Technologies for Electronic Paper Displays

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Abstract

Whilst it is already feasible to read all our documents from our computer screens, we still prefer to read from paper copies. Here we explain why this is currently so, and discuss how far we have come towards realising an E-book technology which people will be comfortable to spend hours at a time reading from.

INTRODUCTION

An unparalleled amount of electronic information is available in the form of text and illustrations. But have you ever dreamed of reading a book on your laptop, telephone or PDA display for hours at a time? Of course not! Without a backlight the displays are just too dark and the reading experience just doesn't feel right. What we need is an E-book with a display which looks (and even feels) like paper. Electronic paper displays for E-books, with a performance identical to conventional paper in terms of brightness and contrast, are a holy grail of the display industry and enable a new usage model of "immersional reading" (i.e. reading a display for hours at a time as you do a book). The obvious technology to fill this demand is the dominant LCD technology – yet this has not happened. Here, we will explain why.

Expectations for electronic paper

The factors that make reading from paper more appealing than from a computer screen are

- Readability, resulting from a combination of high resolution, high reflectivity, insensitivity to viewing angle and lighting conditions;
- Portability and comfortable hand-held reading (as opposed to reading from a fixed screen), resulting from thin and light form factor and flexibility.
- Ultra-low power consumption, where no batteries are required as no power is required to maintain the image once written.

An ideal E book display will combine all of these features.

LCD's FOR E-BOOKS

In most LCD's the liquid crystal modulates the polarization state of the light which passes through the display. For this reason, the displays operate between polariser films whereby a significant portion of the light is lost in the polariser. For this reason, the nematic LCD cannot be as bright as paper, although impressive low power displays have been demonstrated [1].

Other types of liquid crystals can work without polarized light, modulating light using either scattering (Polymer dispersed LC [2]) or absorbing (Guest-host LC [3]) modes of operation. Whilst these LC effects are inherently brighter, turning off the power results in the loss of the image, whereby the low power aspect of electronic paper is not really met.

One LC mode combines a low power and a reasonably high brightness capability, the cholesteric textured LC, which operates by reflecting light of a wavelength defined by the pitch of helix shaped LC molecules [4]. Again, CTLC displays have found application in E-book applications in the Matsushita Sigma Book [5] and the Kolin I-library (see S-C Yeng et al, Proc IDW'04 p.1527-1530 for performance measurements of these 2 products and also the Sony electrophoretic display based LIBRIé), but do not show the viewing angle and lighting condition independent appearance of paper. Recently, impressive black and white signs have been demonstrated with this technology [6].

However, for these reasons, liquid crystals may not be the ideal technology for electronic paper.

OTHER TECHNOLOGIES FOR E-BOOKS

The following technologies meet the list of requirements for electronic paper discussed above (readability, portability, ultra-low power). Whilst these technologies have their individual strengths, they are all intrinsically suitable for application as electronic paper because they do not require the use of polarised light, and hence show brightness levels approaching that of paper.

Moving particle systems

This class of electronic paper systems comprises technologies in which coloured particles in a fluid are manipulated by electric fields. There are two basic classes of systems – those where the particles are displaced (electrophoretic systems [7,8]) and those where the particles rotate [9].

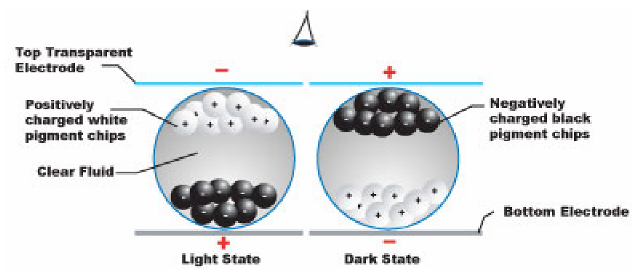

Figure 1. Schematic diagram of a microencapsulated electrophoretic (EP) display

Electrophoretic (EP) displays operate by the motion of charged pigment particles in response to an electric field. Both single particle in a coloured fluid [8] and the dual particle systems of E Ink [7] are used. The E Ink front plane (Figure 1) consists of microcapsules containing a liquid and two kinds of tiny pigment particles: black ones that are, let us say, negatively charged and white ones that are positively charged. The microcapsules are laid down as a layer in making a display. If a positive voltage is applied to a bottom electrode under the microcapsules (relative to the transparent top electrode), the positive particles will migrate to the top and produce a white image, while the black particles will migrate to the bottom. Intermediate grey tones are produced by applying a voltage pulse less than the maximum necessary for a full black to white or white to black transition.

Electrochromic systems

Electrochromic systems are long established and rely upon a colour change induced in a material by an electrically induced oxidation or reduction of the material [10]. Well known electrochromic systems are the viologen molecules and tungsten oxide.

Electrodeposition systems

Electrodeposition [11] is similar to electrochromism in that an electrical current induces a change in optical state. However, in this case material is physically electrodeposited onto an electrode from an electrolyte solution in order to induce an optical change.

