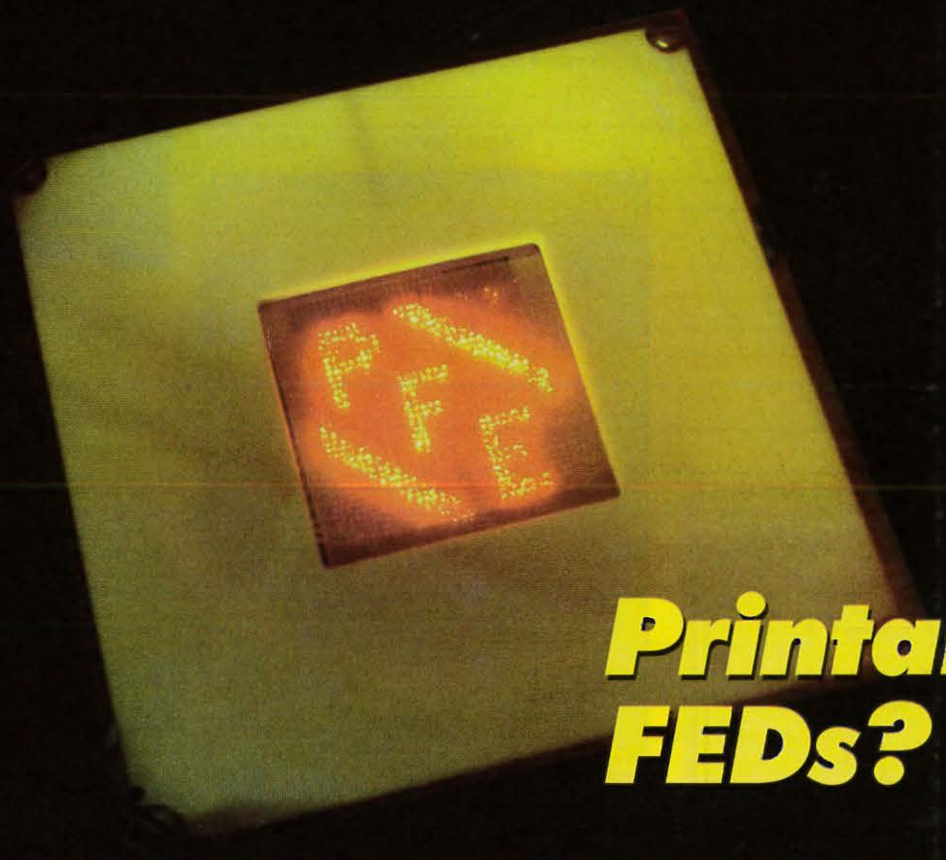
CRT ISSUE

Information DISPLAY

June 2000
Vol. 16, No. 6

SID

Official Monthly Publication of the Society for Information Display



Printable FEDs?

- *Printable Large-Area FEDs*
- *Using FEAs as CRT Cathodes*
- *Computer Entertainment Displays*
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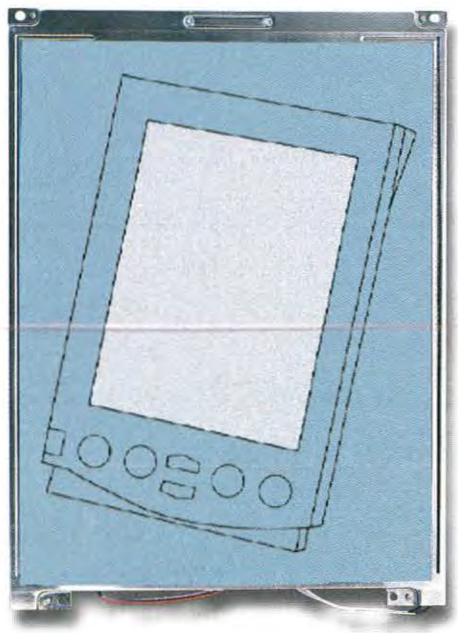

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Circle no. 1

BPA INTERNATIONAL

COVER: If all the materials and structures necessary for an FED could be printed directly on the substrate, an inexpensive large color display could be fabricated. The engineers at Printable Field Emitters, Ltd., believe that all the necessary technologies now exist, as do several 32 × 32-pixel prototypes, one of which is shown here. For more information, see the article beginning on page 14.

Printable Field Emitters, Ltd.

For more on what's coming in *Information Display*, and for other news on information-display technology, check the SID Web site on the World Wide Web: **http://www.sid.org**.

Next Month in
Information Display

Microdisplay Issue
- LCoS Technolgy and Applications
- Manufacturing LCoS Microdisplays
- Microdisplay Markets
- Plastic LCDs to Roll
- IDMC Preview

INFORMATION DISPLAY (ISSN 0362-0972) is published eleven times a year for the Society for Information Display by Palisades Institute for Research Services, Inc., 411 Lafayette Street, 2nd Floor, New York, NY 10003; Leonard H. Klein, President and CEO. EDITORIAL AND BUSINESS OFFICES: Jay Morreale, Managing Editor, Palisades Institute for Research Services, Inc., 411 Lafayette Street, 2nd Floor, New York, NY 10003; telephone 212/460-9700. Send manuscripts to the attention of the Editor, ID. Director of Sales: Michele Klein, Palisades Institute for Research Services, Inc., 411 Lafayette Street, 2nd Floor, New York, NY 10003; 212/460-9700. SID HEADQUARTERS, for correspondence on subscriptions and membership: Society for Information Display, 31 East Julian Street, San Jose, CA 95112; telephone 408/977-1013, fax -1531. SUBSCRIPTIONS: Information Display is distributed without charge to those qualified and to SID members as a benefit of membership (annual dues $75.00). Subscriptions to others: U.S. & Canada: $36.00 one year, $7.50 single copy; elsewhere: $72.00 one year, $7.50 single copy. PRINTED by Sheridan Printing Company, Alpha, NJ 08865. Third-class postage paid at Easton, PA.

Information DISPLAY

JUNE 2000
VOL. 16, NO. 6

editorial

Small Staff, Small World

ID's relatively small staff of editors, contributing editors, advisory editors, and correspondents try hard to bring you the world – the display world, at least.

This year we plan to bring you full-fledged conference and show reports on the SID International Symposium (Long Beach, California, U.S.A.), IDRC (Palm Beach, Florida, U.S.A.), CeBIT (Hannover, Germany), SMAU (Milan, Italy), Computex Taipei (Taipei), EID (U.K.), ASID (Xi'an, China), IDMC (Seoul, Korea), CIC (Scottsdale, Arizona, U.S.A.), and IDW (Kobe, Japan). In addition, we plan to attend INFOCOMM (Anaheim, California, U.S.A.), PC Expo (New York City, U.S.A.), and Microdisplay 2000 (Boulder, Colorado, U.S.A.), and we will bring some information about those meeting to you as well.

Because *ID*'s editorial offices are located in the U.S.A., we have little trouble keeping in touch with what's going on in North America. We try particularly hard to obtain information from Asia and Europe, so that *ID* does not feel too much like a North American magazine. Our goal is to be fully international. We are closer to attaining this goal than we have ever been before. Every year I personally attend more non-North-American conferences, which allows me to obtain more articles from Asia and Europe, as well as to learn from those conferences and report on them. (It is also one of the great pleasures of this job, but we'll keep that a secret.)

Still, we are farther away from attaining the goal of complete internationalism than I would like us to be. I therefore take pleasure in every additional step we take toward the goal. One of those steps involves George Isaacs, *ID*'s very effective advertising executive in Europe. George keeps an eye out for possible articles that I might otherwise miss, while maintaining an admirable sensitivity to the need for keeping editorial and advertising decisions completely separate in a reputable publication. (This is a golden rule that many Web sites seem to have trouble remembering.)

Another step is that the editors of *ID* and the editors of *Advanced Display* have informally agreed to cooperate in order to benefit their readers. *Advanced Display* is a combination of magazine and journal that is published in Chinese to bring global advances in display technology to an audience of about 2000 that is more comfortable reading in Chinese than in English. From time to time the editors of *Advanced Display* will translate articles from *ID* into Chinese, and also translate selected articles from Chinese into English for publication in *ID*.

As many of *ID*'s readers know, there is a great deal of display manufacturing in Mainland China, as well as in Taiwan and Hong Kong, and its continued growth is virtually certain. We look forward to doing a better job of covering this important part of the display world for you.

If you have a particular interest in any other part of this continually shrinking planet, please let us know.

— KIW

We welcome your comments and suggestions. You can reach me by e-mail at kwerner@nutmegconsultants.com, by fax at 203/855-9769, or by phone at 203/853-7069. The contents of upcoming issues of *ID* are available on the *ID* page at the SID Web site (http://www.sid.org).

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a view from the hilltop

Technology.net ...

by Aris Silzars

Suppose that you have recently been asked to join a new project team developing a new display technology, but don't know all that you would like to know about the emission technology being implemented. Or what if you have joined a new start-up company, and in your previous position you were required to sign a non-compete agreement so that you must now develop a somewhat different area of expertise? Or perhaps the large company where you have spent many years and where you expected to retire has decided to divest your business unit, and with each passing day the hallway rumors hint that the prospect of termination notices is becoming ever more likely. Or, in a more positive vein, suppose that you are making great progress and would like your colleagues to hear about your recent discoveries. In these and many similar situations what should you do?

It seems that our choices are limited and easy to enumerate. We can take the lone-inventor approach and try to solve all problems through our own creativity and brilliance. We can try to find someone else on our immediate project team who knows the answers we are seeking. We can enlarge our circle and try to search out someone with the appropriate expertise in our broader corporate organization. We can do an extensive literature and patent search. We can attend a technical conference or two. We can call a colleague at a university or at another company and seek his or her advice. We can contact product vendors or attend trade shows.

Typically, we will do as many of the above as we think will help us find the answers we seek. That is as it should be, and that is where technical societies such as SID become of great value.

Imagine for a moment what our world would be like if there were no technical societies. There would be very few technical journals. There would be virtually no technical conferences, and consequently there would be no conference proceedings. There would be no membership directories to help us locate colleagues with common interests. There would be limited opportunities to share and discuss recent discoveries. There would be few seminars and specialized short courses. Perhaps some trade shows and advertising-supported magazines would still exist and maybe even try to increase their influence by publishing more scientifically important articles. But many of the most important sources of information on which we rely would either no longer exist or be much harder to access. Well, fortunately, we do have technical societies and we don't really need to worry about this peculiar scenario. Or do we?

Consider just a few more "what ifs." What if companies began to seriously restrict the submission of papers and attendance at technical conferences? What if scientists and engineers could no longer find a way to communicate with each other at these meetings? What if additional barriers were created to the interchange of scientific results? What if we all had to work in isolation?

This begins to look like a really ugly scenario. Under these conditions, it seems to me, the rate of technical progress would slow to a crawl. The rate of world economic growth would be similarly affected. The restrictions on technical information exchange would likely create other economic and political

continued on page 42

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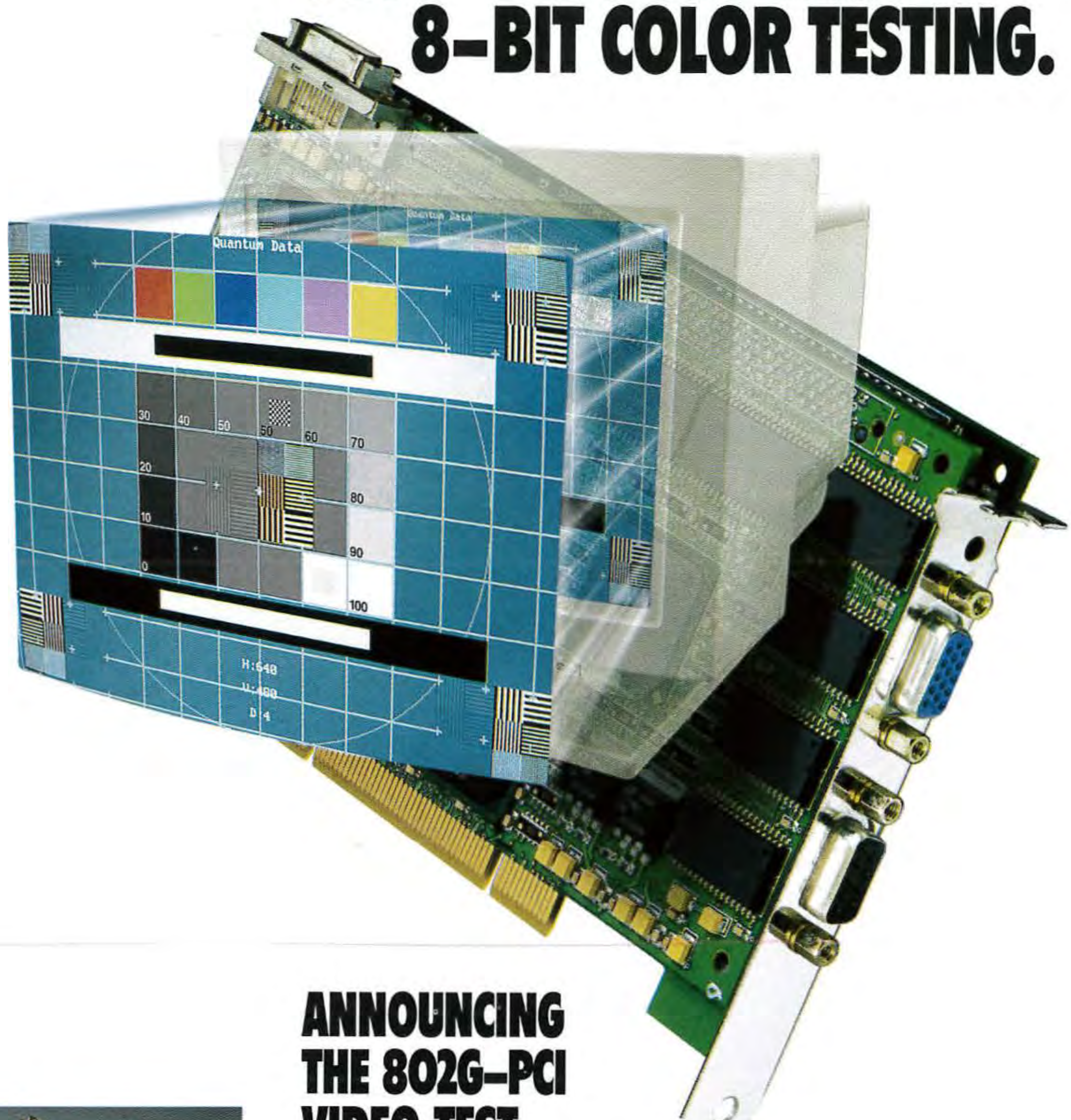

