Perspectives and Challenges of Electrophoretic Displays

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Abstract

The commercialization of an active matrix e-reader display using E Ink micro-encapsulated electrophoretic (MEP) ink marked a big step towards comfortable reading over an extended period of time in an electronic book, as the high resolution display, jointly realized by Philips, E Ink and Toppan, has a true paper-like look and feel. Alternative electrophoretic material systems are being developed by SiPix and Bridgestone and progress has been made in the past two years. In this paper, electrophoretic material systems are briefly reviewed, after which the perspectives and challenges of electrophoretic displays are addressed and methods for generating gray tones are presented and discussed.

1. Electrophoretic materials systems

Electrophoretic material systems comprise technologies in which colored particles in a fluid are manipulated by electric fields. There are two basic classes of systems –

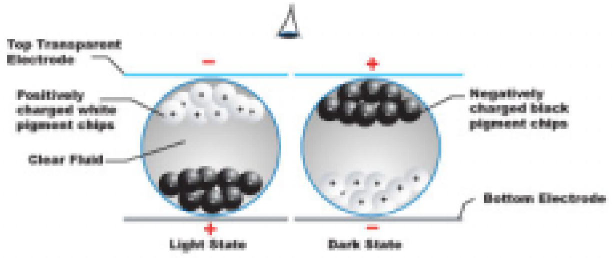
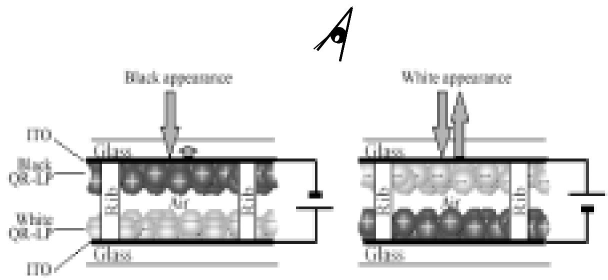


Figure 1. Schematic diagram of E Ink microencapsulated electrophoretic ink system: two kinds of particles move in transparent liquid within a microcapsule

those where the particles are displaced [1,2,3] and those where the particles rotate [4]. Electrophoretic (EP) displays operate by the motion of charged pigment particles in response to an electric field. Both single particle in a colored fluid [1,2] and dual particle systems [1, 3] are used. In the E Ink micro-encapsulated electrophoretic ink system, both particle-dye and dual-particle electrophoretic films have been presented [1] and the dual-particle system is schematically shown in Figure 1, black and white particles of opposite charge move between two planar electrodes in a transparent liquid. When the white particles are on the viewing side of the cell, the display appears light from any viewing direction as incident light is scattered from the white particles. When the black particles are on the viewing side, the display appears dark. The particle displacement is proportional to the time integral of the applied voltage whilst the voltage pulse necessary to reach a given final optical state is a strong function of the initial optical state (see section 4). Intermediate gray tones are produced by applying a voltage pulse less than the maximum necessary for a full black to white or white to black transition.

In the Bridgestone electrophoretic ink system as schematically shown in Figure 2, black and white particles of opposite charge move between two planar electrodes in air. Similar to the E Ink dual-particle system, when the white particles are

Figure 2. Schematic diagram of Bridgestone electrophoretic material system: tow kinds of particles move in air.



on the viewing side of the cell, the display appears light and when the black particles are on the viewing side, the display appears dark. The particles start moving to the opposite electrode when the voltage level is higher than the critical value (switching threshold). The switching time was reported to be about 0.2ms at about 70 volts. Intermediate gray tones were also demonstrated on passive matrix displays by Bridgestone [3]. This display system is also named as the QR-liquid powder display.

Figure 3. Schematic diagram of SiPix Microcup electrophoretic material system: one kind of particles move in absorptive liquid.