Electrowetting systems

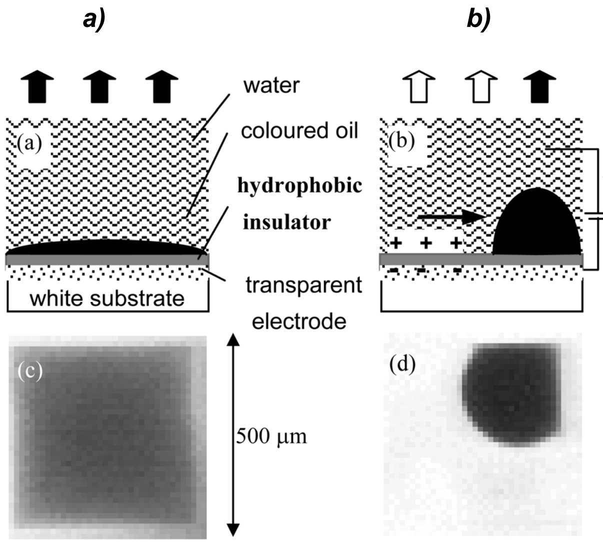

Figure 2: Electrowetting display principle. Schematic cross-section with (a) no voltage applied, therefore a homogeneous oil film is present or (b) dc-voltage applied, causing the oil film to contract. The top view photographs (c) and (d) demonstrate the continuous oil film and corresponding oil retraction obtained with a homogeneous electrode

In the recently introduced electrowetting technology [12], an electric field is used to move a coloured liquid across a surface. Figure 2a shows the optical stack. In equilibrium the coloured oil naturally forms a stable and continuous film between the water and the hydrophobic insulator. However, when a voltage difference is applied across the hydrophobic insulator an electrostatic term is added to the energy balance and the stacked state is no longer energetically favourable. The system can lower its energy by moving the water into contact with the insulator, thereby displacing the oil (Figure 2b) and exposing the underlying white surface. The balance between electrostatic and capillary forces determines how far the oil is moved to the side. Electrowetting can provide an optical switch with a high reflectivity (>40%) and contrast (>15). In addition to the attractive optical properties, the principle exhibits a video-rate response speed (~10 ms) and has a clear route toward a high-brightness colour display and is readily scalable to a pixel size of 170 μm [13].

Micromechanical (MEMS) systems

This class of electronic book systems comprises technologies in which micro-structured foils are either deflected [20] or rolled up [14] by applying an electrical field, thereby modulating the reflectivity of the system.

The deflected foil technologies operate by interference modulation and switch between two modes, a resonance mode where a reflective colour is generated by interference in an air gap between the reflective foil and the substrate, and an absorption mode where the foil is directly in contact with a thin film absorbing stack on the substrate. In this way binary devices with a colour defined by the size of the air gap are formed.

Operation of the rolling foil technologies is conceptually very simple: the foil acts like a roll-blind, which can either block or transmit light depending upon how far it is unrolled.

Table 1: Summary of the properties of the high brightness E book technologies

Effect	Paper Like Appearance	zero power image	Video Speed
Electrochrome	**Yes**	**Yes**	**Not yet**
Electrodeposition	**Yes**	**Yes**	**Not yet**
Electrowetting	**Yes**	**no**	**Yes**
MEMS	**Yes**	**no**	**fast**
Rotating particle	**Yes**	**Yes**	**Not yet**
Moving particle	**Yes**	**Yes**	**Not yet**

COMMERCIAL E-BOOK

Table 1 summarises the properties of the high brightness technologies which are suitable for electronic paper applications. Whilst several of the above technologies meet the list of requirements for E-books (readability, portability, ultra-low power), the moving particle systems are already establishing themselves in the electronic paper market in both E-book products and in signage applications [5,15,17].

Table 2: Characteristics of the Philips/E Ink/Toppan active matrix electrophoretic display in the Sony E-book reader LIBRIé

Diagonal	6”
Columns x Rows	800 x 600 (SVGA)
Resolution	160ppi
Reflectance	36%
Contrast Ratio	9:1
Viewing Angle	180^o

A commercial E-book display using micro-encapsulated electrophoretic electronic ink, with a real paper-like look has been realized by Philips, E Ink Corporation and Toppan [17]. The characteristics of the display, used in Sony's E-book reader LIBRIé (figure 3), are described in the following table. As the image quality improves by adding grey levels, a series of driving pulses were generated in order to switch the display between four grey levels (white, black, and two intermediate grey states) [15].

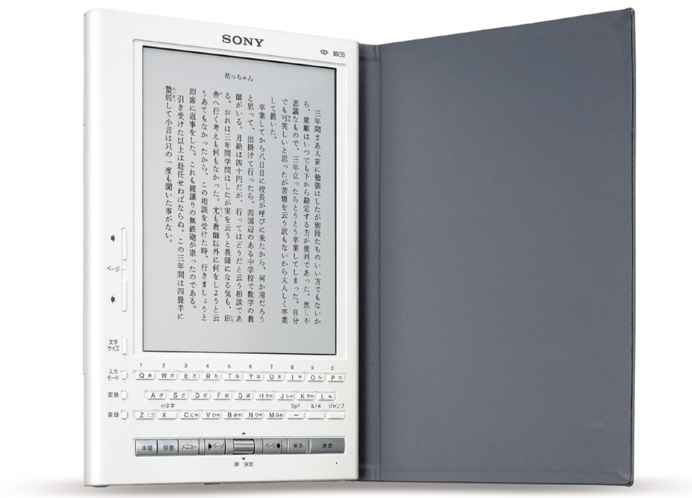

Figure 3: Philips' 160ppi electronic paper display integrated in the Sony LIBRIé E-Book [5, 15, 17].

