic displays satisfy all these requirements, but extending their advantages to full color has proved to be very challenging.

Adding a color filter array (CFA) to a monochrome display is a simple approach but has achieved only limited success for several fundamental reasons. Color filters absorb light and thereby limit reflectivity, most obviously in the white state. Further, the color filter pattern permits only side-by-side combinations of the primary colors, reducing resolution, color saturation and lightness. While approaches to side-by-side color reflective displays without using a CFA result in a more reflective white state [1], colors are still compromised. The ideal color reflective display has no filters, a single backplane, and a design in which every pixel can be switched from the white state to every color.

E Ink recently introduced electrophoretic displays without a CFA that include a highlight color in addition to black and white [2]. The additional color is provided by a light-scattering pigment whose opacity hides the other pigments when it is closest to the viewing surface. It might seem natural to extend this concept to all colors, but in a set of scattering pigments only those at the surface are visible, limiting the range of colors to those corresponding to the pigments. However, a full-color reflective display must render, at a minimum, eight primary colors: the three subtractive primaries (cyan, magenta and yellow), three combinations of two subtractive primaries (red, green, and blue), a combination of all subtractive primaries (black), and white. This is most efficiently achieved by the use of four pigments: a white, scattering pigment, and three minimally scattering pigments that are cyan, magenta and yellow in color. All primary colors may be achieved by mixtures of these four pigments [3].

There have been several prior investigations into four-pigment, full-color electrophoretic displays. Multilayer, stacked electrophoretic displays have been proposed by several research groups and in some cases demonstrated [4]. The three color channels can be independently addressed, since each color pigment layer is provided with its own array of addressing electrodes, but this requires a complex structure that would be costly to manufacture and would suffer from parallax issues at high resolution. Other attempts at stacked reflective color displays using cholesteric LCD [5][6], electrochromic layers [7], or electro-osmosis [8] suffer from similar issues complexity and performance issues.

A full-color display using four pigments and only a single electrophoretic layer has been described in which adhesion thresholds are provided between the pigments and the front and rear surfaces of cavities containing them [9], but in practice only a three-pigment device of this kind, which did not demonstrate full color, has been reduced to practice with a thin-film transistor (TFT) array.

In summary, despite multiple efforts using a wide variety of different approaches, there has been no demonstration of a reflective electrophoretic display using colored pigments and no CFA that can achieve full color without significant compromise. E Ink's new ACeP technology now provides a solution to this problem.

2. Advanced Color ePaper (ACeP)

ACeP uses a single electrophoretic layer that contains three transparent, colored pigments (cyan, magenta, and yellow) and a light-scattering white pigment. Two of the pigments are positively charged and two negatively charged. The four pigments are induced to move in such a way that the relative position of each colored pigment with respect to the white pigment is controlled.

Although the minimum number of pigments required for rendition of full color is four, it is possible to add additional pigments in order to enhance particular colors. For example, the color black in the baseline ACeP formulation is a composite of yellow, magenta and cyan. A more complex system could also include a true black pigment. The techniques for pigment separation described below may be applied to mixtures of more than four pigments, although of course the difficulty of separating the pigments will increase.

Several methods are known for achieving selective electrophoretic motion of particles. The simplest involves "racing" between pigments having different electrophoretic mobilities [10]. Such a race is complicated by the fact that the motion of charged pigments itself changes the electric fields experienced locally within the electrophoretic fluid. In addition, the mobilities of certain pigments are sometimes voltage- or current-dependent [11]. ACeP formulations take advantage of pigment racing, but on its own it is not sufficient to ensure full control of color.

It is well known that when pigments of different types are mixed together they will usually associate in some way. Pigment aggregation may be charge-mediated (Coulombic) or may arise as a result of, for example, Van der Waals or hydrogen bonding interactions. Whatever its origin, the interparticle bonding strength may be influenced by the surface treatment of the pigment particles, the use of polymeric additives, and the choice of charge control surfactants (among other factors).