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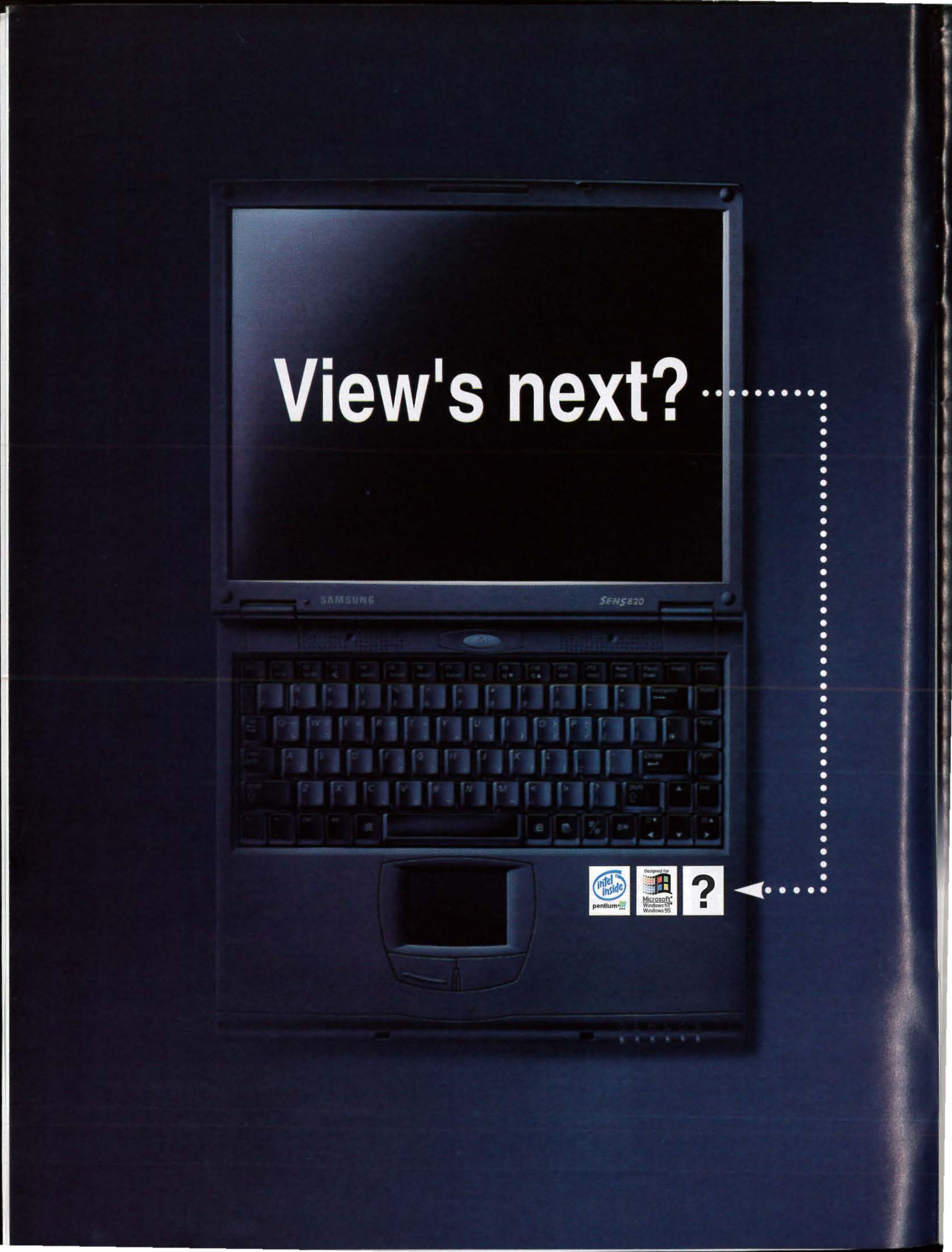
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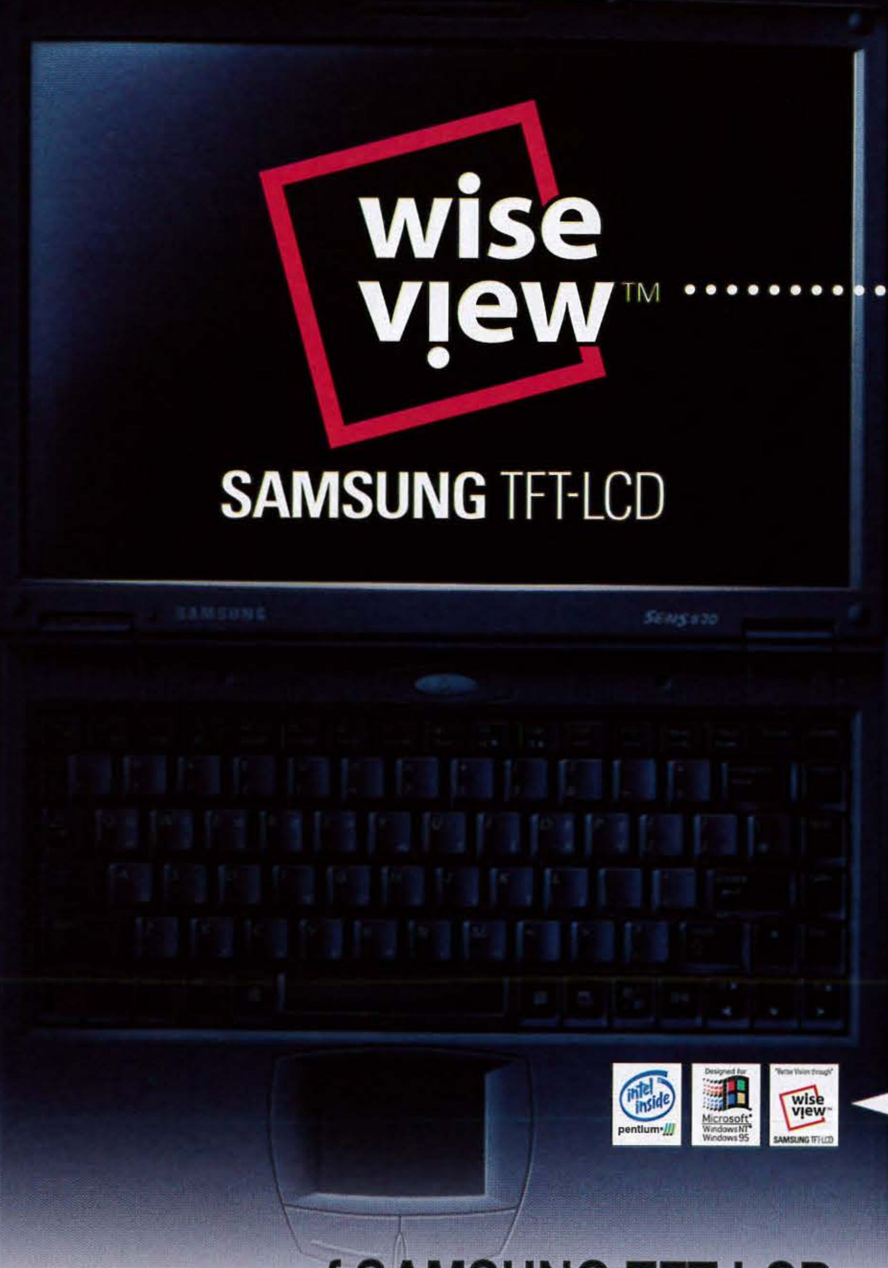

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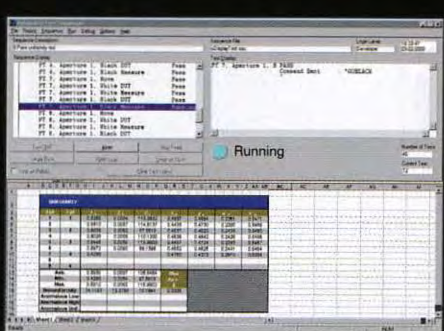

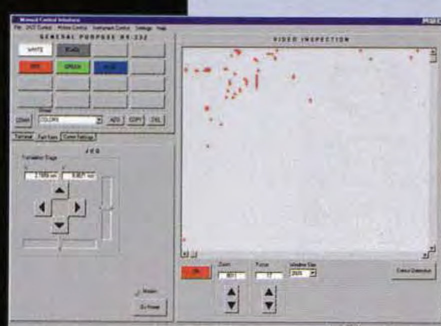

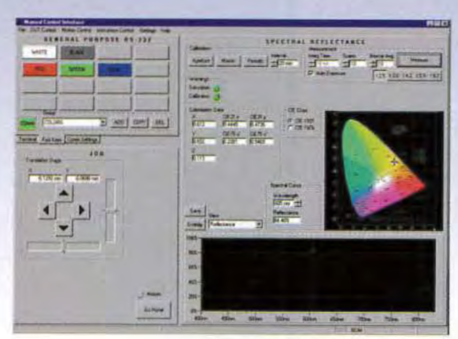

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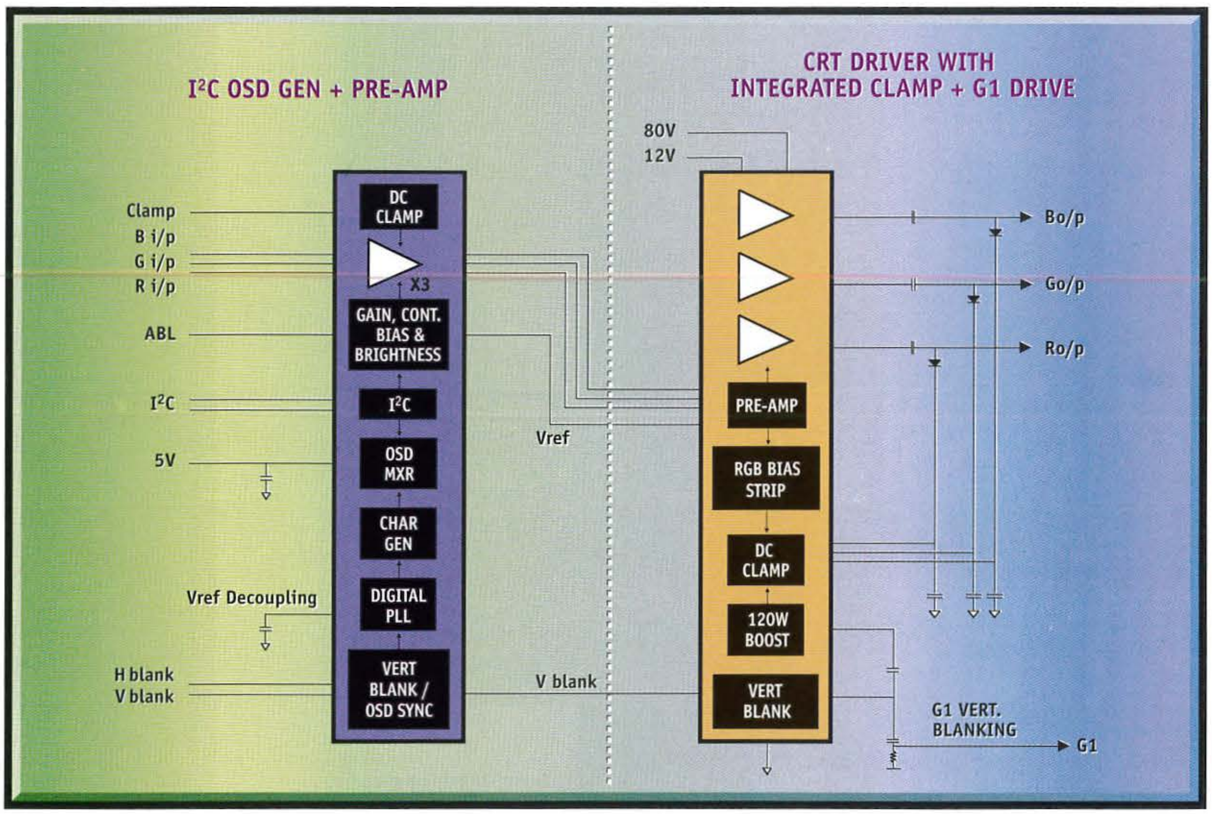

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Printable Large-Area FEDs

How close are we to creating large, affordable displays for mass markets?

by Richard A. Tuck

THE world wants a bigger view – of computer data and of entertainment content. A lot of excitement has been generated by 40-in. and larger plasma-display panels (PDPs), even though the excitement is not generally sufficient to overcome the high purchase price. Is there any hope that large displays can be made affordable for mass markets?

Despite all the work being undertaken on active-matrix LCDs (AMLCDs) and PDPs, it is becoming clear that a new technology is still required to produce 20–40-in.-diagonal displays that are affordable by the typical consumer. Field-emission displays (FEDs) have the potential to fill this gap, but their price must be reduced dramatically. FEDs that are available today, or that will be available in the near future, use gated microtip structures fabricated using semiconductor processes, and are thus locked into cost and size limitations that are similar to those affecting LCDs. Therefore, they are unlikely to exceed 20 in. on the diagonal.

Just over 4 years ago, Printable Field Emitters (PFE), Ltd., proposed the idea of a low-cost printed FED. At that time the idea was regarded as rather far-fetched by the FED community. But the wisdom of this suggestion has become apparent over the last 2 years, particularly for large displays. In fact, it now appears that all of the technology components exist to build a printed FED. Furthermore, much of the conceptual and development work has now been done by PFE. All that remains is to combine the will and the investment required to bring all of the elements together to build a large display.

A number of printed FED and FED-like devices have been demonstrated by companies such as Samsung and Canon. The Canon surface-conduction emission (SCE) display is the most advanced of these, with quite large color prototypes having been demonstrated. But SCE technology is not without its problems. Because the current-driven emitter elements are spread out across the substrate, the technology seems to be limited to displays with large (~1 mm) pixels. There is still a

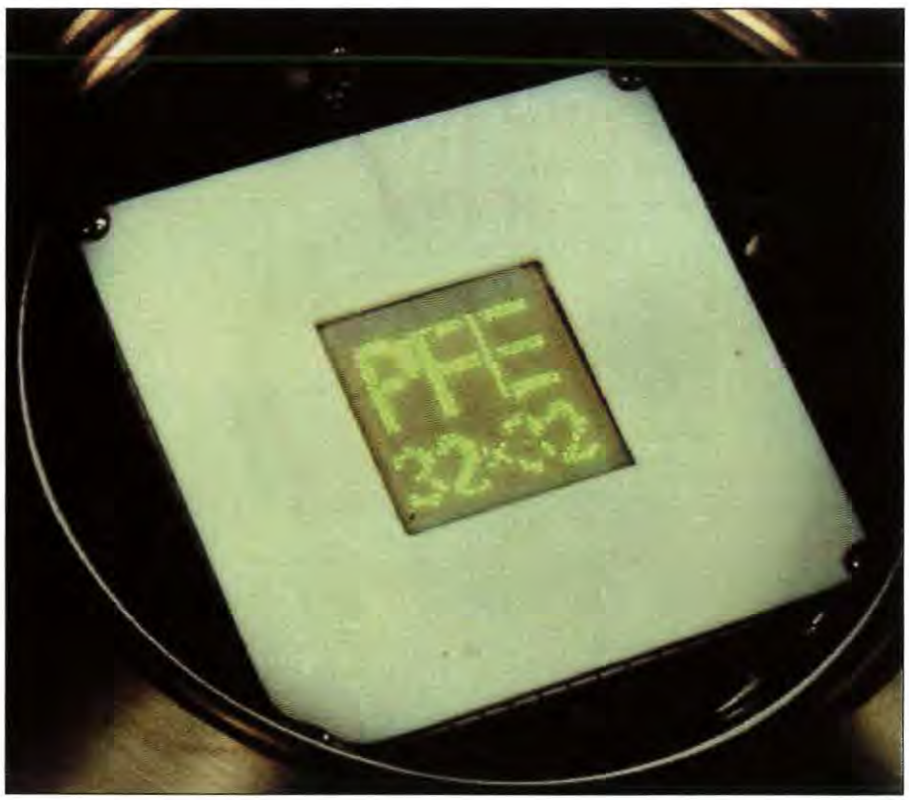

Fig. 1: The FED shown is a 32 × 32-pixel FED that uses YAG phosphors.

