Color Electrophoretic Displays

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ABSTRACT

E Ink Spectra™ 6 is the most recent addition to the Spectra™ product line. It offers superior color saturation as well as a 30:1 black-white contrast ratio. The Spectra™ 6 display module employs a specialized dithering algorithm, enabling full-color image representation. Each pixel on the module can display red, yellow, green, blue, white, or black.

1 Introduction

The commercialization of black and white bichromic EPDs in eReader applications marked a significant milestone in the field of electronic paper. By combining the ink-on-paper visual experience with remarkable image stability, EPDs offer a compelling solution over other epaper technologies for applications that prioritize both readability and energy efficiency. [1]

EPDs offer not only performance benefits, but also health benefits and sustainability advantages. The benefits of EPDs over liquid crystal displays for eye health have been quantified in recent studies [2]. EPDs generally have a significantly lower carbon footprint throughout their lifecycle when compared to LCDs. [3]

In the pursuit of achieving the holy grail of color electrophoretic displays, the commercialization of the first color EPD product E Ink Spectra™ 3000 in 2014 marked a major milestone. [4], [5]

Currently, there are three commercially viable technologies for full color electrophoretic displays. All three architectures feature a single ink imaging layer produced by a roll to roll manufacturing process and a traditional thin film transistor design.

E Ink Kaleido™ employs color filter arrays, printed in close proximity to traditional black and white EPDs while E Ink Gallery™ [6],[7] and E Ink Spectra™ [5], [8], [9], [10] leverage multi-particle electrophoretic technologies, where color originates from the color particles present within the electrophoretic ink. Gallery™ products utilize an advanced ink system that consists of three transparent colored particles (cyan, magenta, and yellow) and a light-scattering white particle. This unique architecture enables the rendering of almost infinite device primary colors within each pixel. Fast image updating of less than 0.5 second can be achieved, making it well-suited for eReader and eNote applications.

Spectra™ 6 [10] represents the latest addition to the product range, incorporating light scattering white particles, reflective red and yellow particles, and semi-transparent blue particles. Geared towards Electronic Shelf Label and smart signage applications, this technology delivers highly saturated colors and an impressive black and white contrast ratio of 30. The imaging film can be manufactured by a roll-to-roll process based on the E Ink Microcup® technology.

2 Spectra™ 6 Electrophoretic ink design

In 2021, Spectra™ 3100 was introduced, containing red, yellow, white, and black particles, providing all of the popular warm highlight colors in one image film. Spectra™ 6 is an advanced four-particle technology, substituting the black particle with a semi-transparent blue particle as depicted in Figure 1.

![Figure 1: Ink design of E Ink Spectra™ 6](image)

The four particles in this electrophoretic ink have been meticulously engineered to carry different amounts of surface charge. The particles vary in surface protection functionalities, densities, and sizes. Through precise control and utilization of these parameters, it becomes possible to orchestrate diverse interactions among the particles and elicit specific responses to different electrical fields.

Figure 2 illustrates the particle configurations for each of the six device colors. The white, red, and yellow states rely solely on the optical properties of a single type of color particle positioned at the viewing side. For the green state, a careful mixture of two types of color particles at the viewing side is employed, which was previously demonstrated in the orange color on Spectra™ 3100 plus. In contrast, achieving the blue and black states requires precise layering of two types of...
color particles on the viewing side. These deliberate and specific particle arrangements are essential to the accurate representation of color states on the display.

![Figure 2. Optical States of E Ink Spectra™ 6](image)

### 2.1 Comparison of technologies used in the Spectra™ product line

The evolution of the Spectra™ product began with a 3-particle ink design and advanced to a 4-particle ink design, as illustrated in Figure 3 and Table 1. The design has evolved into a more complex ink system, offering a broader range of optical functions. Furthermore, the design’s versatility allows for integration with different core particle materials, offering the flexibility to tailor color selections according to specific application needs.

![Figure 3. Evolution of E Ink Spectra™, 2014-2024](image)

### Table 1. Comparison of three E Ink Spectra™ product designs

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Spectra™ 1000</th>
<th>Spectra™ 1100</th>
<th>Spectra™ 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of color particle types</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Light scattering particles</td>
<td>White, Red, Black</td>
<td>White, Red, Yellow, Black</td>
<td>White, Red, Yellow</td>
</tr>
<tr>
<td>Transparent or semi-transparent particles</td>
<td>N/A</td>
<td>N/A</td>
<td>Blue</td>
</tr>
<tr>
<td>Negatively charged particles</td>
<td>White</td>
<td>White and Yellow</td>
<td>White and yellow</td>
</tr>
<tr>
<td>Positively charged particles</td>
<td>Red and black</td>
<td>Red and black</td>
<td>Red and blue</td>
</tr>
<tr>
<td>Color palettes</td>
<td>White, black, or red in every pixel</td>
<td>White, black, yellow, or red in every pixel</td>
<td>White, black, yellow, red, green or blue in every pixel</td>
</tr>
<tr>
<td>Resolution</td>
<td>330ppi</td>
<td>150ppi</td>
<td>200ppi</td>
</tr>
<tr>
<td>Max driving voltage</td>
<td>15V</td>
<td>15V</td>
<td>15V</td>
</tr>
<tr>
<td>Operation temperature</td>
<td>0-40C</td>
<td>0-40C</td>
<td>0-50C</td>
</tr>
<tr>
<td>Image transition time</td>
<td>12s</td>
<td>12s</td>
<td>12s</td>
</tr>
</tbody>
</table>

### 2.2 Colors utilizes layering particles and their control

The advanced driving algorithm and mechanisms employed to produce the six device colors have been comprehensively described in previous publications. [10] Notably, the color layering techniques employed are novel to the Spectra™ product line. In this article, a more detailed explanation of these innovative color layering methods will be provided for the blue state as in Figure 4 and the black state.

