Progress In Electromagnetics Research, Vol. 147, 95–116, 2014

Review of Paper-Like Display Technologies

**Peng Fei Bai[1], Robert A. Hayes[1], Ming Liang Jin[1], Ling Ling Shui[1],
Zi Chuan Yi[1], L. Wang[1], Xiao Zhang[1], and Guo Fu Zhou[1, 2, *]**

(*Invited Review*)

Abstract—With the advancement of wireless networks and cloud computing, people are becoming increasingly surrounded by a variety of displays — rich electronic devices: TV, Phone, Pad, Notebook and other portable or wearable devices. These electronic products put high demands on the quality of the visual interface. Paper-like displays are reflective and do not require a backlight. They have received much attention after electrophoretic-based electronic paper displays were commercialized in 2004. Paper-like displays combine excellent reading experience with ultra-low power consumption. In particular, their outdoor readability is superior to transmissive liquid crystal displays (LCDs) and organic light emitting devices (OLEDs). In this paper, we give an overview on various paper-like display technologies with emphasis of the status and future development of electrophoretic display and electrofluidic display principles. We focus on both technologies because electrophoretic displays have been commercialized successfully, and electrofluidic display has high potential to deliver video and full color.

1. INTRODUCTION

With the rapid development of high-speed wireless communication and cloud computing, we have entered the era of ubiquitous networks. Wherever people are they are surrounded or accompanied by display devices, such as smart phones, tablets, notebooks and advertising screens. The current trend to introduce wearable devices will further drive this behavior. Applications and marketing requirements have led to enhanced specifications such as resolution, size and contrast ratio of flat panel displays (FPD). At the same time, novel flat panel display technologies enable new opportunities for novel applications, such as wearable devices.

FPD's can be divided into two basic types based on differences in their light sources: active lighting displays (ALD) and passive lighting displays (PLD). The light source of active lighting displays is within the display device itself, and includes emissive (CRT, Plasma) and transmissive modes, to modulate emitted light. LCD's are typically transmissive in which images are displayed via the modulation of the backlight intensity. Organic Light Emitting Devices (OLED) emit light from active luminescent material in each display pixel. Conversely, passively lit displays utilize the reflection of ambient light. The electrophoretic display (EPD) is a good example with a visual effect similar to ink-printed paper giving rise to the term "paper-like display". The transflective LCD's have also been developed for improved outdoor viewing.

For mobile electronic devices, it is highly desirable to have excellent outdoor readability, especially under direct sunlight. As the dominant LCD technology is not able to satisfy this basic requirement this creates an opportunity for alternative and novel display technologies. Figure 1 illustrates the

---

Received 4 December 2013, Accepted 12 June 2014, Scheduled 24 June 2014

* Corresponding author: Guo Fu Zhou (zhougf@scnu.edu.cn).

[1] Electronic Paper Display Institute, South China Academy of Advanced Optoelectronics, South China Normal University, Guangzhou 510006, P. R. China. [2] Department of Electrical Engineering, Eindhoven University of Technology, P. O. Box 513, Eindhoven 5600 MB, The Netherlands.

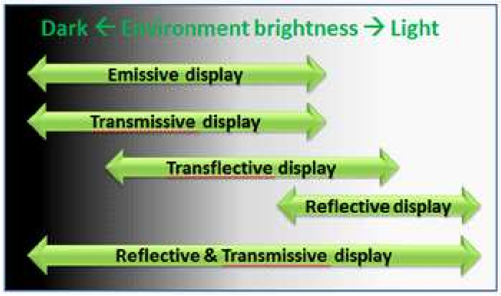


Figure 1. Suitable display environment for flat panel display types.

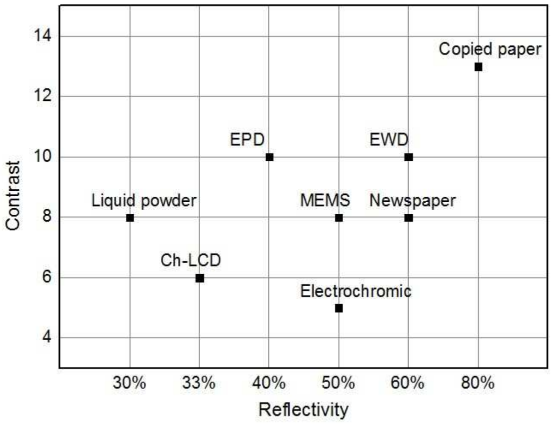


Figure 2. Contrast vs. reflectivity of various paper-like displays.

best working environment for different display types. The ALD devices usually cannot deliver a good user experience outdoors because their contrast ratio is low under sunshine-sunlight effectively competes against the "internal light" of the display panels. Conversely, PLD devices such as EPD provide excellent paper-like readability particularly under sunshine. As a result a lot of attention has been given to the development of reflective displays for use in mobile devices which are often used outdoors — where the combination of good viewability and low power consumption is potentially disruptive.

Human beings visually perceive their environment by sensing light from various sources. Paper is generally considered a superior display medium to a transmissive or emissive display because the reflected image from paper is easier and more comfortable for viewing by the human eye. Based on human perception, the main display characteristics determining display readability are luminance/brightness and contrast. Luminance/brightness is the amount of light that reaches the human eye. In the case of reflective displays, brightness is the amount of ambient light that is reflected by the display. Normally reflectivity is used to represent the luminance of a reflective display which is measured by the comparison with the reflectivity of a standard white source. A sheet of white paper has a reflectivity of 70% to 90%; a newspaper about 60%. Contrast is the ratio of the reflectivity of a display in the white and dark states, which indicates if human eyes are able to distinguish the dark and light areas in detail. If the contrast is too low, the display will appear washed out and the user will have difficulty perceiving image details.

Mobile devices are very sensitive to power consumption. The high power consumption of the display has noticeably slowed down the progress of wearable electronics as they usually have very limited space for the battery. In both emissive OLEDs and transmissive LCDs, power consumption is relatively high because they either need a backlight or emit light. In a LCD-based device, it is very difficult to reduce the energy consumption of the display because of its low optical efficiency, i.e., less than 10% of backlighting can penetrate the LC-multi-layer structure. In OLEDs, fundamental improvement in energy consumption has not yet been fully realized [1]. This has to do with the fact that current is required in an OLED. In contrast to LCDs and OLEDs which are based on the "active lighting" display, reflective displays such as the E-Ink®display can show images by reflecting the ambient light. Thus, higher ambient brightness, as experienced outdoors, contributes to sharper images with reflective displays.

Figure 2 shows the characteristics of several reflective display technologies. Among them the electrophoretic display is the most well known. The reflectivity of white state is only 40%, less than the brightness of paper which exceeds 60%. Another important aspect is the response speed. The display response time of an electrophoretic display (EPD) is above 500 ms which is only suitable for displaying static images instead of video content. However, the display properties of electrofluidic displays (EFD) are closer to those of printed paper. In addition, it has a response time of 10 ms or less, which means that EFD is suitable for displaying video content. EPD is one of the most mature paper-like display technologies and has been widely utilized in e-books and e-labels where its bistability consequently ultra-low power is highly advantageous. EFD has the advantage of higher optical efficiency, low-power and video capability. Similar to liquid crystal displays (LCDs), EFDs may have many different pixel structures and allow all modes of operation: reflective, transmissive, and transflective. In this review we will give an overview on main reflective display technologies with the emphasis on EPD and EFD. Their working principle, fabrication procedure and electro-optic response are handled in detail.

2. A SHORT OVERVIEW OF REFLECTIVE DISPLAYS

In reflective displays, optical design is different from transmissive (LCD) and emissive (OLED) display technologies. In transmissive or emissive displays, low optical efficiency can be overcome by increasing light luminous intensity from the internal light sources. However reflective displays rely on harvesting ambient light to display an image. Thus, the main factors to influence the display performance include the reflectivity of pigment or pixel reflector and the light losses at interfaces. It should be noted that the light passes twice through each layer of the reflective display screen. The effective display area or aperture is also an important factor, especially closely related to the display contrast. Simple structures that can be readily manufactured at low cost are highly desired.

2.1. Electrophoretic Display (EPD)

The electrophoretic display (EPD) is used for showing visible images by vertically positioning charged pigment particles in microcapsules with the help of an external electrical field. As shown in Figure 3, the positively charged black particles and negatively charged white particles both can move to the upper surface under controlled electrical field to form a black or white area (pixel) on the upper surface. By manipulating the electrical field properly, one can control the ratio of black and white particles on the surface thus forming a desired gray scale [2–4].

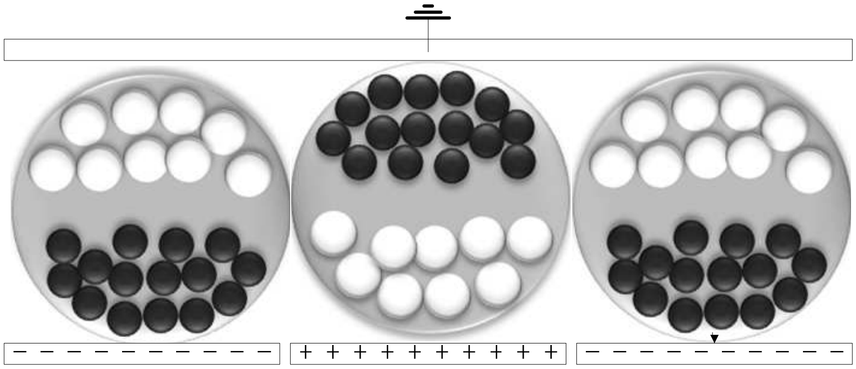


Figure 3. Black and white charged particles in microcapsules.