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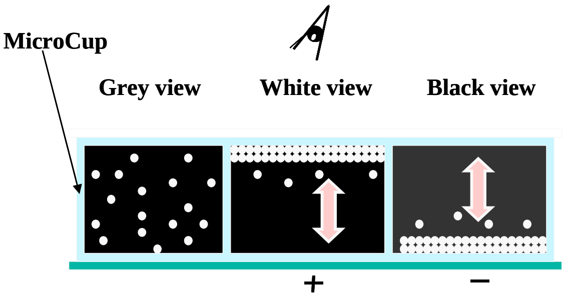

In the SiPix Microcup electrophoretic ink system as schematically shown in Figure 3 [2], a single type of charged white particles are moved between two planar electrodes in an absorptive liquid within a Mictrocup. When the white particles are on the viewing side of the cell, the display appears light and when the white particles are at the bottom, the display appears black, the color of the dye/liquid A black and white display has been recently demonstrated by SiPix at SID05. Similar to the MEP system, intermediate gray tones can be produced by voltage modulation or pulse width modulation.

2. Perspectives of Electrophoretic displays

One of the promises of electrophoretic displays is its true paper-like features: excellent readability resulting from a combination of high resolution, high reflectivity, and insensitivity to viewing angle and lighting conditions; high portability and comfortable hand-held reading (as opposed to reading from a fixed screen), resulting from thin and light form and flexibility and ultra-low power consumption, where no power is required to maintain the image once written. These paper-like features are demonstrated by the commercial e-reader display (Figure 4) using E Ink micro-encapsulated electrophoretic (MEP) electronic ink. The

Figure 4: Philips and E Ink's 166ppi electronic paper display integrated in the Sony LIBRIé e-reader.

high-resolution micro-encapsulated active matrix electrophoretic displays showing 2-bits gray tone images and text with high contrast and high reflectance are commercially available. This device represents a big step toward comfortable reading over an extended period of time in an electronic book. The characteristics of the display are described in the below table.

Diagonal	6"
Columns x Rows	800 x 600 (SVGA)
Resolution	166ppi
Reflectance	36% (typical)
Contrast Ratio	9:1 (typical)
Viewing Angle	180^o

Table 1. Characteristics of the active matrix electrophoretic display

Another important promise of electrophoretic systems is its high potential for flexible or even rollable display. Such an electrophoretic display incorporates another feature of paper: flexibility. Unlike LCD, an electrophoretic display does not require polar and backlight, making it extremely suitable for integrating on a flexible substrate. This has been demonstrated by using E Ink micro-encapsulated electrophoretic (MEP) electronic ink and the organic-based transistor active matrix backplanes of Philips Polymer Vision (Figure 5) [5].

Figure 5: World's thinnest flexible active-matrix display using Philips' ultra-thin back plane with organics-based thin film transistors, combined with E Ink's electronic ink front plane [5].

3. Challenges of Electrophoretic Displays

To achieve the full quality of a real paper print, analog gray tones and/or bright full color must be generated on such displays. It would be further highly desirable if moving

pictures or video material can be displayed. To create color options, several approaches may be considered:

A straightforward option is to add color filters in front of the electrophoretic film similar to color LCDs. The feasibility has been demonstrated by E Ink using transmissive color filters [6]. It is also possible to incorporate intrinsically colored components into the electronic paper, such as colored liquids [1,2,8] or colored particles [7]. In the SiPix Microcup colored liquid system, one concept may be that a pixel consists of three sub-pixels with R, G, B dye and white particles. The combination of particles movement in both vertical and lateral direction and the use of a black absorptive layer at the bottom electrode allow generation of various color without degradation of white reflectivity [8]. In the E Ink dual particle system, a pixel may consist of three sub-pixels with Red/Black, Green/Black, and Blue/Black dual particle pixels. E Ink has demonstrated R, G, B, and black pigment electrophoretic displays for use in side by side color dual particle scheme.