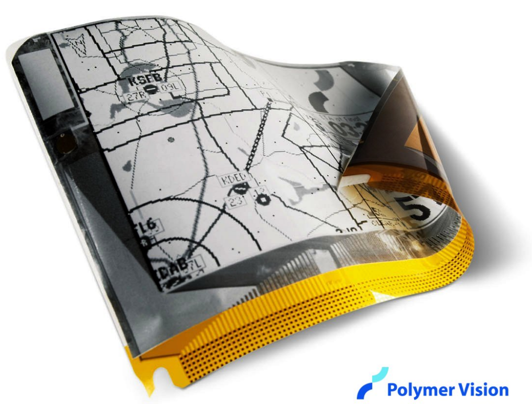

Figure 4: World's thinnest flexible active-matrix display using Philips' Polymer Vision ultra-thin back plane with organics-based thin film transistors, combined with E Ink's electronic ink front plane (20 x 16 cm, 300x300 micron pixels [26]).

FUTURE DEVELOPMENTS

Whilst today's electronic paper gives the look of a black and white book, there are clear benefits of introducing coloured images. Several approaches to colour may be taken:

1) Addition of a colour filter, as used in colour LCDs, on top of the electronic paper. However, this reduces the brightness of the E-book.

2) Introduction of intrinsically coloured components into the electronic paper, such as coloured liquids [8,12], coloured particles [16,21], multi-coloured electrochromic materials [19] or by choosing a technology which is based upon optical interference effects [4, 20].

3) Recently, the concept of increasing the brightness of a coloured electronic paper display by stacking layers of electro-optical material which switch between a transparent and a coloured state has been demonstrated for both electrochromic [22] and electrowetting systems [13]. In addition, approaches have been demonstrated to realise multi-coloured electrophoretic pixels by manipulating 3 different types of coloured particles in a single liquid [23] or air filled [24] capsule.

A further comfortable feature of paper is its flexibility. Several approaches have been taken to creating a flexible electronic paper product using a plastic substrate [25]. Once again, electrophoretic systems have proved to be particularly amenable to produce a flexible electronic paper, where there have been many recent examples of combining flexible electrophoretic front planes with flexible active matrix back planes [26,27,28,29]. An example of a flexible electrophoretic display is shown in figure 4.

Finally, there is always the dream that electronic paper will provide options which real paper cannot. For example, we have seen the development of a pen input system to create, for example an electronic drawing pad [33]. Perhaps a more attractive feature would be moving picture capability, which can be realised by those electronic paper technologies with a response speed of below around 50msec. Some technologies, such as electrowetting [12,13] and the MEMS based systems [14,20], are intrinsically fast enough. We have however recently seen that traditionally rather slow technologies have been speeded up towards video speeds. For example, the Ntera corporation has demonstrated an electrochromic system with fast switching [10,31], whilst moving particle systems have also been brought into the video realm by developments introduced by E Ink [16] and Sunnybrook [32]. Perhaps the most spectacular step towards an ultra high speed electronic paper has been the electrophoretic approach taken by the Bridgestone Corporation [30], to move black and white charged particles in air. Due to the lower viscosity of the air, the response speed of this electronic paper is around 0.2msec, around 100 times faster than an LCD!

CONCLUSIONS

Whilst LCD's are not ideal for electronic paper applications, a range of new technologies is approaching the electronic paper requirements of readability, portability and low power. Already, electronic paper products based upon the electrophoretic technology are appearing whose accurate grey scale reproduction and extremely low power consumption together with a high brightness and near perfect viewing angle combine to give these displays their unique paper-like properties. The future of electronic paper looks ever more colourful, flexible, dynamic and interactive.

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BIOGRAPHY

Kars-Michiel H. Lenssen is a Director and Principal Scientist at Philips Research Europe, leading the color electrophoretic display project. He received an M.Sc. degree in Applied Physics from Eindhoven University of Technology in 1989. In 1994 he received his Ph.D. from Delft University of Technology and joined Philips Research as a Senior Scientist. In that function he initiated and led research projects on (giant) magnetoresistance sensors and on MRAM. In the period 2002-2003 he worked as a Philips assignee in Arizona in the framework of the Motorola-Philips-STMicroelectronics alliance. Kars-Michiel holds 16 granted US patents and is (co-)inventor on over 30 patent applications; he (co-) authored over 25 papers in international scientific journals. He also works as an evaluator of research projects for the European Commission and is a member of the International Advisory Committee of several conferences.