One of the most obvious advantages of the EPD is that it can provide a bi-stable display. Zero power is consumed to maintain the contents being displayed and the displayed image can be kept for a very long time after the removal of external drive voltage. Power will only be consumed when one needs to update the displayed contents and the power consumption will quickly go up if very frequent updates are required. However, for typical e-Reader application, the refresh rate for a page usually exceeds one minute. Thus the EPD is quite suitable to be used for the e-Reader application. The active matrix driven EPD from the E-ink Corporation is commonly used for commercial e-Reader products such as Kindle from Amazon or Nook from BARNES & NOBLE. Recent electronic label products using EPD and in-cell touch technology for flexible e-paper displays have also been demonstrated [5, 6]. EPD can also be coupled with a color filter to make a color display although the brightness of such a display is not ideal as a result of the loss of light in the color filter.

The disadvantage of EPD lies in the difficulty to accurately display the desired gray scale using simple and short drive waveforms. The refreshing speed is relatively low compared to LCD products due to this drive mechanism. Displaying complex animation and video is currently not possible using the EPD technique.

2.2. Liquid Powder Display

Liquid powder display technology has been developed by Bridgestone. Bridgestone called it QR-LPD, quick response liquid powder display. The electronic liquid powder is created by manipulating black and white polymer nanoparticles as illustrated in Figure 4. The basic difference with EPD is that the medium is air rather than a liquid. The low viscosity medium makes the speed of particle movement much higher so fast response times can be obtained. The panel fabrication process is simple and low temperature, which means that flexible plastic materials can be used. Positively-charged black and negatively-charged white powder is then enclosed in each pixel between front and back electrodes. The electronic powder is driven by the applied voltage to display white or black colors. The gray level can be modulated by the electric field.

Liquid powder display doesn't require a backlight and has a quick response time (0.2 ms). The front panels are thin and flexible (Bridgestone has realized a roll-to-roll flexible liquid powder display in 2006 [7]. It can also be bi-stable. However, the liquid powder display has the disadvantage of requiring high driving voltage and limited switching lifetime: 0.2–1 million. Liquid powder display technology never made it to market and Bridgestone recently withdrew from this field.

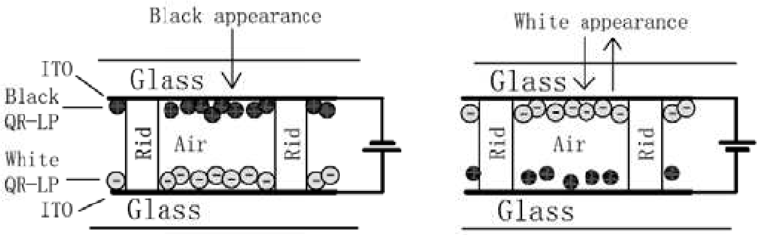


Figure 4. Schematic of LPD architecture and the operation principle [8].

2.3. Electrofluidic Display Technology

Information displays are typically made of tiny 'pixels' beyond the limit of visual resolution. These pixels are either emissive (e.g., CRT, plasma, OLED), transmissive (e.g., LCD, where the switch modulates light coming from the backlight) or reflective (E-ink and others, where the switch modulates ambient light). By modulation of the emission or absorption characteristics of the optical switch, a display image with grey scales can be made. We have demonstrated that the electrofluidic phenomenon can be used to make a very efficient display pixel. The principle that is used in electrofluidic displays is summarized in Figure 5.

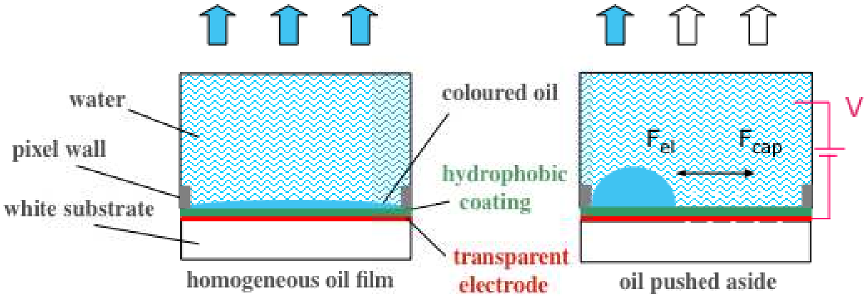


Figure 5. An electrofluidic display pixel — principle and components (NB: Oil thickness and droplet size not to scale).

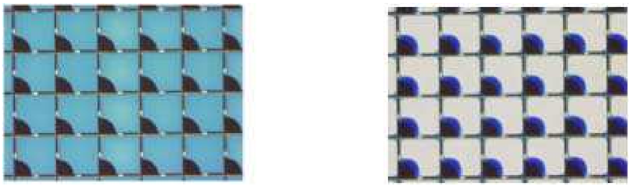


Figure 6. Images of 160 µm electrofluidic pixels.

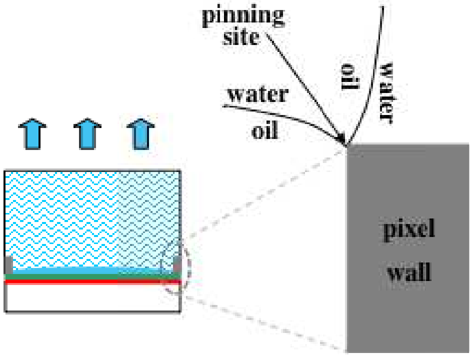


Figure 7. Using material and geometric properties to pin the oil/water interface.

The optical 'stack' consists of solid components — reflective substrate, a transparent electrode (e.g., indium tin oxide), a fluoropolymer insulator coating and the liquids: oil and water. The hydrocarbon oil is colored and is confined by 'pixel walls'. In the absence of a voltage the oil forms a thin film (typically microns thick as determined by the pixel wall height) that covers the entire pixel surface. This is because the hydrophobic surface (i.e., the amorphous fluoropolymer) has a strong preference not to be in contact with water. When a voltage is applied between the water and the electrode the fluoropolymer/water interface becomes polarized as described above and the layer becomes water wettable. This has the effect of pushing the colored oil film aside. The larger the voltage and the corresponding electrical forces, the smaller is the area occupied by the oil residue. So during the on-switch the fluidic motion results from the balance between electrical and capillary forces. For the off-switch the restoring capillary forces prevail. This curtain-like control of the oil, which contains optically absorbing dye, is the basis of a simple, yet highly efficient optical shutter. In Figure 6 images of 160 µm electrofluidic pixels are shown. It can be seen that the oil residue can be confined to less than 20% of the pixel area.

An electrofluidic pixel contains two key solid material components, a uniform amorphous fluoropolymer coating of the substrate as well as a crystalline polymer that makes up the pixel walls. While the oil/water interface moves over the fluoropolymer in a highly reversible manner (low contact angle hysteresis) it remains strongly pinned at the top of the pixel wall — this is due to both the geometry as well as the more heterogeneous nature of the pixel wall photoresist material (high contact angle hysteresis). This situation is shown in Figure 7.

The pixel wall material, being hydrocarbon in nature, is more hydrophilic than the fluoropolymer surface, as such forming a surface with chemical contrast (hydrophobic/hydrophilic patterning). It is important to ensure that the oil film does not migrate to adjacent pixels, which is what would happen if there is insufficient chemical contrast between the pixel area and the pixel walls. It is also worth mentioning that the pinning of the oil/water interface is at the top of the pixel wall, rather than the bottom which is also a potential pinning site. In actual fact the oil is preferentially attracted into the lower corner because the acts like a capillary. The wetting tendency for capillaries is fundamentally greater than for flat surfaces.

The electro-optic characteristics of an electrofluidic pixel are very similar to those for a liquid crystal material. This relationship between optical modulation and voltage is summarized in Figure 8.

In the absence of a voltage the pixel is in its dark state — the spread oil film absorbs light. A threshold voltage is required to initiate the opening of the pixel — this is required to break the oil film at some position inside the pixel. Once the colored oil film has opened, the degree of opening can be controlled by the voltage in a smooth manner. In other words the optical characteristics can be controlled in an analog manner: the larger the voltage the more open the pixel. At any particular voltage, the electrical force opening the pixel is balanced by the increasing capillary restoring force wanting to reform the oil film. This property of the system enables grey scales to be made in an analog fashion, in the same way as it is done for LCD's.

At higher voltages, the electro-optic curve plateaus, meaning that the display does not increase

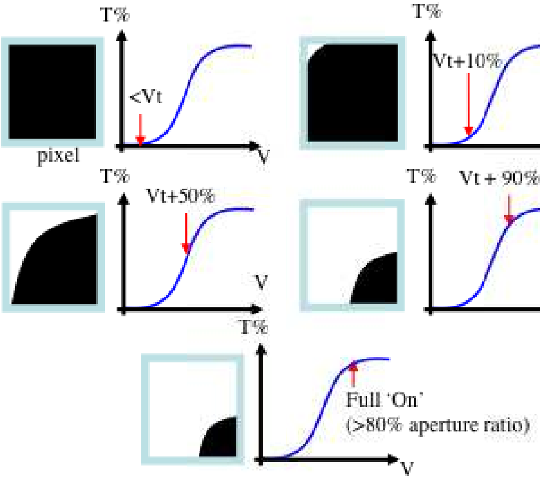


Figure 8. Electro-optic characteristics of electrofluidic display pixels.

its brightness anymore when the voltage is increased further. The degree of modulation that can be achieved depends on a number of pixel parameters and can be controlled. The maximum open pixel area that can be obtained is typically as high as 80%.

One of the key properties of electrofluidic fluidic elements is their switching speed. Compared to other chemical and physical phenomena, e.g., electrophoresis (used in E-ink), electrofluidic motion is very quick. The speed of movement of a liquid interface is typically several cm/s and essentially constant. As the fluid element becomes smaller the switching time therefore decreases linearly. For elements with a dimension of around a few 100 µm, such as display pixels, the switching time is therefore milliseconds (ms). Typical switching data is shown for $315 \times 150\,\text{mm}^2$ pixels in Figure 9. In this case both the on- and off-switches occur in 7–8 ms. Switching times of this order are more than sufficient to show video content on information displays and are in fact shorter than the large majority of LCD's. Video displays are one of the main application areas for electrofluidic technology. As the display resolution is increased (smaller pixel size) the switching time will be further reduced.