There are four possible pairings of oppositely-charged pigments in the simplest ACeP formulations. The electric field strengths

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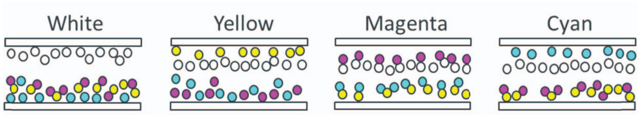
required to separate aggregates corresponding to these pairings are arranged in a particular hierarchy, providing thresholds below which aggregates remains intact and above which they are separated into their constituent pigments (which move in opposite directions in an electric field).

Colors are obtained as shown in Figure 1, in which it is assumed that the viewing surface of the display is at the top (as illustrated). The light-scattering white pigment forms an opaque reflector against which any of the transparent, colored pigment particles above are viewed, and which hides any colored pigment particles located below. Light entering the viewing surface of the display passes through the colored particles, is reflected from the white particles, passes back through the colored particles, and emerges from the display. Colors can be modulated by hiding a fraction of each color pigment behind the white pigment. Because the colored particles are substantially non-light-scattering, their order or arrangement relative to each other is not critical.

The display is addressed with multiple different voltages, the greatest of which does not exceed +/- 30V, using a waveform that exploits the thresholds for pigment separation and the mobility phenomena discussed above to produce the appropriate arrangements of the pigments.



see below (Spectrum 2022)

Figure 1. Schematic representation of pigment arrangements in the electrophoretic layer of an ACEP display module for each of the eight primary colors

Although in its simplest embodiment an ACeP display uses electrodes that span the electrophoretic fluid, the basic mechanism is compatible with the use of concentrator electrodes. As shown in Figure 1 the pigment motion is perpendicular to the viewing plane, but using lateral pigment motion is also possible. It is also possible to incorporate ACeP formulations into shaped cavities. All these techniques have been proposed previously to enhance color separation in electrophoretic displays; however, none were necessary for color rendition using the ACeP devices described below.

3. Device construction and electro-optical performance

Various ACeP color displays were constructed in the same way as conventional black and white reflective displays. Color front planes were made using either microcapsule or Microcup® compartments. The front plane of the display, containing the compartmentalized electrophoretic fluid, was laminated to a conventional TFT backplane using an adhesive with controlled resistivity properties. Displays were fabricated with simple segmented backplanes, 6 inch diagonal TFT backplanes (200 ppi with 1024 by 768 pixels), 13.3 inch TFT backplanes (150 ppi with 1600 by 1200 pixels) and 20 inch TFT backplanes (150 ppi with 2500 by 1600 pixels).

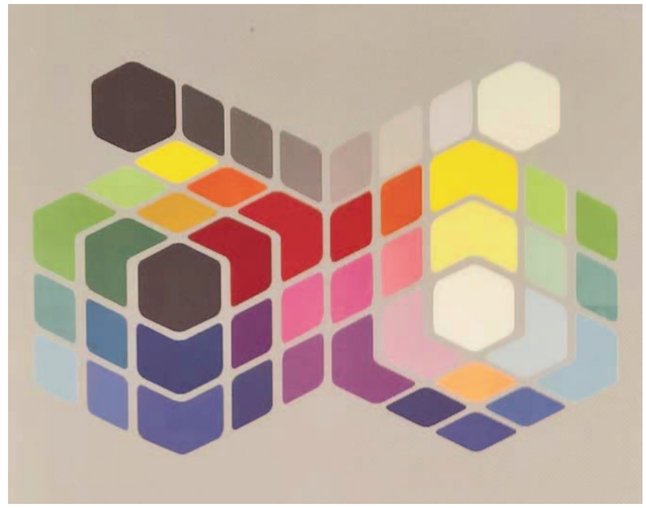


Figure 2 . Photograph of a TFT-driven ACeP display module (150 ppi) showing 32 device primary colors

Figure 3. Photograph of an image rendered on a TFT-driven ACeP display module using dithering with 32 device primary colors

Figures 2 and 3 are photographs of images obtained using an experimental ACeP display that used Microcup® compartmentalization. Images were rendered in this device using 5-bit addressing at each pixel; i.e., using 32 different waveforms each of which produced a different color.

These 32 colors, illustrated in Figure 2, are referred to as "device primary colors", whose number can be greater or less than 32, based on the choice of the addressing electronics. A full-color image is a mosaic produced from these primary colors using dithering techniques. The number of possible colors produced by dithering is limited by the color gamut volume, which in the case of the ACeP module that produced the images shown in Figures 2 and 3 is about 32,000 ΔE^*ab^3.

