Introduction

Move over ink on paper and printed shop sign in the window! The death knell is being heard around the industrialized world as electronic paper starts to gain traction as a viable means of conveying and even storing data. This futuristic view of electronic paper and displays may be a few years away from widespread acceptance (remember the coming of the personal computer and paperless society?), but the basic technology and ideas to make it a reality have been available in laboratories for about 30 years. Electrophoretic display technology, since its inception in the 1970s, has progressed slowly to a maturity that now allows it to take full advantage of the things that make it unique in the display arena, including ease of manufacture, low cost, stability, flexibility, and reliability. Though electrophoretic displays are not the only ones available for application in low cost, low energy consumption, flexible and/or portable electronics, their twisted nematic and super twisted nematic counterparts do not offer the same potential for high brightness or high flexibility with the same ease that electrophoretic particle based displays do. Additionally, direct sunlight is often a problem for competing technologies that do not rely on scattering or diffraction phenomena for their contrast and brightness. In this review paper a brief history of display technology up to early electrophoretic displays, the basic principles of image formation, the behavior of light, the electronics necessary for the backplane, and the application of the electrophoretic concept to flexible substrates will be explored.

History: Early times and progress for display technology

Display technologies have progressed greatly through the ages. Early forms of display were permanent, such as cuneiform clay tablets which served to both display and store information about business transactions thousands of years ago. Three thousand years ago
papyrus leaves and simple colloidal inks were used by Egyptians to provide less permanent, but more portable means of displaying information. Stone inscriptions and graffiti made from simple paints were used during the Roman times to produce long lasting large area displays, but with relatively low data content, low portability, and great difficulty associated with updating the information. Through the centuries since then, up to the 20th century, few improvements were made to display technology save Gutenberg’s printing press. Finally, in the mid-20th century electrified displays started to advance significantly and rapidly. Early displays required relatively high power and yielded relatively low visibility information with limited viewing angles and low resolution, both spatial and spectral. These included most of the cathode ray tube technologies. Static display of information during this period of time continued to be through the use of the time tested ink and paper.

In the early 1970s displays began to be produced that incorporated the principles of electrophoresis, or the motion of a charged particle through a liquid medium due to an applied electric field. The general composition of the displays at that time included a suspension of charged particles (containing or consisting of pigments) usually on the order of several microns in diameter in a dyed insulating fluid. The dyed fluid had to have a resistivity greater than $10^{12}$ ohm cm and relatively low viscosity ($\eta < 5$ mN s m$^{-2}$) to allow for good electrophoretic mobility of the particles. Solutions with these properties, such as Sudan Red dye in a xylene/perchloroethylene mixture or Oil Blue N dye in toluene were commonly used. This suspension was sandwiched between two parallel conducting electrode panels, at least one of which needed to be transparent to visible light. The whole array was encapsulated by a glass plate on one side and an insulating substrate on the other with a photocurable adhesive around the edges to seal everything in. Operation consisted of an applied electric field across the parallel

3
electrodes which would drive the charged particles toward one electrode and allow the viewer to see the light scattered from the particles (i.e. the color of the pigment). If the field is switched, the viewer sees the color of the dyed solvent instead, assuming the dye is in high enough concentration to absorb all light scattered from the particles.

Early displays were rigid displays due to the rigid front glass and rear substrate, such as those for alarm clocks that held many advantages over traditional display technologies.3,4 These advantages are inherent to the design and include a thin active matrix that did not require a bulky cathode ray tube or vacuum of any sort to allow it to produce an image. The display has high optical contrast and is easily viewable from almost all angles and does not rely on front- or backlighting except for viewing in the darkest of conditions (and then only front-lighting). There are no drive mechanics that could break, the modules need very low power for the switching operation (i.e. between light and dark), and they could be used for the persistent display of information with zero power consumption.

