THE BIG BUSINESS OF SMALL DISPLAYS

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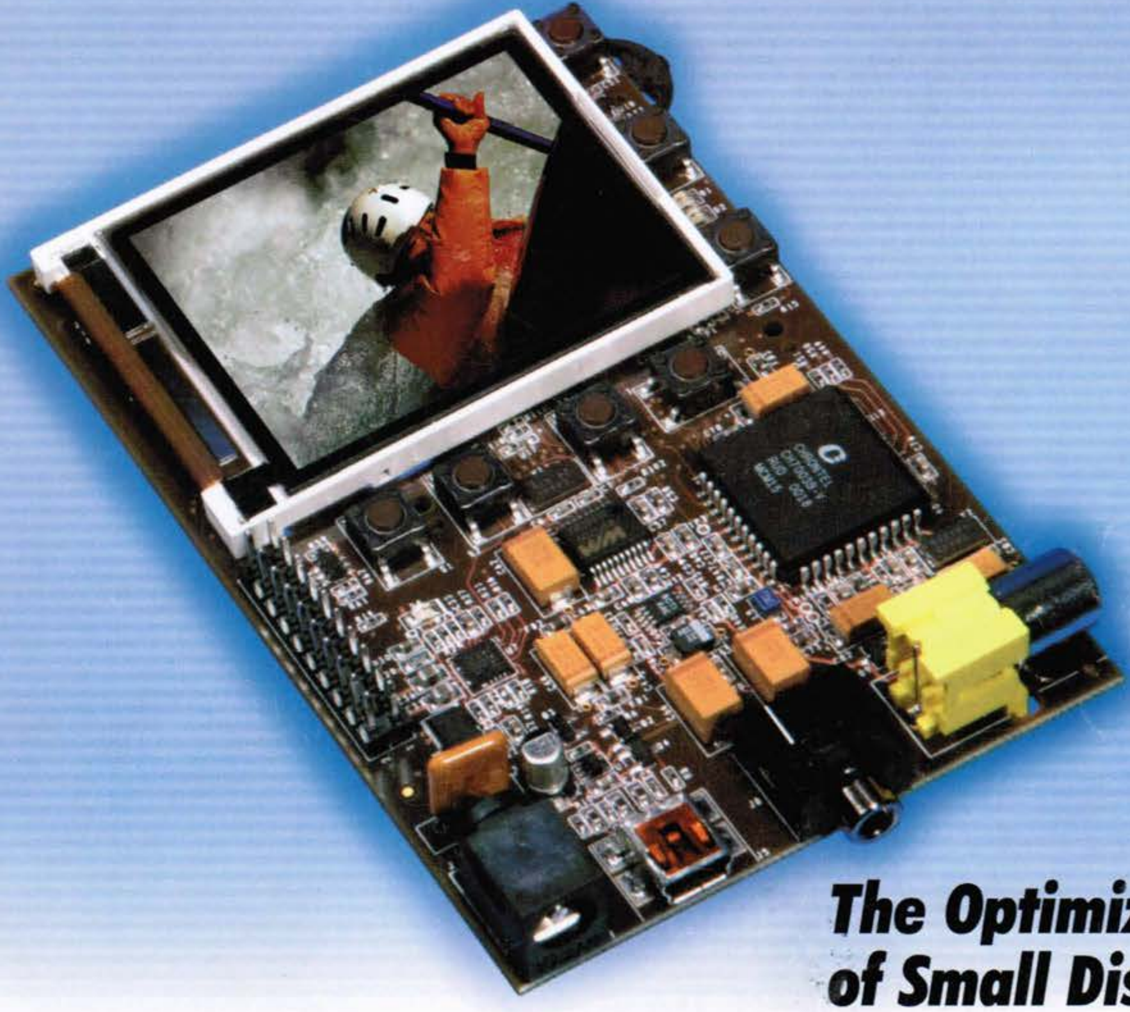

The Optimization of Small Displays

- Optimizing Small Displays
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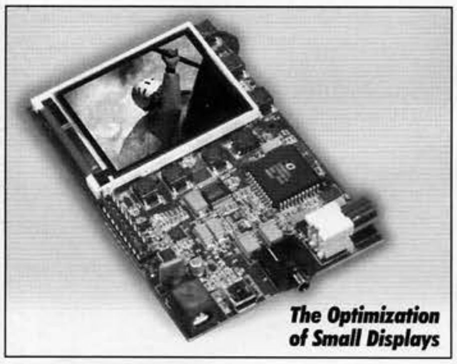
Because small displays are big business, resources and creativity are being poured into their technological development. This QCIF+ reference design kit from Sharp features a 2.2-in. LCD.



Sharp

Next Month in
Information Display

Display-Electronics Issue
- Touch-Enabled Large Displays
- Trends in Video Electronics
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editorial

Changing Focus from Large to Small

The display world has been obsessed with large displays, and with good reason. It is television that has been providing plasma displays with their largest market, and television that is to provide AMLCD manufacturers with their third large application – in addition to notebook PCs and desktop monitors – and thus moderate the "crystal cycle" that has vexed the industry for years.

The production of large-screen AMLCD TVs has required innovative development to improve picture quality and reduce cost, and has challenged manufacturing engineers to fabricate these high-quality displays on ever-larger pieces of motherglass, also to reduce cost.

But while many were looking at large displays, a market for high-quality small displays was evolving rapidly. "The market for small-sized active-matrix LCDs will grow to 850 million units in 2008, up from 404 million units in 2004," wrote Vinita Jakhanwal in the *iSuppli Market Watch* of Sept. 27, 2004. Jakhanwal went on to say, "The market share of small-sized-LCD unit shipments accounted for by AMLCDs will rise to 26% by 2008, up from 14% in 2004. AMLCDs will account for 86% of the small-sized-LCD revenue in 2008."

In terms of unit shipments, mobile telephones are the largest application of LCDs, and they are the third largest in terms of revenue. "The mobile-telephone-display market is expected to be larger than the much-ballyhooed LCD-TV segment in 2004," Jakhanwal said.

With small displays being such a big business, and presenting significant design and application challenges, it is not surprising that these displays have attracted significant resources and engineering ingenuity. That is the subject of much of this issue of *Information Display*.

In "Optimizing Small Displays," Sharp's Marshall Pinder surveys some of the technologies used for the increasing integration of drivers and peripheral circuitry on high-quality LCDs for portable products that converge the functions of previously separate products.

David DeAgazio (Global Lighting Technologies) looks at some of the developments in backlighting for small LCDs, while Makoto Omodani looks at experimental indications of what leads to improved readability in electronic-paper displays.

Erno Langendijk, Michiel Klompenhouwer, and Erik van der Tol (Philips Research Laboratories) explore ways to improve the color rendition of mobile displays with color management, rather than hardware, approaches.

In his Guest Column, Jin Jang discusses the critical role cellular telephones are playing in giving OLED displays their first high-volume shot at the display market. In my review of Asia Display/IMID, the largest display event ever to be held in Korea, small prototype and production displays also make their appearance.

Of course, large displays will continue to be a critical concern of the display industry. We will return to them in future issues of *Information Display*.

For nearly 3 years, the distinguished technology journalist David Lieberman has been writing the "Backlight" column for *Information Display*. This month's

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Information
DISPLAY

guest column

Mass Production of AMOLEDs: The Analogy with AMLCDs

by Jin Jang

The development of active-matrix organic light-emitting-diode (AMOLED) displays has become quite active recently, as was the case for AMLCDs in the early 1990s. But only a small quantity of AMOLEDs is being produced by SK Display, the Sanyo–Kodak joint venture, and the retrenchment of Kodak's and DuPont's AMOLED efforts has been widely noted. Although this is disappointing to those of us who are committed to AMOLED development, it is useful to view the situation in an historical perspective.

The LCD Experience

In the mid-1980s, small AMLCDs for pocket TVs were produced in Japan. These were the first TFT-LCD products. The manufacturing technologies developed for this relatively low-volume application made it possible to develop AMLCDs for notebook computers in the late 1980s and early 1990s.

The notebook LCD of the 1980s was a supertwisted-nematic (STN) device. From 1990 to 1995, notebook TFT-LCDs were manufactured, and they competed with STN-LCDs intensively. Finally, the TFT-LCD became the standard notebook display, thanks to its high image quality and the efficient manufacturing processes that were successfully developed for it.

AMLCDs from 15 to 21 in. were actively developed from 1995 to 2000 for PC monitors. In this arena, the AMLCD competed with the color data tube (CDT) and gradually increased its market share, which exceeded 40% last year.

The years from 2000 to 2005 are proving to be a period of intensive development for AMLCD TV. For example, 55- and 57-in. LCD-TV prototypes were developed recently by LG.Philips LCD and Samsung Electronics, respectively. As a result of this development, the LCD TV will penetrate the TV market and increase its market share over the next 10 years, despite competition from plasma and projection displays.

From this brief LCD history, we learn that the penetration of a new display device into existing markets takes a long time, but it happens if the technology has merit and fulfills a commercial need.

The Path to Active-Matrix OLEDs

OLED technology was commercialized in 1997 by Tohoku Pioneer, but the market was quite small until 2002. In 2003, the OLED market was about US$300 million, thanks to its penetration of the market for mobile-telephone sub-displays. The market will at least triple in 2004, with product coming mainly from Korean, Japanese, and Taiwanese OLED companies.

Samsung SDI's success in the OLED business last year has provided substantial motivation for many small companies to start passive-matrix-OLED manufacturing in Korea, Taiwan, and China. This experience confirms the critical importance of finding an appropriate application for a display technology, especially in the early stages of manufacturing.

AMOLEDs have been studied extensively in recent years because the technology consumes less power and offers a longer lifetime than passive-matrix

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Making the Most of Mobile Displays

New video-processing algorithms significantly improve the image quality of typical mobile displays despite their limited color rendition.

by Erno Langendijk, Michiel Klompenhouwer, and Erik van der Tol

PORTABLE, battery-powered electronic devices, such as mobile telephones and personal digital assistants (PDAs), have transformed business and personal lives throughout the world, enabling us to communicate and perform information tasks at any time and anywhere. Designers must place many constraints on the displays used in these devices, however, in order to minimize weight, maximize battery life, and maintain competitive costs.

As a result, color saturation is often sacrificed in return for better performance in other areas. For example, the blue primary color in organic light-emitting diode (OLED) displays is typically not blue but cyan because of cyan's longer lifetime. For the liquid-crystal displays (LCDs) used in portable devices, sufficient brightness is obtained by applying broadband color filters, which transmit more light but also make the colors less saturated. In mobile displays, the current trend toward higher pixel densities, resulting in lower aperture ratios, will further reduce color saturation because the color filters must transmit even more light.

In addition to this intrinsic limited color rendition, variations in the display's primary colors must be taken into consideration by mobile-device manufacturers. Not only do these colors differ in displays from one supplier to another, but also within a single batch from the same source.

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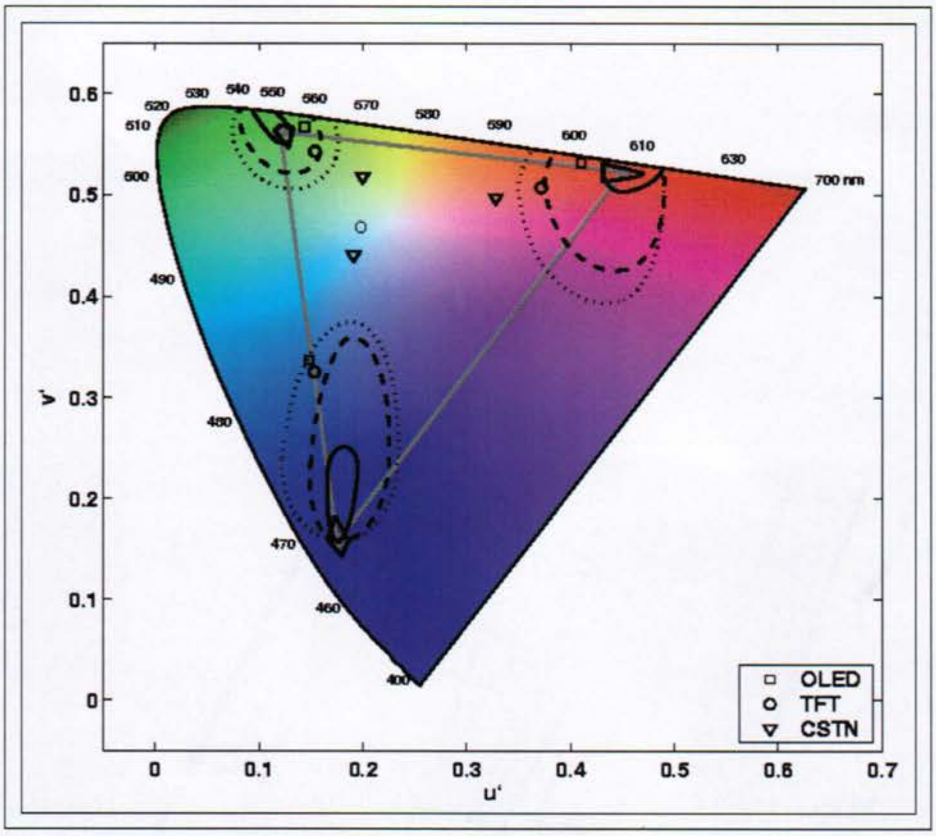

Fig. 1: *The color primaries of three typical mobile displays (see legend) are plotted on the European Broadcast Union (EBU) standard's color triangle (gray line) drawn on the 1976 CIE Uniform Chromaticity Scale (UCS) u',v'-coordinate color space. Displays with primaries in the solid ellipses have optimal color rendition. Those in the dashed and dotted ellipses have a color rendition that is acceptable to 75 and 50% of the viewers, respectively. Those outside the dotted ellipses have unacceptably unnatural color rendition.*

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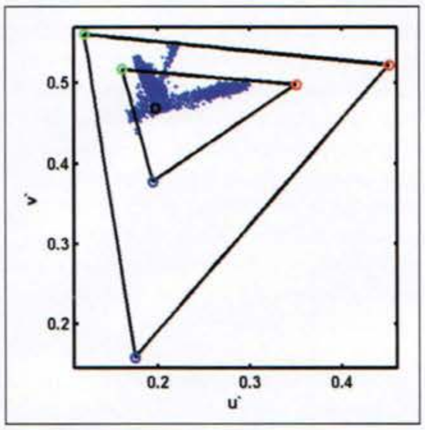

Fig. 2: A display that complies with the EBU standard can reproduce all the colors in the large triangle, but a typical mobile display can only reproduce the colors in the smaller triangle. As a result, the colors outside the smaller triangle cannot be shown on the mobile display and have to be mapped to another color within this triangle.

