

Information DISPLAY

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**Has
E-Paper
Finally
Arrived?**

- **Electrochromics: Unlocking Color in E-Paper**
- **E-Paper Manufacturing**
- **Electronic Paper: Past, Present, and Future**
- **Early Days of LCD Research and Development**
- **Journal of the SID January Preview**

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Cover: On November 19, 2007, Amazon, the world's largest on-line retailer, announced with great fanfare the launch of the Kindle, a portable reader that wirelessly downloads books, blogs, magazines, and newspapers to a high-resolution electronic-paper display. While this certainly is far from the first e-reader that utilizes electronic-paper technology to create a paper-like display, the Kindle introduction sparked hopes that it could serve as the "killer application" that truly launches e-paper products into the consumer mainstream. See the Industry News section on page 3 for more details.



Credit: Amazon

Next Issue of Information Display

Display-Metrology Issue

- Introducing the International Committee for Display Metrology (ICDM)
- Measuring and Rating Electro-Optical Display Performance
- Simulating LCD Moving-Image Representation and Perception
- Diffuse Clarification
- JSID February Preview

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Notes from the Front Lines of Backlights

I had the privilege of attending the LA Chapter one-day technical conference on LED technology for LCD backlights in early January. This was the third installment in this highly successful, sharply focused, technical program describing the current state of the art in LED backlighting for LCDs. The organizers of this event have found the ideal recipe: bringing the right mix of technology details and application overview in just the right balance for a full

but manageable day of education. I commend them for their efforts.

In the opening remarks presented by Program Chair Bill Kennedy (Toyoda Gosei Co., Ltd.), we learned that the conversion efficiency in GaN LEDs has now substantially passed the similar metric for cold-cathode fluorescent lamps (CCFLs). Blue-emission LEDs using yellow bi-chromatic phosphors to make a white mix will dominate the backlighting applications for the near future. These white LEDs represent an efficient and low-cost method to make a white-light mix suitable for many LCD applications. As optical-power-efficiency and color-gamut demands increase, multi-spectrum phosphor versions will become more widely available as well. The most recent products from Toyoda are achieving as much as 70% external quantum efficiency, which puts them remarkably close to laser QE performance. Of course, getting the light out of the die and into the display efficiently is still a challenge.

The increasingly popular technique to use local-area dimming of direct-array LED backlights with matching image processing on the LCD for expanded dynamic range will continue to see investment and deployment in a number of applications. This approach, which has taken on the name Active Local Dimming (ALD), has been widely reported in *ID* magazine and demonstrated at numerous exhibitions in the past few years. While most embodiments being developed currently use white LEDs, there is renewed interest in using RGB arrays and achieving multiple axis of dynamic-range expansion, both in the color and luminance domain.

As the response-time metric of LCDs decreases, so does the renewed interest in color-field-sequential approaches, which eliminate the optical inefficiencies in the color filters. This is a controversial subject to many because of the known issues with color-frame breakup and demands for very high sequential field rates used in projection systems, but the combined opportunities to increase luminous efficiencies, reduce power consumption, and inherently reduce the motion-blur problem are just too compelling to ignore.

The implementation of LEDs in backlights for cell phones and other portable devices is a mature and well-tested marketplace. The same pervasive penetration is just beginning to happen in the notebook-computer market and shows signs of moving rapidly into both the desktop monitor/panel market as well as the large-screen-television market. The penetration into notebooks is being driven at a dramatic pace by the combined demands for better battery life and more efficient use of available real estate.

Matt Knadler, Senior Display Development Engineer (Dell), gave a very candid overview of the challenges and driving factors for Dell's adoption of LEDs. On the one hand are the promising benefits of LED technology: thinner panels, lower power consumption for comparable light output, wider color gamut, reduced support electronics footprint (*i.e.*, eliminating the inverter), absence of mercury, and low-voltage operation (*i.e.*, intrinsic safety). On the other hand is the very real problem of slightly

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industry news

Is Amazon's Kindle the Killer App that Puts E-Paper Over the Top?

SEATTLE – On November 19, **Amazon**, the world's largest online retailer, announced with great fanfare the launch of the **Kindle** (pictured), a portable reader that wirelessly downloads books, blogs, magazines and newspapers to a high-resolution electronic-paper display. While this is certainly far from the first e-reader that utilizes electronic-paper technology to create a paper-like display, the Kindle introduction sparked hopes that it could serve as the "killer application" that truly launches e-paper products into the consumer mainstream.

Kindle uses a high-resolution electronic-paper display from **E Ink Corp.** to provide a sharp black and white screen that E Ink and Amazon claim is as easy to read as printed paper. The display is 6 inches diagonal and has a resolution of 600 × 800 at 167 dpi, with a 4-level gray scale.

The electrophoretic display (EPD) is similar in nature to the electrophoretic display developed by E Ink for the **Sony Reader**. The Kindle device weighs 10.3 ounces, measures 7.5 inches tall × 5.3 inches wide × 0.7 inches thick, and retails for \$399.

Amazon has been tight-lipped about sales figures and projections for the Kindle, but company spokesperson **Andrew Herdener**

said the initial inventory of Kindle sold out in 5½ hours on November 19, and since that time, the Kindle page on amazon.com has stated that "Due to heavy customer demand, Kindle is temporarily sold out."

The first full-fledged assessment of sales of the Kindle was expected when Amazon reported its earnings for the fourth quarter of 2007, which was scheduled to take place January 30. However, **Prime View International (PVI)**, the Taiwanese company that was the first to assemble the E Ink film into display

modules for Amazon, reported in its quarterly earnings filing in January that e-books are expected to double in growth in 2008, and that the company cannot currently meet demand from Amazon, though there is no component shortage problem at present. According to E Ink, **LG.Philips LCD** is also assembling the E Ink displays.

Wireless Accessibility

The Kindle's major step forward from other e-readers currently in the marketplace is that content can be downloaded wirelessly to device using the same technology (EVDO) that allows content to be downloaded to cell phones, as opposed to using WiFi, a PC connection or syncing the device. More than

90,000 books are available in Amazon's Kindle Store.

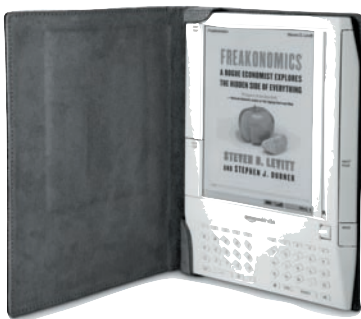
Amazon's Herdener claimed in an e-mail interview that the company didn't focus on competitors when designing the Kindle, but rather aimed to provide the best product to its customers. That led Amazon to E Ink.

"Our No. 1 design goal for Kindle was to make the device disappear, just as the book disappears when you read and become engrossed in the author's words," Herdener explained. "We couldn't make Kindle disappear if the screen had glare, didn't look like real paper, couldn't be read outside, or required constant re-charging of the battery. The E Ink display solved all these problems."

Herdener declined to discuss any of Amazon's future plans, but those would almost certainly have to include a color display.

Still, no matter how many improvements Amazon and other e-reader manufacturers make, many are skeptical that these devices will find widespread traction with consumers. Notable among them is **Steve Jobs**, Apple's CEO, who expressed his doubts at Macworld when asked about the Kindle.

"It doesn't matter how good or bad the product is, the fact is that people don't read anymore," Jobs told reporters. "Forty percent of the people in the U.S. read one book or less last year. The whole conception is flawed at the top because people don't read anymore."



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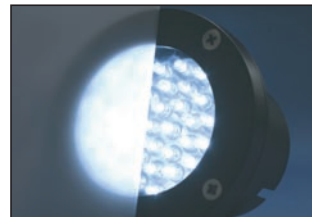


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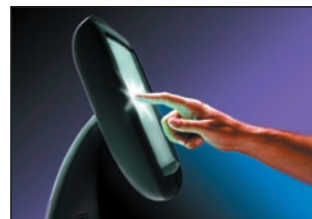


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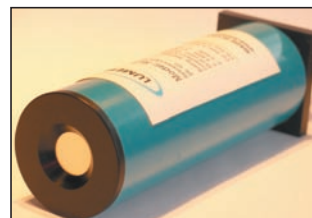


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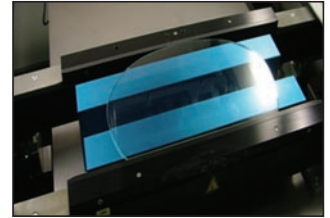


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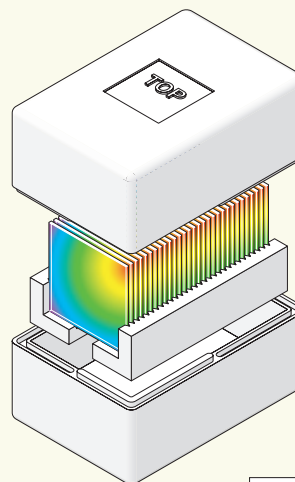
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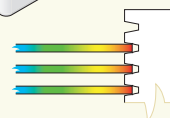
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Technology Asymptotes

by Aris Silzars

Recently, I read an article about an exploratory effort by NHK in Japan to develop a new higher-resolution television system. The NHK Super Hi-Vision system is designed to deliver images with $8K \times 4K$ resolution with a 16:9 aspect ratio. As explained in the article, the objective is to be able to have a 100-in. display and not have the individual pixels

be visible from a distance of 1 m. Wow! Will we really be able to appreciate such spectacular images given that the current HDTV system is already better than the practical resolution of film images we have become so accustomed to seeing in movie theaters? This led me to contemplate the broader question of whether there are limits when we no longer have the need or desire to push for further improvements – or perhaps the product is already so good for its intended purpose that we will not pay for anything better.

Perhaps we can gain a useful insight or two by taking a look at what has happened in other technology areas. Film cameras reached their practical limits of resolution many years ago. Some of the lenses from the 1930s and 1940s achieved resolution levels as good as anything that is available from “modern” optics. Instead of pushing for further refinements in resolution, lens designers found a more-receptive market for added features such as variable focal lengths (wide angle and telephoto “zoom” lenses), larger apertures, and auto-focus. In trying to balance between versatility and resolution, it was not uncommon to actually have the resolution get sacrificed to some degree. The camera makers learned where the optimum balance was between film resolution, lens versatility, and manufacturing cost. That led to many years of products being introduced that continued to be improved in many aspects, but lens resolution was not one of them. Thus, today, most images taken with professional-quality 35-mm-film cameras fall short of the equivalent of HDTV resolution. For those professional photographers who need to produce higher-quality photographs for use in glossy magazines or for art-gallery displays, a niche market developed using larger film formats such as $2\frac{1}{4}$ square or 6×7 cm. A technology asymptote was achieved and sustained for many decades.

Let's now look at a more recent but closely related example. Some years ago, I wrote a column in *Information Display* predicting that 2-Mpixel imagers would be sufficient for digital cameras since they would produce images of comparable quality to 35-mm film. Clearly, I was too conservative in my prediction. To get to the 2-Mpixel number, I was trying to balance what I estimated to be acceptable picture quality with the capacity of storage devices available at that time. I did not anticipate that the camera makers would get into a “horsepower” race to see who could introduce a camera with the next higher megapixel number. Fortunately, the cost of storage continued its rapid decline so that the huge image files that result from today's 5–10-Mpixel imagers are no longer all that difficult to manage. But the pixel count race is also finally reaching its technology asymptote. We seem to be settling on 10 Mpixels – or a bit more – as the magic number for “good enough.” That is sensible since the lenses that are sold with those cameras are marginally adequate to fully utilize this image resolution.

In other areas of electronics, we have seen similar technology asymptotes come to pass – often with frustrating results for product manufacturers and resellers. Consider,

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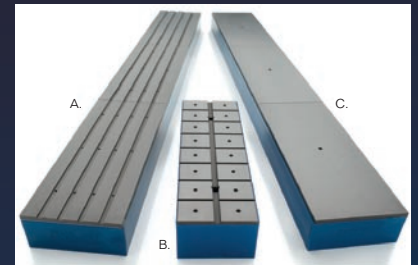
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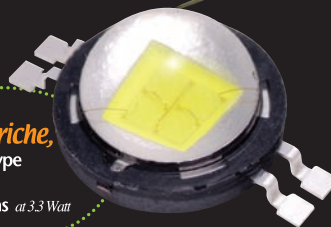
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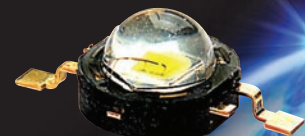
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Electrochromics: Unlocking Color in Electronic Paper

The next step in the evolution of e-paper is to improve its ability to reproduce color images. Some experts have pegged electrochromic technology as the strongest contender to lead to color e-paper displays. This article examines how electrochromics stack up when compared to other e-paper display technologies.

by Chris Giacomponello and Henrik Lindstrom

CONSIDER FOR A MOMENT just how pervasive printed paper is in today's society. Globally, about 300 million metric tons of paper and paperboard are produced each year. More than 2 billion books, 350 million magazines, and 24 billion newspapers are published annually¹ – it is estimated that 45 trillion pages are printed each year, the vast majority of which are now printed in color. These are formidable numbers! This does not even include various paper products, packaging, posters, labels, cards, and signs. This is an extensive range of applications, with different economic values ascribed to the many different uses.

Despite the broad range of usage, certain attributes are common among all of these conventional paper-industry applications:

- They support high-contrast readable print on a flexible medium.
- They are enabled by low-cost high-volume printing.
- They are capable of supporting a broad range of natural color.

Chris Giacomponello is the Vice President of Business Development and Marketing for NTERA, Inc.; telephone 484/534-2143, e-mail: chris.giacomponello@ntera.com.

Henrik Lindstrom is a Senior Scientist at NTERA Limited; e-mail: henrik.lindstrom@ntera.com

These traits point to several important paradigms that must be considered by the information-display industry in its attempts to develop an electronic medium to augment or displace printed paper in several or more of its current roles. First, the user experience offered by an electronic display must suit the human reading experience (optically and ergonomically) as well as printed paper. Secondly, e-paper must be capable of support-

ing a broad array of uses at very low price points – paper is successful and ubiquitous for this very reason. Finally, and perhaps most importantly, if e-paper displays are going to evolve from niche market applications to broad and pervasive deployment, they must be capable of supporting rich, vibrant, natural colors.

This article will examine the emergence of early e-paper technologies and compare the

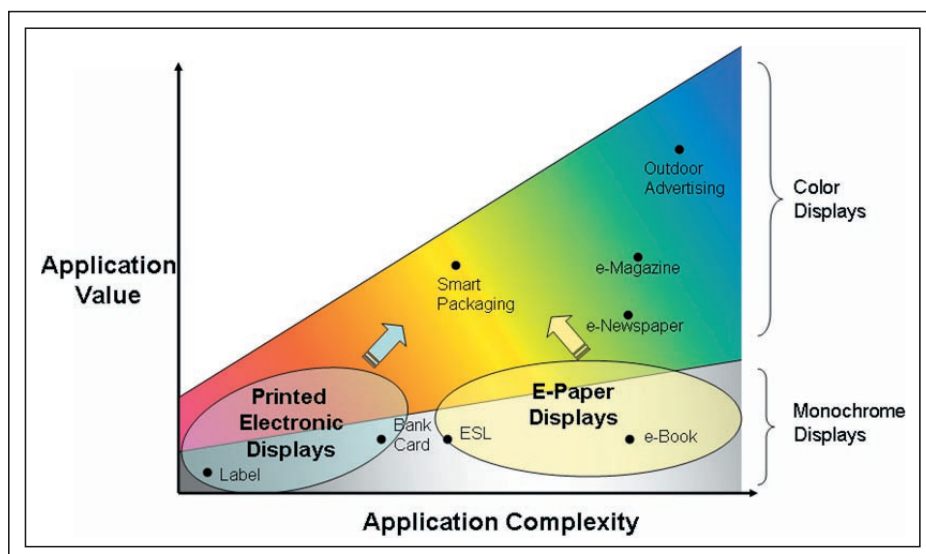


Fig. 1: Emerging market dynamics for e-paper and printed-electronic displays.

suitability of those technologies to e-paper applications in the long term. Because physical limitations relative to color rendering limit the widespread adoption of these early technologies to niche applications (such as e-books), this article will identify and explore technologies that are candidates to overcome these shortcomings and the concurrent developments required to bring these longer-term solutions to market.

Emergence of e-Paper and Printed Electronics

Recently, the first commercial products containing early e-paper display technologies have reached the market. The applications primarily targeted thus far have been electronic-reading appliances (portable electronic reading devices) and shelf-edge price labels.

The most widely utilized e-paper display technology at this time is the electrophoretic display (EPD), which offers good readability, low power consumption, and compatibility with flexible substrates. Several companies manufacture EPD displays, including SiPix Imaging (microcell electrophoretic particles), E Ink (micro-encapsulated imaging films), and Bridgestone (air-gap particle system).

At the same time that e-paper is finding its way to the market through displays, a new industry based on printed electronics has emerged and is having a major impact on the traditional printing industry by bringing electronics into the domain of paper and plastic. The desire to incorporate smart electronics into printed products (labels, packaging, cards, and signs) has created this new industry, which is based on “functional printing.” Through the use of conventional printing processes such as screen, flexo, gravure, and offset, functional e-inks can be printed in an additive manner on high-speed roll-to-roll print lines. This allows for the creation of simple, low-cost electronics and electro-optic functionalities on flexible substrates.