Unfortunately, early displays also suffered from many limiting features that were later overcome, including pigment or particle migration to the electrode edges, floating or settling of particles, bleaching or spectral shift of dyes, and sticking of the particles to one-another or to structures within the active area of the display.3,5 In viewing a schematic, Figure 1, of a simple electrophoretic display cell, it is easy to imagine the reason for at least the floating or migration issues when no barriers existed across the entire cell (vertically in this figure). Almost all of these challenges were associated with image retention, resolution, clarity, contrast, and grey scale.2,4
Figure 1: Schematic of an early electrophoretic display. From Ref. 2.

**Improvements and The Electrophoretic Ink:**

To overcome the drawbacks associated with the early displays, many improvements had to be made. Later models included grid barriers to limit the motion of the particles, as shown in Figure 2, the concept of which would be extensively used in the flexible display application of electrophoretic inks. Alternatively, the dyed solvent and particles could be encapsulated in

Figure 2: Cross-section schematic of spacers on left (from Ref. 5). Image on right is a surface profile of empty grid barriers as measured on a Wyko NT1000 Surface Profiler. Spacing between barrier lines can be varied from 60 to 180 µm. From Ref. 7
polymerized microcapsules and then electronically addressed. Encapsulation or grid-type barriers allow for the restriction of lateral migration due to roll-cell flow induced by the electrical switching of the cell which causes movement of the particles and concurrent displacement of the surrounding solvent medium. The restriction of migration now is to less than the thickness of the active film, as dictated by the possible flow fields in a given display. The distinct advantage associated with each method of reducing roll cell behavior lies in the printability of the encapsulated electrophoretic ink as Jacobson, *et al* claim, and the roll to roll processability of grid-type flow barriers called Microcups as shown by SiPix.6,7

A method of improving the contrast by using two different types of pigment particles—one black and one white, with opposite charge rather than the dyed solvent was introduced by Jacobson, *et al*6 and improved by others8. The issues associated with bleaching of the solvated dyes are also circumvented by using a two particle system, micrographs and a schematic of which are shown in Figure 3.

![Figure 3: Schematic of electrophoretic ink capsule (left) and photomicrographs showing how the microparticles react within a single capsule to a positive (top right) and a negative field (bottom right). From Ref. 6](image-url)
The two color particle system is the current state of the art, with a high dielectric, low viscosity suspending medium that must also be non-toxic, highly stable, and chemically inert to the rest of the system.

Regarding particle stability in solution, the electrophoretic display community took its cues from the better established colloids research arena and coated individual particles with polymers such as polyethylene in order to limit aggregation and sticking by steric hindrance means while allowing for surface charge. Furthermore, the design and production of neutral buoyancy particles by reducing the specific gravity of the particles (normally around 4.2) to that of the surrounding medium (around 1.5) by the addition of the polymer further limited the effects of settling or floating. Finally, charge stabilization and protection allows for particles of opposite charge to reside within the same capsule without aggregating.

**Display basics: Getting light from your display to the reader vs. making a useful device**

Some basic considerations must be addressed in order to understand why image production by an electrophoretic display is different from most displays. Most bright liquid crystal displays (LCD) are backlit in order to allow for ease of viewing while reflective LCDs are referred to “gray on gray” even by the companies who build them into devices. Additionally, LCD displays suffer from washout of the image when in direct sunlight or bright viewing conditions. Electrophoretic displays have the inherent quality of being bright, even in sunlit conditions due to the near Lambertian scattering from the white particles used to form the image and the excellent absorption and low transparency of the black particles. White particles are typically titanium dioxide with a relatively high refractive index of 2.7, which translates to a refractive index difference of approximately 1.3 when compared to the surrounding dielectric
For electrophoretic based displays the scattering arises from the refractive index contrast between the particles and surrounding solvent. Figure 4 illustrates the merit factor for several common passive display media (note that EPID stands for electrophoretic image display) as compared to Lambertian scattering.