The advantages of EFD Technology are its optical efficiency, video capability, low power (no backlight) and LCD-like manufacturability. The disadvantages of EFD Technology are that it is not intrinsically bistable, has a non-white off state and is still an immature technology. This combination of properties makes EFD devices well-suited to portable devices, which are often used outdoors, showing

Figure 9. Switching response time of electrofluidic display pixels.

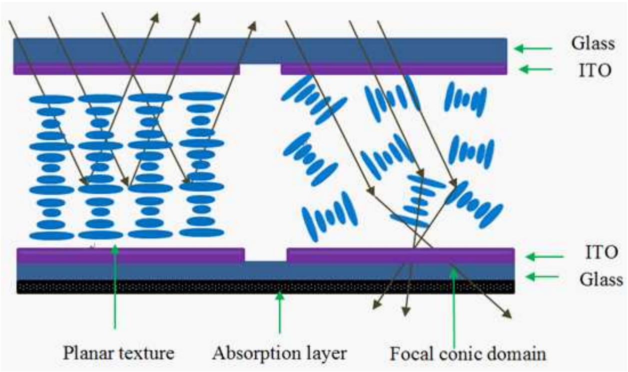


Figure 10. One simple structure of cholesteric liquid crystal display.

video content. Near and mid-term product opportunities are logically in areas such as wearable multimedia, (smart)phone, portable gaming, netbook, and laptops.

2.4. Cholesteric Liquid-Crystal (CLC)

Cholesteric liquid-crystal (CLC) is a class of nematic liquid crystal with the special characteristic that its molecular orientation naturally tends to twist, so that the orientation of the long axes of the molecules traces out helical domains. When the helix of the twist aligns along the normal of the substrate, a planar texture can be achieved. This configuration can reflect a component of the incoming light. When the component of the circularly polarized light which has the same sense of the helical twist, it will be reflected and the other opposite component is transmitted (Figure 10). The CLC display is also a bi-stable display like the EPD, which means zero power is dissipated to maintain the contents displayed [9].

The production line of normal LCD can be easily reused for the production of CLC. The environmental stability of CLC display is also similar to regular LCD. Kent displays and Fujitsu are the main forces commercializing the CLC display technique. The major disadvantage of the CLC display is the high driving voltage and relatively low optical performance compared with other reflective display techniques.

2.5. Microelectromechanical Systems (MEMS)

The display technology is based on display interface modulation (iMoD) using microelectromechanical systems (MEMS) [10]. Figure 11 shows the structure of a basic iMoD element. The air-gap between the glass substrate and the reflective membrane can be modulated as a result of the electrostatic attraction generated by externally applied voltage. Figures 11(a) and (b) show the optical appearance of the iMoD element with the gap open and closed respectively. The size of one iMoD element is typically 10–100 μm. An RGB color scheme can be formed by three basic elements. This display technique has been commercialized by Qualcomm with the trade mark of "mirasol" [11]. The major disadvantage of the MEMS based iMoD display is its limited viewing angle and the complexity (cost) of fabrication for large scale module.

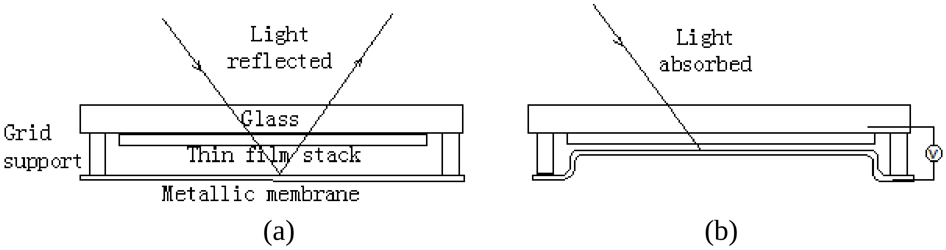


Figure 11. One of display model of MEMS. (a) Gap open. (b) Gap closed.

2.6. Electrochromic Display

Electrochromism is the phenomenon displayed by some materials of reversibly changing color when a charge is applied. To be applied for displays, the electrochromic materials are placed on, or encapsulated in, pixels created by patterned transparent electrodes (ITO). An example of the electrochromic display structure is shown in Figure 12.

The device fabrication and driving mode for this technology is simple, the driving voltage can be as low as about 1 V, and the most important factor in this technology is electrochromic material. Currently, the limits of electrochromic display are switching speed and switching lifetime. The technology is well suited to large area signage which does not need to be refreshed too frequently.

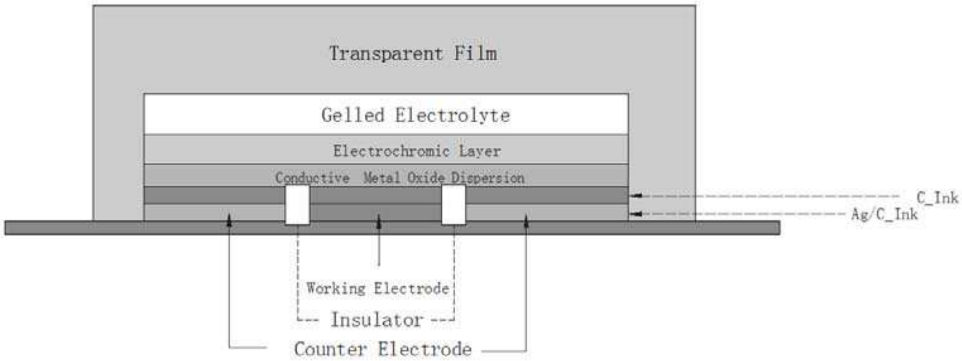


Figure 12. The electrochromic display structure.

2.7. Photonic Crystal

Electrically tunable photonic crystals can clearly provide electronic displays with unique properties [12–14]. The photonic crystal materials can reflect colors having a wavelength that is voltage tunable throughout the visible range, without the need for other color filter elements. Opaluxcompany cofounded by University of Toronto is commercializing the photonic crystal technology. For display application, the device fabrication is simple and the driving mode as well. Each pixel of the photonic crystal display can be driven to its own color without any further treatment. However, the photonic crystal material itself is quite sophisticated, and the stability and range of controllability is quite limited. Moreover, the switching speed of photonic crystal is still quite low. As photonic crystal theory is scalable throughout the whole electromagnetic range, photonic crystal could have a bright future and find its applications in other fields apart from displays.

3. A DETAILED OVERVIEW OF ELECTROPHORETIC DISPLAY (EPD)

3.1. Material and Structure

The idea for an electrophoretic display was presented for the first time in 1973 [15]. Before the major breakthrough of electrophoretic display, "electronic ink", appeared in 1997, people tried numerous methods to develop prototypes of an electrophoretic display based on the principle [16–21]. At the Society of Information Display (SID) Symposium in 1997, Joe Jacobson presented the latest work "Electrophoretic ink". The paper was published in Nature in 1998 by Jacobson et al. describing their novel electrophoretic ink type material [22]. In the same year, the "electronic paper" label was first used by Nick Sheridon at the SID symposium. After 6 years continuous development, the first commercial E-ink display product was announced by Sony which catalysedreal market growth and opened a new area in the display field. In 2007, Amazon entered the market with their Kindle product and a business model based on the provision of electronic content. This type of business model is now well established by leading publishers.

In Jacobson's work, they encapsulated the black and white pigments in the microcapsules which were made by interfacial polymerization reaction [22]. These microcapsules were then incorporated into a front panel laminate which could be easily applied to an electronic backplane. The basic electro-optic mechanism is presented in the Figure 13.

The dark pigments are carbon black and the white pigments are TiO_2 nanoparticles. These two pigments have different charges. Under the DC field, these two particles will move up and down in the microcapsules. When the white pigment is on top, the white color will be viewed, otherwise the black color will be shown. Multi-disciplinary work was required to make these functional microcapsules. Two major processes are involved: polymerizing the microcapsules followed by encapsulation. Jacobson et al. used interfacial polymerization to synthesis the microcapsules in which the internal contents are the black and white mixed pigments. This method has the advantage of enabling the encapsulation using the two phases and polymerization at the interface. Until now, there are few methods applied to form

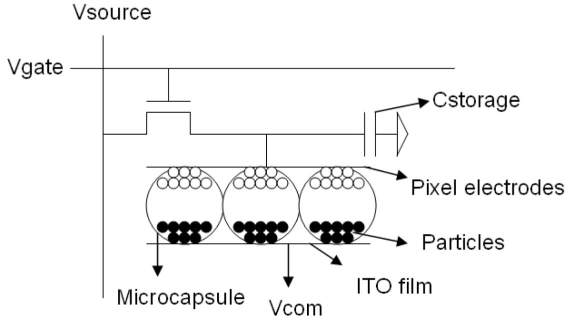


Figure 13. The structure of a TFT-EPD.

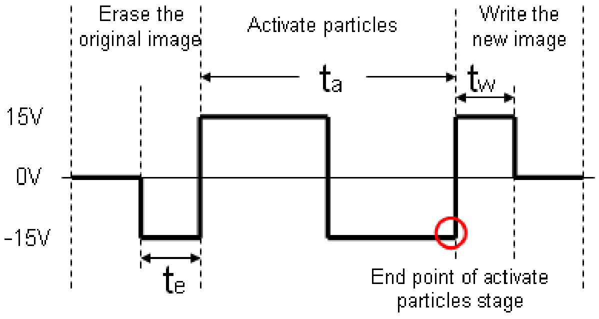


Figure 14. An example of driving scheme.

the microcapsules using this type of interface polymerization [23, 24]. However, the homogeneity of the microcapsules is still significant issue. Another key issue for the electrophoretic display is the pigment. It is well known that carbon black, the commonly used black colorant for industry, is conductive and not very easy to manipulate in electrophoretic display [25–27]. People are trying to find more suitable black pigments for electrophoretic displays. The white pigments are well known commercial white TiO_2 nanoparticles. In order to make colored displays, some different kinds of colored pigments were used [28–30]. With the proper pigments and encapsulation, the interfacial polymerized microcapsules could work under 20 V for a commercialized EPD film.