Taken together, these two market trends provide some evidence of the latent demand for these new applications. However, the mainstream adoption of e-paper and printed-electronics applications will require a combination of a paper-like user experience, low cost, high-volume printing, and color. Figure 1 illustrates the emerging market dynamics and future value migration for printed electronic displays and early market e-paper displays by

comparing the relative value versus application complexity for several representative target products.

NanoChromics™ Technology: A Printed Electrochromic Color Display

Recent advancements in electrochromic technology based on the use of electrodes constructed from modified porous nanocrystalline films² pioneered by NTERA Limited offer several significant advantages that enable the use of this technology in advanced digital displays. These include a paper-like optical quality with excellent contrast in all lighting conditions, rapid switching speed, very low power consumption for content with high-information hold times, a device structure that is fully compatible with low cost, additive print process manufacturing, and a full range of natural reflective colors.

The monolithic NanoChromics™ display structure shown in Fig. 2 consists of several stacked porous layers that are printed on

top of each other on a substrate modified with a transparent conductor (such as ITO or PSS PDOT). Each printed layer has a specific function. The TiO₂ with adsorbed viologen changes color by reduction or oxidation of the viologen molecules. The white reflector layer serves the purpose of increasing the contrast ratio and insulates the TiO₂ layer electrically from the ATO. The ATO layer has high capacitance and counter-balances the charge inserted/extracted in TiO₂ to maintain overall device charge neutrality. The conducting carbon layer adds extra capacitance and serves as a highly conductive back contact for the ATO.

In the last printing step (not indicated in Fig. 2), the porous monolith structure is over-printed with a liquid or polymer-gel electrolyte, dried, and then finally sealed with a PET film. The device can be switched on by applying a negative electrical potential to the transparent conducting substrate relative to the conductive carbon layer. This causes a

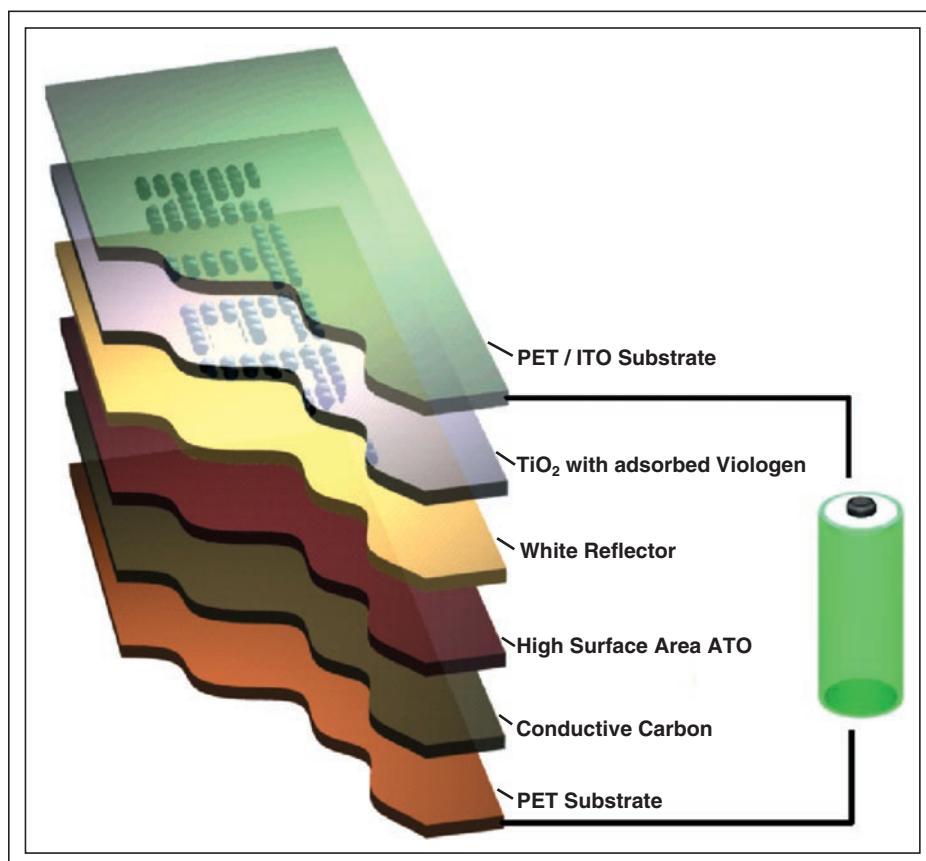


Fig. 2: A printed NanoChromics™ paper-like display.

reduction of viologen molecules (coloration) to occur at the TiO_2 layer. By reversing the applied potential, the viologens oxidize and the device bleaches.

A unique feature of the electrochromic monolith is the relatively low voltage (~ 1 V) needed to color and bleach the device. This can be explained by the small overpotentials (losses) needed to drive the electrochemical reduction of the surface adsorbed viologen, and the small overpotentials needed to drive the migration of the charge-compensating ions in the pores of the monolith. As a direct positive consequence of the low-voltage requirements, the device power consumption becomes relatively low as well. Switching speeds in the millisecond range have been obtained.³

The amount of coloration can be tuned continuously by controlling the amount of injected/extracted charge. By using transparent TiO_2 layers with high densities of adsorbed viologens in combination with an optimized white reflector, intense colors with high contrast ratios can be obtained.² A full color spectrum can be achieved by appropriate design and combination of dye molecules.⁴

The printing inks are based on non-toxic readily formulated materials such as carbon, TiO_2 , ATO, and small amounts of dye. All active layers can be deposited using conventional batch processes such as screen printing or continuous roll-to-roll processes such as flexography. The structure for these printed devices is shown in Fig. 2.

NanoChromics™ displays have demonstrated performance and reliability that is consistent with the needs of advanced display applications. Through a combination of improvements in molecular technology, materials, and compensatory electronic drive circuitry, the performance of NCD™ devices has been demonstrated to meet the needs of commercial device applications. NCD™ displays on glass have been shipped in consumer products with lifetime performance requirements of at least 10 years, while accelerated lifetime testing in the laboratory has demonstrated capabilities exceeding 10 years and more than 40 million cycles.

The transition to flexible substrates with the printed monolithic architecture enables fundamental advancements in device flexibility and lower cost solutions. The monolithic architecture builds all of the layers on a single substrate (like printed media today), and as such

supports flexing and bending in ways that are not possible with conventional displays based upon two parallel spaced-apart substrates. In addition, the cost advantages of an all-printed device based on a single substrate and no back-end assembly requirements are considerable, opening the door to functional applications that will compete with conventional printed media. A printed monolithic NCD™ display on PET is shown in Fig. 3.

Toward a Printed Color Future

Today, most flat-panel displays produce color using a planar RGB color filter, as shown in Fig. 4. While an RGB scheme can produce a broad, rich color gamut when used in an emissive display (where the light mixes in an additive manner), the results are significantly worse when used on a reflective display.

A significant amount of the reflected light is lost (through transmission and absorption

losses), reducing the overall luminance and the impact of the perceived color on the eye. In fact, the maximum white-state reflectivity is 33% less than that of an equivalent monochrome display.⁵ While the luminance can be improved by desaturating the colors within the filters, this further reduces the color gamut that the display can reproduce.⁶

Moving forward, it is widely accepted that the best solution for reproducing deep, rich color on a reflective display will be achieved through an architecture that supports stacked color. Among the leading candidate technologies for achieving stacked color are cholesteric LCD (Ch-LCD) and electrochromic.

Several prototype stacked RGB Ch-LCDs have been demonstrated by Kent Displays, Inc.. Recent investigations into a sequentially coated emulsion of Ch-LCD droplets in a polymer matrix have demonstrated the possi-

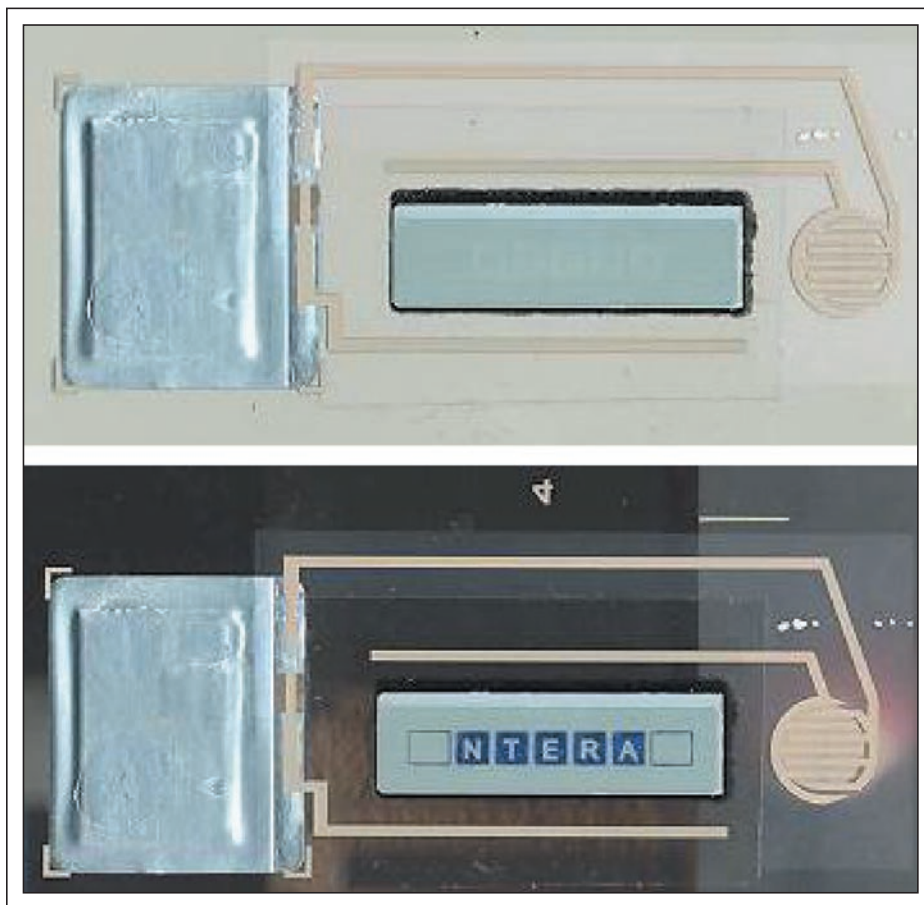


Fig. 3: A printed monolithic NCD™ display on PET is shown. The display is connected to a flat battery with printed silver traces.

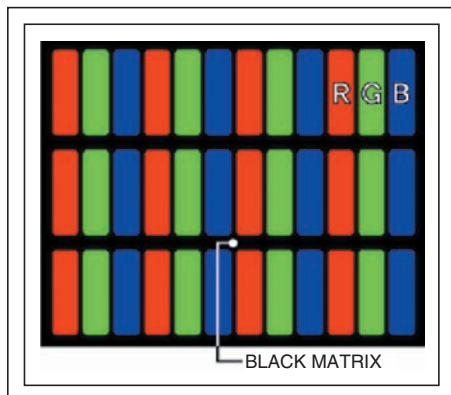


Fig. 4: An RGB color filter.

bility of developing a printed stacked color architecture.⁷ Magink is in the process of commercializing a stacked RGB Ch-LCD solution to address the growing market for outdoor advertising.

These early stacked color displays are promising, and they provide an observable improvement in color rendering over planar RGB filters. However, there are several technical barriers to achieving rich, natural color. Specifically, the color is rendered through spectral reflection (not absorption) in narrow wavelengths, limiting the color gamut. Additionally, critical cell gaps or droplet uniformity must be maintained to achieve optimal color rendering, resulting in significant color shifting with angle when deployed on flexible substrates.

Ultimately, a fully printed light-absorbing natural-color display will provide the best solution for rendering true color. This may be achieved through a planar array of poly-chromatic pixels or a stacked, subtractive array of CMY inks. Electrochromic displays are capable of supporting both architectures, although realization of suitable poly-chromatic electrochromic molecules has remained elusive.

Figure 5 illustrates an architectural diagram of a full-color printed CMY stacked NCD™ e-paper display. Today, this display architecture is gated primarily by the advancements and commercializations of transparent printed OTFTs. Recent advancements in the field of printed electronic transistors are promising. Several companies have indicated success in developing printed organic electronic transistors, with several of these devices now achieving mobilities of 80 cm²/V-sec. As a result, we anticipate that a fully printed, stacked

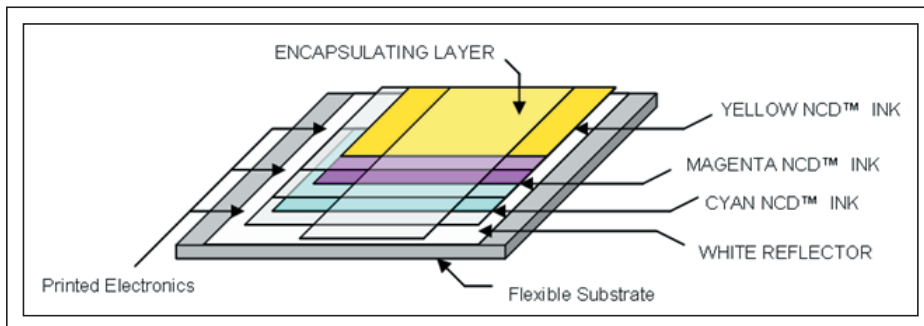


Fig. 5: A stacked NCD™ CMY display.

NCD™ CMY/CMYK display may be realizable in the near future.

Conclusions

The introduction of electronic readers with EPD displays, such as the Sony Reader and Amazon's Kindle, and the emergence of "smart" shelf labels enabled by printed electronics are clear indications that the era of e-paper displays has arrived. In order to move from niche market applications (e-books and printed labels) to more widespread adoption, e-paper display technologies must provide a user experience that is consistent with printed paper, support low-cost printed manufacturing, and be capable of vibrant, natural color.

Many reflective-display technologies have demonstrated a readable reflective contrast, and several more can support high-volume fully printed manufacturing environments consistent with printed electronics. A limited number of others have demonstrated early success at stacked color architectures. However, electrochromics are ideally suited to support all three of these essential capabilities through the realization of an all-printed subtractive color display.

Finally, to really appreciate the importance of color in the printed media markets, consider the following: e-newspapers and e-magazines are frequently identified as a target market application for portable e-paper displays. However, the primary revenue model for newspapers and magazines (unlike books) is not driven by content; it is driven by advertising. In today's market, color is essential for effective advertising. It is reasonable to expect that these applications will struggle to gain traction without an e-paper display technology that can compete with printed color paper.

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From Lab to Fab: A Look at BiNem E-Paper Manufacturing

As e-paper products begin to emerge into the marketplace, it is interesting to examine the roadmap of how these technologies work their way from the development stage into mass manufacturing. Here is a case study that examines how BiNem e-paper displays make use of the existing LCD ecosystem and production lines.

by Jacques Angelé

ONE of the more intriguing developments in display technology in the past decade, electronic-paper displays (EPDs) continue to attract widespread public awareness and business interest, beginning with the pioneering work of Nick Sheridon at Xerox's Palo Alto Research Center in the 1970s and the first steps of the electrophoretic technology invented by Joseph Jacobson (who later co-founded E Ink Corp.) in the 1990s. Electronic-paper displays are competing to achieve the same comfortable reading experience as that of printed paper in ambient lighting conditions, and devices equipped with EPDs are gaining extended battery life due to their "zero power" feature (between image updates). Since 2006, more than ten different

models of e-books embedding EPDs were announced, including Amazon's Kindle.

Electronic-paper display technologies are based on a number of surprisingly different physical principles at various stages of technological or industrial process development¹: electrophoretic (displacement of charged col-

ored particles), bistable liquid crystal (using nematic or cholesteric liquid crystals), micro-electromechanical systems (MEMS), electrochromics, ferroelectric, *etc.* Because of the low cost of printed paper and the diversity of its applications, many feel that we are still a long way from significant diffusion of e-paper

Jacques Angelé, VP Technology Programs and Co-Founder, left the Sagem Group to join Nemoptic when the company was set up in 1999. He successfully developed the bistable BiNem display technology in co-operation with the Orsay Group, a leading Center of Excellence in physics. Prior to that, he was in charge of the Matra Group's Liquid Crystal Laboratory, where he developed new display devices and professional applications in the LCD field. He can be reached at Nemoptic, 1 rue Guynemer, 78114 Magny-les-Hameaux, France; telephone +33-(0)-1-39-30-51-60, fax -61, e-mail: j.angele@nemoptic.com

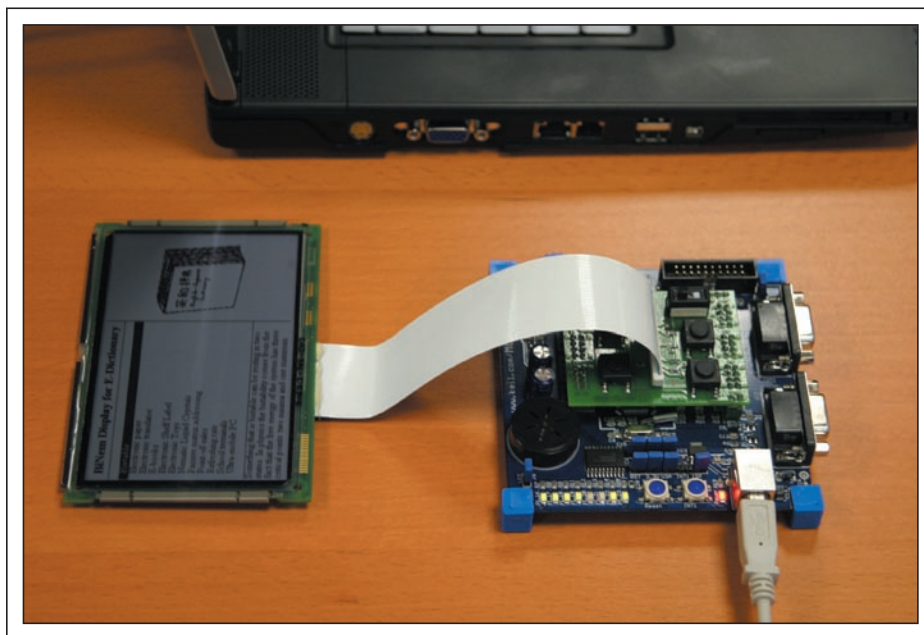


Fig. 1: The HVGA BiNem development kit provides a fast and convenient way for customers to evaluate new applications of bistable displays.

