Microencapsulated Electrophoretic Films for Electronic Paper Displays

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Abstract

Microencapsulated electrophoretic imaging films have been developed for various display applications. These films exhibit an "ink-on-paper" appearance owing to their strong, near lambertian light scattering properties. Image persistence exhibited by these films allows displays to operate without power outside of image updates. This and their ready incorporation into flexible displays make microencapsulated imaging films attractive for portable devices where readability in a wide variety of lighting conditions, low power consumption, and mechanical robustness are important. This report reviews the basic principles of optical and electronic performance of E Ink's microencapsulated electrophoretic films as well as some recent applications, and methods of driving these films in active-matrix electronic paper displays (EPD).

There is considerable interest in electronic paper displays (EPD) for use in portable devices that allow for easy readability under a variety of lighting conditions and viewing angles and which require little power. Electrophoretic films are attractive candidates for these displays because of their high reflectivity, near-lambertian reflection characteristics, and image stability. These films incorporate charged particles in a fluid medium whereby scattering particles are used to achieve a white state. They are driven to the front of the display through coulombic force by applying the appropriately signed voltage to the display backplane. Reversing the sign of the backplane voltage drives these particles to the back of the display behind a dyed fluid or a second, light absorbing set of oppositely-charged particles, thus achieving a dark state. The strong scattering of the particles, along with the absence of polarizers utilized in most liquid crystal displays, gives a bright, near lambertian white state to the display, offering high brightness for all illumination and viewing angles.

Historically, electrophoretic displays have suffered from several primary failure modes associated with lateral migration of the pigment. E Ink has developed a microencapsulated electrophoretic imaging film for incorporation into a variety of display applications. Microencapsulation limits lateral migration of the pigment particles to block these failure modes and impart a solid component between the bottom and top display substrates. The film structure is shown schematically in Figure 1. The microcapsules are designed to be deformable so that properly controlled coating yields a tightly packed array of microcapsules as shown in the microscopic image in Figure 2. This tight packing minimizes the non-active area of the imaging film, and this is important for maintaining a high optical contrast.

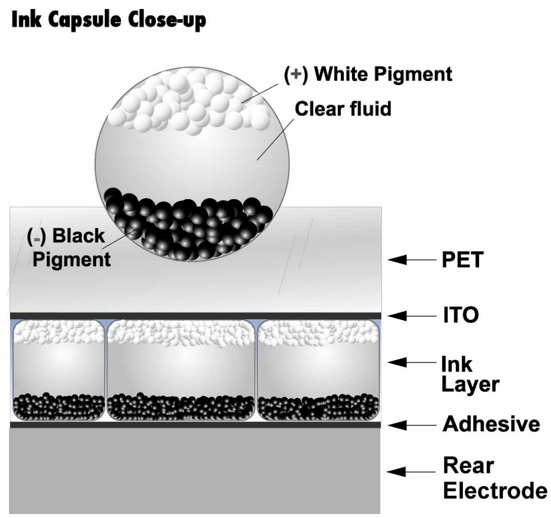

Figure 1. *Cross sectional schematic of a microencapsulated electrophoretic imaging film. Charged pigment particles in a fluid are contained within microcapsules within a solid film between a transparent, conductive top plane electrode (top) and a series of pixel electrodes. Backplane voltages drive either the white or black pigment particles toward the front to achieve light and dark optical states.*

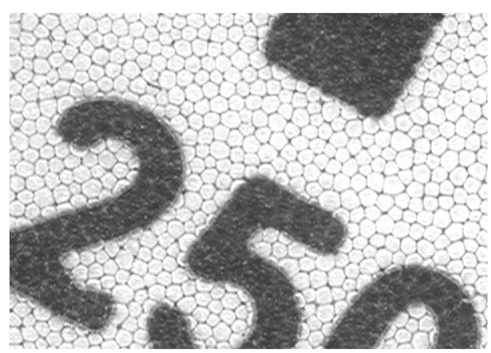

Figure 2. *Microscopic image of a microencapsulated electrophoretic imaging film. The microcapsules are deformable and form a tightly packed array of capsules that impart a high active area fraction to the imaging film.*

E Ink Imaging Film™ has been designed to exhibit image persistence in the absence of a drive voltage, not only for the black and white optical states, but also the intermediate graytones. White and black states are written to the imaging film using a voltage pulse of prescribed duration. Graytones between white and black are achieved by "partial addressing", either by applying a pulse of lower voltage for the same prescribed duration, or by applying a pulse of the same voltage but for a shorter duration. Because graytone images written in these films persist in the unpowered state, power is used only to update an image, but none is required to maintain an image. This allows for very low power consumption in applications where the display is not continuously updated, for example, for an electronic book. In order to take advantage of the image persistence and realize low power consumption a differential driving scheme must be employed. In differential drive, the display controller applies an appropriate voltage sequence to bring each pixel from a current graytone to the graytone necessary for the next image.