![Figure 4: Contrast merit factor for several passive display media. From Ref. 2](image)

It is also important to note that when the current used to create the electrophoretic image is removed, the particles remain on the electrodes, retaining the image for 100 hours or more. The bistable nature of the particle suspensions as either scattering or absorbing, depending on the last voltage applied allows for the long-lasting image retention. Hence, with the same drive electronics, electrophoretic displays may be produced to operate in one of two ways, either as an active or a passive display. For an active display the image is refreshed at a given rate in order to constantly allow the image to change whereas for a passive display the image is maintained with no addition of power and requires external input (and power) only when the image needs to be changed. Applications for both types of displays have been prototyped and Figures 5a and 5b
show two passive displays. The static (but still updateable) electrophoretic display has the distinct advantage of having very low power consumption which makes it practical for battery operated, hand-held devices where video capabilities are not necessary (for example watches) and for dynamic signage applications.9

Figure 5: Two passive displays using E-Ink Inc electrophoretic capsules (a) Sony’s LIBRIe reader and (b) a Seiko watch

For either mode of operation, the act of switching is limited by the electrophoretic mobility of the particle in the given suspending liquid which is a function of the liquid’s dielectric constant and viscosity as well as the particle’s Zeta potential. Hence, the velocity of the particle in relation to the surrounding fluid is based on the product of the electrophoretic mobility of the particle and the applied electric field. This simple relation may be translated into a switching time by taking into account the cell gap. Hence, the switching time may be approximated by the following equations in relation to voltage (V), electrophoretic mobility (µ), and the cell gap (h):

\[ t_{\text{switching}} \approx \frac{h}{\nu} = \frac{h}{\mu E} = \frac{h^2}{\mu V} \]  

(from Ref. 5)

Typical cell gaps for current cells are in the range of 10-100 µm which translates to switching speeds of tens to hundreds of milliseconds when driven at reasonable voltages between 5 and
100V.\textsuperscript{5,10} These types of switching times are a limitation for electrophoretic displays (most of which operate at the high end of the range) and will keep these displays from participating in certain current display markets that require video speed refresh or update rates in the near future.\textsuperscript{9}

**The drive electronics: Ways to provide the voltage to make an image**

The drive electronics in electrophoretic displays may be divided into two classes. The first, and simplest, is the passive matrix addressing system where a top and bottom electrode are overlapped with a gap between them containing the electrophoretic particles and carrier solvent. Each pixel is defined by such an overlap of electrodes. In this setup, each pixel is directly tied to the display controller and each pixel is updated directly by the controller’s application of voltage.\textsuperscript{5} Each line in this type of display is addressed individually. Hence, for a display that has 400 rows and a gap width corresponding to an intrinsic response time of 80ms, the refresh time would be 32s. As indicated by the long refresh time, passive matrix displays are good for applications that are semi-static, such as announcement boards or pricing displays, an example of which is shown in Figure 6. Though very simple, the passive system is cumbersome for a large

![Figure 6: A pricing display in Japanese Yen, with only the actual amount (in light blue) being the actual passive matrix semi-static electrophoretic display. From Ref. 7](image)
number of pixels due to spatial and cost considerations as well as significant cross-talk within the system when the threshold voltage for movement of the particles is low.

The alternative to a passive matrix display is an active matrix. In the active matrix scheme, rather than addressing single pixels, thin film transistors (TFTs) at each pixel act as nonlinear elements, allowing row-by-row addressing. The row electrode acts as the switch to allow the row to be either in conduction or not (i.e. ‘on’ or ‘off’), while the data lines provide the voltage necessary to make the image. This method of addressing the pixels allows the refresh time to drop to the time it takes to update a single pixel. SiPix, E-Ink and others are all exploring this technology due to its compatibility with low threshold voltages and high refresh or update speed as well as its compatibility with current processing of backplanes for other types of displays.

Finally, there are several drive types that are still in research laboratories, but are worthy a mention as possibly viable candidates for specific applications of electrophoretic displays. These methods include external addressing using electrostatic addressing, ion projection, and photoconductor-addressing. Each of these methods are novel means of getting a charge build-up to occur locally to move the charged particles through the fluid. The electrostatic and ion projection addressing methods may be used in the niche market of writeable surfaces, whereas the photoaddressing might be useful for temporary copies of printed material.