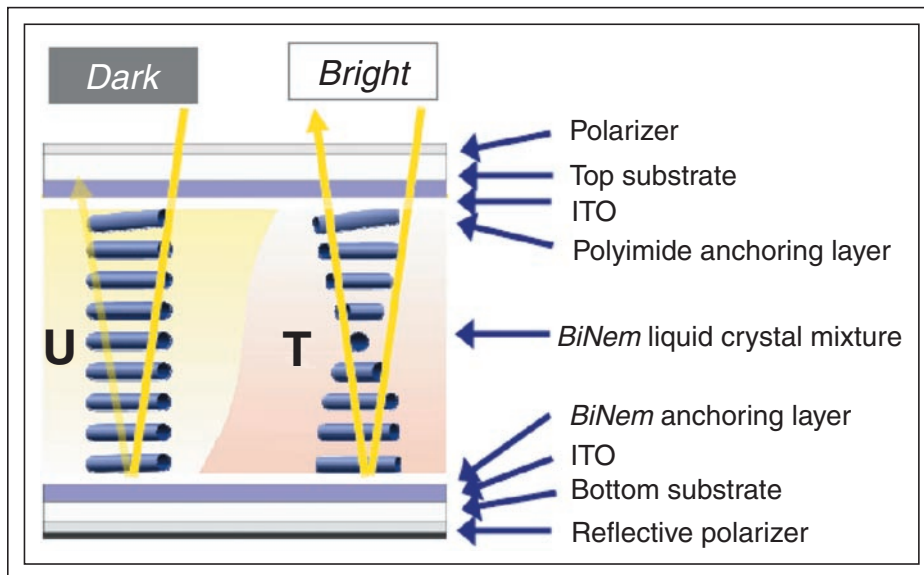


Fig. 2: Structure of a BiNem cell. Without an electrical field, two stable bulk textures, U (dark) and T (bright), exist.

devices. However, the technologies are rapidly maturing. Growth and market-size predictions consistently send green lights to move forward. Big players such as Sony and Amazon have entered the game. It may be the right time for content providers, e-paper terminal manufacturers, as well as others to grab opportunities and invent creative economic models to leverage value from this remarkable innovation.

This article will provide a roadmap for how one e-paper technology, BiNem displays, went from concept to prototype to product (Fig. 1). BiNem, which stands for “Bistable Nematics,” is a liquid-crystal-based e-paper display technology invented by researchers from the French National Center for Scientific Research (CNRS). The start-up company Nemoptic was founded in 1999 to develop and prepare the commercial exploitation of BiNem displays. BiNem technology has been designed to be compatible with existing LCD production lines, ecosystems, and supply chains to achieve competitive cost compared to other e-paper display technologies. BiNem displays have made substantial progress in improving the economies of scale in this area.

Structure of BiNem Displays

BiNem displays have a simple structure that is quite similar to that of twisted-nematic (TN) or supertwisted-nematic (STN) LCDs. They

are sandwich-type cells filled with a nematic liquid-crystal mixture; the main differences are the thinner cell gap ($\sim 1.5 \mu\text{m}$) and the use of a BiNem alignment layer and a BiNem liquid-crystal mixture with specific anchoring properties. Two polarizers are attached to the cell: the top polarizer is transmissive while the bottom polarizer is reflective. Two stable crystal textures exist in BiNem displays, which appear black and white, respectively, in the standard reflective configuration.

The top and bottom substrates are coated with different alignment layers and are rubbed in the same direction. One substrate is coated with the BiNem alignment layer, the other with a conventional polyimide. The BiNem layer gives a nearly planar anchoring with moderately strong zenithal energy, while the polyimide layer gives a tilted anchoring with strong zenithal energy. Both azimuthal anchoring energies are kept strong enough to maintain the azimuthal orientation of the liquid crystal on the alignment layer.

Operation Principles

Passive-matrix BiNem displays can achieve very high resolution (more than 1200 lines for an A4 active area) because Alt and Pleshko’s iron law of multiplexing² does not hold for them. Alt and Pleshko’s law sets a limit to the resolution of any multiplexed display that respond to the root mean square

(RMS) of the applied voltage; for example, it limits STN-LCDs to a maximum practical resolution – video graphics array (VGA). BiNem displays escape the limits defined by the Alt and Pleshko law of multiplexing because this law is only valid for RMS-responding display technologies. A simple example illustrates the non-RMS response of BiNem displays: A rectangular driving pulse immediately preceded by a gradual on-ramp switches pixels in the white state (with appropriate voltage and timing conditions), while the same pulse followed by a similar off-ramp switches pixels in the black state. The two driving waveforms have exactly the same RMS voltage, but drive the display in opposite optical states.

Two stable quasi-planar liquid-crystal textures exist in BiNem displays: the zero-twisted texture U (for uniform) and the half-turn (180°) twisted texture T. The U texture appears black and the T texture white in the standard reflective configuration (Fig. 2). The T texture acts as a medium having a small optical rotatory power: it induces a rotation of only a few degrees of the plan of polarization of the light, while the U texture acts as a simple half-wave plate. The liquid-crystal mixture is doped with a chiral guest to equalize the U and T energies by making the LC spontaneous pitch 4x the cell gap. This compensated cell achieves infinite bistability because it is impossible to transform U to T by continuous bulk deformation in the absence of external fields and defects. The U and T textures are “topologically distinct” – they cannot change each other into the opposite texture by continuous reorientation of the liquid-crystal director inside the cell (with paper and scissors, you would need to “cut” the texture and reconnect it differently to transform it in its opposite); the displayed information will remain stable for an infinite time because the textures cannot transform spontaneously.

The switching between the two textures is obtained by breaking the anchoring of the liquid crystal on the BiNem alignment layer. If the pixel driving voltage is a two-step waveform, the dark state U is induced. If the pixel driving voltage is a single pulse, the cell relaxes rapidly to the bright T texture, after a transient bent state. The texture selection mechanism relies on the magnitude of the liquid-crystal backflow, which is voltage dependant. The texture switching mechanism is illustrated in Fig. 3.

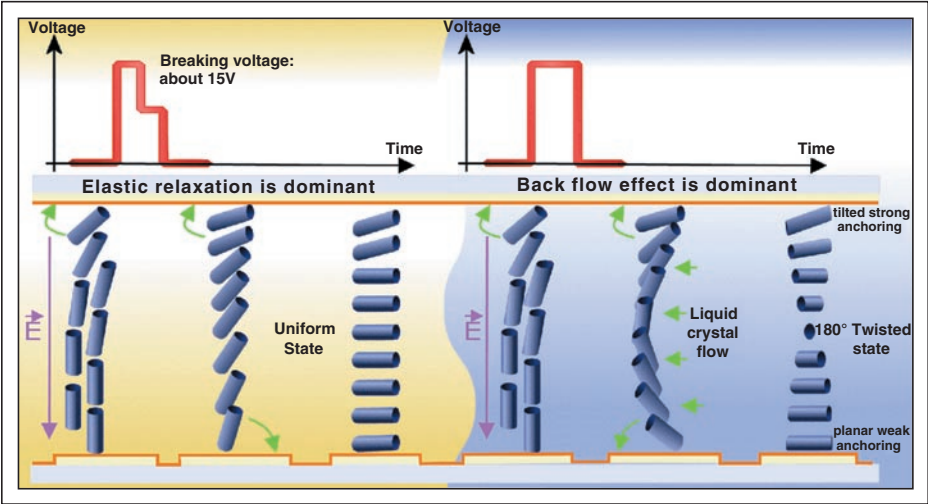


Fig. 3: Texture switching in BiNem displays. (Left) A small or moderate voltage drop drives the pixel in the black U-texture. (Right) A large and fast voltage drop drives the pixel in the white T-texture.

Performance

The typical reflectance of BiNem displays is about 33% at normal incidence in the white-balanced mode and up to 40% in the recently developed high-efficiency mode. The contrast ratio is typically greater than 10 at normal incidence and greater than 4 in a zone extending out to polar angles of 50° with a white paper-like appearance with no discernable color shift over these angles. Typical performance data for BiNem displays are listed in Table 1. A nearly achromatic white state is achieved by BiNem displays, as shown in Fig. 4.

Gray Scale and Color in BiNem Displays

BiNem displays have gray-scale capability. Nemoptic has developed a method to display bistable gray scales called the “curtain effect.” This method provides up to 32 different stable grays at the pixel level. The gray levels appear to be spatially uniform to the eye when viewed normally, but magnification shows they are composed of microscopic white and black domains. This method is similar to the spatial gray scales widely used in ink-jet or offset printing technology to obtain gray levels on physical paper. It involves the control of the liquid-crystal flow inside the pixels. When the driving voltage is switched off, a liquid-crystal flow is created. The part of the flow that has a speed higher than a threshold

value produces the bright T texture, the other one produces the dark U texture. With suitable driving voltages, it is possible to continuously adjust the spatial extension of the two domains that fill the pixel; one in the T texture, the other in the U texture. A constant texture filling ratio is directly perceived by the eye as a spatially uniform gray level. Color BiNem displays are built with color-filter substrates. Color BiNem displays driven with the “curtain effect” gray levels can display large numbers of different colors (up to

Table 1 : Typical performance of BiNem displays	
Characteristic	Typical value (25°C)
Reflectance	Up to 40 %
Contrast ratio	Typically 10:1
Viewing angle	100° (CR > 4)
Pixel density	Up to 200 dpi demonstrated
Addressing time	< 1 msec/line (25°C)
Number of gray levels	32 gray levels demonstrated
Number of colors	32,768 colors demonstrated
Display resolution	1650 × 2340 pixels demonstrated
Display size	A4 demonstrated (14.3 in.)
Temperature range	5°C to 40°C (operating)

32,768 different colors have been demonstrated). The RGBW configuration (each pixel is composed of red, green, blue, and white dots) has been recently introduced in a number of conventional and e-paper display technologies to improve color display performance.³ The quad subpixel structure has been implemented in a BiNem display module

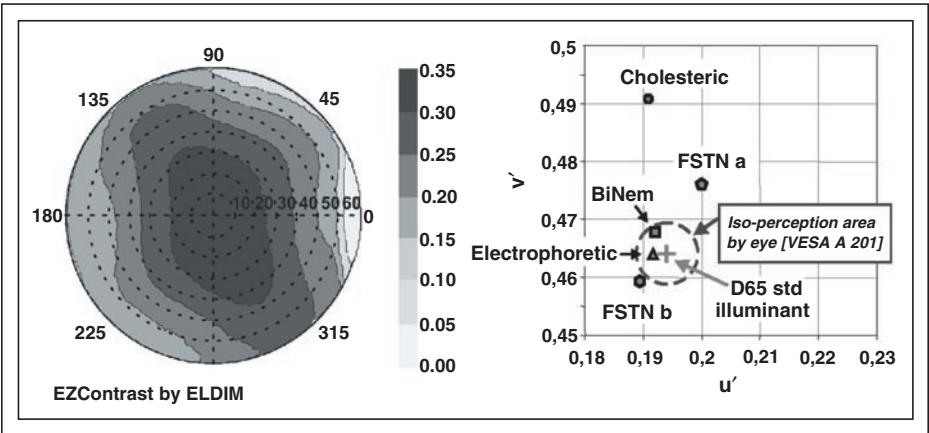


Fig. 4: (Left) Measured iso-reflectance contour of a BiNem display in diffuse light. Reflectance in diffuse light at normal incidence is ~ 35%. (Right) Experimental determination of the hue of the bright-state BiNem display in the CIE 1976 Chromaticity diagram. It lies inside the iso-perception circle centered at the ideal white point.

to improve the brightness while keeping a good level of contrast and reasonable color purity in reflective mode. A 5.1-in.-diagonal 400×300 -pixel color BiNem display with 100-ppi resolution has been recently developed (Fig. 5). It achieves ~20% reflectance (white state) with a maximum contrast ratio exceeding 10:1 under diffuse illumination. Optimization of the brightness/color-saturation trade off is in progress.

Compatibility with Flexible Substrates

Flexible e-paper displays answer the need for thinner devices with higher information content and larger display size. Flexible displays bend but do not break under moderate mechanical stress, an important feature for nomadic applications. Flexible BiNem display samples based on polyethersulfone (PES) substrates with barrier layers have already been demonstrated with satisfactory results in the lab.⁴ Because of their simple passive-matrix structure, flexible BiNem displays do not do suffer from the technical or economical drawbacks caused by the implementation of organic or silicon-based TFTs on flexible substrates in other e-paper technologies.

Applications for BiNem Displays

Electronic shelf labels (ESLs), point of purchase, and promotional displays are major applications for BiNem displays. Graphical ESLs are a large market segment enjoying rapid growth because dot-matrix designs are needed to implement larger amounts of product-related information, such as product names, origin, and barcode. Such barcodes can be read by optical barcode readers as well as by mobile phones with camera capability. BiNem ESLs display barcodes in the labels in order to increase automation in price- and product-logistics management at the super-market or store level. The contrast of a BiNem display remains large regardless of the resolution, and the brightness is relatively constant, depending on the viewing angle.

Display sizes range from less than 3–10 in. on the diagonal or more, with HVGA or higher resolution for large-sized displays. These displays are used in an environment where cost is challenged on an everyday basis, and the price premium for additional functionalities has to remain modest. BiNem electronic-paper technology provides these features by being able to use existing LCD ecosystem and manufacturing plants.

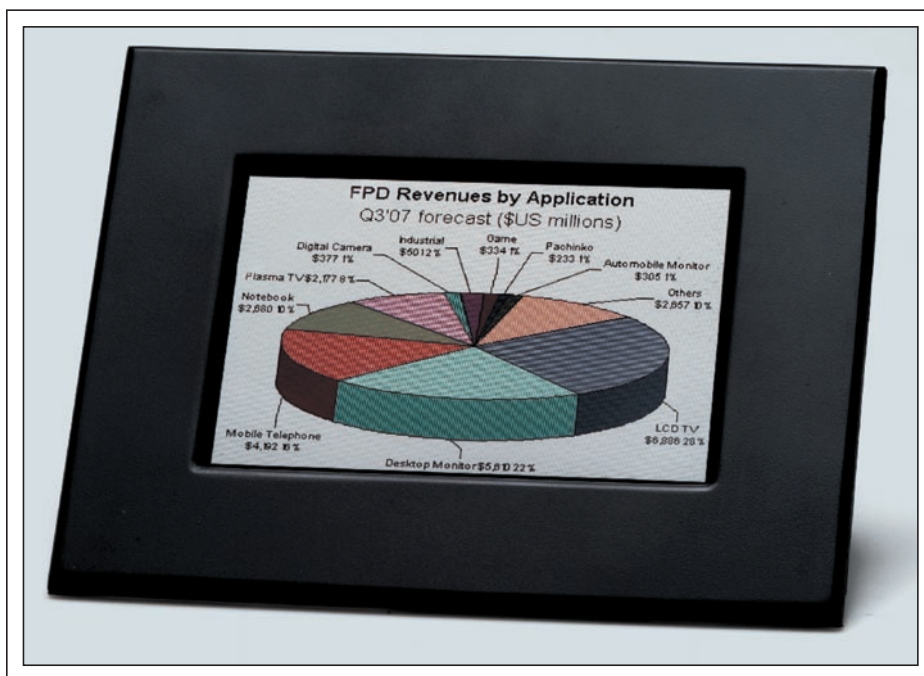


Fig. 5: 5.1-in. color BiNem display with 400×300 pixels and 100-ppi resolution. Contrast ratio is larger than 10:1 and reflectance is about 20%.

Electronic-newspapers and e-books are high-growth high-potential markets. Large-sized high-resolution BiNem displays can provide the required high information content with excellent legibility. In addition, the simple passive-matrix structure significantly reduces the cost of customization of the BiNem module to the specific sizes and resolutions required by the application.

The potential applications of A4-sized 200-dpi electronic-paper displays are huge, especially if the display has some degree of flexibility. A4-sized BiNem displays can offer multimillion-pixel resolution without active-matrix backplanes, bringing significant economic and technical advantages compared to technologies requiring organic or silicon-based TFTs on plastic substrates. These features make BiNem flexible displays an attractive solution for large-sized high-resolution cost-effective e-document applications.

From Lab to Fab

The original BiNem displays invented by Durand, Martinot-Lagarde, and Dozov⁵ included a special alignment layer made by vacuum evaporation of inorganic material under oblique orientation. This method required the use of specific R&D manufactur-

ing tools and was only applicable to small-sized substrates because a uniform and precisely controlled grazing evaporation direction ($15 \pm 0.5^\circ$) was required over the substrate area; this condition is incompatible with the angle deviation induced by a substrate size exceeding a few inches for a reasonable distance between the source and the substrates.