Color Gamut of Mobile Displays

As a result of these requirements and design compromises, the primary colors – red, green, and blue – of mobile displays are often different from those dictated by broadcasting standards, such as the European Broadcast Union (EBU) standard (Fig. 1).[1] In LCDs, the primary colors are typically less saturated and the blue primary color is shifted in hue. In OLED displays, all primaries differ in hue and the blue primary color is also less saturated in order to extend the lifetime. A representative color supertwisted-nematic (CSTN) LCD panel covers only 15% of the EBU color triangle in the 1976 CIE Uniform Chromaticity Scale (UCS) u',v'-coordinate color space. Thin-film-transistor LCDs (TFT-LCDs) and OLED displays are still well below 100% coverage at 51 and 65%, respectively. It should also be noted that the usual measure of display color gamut in terms of NTSC percentage should be obsolete because the NTSC primaries are no longer used in practice. The EBU standard – or the nearly identical ITU-Rec 709 standard[2] – are much more useful.

The human eye will accept limited deviation in a display's color primaries even without the application of additional color processing to the video signal. The primary-color coordinates must fall within relatively small areas in order to optimally reproduce natural images. Larger areas produce results acceptable to 75% of users, and 50% of users will accept an even larger variation. Beyond these limits, however, color rendition is completely unnatural. For example, all three primaries are unacceptable for mobile CSTN-LCDs. The blue primary color is on the border of the acceptable range and the red and green are just within the boundaries, but still far from optimal, for TFT-LCDs and OLED displays.

Without additional color processing, the colors on most portable displays look rather pale and sometimes have incorrect hue. This is because the colors that are reproduced scale with the colors of the primaries of the particular display. For example, if all three display color primaries have only 50% of the saturation of the EBU primaries, then the saturation of all colors is reduced by a factor of two with respect to the EBU standard. This effect applies even to colors well within the display's color gamut. Similarly, if the red primary color is rotated 10° in hue, then all reddish colors are rotated by10°; in this case, flesh tones will appear to be somewhat orange.

Color Correction and Color Management

The color rendition of such narrow-color-gamut mobile displays can be improved by simply applying color processing to the video signal to correct for the non-standard primaries. The required color processing can be divided into two types: color-space conversion and color-gamut mapping.

Although a mobile display's primary colors have different hue and saturation than required by the EBU standard, there is an area in the color space in which the EBU's and the display's color gamuts overlap and can – in theory – be reproduced exactly. In a given image, the pixel distribution will include colors that fall within the color gamut of a typical mobile display, while others will fall outside (Fig. 2). In order to be correctly displayed, the in-gamut colors must be converted from the source color space, such as that of the EBU standard, to the color space as determined by that particular display's primary

Fig. 3: The photograph on the left shows a typical mobile-display image without color processing; the image looks rather pale. By simple color processing, the photograph in the center shows improved colorfulness, but with visible clipping artifacts. Advanced color-gamut mapping shown on the photograph on the right preserves the colorfulness while eliminating clipping artifacts.

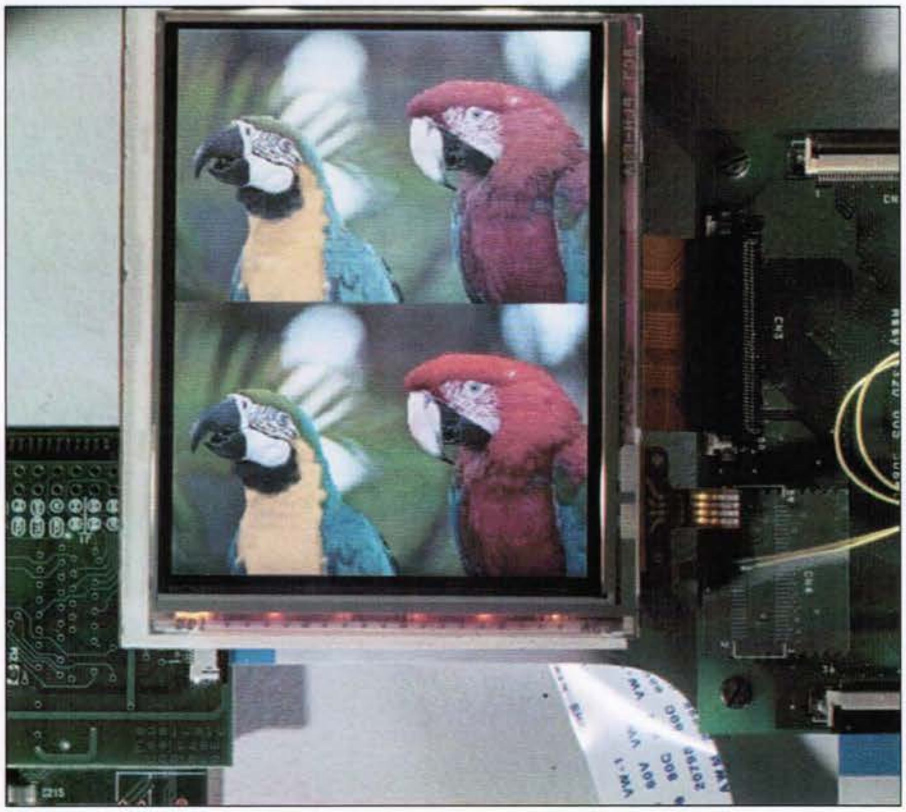

Fig. 4: This mobile AMLCD (240 × 320 pixels) shows an image without color processing (top) and with Philips's LifePix™ color-gamut mapping (bottom). Notice how pale the head of the red parrot is without color processing, and notice also that no detail is lost when applying color processing.

colors. This requires *color-space conversion*, which is a basic technique of color science.

The colors outside a particular display's color gamut cannot be reproduced. After color-space conversion, they correspond to drive signals that exceed the dynamic range of the display, and therefore are clipped to the border of the gamut. This can result in clipping artifacts around contrasting edges and, consequently, in a loss of detail rendering. Notice the center image's loss of detail in the head of the parrot (Fig. 3).

The accurate reproduction of colors in a device with a limited color gamut is known as *color-gamut mapping*, and has been studied in depth by the printing industry. This has led to the development of *color-management systems* that aim to provide color reproduction that is as consistent as possible across different reproduction media, including printers and displays. The International Color Consortium (ICC) has standardized the application of color-management systems. In color-gamut mapping, the so-called *rendering intent* determines the behavior of the mapping. "Colorimetric rendering" aims at accurately reproducing colors inside the display's color gamut by appropriate color-space conversion, but this leads to clipping artifacts as described above. "Perceptual rendering" aims at reproducing the source colors such that the result is perceptually as close as possible to the original. Since this is not a trivial problem, research into this topic is still very active. Consequently, there is no accurately defined standard for perceptual rendering, which leaves developers of mobile displays with an unresolved issue.

Moreover, methods that are common in color-management systems are typically unsuitable for application to mobile devices. For example, most advanced mapping algorithms used in the printing industry operate in perceptual color spaces such as the CIELAB or CIELUV spaces. The conversion to these non-linear spaces requires relatively complex computations, and the mapping procedures themselves are computationally intensive. These methods are not suitable for the low-power low-cost requirements of mobile devices.

Nevertheless, the limited color gamut of mobile devices should not be an excuse for poor color rendition. Dedicated, efficient video-processing algorithms for color-gamut mapping can greatly improve the color rendition of mobile displays.

Improving the color rendition of portable displays is more important in some market segments than others. Users of smart phones and multimedia devices typically are more concerned about color rendition. In a user-attitude survey, In-Stat found that next to checking e-mail on cellular telephones, location services were one of the most important applications, providing views of city maps and photographs of local city attractions. Busy executives on the go prefer color-enhanced displays in their cellular telephones because color provides maximum visibility at normal ambient-light levels. In mid-range to high-end market segments, in which multimedia applications are major purchase drivers, consumers demand enhanced experiences that require colors that more closely match reality.

In the mobile-device market, current applications for color and, in general, image processing are still not found at the device level, but can be found at the level of content or network service providers. For example, FujiFilm's "Keitai Picture" and "Pixabase" technologies are offered over the Internet. These services apply color correction by re-rendering content at transmission time, taking into account the end user's specific portable device. The disadvantage of this kind of service is its limited use by the end user. For example, color correction is only provided for downloaded images and there is consequently no real-time processing of locally generated content from a camera, graphical user interface (GUI), or other source. Another disadvantage is the inability of the handset maker or the end user to tune the settings of the color processing to correct for differences in the display's characteristics within a certain device model or even for personal preference.

More-Efficient Color-Gamut Mapping

In order to prevent clipping artifacts while achieving good color reproduction, Philips

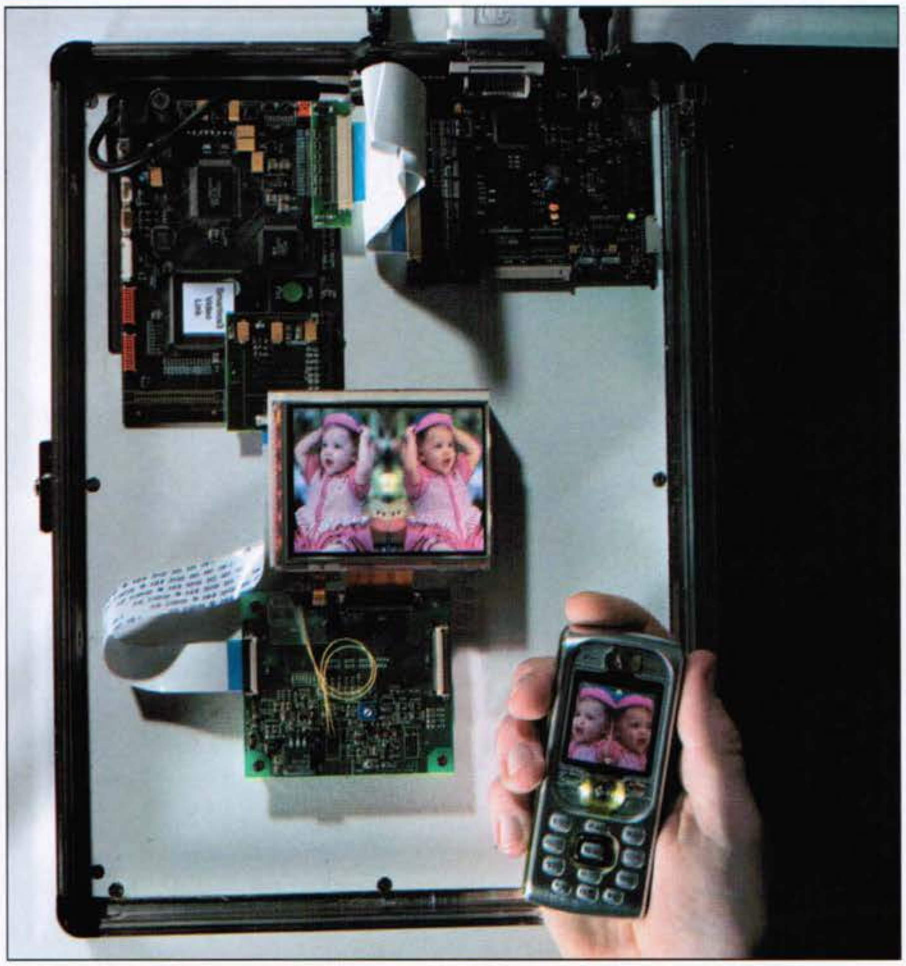

Fig. 5: The AMLCDs used in the 240 × 320-pixel mobile display and a commercial 130 × 130-pixel mobile handset show images without color processing on the left-hand side of the display and images with Philips's LifePix™ color-gamut mapping on the right-hand side. The difference in flesh tones is easy to see.

scientists from three different areas of study – color perception, video processing, and display architectures – collaborated to develop LifePix™ color processing. This new method of color-gamut mapping provides good color rendition for any type of portable display and is a cost-effective low-power solution (Figs. 4 and 5).

The algorithm consists of four steps. The first step reduces the brightness of saturated colors in order to create room for the mapping algorithm. The second step reproduces all the colors inside the display's color gamut with the correct hue and saturation. The third step involves clipping of the pixels outside the display's color gamut by adding a certain amount of white. In the final step, pixels that are too bright are reduced without altering the saturation or hue. This concise mapping algorithm complements the display's characteristics without compromising performance or changing the panel. Consequently, this mapping algorithm can be implemented on any type of display.

The input pixels can be mapped to the color gamut of a typical mobile display (Fig. 6). The brightness of the pixels within the display's color gamut slightly changes towards the edge of the gamut, while pixels outside the display's color gamut are mapped so that they slightly increase in brightness in order to compensate for the inevitable loss in saturation. It works because the colorfulness of an image can be increased by increasing either the saturation or the brightness. Thus, increasing the brightness of saturated colors can compensate for the loss in saturation in narrower-color-gamut mobile displays.

Implementation

Portable applications require a cost-effective and low-power implementation. LifePix™ color processing works directly in the display's color space (RGB domain), so conversion to other color spaces is not required, which makes the system that much simpler.

LifePix™ color processing can be implemented in various ways in a given device. Because the algorithm takes the display's color coordinates as input parameters, a hardware implementation in the display driver IC is a natural choice. This typically results in an expected increase in average power consumption, which is negligible – depending on the resolution, frame rate, and color depth – when compared to the total power consumption of the driver chip. The system can also be implemented in a cellular telephone's companion chip or application engine, either in hardware or software.

Conclusions

Because the primary colors of most of today's portable displays are not within acceptable ranges, these devices have rather poor color rendition unless specific corrective measures are taken. Advanced color processing by color-gamut mapping makes it possible to reproduce natural colors on any type of mobile display. This color mapping provides mobile-display manufacturers with the opportunity to take a big step in accurate color rendition without altering the panel or sacrificing display brightness. Such color processing can give devices a competitive advantage in smart phone and multimedia applications.

This technology can be applied to portable LCDs and OLED displays, delivering optimum brightness and color rendition without increasing power consumption. Just as portable communications and computing devices have transformed the way we work and play, color processing holds the key to making those experiences more effective and enjoyable, using the displays that already exist in the marketplace.