Richard A. Tuck is the Technical Director of Printable Field Emitters Ltd., Atlas Centre, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX1 0QX, U.K.; telephone +44-1235-445-958, fax +44-1235-445-960, e-mail: richard.tuck@pfe-ltd.com. *This article was developed from a paper presented in December, 1999, at IDW '99 in Sendai, Japan.*

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need for a consumer-priced solution for large flat panels, and the printed FED looks like a very promising candidate.

The key elements of a FED are

- A field-emitter cathode.
- An electrode system for low-voltage control.
- An anode plane with efficient phosphors.
- A spacer system between the cathode and anode.
- A gettering system.
- Glass-engineering technology.
- Drive electronics.

Our company has been aggressively developing the first two items. But before these developments are discussed, the status of the other items will be briefly reviewed.

Driven by the needs of low-voltage tip-based FEDs, considerable work has been undertaken to improve the efficiency of low-voltage phosphors. However, conventional CRT phosphors will operate in FEDs provided the anode voltages are ~5 kV or more, which greatly simplifies the problem of finding suitable phosphors.

Spacers present both mechanical and electrical problems, which have been addressed by many companies from a number of different approaches. As a result, the technology has improved over the years and there are now companies, such as St. Gobain, offering commercial products. Samsung recently described a FED with printed spacers. In addition, there are strong similarities between FED spacers and PDP barrier ribs, so it may be possible to take advantage of PDP materials. A large FED will have a larger pixel pitch than a smaller display of the same pixel format, so it may be much easier to accommodate spacers in a larger display.

Getters are required to absorb materials that may outgas in the vacuum of the display. SAES Getters has recently produced a printable getter material that activates during vacuum bake-out. Although they have yet to print it onto glass, in principle this material could be distributed throughout the panel. The ideal location would be on the anode hidden behind the black matrix.

PDP development has ensured that the fabrication of large flat evacuated panels is now a routine process. Providing that the drive voltages can be kept below 40 V, the electronics may be based upon economical CMOS processes.

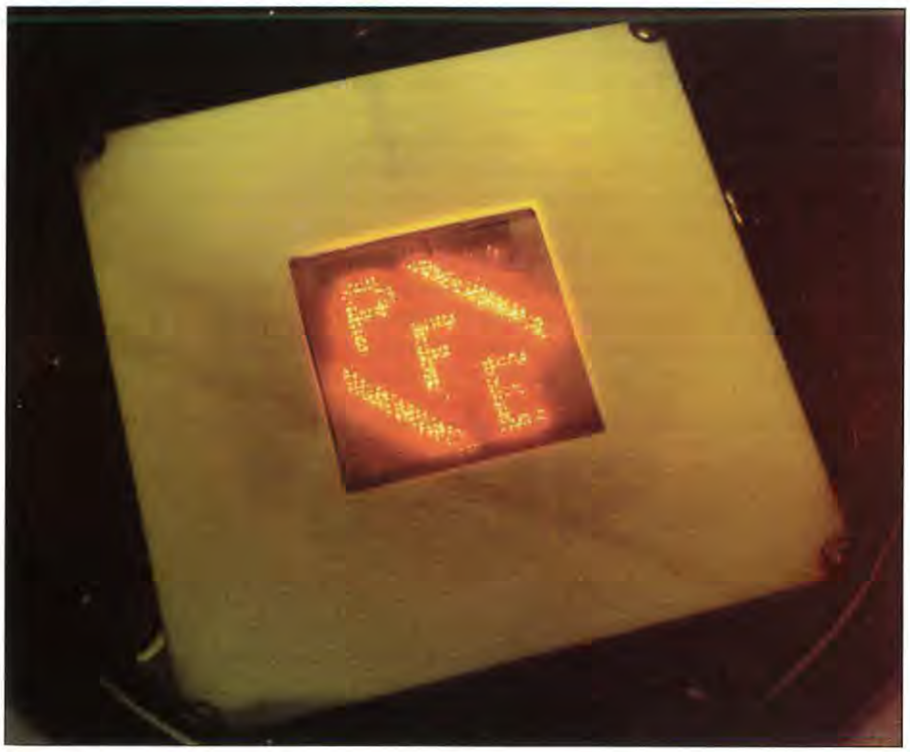

Fig. 2: This FED uses ZnS-Ag phosphors.

It thus seems reasonable that, provided the cathode plane can be made in large sizes and at low cost, FEDs in the size range of 20–40 in. could be developed and manufactured at consumer prices.

The Field-Emitter Material

PFE has created field-emitter materials that have threshold fields down to 3 V/μm and site densities close to 200,000 cm^{-2}. These have routinely been deposited on 3-in. glass wafers by spinning. (The wafer size limit is imposed only by the process equipment used.) As an interim approach, the resulting film was patterned by a lift-off process. We now have screen-printable formulations that are as good as our best spun layers, and we expect the performance of these materials to overtake the spun layers in the very near future.

Life-test data indicate that, following a conditioning period, the emission decay rate is consistent with in-display, *i.e*, pulsed, lives of over 500,000 hours to half-brightness. The materials have not yet been optimized for life, so it is reasonable to expect that these lifetimes could be extended further.

Gated Devices

If these displays are to be made at an affordable price, the key feature is low-voltage control through the use of a gate electrode. Although gated structures using broad-area (flat) emitters have been reported, the teaching was that such structures could only be fabricated on smooth substrates – with a roughness less than ~0.2 μm peak to peak. We are now routinely fabricating well-formed 10-mm-diameter gate structures on substrates with roughness of ~2.5 mm. The PFE device demonstrated at IDW '99 used thin-film deposition and subsequent photolithography for the tracks and gate insulator.

We have made both 8 × 1 and 32 × 32 gated arrays. The 32 × 32 devices were assembled into a small transportable vacuum chamber with getters and an ion pump for pressure monitoring. A number of devices have been made with surprisingly good yields (40%). Working displays have been assembled using different types of phosphors: YAG (Fig. 1), ZnS-Ag (Fig. 2), and advanced nanoparticle phosphors made by Nanox in Oxford (Fig. 3).

Since IDW '99, we have made considerable advances and now have gated devices with screen-printed addressing tracks and emitters.

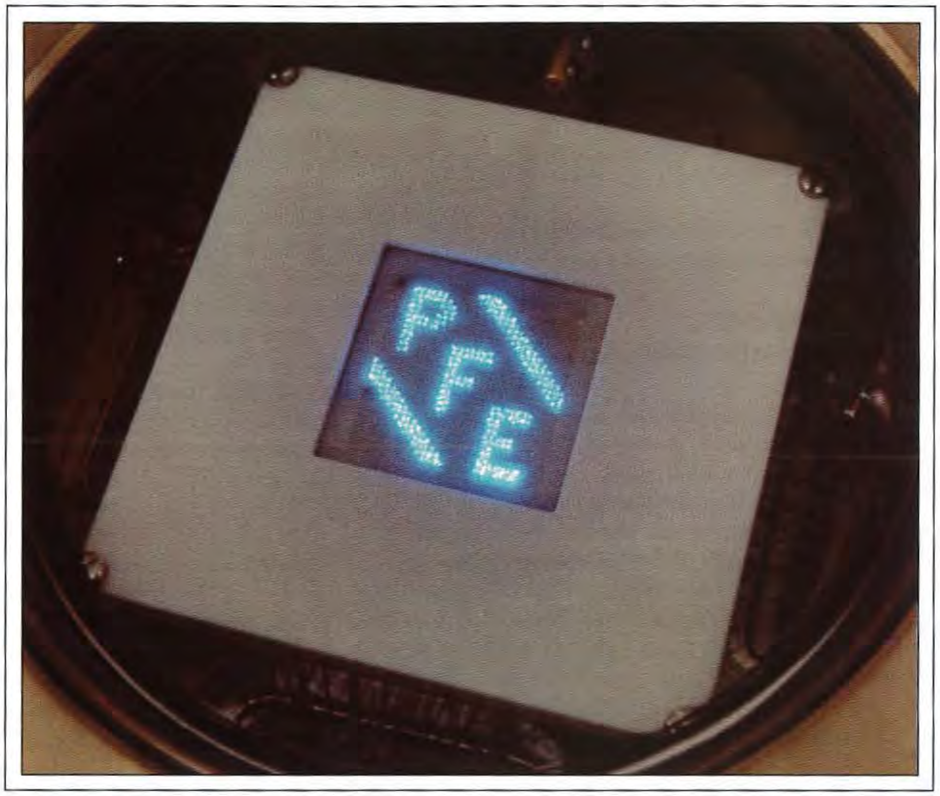

Fig. 3: This FED uses ZnS-Ag phosphors.

The switching characteristics are very similar to the thin-film versions. The devices are very stable in operation and very tolerant of both poor vacuum conditions and the inevitable gate-anode vacuum breakdown that occurs when one is testing prototype devices. For example, in one case a display operated in a stable manner despite an air leak that raised the pressure within the device to $\sim 10^{-5}$ torr.

There is clearly a pent-up demand for larger color displays in a wide range of business and consumer markets. While it appears that existing LCD and PDP technology may be inherently too expensive for mass-market sales, printed FEDs offer the promise of a solution. All of the technologies required to build a large-area low-cost FED now exist within PFE and other organizations around the world. At PFE, we believe that the question is not whether such a device can be built, but rather when will it be built? All it takes is the commitment by a company with sufficient resources to move this technology ahead, making it ready for mass production. ■

Using Field-Emitter Arrays as CRT Cathodes

Combining solid-state technology with traditional CRT designs results in a new hybrid device with distinct advantages.

by Kazuo Konuma, Yuko Okada, Akihiko Okamoto, Yoshinori Tomihari, and Soichiro Miyano

FOR MORE THAN 100 YEARS cathode-ray tubes (CRTs) have relied on a hot cathode to provide the stream of electrons used to create the image on the phosphor layer. The development of field-emitter arrays (FEAs) provides an alternative source of electrons that offers some distinct advantages over traditional CRT designs.

CRTs maintain a commanding lead in the monitor market, largely due to their bright high-resolution images and their low production cost. We may be reaching the limits of the traditional technology, however, as future displays require electron beams with larger current and smaller spot size. Hot-cathode designs may not be able to increase their heat loading much further, and it may not be possible to further improve the hole processing of the electrode.

In recent years, FEAs have been studied extensively – primarily as a technology for thin emissive flat-panel displays. FEAs have hundreds of sub-micron electron guns integrated in a small area. This design can also be used to create a high-current-density electron beam without heating. We have used these arrays in place of hot cathodes in otherwise standard CRT designs, resulting in a new type of display: the FEA-CRT.

__Kazuo Konuma__ is a principal researcher at NEC Silicon Systems Research Laboratories, ULSI Application Laboratory, Shimokuzawa 1120, Sagamihara, Kanagawa, 229-1198, Japan; telephone +81-427-71-0622, fax +81-427-71-0878, e-mail: konuma@mel.cl.nec.co.jp. __Yuko Okada__ is an engineer, __Akihiko Okamoto__ is a manager, and __Yoshinori Tomihari__ is an assistant manager with the NEC Silicon Systems Research Laboratories, Japan. __Soichiro Miyano__ is a manager with the Electronic Component Development Division, NEC Corp., Japan.

The FEA Electron Gun

The FEA chip relies on Spindt-type emitters made of molybdenum cones with sub-micron tungsten gate holes (Fig. 1). A vertical current limiter (VECTL) with a trench structure protects the FEA chips from damage by an arc electric discharge. The FEA chip has 868 electron sources arranged within a 50-μm-diameter emitter circle. The focus electrode surrounds the emitter area like a collar, and controls the potential distribution near the cathodes to converge the emitted electrons.

The electron emission characteristics vary depending on the gate diameters D (Fig. 2). The electron beam has a lower voltage as the gate diameter becomes smaller.

Conventional hot-cathode electron guns and the newly developed FEA electron guns have nearly identical structures. In a hot-cathode design, the BaO cathode is heated and the electrons are converged in the electron gun, which consists of a cathode and G1 and G2 electrodes. This structure requires dimensional precision to form an electron flux with convergence between the control electrodes.

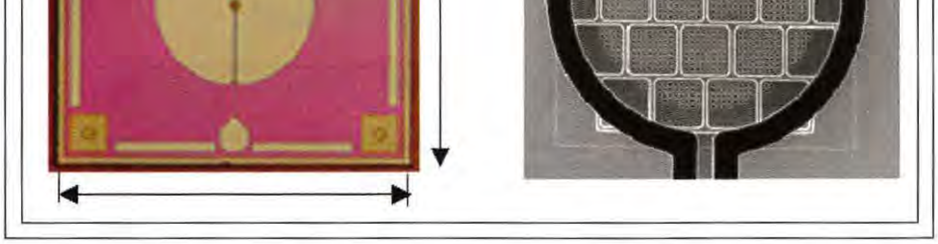

Fig. 1: An FEA chip for CRT cathodes in (a) plane view and (b) an expanded view.