There is always the dream that electronic paper can provide options which real paper cannot. Some attractive features are moving picture capability, which can be realized when the response speed is below or around 50msec. Recent results at E Ink and Bridgestone showed exciting development in this direction [6]. Another feature is to create interactive paper/book on which pen input can be realized within reasonable time. A pen input system to create e.g. an electronic drawing pad [9] has been demonstrated.

Generating gray tones in electrophoretic displays usually is not trivial because of their bi-stable features. It has been reported that voltage pulse modulation and/or pulse width modulation may be used for generating gray tones [8, 10-15]. In the following, methods of generating gray tones and realizing high quality images on active matrix MEP displays are presented and discussed.

4. Gray tones in a dual-particle type electrophoretic display

The dual-particle system MEP displays operate by the motion of charged pigment particles between two planar electrodes, in response to an electric field. By applying a positive voltage on a pixel, the positively charged white particles are forced to move towards the top transparent electrode, creating a white state when the display is viewed from this side. In contrast, by applying a negative voltage on a pixel, the negatively charged black particles are forced to move towards the top electrode, creating a black state. Between these two end states exists an analog range of intermediate-reflectivity gray states.

A MEP display differs significantly from AMLCDs, as electronic ink responds to both voltage and pulse length and is sensitive to polarity. Because reflectance states, including graytones, are stable at zero applied voltage, a drive pulse is required only when the image needs to be changed. At the same time, a drive signal must take into account not only the desired gray tone,

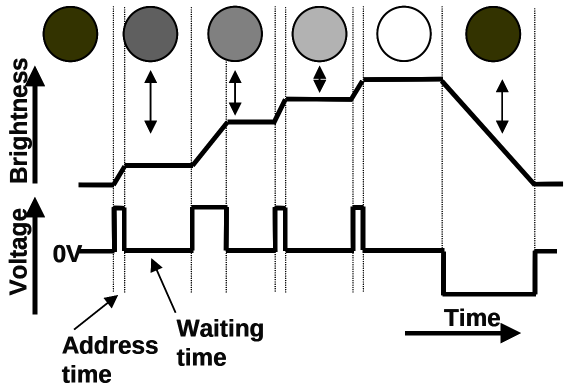

Figure 6: Schematic of switching a MEP display between gray levels using differential driving.

but also the gray tone that a pixel is coming from. We refer to driving in this environment as “differential driving”. Dedicated display electronics and TFT back-planes have been developed including an entirely new display controller system [10-12]. Switching from one gray level to the other in a MEP display is illustrated in Figure 6. The initial state of the pixel is black. A short, positive-voltage pulse is applied to drive the pixel to dark gray. To maintain the dark gray state, zero voltage is applied. In a subsequent update, by using another positive-voltage pulse, a lighter gray state is achieved and remains on the pixel. After two more transitions, the white state is finally achieved, from where the black state can be restored upon the use of a negative-voltage pulse with sufficient duration to drive the imaging layer to the black state. The change in optical state is determined by the relative particle displacement, which is determined by the time integral of the applied voltage, which we refer to as the voltage impulse.

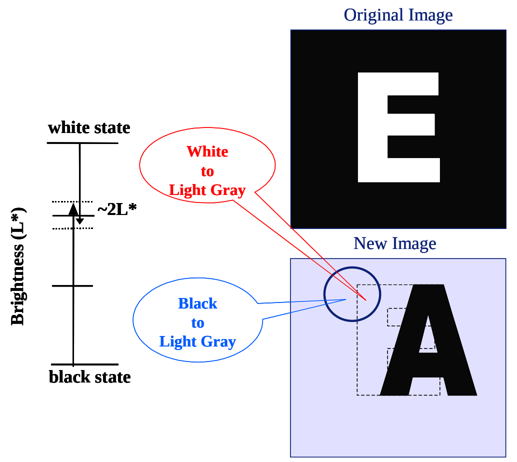

Figure 7. Illustration of the criteria in addressing an active matrix MEP display: the mismatch must be smaller than 1L*.