ACeP displays produce colors that are lighter than those obtainable using a CFA in front of a black and white reflective display, as shown in Figures 4 and 5. In this comparison the CFA display is a TFT-addressed module with 94 ppi resolution and a printed RGBW color filter, while the ACeP display is a TFT-addressed module with 150 ppi resolution that can render 32 different colors at each pixel location. Also shown in these figures is the performance of an ACeP electrophoretic composition in a non-TFT laboratory sample.

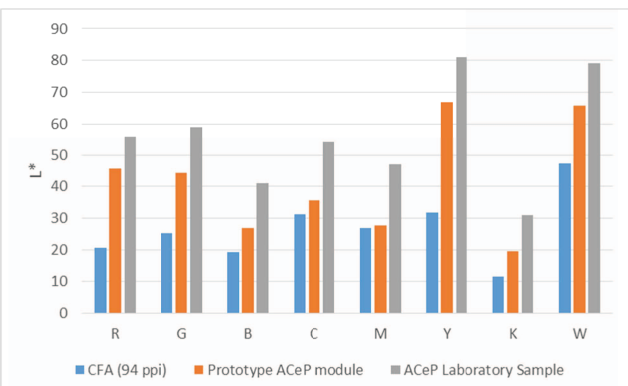


Figure 4. Comparison of lightness of 8 primary colors rendered using a CFA display, a TFT-driven ACeP module, and an ACeP electrophoretic composition in a laboratory sample

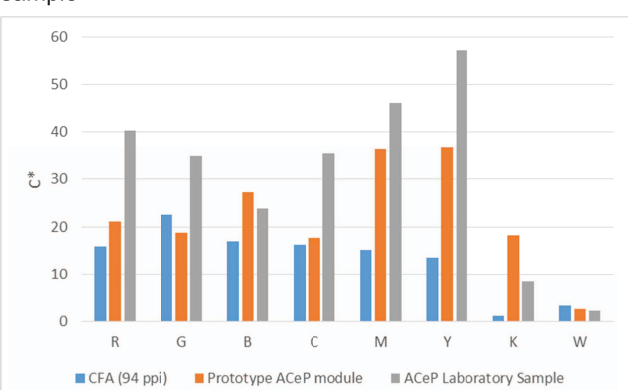


Figure 5. Comparison of chroma of 8 primary colors rendered using a CFA display, a TFT-driven ACeP module, and an ACeP electrophoretic composition in a laboratory sample

It can be seen that the lightness (in L* units) of the ACeP displays is improved over the CFA display and that the chroma (C*) of the colors is generally superior. Note in particular the increased lightness and chroma of yellow. This is an especially hard color to render using a CFA. Further, although pigment separation to produce a broad color gamut has been demonstrated in TFT devices, the potential of ACeP technology for even further improvement has been demonstrated in laboratory samples.

4. Conclusions

A new architecture (ACeP) for a full-color electrophoretic display has been demonstrated. Pigments in each subtractive color are combined with a white pigment in a single electrophoretic layer that is capable of rendering every primary color. The colors are lighter and more saturated than those available from reflective displays that use color filters. Further work is in progress to bring ACeP technology to its full potential in a commercial form.