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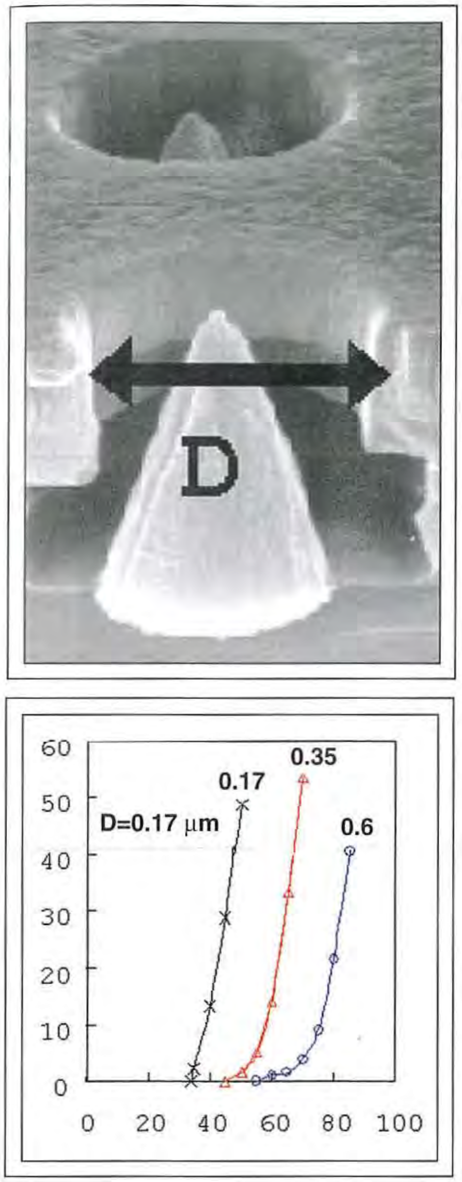

Fig. 2: The emission characteristics of the FEA depend on the gate diameter.

The structure of the main lens in an FEA gun is the same, although the G1 and G2 electrodes have a larger hole diameter. Both designs need just two signal pins. The hot-cathode gun needs them for the heater, while the FEA gun needs them for the gate and focus electrodes.

The FEA electron gun has three important characteristics. First, the gun does not require a heat source to produce the electron beam. The electron-source substrates are mounted just below the G1 electrode, without heater

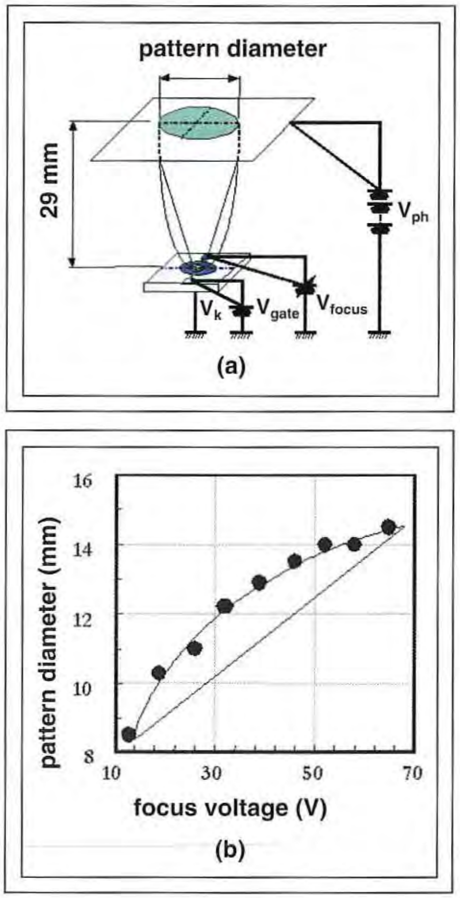

Fig. 3: The emission distribution of an experimental FEA (a) with V_{ph} = 2 kV and V_g = 65 V and a focus-electrode voltage between 15 and 65 V produced a range of illuminated pattern diameters (b).

wires. Second, the electron beam does not cross over the way a hot-cathode beam does.

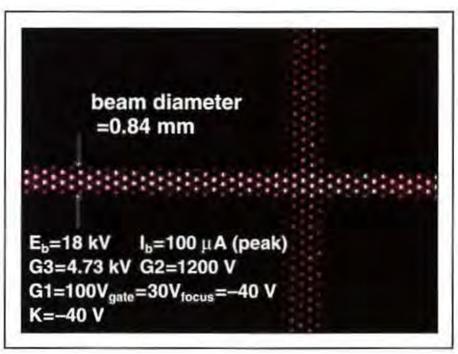

Fig. 4: This magnified view of crossing lines on an FEA-CRT also shows the experimental conditions and the measured beam diameter.

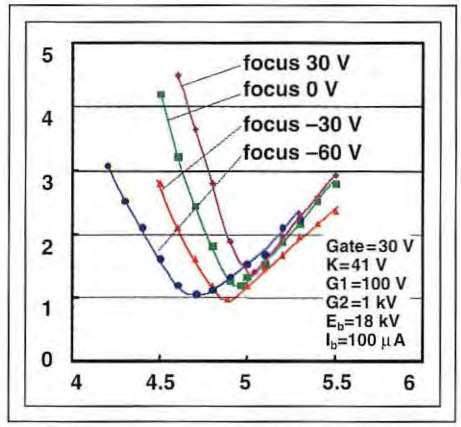

Fig. 5: The FEA-CRT electron-beam diameter is made smaller by applying negative focus voltage.

And, third, the quantity of electrons emitted is controlled inside the gate hole and does not influence other components outside the emitter's and gate hole's immediate vicinity.

The FEA-CRT

An FEA-CRT has nearly the same drive set as a conventional CRT. The main difference is that two bias-potential circuits are needed for the gate electrode and the focus electrode. The FEA-CRT can be driven with a smaller cathode-conversion amplitude than that of a hot-cathode CRT.

Tests of an FEA-CRT demonstrate that the illuminated pattern is smaller when the focus-electrode voltage is lower than the gate volt-

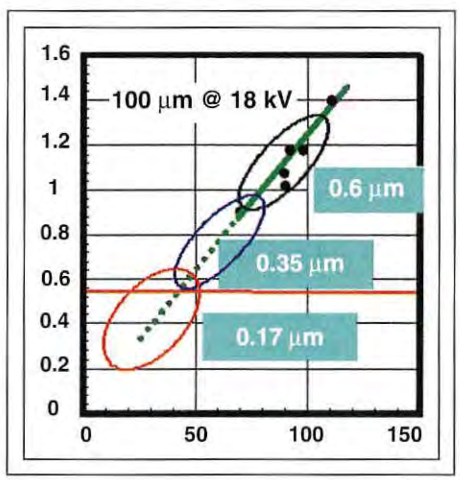

Fig. 6: The FEA-CRT beam diameter gets smaller as the gate cathode voltage is reduced.

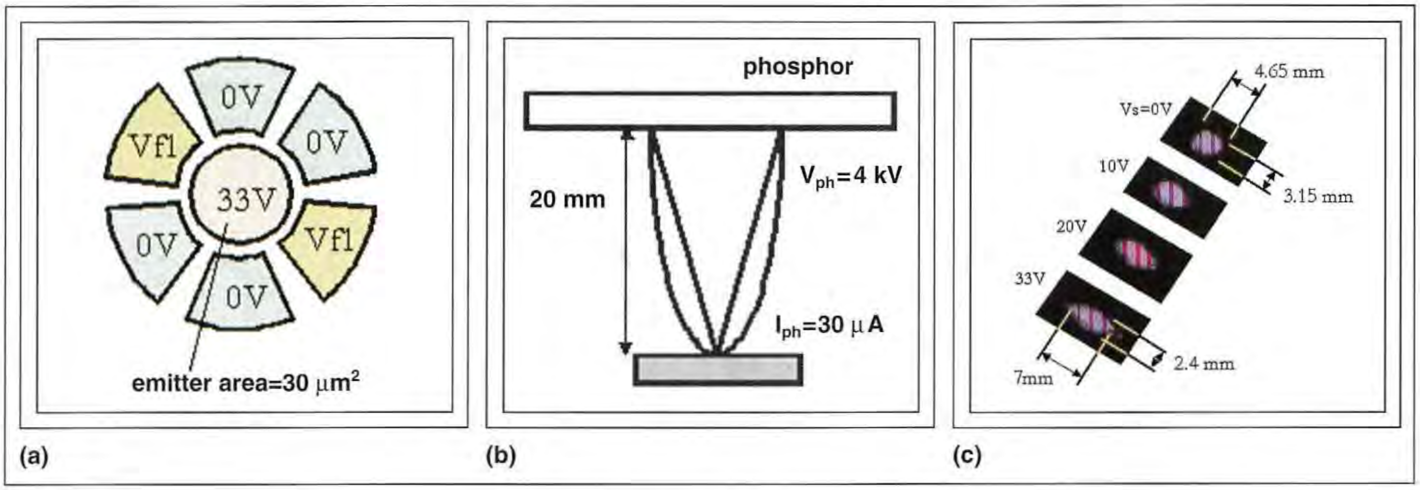

Fig. 7: FEA-CRT beams can control beam spread with focus electrodes; this shows (a) the chip layout, (b) the measurement setup, and (c) the illuminated pattern.

age (Fig. 3). Although the electrons from the cone tops are spread, the beam is immediately converged by the focus electrode, which can precisely control the beam.

The FEA-CRT displayed an excellent color chart on a 15-in. screen using three separate FEA chips in an in-line configuration. The beam diameter was measured for the center electron gun (green) using a grid-pattern signal (Fig. 4). The E_b voltage is 18 kV – lower than in a conventional CRT – and the minimum electron-beam diameter was 0.84 mm.

Beam diameter varied depending on the G3 electrode potential (Fig. 5). The potential of the focus electrode was changed as an experimental parameter. The lower we made the focus potential, the smaller the minimum beam diameter became. The focus potential reduces the spread of the emission electrons and makes the beam narrow at the main lens, which causes the focal point to fall beyond the screen. By lowering the G3 electrode potential and thus making the focus point closer, the minimum spot size is focused at the display face.

The minimum beam diameter for FEA-CRTs became smaller as the gate-cathode voltage was decreased (Fig. 6). This can be explained by the reduced electron velocity perpendicular to the beam direction.

Further improvements can be realized by reducing the gate diameters, which decreases the cone pitch and results in an increase in beam-current density. This may be achieved by improving the FEA production process.

Controlling Beam Shape

Conventional CRTs employ in-line self-convergence methods to control the electron-beam shape, especially in the corners of the screen, where the beam tends to become elliptical. We addressed this problem by fabricating FEA chips with divided focus electrodes, which function as "beam-restoration electrodes" (Fig. 7). By applying different voltages to the beam-restoration electrodes it is possible to restore the form of an electron beam. The beam-spot shape is varied drastically by changing the voltage on only two of six divided focus electrodes.

These experiments with FEA-CRTs demonstrate that the beam characteristics are good, and that the electrons can be controlled using techniques similar to those used in hot-cathode CRT designs. Beam-spot size can be controlled by a low gate-cathode voltage and through the use of beam-restoration electrodes that overcome normal beam deformation. These experiments demonstrate clear advantages over hot-cathode CRT designs, and may lead to displays with better focus characteristics than traditional displays. ■

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Display Technology and Computer Entertainment

The computer-entertainment industry is divided into three parts, each with its own distinct hardware profile, display needs, and business model.

by Shin'ichi Okamoto

COMPUTER ENTERTAINMENT is an important industry. The game market in Japan was $9 billion in 1997, according to the 1999 CESA Annual Report. Computer-entertainment platforms in recent years have fallen into four distinct segments: PC, console, mobile, and location-based. We'll focus on the last three of these.

Consoles

Consoles – such as the Sony PlayStation – are primarily used by connecting them to household television sets. The basic business model is that content publishers pay a royalty to the hardware makers for the use of their hardware and format, and then sell software packages to end users, with either a disk or ROM cartridge as media. The console itself is sold so cheaply that little if any profit is made on its sale; the hardware manufacturers' earnings come from the royalties.

Because the household television set is appropriated as the display device, the display system to which the software must correspond is limited to NTSC or PAL, and the resolution (in an NTSC system) is limited to $256 \times 240 \times 30$ fps non-interlaced or about $640 \times 480 \times 60$ fps interlaced.

The situation with game consoles is very different from that found in the personal-computer (PC) business. In their pursuit of hardware sales, PC makers repeatedly introduce machines with new specifications, but a game console will keep a single specification over its entire lifetime of 4–8 years (Fig. 1). In the game-console business, the pursuit of new hardware sales through frequent model changes is less important than offering a stable technology to the companies that pay royalties to the hardware manufacturers.

This conservatism is not only understandable, it is essential. Creating a game for a leading console platform is a major software project that requires the efforts of a team of 15 creative software writers over a period of 12–18 months at a cost of about $2 million. The content creators must be confident that

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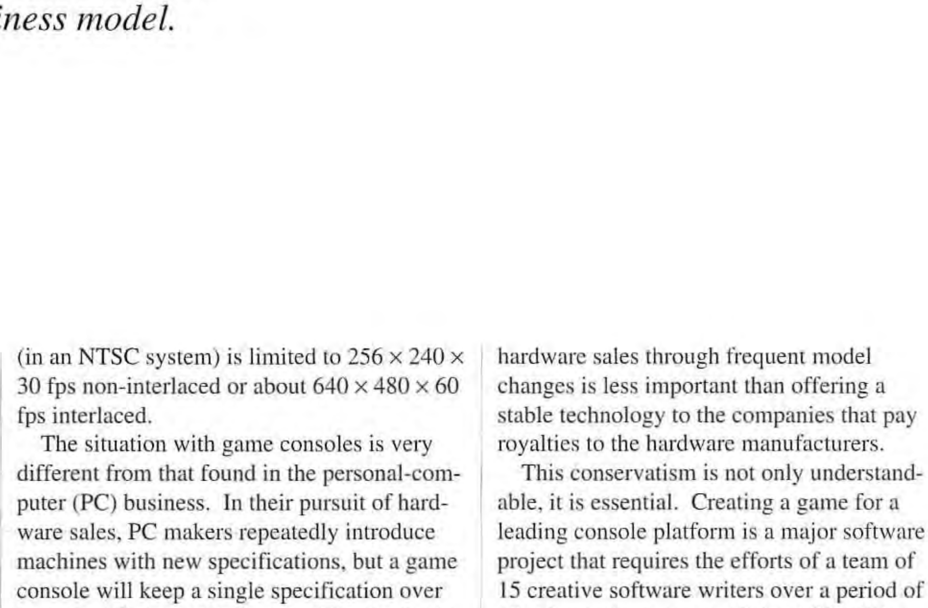

Fig. 1: Game-console platforms have are long-lived, with a life expectancy of 4–8 years.

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Sony Computer Entertainment, Inc.

Fig. 2: The Sony PocketStation is an example of a mobile entertainment platform that can use alternative (not built-in) software.

the platform they are writing for will still be around when the game is completed and placed on the market.

The console segment of the game market is also the most conservative in its use of display devices because part of the strategy for keeping hardware prices low is to exclude the display-device costs from the hardware price. Low cost is critical because high sales volume is an absolute necessity. A manufacturer must sell at least three million consoles in Japan and the U.S. if content suppliers are to be convinced they should enter the business.

The immediate next-generation display device for the console segment is the PC monitor. But because an increase in display resolution leads to an extension of the time it takes to produce the contents, and because the market requires co-existence with NTSC/PAL, a breakthrough in software technology is necessary if we are to target screen resolutions above SVGA.

Mobile Platforms

Mobile game platforms are computer systems equipped with batteries and a small display (Fig. 2). The business model can be largely divided into two parts, one that sells hardware with fixed software built in and another that is similar to the console model. Distribution of content based on network technology is currently being tested.