Nemoptic decided to develop a new BiNem manufacturing process that was completely compatible with that of STN-LCDs (Fig. 6). This approach reduces significantly the level of investment required to address volume markets because there is no need to finance dedicated production infrastructure from zero. Volume production is performed by LCD-manufacturer partners after adjusting their manufacturing processes to meet the BiNem process requirements. These adjustments are light and reversible, and the line configuration is unchanged – runs of BiNem and STN displays can be launched the same day. Competitive costs result from the use of vested and mature infrastructures.

The cost structure for BiNem displays is similar to that of STN-LCDs, and the LCD supply chain is directly applicable. BiNem displays benefit from the low-price/high-volume availability of LCD base materials

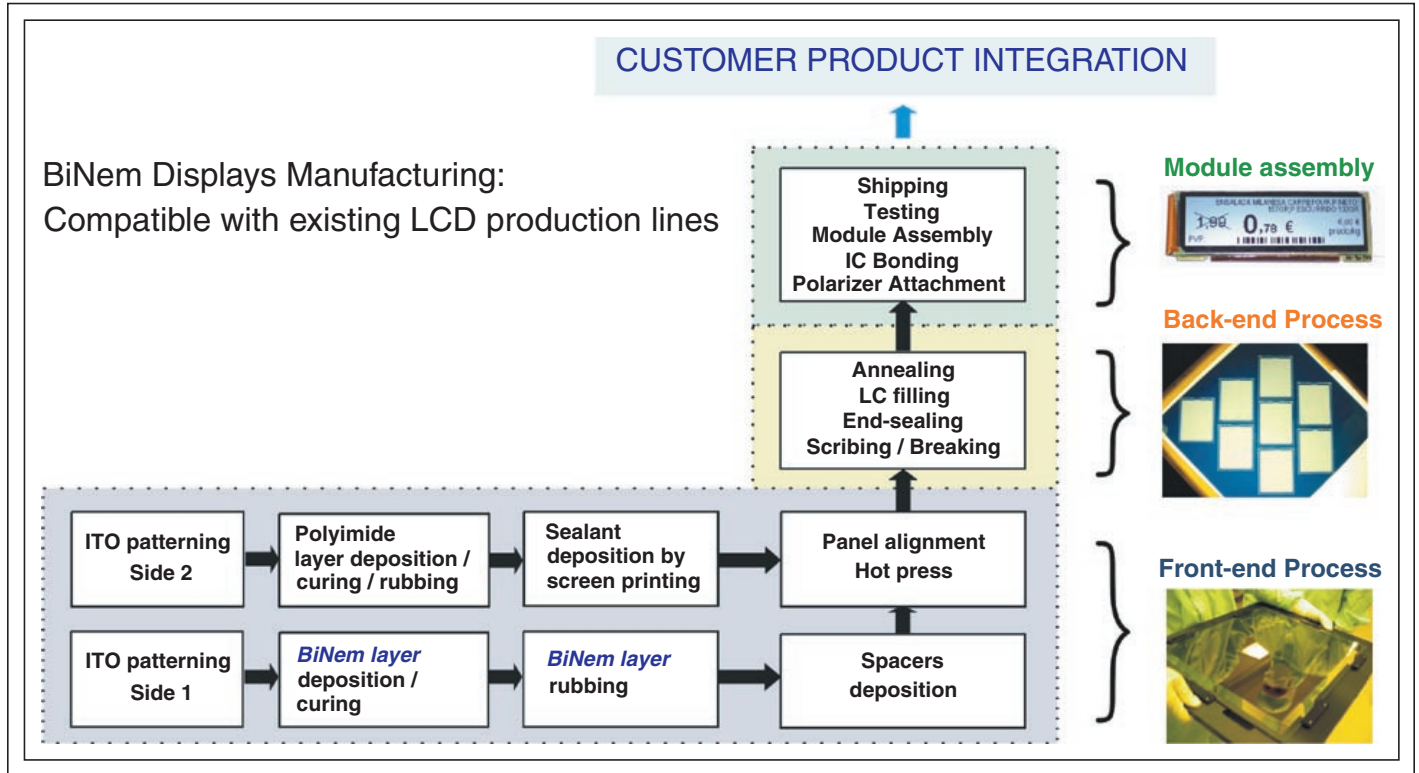


Fig. 6: BiNem display modules manufacturing process flow (front-end, back-end, and module assembly).

(substrates, liquid-crystal mixtures, orientation layers, optical films, and spacers) and electronic components (drivers, controllers, and power supply). They are compatible with any standard driver packaging (TAB, TCP, and COF). Moreover, BiNem displays do not require an active-matrix backplane.

Manufacturing Process

From a manufacturing point of view, two main differences exist between BiNem and conventional LCDs: (1) the alignment layer and liquid-crystal mixture have special anchoring-energy properties and (2) the cell gap of BiNem displays (1.5 μm) is lower than that of LCDs (about 5 μm).

LCD production lines usually use flex-printing to transfer thin layers of polyimide alignment material on the substrates. Nemoptic has focused its efforts to develop weak-anchoring-energy alignment materials that are as simple to process as conventional polyimide alignment materials.^{6,7} These efforts have led to the development of a polymeric BiNem alignment material optimized for flex-printer deposition and achieving the desired

azimuthal/zenithal anchoring energies. This result was a major achievement that opened the way for volume production.

Anchoring properties depend on both the alignment material and the liquid-crystal mixture. Recent research at Nemoptic has focused on improving the LC mixtures to achieve better properties for this application, including addressing rate, response time, operating temperature range, driving voltage, optical constants, and reliability. Because of this, our new BiNem liquid-crystal mixtures usually contain more than 10 pure nematic compounds. The specific details of these compounds are beyond the scope of this article.

The cell gap of a BiNem display is fixed by the diameter of the spacers dispensed on the substrates. The manufacturing process uses the same standard spray-dispensing machines and assembly equipment as LCD manufacturing. The only difference is the use of spacers with lower diameter (about 1.6 μm). To prevent particle contamination during panel production, front-end process steps are carried out in the local environment, and cleaning steps such as wet cleaning and dry ultrasonic

decontamination are used. Fine cell-gap adjustment and low panel-to-panel dispersion is achieved by adequate calibration of spacer density, pressure, and time parameters during end-seal.

The ready-for-use BiNem alignment solutions are printed on patterned ITO glass plates. The rubbing step is performed by using industrial rubbing machines that utilize a commercial velvet rubbing cloth. The assembly process is identical to the standard LCD process and uses thermal-curing sealant deposited using screen printers.

For front-end industrial processes, the key equipments are high-throughput printing machines, rubbing machines, assembly machines, and cleaning machines. The major processing factors are excellent surface cleanliness, low particle contamination, and excellent cell-gap and thickness-layer control. The back-end production process is unchanged compared to that used for conventional LCDs.

Conclusion

The e-paper market is developing fast. To play a central and active role in this market,

Nemoptic has established a high-volume source of BiNem display modules with its manufacturing partner Seiko Instruments, Inc.

Nemoptic has targeted the electronic-shelf-label (ESL) market as one of its priorities because it combines simple b/w design and high-volume needs. Several display modules for small- and medium-sized ESLs are already in production ramp-up. Building up manufacturing experience and stimulating market demand is important in preparing new high-potential e-paper applications that require color, flexibility, higher resolution, and faster response time. Nemoptic is confident that its BiNem display technology will sustain the strong growth and enjoy the multiple business opportunities that are going to open up in e-paper applications.

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The Past, Present, and Future of Electronic Paper

Electronic-paper display technology is finding its way into more products and applications. This article looks at the current state of the technology, what obstacles could prevent further adoption, and what the future holds.

by Minoru Koshimizu

BEFORE CHARACTERS were used as a tool of communications, information was transmitted through speech and stored in human memory. The invention of characters and materials used for writing those characters freed humans from the necessity of storing information in memory, leading to more creative and intellectual life.¹ After a long history of inventing various materials for writing characters and images, paper was developed, initially by the Chinese in the 2nd Century A.D. Because of its ease of use and the later invention of letterpress printing, paper has held an unrivalled position for centuries as the superior medium for the conveyance of information.

The rapid development of platforms that support digital media in the past 20 years, such as PCs and the Internet, made a wealth of information accessible and interactive via computer screens and keyboards. This led to the discussion of the advent of a “paperless age.” But, ironically, these digital media actually caused paper consumption to increase. The huge volumes of digital infor-

mation generated through such digital media ultimately stimulates demand for printing, causing end users to desire usable and low-cost media for reading the information. One possible solution to this situation is the development and implementation of the display technology known as electronic paper.

History of Electronic-Paper Technology

The term “electronic paper” does not refer to a single established technology, but rather represents a technology consisting of certain

display techniques. Currently, no standards and specifications have been established for the technology. However, in general, it is possible to define its technological application area that is characterized by the features of both electronic and paper media. The functional characteristics of electronic paper include the capability to electronically rewrite the displayed information, the memorization of images (with little or no power to maintain images), a reflective type of display, and high flexibility.

Minoru Koshimizu is with the Corporate Technology Planning, R&D Management Group, of Fuji Xerox Co., Ltd., in Japan; e-mail: minoru.koshimizu@fujixerox.co.jp. He is also a member of the Electronic Paper Consortium, sponsored by the Japan Business Machine and Information System Industries Association (JBMA).

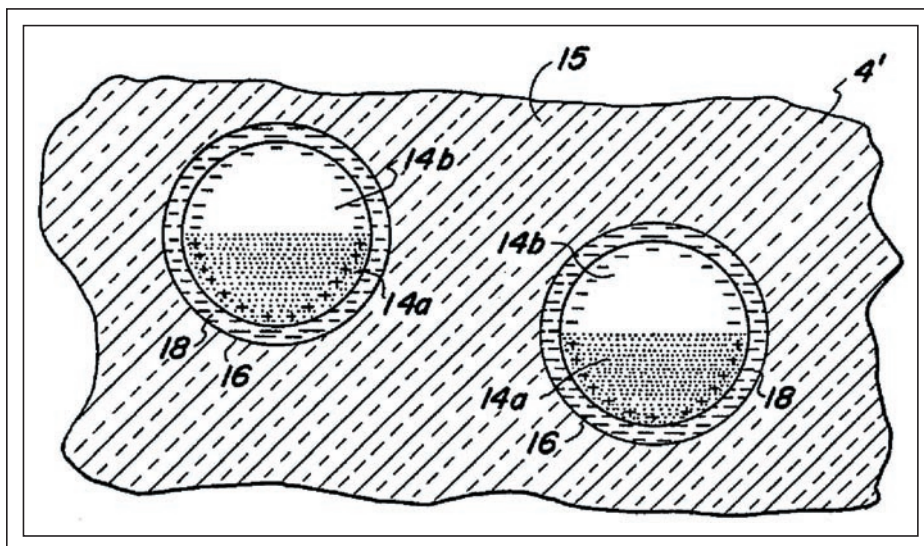


Fig. 1: The cross-sectional view of the Twisting Ball Display.

Xerox PARC

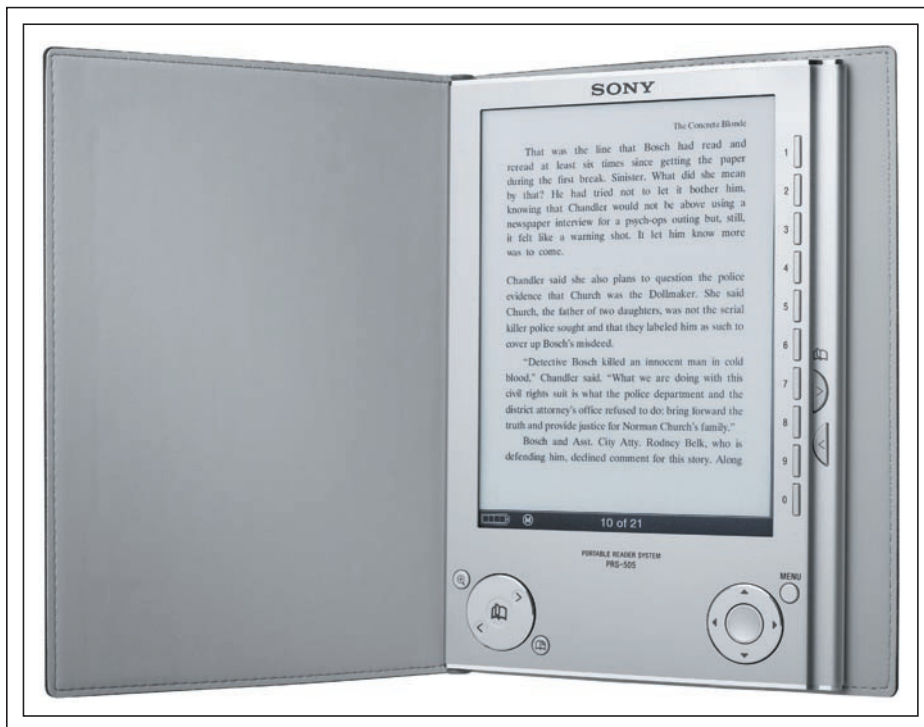
The first electronic-paper model was the Twisting Ball Display (commonly referred to as the Gyricon) invented by N. Sheridan of the Xerox Palo Alto Research Center (Xerox PARC) in the 1970s.² This model's medium was an elastomer sheet containing particulates, composed of two different halves, each of which had a different color and electrification polarity (positive or negative), as shown in Fig. 1. Particulates in the sheet are oriented so that one of the halves faces the display surface through an electric field applied from the outside, resulting in an image displayed on the screen. As a result, Sheridan announced "Electronic Paper" as a new media concept, replacing conventional paper media and printing devices.

Since the announcement of the Twisting Ball Display, many technologies relating to electronic paper have been proposed, too numerous to detail here. However, these technologies can be roughly categorized into three types: those using liquid-crystal material that have information-retention capabilities, those that can physically arrange colored and charged particles, and those employing reversible coloring/discoloring reactions.

Electronic-Paper Products

At the moment, there are two primary types of electronic-paper products in the marketplace: mobile devices intended for use by individuals and "ubiquitous information systems" developed from a totally different viewpoint and designed to be used at a specific place.

The "E-Book" is the first product category to make use of electronic-paper technology and is emblematic of the mobile-device approach to electronic-paper display devices. In April 2004, Sony started selling an e-book reader called LIBRIé, which attracted attention as the first consumer electronic-paper product. Its display module was developed using E Ink Corp.'s Microcapsule-type electrophoresis electronic-paper display technology. This display forms images using electronic ink, which consists of tiny capsules filled with clear insulating fluid in which charged white particles and charged black particles float. Unlike conventional displays, such as liquid-crystal displays (LCDs), this display can provide images that very closely resemble those printed on paper by real ink, which is critical for a product designed to be a dedicated book-reading device.



Sony Corp.

Fig. 2: The latest model of the Sony Reader.

The LIBRIé was the first implementation of the concept, The Last Book,³ invoked in 1997 by J. Jacobson of MIT Media Lab, one of the founders of E Ink. This concept exemplified a dream that readers could read any book in the world with a single device that can rewrite images using electronic ink. Currently, a successor product to LIBRIé, called the Sony Reader, is sold in the U.S. market. This product primarily targets frequent fliers and city commuters as end users (Fig. 2).

In August 2006, Holland's iRex Technologies released a dedicated reading device called iLiad, which also employed the E Ink Corp.'s display technology for its display module. iLiad features an 8.1-in. display screen – slightly larger than that of the LIBRIé – and a built-in LAN interface. One of the primary intended uses is to allow users to download the electronically delivered, latest newspaper information on demand via the Internet for viewing on the device. The French newspaper company Les Echos started selling its electronic newspaper using iLiad in September 2007. A similar service has been introduced in China and is being planned for in Japan. This reading device, which is equipped with a pen-input mechanism, is

expected to allow users in business situations to view electronic manuals.

The latest entry in the e-book category comes from Amazon, which released a new wireless reading device called Kindle in November 2007. This device also utilized E Ink Corp.'s technology. (For more on the Kindle, see the Industry News section in this issue.)

Kent Displays is one of the pioneering players in the "ubiquitous information systems" sector. Kent's cholesteric digital signage holds great promise because of its vivid color capability and bendable form. Early technology from an E Ink product and the short-lived Gyricon product were also aiming to enter this field.

Today, more sophisticated systems have been released by other companies. Hitachi's Albirey combines a content-delivery server and a display device. Released in 2006, it measures 3.7 mm in thickness and 600 g in weight in A4 (210 × 297 mm) paper size. Albirey has a built-in wireless LAN interface, and its display module is based on the technology developed by Bridgestone. The technology is known as QR-LPD (quick-response liquid-powder display) that can control the

overview

positions of two types of colored particles by means of electric fields. Another system called FLEPia was released by Fujitsu Frontech Limited in April 2007. FLEPia adopts an original lightweight cholesteric liquid-crystal panel covered by a touch panel. This product also has a built-in wireless LAN and stereophonic speaker system. All of these products consume less power and can be implemented as a thinner, lighter-weight device than conventional displays, offering the advantage of easy installation any place.