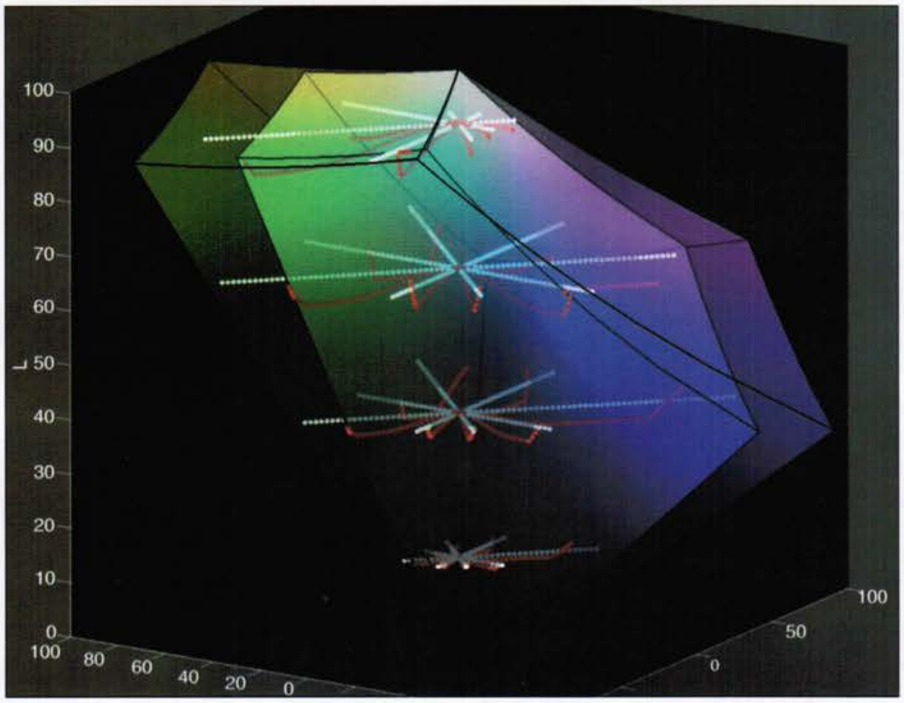

Fig. 6: The larger colored volume represents the input color gamut (EBU standard) and the smaller brightly colored volume represents the display's color gamut in the CIELAB color space. The white dotted lines are input pixels with constant hue and brightness and varying saturation. The red dotted lines are corresponding pixels processed by the color-gamut-mapping algorithm. *Note that the red dotted lines decrease in brightness with increasing saturation until they reach the border of the display's color gamut, where they increase in brightness while remaining at the border of the display gamut.*

Note

[1]See "E.B.U. Standard for Chromaticity Tolerances for Studio Monitors," Tech. 3213-E, August 1975.

[2]The primaries defined by the International Telecommunication Union (ITU) in Recommendation BT.709-5, which was approved in April 2002, are very close to those defined by the EBU. See http://www.itu.int/rec/recommendation.asp? type=items&lang=e&parent=R-REC-BT.709-5-200204-I. Limited free access can be obtained through the ITU's Electronic Bookshop. ■

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Optimizing Small Displays

Converging devices, which combine the functions of formerly independent products, represent the future of mobile electronic products and are driving exciting technological developments in small displays.

by Marshall Pinder

CONVERGENCE is more than a marketing buzzword. Handheld multi-functional devices, such as camera-equipped cellular telephones, PDA/cellular-telephone combination devices, and portable media players are rising in popularity, and their sales growth confirms this. These products integrate into one nicely portable unit having a broad set of functions, such as high-quality graphics, motion and still video, audio, camera, and data-capture capabilities.

From a technology standpoint, these new categories of convergent products will have to meet expectations for display performance that are much higher than they were for earlier versions of each individual product. Consumers typically demand that these new devices have a symmetrical viewing angle of 160° or greater, viewability in ambient light ranging from total darkness to 50,000 lux, and packaging capable of surviving common abuse, such as withstanding a drop of 4 ft. onto concrete. In addition, the newest generation of handheld devices demands a great deal from display technology, particularly as the devices become smaller, lighter, and thinner while still seeking to deliver superior viewability and longer operating time.

Display manufacturers are well aware of this trend and the display requirements of these emerging devices. Rather than viewing these challenges as a daunting and unwelcome shift in the industry, display manufacturers are working to take advantage of the tremendous business opportunity that accompanies the broadening distribution of these new device categories.

"Feature telephones," for example, which constitute the majority of cellular-telephone upgrades, typically incorporate digital cameras and color displays. They currently represent more than one-quarter of all handsets shipped – approximately 125 million units. Industry analyst iSuppli Corp. recently predicted that 90% of the cellular-telephone market will be driven by upgrade sales by 2008.

With millions of unit sales at stake for these devices alone – and millions more for other medical, consumer, and industrial devices that increasingly use small color displays – the race is heating up among display manufacturers to provide small-form-factor displays for these feature-rich devices. Display manufacturers clearly understand that those companies that consistently meet the demands for high quality, power efficiency, and small footprint – all at the best price point – will win the leadership race in small-form-factor-display sales.

New Technologies

It is clear that previous generations of display technologies, such as amorphous-silicon (a-Si) technology, cannot support the needs of the newer handheld devices. While a-Si is sufficient for some devices, the principal drawback of an a-Si display is its inability to fully interconnect with tape-automated-bonding (TAB) or chip-on-glass (COG) assembly technologies. This interconnection is the element in an a-Si display that faces the greatest fabrication challenges, since it only supports a certain amount of current and can be made only so small.

As engineers use electronics of finer and finer pitch in their quest for higher display resolution, the limited reliability of the interconnects becomes apparent. The higher current necessary to drive an a-Si backplane requires more-robust bus bars for connection to the source and gate electrodes, which limits the amount their width can be reduced. The inability to reduce the width of current-carrying elements eventually compromises the aperture ratio and the consequent efficiency of portable displays made with a-Si technology.

Leading display manufacturers have numerous initiatives under way to develop alternative device technologies and to bring to market display solutions that optimize power, performance, viewability, and ruggedness. These approaches include the development of systems-on-glass, the investigation of new display technologies, and creative ways of integrating the display with the external components. Each of these approaches offers unique opportunities for trimming the overall footprint of an electronic device with converging feature sets while providing the necessary functionality.

Integrating onto the Glass

In every new generation of handheld devices, engineers have sought to reduce the footprint of the device while increasing performance

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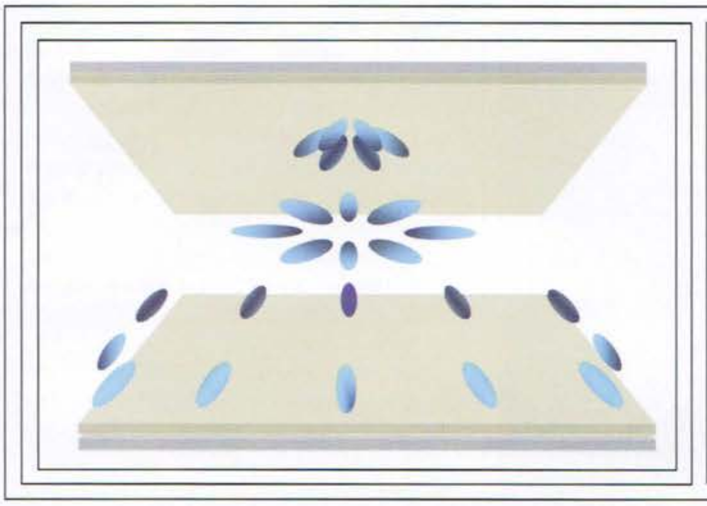

Fig. 1: The liquid-crystal arrangement in a cell of Sharp's Super Mobile display in the ON (light-conducting) state is shown. Light is polarized in all directions by liquid crystals arranged in a pinwheel configuration, thus increasing the viewing angle to 160°.

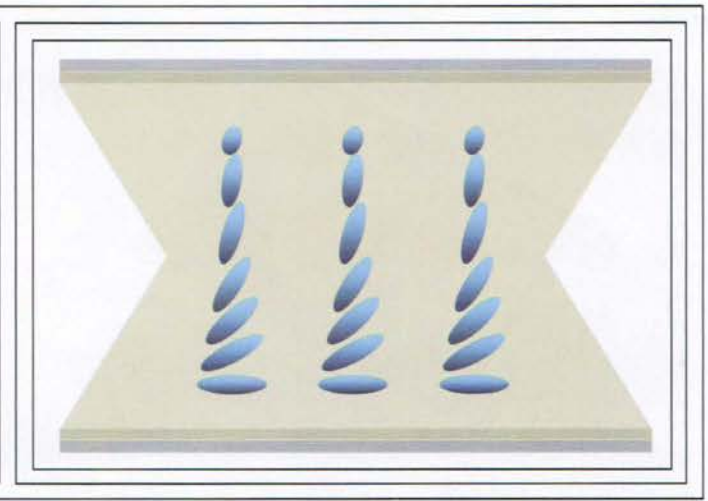

Fig. 2: The typical arrangement of a twisted-nematic liquid-crystal cell in the ON (light-conducting) state is shown. Light is polarized in fewer directions by the liquid crystals, resulting in a much narrower viewing angle.

and display resolution, which is currently up to VGA format. Since a major component in most portable devices is the display, manufacturers have tried to attain this goal by either making incremental improvements to current display technology or by investigating new ways of using silicon process technology.

Changes to process technology now allow manufacturers to take the common circuit elements from variations of a base product (for example, drivers for displays of various sizes in a product range) and integrate those functions onto the display panel. One manufacturer is integrating gate drivers into a-Si directly onto the glass rather than mounting them on the edge, while others have focused their attention on low-temperature-polysilicon (LTPS) technology and Continuous Grain Silicon (CG-Silicon), a next-generation technology developed jointly by Sharp Corp. and Semiconductor Energy Laboratory Co., Ltd., Atsugi, Kanagawa, Japan.

The use of a system LCD based on CG-Silicon technology can achieve VGA resolution in a smaller display. This technology is a fundamental process that allows panel circuitry to be integrated onto the glass substrate at an integration level approaching that of single-crystal-silicon technology. Unlike a-Si and poly-Si technologies, the technologies behind today's thin-film-transistor liquid-crystal-display (TFT-LCD) panels, CG-Silicon technology aligns its silicon grains with continuous atomic-level continuity at the grain boundaries. This continuity permits electrons to travel across the semiconductor with a mobility of 300 cm^2/V-sec, which is approximately 600 times faster than that in a-Si and approximately three times faster than that in the best LTPS.[1]

Since CG-Silicon was introduced in 2002, continual changes in the CG-Silicon design rules have enabled the developers to produce smarter displays and to add other process capabilities. The first generation of this technology used 3-μm design rules and a maximum logic frequency of 3 MHz. This enabled the developers to embed solid-state drivers into a 2-in.-diagonal VGA display for use in mobile telephones.

Current generations of CG-Silicon displays have moved to the 1.5-μm design rule and support a 5-MHz logic frequency. As a result, analog amplifiers for the audio subsystem and display controller can now be added to the driver circuits. In addition, improvements have been demonstrated that enhance display resolution to 300 ppi. These improvements include miniaturization technology to reduce channel length to 2 μm, adapting the color filter and moving it to the array side of the panel, and using spacers to control cell gap. Third-generation improvements, possibly beginning in late 2005, will further enhance electron mobility for products using 0.8-μm design rules. These displays are likely to include more capabilities, such as image sensors and touch sensors, with related signal conditioning and conversion on the same glass substrate.

This system LCD, or system-on-glass, approach reduces the footprint of the display module while allowing more functions to be incorporated on the panel. By doing this, design engineers can reduce their design cycle time because the motherboard designs are simplified and less costly. Until all LCD electronics is integrated onto the glass, a "bridge technology" must be in place. One approach is to place peripheral components on a flex circuit, not just on the glass cell, because it is more cost effective to integrate the most common components there, such as the graphics driver and timing controller. A typical flex circuit can be hard-tooled in 6 weeks *vs.* 6 months to change the glass.

Another approach to system-on-glass is the use of LTPS. Improvements in LTPS have enabled the integration of components, such as peripheral driver and control circuitry, directly onto the LCD. As LTPS technology has developed, commercial modules with built-in SRAM and digital-to-analog converters (for cellular telephones and other devices) were introduced. Recently, prototypes of LTPS LCDs with data-input functionality have been constructed, which indicates improved carrier mobility and better process geometry for the technology.

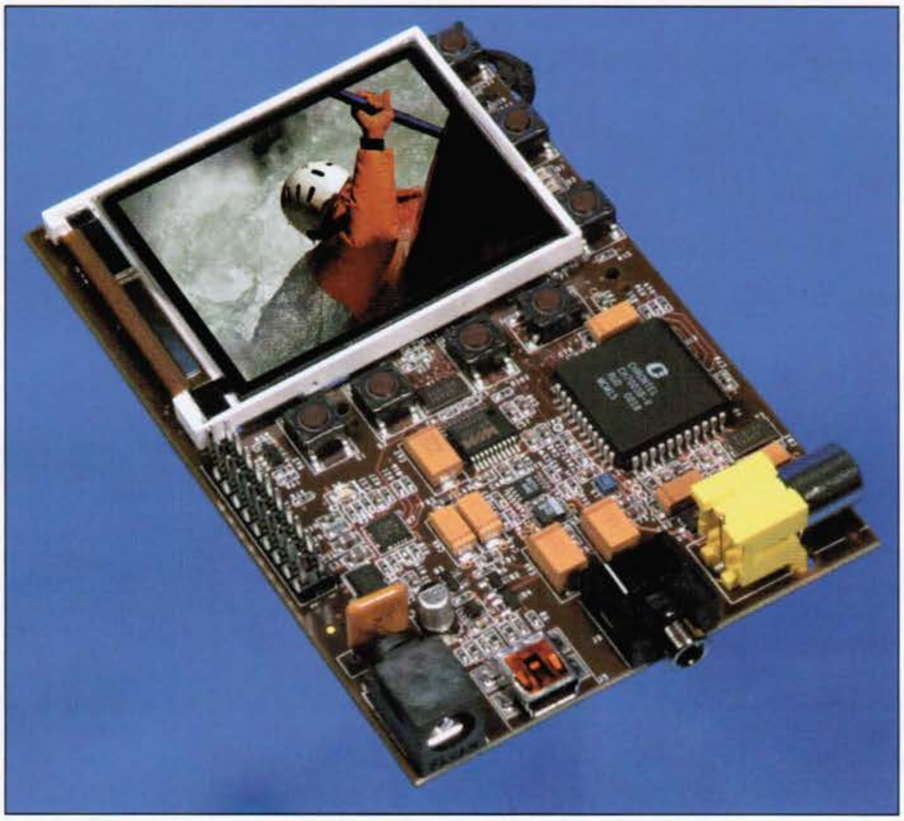

Fig. 3: Sharp's QCIF+ reference-design kit features a 2.2-in. LCD.