This mobile segment, which offers carefully integrated components from processors to display equipment, has the longest history in computer entertainment. In recent years, Japan and North America have seen an expansion of an already large business in this segment. The growth was stimulated by the introduction of new systems that supply software separate from the hardware, which has been made possible by advances in semiconductor technology.

Because energy consumption is the largest system-design issue in this segment, display devices must have low energy consumption, occupy as little space as possible, and be low in weight. Hardware that can use alternative and loadable software often incorporates a relatively high-performance processor, which makes the demand for other components that consume very little energy even more critical.

Location-Based Platforms

The location-based segment consists of entertainment systems that are more or less fixed in a given location and to which users must travel. They range from arcade games to large-scale amusement-industry rides, and include the equipment and software needed to make the system function. The basic business model is that the makers sell both hardware and software to the operators who manage the facilities and who charge the players for their use.

Compatibility with previous generations of equipment is not required in this segment, and limitations on cost and technology are the least severe. The physical size of display devices, along with their resolution and number of frames per second, can be chosen relatively freely.

For content creators, the location-based segment is an experimental arena where they can realize their new ideas for the first time. This segment also offers a chance for hardware suppliers to introduce new technology and products to the entertainment industry.

The relative freedom of hardware selection in amusement-industry entertainment facilities and high-end arcade games provides the display industry with an opportunity to work with system designers in the creation of exciting display solutions. For instance, the sense of immersion gained from connected and linked large-scale displays is the most important entertainment factor that can be offered by such facilities. Three-dimensional visual and sound effects are introduced mainly in this segment.

Capitalization on the improvement of graphics capabilities in the console and PC segments, location-based systems are beginning to concentrate on the abundant variations in display devices. But the actual size of arcade-game displays, excluding those used in high-end systems, is not that large. In many cases, CRTs of PC or consumer-TV quality are used.

How Is a Game like a Movie?

The location-based segment's business model of attracting audiences to fixed facilities is

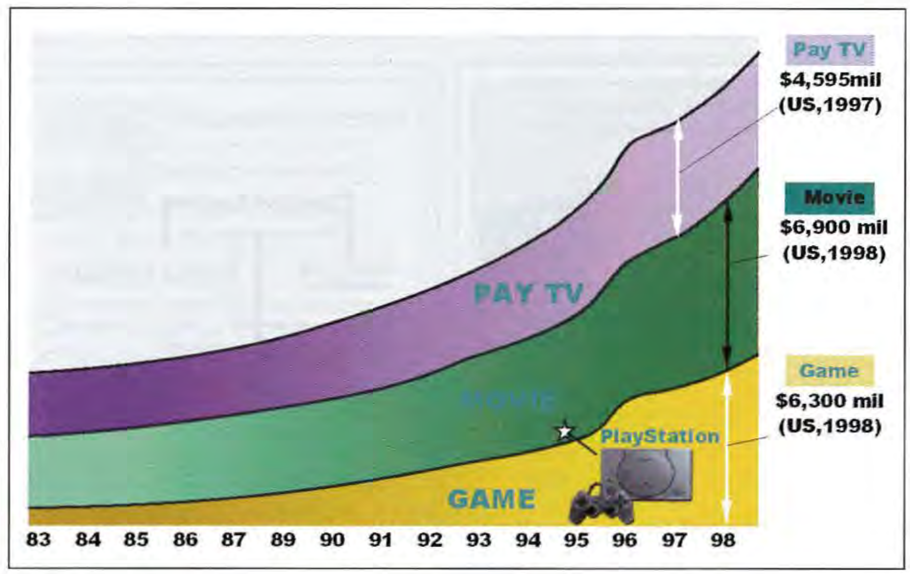


Fig. 3: VCR-based movies and games are the largest categories of paid content viewed on home television sets.

very similar to that of the traditional movie industry. The console-segment's business model, which sells contents recorded on packaged media, is very close to the VCR-based movie business model. In addition, computer-entertainment creators and creators in the movie industry – which is the largest supplier of paid content viewed on home television sets – support the same display technologies and are therefore traveling in the same direction (Fig. 3).

With recent advances in semiconductor technology, the processes of game and movie production – and the facilities in which they are produced – have become very similar. In the near future, creators that supply content to both areas are almost certain to appear, which will probably create more business links between the two industries.

It is likely that the location-based segment will find opportunities to cooperate with movie exhibitors and perhaps experience some degree of unification with movie screening facilities. We expect that display technology will be able to provide a high-resolution image of 2000 × 1000 pixels in the mid-term and 4000 × 2000 pixels in the longer term, which is sufficient to digitize cinema-quality programming.

Demands on Technology

Consoles. Because there is a desire to improve the quality of the displays used with game consoles, and because content suppliers are necessarily conservative, PC monitors with SVGA and XGA resolution are likely to become the next-generation display device, at least in the short term. Consoles will be designed to support these displays in addition to NTSC and PAL TV receivers. Content suppliers always want to expand the installed base, and this implies a narrowing of resolution variations. Although console and display manufacturers might wish it were otherwise, innovations in game-display technology are not likely to originate in the conservative console segment.

Networks. Network technology centered on the Internet is having a great effect on computer entertainment because it is an excellent medium for the communication and distribution of digital contents.

In the console- and PC-based segments, online games have become very popular. Online games have a history that is as old as the Internet itself, and can be called the first generation of network-based computer entertain-

Technology of the Sony PlayStation 2

Although the long-anticipated Sony PlayStation 2 (Fig. A) which was introduced in Japan in March and will be available in the U.S. in October, will use an NTSC/PAL TV set as its display device, it will be able to drive that device with the power of a graphics workstation (Fig. B).

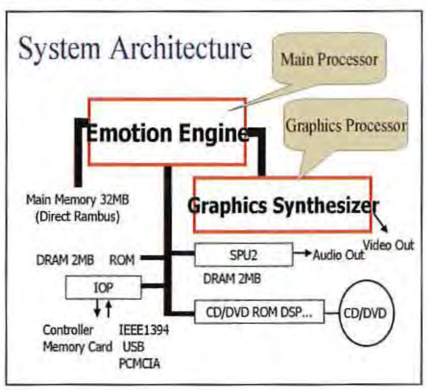
To make upgrading easier, the processing power of the PlayStation 2 is partitioned into a general microprocessor called the Emotion Engine™ and a graphics synthesizer (or rendering engine). The first-generation Emotion Engine (EE1) has 10 million transistors, the same as an Intel Pentium III™. The second-generation version (EE2), scheduled for introduction in 2002, will be made with a 0.13-μm process and will have 40 million transistors. EE3, scheduled for introduction in 2005, will be made with a 0.10-μm process and have 100 million transistors. This makes the rate of growth in processing power much greater for the EE family than for the Pentium family (Fig. C).

The PlayStation 2 will have the power to drive a DTV or HDTV set, but content providers will not create content for DTVs until a large number have been sold. When they do, the results are likely to be exciting.

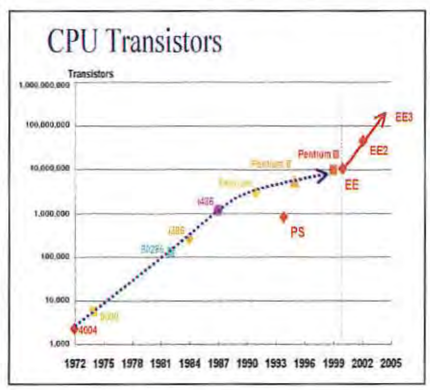
– S. Okamoto and K. Werner

Sony Computer Entertainment, Inc.

A: The new Sony PlayStation 2, a console game machine with the power of a graphics workstation, will continue the tradition of using an NTSC/PAL-format television set as its display device.



B: The PlayStation 2 partitions its computing power into a general microprocessor called the Emotion Engine™ and a graphics synthesizer. The partitioning was done to facilitate upgrading of the Emotion Engine.



C: The Emotion Engine has as many transistors as an Intel Pentium™ III, with a planned upgrade path that will outstrip the processing power of Pentium chips.

ment. The second generation of network applications will probably be based on the new cellular-telephone infrastructure. If this prediction holds true, the mobile-game segment that would be used with the cellular infrastructure could, in the mid-term, become the center of computer entertainment.

Mobile Platforms. A networked mobile platform will require a display device with sufficient resolution to support communications. If communications implies textual information, then VGA will be the initial target resolution. But ultimately, communications is likely to be based on a new man–machine interface centered on moving pictures and speech recognition, which implies an increase in bandwidth. Graphic images, sound, and the entire mix of data comprising a computer-entertainment program will be wholly transacted as digital data. Then, color-display quality consistent with the display of moving pictures will be demanded of display devices. Because input devices using moving pictures and high-quality processors will be essential, the demand for display devices with low energy consumption will continue, even with advances in battery technology.

What's Coming?

Computer entertainment, which exists in a strange land between art and technology, constantly changes by absorbing front-line technology. Improvements in semiconductor and network technology will drive the unification of entertainment and communications. PC monitors will be the next display-technology target in the console segment. We will see the production of small displays that can support moving pictures for the mobile segment and large-scale high-resolution displays that can satisfy the creative standards of the movie industry in the location-based segment. ■

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Do FPDs Need New Image-Quality Metrics?

Our metrics for quantifying image quality have been developed over the last half-century with CRTs in mind. To what extent are they suitable for newer display technologies?

by C. E. Rash, V. Klymenko, T. H. Harding, and J. S. Martin

THE rapid rate at which technology has entered all facets of our lives has influenced us in many ways. One effect is the overwhelming increase in the amount of information available to us – information that invariably is presented on displays. Visual displays are an increasingly important method of efficiently conveying data, symbols, graphs, and still and video pictures. They are on our desks, in our cars, on our wrists, in our airplanes – just about everywhere we look (Fig. 1).

While not all of this information involves life-and-death situations – such as that displayed in aircraft cockpits and nuclear-power-plant control rooms – all of it is important to some degree. For this information to be used it must be "readable." We use the concept of "image quality" to rate the ability of the information on a display to be perceived, interpreted, and used.

Many factors affect the user's ability to perceive and use the displayed information. If the information is a simple reproduction of computer-generated text, symbols, or graphics, then the major factor affecting the fidelity of the information is the capability of the display to faithfully reproduce the image information with respect to characteristics such as size, contrast, brightness, and color. If the information is a representation of some external view of the world, as from an imaging system, then, in addition to the display issues, a number of other factors will affect the user's perception of the information. These include the sensor parameters associated with the imaging system (a camera, for example), transform functions associated with conversions of the scene from one domain to another (such as spatial, spectral, luminance, or temporal), and attenuation and filtering produced by the processing, signal transmission, noise, and similar factors. But ultimately, visual performance is limited by the quality of the final image reproduced on the display.

Figures of Merit

Ensuring image quality requires some defined

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USAARL

***Fig. 1:** There are now many displays based on CRT and non-CRT technologies designed for a wide variety of applications.*

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Table 1: Image-Quality FOM Domains

Domain	Description
Spatial	Associated with angular subtense and correlated to visual acuity and spatial sensitivity
Spectral	Associated with visual sensitivity to color
Luminance	Associated with sensitivity to level of light intensity
Temporal	Associated with sensitivity to changes in light intensity

approach to assessing the image presented on the display. A number of metrics have been developed and used to quantify the various aspects of an image. These metrics are referred to as display figures of merit (FOMs).

For display imagery, FOMs can be loosely classified into four domains: spatial, spectral, luminance, and temporal (Table 1). The spatial domain includes those display parameters that are associated with the display's physical dimensions and correlate with viewer visual acuity and spatial sensitivity. The spectral domain consists of those parameters that reflect the energy distribution (by wavelength) and are associated with viewer visual sensitivity to color (wavelength).

The luminance domain encompasses parameters identified with the level of emitted energy, which correlate with the overall sensitivity of the observer to levels of light intensity. The temporal domain addresses display parameters associated with any time modulation of the emitted energy and with the viewer's sensitivity to changes in levels of light intensity.

Until the last few years, the primary display has been the cathode-ray tube (CRT). Over the past decades, a number of FOMs have been developed for measuring image quality on CRT displays. An excellent summary of a number of FOMs which are commonly used for evaluating image quality on CRTs was provided by Task and are presented in Table 2.[1] They were grouped into three categories: geometric, electronic, and photometric. These FOMs have been widely used to compare images across various CRT models and manufacturers.

But one point must be emphasized. For FOMs to truly quantify viewer ability to use the information presented on a display, these physical metrics must be matched to the requirements of the human visual system. In many cases, what the value of a particular FOM means in terms of the viewer is not known, or only known over a limited range, or for a limited set of conditions. In spite of this caveat, display FOMs have served us well.

New Display Technologies

Towards the mid-90s, several new display technologies began to flourish in varying degrees, challenging (at least potentially) the dominance of the CRT. These new technologies included liquid crystal (LC), electroluminescent (EL), light-emitting diode (LED), and plasma.

Referred to collectively as flat-panel displays (FPDs), these technologies differ from CRTs in three important ways. First, they differ in the physics of how the light energy that creates the image is produced. Plasma, EL, and LED displays are emissive in nature, but have wholly different mechanisms for light generation. LC displays are non-emissive and actually act as an array of tiny shutters, modulating the light produced by a backlight (usually a fluorescent lamp).

Second, displays based on FP technologies are more discrete in nature. While, in general, CRTs present image elements that are discrete in the vertical dimension, they are continuous in the horizontal dimension. FPDs are fully pixelated, discrete in both the vertical and horizontal dimensions. Images on FPDs can largely be thought of as an array of picture

Table 2: CRT Figures of Merit

Geometric	Electronic	Photometric
Viewing distance	Bandwidth	Luminance
Display size	Dynamic range	Gray shades
Aspect ratio	Signal/noise ratio	Contrast ratio
Number of scan lines	Frame rate	Halation
Interlace ratio	Field rate	Ambient illuminance
Scan line spacing		Color
Linearity		Resolution
		Spot size and shape
		Modulation transfer function
		Luminance uniformity
		Gamma

Table 3: Common CRT and FPD FOMs Classified by Domain

	SPATIAL	SPECTRAL	LUMINANCE	TEMPORAL
CRT	Viewing distance Resolution Spot size and shape Modulation transfer function Luminance Uniformity Signal/noise ratio Displaysize Aspect ratio Number of scan lines Interlace ratio Scan line spacing Linearity Focus	Spectral distribution Color gamut Color purity Chromaticity	Peak luminance Luminance range Gray shades Contrast raito Halation Ambient illuminance Gamma Dynamic range	Frame rate Field rate Bandwidth
FPD	Pixel resolution (H x V) Pixel size Pixel shape Pixel pitch Subpixel configuration Number of defective (sub)pixels	Spectral distribution Color gamut Chromaticity	Peak luminance Luminance range Gray levels Contrast (ratio) Uniformity Viewing angle Reflectance ratio Halation	Refresh rate Update rate Pixel rise/fall times

elements (pixels). Third, because of this truly pixelated nature, FPDs can differ further in the way that the pixels are individually lit up (or addressed). This brings us to the question at hand: Do these newer-technology displays differ from CRT displays to the point where new image-quality FOMs are necessary?