The semi-transparent property of the blue particles plays a crucial role in attaining an excellent black state contingent upon the precise placement of the reflective red particles directly underneath the blue particles. Under this mechanism, fully transparent blue particles perform as effectively as semi-transparent blue particles.

Achieving this particular layering state poses a significant challenge. To address this, we strategically imparted a high charge on the blue particles and a low charge on the red particles. This allows for the blue particles to be placed on top of the red particles through particle racing when a high positive charge is applied to the backplane. Conversely, if the blue and red particles are mixed without proper layering, a purple color will appear.

![Figure 4. Driving algorithm to achieve blue color](image)

To achieve the desired blue color in Spectra™ 6, precise layering of semi-transparent blue particles above the reflective white particles is essential to reflect the blue light back to the viewer. Spectra™ 6 accomplishes this through a combination of particle charging arrangements and a carefully designed driving algorithms. The intermediate driving step, as shown in Figure 4b, is optimized to apply a small negative voltage ranging from -3 to -14 volts resulting in precise particle positioning. With the final driving as in Figure 4c, the desired blue color can be achieved.

In the example provided in Figure 5, at -5 volts, both L* (lightness) and b* (yellow-blue axis in color space) are low. This indicates that a significant portion of the light passing through the blue particles is not reflected back by the white particles but rather absorbed by the red particles. As the driving voltage becomes more negative, the L* value increases, and the b* progressively shifts.
towards a more negative value, indicating a shift towards blue in the color space. During this transition, the red particles are gradually replaced by the white particles, leading to a highly saturated blue color with minimal red contamination. The optimum \( b^* \) value is achieved at approximately -8 volts, providing the most appealing blue color. The design demonstrates robustness as it achieves a saturated blue color at a reasonable driving voltage ranging from -7.3V to -9V.

\[ \text{Figure 5. Blue color performance as a function of the driving voltage during the last step in the driving algorithm} \]

2.3 Special image processing

While more mixed colors can be attained through advanced driving algorithms, the strategic selection of six colors allows for efficient management of the remaining mixed colors through dithering. This approach capitalizes on the high-resolution capability of the Spectra™ 6 technology, and ensures cost-efficient implementation in commercial products by simplifying the system requirements. The algorithm used for image processing is significantly different from those used by LCD and OLED displays. A unique dithering pattern is demonstrated in Figure 6 on a full-color image.

\[ \text{Figure 6. Dithering of device palette colors to form a full-color image on a 25.3 inch Spectra™ 6 module} \]

3 Results

This section describes the electro-optical properties of Spectra™ 6 modules.

3.1 Color Performance

Figure 7 illustrates the chromaticity of the six device colors present in a typical Spectra™ 6 display module with measurements taken at 25°C using an X-Rite i1Basic Pro 3 Plus spectrometer. The white state exhibits a subtle tint while remaining close to a neutral hue. Notably, all four colors are highly saturated, with the yellow, red, and blue states positioned at or near the sRGB boundary. The green color accurately matches the desired hue. Despite the black state's departure from neutrality, its low reflectance prevents it from exhibiting a pronounced shade. The contrast ratio on the TFT display module, when combined with a laminated protection sheet, exceeds 30, surpassing that of a typical magazine print. It takes 12 seconds to update the display with the maximum driving voltage of 15 V.

\[ \text{Figure 7. Optical performance of the six optical states} \]

3.2 Device color performance across the operation temperature

Spectra™ 6 shows consistent optical performance when operating across 0°C – 50°C, as shown in Figure 8, showing the robustness of the design. This requires the particle charge architecture, their relative mobility and the particle-particle interactions to be stable across the operation temperature.

\[ \text{Figure 8. Optical performance of the six optical states across the operation temperature of 0°C to 50°C} \]
4 Application
Spectra™ 6 is ideal for applications such as Electronic Shelf Labels and smart signage due to its high contrast ratio, highly saturated colors, and low power consumption.

4.1 Application in Electronic Shelf Label
A variety of display sizes will be offered for ESL applications. Retailers can choose a suitable size of ePaper module for their needs. The All-in-one (AIO) driver IC developed for Spectra™ 3100 can provide all the driving support for small to medium size Spectra™ 6 display modules (Figure 9). These AIO driver ICs provide the functionality of the TFT source/gate drivers, display timing controller, power management, security protection, and memory for storing driving algorithms. Image processing can be executed at the system level.

![Figure 9. Spectra™ 6 modules for smart label and signage applications](image)

4.2 Application for Signage application
Large-sized Spectra™ 6 display modules are currently under development.

![Figure 10. Photo of a 25.3 inch Spectra™ 6 module](image)

As depicted in Figure 10, a 25.3-inch display module tailored for smart signage applications is showcased. A noteworthy feature of this module, as exemplified in the figure, is its remarkable capability to retain the displayed image for an extended duration, e.g. days after the power supply is disconnected. This exceptional attribute positions it as an ideal choice for applications requiring low-power and sustainability in display technology.

5 Conclusions
A four-particle electrophoretic display, Spectra™ 6 can display white, black, and highly saturated red, green, blue, and yellow states in each pixel using a maximum voltage of 15 volts. The six optical states exhibit excellent optical consistency across a temperature range of 0°C to 50°C with a resolution of 200 ppi. The display module offers outstanding readability with its contrast ratio of 30. Additionally, it utilizes an advanced driving algorithm to excel at showcasing highly saturated full-color images, making it ideal for Electronic Shelf Label applications and various signage needs. The module seamlessly integrates with the existing Eco system of 3 bits Spectra™ 3100 products, enabling effortless adoption into existing systems.

References