R&D for Alternative Technologies

Beyond the approaches to system-on-glass, display manufacturers are investing in new display technologies in the hope of improving power consumption, response times, and resolution. These technologies include microelectromechanical systems (MEMS) and organic light-emitting diodes (OLEDs).

In recent years, MEMS have done exceptionally well in advancing very-low-power device technology. These displays have a cantilevered reflective layer perched on top of a post. Upon the application of an electric field, the metallic reflective layer deforms and snaps to a new bistable state, thus redirecting incident light. MEMS does not require a polarizer, which attenuates light, and makes it an excellent technology for reflective displays.

The other striking feature of this technology is that changed images on the display can be stored for very long periods of time – days and even months. Thus, the panel is "static" and does not require continual refreshing. Essentially, zero power is consumed until the static image is changed.

However, for live video, in which the images are continuously changing, the MEMS display draws more power than an LCD. Also, achieving intermediate levels of gray scale is not as easy on a pixel-by-pixel basis as it is for an LCD.

The other main drawback of MEMS displays is that since they are strictly reflective, they cannot be used in a backlit mode. The only way to view their image is *via* reflected light, which means they require a frontlight structure if the user intends to use them in very dim ambient light. However, since frontlights have yet to be perfected, the image quality of the display may not be as good as that of backlit displays. Because of the MEMS display's limitations in medium-to-high ambient-light-level environments, it has not yet been widely pursued for mobile displays.

OLED technology is a relatively new alternative technology that is proving popular. OLEDs have intrinsic capabilities for making a very thin display. They uniformly emit light in a 180° viewing cone and have a response time of less than 1 μsec. Nevertheless, OLEDs have poorer visibility than LCDs in bright ambient light because they are strictly light emitters. For example, in an area with an ambient-light level of 500 lux, typical of an office, an OLED's contrast is reduced to a fifth or less of what it is in a dim environment. OLEDs also have a substantially shorter overall lifetime than LCDs.

The luminous output of an OLED is directly related to the current at which it is driven. To meet the luminance requirements of the mobile market, OLED manufacturers have found it necessary to use LTPS backplanes rather than the more commonly available a-Si backplanes, which do not deliver enough drive current. For mobile displays of QVGA format or less, NMOS versions of LTPS are more than adequate. For VGA or greater, CMOS versions of LTPS must be used.

Recent research performed by Royal Philips Electronics[2] has advanced OLED technology. A layer has been added that introduces a barrier to reduce hole injection, increasing the quantum efficiency about 12%. Not only does this increase the luminance of both the yellow and blue emitters, but it also makes it possible to deal with contrast reduction that occurs when transitioning from an a-Si to an LTPS driver.

Incremental Improvements

Continual improvements in display technology are benefiting the converging electronic-device market. The ongoing efforts to maximize pixel density, improve viewing angle, and reduce power consumption play a large role in ensuring that these devices will be accepted by consumers.

To achieve higher pixel density, many manufacturers have considered using in-plane switching (IPS), which has been utilized for some time. IPS utilizes transverse fields covering greater distances in the liquid-crystal (LC) layer. Higher voltages are required to produce an electric field sufficient to cause the LC molecules to respond.

Another approach is to use LC materials with lower voltage thresholds or higher dielectric constants, which results in better response to these higher electric fields. Unfortunately, LC materials incorporating these properties tend to undergo a phase transition to an isotropic state at temperatures that are lower than those for the LC materials used in conventional twisted-nematic (TN) displays. This results in lower legibility at higher ambient temperatures – in the vicinity of 40°C and above for some panels.

Compromises must be made either in response time or in overall suitability for a wide range of temperatures when IPS is used. That is not the case with all LCD designs. For instance, Sharp's new category of LCDs called Super Mobile displays also have fast response times of 25 msec or less; in addition, they operate over a wider temperature range (–10°C to +60°C), which makes them well suited for portable products that display text and still and moving images. The LC structure of the cells (Fig. 1) also gives these displays a much wider viewing angle than in the case of TN cells (Fig. 2).

One of the challenges in developing new display technologies for mobile devices is how to backlight the display. In order to make consumers feel comfortable, manufacturers try to provide them with displays that present familiar visual and operating characteristics. Because the key to making a low-power rugged display is the backlight, which improves viewability but also consumes more power than any other component in the display module, design engineers also naturally expend a great deal of effort in this area of the design.

Recently, backlight technology started moving from cold-cathode fluorescent tubes (CCFTs) to white LEDs, with a significant reduction in power consumption – on the order of a factor of 3. A white LED by itself is not a backlight. The backlight comprises the light source, light guides, diffusers, and special films to collect the light, distribute it uniformly, and redirect it through the display.

LED backlights offer other advantages as well. They can be dimmed over a continuous voltage range. As a result, when the display is being used in the transflective mode (with much of the light coming from ambient sources), the current to the LEDs can be decreased continuously as lighting conditions allow. Additional advantages are that LEDs do not have the electromagnetic-interference (EMI) signature that CCFTs do, and they are notably more rugged than CCFTs.

LED efficiency continues to improve rapidly. Substantially more luminance can be generated from the same number of LEDs with today's technology than was possible even a year ago. Since LEDs are binned according to luminance, a high-brightness component generally costs more. But newer LEDs offer higher luminance at the same power consumption as earlier models, so fewer LEDs may be needed in a single panel, thus reducing the bill of materials. In addition, these LEDs can be adjusted to reduce luminance and power consumption. The available choices allow engineers greater options when deciding what components best suit their needs.

Next-Generation Designs

In today's competitive environment, OEMs are pressured to reduce design cycles, lower system costs, and speed time to market. Until a full system LCD is developed, display manufacturers can help OEM customers by providing easier integration between the display and other components and by providing reference designs for complete system solutions.

One example of integrating components into the displays of converging devices is the recent introduction of reference designs for portable media players (PMPs) (Fig. 3). PMPs are an emerging category of devices that enable users to manage audio, image, and video files on the go, giving them an alternative to the PC and the wired personal video player (PVP).

Some of these new reference designs apply decode-only solutions and ARM-based system-on-chips (SoCs) for MPEG4 decoding and advanced audio coding (AAC) audio. The ARM-based SoCs allow PMPs to be connected directly to the display and have the advantage of a known interface that is tuned to obtain the optimum performance of 10 hours of audio and 4 hours of video from the display, simultaneously lowering both costs and power requirements. Further advances in these system solutions are on the horizon as display requirements increase.

New Opportunities

Display manufacturers are investing heavily to win the race for technological advantage in resolution, power efficiency, and reduced footprint for small-form-factor devices. Some manufacturers are setting their sights on new display technologies such as OLEDs and elastometrics. Other manufacturers are investigating new process technologies that will allow them to develop a complete system-on-glass and relying on continuous improvements in established LCD technologies to provide them with the revenue sources needed to reinvest in ongoing research.

As new generations of convergent products emerge that allow users to view still images and video, high-resolution color displays are increasingly becoming the norm for handheld products (Fig. 4). As display manufacturers continue to seek improvements in display

Fig. 4: *A camera-equipped mobile telephone with a high-resolution color display, such as the Sharp XG28 with a CG-Silicon display, is a prime example of a convergent device.*

resolution, brightness, and overall component size, these improvements will achieve increased revenue for the entire supply chain, greater overall product functionality, and better user experiences.

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Backlights for Small Displays

Backlight manufacturers are responding to the demands of today's small-display OEMs with higher efficiency, better uniformity, and lower cost – all of which require clever optical technology.

by David DeAgazio

THE INCREASING CAPABILITIES of small displays depend on the improving performance of backlight units (BLUs) and will also determine the direction in which BLUs evolve. One example of the current status of small liquid-crystal displays (LCDs) is the 2.0-in.-diagonal light-emitting-diode (LED) backlit gray-scale LCD used in Apple Computer's 5.6-ounce iPod MP3 player. The increasing demand for portability is driving the market for such products, and Apple has introduced a newer mini-iPod with an LCD of only 1.67 in., illuminated by a blue-white LED backlight.

Music players are just one application. Small displays – classified as those with a 2.5-in.-diagonal screen size or less – are also found in third-generation cellular telephones, PDAs, portable DVD players, digital cameras and camcorders, thermostats, gaming devices, appliances, and tiny microdisplays used in viewfinders for digital still cameras and camcorders.

Manufacturers of backlights for super-twisted-nematic LCDs (STN-LCDs) and thin-film-transistor LCDs (TFT-LCDs) have to address the need for increasingly smaller displays in devices that offer more functionality and integrated capabilities, including full-color still and moving images, Internet and e-mail access, games, and even TV. Heat buildup, power consumption, and costs have to be kept down, while the bar is continually being raised on brightness, color and luminance uniformity, thinness, and efficiency. Backlighting manufacturers are being asked to do more in smaller form factors with fewer components, often in high volumes.

Utilizing Advanced LEDs

Today's state-of-the-art LEDs have come a long way in terms of offering higher brightness in a smaller package, and ongoing advances in LED technology are enabling LCD-backlight manufacturers to better meet the ever-increasing challenges posed by the small displays used in portable and handheld products. These LEDs are available in a broad range of colors, including white, green, blue, red, orange-red, and amber. And they are small and getting smaller. Today, the thinnest production LEDs are about 0.8 mm high; in the near term, more-compact packag-

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Molded Light Extraction Backlighting Technologies

Technology	Efficiency	2D Pattern Possible: Uniformity and Visual Appearance
Printed Dots	Low	Yes
Etched Dots (chemical, laser, etc.)	Good	Yes
V-Grooves	Very Good	No
Pixel-Based	Very Good	Yes

Pixel-Based vs. Printed, Chemical Laser Etched or V-cut
- Greater Control
- Higher Efficiency
- Reduction of film layers
- Higher Repeatability
- Science, not Artwork

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***Fig. 1:** Comparison of molded light-extraction backlighting technologies.*

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ing will bring that height down to about 0.6 mm. Within 12 months or so, we may see production LEDs that are only 0.4 mm high. This is significant since, in many ways, LED height is the limiting factor in manufacturing thinner backlights for small hand-held products.

Molded Light Extraction

The third-generation cellular telephone is a good example of a device that provides a wide variety of features for the user and presents a major challenge to small-display backlight manufacturers. Third-generation cellular-telephone manufacturers demand higher brightness, saturated colors, extreme thinness, lower power consumption for longer battery life, fewer components, and lower manufacturing costs. Companies that meet these demands are the ones that get the contracts, but how do they do it?

Today's high-performance white LEDs can effectively and economically backlight full-color displays in third-generation cellular telephones, PDAs, or digital cameras to the brightness levels required, which was not possible just a few years ago. A backlighting technology that could reduce parts counts and materials costs, and also take advantage of the enhanced performance offered by these advanced LEDs, would be the ideal solution.

Several approaches are available. LED arrays offer very high brightness and can be used in small LCD backlights. An LED array consists of a matrix of LED chips typically mounted to an LCD's PC board. In an LCD with a viewing area of, for example, 16 × 61 mm, as many as 36 LED chips may be required. LED arrays tend to run hot, however, and are typically used only for the less-expensive colors, such as yellow-green, so they are not suitable for the full-color high-resolution displays in third-generation cellular telephones. White-LED arrays are available, but they are expensive.

A better solution is provided by molded light-extraction techniques in combination with LEDs because mechanical holding features can be designed into the backlight, permitting chip-on-glass (COG), chip-on-flex (COF), or an entire display assembly to be conveniently integrated into the customer's end product. This can reduce the parts count as well as assembly and materials costs.

There are a variety of light-extraction technologies, including printed, etched, stamper, V-groove, and pixel-based techniques (Fig. 1). All have their benefits, but let us focus on comparing the efficiency of molded light-extraction devices using printed dots or laser- or chemical-etched dots to that of a pixel-based molded light guide (Fig. 2).

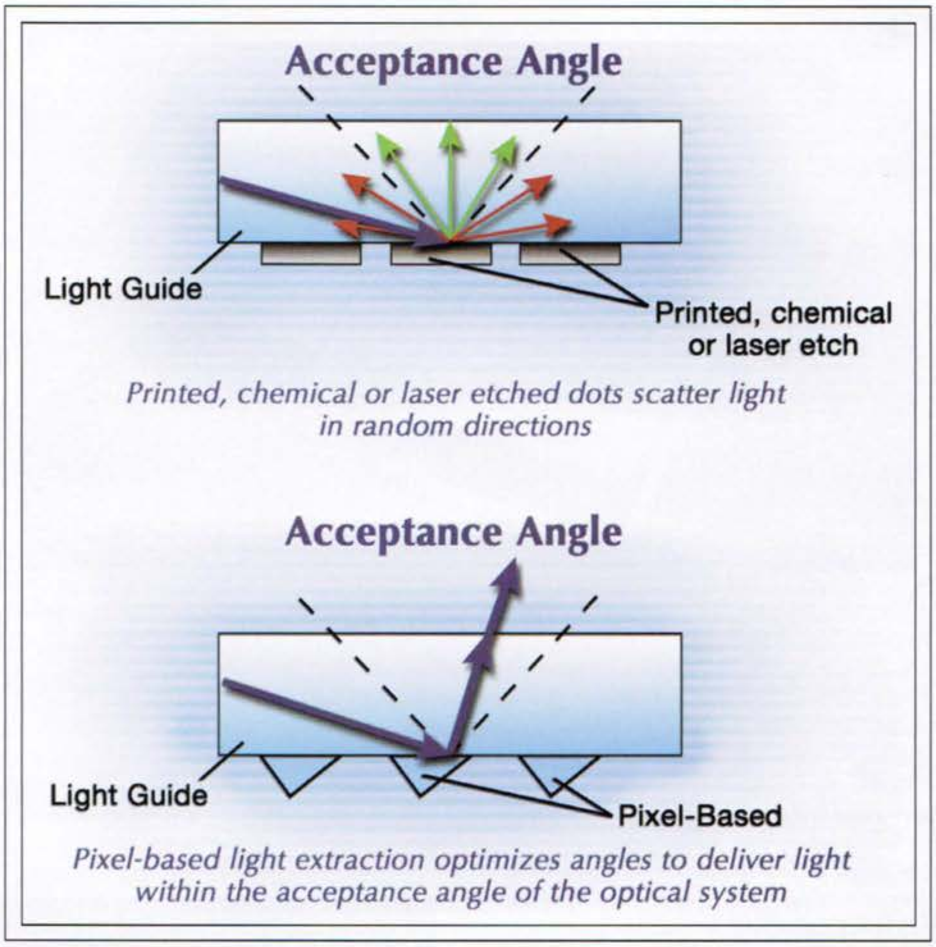

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Fig. 2: *Comparison of light extraction using different molded light-guide methodologies.*

A molded light-guide technology using pixel-based light extraction provides the manufacturing efficiencies of the other LED-based molded light-extraction technologies shown in Fig. 1, but it also enables full control of six key parameters: the size of the individual MicroLens™ light-extraction features, shape, depth, pitch, density, and angle of rotation. In the increasingly ubiquitous flip telephones with dual displays, for example, the color LCD on the inside and the monochrome LCD on the outside can be illuminated by a single molded light guide using a high-brightness white LED, effectively illuminating the outer display without significantly reducing the brightness and luminance uniformity of the main display inside.