FOMs Revisited

It is reasonable to expect many of the FOMs that have been used for CRT displays to be just as usable for quantifying FPD image quality. And this is the case. However, it is equally reasonable to expect that the differences in CRT and FPD technologies must dictate the need for one or more new FOMs. For example, most users of LCDs have encountered the fall-off in luminance and contrast that occurs when these displays are viewed off-axis.

Another example is that FPDs have introduced new methods for image pixel addressing and updating, as well as for gray-scale generation. These new methods affect the temporal characteristics of FPD images as compared to CRTs. And, there is the added parameter of pixel defects. Because the image on an FPD is an array of pixels, which act independently, there is concern about how many defects exist and how they are distributed across the display. Certainly, new FOMs are required to address these issues.

Table 3 shows how current FOMs applied to CRT displays fall into the four previously defined display-parameter domains. These include those identified by Task, as well as others. The table also shows a similar list of current FOMs that can be applied to FPDs. The luminance domain – which also includes contrast – shares many FOMs across CRTs and FPDs. However, where CRTs are Lambertian sources, many LCDs exhibit a change in luminance and contrast as a function of viewing angle (Fig. 2). This angular dependence creates a need to develop a new spatial FOM, which can quantify the effect.

The color domain seems to be the least affected by the emergence of newer display technologies. FPDs and CRTs are both capable of producing monochrome and color

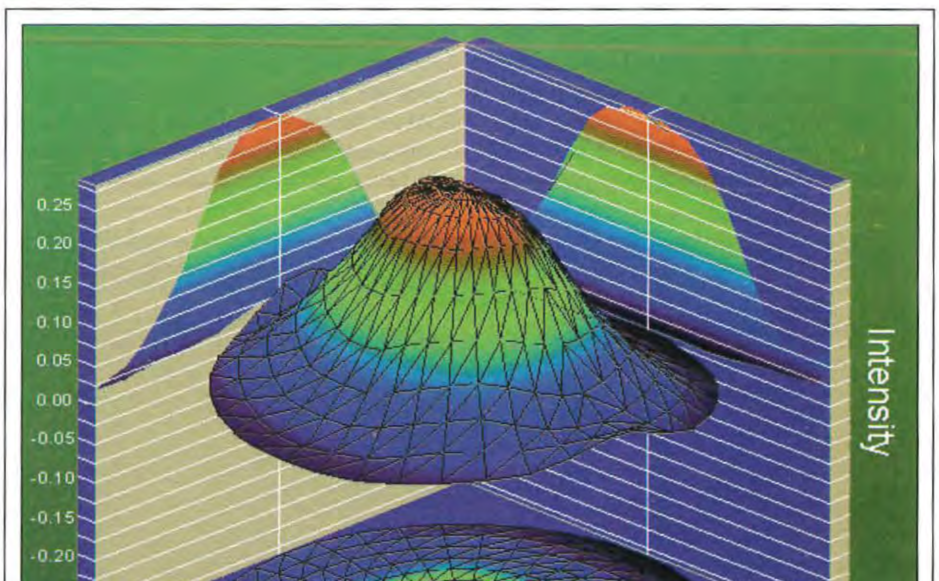

Fig. 2: Among the LCD's characteristics that must be taken into consideration in FOMs is the fall-off in luminance. This curve is representative.

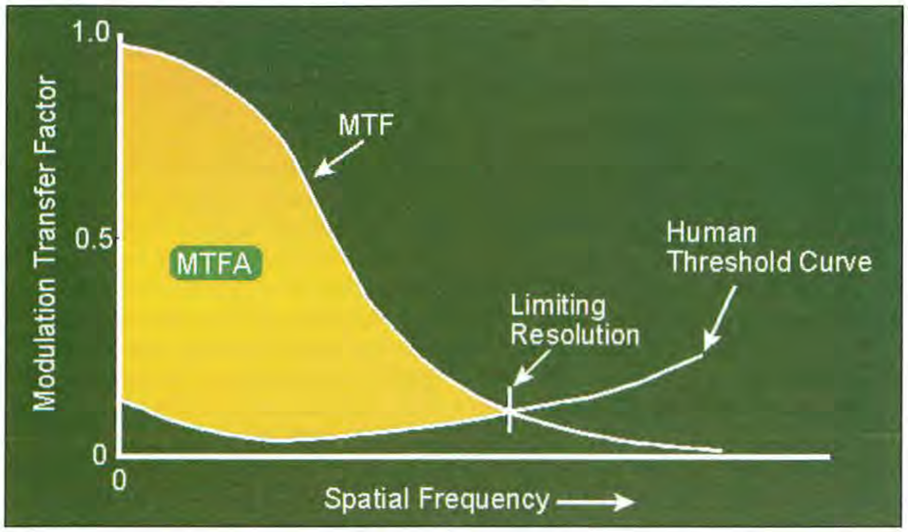

***Fig. 3:** The MTF represents a CRT's efficiency at reproducing maximum contrast over a range of spatial frequencies. The MTFA combines MTF with the human contrast-threshold curve. The point of intersection of the two curves is the point at which the display can no longer generate the contrast required for the human visual system to see the modulation.*

images, and existing FOMs effectively measure color attributes.

In the spatial domain, for FPDs, there is a definitive need for FOMs that capture the discrete nature of the FPD pixels and their potential for defects. Resolution (the ability to produce fine detail) is strongly affected by the pixel discreteness of the new technologies. In CRTs, the modulation transfer function (MTF) is, perhaps, the best-known spatial FOM. The MTF represents a CRT's efficiency at reproducing maximum contrast over a range of spatial frequencies (Fig. 3).

The human eye responds to a range of spatial frequencies. This human contrast-sensitivity function (CSF), the inverse of which is the human contrast-threshold curve, is a measure of the human eye's ability to detect contrast at various spatial frequencies. In order to match the display's MTF to the viewer's spatial/contrast sensitivity, these two functions can be combined.

The most straightforward attempt to combine the two was proposed by Snyder,[2] who developed the concept of the modulation-transfer-function area (MTFA) (Fig. 3). The MTFA is the area bounded by the display's MTF and the human contrast-threshold curve. The point of intersection of the two curves is the upper spatial-frequency limit, the point at which the display can no longer generate the contrast required for the human visual system to see the modulation.

The MTF as used in CRT displays was borrowed from the optical transfer function (OTF) used in optics. Mathematically, it is defined as the absolute value of the Fourier transform of the line-spread function. Infante has developed an MTF for discrete (matrix) displays.[3] This MTF is a function of individual active pixel size (which relates to the actual area that produces light energy) and the pixel pitch (which relates to the number of pixels per linear dimension). Similar work that proposes an improvement over the MTFA concept, and is called the square-root integral (SQRI) method, has been performed by Barten.[4]

Perhaps the most important domain in which new FOMs are needed for FPDs is the temporal domain. Even for CRTs, this domain has been generally overlooked. Some advances have been made by Rash and Becher, who developed a model to define image smearing in CRTs due to phosphor persistence and beam scan rate.[5] However, the major temporal aspects introduced by the image addressing and updating techniques used in pixelated displays pose an even more difficult problem – a problem that is becoming more urgent with the increasing use of displays for real-time video imagery.

In Conclusion

The question asked here – whether there is a need for new FOMs – is not a new one. One of the first to ask it was Snyder.[6] Like most good questions, it was asked long before the answer was available. We have over the last few years gradually adopted FOMs that exclusively address the image quality of FPDs. However, those in use are not exhaustive, and many are not validated by visual-performance studies. Continuing work is necessary, especially in the spatial and temporal domains.

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The Seventh Color Imaging Conference

The Seventh Color Imaging Conference (CIC 7) introduced its first tutorials devoted to color on the Internet, and color imaging with digital cameras was a major topic in the technical sessions.

by Jennifer Gille

THE Seventh Color Imaging Conference (CIC 7) took place November 16–19, 1999, at the SunBurst Resort Hotel in Scottsdale, Arizona. CIC 7, the premier conference for color imaging drew 312 color scientists and engineers from North America, Europe, and Asia, up from 285 last year. The conference is jointly sponsored by the Society for Imaging Science and Technology (IS&T) and the Society for Information Display (SID).

Color management and standards for the transfer of color information between devices were again important foci of the conference. Papers were presented dealing with issues of capture by digital cameras and scanners, and limning on LCDs, CRTs, and printers. Color science was further represented in sessions on color constancy, scene perception, and color appearance.

The conference began on Tuesday with a full day of tutorials, organized in three tracks of four 2-hour classes each. Topics that continued to be in demand this year included color fundamentals, color management, image quality, color appearance, color in complex images, halftoning, and color for devices (hardcopy, digital cameras, displays, and scanners). This year, the Internet debuted at the tutorials with Color Imaging on the Internet and Color Design on the Web.

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The Technical Program

The technical program began Wednesday morning with a keynote address presented by John McCann entitled "Lessons Learned from Mondrians Applied to Real Images and Color Gamuts." This address emphasized the

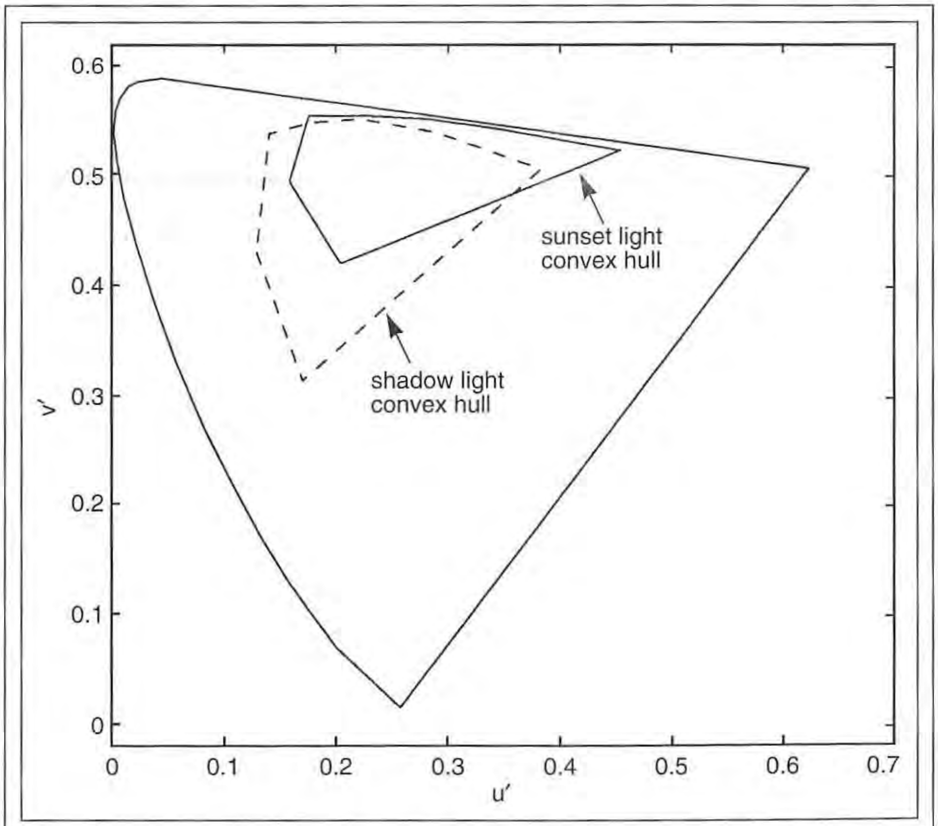

Fig. 1: Scenes captured at dawn or dusk have two sources of illumination, the low sun illuminating the objects in the scene and the skylight that is illuminating the shadows. The gamut discrepancy from the two sources, shown here on two MacBeth ColorCheckers, makes calculation of color balance difficult. (Courtesy of Shoji Tominaga et al.*)*

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importance of spatial comparisons in making color judgments, and suggested a model-based approach to calculating color appearance that relies on spatial information instead of calculating colors one pixel at a time.

In the first session of technical papers, Image Capture, five papers were presented; each dealt with a different aspect of capture by digital camera. Using a digital camera as a colorimeter in a multi-exposure multi-illuminant system was addressed by Wencheng Wu, Jan P. Allebach, and Mostafa Analoui. Francisco H. Imai and Roy S. Berns analyzed the colorimetric and spectral accuracy of spectral reconstruction in imaging using a trichromatic camera and absorption filters. G. D. Finlayson and P. M. Morovic, rather than looking at multispectral imaging, proposed a new method for overcoming the color-reproduction errors introduced by the mismatch between the spectral sensitivities of the capture device and the CIE standard observer (color correction, device metamerism). Quantization error (introduced by digitizing continuous, *i.e.*, analog, image intensities) for multispectral imaging systems was studied by Peter D. Burns and Roy S. Berns. Hiroaki Kotera, Chen Hung-Shing, and Ryoichi Saito presented a virtual color target (computer-generated LAB chips) for calibrating image-capture devices. This target has the advantages of a wider gamut (compared to photographic-material chips) that is tunable, has a uniform distribution in CIELAB space, and allows for quick estimation without real chips.

The second session on Wednesday, Scene Perception, consisted of three papers. Shoji Tominaga, Satoru Ebisui, and Brian A. Wandell presented an improved method for estimating the spectral power of image illumination. Assuming that illumination can be characterized by its color temperature, a modified correlation method was presented and applied to the problem of rendering, under one illumination, an image that was captured under another.

Paul M. Hubel discussed color balance in photographic reproduction for scenes captured at dawn or dusk, when "the light is right." At these times, there are essentially two sources of illumination, the sun that is low on the horizon illuminating the objects in the scene and the skylight that is illuminating the shadows. It is this low-sun lighting that imparts the characteristic and beautiful warm glow to images at dawn and dusk. However, this lighting also breaks the assumptions of most practical color-appearance and color-constancy models, and makes calculation of color balance difficult (Fig. 1). The paper considered which theories might be able to handle color balance for these images.

Shudeish Mahadev and Ronald C. Henry applied the Hunt94 color-appearance model to the problem of measuring air pollutants in haze for national park and wilderness areas, where the protection of visibility is mandated. They found that the model allowed the color appearance measured by an observer with a visual colorimeter to be compared to color appearance calculated from measurements made by a spectrophotometer.

The third session on Wednesday, Color Management, dealt with issues of accurate image rendering across devices. Thor Olson tackled the problem of producing smooth ramps in color-managed systems, where hue accuracy is given a higher priority than avoidance of artifacts such as contouring and banding. These are luminance artifacts, however, and are therefore quite visible. The paper concludes that more successful color management will include considering the spatial-frequency content of an image, using greater-than-eight-bit profiles, and reconsidering printer characterizations.