With the EPD film ready, it has to be laminated on the TFT substrate. Then the common electrode will be laminated on the top of the film. Since the microcapsules and the pigments are UV sensitive, they will be damaged after extended exposure under normal day light. A UV filter will be laminated on top of the EPD film. If people want to integrate the touch panel function to the EPD device, touch panel layer will be bonded on the top. Final edge sealing will be applied to form the main body of display module. The routine technologies for liquid crystal display (LCD) module, like chip on glass (COG), foil on glass (FOG), anisotropic conduction film (ACF) attachment, are normally used for making a functional EPD display module. Then the EPD display module will be sent for the driving and EPD waveform testing before the end user device is made.

A vertical driving waveform is a voltage timing sequence, which can promote the charged particles in cells moving either towards or away from the viewers. The driving waveform of the electrophoretic display plays a decisive role for a good display effect.Driving waveform algorithm optimization is of great impact for improving the electrophoretic display effect. A typical driving waveform consists of three stages: erase the original image, activate particles and display a new image [31]. Generally, there are four questions to be considered for the study of driving waveform: driving time, grayscale, flicker and ghost. The three stages take about 500 ms. The response time is too long for playing videos on the EPD smoothly; the reproducibility of grayscale reflectivity is poor when transformed from different grayscale to the same grayscale, and the reflectivity of a gray scale is unstable when implementing multilevel display; a flicker may be produced with the change of voltage value and refresh display between black and white. The flicker of updating an image affects reader comfort. Also as the time of erasing the original image is limited, the image cannot be erased very well. And thus a ghost of the original image will remain on the display, affecting the next image displayed. The above problems restrict the development of EPD. In this chapter, we discuss ways to overcome these problems.

3.1.1. Driving Time

A typical drive waveform contains three stages: erase the original grayscale and reset to white or black; activate the particles in order to write new grayscale; finally, write the new grayscale [31]. Figure 14 is an example of a typical drive waveform. A reference point of the grayscale appears at the end point of the second stage for writing the new grayscale. The switching time when driven by conventional drive waveform is very long, up to several hundred milliseconds. The path between white and black of grayscale conversion is the longest, which seriously affects the image refresh rate. Therefore, the process of activating particles needs to take full account of the original grayscale and the target grayscale to reduce the response time of grayscale conversion [32].

During updating of the image, the time of update is determined by the length of the drive waveform. Optimizing the algorithm could reduce the length of the drive waveform and then improve the conversion speed between images, thus shortening the response time of the EPD [33]. Kao et al. [34] studied the property of the suspension viscosity, characterized the response latency of the device, and proposed a new driving waveform, which took the white gray scale as a reference, to shorten driving time. However, the driving waveform is unbalanced and the reference gray scale is not very stable. Wang et al. [35] used four kinds of screen update mode to update the display according to the different image that need to update on the EPD to improve the update speed. Zhou et al. [36] proposed a driving principle based on the closest rail reset to reduce the driving time, but this method must consider the content of the image and it may increase the burden to EPD controllers. Johnson et al. [37] designed two display schemes that are black-white and grayscale according to the image content. However, these methods just change the screen refresh modes and could not reduce the duration of the driving waveform radically [38]. In addition, signal processing can also improve the response speed for updating the image, but the speed is still not enough for displaying video content [39].

3.1.2. Grayscale

In the microcapsule EPD [3], the white grayscale is taken as the reference and other gray scales are obtained by driving the white grayscale. The display frame rate is fixed, that is to say, the minimum time for driving particles is fixed, therefore electrophoretic paper cannot display all the gray scales. The number of grayscales that EPD can display determines the quality of image. Optimizing driving waveform could increase gray scales effectively in some cases [40]. At present, the grayscaling from 4 up to 16 gray scales has been achieved by optimizing driving waveform. In multilevel gray scale EPD, the waveform scheme based on negative voltage compensation could be used to increase the grayscale number.

The black and white particles cannot be activated fully because of the limit of the driving waveform length. So it is quite difficult to display a grayscale accurately during displaying [41]. The reflectivity of the same grayscale driven from different original gray scales also could not achieve consistency, and the screen reflectivity of the same driving waveform driving EPD is not identical. Thus the reflectivity of the same target grayscale is different in the process of updating different images.

3.1.3. Flicker

Electrophoretic particles change the direction of movement with the voltage transitions of the driving waveform. Flicker appears when voltage varies according to the applied driving waveform. The flicker generated by updating images affects the user experience and it is not conducive to the development of EPD applications. For this reason, reducing the voltage change to low frequency as much as possible

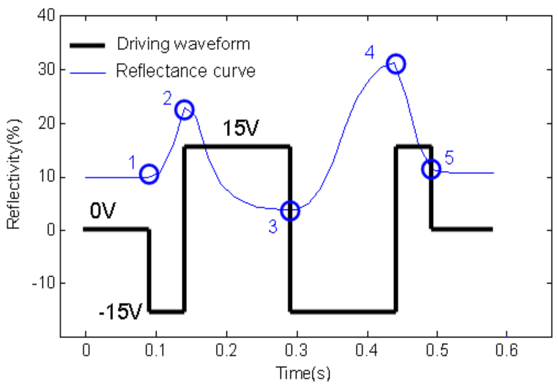


Figure 15. EPD reflectivity curve under the traditional driving waveform.

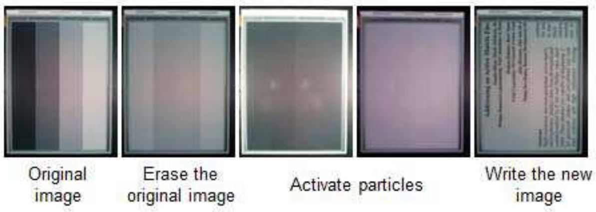
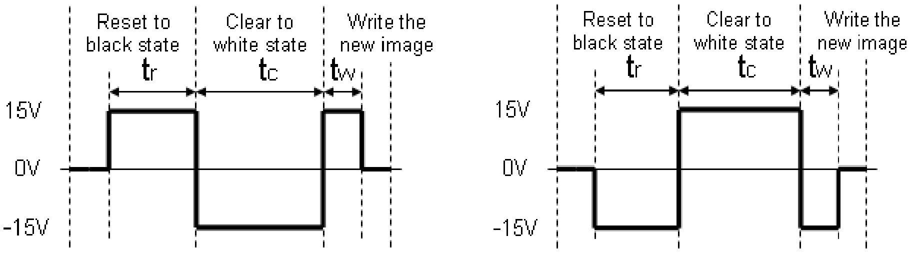


Figure 16. EPD switching process under the traditional driving waveform.

is very necessary when driving a waveform in the design program. Then, flicker can be reduced due to fewer voltage transitions. In addition, the visual effect of the flicker can be eliminated when the flicker frequency is higher than 30 Hz. The waveform algorithm could be improved by using the principle in order to improve the visual effect [42].

As shown in Figure 15, strong flicker appears in the updating process driven by traditional driving waveform, which reduces the reading comfort. Figure 16 is the EPD switching process under the traditional driving waveform. A good driving waveform should erase the original image effectively and activate particles when updating images. As shown in Figure 17, the number of flickers corresponding to the number of voltage variation reduces using the new driving waveform scheme while the time of voltage variation could affect the flicker directly, but the voltage conversion frequency is not sufficiently high.



(a) (b)

Figure 17. New driving waveform schematic [32]. (a) White as the reference when the target more white. (b) Black as the reference when the target more black.

Ways to minimize flicker have been studied. Kao et al. [34] proposed a new driving waveform to reduce the number of flickers and it provides improving readability. However, DC balance was not taken into consideration so that the reference gray scale is not very stable. Wang et al. [35] used four screen update modes to update the display according to the different image that needs to update on the EPD, and it could reduce flicker. However, one of the four modes is the same as the most common refresh mode, so it is not useful enough for the images which need to refresh the whole screen.

3.1.4. Ghosting

As discussed earlier EPD displays comprise white and black particles. The two particles are different in size, density and charge, and they are different in electrophoretic properties as well. In addition, the grayscale variation from white to black is faster than the opposite variation. For the above reasons, it is necessary to take into account the material influence when designing the image updating time of driving waveform. The two particles in the display system must reach mechanical balance before updating the display screen. So the balance must be broken firstly for the purpose of writing a new gray accurately. Otherwise, the particle activity, which could be obtained by driving from positive and negative voltage polarity, is not enough to update, and the ghost of original image would affect the next image display clearly. Hence, the process of activating particles is also considered to be the further erasure of the original image and thus reducing ghost image.

If the original image cannot be erased completely using the traditional waveform scheme, then the ghost would have an effect on the display of next image. The ghost of the original image could be further erased by extending the erasing time of the driving waveform in a certain limit. In Figure 18, the ghost images during the updating of a four level grayscale image are shown. It is an effective method containing improving the first part of waveform and optimizing driving algorithm to erase the original image and weaken ghost, which make the display performance better. Moreover, DC balance is an essential factor to consider in the process of eliminating ghosts in that the DC residue may be a threat to the life of the display. Zhou et al. [43, 44] utilized a method involving adding the control signals in electrodes and voltage compensation to reduce image ghost. At the same time, some workers [34] improved this situation by the means of image processing, however it remains an additional burden to the processor.

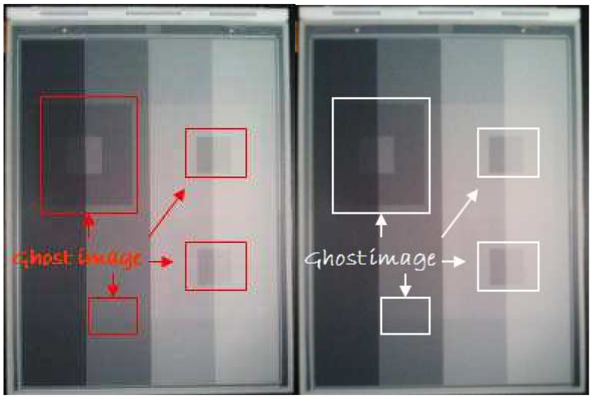


Figure 18. A four-level gray scale image with ghost images.