A pixel-based light-guide technology called MicroLens™ technology, developed by Global Lighting Technologies, Inc., makes it possible to use surface-mounted LEDs in thinner panels by coupling LEDs *via* a flex circuit. This maximizes efficiency and provides a convenient plug-in unit (Fig. 3).

Brightness, Color, and Uniformity

The type of LEDs chosen, the number and spacing of the LEDs, and the LED current determine the brightness, luminance uniformity, and overall color uniformity. Demands for high brightness and color uniformity across the LCD are being met by molded light-extraction backlighting technology, which can provide luminances as high as 10,000 nits with a uniformity as high as 91%. In the cellular-telephone industry, a luminance

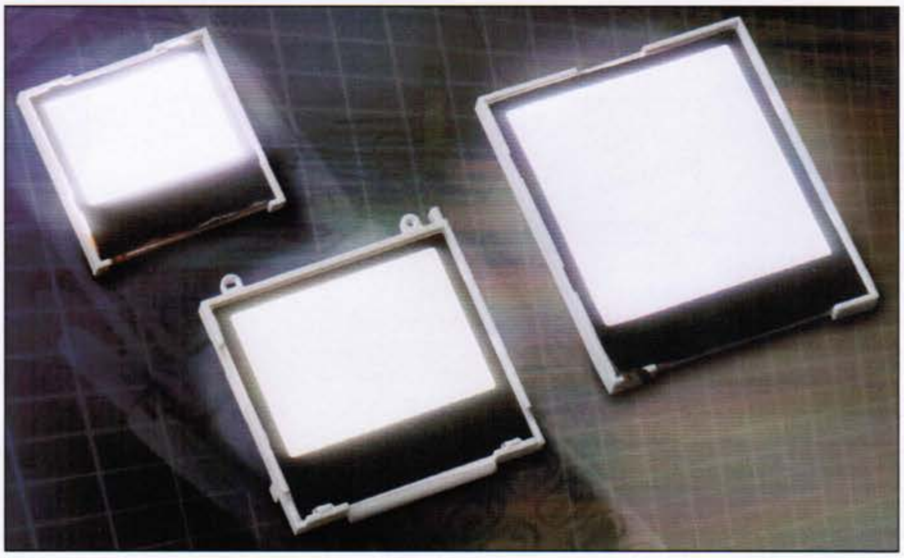

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Fig. 3: These white-LED-based molded light guides are used to backlight third-generation cellular telephones.

uniformity of 70% and higher is typically considered acceptable for high-volume-production programs.

In applications in which the small form factor limits space, light guides can incorporate side-firing LEDs which emit light parallel to the plane of the viewing area of the backlight. LED lifetime is typically rated at 100,000 hours (time to half-brightness) for yellow-greens, reds, and ambers, and 20,000–50,000 hours for whites, greens, and blues.

In addition to positioning light-extraction features on the bottom and edge of the light guide, some manufacturers are now adding such features to the top surface of the light guide. These "top shapes" can take the form of v-grooves or, in recent years, pixel-based light extraction in the form of molded-in lenses that have the ability to control luminance uniformity at every point across the panel while providing a more-collimated lighting system. The purpose of the top shapes is twofold. First, the shapes help to redirect and collimate the light, so that the luminance of the backlight is increased by 20–30% in the viewing direction. Second, the top shapes provide another means of improving the uniformity of the light emitted by the backlight. The addition of top shapes does add another level of complexity to the design and manufacture of the backlight, but the improvements in brightness and luminance uniformity can be significant, making the extra step worthwhile.

Techniques used to enhance brightness and luminance uniformity include the use of lens arrays – light-extraction features that are located on the edge of the light guide in front of the LED. They help to provide a uniform visual appearance despite a reduction in the number of light sources by widening the distribution angle of the LED and minimizing the hot spots that can occur when an LED is too close to the viewing area. The use of lens arrays permits the number of LEDs to be reduced while maintaining uniform backlight emission. This enables cost, space, component, and power savings.

White-LED backlights have provided high brightness for monochrome LCDs and are now widely used for color LCDs. White LEDs are typically not full-spectrum light sources – most have minimal output in the red region. Emerging LED technologies, such as UV LEDs, are expected to address this issue. How they do so is interesting, and it may not be immediately obvious.

Mainstream "white" LEDs are actually blue LEDs with a yellow/amber phosphor; when the colors are mixed, they yield a whitish light. There is a problem, however, with color consistency because of the intensity of the blue LED and the phosphor itself. UV LEDs would more properly be called violet LEDs because the center of their emission is at 405 nm, just above the 400 nm of UV, and

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Fig. 4: This MicroLens™ molded light guide can be embedded with a uniformly illuminated company logo consisting of virtually any text or image.

Global Lighting Technologies, Inc.

Fig. 5: *Most of the electronic viewfinders (EVFs) in digital still cameras are very small LCDs, which make substantial demands on the backlights that illuminate them.*

they are still just barely visible. Because the output of the violet LED is barely visible, LED-to-LED variation is very small, and virtually all of the visible light is emitted by an RGB phosphor which is highly stable, highly controllable, and producible in very large batches, in addition to its excellent color consistency. It is also possible to tweak the phosphor to "spike" the red or blue content to adjust the color temperature.

But even today, high-performance LEDs, combined with the new high-efficiency molded light-extraction technologies, have evolved to the point at which they can backlight color displays in devices such as cellular telephones, PDAs, and digital cameras at brightness levels not possible as recently as a year ago. For example, molded light guides utilizing three white LEDs that can produce a luminance of 6300 nits are now available.

Extra Features

Display manufacturers are always looking for ways to add extra features to their backlighting without adding an extra manufacturing step. That means the backlighting technology had better be versatile. A backlighting technology such as pixel-based molded light guides offers the capability of embedding the company's logo in the light guide, saving OEMs the extra manufacturing step of adding an overlay and adhesive to illuminate the logo on their products (Fig. 4). It is an efficient way to help customers increase brand recognition while retaining the existing backlight.

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Fig. 6: *These MicroLens™ molded light-guide backlights used in EVFs measure only 8 × 14 × 0.8 mm. The output area is 7 × 11 mm.*

Getting *Really* Small

Another industry development that poses new challenges for backlight manufacturers is microdisplays for handheld devices, such as those used in the electronic viewfinders (EVFs) of newer digital cameras and camcorders (Fig. 5). Because of parallax error, the conventional optical viewfinder used in such products does not permit the viewer to capture the exact frame shown in the lens; this effect is called framing inaccuracy. Alternatively, the user could look at the LCD in the camera, but that would shorten battery life, and the reduced contrast when viewing the display in bright sunlight would make it difficult to follow moving images. The newer, more-sophisticated camera and camcorder models incorporate EVFs that function like the LCD and show in real time what is projected onto the sensor by the lens (Fig. 5).

The EVF *is* an LCD, a very tiny one about half the size of a thumbnail and typically measuring 0.5 in. diagonally, with 235,000 pixels. A lens placed in front of the LCD enables more accurate framing of the shot and eliminates parallax error.

Developments such as EVFs pose both an opportunity and a challenge for the companies producing backlights for the tiny LCDs (Fig. 6). The form factor is very small; the LCD is only a few millimeters thick. The challenge is to achieve the necessary brightness and resolution because these LCDs have a high density of small pixels. As a result, a relatively small percentage of each pixel's area is able to transmit light, and the overall display has relatively low light transmission.

What EVF designers need is a very bright, highly efficient backlight with uniform emission, illuminated by just one super-bright white LED. Current production EVF backlights produce approximately 5000–8000 nits, using one brightness-enhancement film (BEF) and one LED; designers have asked for at least a doubling of these numbers. By adding a second BEF, the range can be increased to 7500–12,000 nits. Reaching a level of 10,000–16,000 nits requires two BEFs and the use of a pixel-based light guide.

An obvious, and effective, solution would be to backlight the LCD with a single super-bright white LED shining through a diffuser film on the back of the LCD – a "light box" type of approach. The problem is that direct lighting from an LED requires more room, which is not available in this application. At present, the best solution is to use edge-lit molded light guides instead of direct illumination. Of course, if an edge-lit light guide is used, it must be highly efficient, bright, and very uniform.

What levels of efficiency are we talking about? Today, the overall efficiency of a production EVF backlight is typically in the range of 130–150 nits/mW. With exactly the same construction and the same LED, the addition of one BEF would increase the efficiency to approximately 190–220 nits/mW. With the addition of the latest pixel-based light-extraction techniques, and with the same construction (BEFs, LED, trays, *etc.*), it is now possible to achieve 16,000–20,000 nits, with backlight efficiencies in the range of 240 nits/mW.

Meeting the ever-greater demands of the makers of today's small color displays requires backlighting manufacturers to continually adapt, customize, and improve their technologies to keep pace. To be successful, the backlight manufacturers must develop technologies that satisfy today's customer needs and have the flexibility to be adapted to handle future needs. ■

Expecting Readability

Paper-like readability is the most urgent objective of electronic paper – especially when there is no electronic medium that provides comfortable reading.

by Makoto Omodani

ELECTRONIC PAPER has been promoted as a potential next-generation display. Conceptually, at least, it combines the benefits of hardcopy and electronic displays (Fig. 1). But the present state of development of electronic paper is actually quite chaotic because the expectations of the technologies involved diverge so widely.

The various expectations for electronic paper can be summarized as paper-like readability; paper-like compactness; and multi-functionality, unlike paper. It goes without saying that less resource consumption is a common expectation. Particular applications have been linked with each of these expectations (Table 1). It is also important to clearly indicate the properties that relate to each of three key expectations.

Expectations

Readability. We generally hesitate before reading long novels on a computer screen; paper is the preferred medium. Paper-like readability is the most urgent objective of electronic paper, especially when the absence of an electronic medium that can be read comfortably is taken into consideration. Tatsuo Uchida of Tohoku University has proposed the separation of display devices into two types. Type A consists of displays that show scenes with a great deal of motion and Type B displays are for reading documents. Some of the properties of these display types would, of course, be different.

The development of specialized Type B display devices for reading documents is rare.

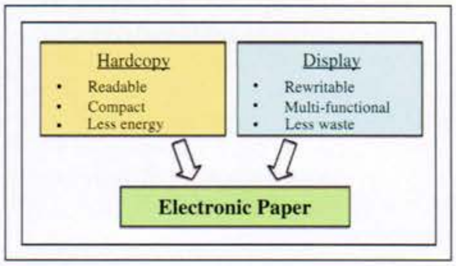

Fig. 1: Electronic paper is intended to combine the benefits of hardcopy and electronic displays.

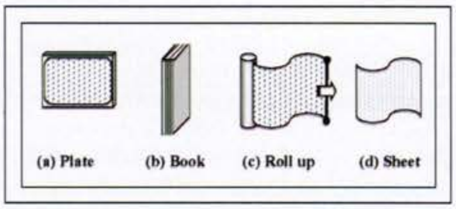

Fig. 2: Although the sheet style (d) of electronic-paper displays is the variation that receives the most attention, the (a) plate, (b) book, and (c) roll-up types may be more appropriate for some applications, particularly in the short and medium time frames.

It has been widely assumed that display devices with motion-picture capability are automatically suitable for reading static documents, but this is not the case.

Compactness. Paper-like compactness has long been a goal of display technologies. Flexibility, a currently popular technique for obtaining compactness, should be considered in more detail. There are four grades of flexibility, each with its own merits and applications (Table 2).

The first grade, "elastic," offers a very important benefit and is linked to many useful applications, although elasticity is not ordinarily regarded as a type of flexibility. Non-fragile electronic paper will, for example, enable the realization of electronic books that provide paper-like ease of handling.

The fourth grade, "folding," may seem overly ambitious; it may in fact be much more easily achieved in rigid displays with smart hinges. The grade of flexibility required should be carefully tailored to suit the application.

Table 1. Three Expectations for Electronic Paper

Expectations	*Target properties*	*Applications*
Readable	Less fatigue, Comfortable	Electronic book, Electronic newspaper
Compact	Flexible, Thin, Light	Wearable computer, Roll-up display, Portable TV
Multi-functional	Input function, Sound function, Radio-communication function	Paper PC, IC paper, Ubiquitous terminal

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Table 2. Four Grades of Flexibility

Grade	*Properties*	*Merits*	*Applications*
(1) Elastic	Non-fragile	Permits rough handling	Book, Newspaper, Portable TV
(2) Curved More difficult	Hugs curved surface	Attached to various devices	Free form display
(3) Bending	Rolls up	Cylindrical, Wearable	Roll-up display, Wearable display
(4) Folding	Folds into small area	Paper-like compactness	Folding display

Multi-functionality. Multi-functionality will be required of paper computers or ubiquitous terminals. Audio functionality and/or image input are welcomed in these applications, along with radio-communications functions, and these functions should be incorporated in compact and/or readable electronic-paper displays.

Types of Electronic Paper

Electronic-paper media can be grouped into two categories. The first is a self-rewriting medium, which is also called a "paper-like display." The second medium, which is called "rewritable paper," requires a rewriting unit.

There are several style variations of electronic paper, each of which can be realized as either a paper-like display or as rewritable paper (Fig. 2). Generally, the "sheet" style [Fig. 2(d)] is the only style that has received serious consideration as a candidate for electronic paper. But the sheet style is not always necessary if the dominant requirement is readability.