A number of grayscale addressing schemes for driving microencapsulated electrophoretic imaging films have been developed. In the simplest scheme, the transition from one graytone to another is direct, with a single voltage pulse driving from the initial graytone to a final graytone in a direct path as illustrated by the solid line trace in Figure 3. We have found that errors in the image reflectance are larger for this direct scheme than for some other driving schemes, and, in fact, for applications requiring high-quality graytone imaging, low-error driving schemes are preferred. Very precise graytones can be achieved in a scheme whereby the display is driven multiple times to optical extremes before being driven to the final graytone. Such a scheme is illustrated by the dashed trace in Figure 3. The cost of such updates is that they are long and they introduce flashiness to the transition.

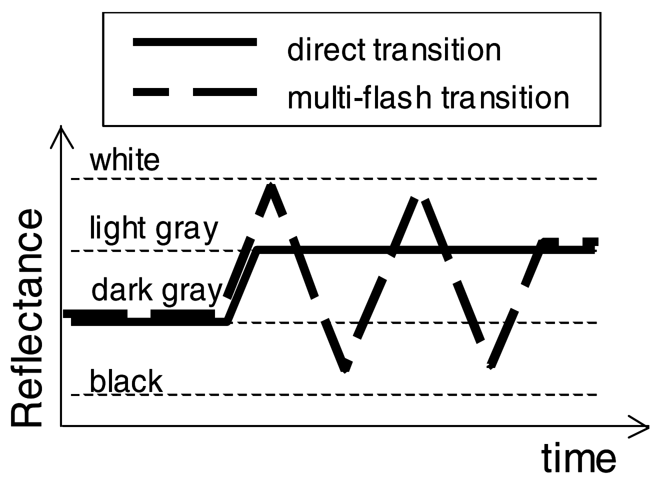

Figure 3. Transition from dark gray to light gray in 2-bit grayscale. Solid line shows a direct transition and the dashed line a multi-flash indirect transition.

A generalized method for developing transition schemes that achieve graytone precision normally associated with such very flashy updates was created, but using transition schemes with much lower flashiness. E Ink's method involves making small modifications to a basic transition scheme structure through an optimization scheme. The optimization scheme minimizes metrics that relate to variations of reflectance within each graytone, and in this way achieves high graytone precision. Schematic examples of the action of such update schemes are illustrated in Figure 4.

Testing for graytone precision in an image stable display film requires special methods that take into account the image persistence of the display. Among other methods, we utilize a test protocol based upon a carefully designed pseudo-random sequence of transitions in order to characterize the performance of a transition scheme. The testing sequence is designed to include all graytone sequences to a certain history depth. To clarify, consider a 2-bit grayscale scheme. We denote the four graytones "1", "2", "3", and "4". A sequence that includes all possible transitions from one graytone to another (all $i \rightarrow j$ transitions, i,j = 1, 2, 3, 4) is said to be complete to depth two, a sequence that includes all transitions from one graytone to another and yet to another (all $i \rightarrow j \rightarrow k$ transitions) is called complete to depth three, and so on. For example, a depth two complete sequence is:

$$2\rightarrow4\rightarrow1\rightarrow1\rightarrow3\rightarrow2\rightarrow3\rightarrow3\rightarrow4\rightarrow2\rightarrow1\rightarrow4\rightarrow4\rightarrow3\rightarrow1\rightarrow2\rightarrow2$$

because all sequence pairs "$i \rightarrow j$" are represented. To run this sequence, the display is sequentially driven to each of the graytones in the list. The reflectance is recorded after each transition. Afterwards, the reflectances are arranged in a prior-sequence indexed fashion so that all the graytone 1 reflectances are in the left quarter of the plot, all graytone 2 reflectances are in the second quarter, and so on. Reflectances from a depth-3 complete sequence are shown in Figure 5. The graytones in the left quarter are for graytone 1, and each point represents one of the possible