3.1.5. Summary

The driving waveform is an important part of the electrophoretic display system as the driving scheme would determine the image quality, updating time, flicker effects and ghost to a large extent. It is likely that the EPD product area will evolve rapidly over the next year. At the same time, the driving waveform can also be expected to develop rapidly.

One of the important ways to improve the update speed and display quality is driving waveform optimization. It is necessary to take various factors into consideration during waveform design: driving time, number of flickers and ghost. However, optimizing driving waveform could only reduce the driving time and weaken the flicker and ghost partially due to the limit of the electrophoretic display material. The response time of grayscale change from black to white or from white to black is more than 100 ms. Therefore, none of the EPD's can play video. For showing video in paper-like display, further development of electrofluidic display technology could be a good choice [45].

3.2. The Applications of Electrophoretic Electronic Paper

Electrophoretic electronic paper has a series of advantages. For example: the reflective display style, easy to realize flexible display, low power consumption [46], and so on [3]. Hence, it has been widely applied in many fields where there has not been a very high demand for video content. New electronic paper products are being shown every year by many big companies, but the main focus is on E-reader, billboards, tags, watches, mobile phone, flexible display device, etc..

3.2.1. E-Reader

Electrophoretic electronic paper has good paper-like display characteristics, reading comfort is better than the display which relays on active light-emission [47]. Hence, E-reader is currently the most mature technology application for electronic paper displays. Since the launch of the first Librie E-reader by Sony [48] in 2004, more than 20 companies have developed their own E-readers. These include Amazon (US) [49], Hanvon (CN), iRex (NL), Elonex (GB), Japan's iRiver [49] (JP), Samsung electronics [50] (KOR), Founder (CN) and Unihan Tech (TW) who have launched many kinds of e-readers. The activity of these companies has grown the E-reader market considerably.

However, most of the display modules are provided by Taiwan PVI whose product is micro-encapsulated electrophoretic electronic paper [50]. In recent years, AUO launched rival products using SiPix micro-cup type display module which is also based on the electrophoretic display principle [51]. With the development of process technology, there will be more formal electrophoretic display modules, which should change the current market situation which is dominated by PVI.

On the application of E-reader, Amazon is leading. Its product Kindle also needs the display module from PVI. But Amazon created a new E-reader business model. The user of Kindle can access digital resources from the Amazon Kindle store. This new business model is attracting a large number of consumers to make the long awaited switch from books to e-Readers. This has expanded the E-reader market and changed the profit model of the E-reader, and E-reader sales have risen steadily [52].

At present, the bottleneck of the E-reader is its high price and the application support [53], but with the development of other related companies, for example: Guangzhou OED and SiPix micro-cup type EPD, and the diversification of the business model, the breaking of the display module monopoly should occur.

3.2.2. Billboards and Label

Electrophoretic displays are well suited to billboards and labels [54, 55]. Smart paper based on Gyricon was introduced into Macy's, a major US Department stores in 2001 [8]. The electronic paper billboard has been used in Japan since 2005. A test broadcast equipment based on the electronic paper display is implemented in Tokyo Station by Hitachi [56]. In December 2006, the Yamanote Line light rail train introduced color electronic paper for advertising [57]. The prospect for electronic paper on billboards is very good, so the system is constantly being improved by some Japanese firms.

Shelf-edge labelling is widespread. Almost all electronic paper display technology has demonstrated such prototypes. Testing label and inventory management have been done in the cooperation between New York Runway and Fujitsu since 2006. NEC and Ishida demonstrated the price label, which are based on SiPix and Bridgestone electronic paper, in "RETAILTECH JAPAN" [58]. Bridgestone has shown its electronic paper label which is as thin as paper and flexible in 2009 [59]. ZBD also launched an electronic paper label based on a glass substrate, and it can also provide an electronic paper label [60].

3.2.3. Watch and Mobile Phone

The watch and mobile phone are common portable products in our daily life, but the energy which is stored by the battery is very limited, so that the display application ability is limited. The electronic paper display which has the characteristics of low power consumption can be used as the display in the watch and mobile phone.

The first kind of watch whose display is electronic paper was made by Solomon Systech who won the Hongkong Electronic Chamber of Commerce Innovation Award in 2004 [61]. Seiko watches introduced its new product "Seiko SPECTRUM" which is based on electronic paper watch in 2006 [60]. GREEN VIEW electronic paper watch made its debut in Shenzhen city of Southern China in the fifth consumer electronics exhibition in 2012, and this is the first China electronic paper watch based on E-Ink application technology [62].

Electronic paper display technology on mobile phones offers more rich and colorful possibilities than on watches. The most representative product is Motorola's Motofone F3 [63], the battery power can be used longer than before due to the display being electronic paper. The mobile phone got attention in 2007 International CES, and it had a very good market performance when it entered the India market. The Hitachi W61H is equipped with a 2.7 inches E-ink screen to display content clearly in the sunlight in 2008 [64]. PopSlate (US) (www.popslate.com) has launched the $119 iPhone5 E-Ink electronic paper screen (4 inch) back shell "popSLATE". It weighs less than 75 grams, is expected to start shipment in 2013 June, but it currently only supports apple (Apple Inc.) iPhone5 model. The user also gets an E-reader when they buy "popSLATE" [65].

The most interesting application is electronic paper being used as a keyboard in the mobile phone. In the "CEATEC JAPAN 2007" exhibition, NTT DoCoMo exhibited a mobile phone which could change keys position according to the state of the phone based on electronic paper display [66]. The key cap of the mobile phone is transparent resin, and the micro-cup electronic paper is arranged under each key, the power key is shown only when the power is shut down. The keys will display the icon and digits as for an ordinary mobile phone when the power button is pressed to enter the standby mode. In addition, the display could change its modes according to the actual situation, for example, when an E-mail is received. CITIZEN SEIMITSU announced that its electronic paper display has been adopted by the Sharp SOLAR PHONE SH002 mobile phone and Samsung Electronics 'Alias2 SCH-u750' [67]. The two mobile phones were equipped with E-ink's 'Vizplex' electronic paper film. SOLAR PHONE SH002 is KDDI's 09 summer mobile phone equipped with multi-crystalline silicon solar cell on the back of the module, and the information can be displayed on the electronic paper when the solar battery is charging. Alias2 SCH-u750 is Verizon's Wireless 09 mobile phone, the electronic paper is used on the keyboard and the display of the keyboard and can change its direction according to the opening and closing direction of the mobile phone body.

E-ink combined with a lighter, more flexible display device can make the mobile phone smaller, lighter, and more durable, and the paper-like display apparatus will create a traditional reading feeling which could encourage uptake by less technology literate consumers.

3.2.4. Flexible Electronic Paper

Compared with the traditional electronic paper, flexible electrophoretic display components fabricated on plastic substrates rather than a glass substrate can be bent repeatedly, so that it is closer to real paper. Flexible displays are a future direction for all display technologies, and e-paper technologies are well placed to drive this transition [68, 69].

E-ink demonstrated the first flexible electronic paper display (16 × 16 Array) based on organic crystal technology from Baer Laboratory in 2000 [70]. However mass production of flexible electronic paper screens remains in its infancy. Polymer Vision which is the subsidiary company of the Philips Group developed the world's first flexible screen mobile phone Readius in 2007. Readius has a 5 inch large screen, but the volume is much smaller than other mobile phones with the same size screen due to the electronic paper screen being rollable [71]. Because of the "electronic paper screen" power-saving advantage, the battery of the mobile phone needs recharging only every 10 days. AUO (TW), committed to green innovation, have published a series of technological achievements, including AUO's first 6 inch flexible electronic paper based on Sipix technology in 2009 [72]. PVI has shown two kinds of flexible electronic paper at FPDI2009: one is a 9 inch product whose resolution is 1200 × 825, the other is a 6 inch product whose resolution is 800 × 600 [73]. LG Display (KOR) announced that it had started production of the world's first plastic electronic paper screen, and this kind of flexible electronic paper screen will supply the Chinese market for the first time in 2012. The resolution of the product is 1024 × 768, and the maximum bend is 40 degrees, and at a the thickness of only 0.7 mm, it is thinner than current electronic paper. In addition, the flexible electronic paper has certain advantages in strength, it could remain intact when it falls to the ground from 1.5 meters high due to the substrate being flexible [74]. Top pan Printing and the Plastic Logic (UK) jointly exhibited a large size flexible digital signage product in RETAILTECHJAPAN2013, the product is equivalent to a 42 inch flexible electronic paper, it tiled 16 pieces of 10.7 inch 1280 × 960 pixels monochromatic electronic paper [75].

3.2.5. Other Applications

At present, there are many concepts applications for electronic paper. The bistable characteristics of electronic paper display could potentially supply many applications in our daily lives. For example: RFID, small display, smart card, and others [76].

Seiko Epson showed fusion electrophoretic electronic paper and radio tags (RFID tags) of the new display element in "Embedded Technology 2004". The application could be used where one needs to change the content regularly [77]. A U-disk with an electronic paper display was shown in the "2006 International Consumer Electronics Show" by Lexar (US) media [78]. The electronic paper display could show the remaining memory capacity without connecting to a personal computer. E-Ink produced many of the most popular E-reader devices, a new electrophoretic electronic paper which can be used on bikes is shown in information display conference Association in 2012 [79]. The company also showed smart display cards, personal identification numbers on a smart card based on an electronic paper display. With the continuous development of electronic paper there will be more and more applications and it will bring new opportunities for content publishers, mobile operators and the advertising industry.

3.3. Overall Analysis to EPD

EPD based on microcapsules has matured well and attracts a lot of third-party support in driving ICs and TFT arrays. Its monochrome performance has reached newspaper, and its power consumption is far below LCD. So EPD has been applied widely to e-readers and e-labels. However, its cost is still higher than LCD and its color performance is poor and it cannot display animation. In this era of information explosion, its application field is quite limited.