It may take considerable effort and time to realize a sheet-style electronic-paper display with a self-rewriting function, but using a separate rewriting unit is realistic if we really want to implement the sheet style as soon as possible. The application should determine the most appropriate style, and it should not be assumed that the sheet style will always be the most appropriate.

Candidates for Electronic Paper

Display systems are generally constructed by combining a display medium with a writing method. Many combinations of writing methods and medium-transformation modes are possible, and many candidate technologies for electronic paper exist (Table 3). (The vacant boxes in the table provide opportunities for future research.)

As an example, researchers at Tokai University have developed a prototype of an electronic-paper system based on liquid-crystal technology [H. Yoshikawa *et al.*, "Digital Paper with Guest-Host-Type Liquid-Crystal Medium," *J. Imaging Science and Technology* **47**, No. 4, 304–308 (2003)] (Fig. 3). The surface-charge-driven guest-host polymer-dispersed liquid-crystal (PDLC) display delivers paper-like flexibility and an omni-directional viewing angle. A compact ion-projection head was used to form the surface charge, and paper-like thickness was achieved by separating the rewriting unit from the medium. The ion-projection head uses a corona-discharge ion source with many apertures through which the ion flow passes. An LC sheet attached to a sliding stage receives projected ions from the linear ion source above the stage and forms a charge pattern on its surface. This surface charge provides the LC sheet with a driving electric field. The alignment of host LC molecules and guest dichroic dye in droplets in the sheet is controlled by the surface charge. Image contrast is determined by the alignment of the guest dichroic dye. This arrangement allows the user to hold many sheets of a low-cost compact medium that offers comfortable paper-like browsing but at the cost of requiring a separate rewriting unit.

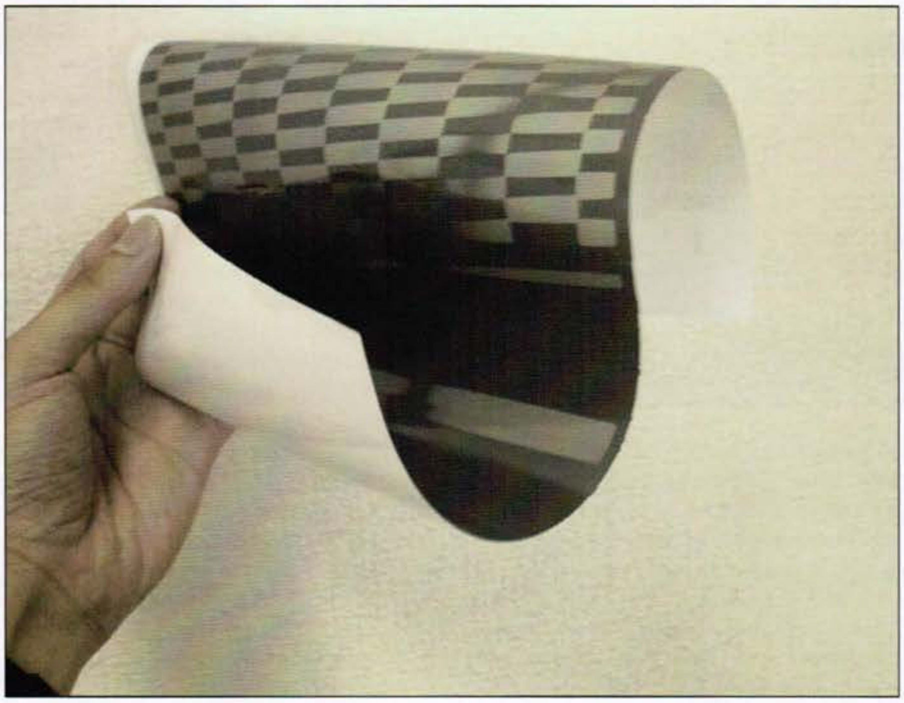
Studies on Readability

It is not clear how we should pursue the issue of readability. Why we do not like to read books and other long documents on computer screens remains an open question. Studies have concentrated on rather simple measurable qualities such as contrast; the existing body of work remains incomplete.

We have recently focused on this theme and are now trying to determine how to achieve readability experimentally. We have compared the efficiency and fatigue levels of subjects performing reading tasks on paper and displays. Our recent results have shown

Table 3. Combinations of Writing Methods and Medium-Transformation Modes

Medium / **Writing method**		**Medium transformation modes**				
		Physical			**Chemical**	
		Migration	*Rotation*	*Molecular movement*	*Phase change*	*Structure change*
Writing methods	*Electric*	Electrophoretic, Toner migration	Twisting ball	Liquid crystal		Electrodeposition, Electrochromism, EL, OLED, PDP, FPD
	Magnetic	Magnetic migration	Twisting ball			
	Light			Liquid crystal		Photochromism
	Heat	Thermo magnetic		Liquid crystal	Micro phase separation	Leuco dye, Thermochromism



Tokai University

Fig. 3: This electronic-paper system, which uses ion-projection driving of a guest-host-type PDLC, was developed at Tokai University.

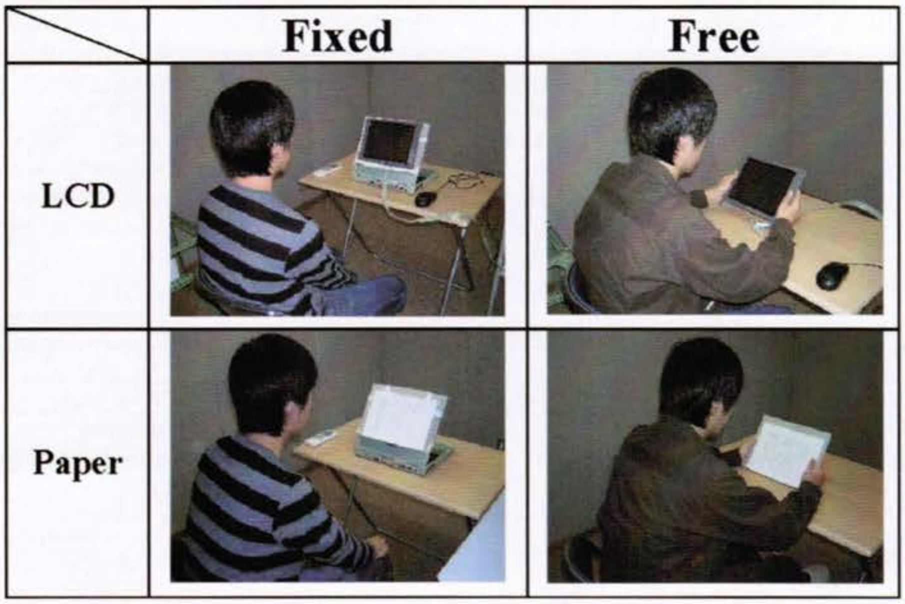


Fig. 4: Experiments were carried out to measure reading speeds and fatigue levels under four different reading conditions.

that there is a large difference in the measured fatigue levels for the two media, while there is only a small difference in the measured efficiency.

We are attempting to clarify the causes of the different fatigue levels for the two media. A possible cause is the difference in reading styles. "Freehand holding" is a popular way of reading text on paper, and this reading style is totally different from the fixed reading style used with rigid displays on a desk.

Our recent studies of subjects using model displays have shown that the freehand-reading condition yields lower fatigue levels than the fixed-reading condition [M. Omodani, "What Is Electronic Paper: The Expectations," *SID Symposium Digest* **34**, 128–131 (2004)]. Experiments were carried out to measure reading speeds and fatigue levels under four different reading conditions. The media were bundled paper and a lightweight LCD unit. Two different reading styles were examined: freehand reading (usually handheld) and fixed reading (the medium was set on a desk). Figure 4 shows the four reading conditions. Reading volumes were measured after 30 minutes of reading, and the fatigue levels were indicated by the subjects just after the reading task.

Figure 5 shows measured reading speeds for the four conditions as calculated from the reading volumes. Slight advantages were indicated for freehand reading, particularly for the LCD. Figure 6 shows the five fatigue levels under the four conditions. It should be noted that freehand reading shows lower fatigue levels than fixed reading. The reason for this difference is thought to be associated with eye fatigue. The subjects exhibited smaller decreases in focusing ability after freehand reading than after fixed reading.

This result indicates that it may be possible to improve display readability by simply adopting the freehand-reading style. Since freehand reading is generally performed on a handheld display, we must improve the compactness of display devices to realize the style more broadly. This goal should be added to the usual objectives of resolution, contrast, viewing angle, *etc*. Screen size is obviously critical; the readability of PDAs is not really satisfactory.

An experimental approach to investigating display readability, as contrasted with paper, has just been developed. However, it is already clear that this approach will assist in

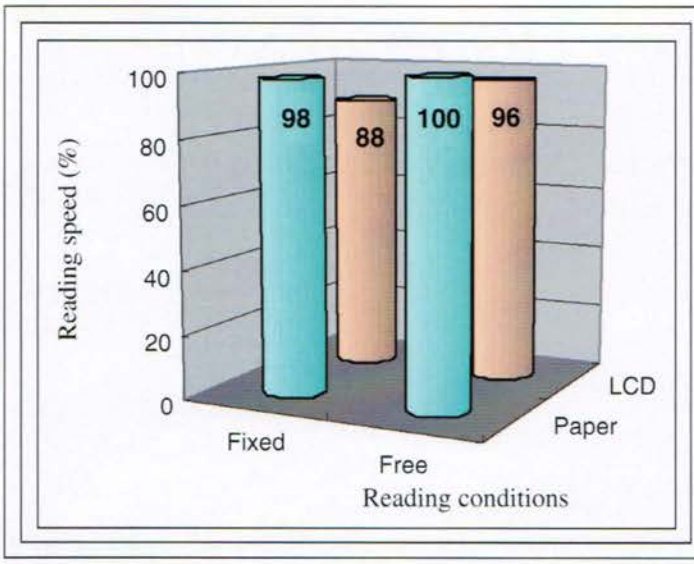


Fig. 5: Shown are the measured reading speeds for the four conditions.

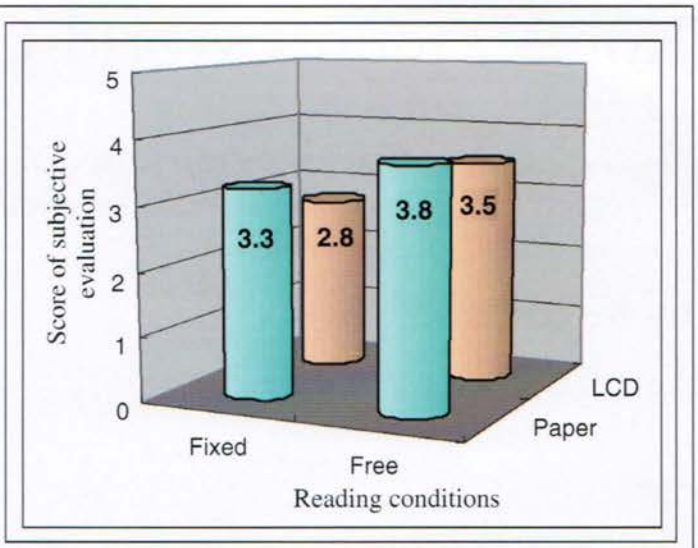


Fig. 6: In these measurements of fatigue levels, a high score indicates less fatigue.

finding the causes of the poor readability on displays and in discovering how to make readable electronic paper.

Applications

Electronic paper is expected to have wide application, especially for electronic books and newspapers. It goes without saying that present distribution systems, which demand the physical handling of large quantities of bulky paper, are not efficient – especially when considering the very high cost of paper itself, printing, transportation, and stocking. The rapid aging of printed information is an additional disadvantage of the paper system. We believe the absence of readable displays is one of the highest barriers to the replacement of the paper systems currently in use. Readable electronic paper would help put in place more-convenient distribution systems for books and newspapers.

We see electronic paper as having an essential role as a bridge between the virtual world consisting of computers and networks and the real world (Fig. 7). ■

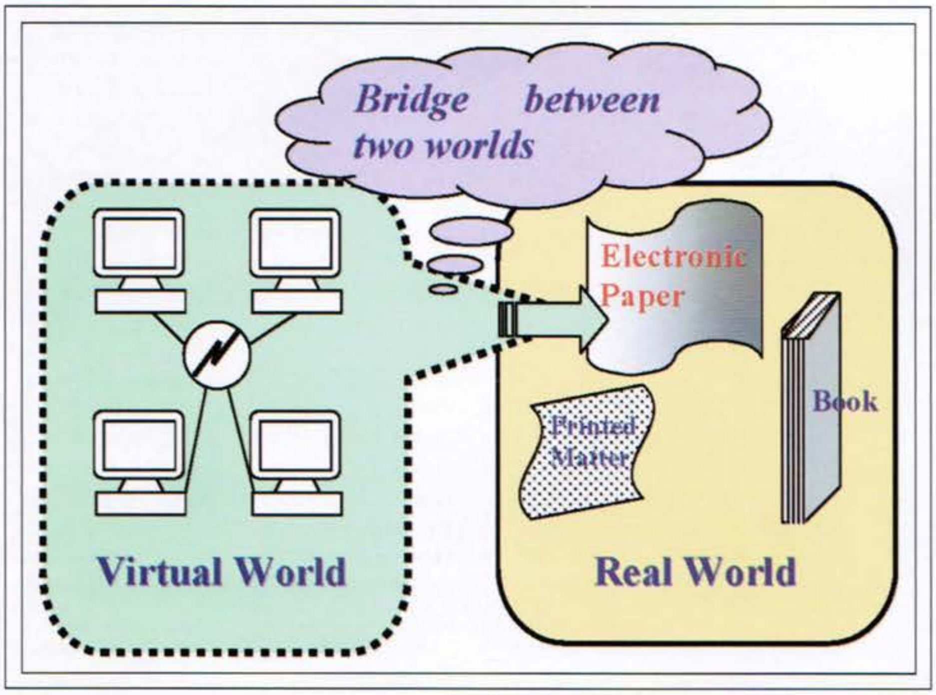


Fig. 7: Electronic paper bridges the virtual and real worlds.

conference report

Korea Mounts World-Class Display Event

The combination of Asia Display and the International Meeting on Information Display was the largest display event ever held in Korea.

by Ken Werner

THE 24th International Display Research Conference (Asia Display '04), sponsored by the Society for Information Display (SID), and the International Meeting on Information Display (IMID '04), sponsored by the Korea Information Display Society (KIDS), were combined to create the largest display event ever held in Korea. The conference ran from August 23 to 26, 2004, at the Daegu Exhibition and Convention Center (EXCO) in Daegu City, Korea (Fig. 1). Final attendance for the technical conference was about 1700, compared with about 1000 for IMID itself last year.