Figure 7 illustrates the image quality criteria in addressing an active matrix MEP display, in which a new black letter **A** on light gray background is obtained from a white letter **E** on black background. The light gray background on the new image obtained partially from black to light gray transition and partially from white to light gray transition should have the same level or a difference smaller than 2L* to fully erase the original image (L* is a unit of lightness as defined in the CIELAB standard, and can be calculated from reflectivity as $L^* = 116\,(R/R_0)^{1/3} - 16$, where R and R_0 are the reflectivity of the sample and a 100% reflective standard, respectively).

5. Grayscale driving schemes for a MEP display

Rail-stabilized driving schemes have been found to be promising schemes for achieving accurate gray tones in a MEP display. This means that the display is first reset to one of the two extreme or "rail" optical states: black or white, after which the display is driven to the desired gray tones. The gray tone accuracy is ensured by the fact that the rails are the most reproducible reference states. It is preferred to have a single reset towards a rail to minimize the visibility of optical flicker and shorten the update time. Figures 8 illustrates a rail-stabilized driving principle based on reset to the closest rail [13]. In this approach, the reset state is determined by the next image content regardless of the previous image and the gray tones are always achieved via the closest rail. To achieve a light gray (G2) gray tone between white and the middle gray, the white state is selected as the reset state because it is the closest to the light gray. In contrast, to achieve a dark gray (G1) gray tone between black and the middle gray, the black state is selected as the reset state as it is the closest to the dark gray. In this way, in an image update, the monochrome version of the new image is obtained first, followed by the addition of the gray tones from their respectively closest rail states [13, 15]. A reasonably accurate gray tone is achieved with minimized optical flicker and shortened update time (figure 8, top section).

The gray tone accuracy can be further improved by introducing an additional reset impulse as illustrated in the lower section of Figure 8. The additional reset impulse is in fact an over-reset for ensuring that an identical reset state is obtained from various initial optical states. In an image update, the display is first switched to the white rail from the initial black or dark gray states by applying the appropriate reset/rail drive impulse. From the white rail, the light gray is achieved by applying the opposite gray tone drive impulse. The white rail is again selected as it is closest to the light gray state of the next image. The additional reset is needed to guarantee the image quality. The mechanism by which the over-reset influences the gray tone accuracy could be related to the mechanism of counter ion induced fluid motion as proposed from the simulation work of Kodama et al [14].

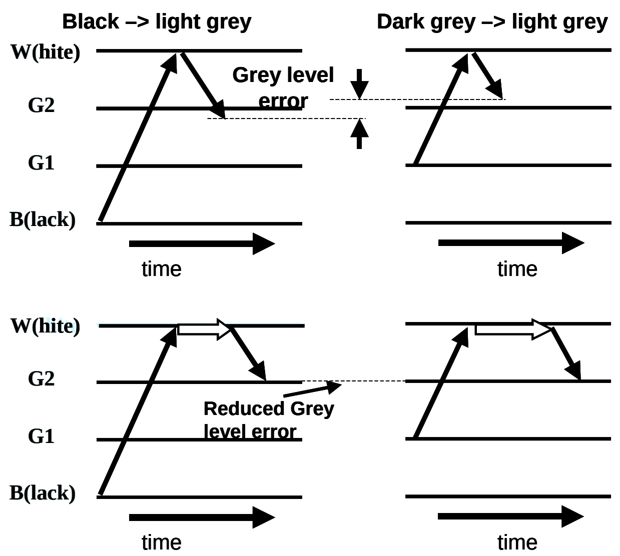

Figure 8: Examples of image update sequences from black (left hand side) and dark gray (right hand side) to light gray, using the closest rail approach. The lower figures illustrate the improvement in gray tone accuracy by introducing an additional reset impulse

As the gray tone accuracy is improved by the over-reset, we have also considered introducing an artificial over-reset into pixel transitions where no reset is strictly required, for example gray tone transitions starting from an extreme optical state e.g. white-to-light gray. In these examples, we have chosen to apply a series of impulses to move the particles away from the rail state, before again moving them towards the rail and creating an over-reset. The transition proceeds further to achieve the accurate final gray level [15].