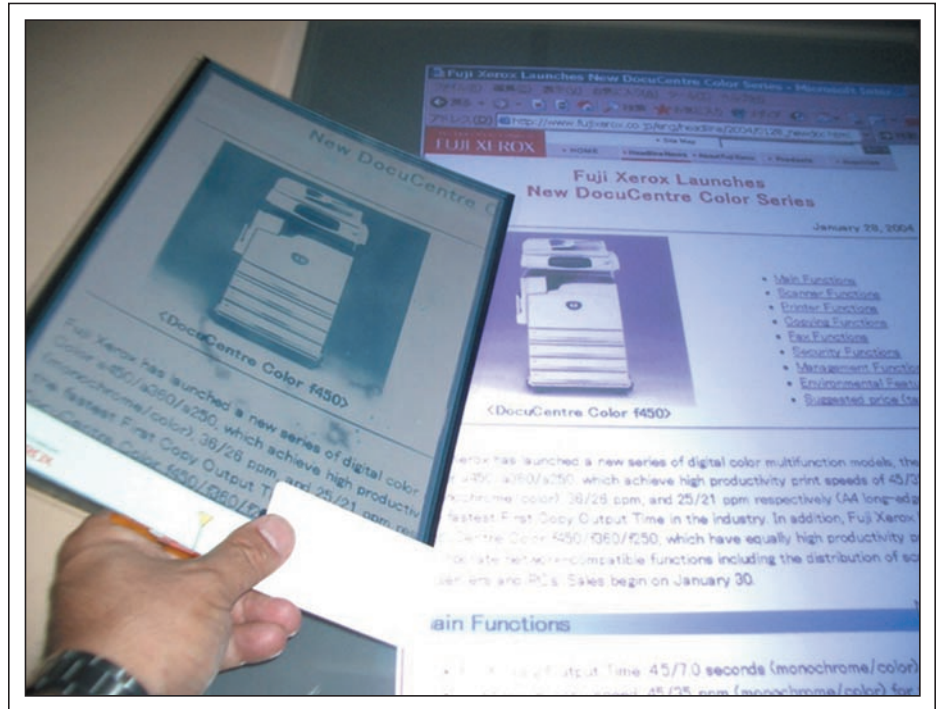
Obstacles for Electronic Paper

Most of the currently marketed electronic-paper devices use a rigid substrate panel for their display screens. Therefore, it can be difficult to clearly differentiate them from existing display devices such as LCDs. Current challenges facing electronic paper include not only a paper-like look, but also a form having the thinness, lightweight, and flexibility that are characteristic of paper.

Why does electronic paper need to have the characteristics of real paper? The answer includes its functional advantages – *i.e.*, it cannot be broken even if dropped – and the ease of transport due its light weight. In addition, another answer can be provided as a hypothesis that the user's physical operations – such as looking at information, touching and holding the paper, and dealing with multiple sheets of paper at the same time – may have a positive effect on the human understanding of information and the thinking process. It is not easy to directly validate this hypothesis by exploring the mechanism of human thinking. However, a study, based on usability evaluations, stressed the importance of the electronic paper's appearance and characteristics as mentioned above.⁴

One example of electronic paper having the appearance and characteristics of real paper is Photo-Addressable Electronic Paper that is now under development by Fuji Xerox. This electronic paper consists of a flexible medium created using thin, lightweight film substrates. The display medium has no other components such as power supplies and drive circuits and provides the ability to instantly write an image through the irradiation of an external optical pattern and the uniform application of a voltage pulse to the entire medium.

The medium consists of a pair of plastic substrates, with a transparent electrode layer formed on the inner surface of each of sub-



Fuji Xerox Co., Ltd.

Fig. 3: Photo-Addressable Electronic Paper with the optical image copied on the screen.

strate, between which are a display layer consisting of cholesteric liquid crystal that has a good image-retention capability, a light-absorption layer, and an organic photo-conduction layer.

Figure 3 shows the Photo-Addressable Electronic Paper, onto which the light-emitting optical image on the display screen has been copied. This type of electronic paper allows the user to copy digital information displayed on a screen directly onto its medium, instead of just looking at the information on the screen, as well as allowing the user to see the information with the paper in hand, hand the paper itself over to another user, or share the paper with other people. Thus, electronic paper helps users to handle information in a more natural, human manner.

The composition of the cholesteric liquid crystal can be controlled so that only the light of specific wavelengths in the incident light will be reflected. Color displays with a wide color gamut can be achieved by stacking three layers that reflect three primary-color lights (RGB). Figure 4 shows the latest prototype for the full-color version of this technology.⁵

On the other hand, flexible electronic-paper devices with all of the drive components con-

tained inside the device, such as that of conventional displays, have been under development. Bridgestone, Fujitsu, Epson, Plastic Logic, and Polymer Vision are major manufacturers that have been engaged in the development of this type of device. Bridgestone and Fujitsu have announced a prototype based on a passive-matrix drive method. Figure 5 shows a prototype of the flexible full-color version of Bridgestone's electronic paper.

Other companies have announced prototypes using a combination of the proprietary thin-film-transistor (TFT) active drive element technology and the display layer technology developed by E Ink.

These technologies are expected to encourage the development of a personal-information terminal with excellent mobility and a larger display area, and a digital advertising medium that can be easily installed on a wall or ceiling.

Conclusions and Expectations of Electronic Paper

Various types of electronic-paper technologies have been studied, with some of them already introduced into practice. Since 2003, the Electronic Paper Consortium, sponsored by

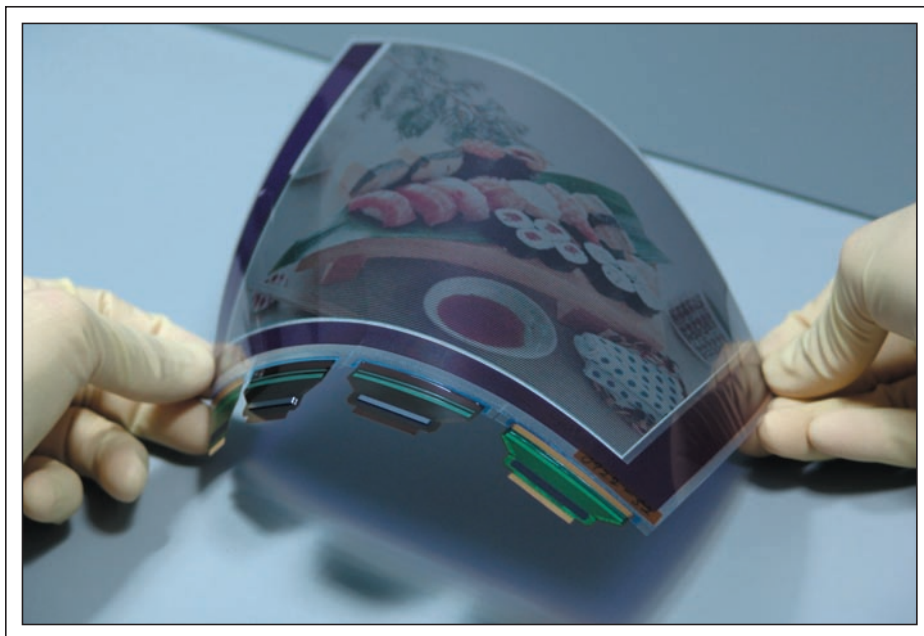


Fuji Xerox Co., Ltd.

Fig. 4: Prototype of the full-color version of Photo-Addressable Electronic Paper.

the Japan Business Machine and Information System Industries Association (JBIMIA), has

continuously researched electronic-paper technology, including its marketability,



Bridgestone Corp.

Fig. 5: Bridgestone's electronic paper (prototype of the flexible full-color version).

technical trends, and future direction as new media. Our suggestion made at the 3rd Electronic Paper Symposium was that, though this may sound a bit abstract, electronic paper is a digital medium that supports "reflective cognition." The term "reflective cognition" here refers to the workings of the mind that are essential for the intellectual activities of humans, through which various items of information are compared before appropriate decision-making can take place.

Historically, pen and paper have been the most effective tools to support such human cognition. Electronic paper shows the potential to be able to not only replicate this traditional paradigm, but now provide the additional interface that allows electronic pen input to be shared by an endless number of people without regard to physical boundaries.

With its potential for ease of use and intuitiveness, electronic paper stands on the precipice of becoming a technology that alters the way we work, think, and interact with each other in a way that other display technologies have not yet enabled.

When fully developed, electronic paper will distinguish itself from other display technologies because it can serve as a medium for communications and interaction in addition to being solely a visualization mechanism. It is this great promise that makes electronic-paper developments in the not-too-distant future very much worth watching.

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History Crystallized: A First-Person Account of the Development of Matrix-Addressed LCDs for television at RCA in the 1960s

The path to ubiquity for LCD TVs began 45 years ago at the RCA Laboratories in Princeton, New Jersey. RCA veteran Bernard J. Lechner was there, and he takes a look back at the earliest days of LCD research and development.

by Bernard J. Lechner

ON May 28, 1968, RCA held a press conference in New York City to present the results of a major project to make liquid-crystal displays (LCDs), including television displays. The work had been conducted in secret for more than 3 years at the RCA Laboratories, David Sarnoff Research Center in Princeton, New Jersey. At that press conference, I gave the first public demonstration of an LCD, albeit only 36 pixels,

Bernard J. Lechner spent 30 years at RCA Laboratories in Princeton, New Jersey, in positions of increasing responsibility from Member of the Technical Staff to Staff Vice President for Advanced Video Systems Research. When GE acquired RCA, he took early retirement in 1987 and became an independent consultant. He has received many awards for his work in displays and television, is a Life Fellow of SID, IEEE, and SMPTE, and holds 10 U.S. patents relating to matrix displays and television systems. He was President of SID from 1978 to 1980. He can be contacted at tvbernie@ieee.org.

Editor's Note: This is the first in a series of articles that will run throughout 2008 that will examine critical moments and developments that shaped today's display industry.

reproducing a moving gray-scale image at full NTSC television rates. (More about the press conference later.)

The Beginning

The liquid-crystal story at RCA Laboratories began for me in the spring of 1962. My recollection of first seeing an electro-optic effect in a liquid crystal is very clear. My boss, Jan Rajchman, walked into my lab and said, "Si (Simon) Larach has something to show us." We went upstairs to Larach's lab where he had two pieces of glass with a transparent conductive coating, some yellowish powder, a hot plate, a microscope lamp, a couple of clip leads, and a 22.5-V "C" battery. He placed the powder (para-azoxyanisole) between the two pieces of glass, put the resulting sandwich on the hot plate, and shined the microscope lamp on it. Carefully adjusting the hot plate so the powder just melted (para-azoxyanisole is a liquid crystal over a very narrow temperature range at about 120°C), he then used the clip leads and the battery to demonstrate the electro-optic effect that later became known as dynamic scattering. When the electric field was applied, there was a dramatic change – the liquid turned from clear to milky white.

What he showed us was based on the work of Richard "Dick" Williams, who worked for

Larach at the time. Williams had discovered an electro-optic effect in para-azoxyanisole earlier that spring. At a field of about 1000 V/cm, he observed that visible domains, which became known as "Williams Domains," formed in the liquid-crystal layer. Williams described these results in a 1963 article,¹ where he also explained that at higher fields (e.g., 2000–3000 V/cm), a stronger effect was observed characterized by vigorous agitation and stirring of the liquid. Based on recent conversations with Williams, I am certain that it was the stronger effect, which occurs under high fields, that Larach demonstrated to Rajchman and me.

Larach did not promote the discovery further, and Williams stopped working on liquid crystals in mid-1962 when he took on a new assignment at RCA in Zurich. He did, however, file a patent application on November 9, 1962. The patent² did not issue until May 30, 1967, so its contents remained secret until then. It was RCA's first LCD patent and, although there were other disclosures and applications pending, it was RCA's only issued LCD patent at the time of the press conference the following May. Figures 1–3 of the Williams patent are reproduced in Fig. 1. Figure 3 of the patent shows the structure of a basic x-y addressed

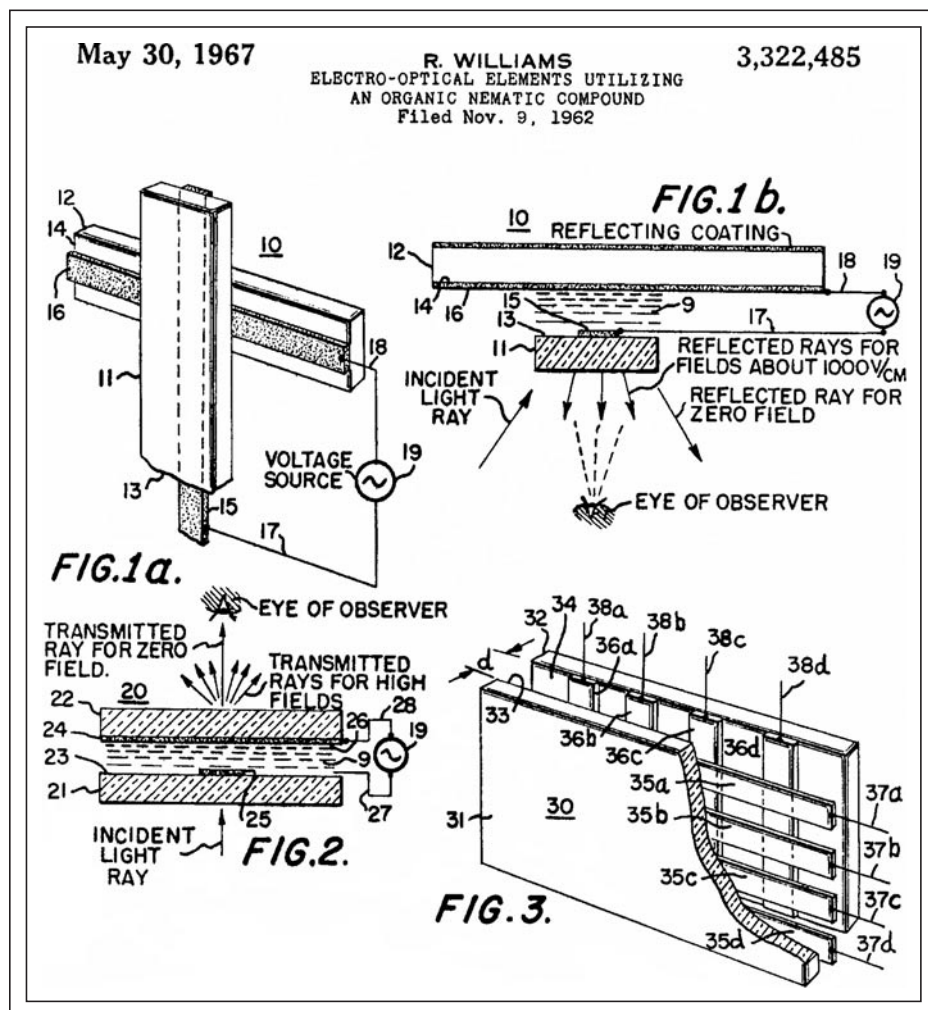


Fig. 1: U.S. Patent 3,322,485 to Richard Williams, filed Nov. 9, 1962.

liquid-crystal matrix display.^a Williams described both transmissive and reflective modes of operation in the patent, and they are illustrated in Figs. 2 and 1(b) of the patent, respectively.

A New Start

Jan Rajchman and I were excited by what we saw. The immediate problem, of course, was the high operating temperature required. Rajchman urged that the RCA Laboratories initiate a program to search for or synthesize

materials that would operate at room temperature and over a wide temperature range. No further work was done on liquid crystals, however, until the fall of 1964, when George Heilmeier revisited Williams's discovery and began to investigate the physical mechanism and optical properties of the electro-optic effect in far more detail. Heilmeier worked primarily at the higher fields and called the effect "Dynamic Scattering," consistent with the turbulent nature of the activity in the liquid at the higher fields.³

As a result of Heilmeier's work and his enthusiasm about the potential of LCDs, in early 1965 RCA Laboratories' management decided to initiate a formal liquid-crystal project to understand the electro-optic effects, find or create room-temperature materials, and

ultimately make a flat-panel TV display. Heilmeier and his colleagues, including Louis Zanon and Lucian Barton, continued to investigate the electro-optic properties of various liquid-crystal materials and cell configurations. They and others at RCA Laboratories also began to make a variety of displays, mostly based on seven-segment numeric indicators, to demonstrate the potential of LCDs for clocks, wristwatches, and similar applications. Electronic shutters and dimmable mirrors were also explored. RCA made it a secret research project, where the internal progress reports were numbered and limited in distribution.⁴

The Chemists Come Through

Two chemists, Joseph Castellano and Joel Goldmacher, joined the project in 1965 to seek or make new liquid-crystal materials that would work at room temperature. By 1966, Castellano and Goldmacher had synthesized liquid-crystal materials that would operate at room temperature and over a sufficiently wide temperature range to be useful in practical displays. The formula for success turned out to be to use mixtures of materials that were not, on their own, liquid crystals at room temperature. Figure 2 illustrates the first nematic liquid-crystal room-temperature mixture.⁵ Now, it was time to get serious about applying liquid crystals to practical displays, including television.

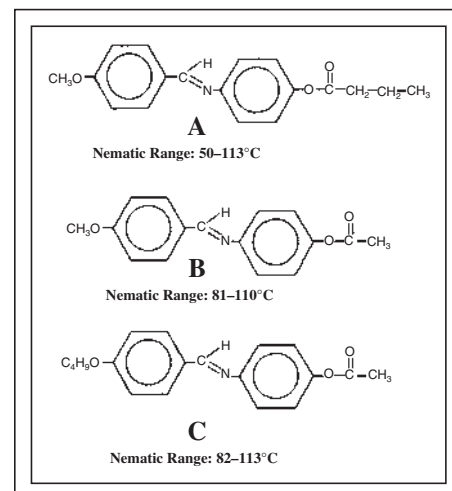


Fig. 2: Composition of first room-temperature nematic liquid-crystal mixture. (Source: Joseph Castellano.)