Raja Balasubramanian proposed three different methods for reducing the computational cost of color management, specifically color transformations using LUTs with multidimensional interpolation. The methods not only deal with the computational details of the transformations, but also exploit properties of the human visual system; all three show promise.

It may seem like trying to lift oneself up by one's bootstraps, but calibrating a scanner for a given medium without a calibration target for that medium was the topic of a paper by Guarav Sharma. The paper describes a model-based scheme that uses the spectral sensitivity of the scanner and the spectral measurements of the images to be scanned to model the medium, and then uses the scanner and medium models to provide the color calibration.

Lindsay MacDonald used the analogy with color management to propose a framework for image-sharpness management. The driving forces behind the automation of color image processing – cost, productivity, device independence, and inter-operability – are also in effect for image-sharpness processing. The paper relates the human CSF, device MTF, and the use of sharpening routines to enhance image quality. Input- and output-device profiles are used to determine luminance-channel transforms, so that an image can be expressed in a device-independent form that may include information about rendering intent.

Jack Holm wrapped up the technical program for Wednesday with a comprehensive discussion of the implications for color management of the new color-image-processing techniques that have been developed in response to the rise of digital photography, in which a digital image is produced without an intervening step as a reproduction-medium image (*e.g.*, photographic print). The many different ways that images are reproduced – displays, printing, photography – all have inherent limitations, but the errors of a good system will be visually insignificant to the viewer.

In the Thursday morning keynote address, "How to Make Pictures and Please People," Robert W. G. Hunt discussed various system limitations, the bases for assessment by viewers, and priorities and objectives in color reproduction. He found that the least objectionable errors are those likely to be changes common in everyday life, that the objectives for a system are tied to the likely use of the images, and that certain "errors" may result in images that are actually preferred.

Color Appearance and Other Matters

The Thursday technical papers began with the Color Appearance session. Mark D. Fairchild's paper explored the relationship between image contrast and overall perceived brightness. Variegated backgrounds, all of the same mean luminance but with different contrasts, were matched to uniform grays. Some observers consistently perceived increasing brightness with increasing contrast, while others judged the opposite. Averaged over the observers, luminance integration was successful in explaining the results. A related simultaneous contrast experiment found the same kind of inter-observer variability; the take-home message is that the idea of the overall brightness of a complex scene is a high-level perceptual function.

Nathan Moroney used a mathematical model of a CRT function and CIECAM97s to estimate color tolerances for an sRGB monitor. For example, he was able to show differ-

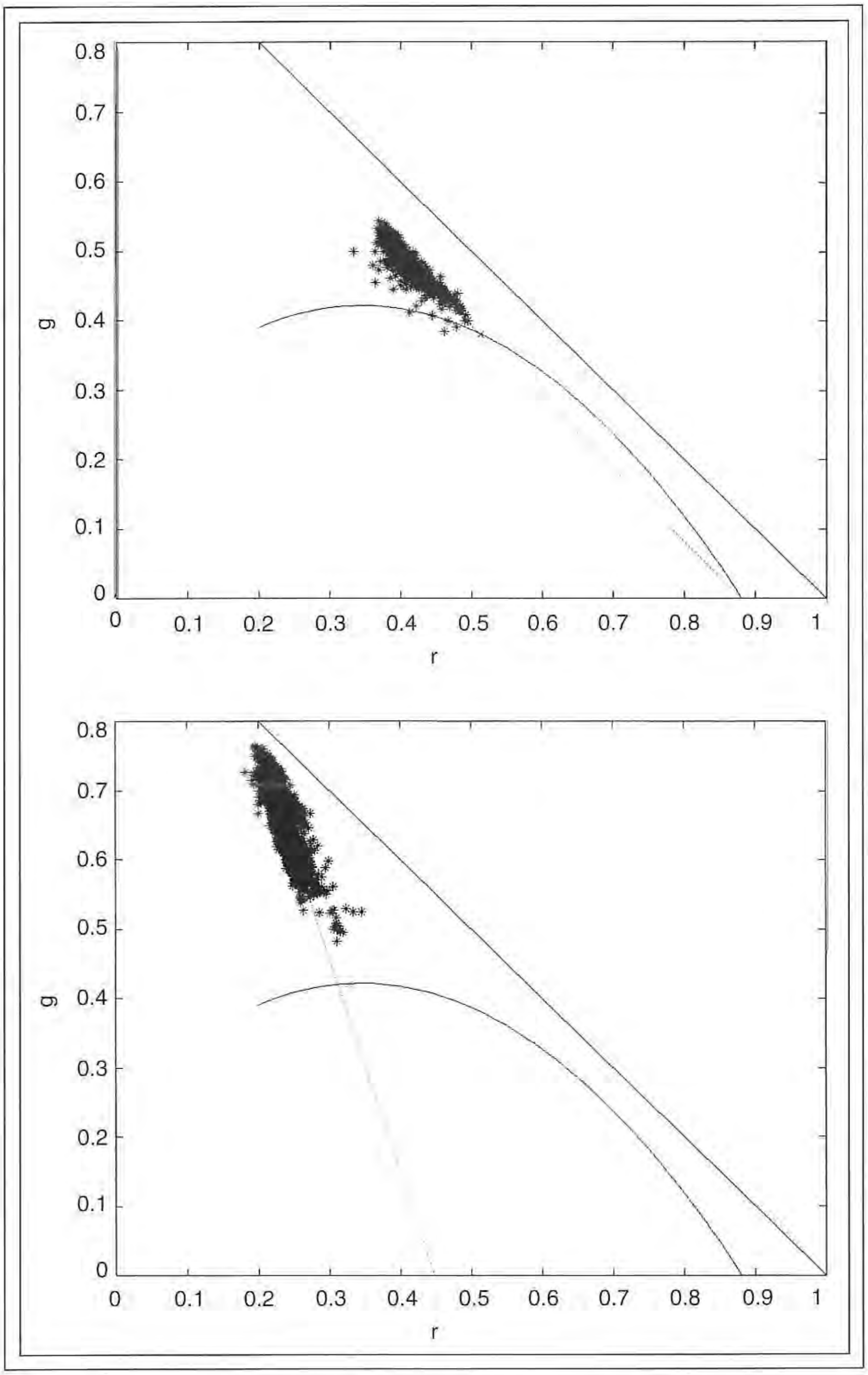

Fig. 2: The illuminant in a scene can be estimated by the intersection of the dichromatic chromaticity line and the Planckian locus. Top, illuminant A; bottom, TL84. (Courtesy of Graham D. Finlayson and Gerald Schaefer.)

ent tolerance functions for the three phosphors. Vlad C. Cardei, Brian Funt, and Kobus Barnard compared four different methods for white-point (illumination) estimation of uncalibrated images. A white-patch algorithm, a gray-world algorithm, and two neural-net methods were used. The neural-net method that was trained using the measured chromaticity of the known white patch in the training images produced the fewest errors in illuminance estimation. Adapted white points for variegated backgrounds under various viewing conditions were measured by Peyma Oskoui and Elizabeth Pirrotta. They found that the best predictor of adapted white points is the measured color of the variegated achromatic background plus ambient, and that the adapted white point for the sRGB environment is close to D65.

Color Constancy was the subject of the Thursday afternoon technical-paper session. Graham D. Finlayson and Gerald Schaefer were able to show that the illuminant in a scene can be estimated, and color constancy therefore attained, by using two pieces of information. First, statistically, most illuminants, including daylights, fluorescents, and certainly incandescents, fall very near the Planckian locus in chromaticity. Second, even a single-surface scene contains the information necessary to use the physics-based dichromatic model of image formation to plot the dichromatic chromaticity line. The intersection of this line and the Planckian locus is shown to give an excellent estimate of illumination, and to allow a superior color correction of real images (Fig. 2).

The second paper, by Kobus Barnard and Brian Funt, also presented a computational color-constancy algorithm. Some algorithms use specularities in an image to estimate the illuminant, but these rely on the presence of identifiable specularities in the scene that do not saturate the camera sensors and are the color of the illuminant, which will not be true for colored metals. The algorithm presented by the authors overcomes these limitations, and will estimate the illuminant even in the absence of specularities. Graham D. Finlayson, Steven Hordley, and Paul M. Hubel used a correlation method for estimating the illuminant in a scene, and showed that most existing color constancy algorithms can be formulated within the correlation framework.

Thursday afternoon was devoted to the Poster Session, with 26 papers, some with demonstrations, spanning the full range of topics of the conference. The high quality of the presentations made the choice of Best Poster Paper particularly difficult. The outcome was a tie between two papers, each concerned with wavelet encoding of images for different purposes. "Opponent Color, Human Vision, and Wavelets for Image Compression," by Marcus J. Nadenau and Julien Reichel, examined three color spaces that were incorporated into the JPEG 2000 compression codec, and compared their performances.

Bo Tao, Ingeborg Tastl, Ted Cooper, Mike Blasgen, and Eric Edwards looked at demosaicing algorithms for digital cameras in "Demosaicing Using Human Visual Properties and Wavelet Interpolation Filtering." The proposed algorithm differs from others in two ways: the RGB data is transformed to a perceptually uniform color space, and wavelet interpolation filters are used. Several examples demonstrated the finding that the new algorithm is superior to previous ones.

The Thursday evening talk is traditionally the forum for a different kind of presentation, something of special interest to all the participants, and this year's talk was particularly enjoyable and informative. John Warnock, CEO and founder of Adobe Systems, discussed his new company, Octavo, which is devoted to the imaging and then digitizing and recording of rare books on CDs. The motivations for this endeavor grew out of his love of old books and the desire that they be widely available for appreciation and study. For an understanding of the issues involved in imaging and reproducing rare books, the reader is directed to the company's Web site, www.octavo.com.

Friday morning began with a keynote presentation by Noboru Ohta, "Designing Color Reproduction Systems: A Perspective View." Using color photography as an example, the discussion concerned the development of improvements in color reproduction, and shed light on the interrelations among factors affecting the quality of color reproduction. The optimum color-reproduction systems which have been predicted by theoretical models turn out to be very close to systems that have evolved over time.

The first Friday morning session, Standards, contained two papers. Sabine Suesstrunk, Robert Buckley, and Steve Swen discussed differences between various standard RGB color spaces, and where each might be appropriate for the archiving, communicating, compressing, or viewing of images. Tim Kohler and Michael Rodriguez discussed standard color spaces used in ICC color management. They found that profile-based color management can run into trouble in practical implementations because of varying scenarios in print reproduction, and suggested ways that standard CMYK color spaces can be used within the ICC framework.

The second Friday morning session and the first afternoon session were Gamut Mapping I and II, with a total of seven papers. Jan Morovic and Pei-Li Sun gave an overview of statistical, spatial, and cognitive image characteristics that affect the performance of gamut-mapping algorithms, and analyzed which were most influential. Patrick G. Herzog and Hendrik Buering evaluated gamut-mapping algorithms for monitor-to-monitor reproduction, with the goal of illuminating the mechanisms of gamut mapping. Their psychophysical experiments also showed that the new "relative lightness change" technique was superior to centroid mapping. Gustav J. Braun and Mark D. Fairchild tested a set of general-purpose gamut-mapping algorithms that utilize contrast-preserving scaling functions. Their experiments examined monitor-to-printer and printer-to-printer mapping, and found that sigmoidal lightness remapping functions preserve tone and perform better than linear functions, and that chromatic compression that preserves chromatic contrast performed better than linear chromatic compression.

Printing, the final session of the conference on Friday afternoon, consisted of four papers. Patrick Emmel and Roger David Hersch introduced new mathematical models of light scattering and ink spreading for paper, and were able to make good predictions of the spectra of 100 real paper samples from two ink-jet printers. Di-Yuan Tzeng and Roy S. Berns followed up on their presentation at CIC 6 with a paper on optimal ink selection. They describe an algorithm that selects a set of six inks from a given ink database that minimizes metamerism in a halftone color-reproduction system. Gary G. Field closed the conference with a presentation defining guidelines for selecting, designing, and evaluating test images for color-reproduction quality.

CIC 8 will be held November 7–10, 2000, at the SunBurst Resort Hotel in Scottsdale, Arizona (visit http://www.imaging.org/conferences/cic8/). Among the plans for the conference are a series of "How-To" workshops on topics that have been requested by the attendees: Writing Photoshop plug-ins, understanding PDF and Postscript, building and using ICC profiles, and ColorSync workflow. These more practical workshops will be offered alongside the tutorials.

The Poster Session has been refashioned into the Interactive Papers Session, to emphasize its importance to the conference and its ability to combine attractive features of both oral and poster sessions. A Cutting-Edge Display Technologies session is planned for the demonstration of prototype displays and developers kits. Interested display developers should visit http://www.imaging.org/conferences/cic8/demonstrations.html for more information. As always, three keynote addresses will be presented by noted experts in the color-imaging field, including, by popular demand, Dr. R. W. G. Hunt. ■

7 **00**

NOVEMBER

8th Color Imaging Conference: Color Science, Engineering, Systems & Applications

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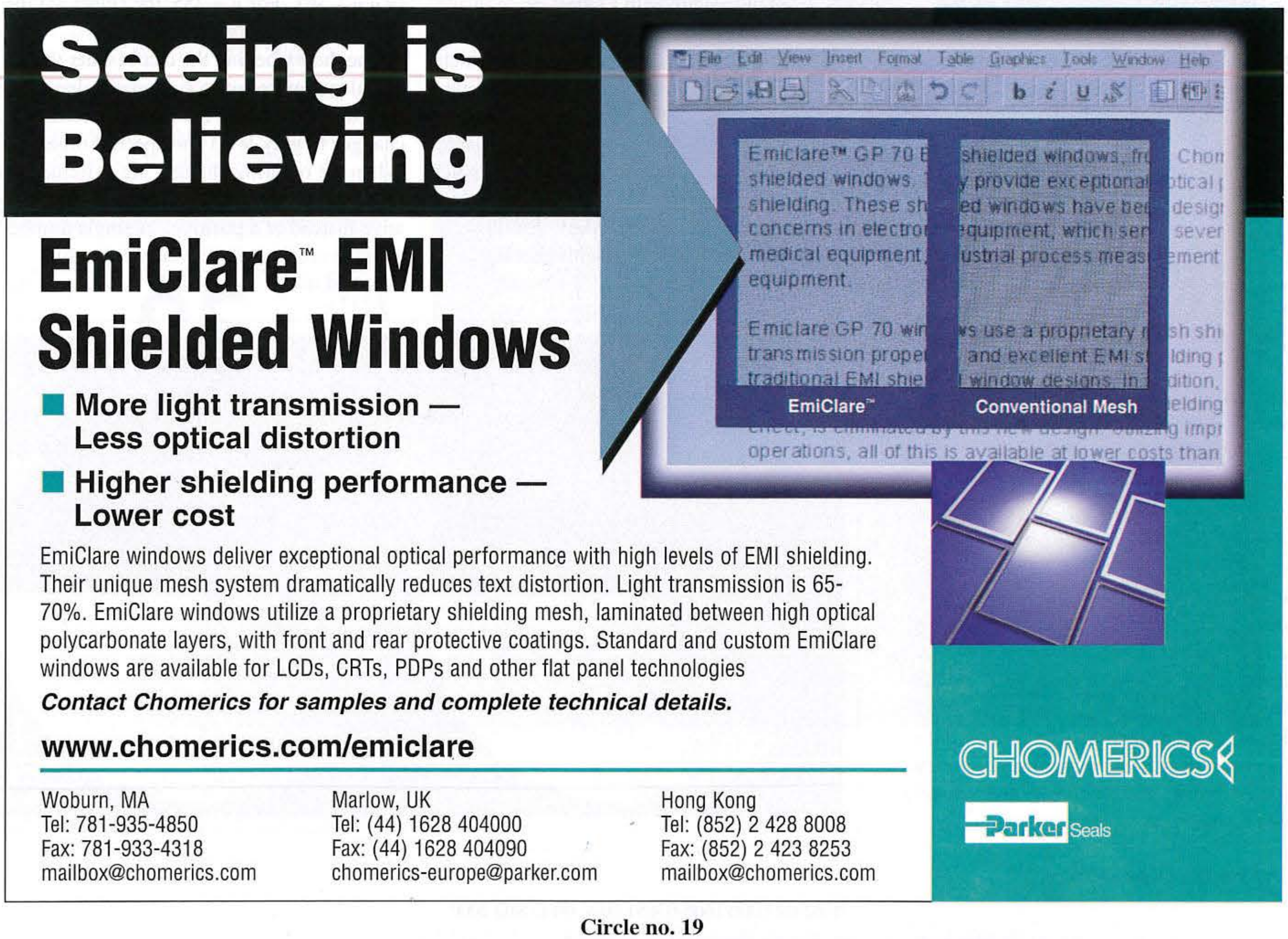