At the exhibition – organized by the Electronic Display Industrial Research Association of Korea (EDIRAK), the Korean Information Display Society, and *The Electronic Times* – 114 exhibitors from seven countries occupied 270 booths. Exhibits Chair W. Y. (Wayne) Kim said that some exhibitors had to be turned away because of a lack of space.

Monday Workshop

The event started with a day of tutorial presentations on Monday, August 23. David Mentley noted that the TV market demands a display price of 1–3 dollars per square inch based on CRT-set prices. There is plenty of room for both plasma-display-panel (PDP) and rear-projection-TV (RPTV) sales, he said, but supply issues remain.

The afternoon session began with a renewal of the running battle between LG.Philips LCD and Samsung Electronics concerning which of their large-screen-LCD technologies is superior for TV. Using photos and specifications, Wayne Kim of LG.Philips LCD compared the performance of True Wide In-Plane Switching (TW-IPS) technology, the latest improvement to the company's Super IPS (S-IPS) technology, to Samsung's patterned vertically aligned (PVA) technology. TW-IPS adds a "True Wide" optical-compensation film to S-IPS for even less mid-tone color shift at wide viewing angles, which was impressively demonstrated on the show floor.

But Kim went beyond comparisons of IPS and PVA. He identified overdriving, liquid-crystal (LC) materials with lower rotational viscosity, smaller cell gap, and scanning backlights as ways to improve response time. Conventional LCDs use sample-and-hold driving, he said, which results in blurred mov-

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***Fig. 1:** The combination of Asia Display and IMID, held from August 23 to 26, 2004, at the Daegu Exhibition and Convention Center (EXCO) in Daegu City, was the largest display event ever held in Korea.*

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ing images. A shortened illumination time produces an impulse-driving effect.

He noted that the conventional definition of LCD response time makes it hard to measure motion blurring. He explained a relatively new measure, Moving-Picture Response Time, which is indicated by the width of the blurred edge of a rectangular image moved across the screen, a metric that is now called the Blurred-Edge Width. In the near future, response time will go from 12 to 8 msec, and gray-to-gray response time will go from 8 to 4 msec, Kim said.

To improve contrast ratio, he suggested a low-scattering color filter. For further improvement, we must control the backlight as well as the LCD *via* Dynamic Contrast Ratio. "We need to control peak brightness, as is done for CRTs," he said, and "In order to become the display of preference, we must innovate not only in performance but also in process and cost."

In "Advancement of PVA Technology for HDTV," K. H. Kim (Samsung Electronics) said that PVA mode has a better and more uniform black state at all viewing angles than S-IPS. There is also a new optical-compensation film. In the new version of PVA, called S-PVA, contrast ratio improves from 1040:1 to 1300:1.

Kim extolled the advantages of LC drop filling and showed a flow chart comparing it to conventional capillary filling. In drop filling, a drop of LC material is deposited on one of the LCD plates and the second plate is then placed in position over it, causing the LC material to spread throughout the display. The new process is much simpler, he said.

AU Optronics Corp. (AUO) uses Premium-MVA (P-MVA), which is in the same family of cell designs as PVA. In "Advanced Technologies for LCD TV," C-T. Liu summarized the specs of AUO's 46-in. TFT-LCD. "AUO is the first manufacturer in Taiwan and the second worldwide to produce a 46-in. LCD-TV module with the most advanced technologies, outperforming PDPs," he said.

The luminance of the 46-in. module is now 600 nits and will be 800 nits in 2006 and beyond. More than that is not required, Liu thinks. The present color gamut is 75% of the NTSC standard area and will be 85% from late this year to beyond 2006. (Among Asian suppliers, color gamut is most commonly specified as a percentage of NTSC, with the "of NTSC" often omitted.)

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Fig. 2: The design of Woo Young's Wytech monitor with pivot-out speakers appears to have been inspired by a Flash Gordon *movie serial of the 1930s.*

Liu explained the operation of P-MVA, and said that it had a good dark state and high contrast ratio. An optical-compensation film reduces light leakage and improves the off-axis contrast ratio. P-MVA has a better color gamut than S-IPS, he said, but the recent application of compensation film to S-IPS to make TW-IPS may bring it back to equality with P-MVA. But the previous superiority of IPS is gone, he said.

Liu also said that the moving-picture quality is not good enough because a "hold-type display" induces blurring when a picture moves fast. He mentioned four types of backlight control to improve the situation: an image-tracking backlight, a blinking-backlight system, gray-field insertion, and super black-line insertion. The latter is an impulse-type display using a synchronized light source.

He mentioned that AUO will use U-shaped fluorescent lamps in the backlight unit from Q2 '04 for power and cost savings. He also said that one-drop filling takes less than 5 minutes for the entire sheet, while capillary filling takes 2 days.

In addition to reducing the number of mask steps and increasing glass size, Liu noted that cost reduction can be achieved in either roll-to-roll or ink-jet printing of the color filter, black matrix, and polyimide alignment layer, *i.e.*, all the organic layers.

Chong H. Kim of Credit Lyonaise said that the high margins of LCD TVs are due to the set makers, not the panel makers, and these margins cannot last. "There's a legion of Chinese assemblers ready to get into TV assembly of LCD TVs and projectors at 5% margins. The assembly task is a snap and components are widely available," he said.

He also said, "TVs are swallowing up enough square inches of AMLCD capacity that they are creating a shortage of capacity and a firming up in notebook and monitor panels. Otherwise, there would be remarkable oversupply. When Gens 6 and 7 come on line, smaller-panel prices will drop sharply as the TV moves from current Gen 5 to the new Gen 7 plants."

Opening Session

In the opening session on Tuesday, Conference General Chair S. W. Lee of Samsung noted that more than 340 papers would be presented at Asia Display/IMID.

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*Fig. 3: A 30-in. QXGA+ (2460 × 1600-pixel) TFT-LCD from LG.Philips LCD used the copper bus-line technology that won the SID/*Information Display *2003 Display of the Year Gold Award.*

SID President Shigeo Mikoshiba observed that the center of display manufacturing had moved from the U.S. to Japan to Korea, making it particularly appropriate to hold a major international conference and exhibition there. He noted that PDPs will soon offer lifetimes of 20,000 hours to half-luminance and that LCD developers are working hard to mount an effective challenge to PDPs. Mikoshiba said that he hopes for "productive competition that will lead to breakthroughs in both technologies."

In the first keynote address, Hirotoshi Matsuda (NEC–Mitsubishi Electric Visual Systems Corp.) made an appeal for enhanced color spaces for displays, which, he said, have more-limited color spaces than digital cameras, image scanners, and other devices. It is feasible, he said, to incorporate Adobe RGB into LCD monitors, and pointed to the NEC–Mitsubishi 21.3-in. UXGA AMLCD with an LED backlight and the 22.2-in. UXGA with a CCFL backlight that were demonstrated at the 2004 SID International Symposium.

Printers have unique color spaces, but those spaces, too, are much wider than those of displays. Printers, scanners, and cameras, he said, are totally compatible with the Adobe RGB color space, and he urged the support of Adobe RGB.

In the second keynote, Jun B. Kim, Director of Strategic Materials and Appliances Procurement at Hewlett-Packard Mobile Computing in Houston, Texas – who stood in for Senior V.P. and General Manager Alex Gruzen – spoke about Hewlett-Packard and the LCD industry. That is a big subject because H-P has the IT industry's biggest materials budget and is the IT industry's largest supply chain.

Kim said that focus groups indicate a substantial interest in notebook computers with 17-in. displays for commercial buyers. He said that the commercial market for portable devices is driven by wireless connectivity and security, while the consumer market is driven by the desktop gaming experience, the ability to burn movies on DVD+RW, and similar features.

In response to a question from *Information Display*, Kim said that the focus-group demand for 17-in. displays was for wide-format displays. A follow-up question was "Do you think it will get larger?" Kim's response was "Yes, up to 20 in. so people can do serious spreadsheet work. Of course, it is not exactly a notebook, but there is interest."

Technical Program

In "PDP with High Luminous Efficiency," Jeong Doo Xi described Samsung SDI's new MARI PDP, which has an extra "M" scan electrode. This structure results in high efficacy because it reduces ionic heating, Xi said. The new display contains 12% xenon gas and has an efficacy of 2.4 lm/W. It produces a peak luminance of 1200 nits and an average white luminance of 250 nits. The panel consumes 210 W at full white and has a 235-V sustain voltage. The panel has 852 × 480 pixels, but Samsung SDI plans to make a higher-resolution version.

In the Q&A, Larry Weber commented that using the extra electrode adds capacitance that the sustain driver must drive, thus increasing power consumption. He asked, "Can you estimate the increase?" A senior member of the MARI team answered from the floor that the increase is less than 10% and that the total power consumption decreases.

In "The Moving-Picture Quality of FPD TVs," Jumpei Nakamura said that in Japan they are preparing the Moving-Picture Response Time as an LCD standard. He said turning the backlight off for 25% of the frame time achieves moving-picture performance similar to that of a CRT.

Y. Yoshida discussed the development of Sharp's LC-45GD1 45-in. LCD TV, which, he said, had been introduced to the market earlier in August. The unit's lifetime is specified at 60,000 hours. The TV set incorporates adaptive control of the backlight unit, which reduces the maximum luminance to less than 150 nits when the unit is placed in a dark room. This allows the LC-45GD1 to represent "visually optimal pictures, even for a low-contrast source picture under dim viewing conditions."

Fujio Okumura (SOG Research Laboratories, NEC Corp.) said that NEC is using low-temperature polysilicon (LTPS) in its system-on-glass (SOG) program. Among the company's current developmental displays are a 230-ppi reflective SOG LCD and a 333-ppi 2.5-in. 2-D/3-D autostereoscopic display. Putting more functions on the panel would require too much peripheral area, so they need next-generation lithographic tools to make things smaller.

In a private conversation, David Mentley of iSuppli Corp. said that there is a shortage of indium tin oxide (ITO) because of a shortage of indium. A possible alternative is a thin coating of selected carbon nanotubes (CNTs), but only for low-conductance applications so far.

N. C. van der Vaart (Philips) discussed next-generation active-matrix polymer-LED displays, which will be used as mobile-telephone main displays by 2005, he said. Philips is building the world's first full-color polymer-OLED mass-production line. The line should be completed by the end of 2004, and in production by 2005.

Larry Guzowski (Performance Display Systems) discussed using U-shaped T5 hot-cathode fluorescent lamps to make a high-brightness long-lifetime backlight system for large-screen television. Controlling lamp surface temperature is a critical step in attaining the long lifetime, he said. The backlight design uses fewer lamps, fewer inverters/ballasts, and no polymer films or BEF, so it can be considerably less expensive than conventional designs, Guzowski said.

In "Carbon-Nanotube FED: Japanese National Project," S. Okuda (Mitsubishi Electronics) said the project has now started. The primary issue is a uniform electron source. The secondary issue is developing a spacerless panel. He noted that Canon and Toshiba have announced they will start FED production in 2005–2006 with either Spindt tips or surface emitters, but these emitters are not good enough for large-area displays, Okuda said.

Tuesday Evening Session and Posters

In the evening session, Larry Weber continued his analysis of PDP and LCD lifetime and performance that reaches the conclusion that PDP lifetime is greater than LCD lifetime, which is the opposite of what LCD makers have been saying for some time. Much of the argument is presented in detail in the August issue of *Information Display*.

In "The FP Industry in China," Zhengmin Sun presented extensive industry data, including the fact that PDP-TV sales in China in 2003 were 80,000. He also said that BOE's Gen 5 TFT-LCD plant outside Beijing will begin production in Q1 '05, and that eight companies from Taiwan and Korea are putting

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Fig. 4: *Samsung's 17-in. WXGA display with pixels containing six different colored subpixels provided more-subtle color renditions and an expanded color gamut.*

module-assembly operations in China. He said there will be three or four Gen 5 and 6 production lines by the end of 2008, as well as glass-substrate lines; and five or six color-filter lines by the end of 2010. There is a goal to manufacture 500,000 LCoS projection engines per year.

Horng-Show Koo surveyed the development of the TFT-LCD industry in Taiwan. Along the way, he mentioned that driver ICs are now available in Taiwan for one dollar and that the domestic supply chain is getting very good. There are independent color-filter manufacturers, including AMTC and Hotek.

The Poster Session showcased an impressive amount of varied display research from Korean universities. There were quite a few cooperative activities with Russian and Ukrainian universities. An intriguing, purely Russian presentation was "Porous Fiber Filled by Liquid Crystal for Flexible Displays and E-Paper Technology," by a team from the Lomonosov Moscow State University and the Cometa Central R&D Institute. Vladimir Mashchenko said that the Russian team was doing the science, and they would like to find a technology partner.

Exhibition

Some reports said that nearly 10,000 people passed through the exhibit halls at Asia Display/IMID. That might be a bit high, but many who appeared to be students and members of the general public crowded the large LG.Philips and Samsung booths to look at the latest in production and prototype displays. The remainder of the floor space in the two exhibit halls was devoted to manufacturing equipment, materials, components, and other elements of the display-manufacturing infra-structure.

Woo Young showed 1.8–7.0-in. LED-backlight units (BLUs) and 2.5–7.0-in. CCFL BLUs. A 15-in. LED BLU used RGB LEDs and a light-guide panel. There was a 32-in. BLU with eight thin U-shaped lamps, and several sizes of prism light-guide-panel BLUs of monitor and notebook size were shown.

Although primarily a backlight manufacturer and molder of cabinets for electronic products, Woo Young is also involved in the

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Fig. 5: *AVACO's cassette-transfer robot system can lift and position loaded Gen 6 cassettes weighing 550 kg.*

LCD-TV and LCD-monitor business, both under its own Wytech brand and for OEMs. One monitor had a striking design that seemed to be inspired by old *Flash Gordon* movie serials of the 1930s (Fig. 2). There was also a series of hang-on-the-wall picture-frame monitors. Hansol showed BLUs up to 46 in.