^aToday it would be called a "passive" matrix, but the terms "passive matrix" and "active matrix" had not yet entered the display lexicon in 1962.

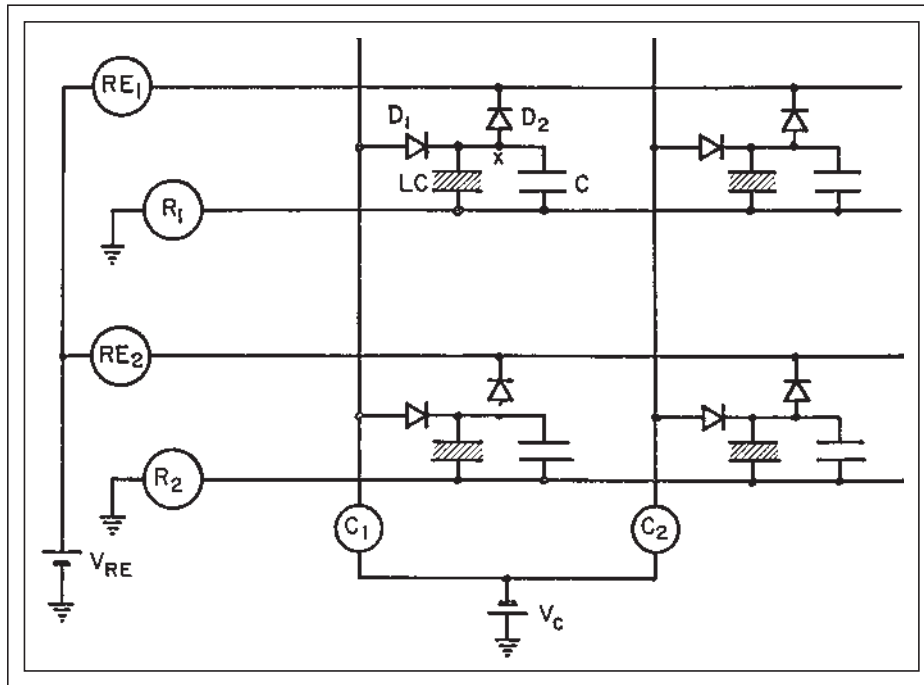


Fig. 3: D^2C addressing scheme. [Source: "Liquid Crystal Displays," by Bernard J. Lechner, University of Illinois, March 31, 1969, published in *Pertinent Concepts in Computer Graphics* (University of Illinois Press, 1969).]

Time For Television

In early 1966, I was asked formally to consult to the project concerning the matrix-addressing issues essential to making a television display. At the time, I was just completing a program to develop a 1200-element ferroelectric-controlled electroluminescent matrix-addressed flat-panel display that produced moving gray-scale television images in real time.⁶ Juri Tults and I delivered the working display to Wright-Patterson Air Force Base in Ohio in the Spring of 1966. By that Summer, a significant fraction of my group, including Frank Marlowe, Ed Nester, and Juri Tults, and I had begun a full-time effort to solve the matrix-addressing problem for LCDs and to build a liquid-crystal television display. We had determined that individual liquid-crystal cells could be addressed with 60- μ sec pulses, thus allowing line-at-a-time TV addressing. The cells did not, however, have the threshold required for matrix addressing and, other than the dielectric relaxation time of the liquid-crystal material, there was no storage. The simple approach, which bore some resemblance to the electroluminescent matrix display and which I called the "classical"

method, was to use a series diode to provide a threshold and possibly to add a parallel capacitor to provide storage.

Despite efforts during 1966 to fabricate integrated thin-film diodes on glass and sapphire substrates, it became clear that using just a diode, with or without a capacitor, would not work. To overcome the poor performance of the simple classical method, I decided to add a second diode and a reset generator as shown in Fig. 3, which is reproduced from my 1969 University of Illinois paper.⁷ This allowed a larger capacitor and lower-amplitude addressing pulses to be used and resulted in a significant improvement in performance. This scheme was called D^2C , and Philips used a variant of it in an LCD product during the 1990s.

I soon realized that a better approach would be to replace the diodes and the reset generator with a field-effect transistor. This arrangement, shown in Fig. 4, also reproduced from my 1969 University of Illinois paper,⁷ was called FETC. Since the field-effect transistor conducts current in both directions, the reset generator and extra bus bar are not needed. Also, reversing the polarity on alternate fields to provide AC drive is simpler. The FETC

scheme is basically the same circuit configuration used in all LCD TV and computer displays today. To test and demonstrate these schemes, as well as any others that might be proposed, Tults designed and built a set of electronics, which we called "the exerciser," to drive a 2×18 matrix at full NTSC television rates and produce moving gray-scale images. The 36 elements were electrically buried in a full NTSC-resolution panel and addressed using the line-at-a-time addressing technique that had been developed earlier for the ferroelectric-controlled electroluminescent matrix display.

By the end of the first half of 1967, both the FETC and D^2C schemes had been tested and demonstrated with external discrete components using the exerciser. Figure 5 is a photograph of a 2×18 display using the FETC scheme being driven by the exerciser.⁷ The pixels are 0.06 in. square. The exerciser's electronics provided 60- μ sec wide column pulses at a rate of 15.75 kHz. All 18 column drivers were activated simultaneously (line-at-a-time addressing). Each successive group of 525 column pulses contained 523 pulses of full amplitude (corresponding to a fully on pixel) followed by two pulses whose amplitude represented the brightness of a particular one of the 36 pixels in the display. The row drivers for the 2 rows each provided full-amplitude 60- μ sec pulses during the 524th and 525th column pulses, respectively. The row pulse rate was thus $1/525$ th of 15.75 kHz, which is the 30-Hz NTSC frame rate. The video or "camera" signal that was supplied to the column drivers for the 524th and 525th column pulses was obtained from a bank of 36 potentiometers that could be set to provide whatever pattern was desired, e.g., the checkerboard and gray-scale bar shown in Fig. 5. The potentiometers were connected to the column drivers through a set of shift registers that permitted the pattern to be moved from left to right at a continuously variable rate from 0 pixels/sec (i.e., a stationary image) to 10 pixels/sec. Thus, the 2×18 display was capable of showing moving images and was, in fact, electrically embedded in a full 525-line NTSC display. The liquid-crystal material used had a turn-on time of 3–4 msec and a turn-off time of about 50 msec at room temperature. Thus, there was noticeable smear at motion rates above about 6 or 7 pixels/sec. However, a fairly simple scheme for achieving fast turn off is

described in Refs. 7–9 and was actually tested with the 36-element display shown in Fig. 5.

Of course, I was aware of Paul Weimer's work at RCA Laboratories on evaporated thin-film field-effect transistors^b as well as the efforts on monolithic-silicon integrated circuits and silicon-on-sapphire technology, and I recognized that they all were candidates for the construction of fully integrated LCDs. Frank Marlowe worked with Weimer's group using their thin-film fabrication facility to apply the techniques of evaporated thin-film semiconductors, both diodes and field-effect transistors, to LCDs, and Ed Nester worked with the RCA Laboratories Integrated Circuit Center to do the same using a monolithic-silicon substrate as well as silicon-on-sapphire technology.

In mid-1967, we decided to design and build two 1200-element (30 × 40) integrated TV displays, one based on the D²C addressing scheme and one based on the FETC scheme. The liquid-crystal cells were to be 0.015 in. square, resulting in a 3/4-in.-diagonal display. Both displays were to be reflective, and the D²C display was to be made with evaporated thin-film diodes on a glass substrate. The FETC display was to be made using a single-crystal silicon wafer. Figure 6 shows a photograph of a test wafer for the 1200-element FETC display that was, unfortunately, not operative.

The Press Conference

On May 28, 1968, RCA's vice president for RCA Laboratories, James Hillier, presided over the famous LCD press conference during which I described and demonstrated the 2 × 18 matrix display.^c Hillier opened the conference with some words about the importance of displays in the "information handling" business. He hailed the low-power reflective LCDs to be described as a breakthrough in solving the man-machine interface problem. Heilmeier then used a series of slides to give a tutorial presentation defining liquid crystals and how they can be used to make displays. He described the dynamic-scattering effect in

^bThe abbreviation "TFT" was not yet in common use in 1967.

^cI kept copies of the outlines of the presentations made at the press conference by Heilmeier and me, but not the slides we used. I also kept copies of the scripts used by Jim Hillier and me for our presentations and have deposited all these documents at the David Sarnoff Library.

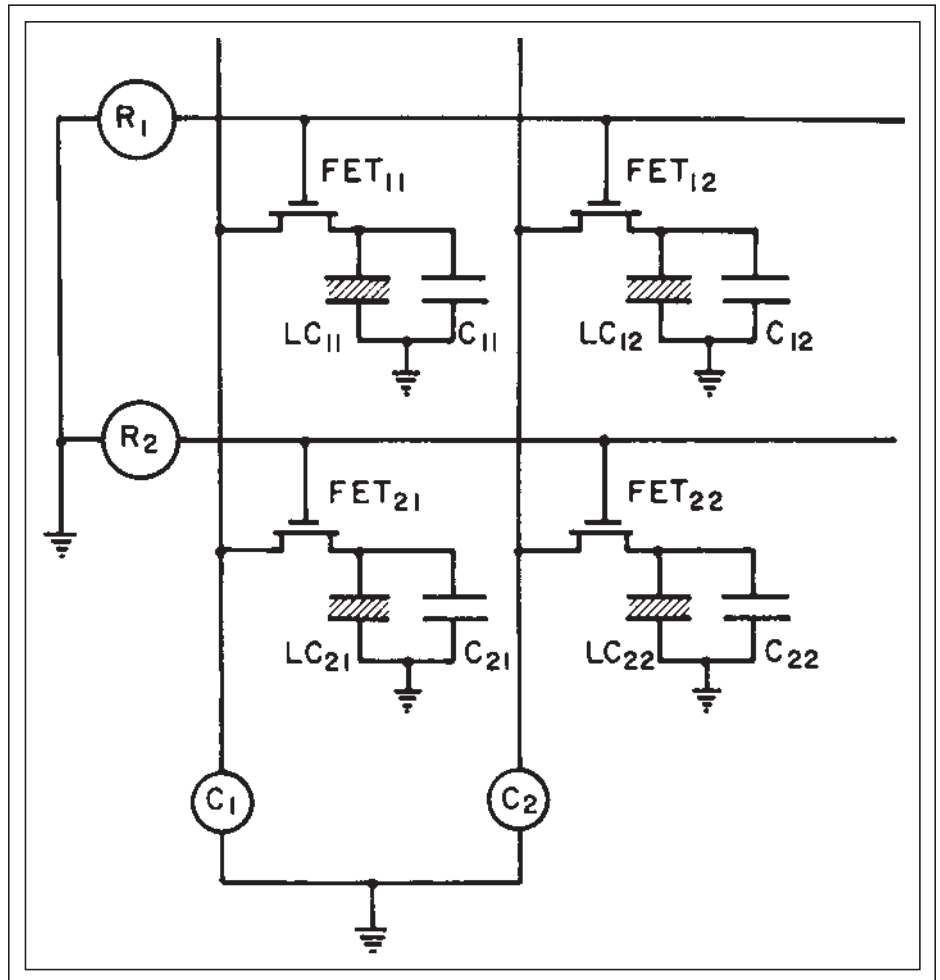


Fig. 4: FETC addressing scheme. [Source: "Liquid Crystal Displays," by Bernard J. Lechner, University of Illinois, March 31, 1969, published in *Pertinent Concepts in Computer Graphics* (University of Illinois Press, 1969).]

some detail and summarized the display-related parameters that RCA Laboratories' researchers had thus far achieved, including a contrast ratio of 15:1. Next, Hillier demonstrated several displays, including a simple electronic shutter, a static display (merely a fixed pattern etched onto the electrode), a seven-segment indicator, a side-lit display that did not rely entirely on ambient light, and "an all-electronic clock that has no moving parts whatsoever." He mentioned possible applications such as traffic signs, scoreboards, and automotive and aircraft instrumentation, and said that an all-electronic wristwatch might be possible in a few years.

Hillier then introduced me to describe our work to make a TV display using liquid crystals.

I used a series of slides to describe how a matrix-addressed LCD would be constructed, the need for circuitry associated with each display element in the matrix, and the need for a line-at-a-time addressing scheme. Using the exerciser electronics, Juri Tufts and I then demonstrated a 2 × 18 model such as the one shown in Fig. 5. I did not mention the 1200-element displays, and, in fact, Hillier and I both made it clear that a practical liquid-crystal TV display would be very difficult to achieve because of the need to integrate the required addressing circuitry.

The End

The schedule for the 1200-element integrated displays called for them to be operational by the end of the first quarter of 1968. This

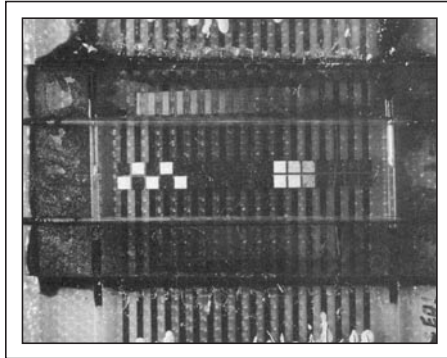


Fig. 5: A 36-element 2×18 LCD operated at full NTSC TV rates. [Source: "Liquid Crystal Displays," by Bernard J. Lechner, University of Illinois, March 31, 1969, published in *Pertinent Concepts in Computer Graphics* (University of Illinois Press, 1969).]

proved to be overly ambitious, not only for the technical difficulty, but also because of lack of support from the RCA Laboratories Integrated Circuit Center and the thin-film fabrication facility. Neither of these facilities was under the management control of the liquid-crystal project and each had ambitious objectives of its own that did not include LCDs. Delays and technical problems arose each quarter until finally, at the end of 1968, RCA Laboratories' management decided to stop the effort on the 1200-element displays.

During 1969, RCA abandoned entirely the objective of making a liquid-crystal TV display, although other applications, *e.g.*, watches, calculators, printers, automobile mirrors, *etc.*, were pursued until 1972. By 1969, RCA's color-TV-receiver business was mature and the smallest consumer product of significance was a 13-in. color set. Because we could not promise to compete with such a product in any foreseeable time frame, management had no interest in investing further. I tried to keep our effort alive by writing a proposal for a government contract to continue work on the 1200-element models. I still have the typewritten original copy, complete with the standard RCA Government Proposal proprietary notice at the bottom of each page, but I do not recall that I ever got management permission to shop it with various government agencies. We did publish a paper in the *Proceedings of the IEEE* that described the matrix-addressing work in some detail.⁹

Post Script

Although RCA gave up on liquid crystals for television in 1969 and for all other applications except its fledgling wristwatch business^d in 1972, the message presented at the 1968 press conference was heard around the world, especially in Japan. By the time RCA had stopped, major efforts were under way elsewhere and, as they say, the rest is history. It is interesting that the first important commercial application of liquid-crystal matrix displays was to laptop computers, fulfilling Jim Hillier's prophecy from the 1968 press conference that the technology would solve the man-machine interface problem.

Acknowledgments

I want to thank Joseph Castellano, John van Raalte, and Richard Williams for reviewing the manuscript and providing helpful comments. I especially want to thank Alexander Magoun, Executive Director of the David Sarnoff Library, not only for his review and helpful suggestions, but also for making available the progress reports, laboratory notebooks, and other archival material from the 1960s that enabled me to refresh and confirm my memories of our work during that historic era.

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- ²U.S. Patent 3,332,485 to Richard Williams, filed Nov. 9, 1962 and issued May 30, 1967.
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- ⁵J. A. Castellano, *Liquid Gold: The Story of Liquid Crystal Displays and the Creation of an Industry* (World Scientific Publishing, Singapore, 2005).

^dRCA sold the wristwatch business to Timex in 1976.

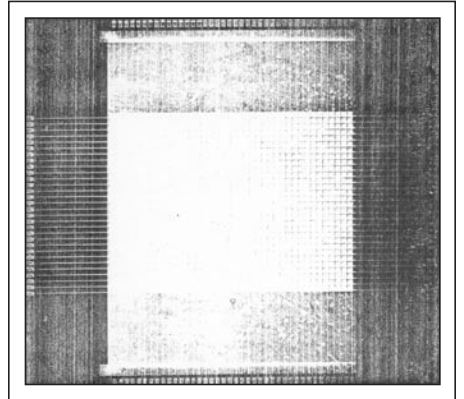


Fig. 6: "Monolithic-Silicon Test Chip for 1200-Element Liquid Crystal Matrix Display." [Source: B. J. Lechner, et al. (unpublished paper, 1969).]

⁶B. J. Lechner, A. G. Samusenko, G. W. Taylor, and J. Tufts, "Ferroelectric Controlled Electroluminescent Displays," *Proceedings of the National Aerospace Electronics Conference* (May 1966).

⁷B. J. Lechner, "Liquid Crystal Displays," presented at a conference on Pertinent Concepts in Computer Graphics held at the University of Illinois from March 31 to April 2, 1969 and published in *Pertinent Concepts in Computer Graphics*, edited by M. Faiman and J. Nievergelt (University of Illinois Press, 1969).

⁸B. J. Lechner, F. J. Marlowe, E. O. Nester, and J. Tufts, "Liquid Crystal Matrix Displays," 1969 *IEEE International Solid State Circuits Conference Digest of Technical Papers*, 52-53 (Feb. 1969).