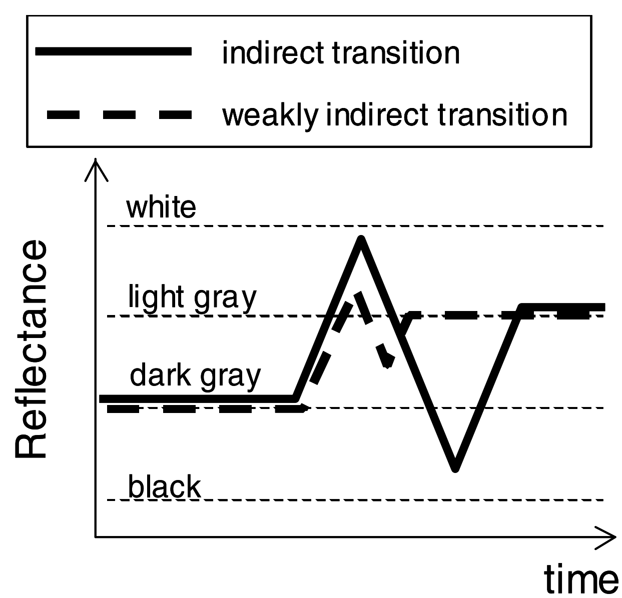

Figure 4. Transition from dark gray to light gray in 2-bit grayscale. Solid line shows an indirect transition and the dashed line a weakly-indirect transition.

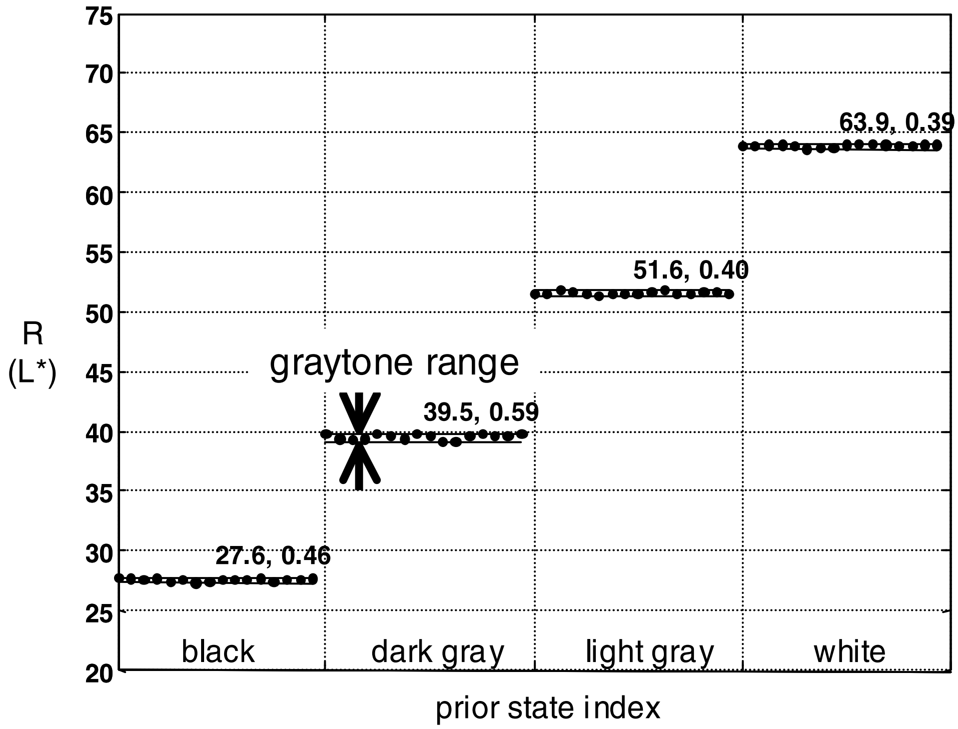

__Figure 5.__ Reflectances from pseudo-random sequence test of depth 3, shown in L reflectance scale for an indirect transition scheme like that shown in Figure 4. Variations within each of the four graytones is very small.*

sixteen combinations of two states prior to graytone 1. For a very precise transition schemes, variations of the reflectances in each of the quarters will be small. Figure 5 shows that the graytones achieved using the test transition scheme gave good results, because the maximum range within any one graytone is less than one L* reflectance unit.