4. ELECTRO-FLUIDIC DISPLAY (EFD)

4.1. EFD Pixel Architecture

The basic 2-dimensional 'oil-curtain' EFD architecture (Figure 5) is just one possible configuration for generating the required electro-optic switch for display pixels. Other architectures have been proposed and demonstrated. Start-up companies ADT [80] and Gamma Dynamics [81] have focused on the configuration shown in Figures 19 and 20. In these cases the water has been colored rather than the oil phase. In addition the adoption of 3-dimensional architectures has allowed the contracted oil residue to be removed from the optical plane. It remains to be seen whether the improved peak display brightness and contrast justify the complication in pixel architecture and consequent additional manufacturing complexity.

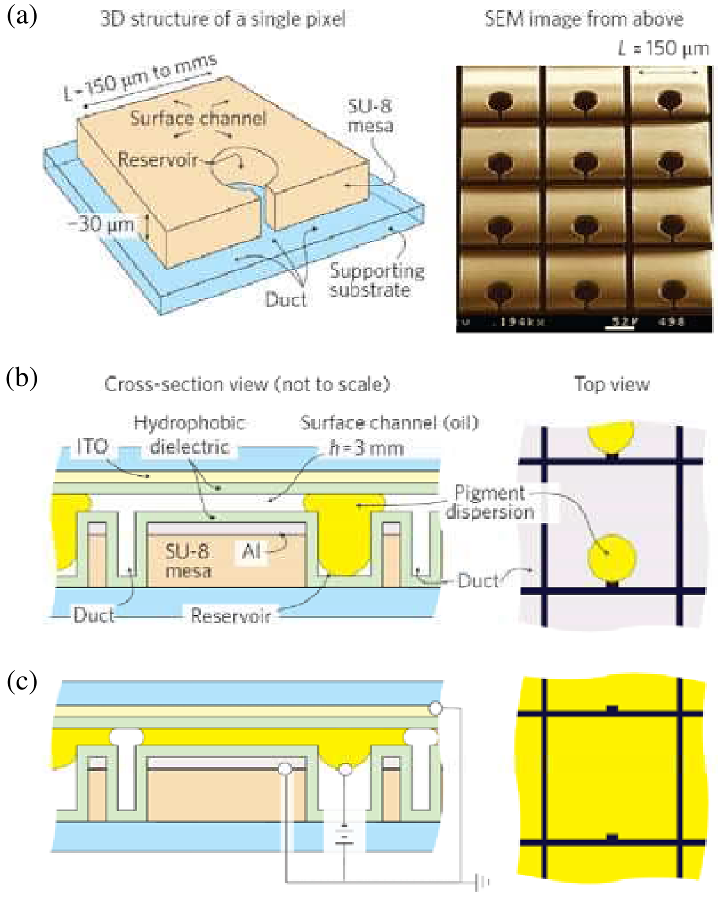
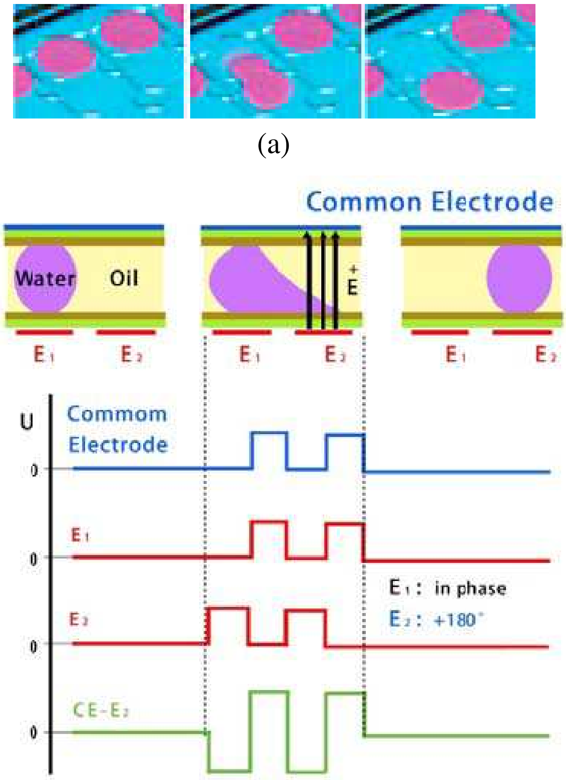


Figure 19. Alternative EFD pixel architectures (U. Cincinnatti), (a) three-dimensional diagram of a single pixel (left) and scanning electron microscope (SEM) image (right) of the SU-8 mesa structure; (b) and (c) cross-section (left) and top view (right) of the pixel with no voltage applied (b) and a voltage applied (c) sufficient to cause the pigment dispersion to fill the surface channel.

4.2. Current Status

4.2.1. Materials & Processing

The architecture of an EFD cell is shown in Figure 21.



(a)

(b)

Figure 20. Alternative EFD pixel architectures — ADT (www.adt-gmbh.com), (a) pixel movement droplet driven displays and (b) adt's — dual cavity structure and bistable driving scheme.

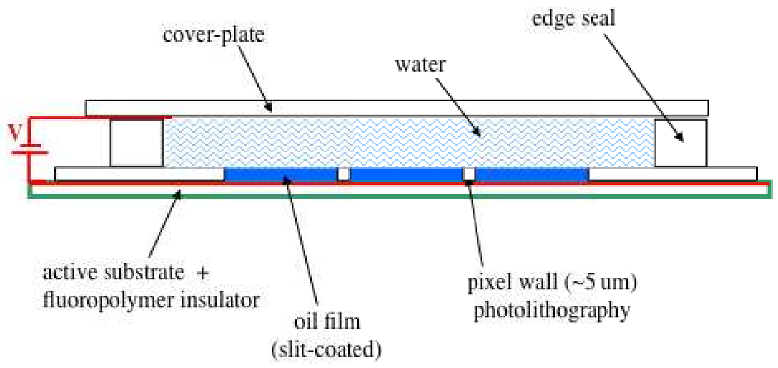


Figure 21. Electrofluidic display materials and architecture.

4.2.1.1. Backplane (Segmented, TFT)

Electrical backplanes for EFD technology can comprise either segmented or thin film transistor (TFT) substrates. This depends primarily on the information content required for the particular application. The EFD optical front plane technology ports readily onto either substrate. EFD's are capacitive and voltage, rather than current, driven. As a result the requirements for TFT performance are readily met by standard amorphous-silicon. The pixel electrodes need only have resistances in the order of 100 Ω sq. or higher. In combination with electro-optic performance being insensitive to cell-gap this will enable flexible low cost EFD's to be made in the future once the technology is established on standard glass substrates.

To date TFT substrates used for EFD prototyping have been those designed for LCD or EPD type displays. In future the provision of dedicated EFD-TFT substrates will open the door for further optimization of display performance encompassing both pixel architecture as well as driving waveforms.

4.2.1.2. Insulator

Amorphous fluoropolymer materials [82] have been shown to combine both the hydrophobicity and insulating properties for EFD's. EFD's have rather extreme requirements in terms of low surface energy. This is conferred by perfluorination and the presence of CF_3 groups. As exemplified by Dupont's AF1600 [83]. Amorphous materials with only CF_2 groups, for example Cytop [84], while excellent insulators are not sufficiently hydrophobic to be used on the standard architecture shown in Figure 5. At the same time there remain opportunities to enhance device performance by introducing stacked dielectrics with a hydrophobic top layer [85, 86].

4.2.1.3. Pixel Wall

Chemical contrast between the hydrophobic fluoropolymer and the pixel wall material is essential for reliable operation of the individual microfluidic elements making up each display pixel. The pixel wall material is typically made lithographically using a negative type photoresist, for example SU-8. These materials tend to be rather hydrophobic which is not ideal. This necessitates an additional process step to selectively activate the wall material. The pixel wall height is 3–5 μm and the wall width 5–15 μm. The former dimension is used to control the colored oil film thickness during filling while the latter is defined by the resolution of the lithographic process.

4.2.1.4. Liquids

Two immiscible liquids are used in an EFD. Both liquids are low in viscosity which simplifies both the assembly process as well as allowing for rapid fluidic motion even at low temperatures which typically result in increased liquid viscosity. This is a significant issue for liquid crystal displays. The first EFD liquid is polar, as exemplified by water. To extend the environmental range of the EFD, electrolytes can be added to the water phase to reduce the freezing point to the required level. Non-aqueous polar liquids can also be used, for example, glycols and ionic liquids [87].

The non-polar liquid is typically a saturated alkane (e.g., dodecane) in which non-polar dyes have been dissolved to meet the optical requirements for a high contrast display. In this way an intensely colored oil is formed. Typical oil films have a thickness of 3–5 μm. Unsaturated alkanes do not exhibit the high modulation and reversibility required for device performance.

4.2.1.5. Assembly

The assembly process consists of the dosing of liquids and encapsulation to yield the EFD cell. The dosing of liquids is greatly facilitated by the proper engineering of the display substrate, specifically fluoropolymer and pixel wall. When the fluoropolymer is sufficiently hydrophobic and oil wetting and the pixel wall sufficiently hysteretic to the motion of a water/oil interface then the assembly process is virtually one of 'self-assembly'. The motion of an air/oil/water interface at controlled speed across an EFD substrate is sufficient to dose the required amount of colored oil to the individual pixels. This can be done in a range of geometries, for example slit-coating across a horizontal substrate or dip-coating a vertical substrate. The maximum dosing speed consistent with a homogenous oil distribution per pixel is typically about 1 mm/s. The more pixels that are dosed by the moving interface simultaneously the more homogeneous the resulting distribution of oil volume per pixel. So although the dosing speed is rather low it does lend itself to filling at mother glass rather than individual display cell level. In combination with the low viscosity of the EFD liquids and the process occurring under ambient conditions this means that liquid dosing to EFD's is intrinsically simpler than liquid crystal displays. Liquid crystal materials are rather viscous and so are dosed to individual displays at elevated temperature and low pressure to accelerate the process. In contrast EFD's can be dosed at mother glass level and can then be singulated after sealing without the usual particulate contamination risk due to scribe and break prior to filling.