⁹B. J. Lechner, F. J. Marlowe, E. O. Nester, and J. Tufts, "Liquid Crystal Matrix Displays," *Proc. IEEE* **59**, No. 11, 1566-1579 (Nov. 1971). ■

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Edited by Aris Silzars

System design for a wide-color-gamut TV-sized AMOLED display

**John W. Hamer
Andrew D. Arnold
Michael L. Boroson
Masahiro Itoh
Tukaram K. Hatwar
Margaret J. Helber
Koichi Miwa
Charles I. Levey
Michael Long
John E. Ludwicki
David C. Scheirer
Jeffrey P. Spindler
Steven A. Van Slyke**

Eastman Kodak Co.

Abstract — By using current technology, it is possible to design and fabricate performance-competitive TV-sized AMOLED displays. In this paper, the system design considerations are described that lead to the selection of the device architecture (including a stacked white OLED-emitting unit), the backplane technology [an amorphous Si (a-Si) backplane with compensation for TFT degradation], and module design (for long life and low cost). The resulting AMOLED displays will meet performance and lifetime requirements and will be manufacturing cost-competitive for TV applications. A high-performance 14-in. AMOLED display was fabricated by using an in-line OLED deposition machine to demonstrate some of these approaches. The chosen OLED technologies are scalable to larger glass substrate sizes compatible with existing a-Si backplane fabs.

With respect to lifetime, steady advances in OLED materials and OLED formulations have resulted in lifetime characteristics that are thought to be acceptable for many AMOLED display applications, especially imaging-centric applications. The key unresolved issue is whether AMOLED displays can be designed and fabricated that will have a unit manufacturing cost (UMC) lower than other flat-panel-display (FPD) technologies. In order to achieve this goal, we describe in this paper a design that uses TFT backplanes made with amorphous Si (a-Si) combined with an advanced white-emitting structure and display configuration that provides superior performance to existing FPD technologies in the 32–52-in. range.



FIGURE 19 — Prototype large-area AMOLED TV.

A flexible full-color AMOLED display driven by OTFTs

Iwao Yagi
Nobukazu Hirai
Yoshihiro Miyamoto
Makoto Noda
Ayaka Imaoka
Nobuhide Yoneya
Kazumasa Nomoto
Jiro Kasahara
Akira Yumoto
Tetsuo Urabe

Sony Corp.

An effective way to achieve a full-color pixel structure is to employ a top-emission structure. In the top-emission structures, OLEDs and the pixel circuit are arranged in a tandem configuration. Such a configuration enables smaller pixel sizes than those achievable using a conventional bottom-emission structure, in which OLEDs and the pixel circuit are arranged in a side-by-side configuration. Unlike bottom-emission structures, a top-emission OLED does not require a transparent substrate, allowing a wider selection of plastic substrates to be used. Top-emission structures are thus advantageous for producing flexible OTFT-OLED displays.

Abstract — Organic thin-film-transistor (OTFT) technologies have been developed to achieve a flexible backplane for driving full-color organic light-emitting diodes (OLEDs) with a resolution of 80 ppi. The full-color pixel structure can be attained by using a combination of top-emission OLEDs and fine-patterned OTFTs. The fine-patterned OTFTs are integrated by utilizing an organic semiconductor (OSC) separator, which is an insulating wall structure made of an organic insulator. Organic insulators are actively used for the OTFT integration, as well as for the separator, in order to enhance the mechanical flexibility of the OTFT backplane. By using these technologies, active-matrix OLED (AMOLED) displays can be driven by the developed OTFT backplane even when they are mechanically flexed.



FIGURE 7 — Photograph of the flexible AMOLED display driven by pentacene TFTs.

A flexible 2.1-in. active-matrix electrophoretic display with high resolution and a thickness of 100 μm

Taimei Kodaira
Saichi Hirabayashi
Yuko Komatsu
Mitsutoshi Miyasaka
Hideyuki Kawai
Satoshi Nebashi
Satoshi Inoue
Tatsuya Shimoda

Seiko-Epson Corp.

Abstract — A paper-thin QVGA, flexible 2.1-in. active-matrix electrophoretic display (AMEPD) that features a thickness of 100 μm and a 192-ppi resolution has been developed. An LTPS-TFT backplane with integrated peripheral driver circuits was first fabricated on a glass substrate and then transferred to a very thin (30- μm) plastic film by employing surface-free technology by laser ablation/annealing (SUFTLA[®]). A micro-encapsulated electrophoretic imaging sheet was laminated on the backplane. A supporting substrate was used to support the LTPS-TFT backplane. Fine images were successfully displayed on the rollable AMEPD. The integrated driver circuits dramatically reduce the number of external connection terminals, thus easily boosting the reliability of electrical connections even on such a thin plastic film.

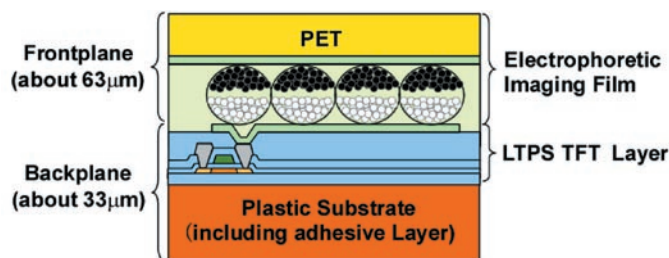


FIGURE 5 — Sectional view of the very thin AMEPD.



FIGURE 6 — Photograph of the rollable AMEPD.

Substrate-free cholesteric liquid-crystal displays

Irina Shiyanovskaya
Seth Green
Asad Khan
Greg Magyar
Oleg Pishnyak
J. William Doane

Kent Displays

Abstract — This paper describes the first substrate-free cholesteric liquid-crystal displays. The encapsulated cholesteric displays are ultra-thin (with a total thickness around 20 μm) and ultra-light-weight (0.002 g/cm^2). The displays exhibit unprecedented conformability, flexibility, and drapability while maintaining electro-optical performance and mechanical integrity. All functional display layers are sequentially coated on a preparation substrate and then lifted-off from the preparation substrate to form a free-standing display. The display fabrication process, electro-optical performance, and display flexibility are discussed.

The release of the display from the preparation substrate does not seem to reduce its optical performance. The display is rugged, can be folded, and can sustain some reversible stretching (1–2%) without loss of the display integrity and electrical addressability. All materials in the display, including polymers for the carrier film, the binder for the liquid-crystal droplets, conductive electrodes, and clear coat are elastic and durable enough to allow for a rather tough handling despite the very thin display thickness. Figure 5(a) demonstrates a passively driven 13×13 monochrome cholesteric display on the preparation substrate. Figure 5(b) shows the same display lifted from the preparation substrate. The total thickness of this substrate-free display is about 20 μm .

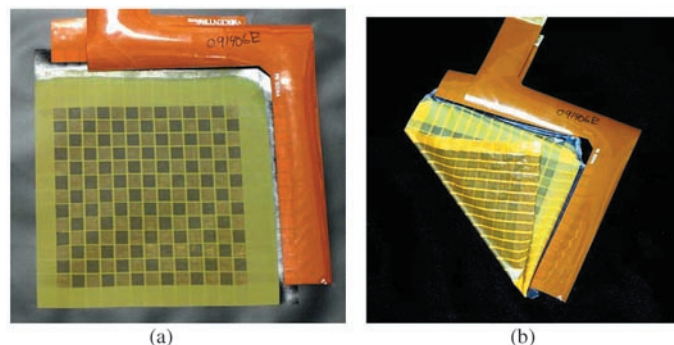


FIGURE 5 — (a) Photograph of a 13×13 monochrome cholesteric display with attached flexible PCBs for passive-matrix driving on the preparation substrate. (b) The photograph of the same display after release from the preparation substrate. The substrate-free display is fully addressable and can be folded due to the high flexibility and very small thickness of all display layers.

Super-reflective color LCD with PDLC technology

Kiyoshi Minoura
Shigeaki Mizushima
Yasushi Asaoka
Ichiro Ihara
Eiji Satoh
Sayuri Fujiwara
Yasuhisa Itoh

Sharp Corp.

Abstract — A novel reflective color LCD without polarizers has been developed using a PDLC film and a retro-reflector. Bright color images including moving images are achievable with ambient light. This novel LCD will enable the new application area of electronic paper.

The power consumption has been simulated for a QVGA (320×240) resolution panel. For the color panel that displays 256 gray scales with 60-Hz driving, where both source lines and common electrode are driven by 5 V_{p-p} , the power consumption is 32 mW. For a b/w display, the power consumption decreases to 1/3 because the number of pixels to be driven decreases to 1/3. By applying 6-Hz driving instead of 60-Hz driving, the power consumption decreases to 1/10, which is quite low. By decreasing the gray-scale displays from 256 to 2 steps, the power consumption decreases to 43%.



FIGURE 13 — Photograph of our newly developed color display.

Flexible area-color reflective displays based on electric-field-induced blueshift in a cholesteric liquid-crystal film

Haiqing Xianyu
Kuan-Ming Chen
Shin-Tson Wu

University of Central Florida

Abstract — An electrically controllable blueshift of the reflection band is observed in a cholesteric liquid crystal with either positive or negative dielectric anisotropy. The change in optical properties is a result of a two-dimensional periodic undulation of the cholesteric texture, known as Helfrich deformation. This blueshift mechanism was used to demonstrate area-color reflective displays in a cholesteric cell and a rollable polymeric film.

The electrically induced color change in cholesteric reactive-mesogen cells can be permanently recorded through UV curing when the voltage is applied. An area-color pattern can be recorded into a single cell by masked curing each part when different voltages are applied. The film thickness is controlled by the cell gap, which is 8 μm in our experiment. The glass substrates can be peeled off and a flexible film with an area-color pattern is fabricated.

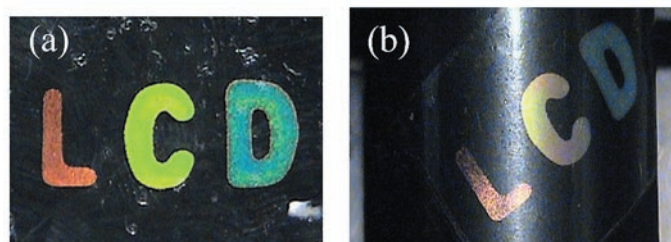


FIGURE 4 — A three-color rollable cholesteric polymer film: (a) before bending and (b) when the film is attached to a cylindrical post holder. The “LCD” characters were exposed when different voltages were applied. The film thickness is 8 μm .

Nanoparticle-embedded polymer-dispersed liquid crystal for paper-like displays

Akira Masutani
Tony Robert s
Bettina Schüller
Nadine Hollfelder
Pinar Kilickiran
Akira Sakaigawa
Gabriele Nelles
Akio Yasuda

Sony Deutschland GmbH

Abstract — A polymer-dispersed liquid-crystal (PDLC) matrix template embedded with nano/microparticles can be backfilled/infiltrated with a dye-doped liquid crystal for a paper-like reflective display. In this way, a desirable degree of diffusion can be realized to reduce the viewing-angle dependency of a gain reflector and metallic glare without changing other electro-optical properties.

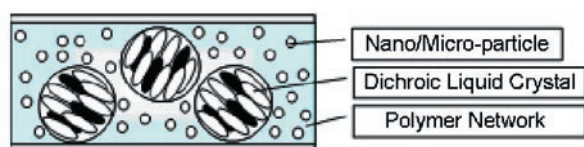


FIGURE 1 — Schematic drawing of nanoparticle-embedded D-PDLC.



FIGURE 8 — Nanoparticle-doped D-PDLC on 3.8-in. test panel with patterned ITO. At the back of the panel is a common office white paper with black laser-printer text for visual comparison.

The Zenithal Bistable Display: From concept to consumer

J. Cliff Jones

ZBD Displays, Ltd.

Abstract — The first commercial use of the Zenithal Bistable Display (ZBD™) is for electronic point-of-purchase (epop™) signage in the retail sector. As a reflective bistable display, this novel LCD technology only consumes power if new information is required and the image is updated. This allows complex images to be shown constantly for several years from the energy of a single low-cost battery, when the display is updated up to ten times each day – ideal for signage applications. Excellent performance characteristics are achieved in a TN-like STN-LCD in which one of the alignment surfaces is a relief grating. Correct design of the grating shape and surface properties not only imparts the bistability, but allows control of the optical performance, the latching voltages, and the temperature range. Being addressed using a simple passive-matrix approach, without the need for a thin-film-transistor backplane, large amounts of information may be displayed by STN drivers. A low-cost fabrication method has been devised that is compatible with conventional TN and STN manufacture, and with negligible equipment outlay. The device operating principles, manufacturing method, and performance of ZBDs are reviewed.

There are several potential device geometries depending on the opposing surface to the ZBD grating. The simplest structure is a simple TN-type geometry shown schematically in Fig. 1. The grating is used opposite the conventionally rubbed polymer alignment layer to give a 90° twist in the low-tilt state at the grating surface or a hybrid aligned (HAN) state without twist when in the high-tilt state at the grating surface. Optical contrast results from polarizers attached on either side of the panel and crossed with respect to each other. The device is usually operated in reflective mode using a reflective rear polarizer.

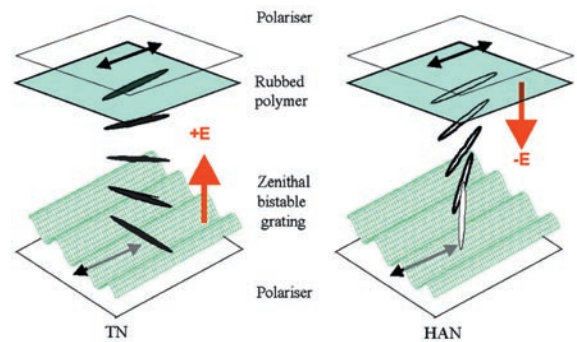


FIGURE 1 — Schematic of the Zenithal Bistable LCD operating in the TN configuration: (a) high-tilt (HAN) and (b) low-tilt (TN) alignment states.

A flexible electronic-paper display with an ultra-thin and flexible LSI driver using quick-response liquid-powder technology

Ryo Sakurai

Reiji Hattori

Michihiro Asakawa

Takuro Nakashima

Itsuo Tanuma

Akihiko Yokoo

Norio Nihei

Yoshitomo Masuda

Bridgestone Corp.

Abstract — A thin and flexible LSI driver with a thickness of less than 35 μm for a passive-matrix-driven Quick-Response Liquid-Powder Display (QR-LPD™) was successfully mounted onto the flexible printed circuit (FPC) and the back substrates of a flexible QR-LPD™. A mounted LSI driver on a plastic substrate shows no significant degradation in the driving performances and maintains physical flexibility without any connection failures. This technology can realize a fully flexible electronic paper in combination with a plastic-substrate QR-LPD™ fabricated by a roll-to-roll process.

In this study, we tried to mount a flexible driver on a flexible printed circuit (FPC) film in order to confirm the possibility of a fully flexible electronic-paper display. Figure 5 shows a photograph of a FPC with a flexible LSI driver. One can see that it has mechanical flexibility. In this case, the minimum radius of curvature without mechanical destruction is 20 mm. Some difficulty is expected in the bonding process because of the chip flexibility.

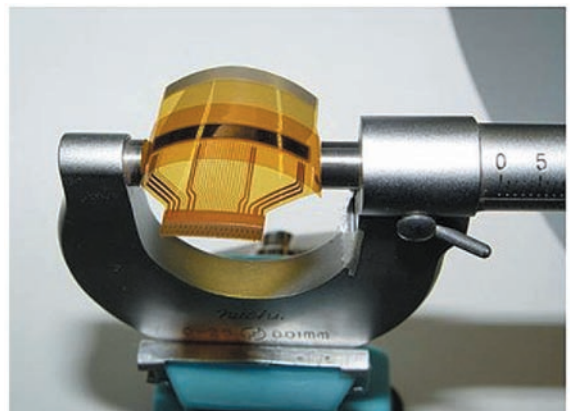


FIGURE 5 — Flexible driver on flexible printed circuit.

High-mobility solution-processed organic thin-film-transistor array for active-matrix color liquid-crystal displays

**Masahiro Kawasaki, Shuji Imazeki,
Shoichi Hirota, Tadashi Arai,
Takeo Shiba, Masahiko Ando,
Yutaka Natsume, Takashi Minakata,
Sei Uemura, Toshihide Kamata**

Hitachi Ltd.

Abstract — A solution-processed organic thin-film-transistor array to drive a 5-in.-diagonal liquid-crystal display has been fabricated, where semiconductor films, a gate dielectric film, and passivation films have all been formed using solution processes. A field-effect mobility of $1.6 \text{ cm}^2/\text{V}\cdot\text{sec}$, which is among the highest for solution-processed organic thin-film transistors ever reported, was obtained. This result is due to semiconductor material with large-grain-sized pentacene crystals formed from a solution and adoption of three-layered passivation films that minimize the performance degradation of organic thin-film transistors.

A planar view of the solution-processed OTFT array with patterned and passivated pentacene films is shown in Fig. 10. The purple pentacene island covered with passivation films can be clearly observed. The TFT performance is comparable with that of amorphous silicon, so the TFT size can be reduced such that the channel width and length are 50 and 8 μm , respectively. Therefore, the aperture ratio of a dot with a $318 \times 106\text{-}\mu\text{m}$ size is designed to be 60%, which is the same level as that of commercial TFT-driven LCDs.