Gray tone accuracy can be further improved by introducing a series of AC pulses prior to the addressing pulses as demonstrated in Figure 9, in which the reflectivity is plotted as a function of voltage pulse without AC pulses (upper) and with AC pulses (lower). The display was initially at black state. After an undefined waiting time (t_{wait}), the display needs to be switched to white state with a desired reflectivity of about 35% by a pre-defined voltage pulse of –15V for 200ms. The achieved white state has a lower than desired reflectivity and is also different on t_{wait}. When a series of short voltage pulses alternating between positive and negative prior to the drive pulse is used, the white state error is significantly reduced (see the lower figure). In this experiment, 6 up and down pulses with a time period of 20ms are applied prior to the drive pulse. The desired reflectivity is achieved, independent of t_{wait}. The image quality is significantly improved and white reflectivity is maximized.

The above-described driving schemes have been applied to the AM paper-like display integrated in the Sony

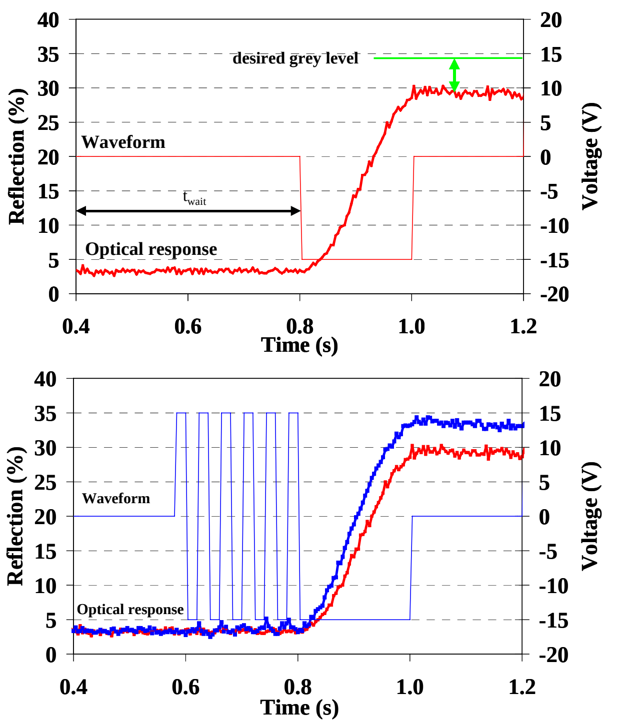

Figure 9: Method of increasing gray tone accuracy by applying a series of AC pulses prior to the driving pulse.

LIBRIé e-reader shown in Figure 4. The high image quality has been confirmed by both visualization and experiment [13, 15].

6. Conclusions

Electrophoretic displays have true paper like feature in terms of readability, portability and flexibility. Several electrophoretic materials systems are being developed by E Ink, SiPix and Bridgestone with continuous improvement towards higher switching speed, more colour and lower costs. Several methods are presented and discussed forgenerating accurate gray tones in electrophoretic displays, specifically the E Ink MEP system. Rail-stabilized driving schemes based on reset to the closest rail combined with an additional reset period are found to be promising in achieving accurate graytones in an active matrix electrophoretic display using a single reset. The greyscale accuracy can be further improved by applying a series of AC pulses prior to the driving pulse. These driving schemes are successfully applied to the AM paper-like display used in the Sony LIBRIé e-reader. Accurate gray tone reproduction and extremely low power consumption combined with a high brightness and near perfect viewing angle combine to give the display its unique paper-like properties.

7. Acknowledgement

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