Coupling of EFD's is typically performed using a pressure sensitive adhesive (PSA) edge seal. High performance chemically inert PSA materials have been developed to meet the demanding O_2 and H_2O barrier requirements of flexible OLED displays. EFD's have much less demanding requirements than OLED displays, simply requiring that enclosed water is retained at the most extreme operating temperatures of the device.

4.2.1.6. Performance

The electro-optic curve for an EFD is shown in Figure 8. Intermediate gray scales can be generated in both an analog and digital manner. Pixel to pixel uniformity and drive waveform ultimately define the number of gray scales that can be attained. The former is primarily determined by uniformity in insulator thickness and oil volume. Dedicated waveform development to enhance display performance remains in its infancy and is sure to be a valuable area for IP generation in the future as EFD' panels become more readily available.

Reliability. One of the features of the electrofluidic switch is its high speed which enables video content to be shown on reflective panels. This high switching speed is both necessary for a video enabled device but demanding in terms of switching lifetime. It has been shown that with appropriate materials choice and processing the required number of switches for a video device, typically a billion can be made without any obvious deterioration in the electro-optic behaviour. At the same time it is also clear that sustained application of the DC driving voltage has the potential to reduce device lifetime due to charging effects. There is much work to be done to better understand the link between materials and processing, driving and performance for EFD's.

Environmental. The environmental window of an EFD is intrinsically large due to the wide range of both polar and non-polar liquids that can be utilised. However the practical environmental window is more typically determined by the effectiveness of the seal material to maintain its integrity at the extremes of temperature and humidity. Temperature changes inevitably lead to changes in internal pressure which need to be accommodated. Consumer and Telecom specification for electronic devices are readily met by existing seal solutions. Continued testing of EFD's at extreme temperatures and humidity as well as thermal shock testing is required to drive the encapsulation improvements required for product release into attractive yet more demanding markets in future, e.g., automotive.

4.2.2. Commercial

EFD technology was pioneered by Philips Electronics. A spin-out company, Liquavista, funded by venture capital, was established in 2006 to commercialise the technology. Independently start-up companies in Europe and the US and recognized display companies in Asia have been actively developing and undertaking commercialisation activities. In 2011 Liquavista was acquired by Samsung. In 2013 Amazon purchased Liquavista from Samsung as part of its plans to transition from monochrome to color e-books. A Chinese company, Guohua has also recently begun commercialization activities.

4.3. Challenges & Opportunities

Like any new display technology EFD can do well to mimic the commercialization route of the dominant LCD technology. The choice of launch product is inevitably key. Small format displays offer a less demanding route to market. At the same time EFD's can build on the experience of E-Ink displays which have clearly demonstrated both the industry and consumer appetite for paper-like displays. By providing a color video paper-like display EFD technology can differentiate significantly from its competitors.

The manufacturing route should be as LCD-like as possible so as to avoid the requirement for capital intensive manufacturing strategies. This is one of the reasons why OLED technology, despite its promise, has taken so long to enter the manufacturing phase and still lags well behind LCD technology in terms of yield and manufacturing cost. In the case of EFD, cell-making involves solution, as opposed to vacuum, processing. Liquavista have shown that the technology can be readily ported into LCD cell-making lines. The Assembly process involves liquids dosing and encapsulation at mother glass level. Although intrinsically simpler than the filling process used for LCD's, the process remains immature and requires significant equipment development for manufacturing roll-out.

Materials supply-chain development for EFD technology is a key challenge. The dedicated materials required are amorphous fluoropolymer insulators, hydrophilic photoresist, non-polar dyes and sealing materials. Of these four materials, only non-polar dyes can currently be readily provided at sufficiently low cost by existing suppliers. In other areas the number of suppliers is rather small and their response to the needs of potential manufacturers in terms of technical specification, volume and price has been disappointingly slow. It is to be hoped that existing suppliers in the US and Japan begin to take the opportunity more seriously or alternatively new and more dynamic suppliers emerge to support nascent manufacturing activities.

ACKNOWLEDGMENT

This work is supported by Guangdong Innovative Research Team Program (No. 2011D039), National Science Foundation Council Grant (No. FC61350013) and Changjiang Scholars and Innovative Research Team in University (No. IRT13064).

REFERENCES

1. Stokes, J., "This september, OLED no longer 'three to five years away'," 2009.
2. http://www.ziljak.hr/tiskarstvo/tiskarstvo08/Radovi08/ZA%20WEB/Epaper180.html.
3. Comiskey, B., J. Albert, H. Yoshizawa, and J. Jacobson, "An electrophoretic ink for all-printed reflective electronic displays," *Nature*, Vol. 394, No. 6690, 253–255, 1998.
4. Inoue, S., H. Kawai, S. Kanbe, T. Saeki, and T. Shimoda, "High-resolution microencapsulated electrophoretic display (EPD) driven by poly-Si TFTs with four-level grayscale," *IEEE Transactions on Electron Devices*, Vol. 49, No. 9, 1532–1539, 2002.
5. Harrigal, C., V. Brajovic, W. Little, et al., "A backplane fabricated by evaporation printing for the production of a cost-competitive electrophoretic e-paper electronic shelf label display," *SID Symposium Digest of Technical Papers*, Vol. 43, No. 1, 702–703, Jun. 2012.
6. Lee, J. K., S. S. Kim, Y. I. Park, C. D. Kim, and Y. K. Hwang, "In-cell adaptive touch technology for a flexible e-paper display," *Solid-state Electronics*, Vol. 56, No. 1, 159–162, 2011.
7. Sakurai, R., S. Ohno, S. I. Kita, Y. Masuda, and R. Hattori, "Color and flexible electronic paper display using QR-LPD® technology," *SID Symposium Digest of Technical Papers*, Vol. 37, No. 1, 1922–1925, Wiley Online Library, 2006.
8. Wilson, R., "Displaying digital information on paper-like devices," *A Technology and Standards Watch Report*, 03-01, Joint Information Systems Committee, 2003.
9. Yang, D. K., J. L. West, L. C. Chien, and J. W. Doane, "Control of reflectivity and bistability in displays using cholesteric liquid crystals," *Journal of Applied Physics*, Vol. 76, No. 2, 1331–1333, 1994.
10. Miles, M. W., "A new reflective FPD technology using interferometric modulation," *Journal of the Society for Information Display*, Vol. 5, No. 4, 379–382, 1997.
11. http://www.qualcomm.com/mirasol.
12. Kim, H., J. Ge, J. Kim, et al., "Structural colour printing using a magnetically tunable and lithographically fixable photonic crystal," *Nature Photonics*, Vol. 3, No. 9, 534–540, 2009.
13. Arsenault, A. C., D. P. Puzzo, I. Manners, and G. A. Ozin, "Photonic-crystal full-colour displays," *Nature Photonics*, Vol. 1, No. 8, 468–472, 2007.
14. López, C., "Materials aspects of photonic crystals," *Advanced Materials*, Vol. 15, No. 20, 1679–1704, 2003.
15. Ota, I., J. Ohnishi, and M. Yoshiyam, "Electrophoretic image display panel," *Proceedings of IEEE*, Vol. 61, No. 7, 832–836, 1973.
16. Kostelec, J. and R. Liebert, "Design, fabrication and performance of an electrophoretic display," *Am. Ceram. Soc. Bull.*, Vol. 53, No. 8, 606–606, 1974.
17. Singer, B. and A. L. Dalisa, "X-Y addressable electrophoretic display," *Proc. SID*, Vol. 18, No. 3–4, 255–266, 1977.
18. Hopper, M. A. and V. Novotny, "Characteristics of a TiO_2-based electrophoretic display," *J. Electrochem. Soc.*, Vol. 126, No. 8, C339–C339, 1979.