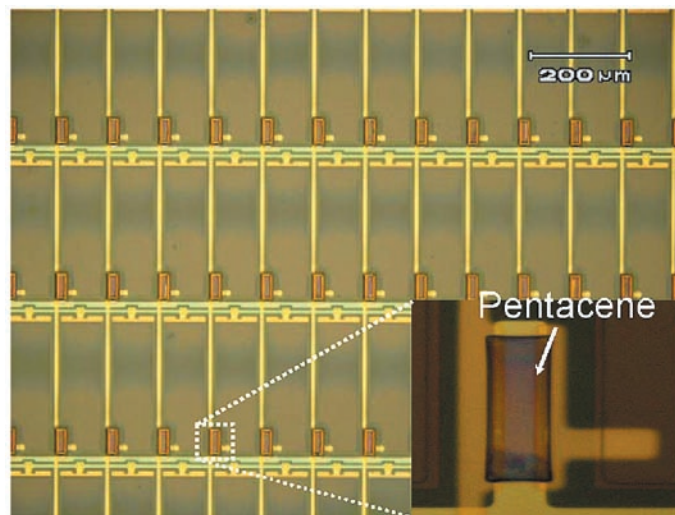


FIGURE 10 — Planar view of solution-processed OTFT array with patterned and passivated pentacene films shown in the inset.

Flexible active-matrix OLED displays: Challenges and progress

**Rui-Qing Ma
Richard Hewitt
Kamala Rajan
Jeff Silvernail
Ken Urbanik
Michael Hack
Julie J. Brown**

Universal Display Corp.

Abstract — Organic light-emitting-device (OLED) devices are very promising candidates for flexible-display applications because of their organic thin-film configuration and excellent optical and video performance. Recent progress of flexible-OLED technologies for high-performance full-color active-matrix OLED (AMOLED) displays will be presented and future challenges will be discussed. Specific focus is placed on technology components, including high-efficiency phosphorescent OLED technology, substrates and backplanes for flexible displays, transparent compound cathode technology, conformal packaging, and the flexibility testing of these devices. Finally, the latest prototype in collaboration with LG. Philips LCD, a flexible 4-in. QVGA full-color AMOLED built on amorphous-silicon backplane, will be described.

A flexible full-color AMOLED-on-metal-foil prototype, combining LG.Philips LCD's innovative a-Si backplane with our team's high-efficiency PHOLED and FOLED flexible technologies has been demonstrated. The prototype is a portrait-configured 4-in. QVGA 100-ppi top-emitting OLED display, as shown in Fig. 7. The razor-thin display was built on 76- μm -thick metal foil and offers 256 gray-scale levels per color (8 bit). The display can portray a variety of images, including full-motion video.



FIGURE 7 — A flexible 4-in. full-color QVGA display with an a-Si backplane on metal foil (in collaboration with LG.Philips LCD).

Advanced impulsive-driving technique for Super-PVA panel

Taesung Kim
Byung-Hyuk Shin
Hyoung Sik Nam
Brian H. Berkeley
Sang Soo Kim

Samsung Electronics

Abstract — Super-PVA (S-PVA) technology developed by Samsung has demonstrated excellent viewing-angle performance. However, S-PVA panels can place extra demands on charging time due to the time-multiplexed driving scheme required to separately address two subpixels. Specifically, a 2G-1D pixel structure theoretically requires subpixel charging in one-half of the time available for a conventional panel. In this paper, a new LCD driving scheme, super impulsive technology (SIT), is proposed to improve motion-blur reduction by driving an S-PVA LCD panel at 120 Hz. The proposed scheme allows a 120-Hz 2G-1D panel to be driven with an adequate charging-time margin while providing an impulsive driving effect for motion-blur reduction. Considering that the cost of a 2G-1D S-PVA panel is comparable to that of a conventional 60-Hz panel, this method achieves good performance at a reasonable price. The detailed algorithm and implementation method are explored and the performance improvements are verified.

The basic concept of the proposed algorithm in this paper is shown in Fig. 4, and we call it super impulsive technology (SIT). To eliminate gamma switching during the active charging time, only one gamma voltage set is used to drive the pixels within any given frame. In SIT driving, each frame is duplicated first at double speed so that the panel's frame frequency becomes 120 Hz, and even frames are just simple copies of the odd frames.

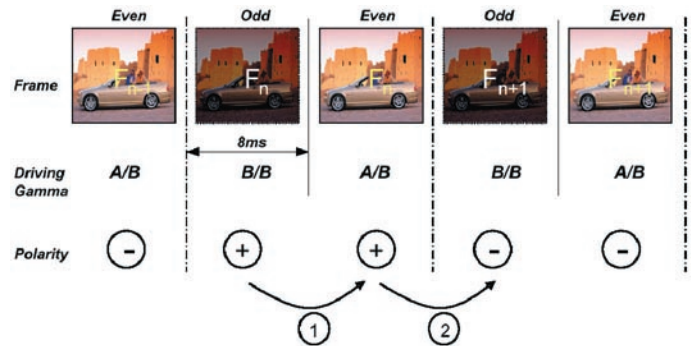


FIGURE 4 — Frame sequence of proposed driving scheme.

A novel TFT-OLED integration for OLED-independent pixel programming in amorphous-Si AMOLED pixels

Bahman Hekmatshoar
Alex Z. Kattamis
Kunigunde Cherenack
Sigurd Wagner
James C. Sturm

Princeton University

Abstract — The direct voltage programming of active-matrix organic light-emitting-diode (AMOLED) pixels with *n*-channel amorphous-Si (a-Si) TFTs requires a contact between the driving TFT and the OLED cathode. Current processing constraints only permit connecting the driving TFT to the OLED anode. Here, a new “inverted” integration technique which makes the direct programming possible by connecting the driver *n*-channel a-Si TFT to the OLED cathode is demonstrated. As a result, the pixel drive current increases by an order of magnitude for the same data voltages and the pixel data voltage for turn-on drops by several volts. In addition, the pixel drive current becomes independent of the OLED characteristics so that OLED aging does not affect the pixel current. Furthermore, the new integration technique is modified to allow substrate rotation during OLED evaporation to improve the pixel yield and uniformity. The new integration technique is important for realizing active-matrix OLED displays with a-Si technology and conventional bottom-anode OLEDs.

The schematic cross section of an a-Si AMOLED pixel fabricated with the inverted integration process is shown in Fig. 3. The a-Si TFT back-plane is fabricated at temperatures up to 300°C on glass. The apparent (*i.e.*, not corrected for contact resistance) saturation mobility and threshold voltage of the driving TFTs ($L = 5 \mu\text{m}$) are $0.65 \pm 0.04 \text{ cm}^2/\text{V}\cdot\text{sec}$ and $1.7 \pm 0.2 \text{ V}$, respectively. After processing the TFT back-plane (including ITO as the OLED anode), insulating “separators” are formed by patterning a layer of positive photoresist using conventional photolithography. As shown in Fig. 3(a), the organic layers are then evaporated at an angle in such a way that an interconnect extension connected to the driving TFT is not coated with the organic layers, taking advantage of the separator’s shadowing effect.

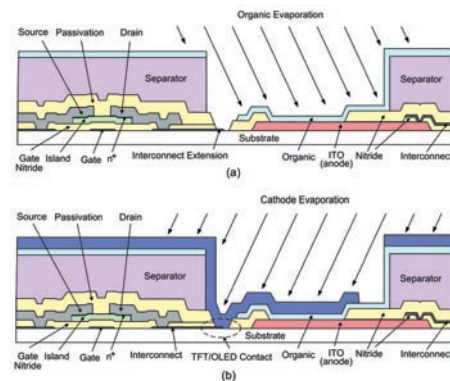
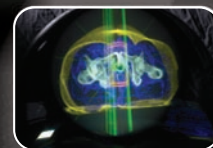
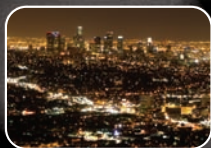


FIGURE 3 — Schematic cross section of the fabricated new “inverted” AMOLED structure, during the evaporation of (a) the organic layers and (b) cathode.

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the business of displays

continued from page 6

for example, the market for audio components. A few decades ago, audio-signal reproduction became so precise and distortion-free that it was no longer possible to hear the difference between many of the system components such as amplifiers, tuners, and CD players. Speakers, as electromechanical devices, have not yet been able to achieve such perfection, but the end result has been that about the only way to distinguish products is on their styling, audio power output, and price. Since we can no longer hear the difference, and because profit margins on these components are now so small, many resellers have adopted shady practices to increase profits – such as selling connecting cables and speaker wire at exorbitantly inflated prices with the claim that these accessories will bring out the “full audio capabilities” of the system.

In the mid-80s, we were introduced to the first personal computers. The IBM PC and the Apple II gave us our first glimpse into a future that would soon be upon us. The IBM PC and its clones had a clock speed in the vicinity of 10 MHz and a hard disk that could store about 20 Mbytes. Not so many years after that, we were introduced to desktop computers with 100-MHz clock speed, then 500 MHz, and then the magic 1-GHz number was achieved. There were plenty of predictions for when we would see 10-GHz clock speeds and beyond. Having started my career as a microwave engineer, I knew how difficult life can get as one tries to work with signals in the many-GHz range. Well, sure enough, we made it to about 3 or 4 GHz and then life got really difficult – we hit the wall. The speed race ended, and we were forced to switch over to multi-core processors to continue to increase computational capabilities. Now the race is on to see who can introduce the next highest number of cores. And, in fact, we never even achieved the 3- or 4-GHz operation. That speed is only for the arithmetic unit within the core of the processor. The information that is swapped in and out of memory is typically at speeds of well under 1 GHz. So again, we have approached and reached a technology asymptote.

It seems that with every product and every technology, there comes a time when either “good enough” is achieved, or that further increases are so difficult and/or so expensive to attain – or are of such marginal benefit – that it is commercially prudent to develop other interesting capabilities instead. We

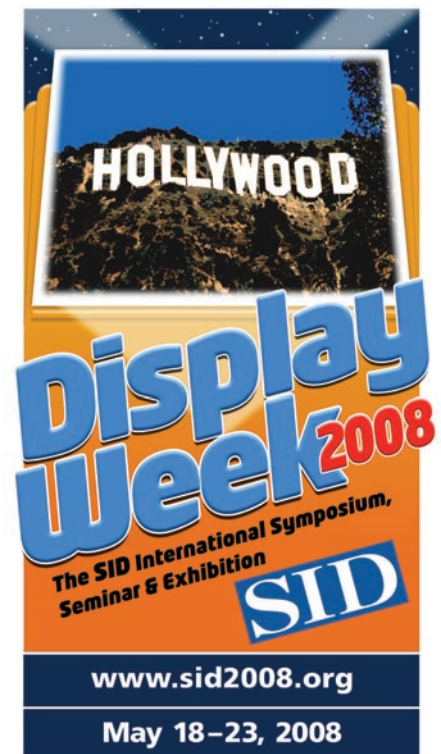
have come to such a time in the capabilities of desktop and laptop computers. For a number of years now, we have been stagnant in our use of personal computers as word processors, spreadsheet manipulators, and for the preparation of presentations. What has evolved instead is that we are now using our computers more as communication and data-storage devices. That would lead one to conclude that Windows® is a mature product of limited future usefulness. So why is it still growing and producing major profits for Microsoft? It appears that along with the concept of technology asymptotes, we also need to explore the concept of “technology momentum.” We will do that in more detail in a future column. Specifically, we will look at what keeps technologies going even after they seem to have lost their predominant position and why new entrants find it so difficult to unseat an incumbent technology.

To return to display technology, can we say when we will have achieved the technology asymptote for display resolution? Are we really going to be watching 4K × 8K displays in our living rooms anytime soon? Even NHK admits that their effort is for the long term. Since it took about 30 years to develop and implement the current HDTV standard, they are similarly thinking long term – several decades out. But other than for special entertainment applications, there is no assurance that we will ever see such high-resolution displays in our homes – even in 30 years. We may find it more interesting to add other features and leave the resolution about where it is with HDTV. We may have already reached the technology asymptote for display resolution.

Are we there yet? Is 1920 × 1080 resolution with 256 levels for each color the final frontier for home entertainment? If you do not agree, then where do you think it is? I welcome your comments on this or other topics. ■

Aris Silzars is a Contributing Editor of Information Display magazine. He can be reached by e-mail at silzars@attglobal.net or by telephone at 425/898-9117.

We are always interested in hearing from our readers. If you have an idea that would make for an interesting Business of Displays column or if you would like to submit your own column, please contact Aris Silzars at 425/898-9117 or email: silzars@attglobal.net.



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editorial

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higher material cost (on the order of \$10–\$20 per display), the new supply-chain challenges in this very young component market, and the business/technical risks of using a new technology whose working lifetime is just now approaching that of CCFL. In Dell's case, this results in a very complex set of business-model tradeoffs that has resulted in their very careful but determined entry into this space, following closely behind Sony, Apple, and others. The consumer marketplace for notebook computers and its characteristic side-by-side display environment in retail channels results in the display being one of the most visible and obvious comparison factors between competing products. Dell's objective is to have "TV-like" displays that rival those of any other manufacturer, along with realizing other additional performance goals that together will overcome the near-term price penalty. Those additional goals are "all day" notebook run times; meeting all global "Green" requirements; improved color accuracy and control of color rendering; and the driving of long-term lower costs by enabling the supply chain.

Currently, Dell offers white-LED-backlit displays. In 2008, it plans to introduce RGB-backlit displays and have a technology roadmap that shows color field-sequential RGB products available by mid 2009. Even if that last step is not realistic, it still shows a very aggressive ramp that will change the economics of everyone in their supply chain.

In order to enable the notebook-PC marketplace, panel manufacturers such as Chi Mei Optoelectronics, Samsung, and others are developing notebook LCD panels with LED backlights. The presence of these panels in the marketplace from the major manufacturers, along with the pull of notebook and TV manufacturers to build volume in the supply chain, now virtually ensures that the general display-applications community will soon have a variety of options to choose from at reasonable price points.

As the day wore on, it occurred to me that all the implementations being discussed used large arrays of very-small low-power LEDs. This is in contrast to the approaches involving a small number of high-power LEDs being presented just a few years ago. At that time, there was significant interest in the very-high-current-density offerings from Lumileds and Osram that promised to keep the system costs low due to low interconnection demands, low

device count, low driver costs, *etc.* It appears from those I spoke to at this conference, those promises have not been fulfilled as the devices themselves remain somewhat expensive, their luminous efficiency is in some cases not as good as the low-power devices, and there is an increased system cost due to the complexity of the optical and thermal-management systems required for this approach. As a result, it looks like the low-power devices are going to be used in most new designs.

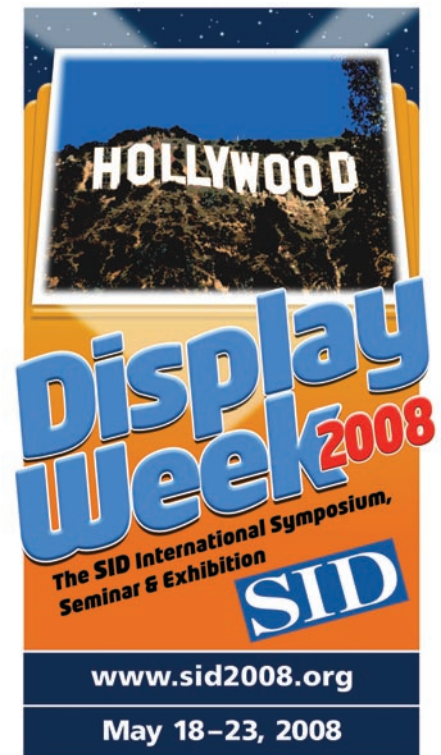
So, once again, as it did many years ago, the ubiquitous notebook-PC market has become the "killer application" that is driving a major technological evolution in the world of displays – first with the mass adoption of CCFL TFT-LCDs and now the coming mass adoption of LED TFT-LCD technology.

It is a privilege for me to introduce this month our Guest Editor Paul Drzaic, who is also our President-Elect of SID. Paul has provided us with a nice assortment of articles revealing important new advances in the field of Electronic Paper. Electronic-paper technology has been advancing rapidly of late with several new product launches and commercialization of some very unique developments. In his article discussing the role of Electrochromics as an alternative to Electrophoretics, Chris Giacomponello from NTERA reveals their latest efforts to achieve full-color capabilities. Jacques Angelé from Nemoptic discusses the ins and outs of manufacturing e-paper displays with their liquid-crystal-based technology. And, for those of you not up on the overall state of the field, Minoru Koshimizu from Fuji Xerox Co., Ltd., provides a very valuable survey of the past, present, and future outlooks for e-paper technology.

Last November, Guest Editor Bernie Lechtner gave us a great portfolio of information about High-Definition-Television technology. In case you did not realize it, Bernie was also a very key contributor to the early developments of matrix addressing in LCD technology. I am very pleased to bring to you his personal account of those days and how some very crucial elements of that technology were developed and demonstrated. This is the first of a regular series of articles we're developing which will recount the history and pivotal moments in the development of various display technologies. Look for future installments later in this year.

As usual, we welcome your feedback on this or any other topic and look forward to serving your needs in 2008. Happy New Year!

Stephen P. Atwood



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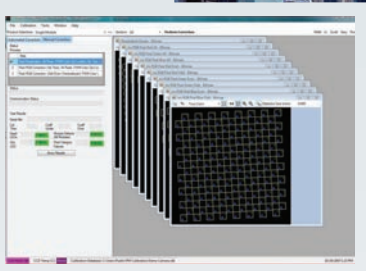
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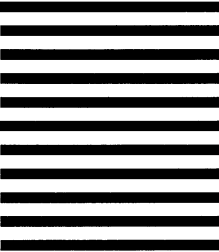
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