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LCD Color Reversal at a Glance

A new test pattern developed at NIDL and NIST provides a quick evaluation of LCD color and gray-level shifts with changes in viewing angle.

by Michael H. Brill

IF ONE LOOKS at a liquid-crystal display (LCD) driven by the test pattern shown in the figure, head motion reveals some interesting changes in the color and gray-level relationships. Here, "interesting" is a bad thing, as in the Chinese curse, "May you live in interesting times." Perhaps the red, green, and blue areas change to their respective complements (cyan, magenta, and yellow). Perhaps the counterclockwise progression of gray levels from dark to light is suddenly disrupted. Perhaps some sectors of one of the disks visually fuse together, and the boundary between them vanishes.

The chart shown here (by M. H. Brill, National Information Display Laboratory and E. F. Kelley, National Institute of Standards and Technology) is designed for easy detection of such "interesting" behavior. Armed with this knowledge, one can avoid annoying reversals by selecting either the display or the viewing angle. The chart – in a variety of pixel formats – has been included in the 2000 version of the SID Display Technology Showcase CD-ROM.

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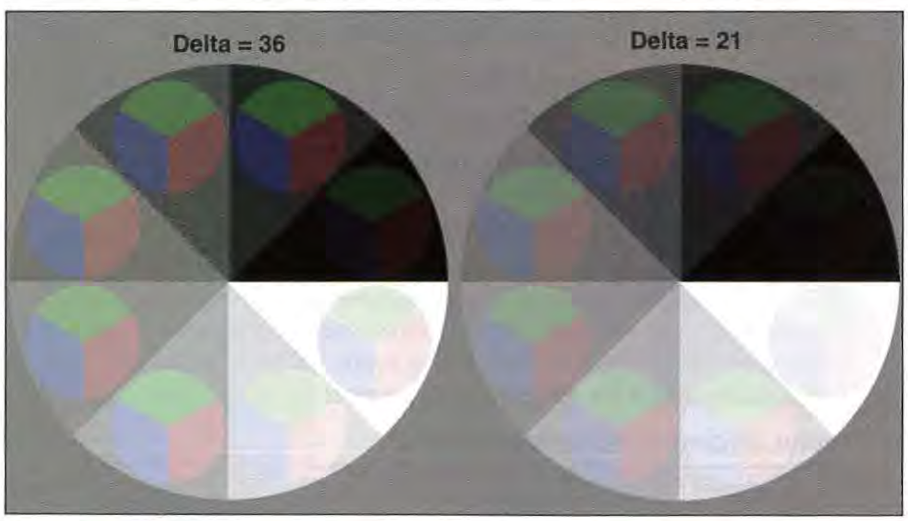
The chart is both a large-area test and a screen-uniformity test. For a large-area test, the largest circle encompasses the basic pattern; for a screen-uniformity test, that pattern is replicated (in reduced form) at nine locations on the screen, including screen corners, edges, and center.

Each major section of the large circle is a gray-level pie wedge with a small circle inside it. The small circle contains red, green, and blue perturbations on the gray wedge in which it is embedded. At the optimal viewing angle, the gray levels ascend (from darkest to lightest) counterclockwise (CCW) around the large circle. Also, the colored sections of the small circles are arranged in the CCW order red, green, and blue (a spectral order). But this spectral order might change with viewing angle.

To be quantitative, the digital value for each gray level is denoted as the same number n in all three color channels (red is r, green is g, blue is b). For a pie wedge of gray level n (one of the values 0, 36, 73, 109, 146, 182, and 219), the embedded colors have the following (r,g,b) digital values: reddish $(n + 36, n, n)$, greenish $(n, n + 36, n)$, and bluish $(n, n, n + 36)$. For $n = 255$, the colors are the same as for $n = 219$.

The theory behind the chart is that the visual system forgives systematic changes in gray level and color, but is highly sensitive to changes in gray-level and spectral ordering. When the ordering changes are extreme, it is as if we were suddenly confronted with a negative instead of a positive. A single number quantifying the color reversal is readily obtained from CW *vs.* CCW ordering of three



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labeled colors in chromaticity space. Standard color-blindness tests (such as the Farnsworth–Munsell hundred-hue test) reveal in normal individuals the visual system's ability to recognize and create such orderings [M. H. Brill and H. Hemmendinger, "Illuminant Dependence of Object-Color Ordering," Die Farbe **32/33,** 35–42 (1985/1986)]. Based on this background, a measurement procedure has been described for assessing color reversal (VESA FPDM Standard, 1998, Section 307-5). ■

7 00

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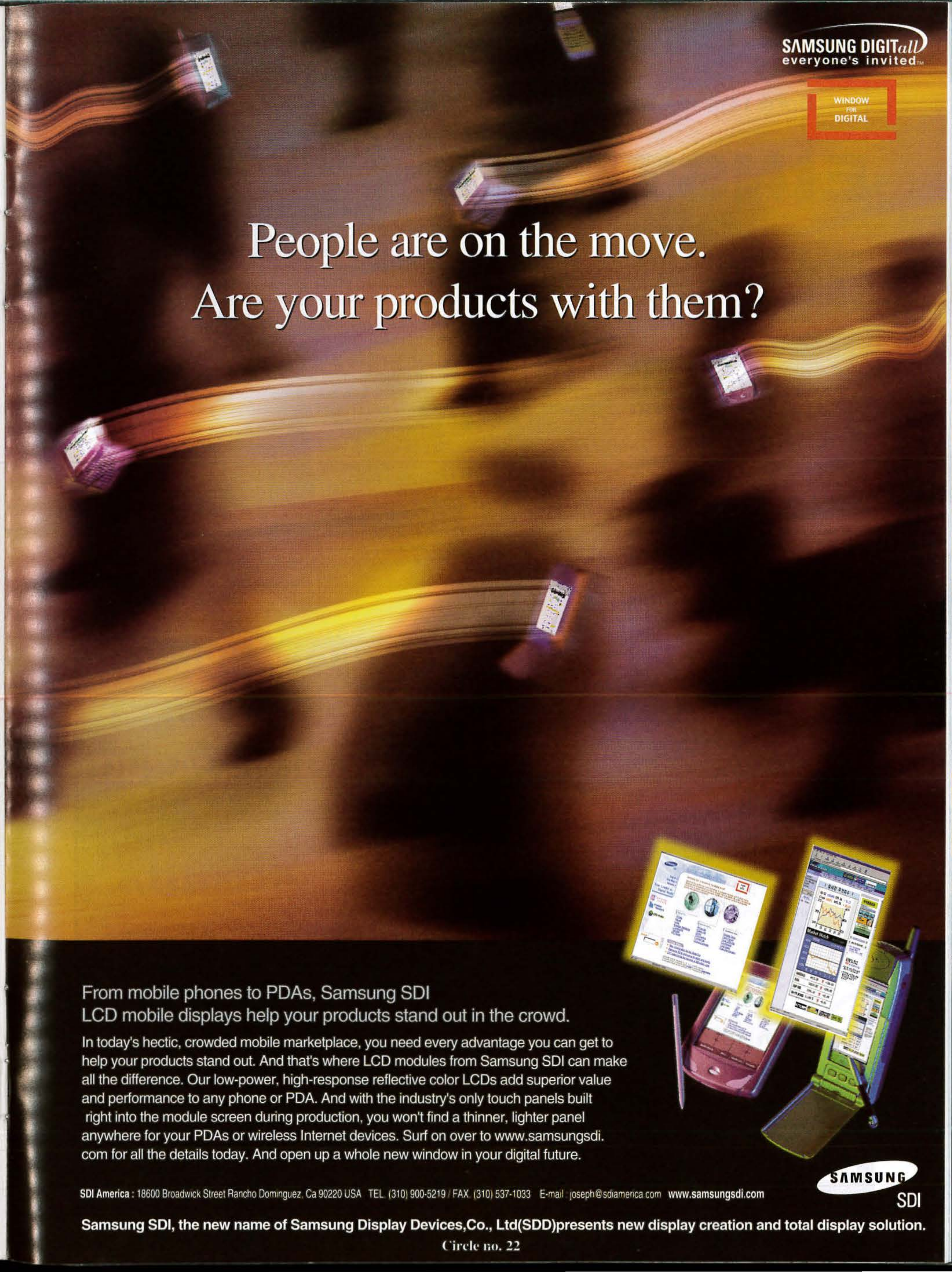
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continued from page 4

barriers. All in all, it is not a direction that most of us would want to see our world go.

Over the last several years, the Society for Information Display has been able to achieve healthy membership growth and has adhered to the principles of continuous improvement in its publications, conferences, chapter activities, and other member services. Nevertheless, we have noted that many of our members are finding it ever more difficult to justify their travel and active participation at key technical events to their managers. In spite of generally healthy economic conditions, it seems to be getting harder rather than easier to get management approvals. Temporary budget restrictions, once enacted, have the peculiar tendency to become the guideline numbers for the following year's planning. The short-term-profit culture of many companies and the need to show aggressive cost cutting to stockholders makes conference travel an easy target. Writing and publishing papers is similarly easy to restrict or eliminate for not having an immediate profit-line benefit.

Can these small decisions eventually add up and reverse our recent growth trends? Of course they can. Thus, it becomes our collective responsibility to make sure they don't. SID can and will do its part by striving to organize technical events of the highest caliber, by continuing to improve the quality and timeliness of its publications, by encouraging chapter activities that allow for the building of local professional networks, and by instituting electronic communications capabilities that allow for the dissemination of information and for interaction among all members of the display community. However, each one of us must also do our part by convincing our bosses and managers of the importance of our active participation through paper submissions and attendance at international conferences as well as chapter meetings.

In today's world, lonely inventors are very few. Even large corporations, with equally large budgets, that have tried to develop new technologies in isolation have failed spectacularly. Only by sharing our results and interacting with our colleagues do we seem to be able to keep up with the pace of technological progress and contribute to it.

Therefore, the development of a personal network of contacts within the display community takes on a major and very personal significance in regard to how successful we will be in our career growth. Once developed, this network of contacts becomes the most efficient method for gaining nearly instant access to whatever knowledge we seek. A few e-mails or a few phone calls (typically not more than three) are all that is necessary for us to be guided to the best answer that current knowledge can provide.

You may wish to start, or continue to build, your personal network by contacting me and sharing your work- or SID-related experiences. Your method of contact may be any of the following: by e-mail at silzars@att-global.net, by phone at 425/557-8850, by fax at 425/557-8983, or by the traditional (but increasingly rare) post office method at 22513 S.E. 47th Place, Issaquah, WA 98029.

Aris Silzars is President of the Society for Information Display. He lives on a hilltop in Issaquah, Washington.

SID Conference Calendar

Next Show!

The 2000 International Display Research Conference (IDRC '00)

The 20th edition of the International Display Research Conference will be held at The Breakers Hotel, Palm Beach, Florida, September 25–28, 2000. This year's conference is comprised of papers from Asia, Europe, the U.S. and Canada. The presentations reflect the current thrust of flat-panel research on organic LEDs, virtual displays, and light valves on Si for projection, printing replacing vacuum processes, and reflective displays with color or multiline addressing.

25 SEPTEMBER 00

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  - Hard Copy & Storage, Input Systems
  - Integrated Devices and Applications
  - Image and Signal Processing,
  - Color Perception, Human Factors

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Electrical Characteristics

Typical DC Magnetic Properties for AD-MU Shielding Alloys

	Material	Initial Permeability at 40 gauss	Permeability at 100-200 gauss	Maximum Permeability	Saturation Induction gauss	Coercive Force oersteds
High Permeability	AD-MU-80	75,000	100,000	300,000	8,000	0.015
	AD-MU-78	60,000	43,000	250,000	7,600	0.01
Med. Permeability	AD-MU-48	11,500	20,000	130,000	15,500	0.05
Low Permeability	AD-MU-00	*300	1,300	3,000	22,000	1.00

*Unannealed State

Typical Physical Properties of AD-MU Alloys

(Forming Temper – Not Annealed)

	AD-MU-80	AD-MU-78	AD-MU-48	AD-MU-00
Density (lb/in^3)	0.316	0.305	0.294	0.283
Thermal Expansion Coefficient/°F(68°-212°F)	7.0×10^{-6}	7.5×10^{-6}	4.6×10^{-6}	7.6×10^{-6}
Thermal Conductivity (BTU/in/ft^2/hr/°F)	136	115	90	–
Electrical Resistivity (ohm-cir mil/ft)	349	331	290	–
Curie Temperature (F)	845	761	932	–

Typical Mechanical Properties of AD-MU Alloys

(Forming Temper – Not Annealed)

	AD-MU-80	AD-MU-78	AD-MU-48	AD-MU-00
Tensile Strength (lbs/in$^2 \times 10^3$)	90	85	85	45
Yield Strength (lbs/in$^2 \times 10^3$)	35	30	40	30
Modulus of Elasticity (lbs/in$^2 \times 10^3$)	32.0	30.0	24.0	29.5
Elongation in 2" (%)	40	30	25	30
Hardness (rockwell B)	62/75	64/74	59/68	65

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