DSM Desotech was demonstrating its self-assembling single-layer AR coating, which has approximately 1% reflectivity, quite flat across the optical range. The material is easy to apply, and the thermodynamics of the chemical system gives material no choice but to assemble in the intended way, said Chander Chawla. There has been a great deal of interest, both at SID 2004 and in Daegu, Chawla said. The first customer quotes were scheduled to go out in the fall.

LG.Philips LCD was showing field-sequential-color TFT-LCDs using OCB mode. A 2.2-in. QVGA OCB and a 3.5-in. VGA OCB were both specified at a response time of 5 msec and a luminance of 200 nits, with a color gamut of over 90% (NTSC). A 3.8-in. HVGA (320 × 480-pixel) LCD had an all-in-one module containing gamma, TCON, dc-dc, and V_{com} drivers. Gate and data drivers were integrated on the panel.

A 42-in. TFT-LCD with 1366 × 768 pixels, a luminance of 600 nits, and a contrast ratio of 1200:1 featured a scanning backlight for reduced motion blur and a dynamic contrast ratio by using a backlight modulation technique. It worked, and moving images looked good.

A 19-in. 1280 × 1024-pixel S-IPS TFT-LCD featured a color filter on the TFT plate and a contrast ratio of 500:1. LG.Philips LCD said that the 300-nit luminance represented a 35% improvement over a similar display with a conventional color filter on the opposite plate. There was no change from the standard TFT device structure, and the display was made with conventional LCD-manufacturing equipment. The display produced vibrant still images.

A 30-in. QXGA+ (2460 × 1600-pixel) TFT-LCD used the copper bus-line technology that won the SID/*Information Display* 2003 Display of the Year Gold Award. The display produced beautiful images (Fig. 3). LG.Philips LCD claims uniform image quality, improvement in both contrast ratio and aperture ratio, unification of electrode methods, process simplification, and cost reduction. In a paper concerning this display, H. C. Choi said that use of the copper bus lines increased the aperture ratio by 3–5 percentage points, and commented that the planarization of the copper is an important contributor to the improved contrast ratio. The display is in mass production, he said.

A variety of production displays were being shown, with LCD-TV panels up to 55 in. Complete LG Electronics LCD-TV sets were on display, including 32- and 37-in. models with 1366 × 768 pixels, a luminance of 500 nits, a contrast ratio of 1000:1, and a response time of 8 msec.

LG Electronics was also showing Xcanvas PDP TVs up to 71 in., with high definition, a luminance of 800 nits, a contrast ratio of 1200:1, and LG's XD engine. This is the world's largest mass-production PDP TV, LG says.

Crowds made it hard to get through the Philips booth after lunch on Wednesday. The Philips WSRF SuperSlim Cybertube+ CRT attracted considerable attention, as did an apparently similar tube from Samsung. The tubes had received considerable newspaper coverage earlier in the week. [For a description of the design of the SuperSlim Cybertube+ thin CRT, see "A Slim CRT to Compete with Flat Panels" by Frits C. Gehring *et al.*, *Information Display*, 22–24 (March-April, 2004)].

Samsung SDI's thin color picture tube was called the VIXLIM, and a 32-in. VIXLIM-based TV in a 38-cm-deep cabinet was impressive when compared with a standard CRT TV in a 60-cm-deep cabinet.

Samsung's PDPs were generally looking good, and the 80-in. HD unit continues to be impressive. The 42-in. MARI PDP discussed in the technical session had 852 × 480 pixels, a luminance of 1200 nits, a luminance efficiency of 2.4 lm/W, and a dark-room contrast ratio of 2000:1.

On the small-display side, Samsung had a 2.6-in. VGA TFT-LCD with 300 ppi. It had amorphous-silicon gate drivers integrated on the glass, and Samsung billed this the "world's highest pixel density" display using this technology.

The 17-in. UXGA AMOLED prototype was on display, as it had been at SID 2004, and it is still beautiful. It consumes 10 W of power with 30% of its pixels on. A good-looking 2.2-in. QCIF (176 × 220-pixel) AMOLED was also on display. It had a luminance of 150 nits, a color gamut of 68% of NTSC, and a contrast ratio of more than 1000:1. The power consumption was 150 mW with 30% of the pixels on.

An RGBCMY 6-subpixel TFT-LCD was shown. The display gave a more subtle rendition of colors than an adjacent RGB unit, but it was hard to see the difference in some images (Fig. 4). The fact that the white point was not the same in both displays made comparison more difficult; still, the more one looked, the more one could see the expanded color gamut. The 17-in. WXGA display had a color gamut 98% of NTSC and a luminance of 540 nits. The RGB to RGBCMY color algorithm implements decomposition, gamut expansion, and luminance correction on the fly. In the same corner of Samsung's booth were 14.1-, 7.0-, and 2.4-in. polymer AMOLEDs with a-Si TFTs.

Finally, AVACO Co., Ltd., of Daegu was exhibiting a variety of display-manufacturing equipment, including an actual cassette-transfer robot system with a huge Gen 6 cassette that weighs 550 kg when loaded (Fig. 5). ■

continued from page 4

OLEDs. But the manufacture of AMOLEDs is not easy, which is why SK Display produced only a small number of devices for a digital still camera and Sony did not begin to mass-produce a 3.8-in. top-emission AMOLED (for the Sony Clié PEZ-VZ 90) until September of this year. Many AMOLED prototypes ranging from 2 to 40 in. have been developed recently, mainly by Asian companies, and these prototypes remind me of the AMLCD prototypes developed in the mid-1990s. Sharp, for example, developed a 40-in. tiled AMLCD in 1996. The year 2005 should see the production of the first commercial AMOLED for the main display of mobile telephones. The manufacturing will be done by Korean and Japanese companies.

During the past few years, the lifetime and quantum efficiency of OLEDs have greatly improved. Universal Display Corp. and other companies achieved 100% internal quantum efficiency in green. The lifetime of developmental small-molecule OLEDs has now reached 35,000 hours at 500 cd/m^2 in red, 20,000 hours in green at a luminance of 1000 cd/m^2, and 1000 hours at a luminance of 200 cd/m^2 in blue [see M. Hack and J. Brown, *Information Display* **20**, No. 6, 12–14 (June 2004)]. This development should ensure that commercial AMOLED products for mobile telephones are just around the corner. Last year, Samsung SDI achieved a 10-lm/W luminous efficiency for a 2.2-in. full-color mobile-telephone AMOLED.

When we look back at the history of the AMLCD, we see that Sharp first mass-produced AMLCDs for notebook PCs in 1990, following tremendous R&D efforts in the industry from 1985 to 1990, but there was keen competition between STN-LCDs and TFT-LCDs until 1998. Following their commercial introduction, TFT-LCDs took eight years to become the king of laptop displays. Primary displays for mobile telephones would be the first large-volume AMOLED products, which could lead to the growth of future applications such as PDA and TV displays.

The main hurdle for the AMOLED business is its backplane manufacturing. The TFTs in the backplane should have uniform performance at each pixel level, which is a demanding requirement because OLEDs are current driven. The mobility, threshold voltage, and subthreshold slope should be very uniform, a particularly difficult requirement for low-temperature polycrystalline silicon (poly-Si).

Poly-Si is conventionally made by excimer-laser annealing (ELA) of amorphous silicon (a-Si), which results in some non-uniform material structure because of grains with irregular sizes and different orientations. Amorphous silicon, on the other hand, has uniform material properties and thus gives quite uniform TFT performance. The recent big improvement in phosphorescent-OLED (PHOLED) performance make it possible to use a-Si TFTs.

The current that can be produced by an a-Si TFT is much lower than that of a poly-Si TFT because of a-Si's low electron mobility. However, the much higher luminous efficiency offered by PHOLEDs makes it possible to achieve a luminance greater than 300 cd/m^2 with just a few μA of OLED current, which is within the capabilities of a conventional a-Si TFT. As a result, a-Si has become a strong competitor to LTPS in active-matrix-backplane applications.

However, the threshold voltage of an a-Si TFT shifts during operation because defects are generated in the channel of the TFT, which degrades the OLED current. This is the most important issue to be overcome in the application of a-Si TFTs to AMOLEDs. Several approaches are being explored to overcome this problem, including the placement of a compensation circuit in the pixel and process modifications to make the TFTs more stable in operation.

The manufacture of active-matrix backplanes for OLEDs is quite difficult compared to that for LCDs. LCDs are voltage driven and the TFT is used only for switching, so we only need specifications for the on and off currents and the threshold voltage of the TFT. An OLED, however, is driven by current, so the performance of the TFTs must be very uniform. This requirement makes manufacturing very difficult. The success of AMOLEDs depends on achieving uniform TFT performance over the entire display area. The circuits that have been proposed to compensate for the non-uniform TFT performance provide some improvements in the non-uniformity of OLED currents over the display area, but cannot compensate completely for the non-uniformity.

The success of AMOLEDs will depend on manufacturing the active-matrix backplane with high yield and uniformity. Some companies will try to do this with existing or improved LTPS technology, and some others will do it with a-Si technology.

The AMOLED market is expected to be greater than US$10 billion in 2010. This may the turning point at which AMOLEDs will begin to have a great impact on the display business. The most important advantage of OLED technology might be its simple display structure, which could put AMOLEDs in a position to compete with AMLCDs, probably from 2010 on.

The ideal display might be an emissive flexible display. For this, an AMOLED on a flexible substrate could be a strong candidate. Before such a display can be realized, however, there are many problems to be overcome, such as those involving the substrate, gas barrier, thin-film encapsulation, active matrix on flexible substrate, and interconnection with driver ICs. My students are working hard to solve these problems and realize the dream of a flexible AMOLED. ■

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backlight

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devices and other technologies. Cardboard movie posters, which today are manually swapped out each time the slate of movies changes, will become as obsolete, as LCDs and PDPs – installed once and then reprogrammed on demand – take over their role. And traditional outdoor movie marquees, whose contents are painstakingly changed today, plastic letter by plastic letter by teenagers atop tall ladders, will give way to LED signs.

If the future continues to show consolidation and strategic partnering in display companies, geographical shifts in manufacturing centers, and convergence of functions in display-based products, then we will all be wearing computer-communications-entertainment hats in 2014 made by one huge Chinese company. (I do not really expect that to happen, but felt obliged to extend at least one set of current trends to a logical though absurd consequence.)

And if the technologists and marketers can finally get their communal act together, 2014 will bring the first portable computers that can cope with outdoor ambient lighting so we can finally use our computers outside. How I hope that happens well before 2014!

Ten years is a long time in terms of display-industry changes, and 2014 may see a number of other things emerge. By then, conformal displays will have carved (or curved) out a niche, freeing designers from the tyranny of flatness and enabling creative display implementations. By then, second-generation FEDs may have proved their mettle and shaken up the technology mix. And certainly by then, if FPDs can match CRTs in both image quality and cost, the venerable CRT, which has served so well for so long, will finally bite the dust. ■

David Lieberman *is a veteran display journalist residing in Massachusetts. He is the co-author of* **Flexible Displays and Electronics: A Techno-Economic Assessment and Forecast** *published by Intertech Corp. (www.intertechusa.com). He can be reached at davidlieberm@verizon.net.*

editorial

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column, the 30th, is also his last, as David relocates his offices to Waltham, Massachusetts, and refocuses his energies. He can now be reached by phone at 781/893-8760 and by e-mail at davidlieberman@verizon.net. And I will need a new excuse to exchange e-mails with David and enjoy his wit and insights. I am sure I will find one.

— KIW

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Going Out on a Limb

by David Lieberman

I received a letter from a reader a few weeks ago expressing appreciation for a particular column that looked at the state of displays ten years ago in 1994 ("A Stroll Down Memory Lane," *Information Display*, June 2004). The reader also expressed disappointment, however, that I did not also project my gaze forward and discuss how things might be a decade in the future and "what the display business will look like in 2014."

Quite a challenge. As a journalist, I tend to spend my mental energies trying to understand the present (a difficult enough task), how we got to the current state of affairs (a ponderous chore), and what the near-term movements might be, *not* what might happen well down the road. Nevertheless, a reader request is a reader request, so, unaccustomed as I am to prognostication, I will don a seer's cape, put on a prophet's hat, borrow a crystal ball, and go out on a limb to explore some possibilities. I will, however, take refuge in the pose of the logician, resorting to "if...then" statements.

If OLED makers focus their efforts on small displays in the near term, then they will be well positioned to achieve critical mass in the next decade, and, by 2014, they will be well entrenched in a number of market segments, ready to move on to expand their conquests. The vacuum fluorescent displays used in radios, appliances, and elsewhere are in a vulnerable position, as are the LCDs used in radios, cellular telephones, and handheld gaming equipment. With the right mix of pricing and performance, OLEDs may also extend the use of displays to applications that now incorporate only idiot lights (indicators) or have no visual-feedback medium at all.

If the makers of the various kinds of so-called e-paper displays can capture and maintain the support of large corporate champions, either as co-developers or customers, they will gain a modicum of success. I have not yet been convinced that there is a bright future for e-books, despite the sensible arguments surrounding their appeal. Nevertheless, there are a number of other mid-sized-display applications that would benefit from the high pixel density and low power consumption of e-paper displays.

If economic conditions improve to the point where companies serving certain market segments are willing to make short-term investments for the sake of long-term gains, electronic signage will become an explosive arena for flat-panel displays. By 2014, point-of-sale displays will be pervasive, and, if all the infrastructure issues can be worked out, grocery stores, department stores, and other retail outlets will be awash in dynamic signs. These will include small alphanumeric shelf signs with pricing instantly changeable and consistent with the store's database; overhead signs identifying the products in particular sections or aisles; and promotional signs drawing shoppers' attention to particular items and ad hoc specials.

If display prices come down (as they are expected to) and infrastructure issues are resolved (as they will be), electronic displays will become common in such venues as movie theaters by 2014. Reels of film will go the way of the dodo, upstaged by cinema-quality digital projectors based on digital micromirror

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calendar

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December 8–10, 2004 Niigata, Japan

International Display Manufacturing Conference & Exhibition (IDMC '05). Contact: www.di.nctu.edu.tw/IDMC05.
February 21–24, 2005 Taipei, Taiwan

SID International Symposium, Seminar & Exhibition (SID '05). Contact: SID HQ, 408/977-1013, fax -1531, e-mail: office@sid.org.
May 22–27, 2005 Boston, Massachusetts

The 25th International Display Research Conference (EuroDisplay 2005). Contact: Mark Goldfarb, PCM, 212/460-8090 x202, e-mail: mgoldfarb@pcm411.com
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