19. White, R., "An electrophoretic bar graph display," *Proc. SID*, Vol. 22, No. 3, 173–180, 1981.
20. Fernandez, J. C., F. J. Delasnieves, R. M. Garcia, and R. Hidalgoalvarez, "The role of zeta-potential in the colloid stability of calcium-oxalate dihydrate dispersions," *Colloid Surface*, Vol. 61, 123–135, 1991.
21. Barany, S., N. A. Mishchuk, and D. C. Prieve, "Superfast electrophoresis of conducting dispersed particles," *J. Colloid Interf. Sci.*, Vol. 207, No. 2, 240–250, 1998.
22. Comiskey, B., J. D. Albert, H. Yoshizawa, and J. Jacobson, "An electrophoretic ink for all-printed reflective electronic displays," *Nature*, Vol. 394, No. 6690, 253–255, 1998.
23. Baba, A., S. Sunohara, and T. Kitamura, "Electrodeposition of microcapsule containing electrophoretic pigments for electrophoretic display," *Proceedings of the 12th International Display Workshops in Conjunction with Asia Display 2005, IDW/Ad'05*, Vols. 1 and 2, 911–914, 2005.
24. Wang, D. W. and X. P. Zhao, "Fabrication and properties of electrophoretic display thin film for electronic paper," *Mol. Cryst. Liq. Cryst.*, Vol. 503, 129–142, 2009.
25. Sim, H. H., Y. J. Kim, and H. J. Choi, "Polymer encapsulated inorganic black pigment nanoparticles and their electrophoretic characteristics," *J. Nanosci. Nanotechno.*, Vol. 12, No. 12, 9254–9258, 2012.
26. Yu, D. G. and J. H. An, "Preparation and characterization of acrylic-based black particles of poly(methyl methacrylate-co-ethylene glycol dimethacrylate) by dispersion polymerization for electrophoretic displays," *J. Polym. Sci. Pol. Chem.*, Vol. 42, No. 22, 5608–5616, 2004.
27. Meng, X. W., T. Wen, S. W. Sun, R. B. Zheng, J. Ren, and F. Q. Tang, "Synthesis and application of carbon-iron oxide Microspheres' black pigments in electrophoretic displays," *Nanoscale Res. Lett.*, Vol. 5, No. 10, 1664–1668, 2010.
28. Kwak, Y., J. Park, D. S. Park, and J. B. Park, "Generating vivid colors on red-green-blue-white electronic-paper display," *Appl. Optics*, Vol. 47, No. 25, 4491–4500, 2008.
29. Hou, X. Y., S. G. Bian, J. F. Chen, and Y. Le, "High charged red pigment nanoparticles for electrophoretic displays," *Opt. Mater.*, Vol. 35, No. 2, 201–204, 2012.
30. Niu, X. W., Y. M. Sun, S. N. Ding, C. C. Chen, and B. Song, "Preparation and characterization of novel yellow pigments: Hollow TiO_2 spheres doped with cerium," *J. Mater. Sci.-Mater. EL*, Vol. 22, No. 12, 1865–1874, 2011.
31. Kao, W., "Electrophoretic display controller integrated with real-time halftoning and partial region update," *Journal of Display Technology*, Vol. 6, No. 1, 36–44, 2010.
32. Bai, P., Z. Yi, and G. Zhou, "An improved driving scheme in an electrophoretic display," *International Journal of Engineering and Technology*, Vol. 3, No. 4, 2013.
33. Zhou, G., N. N. Ailenei, J. P. van de Kamer, et al., "Electrophoretic display with rapid drawing mode waveform," US7804483 B2, 2010.
34. Kao, W., W. Chang, and J. Ye, "Driving waveform design based on response latency analysis of electrophoretic displays," *Journal of Display Technology*, Vol. 8, No. 10, 596–601, 2012.
35. Wang, Z. and Z. Liu, "The key technology of e-reader based on electrophoretic display," *2010 2nd International Conference on IEEE Software Technology and Engineering (ICSTE)*, Vol. 1, V1-333–V331-336, 2010.
36. Zhou, G., M. Johnson, and R. Cortie, "Addressing an active matrix electrophoretic display," *Proc. IDW'04*, 1729–1732, Japan, 2004.
37. Johnson, M., G. Zhou, and J. van de Kamer, "Transition between grayscale and monochrome addressing of an electrophoretic display," WO Patent 2,005,088,603, 2005.
38. Zhou, G., M. T. Johnson, J. van de Kamer, R. Cortie, and M. E. T. Nelis, "Scrolling function in an electrophoretic display device," US7796115 B2, 2010.
39. Kao, W., S. Liu, and W. Chang, "Signal processing for playing videos on electrophoretic displays," *2012 IEEE 55th International Midwest Symposium on Circuits and Systems (MWSCAS)*, 872–875, 2012.
40. Zhou, G., A. V. Henzen, J. van de Kamer, and M. T. Johnson, "Driving method for an electrophoretic display with accurate greyscale and minimized average power consumption," Google

Patents, US 7839381 B2, 2010.

41. Zhou, G., M. Johnson, R. Cortie, et al., "Driving schemes for active matrix electrophoretic displays," *Proc. IDW, AMD2/EP1-1*, 239–242, 2003.
42. Heikenfeld, J., P. Drzaic, J. S. Yeo, and T. Koch, "Review paper: A critical review of the present and future prospects for electronic paper," *Journal of the Society for Information Display*, Vol. 19, No. 2, 129–156, 2011.
43. Zhou, G., E. Niessen, and M. Johnson, "Method of increasing image bi-stability and grayscale accuracy in an electrophoretic display," WO Patent 2,005,088,600, 2005.
44. Zhou, G., "Electrophoretic display with uniform image stability regardless of the initial optical states," US Patent Application 20070164982, 2005.
45. Hayes, R. A. and B. Feenstra, "Video-speed electronic paper based on electrowetting," *Nature*, Vol. 425, No. 6956, 383–385, 2003.
46. Pitt, M. G., R. W. Zehner, K. R. Amundson, and H. Gates, "Power consumption of microencapsulated display for smart handheld applications," *SID Symposium Digest of Technical Papers*, Vol. 33, No. 1, 1378–1381, Wiley Online Library, 2002.
47. Omodani, M., "Invited paper: What is electronic paper? The expectations," *SID Symposium Digest of Technical Papers*, Vol. 35, No. 1, 128–131, Wiley Online Library, 2004.
48. Pilato, F., "Sony LIBRIe — The first ever E-ink e-book reader," *Mobile Magazine [online]*, Vol. 25, 2004.
49. http://china.nikkeibp.com.cn/news/digi/46334-20090603.html.
50. http://news.mydrivers.com/1/140/140595.htm.
51. Peruvemba, S. K., "Dual-pigment electrophoretic displays for reading textbooks," *Display*, Vol. 2, No. 12, 1226, 2012.
52. Anscombe, N., "E-reader revolution," *Engineering & Technology*, Vol. 7, No. 2, 68–71, 2012.
53. Clark, D. T., S. P. Goodwin, T. Samuelson, and C. Coker, "A qualitative assessment of the kindle e-book reader: Results from initial focus groups," *Performance Measurement and Metrics*, Vol. 9, No. 2, 118–129, 2008.
54. Ho, A., "Embedding e-paper in smart cards, pricing labels & indicators," *Presentation Conducted at Smart Paper Conference*, Nov. 15–16, 2006.
55. Zehner, R. W. and W. Malcherek, "Tiled displays and methods for driving same," Google Patents, US 20050253777 A1, 2005.
56. http://china.nikkeibp.com.cn/news/elec/9828-200512060111.html.
57. http://china.nikkeibp.com.cn/news/elec/4648-200612190130.html.
58. http://china.nikkeibp.com.cn/news/elec/14300-200603100101.html.
59. Chim, W. M., "A flexible electronic paper with integrated display driver using single grain TFT technology," Ms.C. Thesis, 2009.
60. Graham-Rowe, D., "Electronic paper rewrites the rulebook for displays," *Nature Photonics*, Vol. 1, No. 5, 248–251, 2007.
61. http://china.nikkeibp.com.cn/news/semi/42682-200512020117.html.
62. http://tech.hexun.com/2012-06-06/142186663.html.
63. Moberg, Å., M. Johansson, G. Finnveden, and A. Jonsson, "Screening environmental life cycle assessment of printed, web based and tablet e-paper newspaper," *Reports from the KTH Centre for Sustainable Communications*, 2nd Edition, 2007.
64. Hyytiainen, I. A., "Electronic device wireless display," Google Patents, 2008.
65. http://www.indiegogo.com/projects/popslate-second-screen-case-for-your-smart-phone.
66. http://www.enet.com.cn/article/2007/1008/A20071008854846.shtml.
67. http://techon.nikkeibp.co.jp/article/NEWS/20090714/172975/.
68. Lahey, B., A. Girouard, W. Burleson, and R. Vertegaal, "PaperPhone: Understanding the use of bend gestures in mobile devices with flexible electronic paper displays," *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 1303–1312, ACM, 2011.

69. Amundson, K., J. Ewing, P. Kazlas, et al., "Flexible, active matrix display constructed using a microencapsulated electrophoretic material and an organicsemi conductor based backplane," *SID Symposium Digest of Technical Papers*, Vol. 32, No. 1, 160–163, Wiley Online Library, 2001.
70. Rogers, J. A., Z. Bao, K. Baldwin, et al., "Paper-like electronic displays: Large-area rubber-stamped plastic sheets of electronics and microencapsulated electrophoretic inks," *Proceedings of the National Academy of Sciences*, Vol. 98, No. 9, 4835–4840, 2001.
71. Huitema, E., F. Touwslager, E. Veenendaal, N. Aerle, and P. Lieshout, "Rollable displays: From concept to manufacturing," *SID Symposium Digest of Technical Papers*, Vol. 40, No. 1, 104–107, Wiley Online Library, 2009.
72. http://www.auo.com/?sn=109&lang=zh-CHS&c=18&n=228.
73. http://china.nikkeibp.com.cn/news/taiw/48610-20091028.html.
74. http://www.engadget.com/2012/03/29/lg-flexible-e-paper-display-launch/.
75. http://www.bisenet.com/article/201303/124481.htm.
76. Moriya, S., T. Miyamoto, T. Saeki, H. Kawai, and S. Nebashi, "Flexible electrophoretic display with inkjet printed active matrix backplane," *NIP & Digital Fabrication Conference*, Vol. 2007, No. 2, 839–842, Society for Imaging Science and Technology, 2007.
77. http://cisco.chinaitlab.com/wireless/27011.html.
78. http://old.xmsme.gov.cn/2006-1/20061171748451765.htm.
79. http://www.cnbeta.com/articles/191160.htm.
80. http://www.adt-gmbh.com/en/products/products.html#c15.
81. Heikenfeld, J., K. Zhou, E. Kreit, et al., "Electrofluidic displays using Young-Laplace transposition of brilliant pigment dispersions," *Nature Photonics*, Vol. 3, No. 5, 292–296, 2009.
82. Seyrat, E. and R. A. Hayes, "Amorphous fluoropolymers as insulators for reversible low-voltage electrowetting," *Journal of Applied Physics*, Vol. 90, No. 3, 1383–1386, 2001.
83. Resnick, P. R. and W. H. Buck, "Teflon AF amorphous fluoropolymers," *Modern Fluoropolymers*, 397–419, 1997.
84. http://www.agc.com/english/chemicals/shinsei/cytop/index.html.
85. Koo, B. and C. J. Kim, "Evaluation of repeated electrowetting on three different fluoropolymer top coatings," *Journal of Micromechanics and Microengineering*, Vol. 23, No. 6, 067002, 2013.
86. Papathanasiou, A., A. Papaioannou, and A. Boudouvis, "Illuminating the connection between contact angle saturation and dielectric breakdown in electrowetting through leakage current measurements," *Journal of Applied Physics*, Vol. 103, No. 3, 034901, 2008.
87. Paneru, M., C. Priest, R. Sedev, and J. Ralston, "Electrowetting of aqueous solutions of ionic liquid in solid-liquid-liquid systems," *Journal of Physical Chemistry C*, Vol. 114, No. 18, 8383–8388, 2010.