5. Acknowledgements

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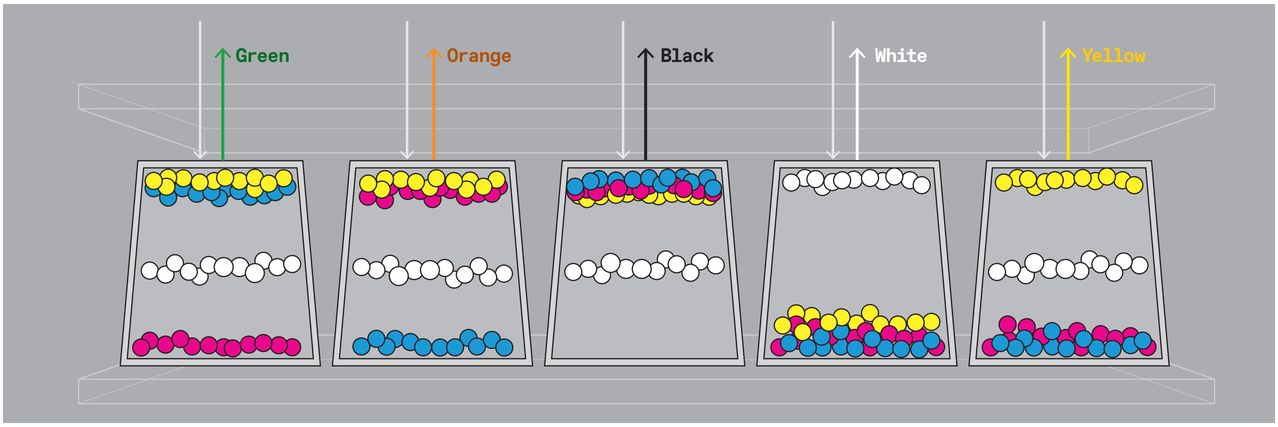

E Ink's Advanced Color ePaper (ACeP) uses four different types of pigment particles, varying in size and charge. The system applies varying electric fields to push and pull them to different positions in each trapezoidal Microcup to create the desired colors.

While our researchers were coming up with this filtered display, others in our labs focused on a different approach, called multipigment, that didn't rely on color filters. However, that approach requires far more complicated chemistry and mechanics.

Multipigment e-paper also shares fundamentals with its monochrome predecessors. However, instead of only two types of particles, there are now three or four, depending on the colors chosen for a particular application.

We needed to get these particles to respond uniquely to electric fields, not simply be attracted or repelled. We did a few things to our ink particles to allow them to be better sorted. We made the particles different sizes—larger particles will generally move more slowly in liquid than smaller ones. We varied the charges of the particles, taking advantage of the fact that charge is more analog than digital. That is, it can be very positive, a little positive, very negative, or a little negative. And a lot of gradations in between.

Once we had our particles differentiated, we had to adapt our waveforms; instead of just sending one set of particles to the top as another goes to the bottom, we both push and pull them to create an image. For example, we can push particles of one color to the top, then pull them back a little so they mix with other particles to create a specific shade. Cyan and yellow together, for example, produce green, with white particles providing a reflective background. The closer a particle is to the surface, the greater the intensity of that color in the mix.

We also changed the shape of our container, from a sphere to a trapezoid, which gave us better control over the vertical position of the particles. We call these containers Microcups.

For the three-particle system, now on the market as E Ink Spectra and used primarily in electronic shelf labels (ESLs), we put black, white, and red or black, white, and yellow pigments into each Microcup. In 2021, we added a fourth particle to this system; our new generation uses black, white, red, and yellow particles. These are great for generating deeply saturated colors with high contrast, but these four colors cannot be combined to create full-color images. This technology was first launched in 2013 for retail ESLs. Companies have built E Ink screens into millions of these tags, shipping them throughout the world to retailers such as Best Buy, Macy's, and Walmart. Similar electrophoretic shelf labels that use displays from China's DKE Co. have since come on the market.

For our true, full-color system, which we call Advanced Color ePaper (ACeP), we also use four particles, but we have dropped the black and rely on white—our paper—along with cyan, magenta, and yellow, the colors used in inkjet printers. By stopping the particles at different levels, we can use these particles to create up to 50,000 colors. The resulting display renders colors like those in newspapers or even watercolor art.

E Ink launched ACeP as E Ink Gallery in 2016. Again, it wasn't appropriate for consumer devices, because of slow refresh rates. Also, as it's a reflective display without a backlight, the colors were too muted for consumers accustomed to bright smartphone and tablet displays. For now, it has been geared predominantly toward use in retail signs in Asia.

Realizing we still weren't hitting the consumer-market sweet spot with our color displays, our R&D team went back to take another look at Triton, the system that used RGB color filters. What worked and what didn't? Were there modifications we could make to finally produce a color e-reader that consumers would want?

We knew the filters were sapping brightness. We were pretty sure we could significantly reduce this loss by getting the filters closer to the electronic ink.

We also wanted to increase the resolution of the displays, which meant a much finer color-filter array. To get a resolution more in line with what consum-

Illustrations by James Provost

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