There is a trade-off between transition flashiness and graytone precision. For some applications, there is a premium on minimizing transition flashiness and a tolerance for lower graytone precision. For others, graytone precision is critical and transition flashiness is more tolerated. Our optimization scheme allows us to re-optimize for various applications. By changing the emphasis between low transition flashiness and high graytone precision, we can realize a range of optimum transition schemes. The prior-sequence-indexed, depth-3 reflectance plot for a lower-flash transition scheme is shown in Figure 6. Note that the reflectance variations for a single graytone are greater than for the related transition scheme that yielded the results of Figure 5. This cost comes with the benefit of reduced update flashiness. This work shows how transition schemes can be adjusted to meet the needs of a variety of applications.

One such application is an electronic book being developed by Sony and shown in Figure 7. This handheld device uses E Ink's microencapsulated imaging film to give an ink-on-paper appearance to the display. The fact that the display requires power only to update the image enables a long battery life.

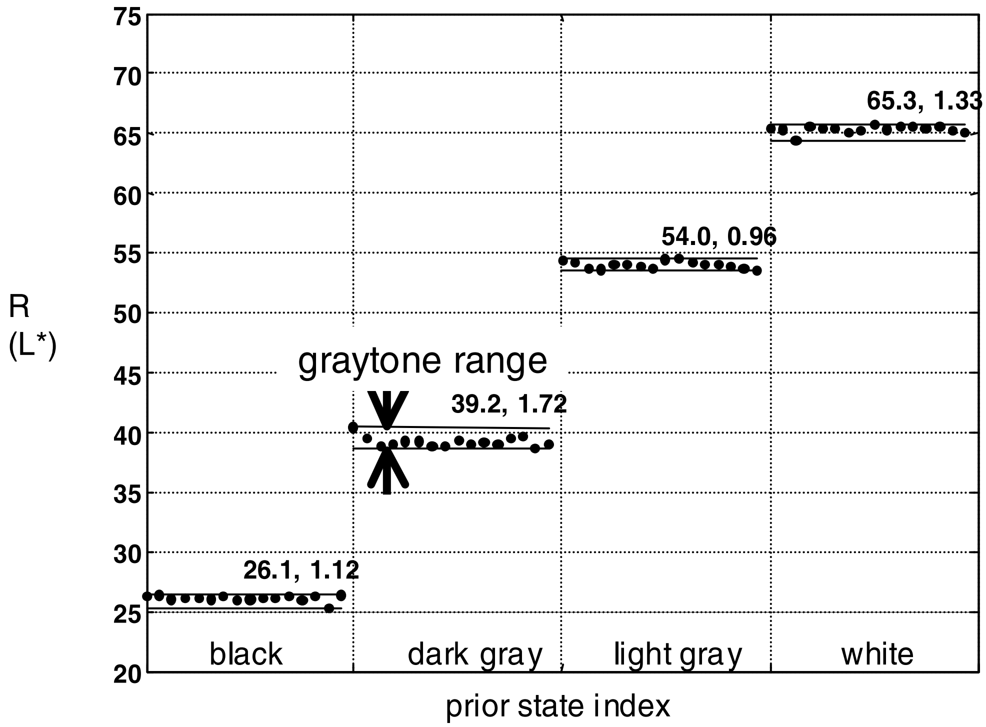

Figure 6. *Reflectances from pseudo-random sequence test of depth 3, shown in L* reflectance scale for a weakly indirect transition scheme in the spirit shown in Figure 4.*

Figure 7. *An electronic book being developed by Sony uses E Ink's microencapsulated electrophoretic imaging film.*

References

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Author Biography

Karl Amundson received his B.S. in Physics and B.S. in Chemical Engineering from the University of Minnesota (1983), and Ph.D. in Chemical Engineering from the University of California at Berkeley (1989). He was a Member of Technical Staff at Bell Laboratories, Lucent Technologies (1989-1998), where he performed experimental and theoretical work on polymeric and liquid crystalline materials and electro-optic devices. Karl joined E Ink in 1999 as a Principal Scientist, and is currently heads a team that develops electrical models and driving schemes for microencapsulated electrophoretic films, and supports integration into displays.