The move from rigid to flexible substrates: challenges and market opportunities:

The desire for a display that has the flexibility and even “foldability” of paper, but with the capability to update the information on the page almost instantly is what drives the interest and commercial funding of flexible electrophoretic devices. Though the electronic paper application is probably in our near future, with some prototypes already available, it is likely that other applications will be more interesting from a commercialization and social acceptance point of view. Large area displays,
smart cards, mobile phones, and automotive applications will be some of the targets for flexible electrophoretic displays.

For large area signage and displays, flexible electrophoretic display technology holds promise for several reasons. First, for applications where flexibility or even conformability is desired or useful, the strong optical contrast at nearly all viewing and illumination angles is of interest. The compartmentalization of the ink and the drive electronics into physically separated pixels also allows for greater flexibility than polycrystalline or polymeric materials. Additionally this technology holds promise for remote or mobile display applications due to its low power usage and relative toughness when built with polymeric substrates. The slow refresh time in these applications is a minimal issue because most signs are updated on much longer time scales. At the same time, companies are making significant strides toward higher refresh rates, nearing video speed. Finally, the electrophoretic display technology is the only technology with which large area (up to 30 inches wide) flexible displays have already been realized and are in the process of commercialization, giving this technology a market lead.

With a higher refresh rate, electrophoretic displays will be able to break into the low end automotive and mobile phone markets. While stability and environmental sensitivity are of much lower concern than for organic display materials, the addition of color capabilities, either through novel multi-filter stacking or through novel colored particle technology is more challenging than with the organic display materials. The automotive and mobile phone markets are likely to fully embrace the electrophoretic display when color becomes widely available due to its wide viewing angles, robustness and flexibility as well as the fact that the displays may be made in large volume with large active areas and have relatively low weight. Color capabilities will be the largest challenge for electrophoretic displays, requiring innovative approaches to overcome the inherent bi-color, bi-stable paradigm that the display technology has grown to embrace. E-Ink has already made some progress toward this end by partnering with the Toppan Printing company to make color filters to overlay the electrophoretic display layer.
**Roll to Roll processing and the Future of Electrophoretic Display Technology**

Electrophoretic display sheets may already be made in a roll-to-roll format using polymer sheets as the front planes with back planes of metal foil or polymeric sheets with organic-semiconductor for the electronics. E-Ink Corporation began selling conventionally produced electrophoretic displays on Mylar in 2001. As early as 2002 SiPix reported that it already produces its electrophoretic display material on a roll-to-roll synchronized lithographic process capable of handling up to 30 feet per minute, while the fully assembled flexible panels may be produced at greater than 10 feet per minute. A schematic of their Microcup sealing technology, using a predispersed sealing material that floats to the top of each Microcup and then hardens is shown in Figure 7.

![Figure 7: SiPix microcup sealing process schematic, moving from top to bottom. From Ref. 7](image-url)
Figure 8: SiPix Roll-to-Roll Process (Available in Ref.7 or from SiPix website in color)

As shown in Figure 8, above, for typical roll-to-roll production of the Microcup electrophoretic display material, the SiPix process starts with a radiation curable coating on an ITO/PET film. It then continues with embossing the coating with a prepatterned male mold to produce the individual Microcups, filling the arrayed Microcups with a premixed electrophoretic fluid and then top-sealing the filled Microcups via either a pre-emulsified sealing composition that separates out from the electrophoretic fluid or using a top-sealing material that is overcoated after filling. Either way, after sealing the array, it must be laminated with a second conducting substrate film to form the top (or bottom) electrodes.  

The high volume production capacity and the capability to remove defective display material from a roll by the simple act of cutting it away ensures a bright future for flexible electrophoretic display production. The technical challenges that remain to be overcome for these types of flexible displays to be widely accepted by industry are inexpensive full color capability, higher refresh or update rates, the refinement of the electronics including drive electronics and power storage, and ultra low cost production. The final, and perhaps most formidable, hurdle for flexible displays in general may be finding a
compelling first application for business or consumer applications where flexible displays will be better than conventional displays. Overall, though, flexible electrophoretic display materials are at the forefront of the flexible displays movement with a promising future in many areas of application.

References